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Comparing the Feasibility of Cutting Thin-Walled Sections from Five Commonly Used Metals Utilizing Wire Electric Discharge Machining

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COMPARING THE FEASIBILITY OF CUTTING THIN-WALLED SECTIONS FROM FIVE COMMONLY USED METALS UTILIZING WIRE ELECTRIC DISCHARGE MACHINING

by

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A thesis submitted to the faculty of

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Richard C. Stephenson

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Richard C. Stephenson in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

COMPARING THE FESABILITY OF CUTTING THIN-WALLED SECTIONS FROM FIVE COMMONLY USED METALS UTILIZING WIRE ELECTRIC DISCHARGE MACHINING

Richard C. Stephenson

School of Technology

Master of Science

Wire Electric Discharge Machining (wire-EDM) is a non-traditional machining process. Controlled electric sparks are successively used to vaporize part of a workpiece along a programmed path in order to machine a desired part. Because there is no tool that comes in direct contact with the workpiece, it is possible to machine thin, delicate parts.

This thesis was designed to observe and analyze the differences in cutting capabilities for a conventional wire-EDM machine when cutting thin-walled sections from five commonly used metals utilizing a variation of roughing and finishing passes. The five metals that were used in this study are: Aluminum 6061 T6, Yellow Brass SS360, 420 Stainless Steel, D2 Tool Steel at 25 to 30 RC, and D2 Tool Steel at 60 to 65 RC. The thin-walled sections were constrained on each end by the parent material to which they remained attached, and they ranged in thickness from 0.05 millimeters (0.002

inches) increasing incrementally by 0.05 millimeters (0.002 inches) until they reached a thickness of 0.30 millimeters (0.012 inches). A Sodick AQ325L wire-EDM machine was employed to perform the machining.

It was observed that differences exist in the capabilities of cutting thin-walled sections from the five different metals. This could be both observed visually through inspection and statistically through the analysis of each data set obtained by measuring the resultant thickness of each section. It was also observed that differences exist for the same material while utilizing the variations of cutting parameters: a roughing with no finishing passes, a roughing with one finishing pass, and a roughing with three finishing passes. Thus both the material properties and the cutting parameters play a significant role in determining the capability of cutting thin-walled sections with a wire-EDM machine.

ACKNOWLEDGMENTS

It would be remiss of me to not acknowledge the help and support that has been graciously given to me in conjunction with this project and throughout my educational endeavors. Those at the forefront are the members of my graduate committee, the professors in my department, my family, and my friends. Each of these individuals has given me timely instruction, assistance, and encouragement. Each has been willing to share their insights and knowledge on this and a variety of other subjects and has made a lasting and indelible impact upon me as an individual. I express to each of these individuals heartfelt gratitude for their interest in me and my education, and for instilling in me a love of and a persistent drive towards the attainment of knowledge.

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1 Introduction

Electrical Discharge Machining (EDM) is a non-traditional manufacturing process because no tool physically touches the workpiece. The process uses an accurately controlled electrical discharge that creates a spark between the workpiece and an electrode. Each spark vaporizes a small portion of the workpiece. As the workpiece slowly moves along its cut-path, successive sparks continually erode material in the movement direction, thereby cutting the desired part.

Many different machining applications use the theory of EDM, such as Wire Electrical Discharge Machining (wire-EDM), Electrical Discharge Milling, Electrical Discharge Grinding (EDG), Electrical Discharge Dressing (EDD), Ultrasonic Aided EDM (UEDM), Abrasive Electrical Discharge Grinding (AEDG), Micro Electrical Discharge Machining (MEDM), Micro Wire EDM (MWEDM), Mole EDM, and Double Rotating Electrodes EDM.[1] Wire-EDM differs from these other processes because it utilizes a wire traveling longitudinally through the workpiece as the electrode. Wire Electrical Discharge Machining (wire-EDM) is the focus of this thesis.

Due to the use of the electric spark, practically no forces are applied to the workpiece. The absence of cutting forces achieved by the EDM process creates very unique capabilities, some of which include thin, small, and delicate part machining.

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[1] Dean Brink, "Different Types of Machining Processes That Use EDM," *EDM Technology Transfer* (2000), available from http://www.edmtt.com/articlesreports/edmprocesses.html; Internet; accessed 6 April 2006, 1-2.

1.1 Problem Statement

It is impractical to use traditional machining methods in order to cut thin parts due to the machining forces that are applied to a workpiece by the cutter. These cutting forces would destroy these delicate parts, and therefore other methods of machining need to be employed in order to produce the required parts. EDM is a process that should be conducive to this type of machining due to the absence of cutting forces. Although the technologies utilized in wire-EDM are relatively new, their use in the industrial sector has been rapidly increasing. However, very little research has been done in cutting thin-walled parts of less than 0.127 millimeters (0.005 inches) with conventional wire-EDM machines.[2] Sangseop Kim performed some research where he tested "how different materials and web thicknesses affect the capability of cutting thin walled parts."[3] The thin-walled sections that Kim cut were machined in such a way so that only one end of the specimen remained attached to the parent material.[4] The primary objective of this study is to observe the limitations in cutting thin-walled sections, which are constrained on each end, from five different commonly used metals with a conventional wire-EDM machine while utilizing the machine's default settings for different combinations of the roughing and finishing passes. This research differing from that performed by Kim in that both ends of the thin-walled sections remained attached to the parent material. This research can help to establish the threshold at which thin parts can be successfully machined while utilizing the cutting parameters just mentioned. Limitations in feasible

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[2] Kent Kohkonen, "Manufacturing Precision and Delicate Parts," *Electric Motor/Coilwinding Conference Proceedings*, (2001): 115.

[3] Sangseop Kim, *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* (School of Technology, Brigham Young University, Thesis. April 2005), 3.

[4] Ibid., 4.

cutting thicknesses were determined by comparing the data sets – measurements taken from each of the thin-walled sections – of the five different materials. ANOVA tests was performed in order to determine if there were statistically significant difference between the thin-walled sections cut from five different commonly used metals. The data was analyzed to show the effects of both material type and cutting parameters when machining thin-walled sections. A Sodick AQ325L wire-EDM machine, shown in Figure 1.1, was used to perform the experiment.

Figure 1.1 - Sodick AQ325L wire-EDM Machine[5]

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[5] Ibid., 3.

1.2 Hypothesis

The null hypothesis for this study asserts that there is no significant difference of wire-EDM cutting performance of thin-walled sections in five different commonly used metals while utilizing a variation of the rough and finishing parameters.

1.3 Delimitations

The object of this study was not to fully determine the cutting capabilities of the wire-EDM process or to determine the optimum cutting parameters and settings for a given wire-EDM machine. The machine settings were limited to the machine's default settings for the different materials, roughing passes, and finishing passes required to perform this study. The study was further limited to the use of 0.25 millimeter (0.010 inch) diameter brass wire, which has previously been specified. Six different web thicknesses were cut from five different types of materials. The largest web thicknesses represent those which were known to be achievable by current wire-EDM processes. These were used as a control, and smaller thicknesses were cut in order to provide observable data. Web thicknesses were not cut thinner than 0.05 millimeters (0.002 inches). The conclusions of this study are limited to the specific material types at their given Rockwell hardness.

1.4 Definition of Terms

Accuracy – The degree of conformity to a specification.

Alternating Current (AC) – An electrical current that flows in one direction and then reverses and flows in the opposite direction.

Ampere – The rate of flow of electrons in an electrical circuit. One ampere is equal to 6.24 billion (6.24 x 10^{18}) electrons passing a given point in one second.

Anode – A positively charged electrode.

Arch – The flow of electricity across the gap between the electrode and the workpiece.

Cathode – A negatively charged electrode.

Contamination – The particles and debris found in the dielectric fluid.

CNC – Computer Numerical Control

C_p – A measure of potential process capability. It is the ratio of the six-sigma spread of a process distribution to the tolerance of that distribution.

C_{pk} – A measure of the actual process capability. It is calculated by dividing the distance of the process mean to the nearest tolerance limit by 3 standard deviations of the process.

CTE – Coefficient of Thermal Expansion

Deionize – To have the dielectric fluid return to a non-conductor of electricity or to remove an electrically conductive substance from water to make the water a dielectric fluid.

Deionized Water – Water that has been processed through a resin bed to remove the electrically conductive substances.

Dielectric Fluid – A liquid of low conductivity, which is used to control the spark gap, control the temperature of the workpiece, cool and solidify particles, and to flush out the kerf.

Dielectric Strength – The electrical rating of a dielectric fluid that determines the point at which it changes from an electrical insulator into an electrical conductor. Normally specified as volts per mil.

Direct Current (DC) – An electrical current that constantly flows in one direction.

Discharge – The flow of electricity in the form of a spark.

EDM – Electrical Discharge Machining

Electrode – Electrically conductive tool used to carry the current to the workpiece.

Electrode Wear – The amount of electrode material consumed during the EDM process.

Electron – A negatively charged particle that orbits around the nucleus of an atom.

Filter – The component or assembly used to remove EDM chips and byproducts from the dielectric fluid.

Frequency – The number of sparks per second as determined by the spark-ON time and the spark-OFF time.

Heat-Affected Zone – The depth that the heat of the sparking has changed the characteristics of the original workpiece material.

Insulator – A material or substance that is a poor conductor of electricity.

Ion - An electrically charged atom which is formed by the loss or gain of an electron.

Ionization – The point at which the dielectric fluid changes from an insulator to a conductor of the electric current.

Kerf – A grove or notch made by a cutting tool by the removal of material from a workpiece.

Machining Voltage – The voltage between the electrode and the workpiece during sparking.

Material Removal Rate – The volume of workpiece that is removed in a given unit of time. Usually measured in cubic inches per hour.

OFF Time – Time between sparks as set by the power-supply control.

Ohm – The unit used to describe the resistance of an electrical current to the flow of an electric current.

ON Time – Time when the sprk’s electric current may flow as set by the power-supply control.

Parent Material – The material unaffected by the EDM-spark-energy temperatures.

Precision – The consistency of results in repeated experiments.

Pulse Generator – Part of the EDM machine that creates a surge of electrical current.

P-value – A measure of probability showing how likely it is that the results of an experiment have occurred randomly.

Recast Layer – The workpiece-EDM surface that consists of material that is vaporized by the spark and re-deposited onto the workpiece also including the workpiece material that is melted by the spark.

Sinter – To form a coherent mass by heating without melting.

Start Hole – Predrilled opening in the workpiece that provides a location to thread the wire.

Spark – The controlled electric discharge between an electrode and workpiece through an ionized dielectric fluid.

Spark Gap – The distance between the electrode and workpiece during sparking with the dielectric fluid in an ionized condition.

Speed – The advance rate of the workpiece perpendicular tot eh wire. Usually measured in inches per minute.

Sublimes – When a solid goes directly to a gas without melting or going through a liquid state.

Surface Finish – The EDM-machined surface produced by sparking.

Thermal Conductivity – For steady-state heat flow, the proportionality constant between the heat flux and the temperature gradient. Also, a parameter characterizing the ability of a material to conduct heat.

Tolerance – The permissible deviation from an ideal.

Vaporize – To cause to change to vapor. With EDM this often occurs through sublimation.

White Layer – A surface condition caused by the rapid quenching of vaporized and melted ferrous material in the dielectric fluid. This material has a high carbon content and becomes martensite. This martensite appers as a white layer during metallurgical inspection.

Workpiece – The material being formed into a part.

2 Background and Review of Literature

2.1 Introduction

In order to help further the utilization, capabilities, and applications of wire Electric Discharge Machining (wire-EDM) throughout the manufacturing sector, this study explored the feasibility of wire-EDM in cutting small, thin-walled sections from five different commonly used metals. Relative to the majority of other machining processes, wire-EDM is a comparatively new process. Due to its method of material removal, it has often been considered a non-traditional machining process.

> Expanding from its initially small niche of precision tooling manufacturing, its broad capabilities have allowed it to expand its influence to encompass production, aerospace/aircraft, medical, and virtually all areas of conductive material machining. Further augmented by automatic tool changers, automatic threading, slug removers, robotic workpiece changers, and palletization, this fascinating manufacturing process has attained almost virtual machining autonomy and has rightfully taken its place alongside the more conventional machining processes of lathes, mills, and grinders as self-supporting profit centers.[6]

In order to understand and study the capabilities and limitations of the wire-EDM process, one needs a basic knowledge of that process and an understanding of the machining parameters that affect the products being manufactured. A review of literature was begun by reading articles and books which provide an overview of the process, the specific components of the machine, and the parameters by which the machine functions. Some of these include *The EDM Handbook* by E. Bud Guitrau, and *Complete EDM*

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[6] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 3.

Handbook by Carl Sommer and Steve Sommer. After gaining a base of knowledge, specific articles and studies, which focus to a greater degree and depth on the key components and issues, were reviewed. A thesis written by Sangseop Kim, *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* served as a major resource for this study.

Utilizing the knowledge that I gained from this review of literature, an overview of the wire-EDM machine, its components, and machining parameters is set forth and can be seen hereafter. The subjects that will be discussed are the wire-EDM process, which includes the EDM wire, electrical discharge power units, dielectric fluid, filtration, machine movements; surface characteristics which include surface finish, thermal effect, corrosion effect, electrolysis effect; cutting speed; and accuracy. These components and parameters were important to understand given that their proper selection and use play a vital role in the cutting capabilities of the wire-EDM process.

The research conducted for this thesis is based on work done by Sangseop Kim, the difference being the degree to which the sections were constrained during the machining process. In this study, each of the thin-walled sections remained attached to the parent material on both ends while in the research performed by Kim the thin-walled sections only remained attached to the parent material on one end.

2.2 Wire-EDM Process

Electrical Discharge Machining (EDM) is a nontraditional machining process utilized to machine electrically conductive materials. Sparks which jump between an electrode and the workpiece are precisely controlled in order to successively cut a programmed path through the workpiece. One of the fundamentals "of the process is that only one spark occurs at any instant. Sparking occurs in a frequency range from 2,000 to 500,000 sparks per second causing it to appear that many sparks are occurring simultaneously."[7] Each spark vaporizes part of both the electrode and the workpiece thus increasing the distance between them at that point. As a result, the subsequent spark occurs at another location where the electrode and the workpiece are closest. This progression of sequential sparks is shown in Figure 2.1 which depicts the plunge-EDM process.

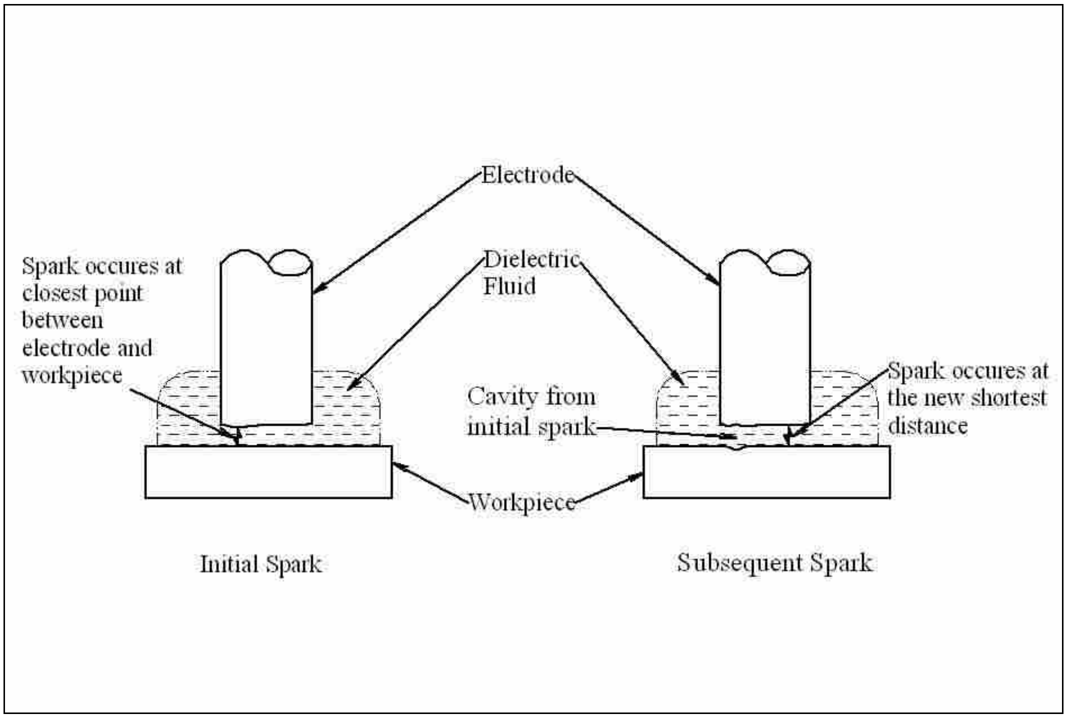

Figure 2.1 – Diagram of Sequential Sparks

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[7] Elman Jameson, *Electrical Discharge Machining* (Dearborn, Michigan: Society of Manufacturing Engineers, 2001) 1.

With regards to spark progression, wire-EDM and plunge-EDM function in exactly the same manner. A diagram of the plunge-EDM process is shown because it is easier to visualize and depict spark progression through this process.

In all EDM processes, a dielectric fluid is used to help control the spark gap between the electrode and the workpiece, to flush away eroded material, and to control the temperature of the workpiece and its surroundings.

The EDM process is being utilized in many tooling applications and "has found a home in the manufacturing of production parts, especially small parts less than one half inches square with thickness in the range of [0.127 to 2.032 millimeters (0.005 to 0.08 inches)] in wall thickness."[8] EDM is also used to produce punch and stamping dies for the automotive industry that can reach sizes of 100,000 pounds.[9] One of the most significant advantages of EDM is that it can machine any conductive material regardless of that material's hardness. Consequently, EDM has become the machining process of choice for cutting materials such a Poly Crystalline Diamond and Tungsten Carbide.

In wire-EDM the electrode is a wire. These wires can range in diameter from 0.03 to 0.3 millimeters (0.001 to 0.012 inches).[10] The wire is unwound from a spool at the top of the machine and travels vertically down through the workpiece, after which the spent wire is collected. Due to its reduction in diameter, as a result of the machining process,

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[8] Kent Kohkonen, "Manufacturing Precision and Delicate Parts," *Electric Motor/Coilwinding Conference Proceedings*, (2001): 115.

[9] EDM Technology Transfer, "Fundamentals of EDM," available from http://www.edmtt.com/techpapers/characteredm/charedm.html#abstract1; Internet; Introduction.

[10] Intech EDM, "A Reference to Understanding, Selecting and Using Wire on Wire-cut EDM Machines," available form http://www.intech-edm.com/newsroom/documents/wirebook.pdf; Internet; accessed 6 March 2006, 6.

the wire can be used only once. Figure 2.2, a diagram representing a wire-EDM, shows the travel direction of the wire along with the general motions relatively possible by the wire and the workpiece.

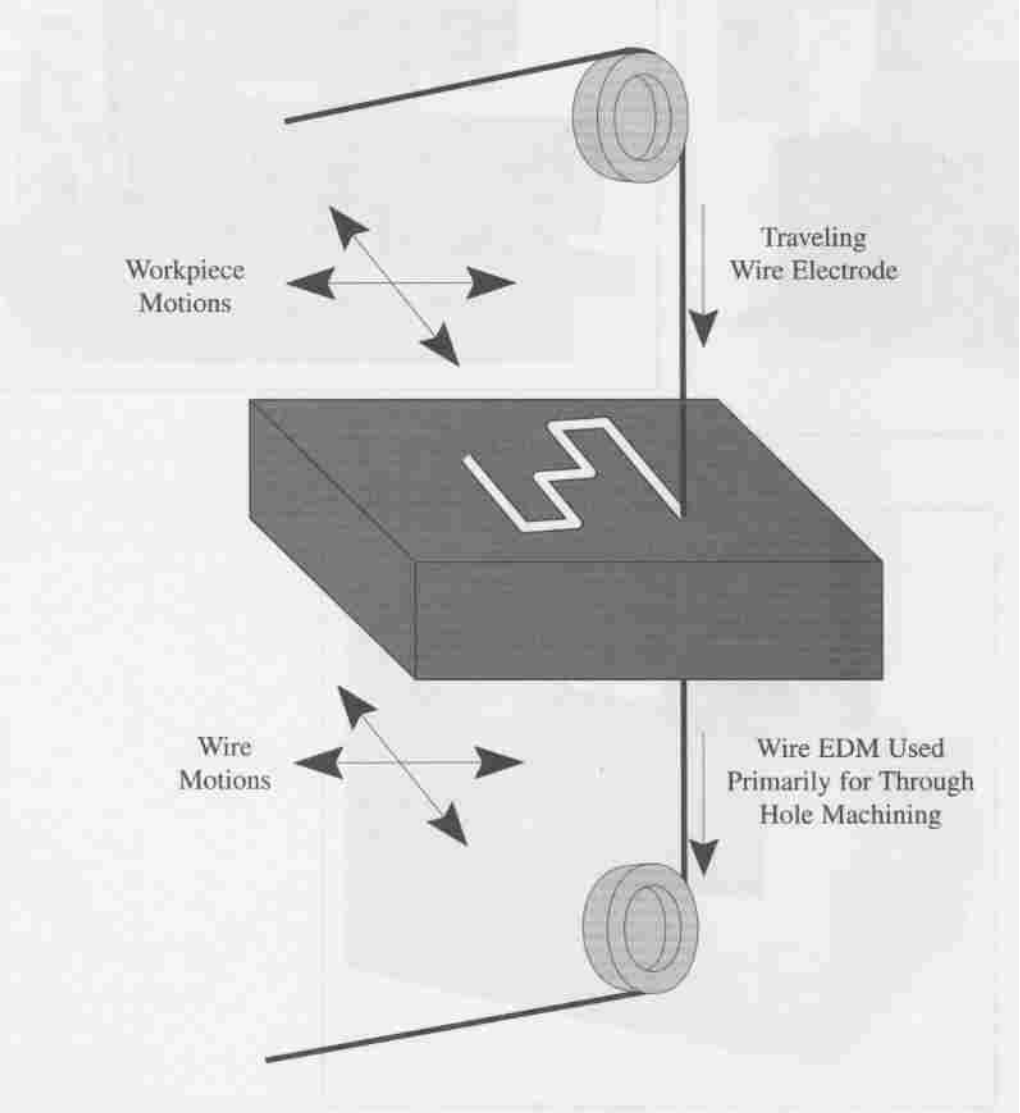

Figure 2.2 - Diagram of a Wire Fed through a Workpiece, and their Relative Motions[11]

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[11] Carl Sommer and Steve Sommer, *Complete EDM Handbook* (Houston, TX: Advance Publishing, Inc., 2005), 30.

2.2.1 EDM Wire

Even though the EDM wire never makes contact with the material being machined, it is considered the tool of the wire-EDM machine. The wire is continually being fed vertically through the workpiece while the workpiece is moved along a horizontal plane. The resultant motion along this horizontal plane cuts a slot through the workpiece that is slightly larger than the diameter of the wire. The wire is typically perpendicular to the surface of the workpiece, except when tapers are being machined, in which case the wire can pass through the material at an angle of up to 30 degrees.[12]

According to Intech EDM, "The ideal wire electrode material for [the wire-EDM] process has three important criteria: high electrical conductivity; sufficient mechanical strength; and optimum spark and flushing characteristics."[13]

The electrical conductivity of the wire is important inasmuch as the heat of each spark is determined by the amount of current that passes through the wire and across the spark gap. This causes more material to be vaporized per spark and thus achieves faster cutting speeds.

In order to maintain a straight cut in the direction the wire travels, the wire is placed under tension by the wire-EDM machine. This force also reduces the amount of vibration in the wire and deflection due to the flow of the dielectric fluid around the wire. The mechanical strength of the wire needs to be sufficient to withstand these forces even after its diameter has been reduced by the machining process.

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[12] EDM Technology Transfer, "Fundamentals of EDM," available from http://www.edmtt.com/techpapers/characteredm/charedm.html#abstract1; Internet; Wire-cut EDM: Principals of Operation.

[13] Intech EDM, "A Reference to Understanding, Selecting and Using Wire on Wire-cut EDM Machines," available form http://www.intech-edm.com/newsroom/documents/wirebook.pdf; Internet; accessed 6 March 2006, 2.

The material properties of the wire are one of the major factors that help to optimize the spark and flushing through the kerf.

> It is highly desirable for the wire to erode, or wear, because the vaporized wire material aids in the formation of subsequent spark ionization channels. In addition, a higher degree of vaporization into microscopic particles, rather than melting, greatly improves the efficiency of the flushing process and, by suppressing arcing, the stability of the cut.[14]

Different materials have been utilized in order to provide situation specific solutions to these needs. The factors that help to determine these different solutions are the EDM machine, workpiece thickness, final tolerances, desired finish, size of the inside radii, taper angles, and the workpiece material.[15]

The first material used in the production of EDM wire was copper. As the power supplies and controllers for the wire-EDM became more sophisticated, they exceeded the capabilities of the pure copper wire. Developers subsequently experimented with the use of brass in order to meet the new demands. Brass is an alloy of copper and zinc, typically alloyed at 63-65% Cu and 35-37% Zn. "The addition of zinc provides significantly higher tensile strength, a lower melting point and higher vapor pressure rating, which more than offsets the relative losses in conductivity."[16] Once the EDM industry started pushing the cutting capabilities of brass wires, manufacturers developed coated wires. Zinc is very desirable in EDM wire because of its vaporization temperature, but brass wires cannot efficiently be produced with higher percentages of zinc than those that have been listed above. In order to obtain the desired properties that are provided by zinc while maintaining sufficient levels of tensile strength and conductivity, a brass or copper

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[14] Ibid., 2.

[15] Ibid., 4.

[16] Ibid., 3.

wire core is coated with zinc. This further enhanced the properties of spark formation and flushing over the brass wire. Fine wires of molybdenum and tungsten have been developed for highly specialized situations, and therefore, a discussion of these would be beyond the scope of this research.

Even though coated wire is appropriate for 95% of the jobs currently being run and has been proven to outperform brass wire, brass wire is still the product of choice for the majority of EDM shops.[17] Due to this trend in industry, I used Intech SuperBrass 900 for this study. It has a Ø 0.25 mm (Ø 0.010 in), Cu 63% and Zn 37%, 1% elongation, and 900 N/mm^2 tensile strength.[18]

2.2.2 Electrical Discharge Power Units

The electrical discharge power unit is the system that controls the electricity so that it is delivered to the electrode in the appropriate amounts and at the correct time. "Wire discharge machines, for example, generate extremely short pulsed currents at steady repetitive intervals by using a current generating power unit and controlling the current into pulse forms.[19] The system executes this function by controlling the on-time, the off-time, and the amperage that is run through the electrode. A single cycle of the EDM process is the combination of the on-time and the off-time. This time is measured in microseconds (μsec). A basic representation of the electrical circuit is shown in Figure 2.3.

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[17] Ibid., 5.

[18] Intech EDM, "Wire," available from http://www.intech-edm.com/pdf/WCwire.pdf; Internet; accessed 6 March 2006, 2-9

[19] Sodick Co., Ltd, "Electrical Discharge Power Units," available from http://sodick.jp/tech/discharge.html; Internet; Accessed 11 April 2006.

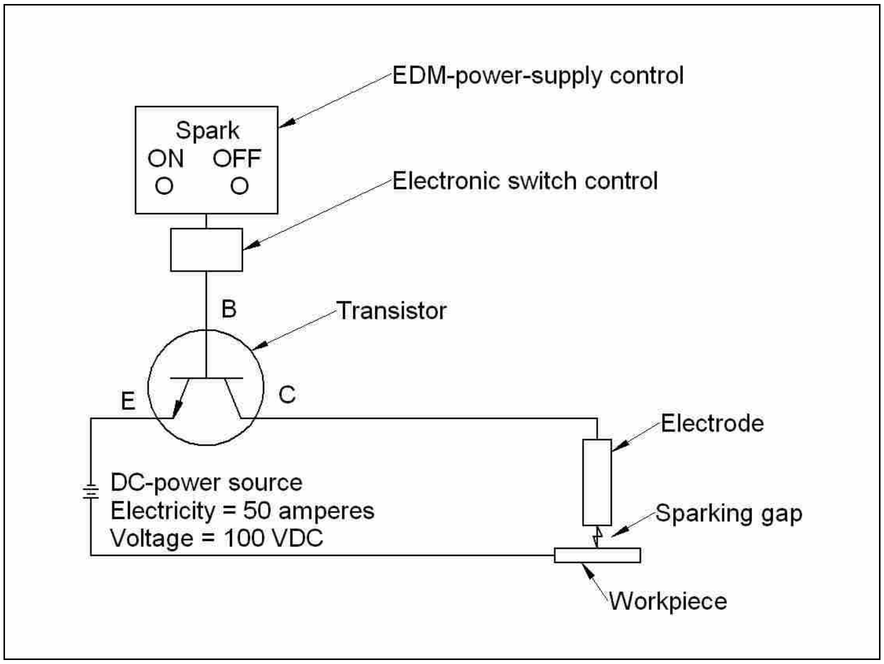

Figure 2.3 - Basic Electrical Circuit[20]

The on-time is defined as the time when the current is turned on. During this time several things are happening. The voltage increases until it has a sufficient amount of energy to align the few ions and microscopic particles in the dielectric fluid and jump the spark gap between the electrode and the workpiece. Once the spark connects the two pieces the voltage decreases and the amperage increases. The material that is in direct contact with the spark is vaporized, and a gas bubble is created around the spark. At some point, enough of the spark energy is used so that vaporization ceases and melting begins. At this point, power is turned off thus beginning the off-time. The bubble that formed around the spark now implodes, pulling most of the molten metal out of the crater created by the spark. Dielectric fluid rushes in and cools the affected areas. The compromised dielectric fluid and the debris are flushed out of the kerf allowing the

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[20] Elman Jameson, *Electrical Discharge Machining* (Dearborn, Michigan: Society of Manufacturing Engineers, 2001) 124.

process to begin again.[21] Diagrams of the spark sequence briefly described above are shown in Figure 2.4.

2.2.3 Dielectric Fluid

There are typically two different dielectric fluids that may be used in an EDM process. The vast majority of wire-EDM machines use deionized water for the dielectric fluid. Oil, which is normally used as a dielectric fluid in vertical or plunge EDM and occasionally in special cases with wire-EDM, is the other alternative. “However, this countermeasure, [dielectric oil], causes microfissures, because the oil does not cool down the part surface as quickly as water does. Microscopic cracks result.”[22] For this reason, deionized water has almost totally replaced oil as the dielectric fluid of choice for wire-EDM.

> EDM dielectric fluids perform four functions necessary for spark machining. The fluids provide
>
> 1. a known electrical barrier between the electrode and workpiece;
> 2. cooling for the electrode and workpiece;
> 3. cooling for the vaporized material that becomes the EDM chip upon solidification; and
> 4. a means for removal of the EDM-spark debris from the spark gap.[23]

In order to use water as a dielectric fluid, all of the ions have to be removed from the fluid through a chemical process leaving pure H_2O. This process reduces the electrical conductivity of the water and thus creates a substance which can be utilized in helping to control the gap distance between the wire and the material being cut, through its creation

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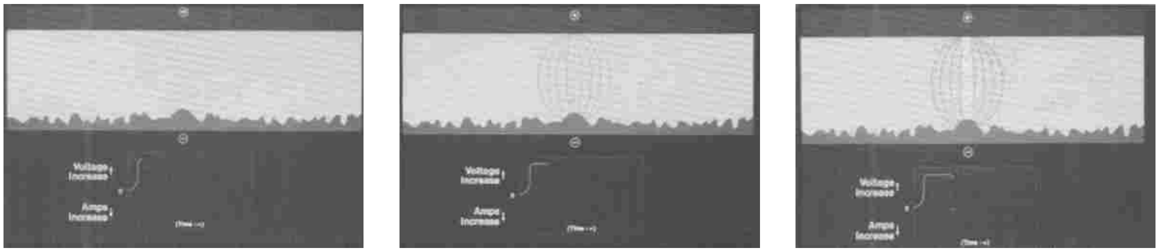
[21] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 19-24.

[22] Jean Dewarrat, “Eliminating EDM Electrolysis Electrically,” *Cutting Tool Engineering*, 46, no. 3 (April 1994): 38.

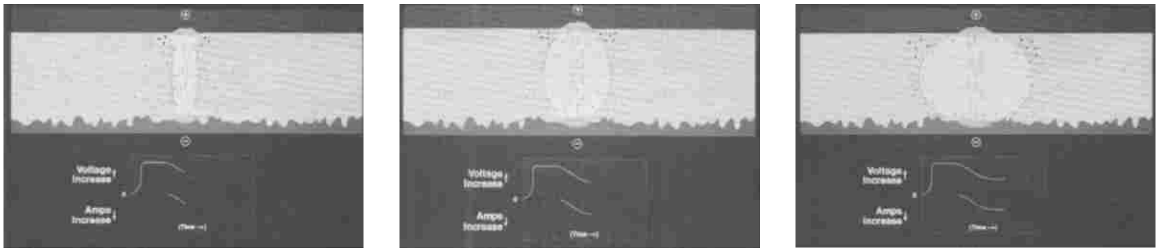
[23] Elman Jameson, *Electrical Discharge Machining* (Dearborn, Michigan: Society of Manufacturing Engineers, 2001) 154.



Item a - "Open-gap voltage. The electrode is seeking the workpiece while "cutting air." Graph shows high potential voltage only, and no current. Time-line runs horizontally.

Item b - Displays the electromagnetic field created between electrode and workpiece. Dielectric within this field becomes polarized as resistance decreases. Voltage levels off.

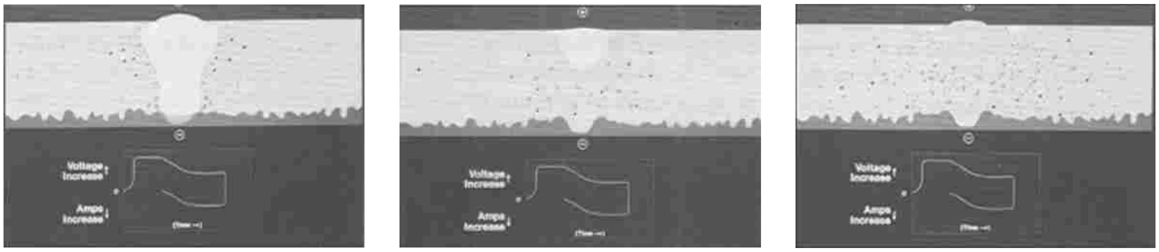
Item c - "On-time" begins. Dielectric resistance is overcome and spark occurs, generating current which vaporized the workpiece. As amperage increases, voltage will decrease.



Item d - Spark is plasma hot and enclosed within a sheath of gases. Vaporization of workpiece continues.

Item e - Gas bubble continues to expand rapidly (vapor pressure). At a certain point, vaporization will cease and melting begins. Dielectric contamination increases.

Item f - Amperage and voltage have leveled off as contamination and thermal damage of dielectric increases. Dielectric is now severely compromised and its electrical resistivity continues to rise. If allowed to continue, conditions will cause "dc arcing" or a wire break.



Item g - Power is interrupted during "off-time" part of the EDM cycle. Current drops to zero. Gas bubble collapses upon removal of heat source.

Item h - Gases and contaminated dielectric will naturally disperse, but providing forced or "sealed" flushing is best and will significantly reduce dielectric recovery time and increase cutting speed.

Item i - Contaminants and damaged dielectric are expelled, revealing EDM crater on workpiece and wear on electrode. Dielectric begins reionization, allowing repeat of cycle.

Figure 2.4 - Diagrams of the Spark Sequence[24]

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[24] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 20-21.

of an electrical barrier. This property is referred to as dielectric strength – “a measure of the insulating capacity of a given fluid in an EDM environment. Higher dielectric strength helps minimize DC arcing and is frequently touted as an indicator of overall EDM performance.”[25]

Because the dielectric fluid is compromised due to contamination and the creation of ions which results from the EDM process fresh dielectric fluid needs to be introduced into the cutting environment. “Flushing is the process of introducing clean dielectric fluid into and through the spark gap. This serves several purposes. Flushing

1. introduces ‘fresh’ dielectric to the cut for reionization,
2. flushes away the ‘chips’ and debris from the spark gap, and
3. cools the electrode (or wire) and workpiece.”[26]

Without sufficient flushing the cutting speed of the machine would be reduced, and in extreme cases, the machine would cease to function due to DC arcing. Flushing helps the dielectric fluid perform these functions.

2.2.4 Filtration

In order to maintain the quality of the dielectric fluid, wire-EDM utilizes two different filtration processes: 1) mechanical filtration, which filters out the particles that have contaminated the dielectric fluid; 2) chemical filtration, which removes the ions from the dielectric fluid which were created through the EDM process.

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[25] Intech EDM, “A Guide to Understanding and Selecting EDM Dielectric Fluids,” available from http://www.intech-edm.com/newsroom/documents/dieloil.pdf; Internet; accessed 6 March 2006.

[26] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 161-162.

When a spark is discharged between the electrode and the workpiece, it vaporizes some of the material from both the electrode and the workpiece. At the end of the on-time cycle some material is also melted. This molten material solidifies and is flushed away by the dielectric fluid. Before the dielectric fluid can be reused, these contaminants need to be removed through a filtration process. Disposable paper filters are the most common form of mechanical filtration used in wire-EDM. The water is pumped through these filters which typically have a filtration range of 5 to 25 microns.[27] These filters need to be replaced periodically depending on their size, the usage of the machine, and the types of material being cut.

Other common mechanical filtration systems are permanent paper media, plastic cartridge filters, diatomaceous earth filters, electrostatic filtration, and centrifuge. These systems can be implemented for individual machines, or they can be installed as a central filtration system for many machines in one shop.[28]

Because of the different components found in alloyed materials and the impurities found in all material, ions are created in the dielectric fluid due to the thermal reaction that occurs during the machining process. An ion is an electrically charged atom which is formed by the loss or gain of an electron. These ions exist as either positively charged cations or negatively charged anions. In order to maintain the nonconductive property of the dielectric fluid, these ions need to be removed.

Table 2.1 lists some of the common ions found in tap water. Several of these same ions are dissolved into the water when the spark from the EDM process vaporizes

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[27] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 174.

[28] Ibid., 174-176.

Table 2.1 - Common Ions Found in Tap Water[29]

Positive Cations	Negative Anions
Aluminum	Carbonate
Calcium	Bicarbonate
Magnesium	Sulfate
Sodium	Chloride
Potassium	Nitrate
Ferrous	Phosphate

and melts the electrode and the workpiece. Mixed-bed resins are used in order to remove these dissolved solids from the dielectric fluid.

"The resin bed is made up of a mixture of positively charged (cation) and negatively charged (anion) polystyrene plastic beads; which is why it is referred to as a 'mixed-bed resin'."[30] Figure 2.5 is a picture of a mixed bed resin. The dielectric fluid is

Figure 2.5 - Mixed Bed Resin[31]

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[29] Ibid., 178.

[30] Intech EDM, "Wire-cut D.I. Resin: Understanding D.I. Resin, and Four Engineered Solutions," *Sparks,* (Spring 2000): 1.

[31] Res-Kem Corp., "Resin," available from http://www.reskem.com/pages/resin.php; Internet; accessed 30 October 2006.

forced through a container filled with the mixed-bed resin. Due to the charges of the ions in the dielectric fluid, they react with the charged beads in the resin and are thus extracted from the dielectric fluid.

> The beads themselves are highly porous, and most of the ion exchange process takes place throughout the structure of the bead, not just on the surface. This is the reason that the [deionization] process takes place *after* the water has been filtered; otherwise the bead surfaces would become clogged or coated, and they would lose much of their capacity.[32]

This process restores the insulating property of the dielectric fluid making it possible for the fluid to be reused.

Another important component of the filtration system is a chiller which maintains the temperature of the dielectric fluid. Heat is transferred to the dielectric fluid from the energy released during the cutting process. Although the sparks can reach temperatures ranging from 8,000 to 12,000˚C (14,432 to 21,632˚F),[33] the pumps that move this fluid through the system serve as the main heat contributors to the dielectric fluid. Modern machines have flushing pressures that can reach 300 psi. The heat generated from the motors and pumps is transferred to the dielectric fluid as it passes through the system.

> A large share of part accuracy (besides the capability to cool the machine) is the result of maintaining uniform machine component, tooling, and part temperatures in relation to the temperature of the room. Temperature changes during cutting can cause the part to bend, twist, or distort in addition to 'growing' or elongating due to the coefficient of expansion for a given material.[34]

Therefore, in order to maintain the desired part accuracies a chiller is an essential component of a wire-EDM machine.

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[32] Ibid.

[33] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 19.

[34] Ibid., 179.

2.2.5 Machine Movements

Several components are necessary for the EDM machine to follow a programmed path in order to create a specific part. In comparing the different systems of an EDM machine to the human body, there are muscles, the brain, and the nerves. Respectively these systems translate to the linear motors, the Computerized Numerical Control (CNC) system, and the motion controllers.

Servo systems are utilized in the older EDM machines, in vertical or plunge EDM machines, and in the vertical axis of some of the newer wire-EDM machines, but the majority of the servo systems in wire-EDM machines have been replaced by linear motors. Linear motors are superior to rotating motors in traveling speed and positional accuracy. These motors can move with accuracy in increments of 1 micrometer.[35] The linear motors and/or servo systems are the muscles of an EDM machine enabling it to move along the programmed path.

The CNC system is the brain of the EDM machine. It controls the motions of the EDM machine. The CNC system follows the inputs given to it through a program which tells the machine what functions it needs to perform and where it needs to move. Modern CNC units are "capable of controlling up to eight axes simultaneously."[36]

The motion controllers or "nerves" of an EDM machine work in conjunction with the CNC system and the linear motors. They "control the high-speed and high-precision

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[35] Sodick Co., Ltd, "Linear Motors," available from http://sodick.jp/tech/linear.html; Internet; Accessed 11 April 2006.

[36] Sodick Co., Ltd, "CNC Units," available from http://sodick.jp/tech/nc.html; Internet; Accessed 11 April 2006.

motions of [the] linear motors based on commands from the CNC units."[37] The motion controllers tell the machine where it is in comparison to the electrode. The entire system works on the principal of the Cartesian Coordinate System. Every point within the work envelope of the machine can be defined and located thus enabling the machine to follow a given path allowing it to cut the programmed part.

"With the advent of ever-improving electronic circuitry, advanced motion techniques, computer numeric controls (CNC) and other modern controlling mechanism's, EDM machine tools have become extremely reliable, accurate and dependable."[38]

2.3 Surface Characteristics

The surface of a part machined by wire-EDM can be discussed on two different levels, surface finish and surface integrity. Although the two subjects are related they warrant individual attention and discussion of their causation.

2.3.1 Surface Finish

The surface finish refers to the smoothness of the part surface machined by a given process. Unfortunately, no standard has been universally accepted for measuring the surface finish of parts. Table 2.2 lists several of the different methods for calculating the numerical representation of the surface finish and the typical units used to define the measurements. The representation closest to a standard utilized in the United States is the Roughness Average (R_a). This is defined as "the arithmetic average of all departures

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[37] Sodick Co., Ltd, "Motion Controllers," available from http://sodick.jp/tech/smc.html; Internet; Accessed 11 April 2006.

[38] The Damm Company, Inc., "What is EDM?" available from http://www.thedammcompany.com/whatisedm.html; Internet; Accessed 11 March 2006.

Table 2.2 - Commonly Used Surface Finish Measurements

Scale	Definition	Unit*
RMS	Root Mean Square	µin.
AA	Arithmetic Mean (average)	µin. or µm
R_a	Roughness Average	µin. or µm
H_{max}	Maximum Roughness Depth	µin. or µm
R_{max}	Maximum Roughness Depth	µin. or µm

* 1 µin. = 1/1,000,000 inches or 0.025 µm
1 µm = 1/1,000,000 meter or 40 µin.

of the roughness profile from the centerline of the evaluation length. It is also known as the arithmetic average (AA) and the centerline average (CLA)."[39] "The finest surface finishes will be of the order of R_a 0.10 [µm], and the visual effect is almost like a mirror finish."[40]

Researchers cite several factors that affect the surface finish of a part machined by wire-EDM, namely: discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, average working voltage, dielectric flushing pressure, conductivity of dielectric fluid, current-limiting resistance, pulse generating circuit, table speed, and gap distance. All of the various researchers performed finishing passes in their experiments while adjusting some of the parameters listed above. Because each of the researchers was focusing on different variables of the finishing process, their conclusions are not totally consistent; however, there is fairly consistent agreement that the voltage and pulse on-time are the two leading determinants of the surface finish. One other factor that warrants discussion is the type of pulse-generating circuit used in the

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[39] Ibid.

[40] Charnilles US, Corporate Publications, "Principle," available from http://www.charmillesus.com/products/whatsedm/principle.cfm; Internet; accessed 6 March 2006.

machining process.[41, 42, 43] By varying the voltage and pulse on-time in the appropriate manner, a finer surface finish can be achieved. This is the basic definition of finishing passes and how they are achieved. In discussing roughing and finishing passes hereafter we will examine in more detail the effects that voltage and pulse on-time have on the surface finish and it's characteristics.

In order to cut materials as quickly as possible during the roughing pass, high voltage and long on-time settings are utilized. The longer on-time and higher voltage equate to more thermal energy in the spark thus vaporizing and melting more of the workpiece material. This results in larger craters left in the surface of the workpiece, and a thicker recast layer and heat affected zone. Figure 2.6 shows magnified pictures of the

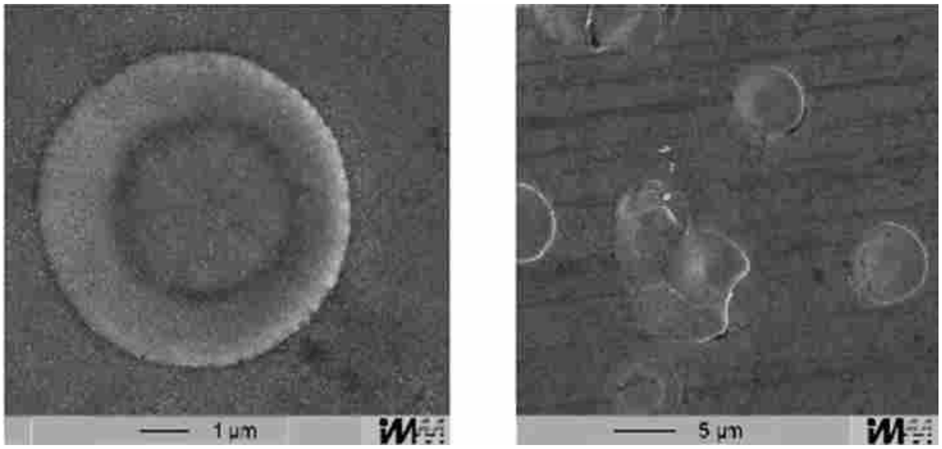

Figure 2.6 - Magnified Pictures of Craters Created by Single Sparks[44]

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[41] N. Tosun et al., eds., "The Effect of Cutting Parameters on Workpiece Surface Roughness in Wire EDM," *Machining Science and Technology*, 7, no. 2 (2003): 217.

[42] Y. Liao et al., eds., "A study to achieve a fine surface finish in Wire-EDM," *Journal of Materials Processing Technology*, 149, no. 1-3 (2004): 169.

[43] J. Huang et al.,eds., "Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining," *Journal of Materials Processing Technology*, 87, no.1-3 (1999): 80.

[44] Michel Frank et al., eds., "EDM for Micro Fabrication – Technology and Applications," available from http://www.public.iastate.edu/~weichiat/527/EDM_Microfab.pdf; Internet; accessed 6 March 2006, 3.

craters created by single sparks from the EDM process. At the bottom of each picture is a scale which gives the size of the individual craters. It should be noted that the sizes of the craters is effected by the amount of current that is allowed to pass through each of the sparks, and therefore these pictures are only a representation of approximate size and shape.

Finishing passes are utilized to remove the recast layer, the heat affected zone, and the rougher surface finish left by the roughing pass. Figure 2.7 shows magnified pictures of the surface finishes which can be obtained through the use of roughing and finishing passes. The roughness average for each of the surfaces is given, and each of the pictures show a scale of 10 μm.

Rough Cut – R_a 3.2 μm. 1st Finish Pass – R_a 2.03 μm. 2nd Finish Pass – R_a 1.5 μm.

Figure 2.7 - Magnified Pictures of Surface Finish[45]

In order to enhance the effects of the finishing passes and obtain a smother surface finish, the voltage is dropped and the on-time is reduced. Because of the drop in voltage, the wire is moved closer to the workpiece thus reducing the gap which allows smaller sparks to be generated at a greater frequency. The wire will follow a similar path to that which it traveled in the roughing cut around the workpiece. This process can be

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[45] J. Huang et al.,eds., “Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining,” *Journal of Materials Processing Technology,* 87, no.1-3 (1999): 77.

repeated successively creating finer surface finishes each time. With the appropriate settings of the different parameters a surface finish of $R_a = 0.22$ μm can be achieved.[46] Figure 2.8 is a schematic showing the decrease in surface roughness due to finishing passes.

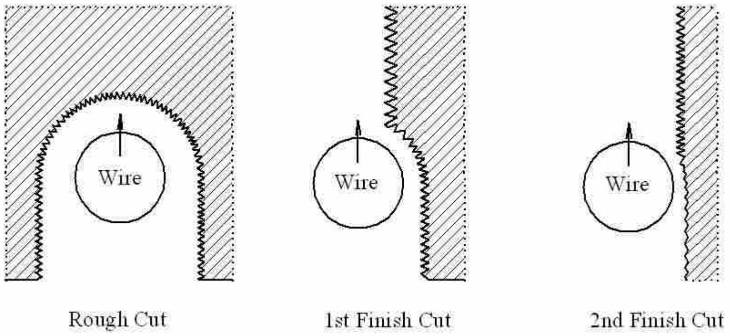

Figure 2.8 - Decrease in Surface Roughness due to Finishing Passes

The pulse-generator can also have a slight effect on surface finish. Typically, pulse-generators for wire-EDM machines can be utilized in three different ways: DC arching with the wire being the anode and the workpiece being the cathode, DC arching with the wire being the cathode and the workpiece being the anode, and AC arching

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[46] Y. Liao et al., eds., "A study to achieve a fine surface finish in Wire-EDM," *Journal of Materials Processing Technology*, 149, no. 1-3 (2004): 166.

where the wire and workpiece alternate between anode and cathode. A spark will typically jump from the positively charged anode to the negatively charged cathode. It has been observed that there is a greater amount of material removed from the cathode. By properly defining the direction the sparks will jump, an operator can successfully decrease the roughness of the surface finish. At times, other more significant parameters will override this principal.

2.3.2 Thermal Effect

After a part has been cut by EDM, there are basically three resultant layers of material with varying characteristics. These layers starting from the surface are the recast layer, the heat affected zone, and the parent material. Figure 2.9 is a diagram depicting these different layers. The recast layer is part of the parent material that has been melted, and

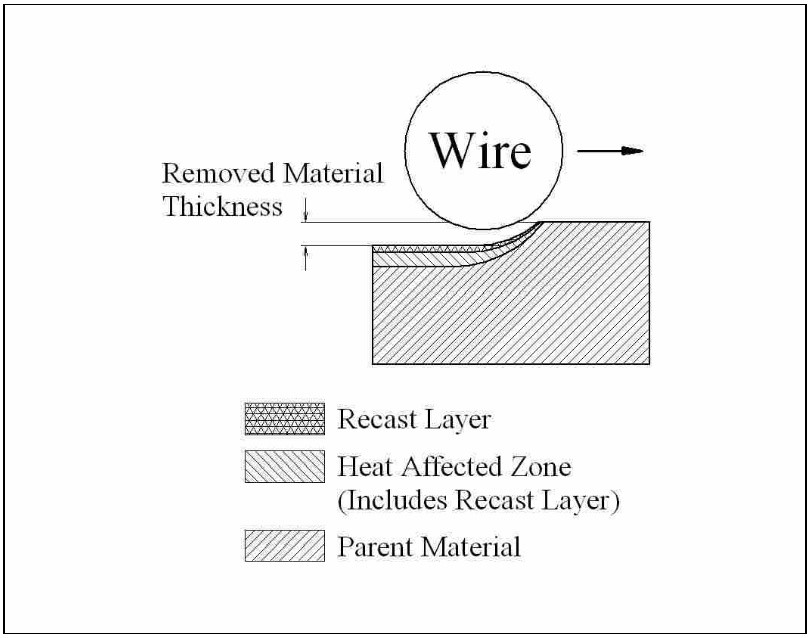

Figure 2.9 - Thermally Affected Zone

has then re-solidified on the surface of the part. The heat affected zone is a layer of the parent material which has been affected by the heat generated during the machining process. In both of these layers the crystalline structure of the parent material has been affected and/or changed. Sometimes, the chemical composition of the recast layer may also be altered.

As discussed in earlier sections, the thickness of the outer two layers will very depending on the voltage and on-time settings of the EDM machine. When the machine settings for rough cutting are used the thickness of the outer two layers can approach 0.76 mm (0.030 in.). This thickness can be dramatically reduced to approximately 0.05 mm (0.002 in.) when finishing settings are utilized.[47] Figure 2.10 shows magnified pictures of the recast layer which can be obtained through roughing and finishing passes. The pictures are oriented such that you are looking vertically down the cut surface so that the thickness of the recast layer can be observed. A thickness of less than 3 μm was achieved by the 2nd finishing pass.


Rough Cut 1st Finish Pass 2nd Finish Pass

Figure 2.10 - Magnified Pictures of the Recast Layer[48]

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[47] Elman Jameson, *Electrical Discharge Machining* (Dearborn, Michigan: Society of Manufacturing Engineers, 2001) 256-257.

[48] J. Huang et al.,eds., “Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining,” *Journal of Materials Processing Technology*, 87, no.1-3 (1999): 77.

Because of the heat differential between the dielectric fluid and a recently created spark cavity, internal stresses in the workpiece can be created. These stresses can create micro-cracks in the surface of the workpiece. Due to the mechanical stresses applied to a tool, manufactured by the EDM process, during its utilization, these micro-cracks can propagate into the parent material causing the tool to crack and fail. As a result, for most high impact tools, the recast layer, which is very hard, brittle, and highly stressed, may need to be removed entirely in order to prevent failure of the tool.[49] Subsequent processes utilizing other machines are used in order to achieve this goal.

2.3.3 Corrosion Effect

Because the dielectric fluid of choice for wire-EDM is deionized water, other factors are introduced into the EDM process. Water is the universal solvent, and therefore will start to dissolve whatever it comes in contact with. "On steel workpieces, [where deionized water is used as the dielectric fluid] corrosion increases, the surface is weakened, and rusting accelerates."[50] Even though the deionized water has these effects, the advantages it creates still outweigh its negative effects.

2.3.4 Electrolysis Effect

It is impossible for any purification system to remove all of the ions from the water being used as the dielectric fluid. A very small portion of the H_2O molecules will naturally split into H+ and OH- ions. Due to this phenomenon, electrolysis sometimes

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[49] Ibid., 257-259.

[50] Jean Dewarrat, "Eliminating EDM Electrolysis Electrically," *Cutting Tool Engineering*, 46, no. 3 (April 1994): 38.

becomes a problem when using deionized water as a dielectric fluid. Electrolysis is a chemical reaction that will deposit or remove material from an electrode through the utilization of an electrical current. "The problem has become even more widespread due to the increased use of sintered materials, such as tungsten carbide, which are extremely sensitive to the effects of electrolysis."[51] Because the workpiece has an electric charge it attracts the anions or cations in the dielectric fluid, deionized water. These ions bombard the surface of the workpiece. In the case of tungsten carbide, the ions attack the cobalt binder which is used to sinter the tungsten carbide thus weakening the surface and corners of the resultant tool. Studies have been performed to research different methods of reducing electrolysis. One alternative is to use AC power, thus decreasing the degree to which the surface of the part is bombarded by the ions in the dielectric fluid.[52] Another study was performed in which high-performance spark generators were used to emit high-voltage pulses that caused the ions in the dielectric fluid to oscillate thus practically eliminating their migration towards the workpiece. This almost eliminated the bombardment of ions on the surface of the workpiece.[53]

2.4 Cutting Speed

Cutting speeds for EDM machines are measured in square inches per hour (sq. in./hr) regardless of the type of machine. The advances in technology and machine

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[51] Jean Dewarrat, "Eliminating EDM Electrolysis Electrically," *Cutting Tool Engineering,* 46, no. 3 (April 1994): 38.

[52] Haruki Obara et al., eds., "Fundamental study on corrosion of cemented carbide during wire EDM," *Journal of Materials Processing Technology,* 149, no. 1-3 (2004): 370.

[53] Jean Dewarrat, "Eliminating EDM Electrolysis Electrically," *Cutting Tool Engineering,* 46, no. 3 (April 1994): 40.

capabilities over the years have enabled increased cutting speeds in EDM. Cutting speeds are not only influenced by the age and type of machine, but also by the properties and characteristics of the workpiece being cut. The workpiece melting temperature and its electrical conductivity are the two greatest factors relative to the workpiece that affect the cutting speed. It needs to be noted that the cutting speeds which manufacturers publish for their different machines have been obtained under ideal cutting conditions. Manufacturers will typically use 57 mm (2 ¼ in.) D2 hardened tool steel with ideal flushing conditions in order to obtain a cutting speed for wire-EDM machines.[54] Currently, wire-EDM machines have the capability of cutting 30 sq. in./hr. in tool steels. Although this will provide a benchmark for comparison, it does not represent the cutting speeds of other materials. Due to the high conductivity and low melting temperatures of aluminum, some manufacturers have achieved cutting speeds exceeding 80 sq. in./hr.[55]

The machine settings set by the operator and programmer also affect the cutting speed. The settings which have the greatest impact on cutting speeds are the amount of amperage, the on-time, and flushing conditions. The greater the amount of amperage allowed to pass through the spark, the hotter the spark will be. Related to this is the on-time. Instead of increasing the amperage, the length of time the spark is allowed to exist will also increase cutting speeds. Both of these settings, when maximized, will vaporize a greater amount of material from the workpiece. It is possible to increase these settings to the point where an adverse effect occurs to both the cutting speed and the workpiece.

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[54] Carl Sommer and Steve Sommer, *Complete EDM Handbook* (Houston, TX: Advance Publishing, Inc., 2005), 76.

[55] Bud Guitrau, *The EDM Handbook* (Cincinnati, OH: Hanser Gardner Publications, 1997) 162.

If increased too much, the spark will destabilize and may cause the wire to rupture do to the increased heat.

Flushing helps stabilize the area around the electrode in order to maintain the required conditions for a subsequent spark to generate. If the damaged dielectric fluid and the contaminants are not flushed out of the kerf, the sparks will destabilize and DC arching will occur, thus reducing cutting speeds.

2.5 Accuracy

The Sodick AQ325L wire-EDM machine that was used to cut the parts for this thesis was also used by Joel Mundt for his thesis on *Wire Electric Discharge machining Performance with Multiple Finishing Passes*. Part of that study included the cutting of octagonal parts from 25.4 millimeter (1 inch) thick D2 Tool Steel that had been heat-treated to a hardness of RC 64.2.[56] Part of his thesis was to observe the accuracy of the wire-EDM machine by measuring the distance between opposite sides of these octagonal specimens and compare the results with the target values. Mundt concluded, for this part of his thesis, that the data showed a trend of increasing accuracy when going from one to three finishing passes. His observances are as follows

- A mean deviation of a negative .0088 millimeters (.00348 inches) with one finishing pass,
- A mean deviation of a positive .0038 millimeters (.000151 inches) with two finishing passes, and

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[56] Mundt, Joel, *Wire Electric Discharge Machining Performance with Multiple Finishing Passes* (School of Technology, Brigham Young University, Thesis. April 2002), 22-23.

- A mean deviation of a positive .0011 millimeters (.000042 inches) with three finishing passes.[57]

This was used in comparison to the data obtained in this thesis in order to eliminate bias due to the accuracy of the wire-EDM machine.

Other important parameters which will also affect the accuracy of the wire-EDM machine are the settings which are used for the pulse generator and the tool offsets, which are used dependent on the number of finishing passes being run. It was that the default parameters for each of these settings were used in both of the previous theses by Mundt and Kim.

2.6 Related Research

Sangseop Kim performed some related research for his thesis, *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process*, and thus laid the groundwork for further research in cutting thin-walled sections with a conventional wire-EDM machine. Kim stated that, "The purpose of [his] thesis study was to determine of there are significant differences in the height of the [thin-walled sections] when the thickness becomes smaller and when different materials are cut on the [wire-EDM] machine."[58]

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[57] Ibid., 77

[58] Sangseop Kim, *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* (School of Technology, Brigham Young University, Thesis. April 2005), 65.

Five different metals were tested which are commonly cut by wire-EDM machines. Namely: Aluminum 6061 T6, Yellow Brass SS360, 420 Stainless Steel, D2 Tool Steel at 25 to 30 RC, and D2 Tool Steel at 60 to 65 RC.[59]

Kim cut thin-walled sections ranging in thickness from 0.05 millimeters (0.002 inches) increasing incrementally by 0.05 millimeters (0.002 inches) until they reached a thickness of 0.30 millimeters (0.012 inches) from a block of material approximately 56 millimeters (2.2 inches) long and 25.4 milimeters (1 inch) square. Only one end of each section remained attached to the parent material.[60] A diagram depicting the layout of the test specimens can be seen in Figure 2.11.

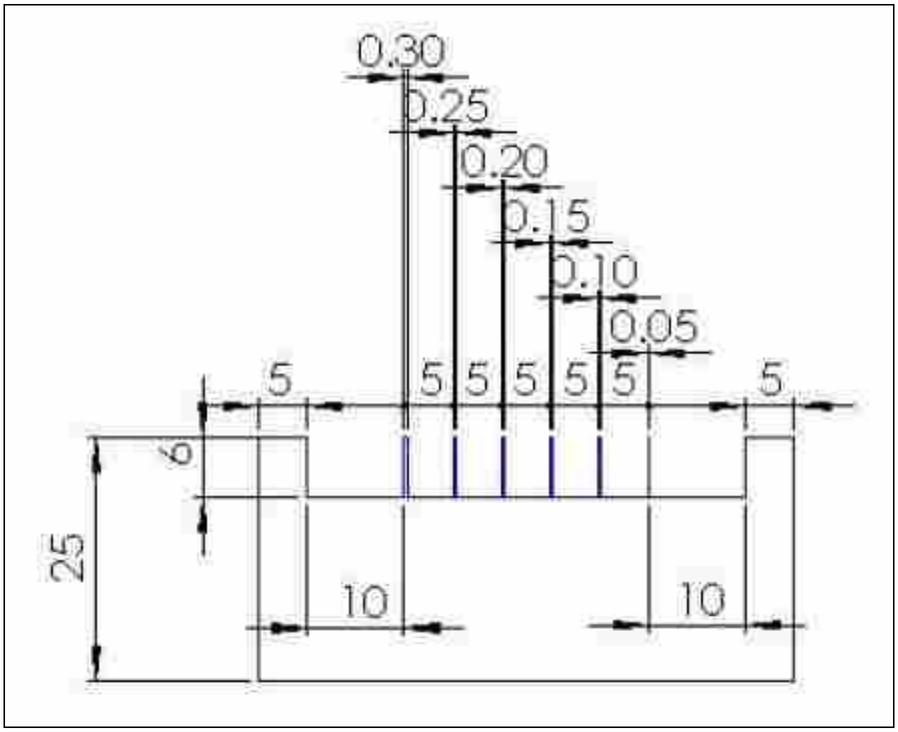

Figure 2.11 - Design and Layout of Thin-walled Sections for the Test Specimen[61]

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[59] Ibid., 26

[60] Ibid., 24-25

[61] Ibid., 25

Through his research, Kim determined that there are significant differences in the height of the [thin-walled sections] as the thickness becomes smaller.[62] He also determined that there are significant differences in the height of the [thin-walled sections] when cutting different metals.[63] It will be possible to compare these conclusions to those presented at the end of this thesis in order to determine if there are differences due to the degree in which each of the thin-walled sections is constrained.

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[62] Ibid., 65

[63] Ibid., 66

3 Method and Procedures

3.1 Introduction

The sections in this chapter give an in-depth description of the methods and experimental procedures which were used in order to conduct the research for this thesis. These sections consist of: test materials, test blank design, machine parameters, measurement methods, and experimental design.

3.2 Test Materials

As indicated earlier in this paper, five different types of metals were tested in order to observe the machining performance of wire-EDM in cutting thin sections from these different materials. These materials are Aluminum 6061 T6, Yellow Brass SS360, 420 Stainless Steel, D2 non-heat-treated tool steel 25-30 RC, and D2 heat-treated tool steel 60-65 RC. These materials were chosen because of their extensive use in the industrial sector, and their prominence for being machined by wire-EDM. It is assumed that, due to the properties and characteristics exhibited by these five metals, the testing and analyzation of these materials created a breadth of data and knowledge about these materials that can be used as a baseline from which industry can work and inferences can be drawn.

The physical properties, due to chemical composition, of these metals have a significant impact on the settings of the wire-EDM machine, and the speed with which they can be machined. The two greatest factors due to chemical composition are the electrical conductivity and the vaporization points of the materials. Related to the vaporization point, but not as prolific, is the temperature at which melting in lieu of vaporization occurs. Table 3.1 lists the chemical compositions of the five different test materials.

Table 3.1 - Chemical Composition of Test Materials

Material	Composition by Weight %
Aluminum 6061 T6	Al 98, Cr 0.04-0.35, Cu 0.15-0.4, Mg 0.8-1.2, Si 0.4-0.8
Yellow Brass SS360	Cu 60-63, Pb 2.5-3.7, Zn 35.5
420 Stainless Steel	C 0.15, Cr 13, Fe 85
D2 Tool Steel 25-30 RC	C 1.5, Cr 12, Fe 85.6, Mn 0.3, Mo 0.75, Si 0.3, V 0.9
D2 Tool Steel 60-65 RC	C 1.5, Cr 12, Fe 85.6, Mn 0.3, Mo 0.75, Si 0.3, V 0.9

This information was obtained from industry standards, and the data sheets provided by the manufacturers of the different metals are included in the appendix (see Appendix A). It should be understood that the weight percentages that are given in the preceding table represent averages, and the exact composition of the test materials will vary slightly from the percentages listed above. There are also other elements which may be found in small amounts in the test materials.

Electrical conductivity of the material being machined becomes a factor because it dictates the amount of current that can pass through it at a given time. The greater the electrical conductivity equates to more electrical current thus increasing the speed with which the material can be machined. Table 3.2 lists the electrical resistivity of the test materials.

Table 3.2 - Electrical Resistivity of the Test Materials

Materials	Electrical Resistivity
Aluminum 6061 T6	4e^{-006} ohm-cm
Yellow Brass SS360	0.090 x 10^{-6} Ωm
420 Stainless Steel	5.5e^{-005} ohm-cm at 20˚C
D2 Tool Steel 25-30 RC	0.196 μΩm at 20˚C
D2 Tool Steel 60-65 RC	0.196 μΩm at 20˚C

Other properties of interest that the test materials possess are their thermal conductivity, coefficient of thermal expansion (CTE), and hardness. The thermal conductivity of a material being machined by EDM will help to dictate the amount of material that each spark will remove and the resultant thickness of the heat affected zone. The lower the thermal conductivity of the material will result in a greater amount of material removal along with a thinner heat affected zone. This is due to the fact that a greater amount of the heat from each spark is maintained at the surface of the cut and kept from defusing into the material. Table 3.3 lists the thermal conductivity of the test materials.

Table 3.3 - Thermal Conductivity of the Test Materials

Materials	Thermal Conductivity	
Aluminum 6061 T6	166.9 W/m - K	1160 BTU-in/hr-ft^2 - ˚F
Yellow Brass SS360	115 W/m - K	798 BTU-in/hr-ft^2 - ˚F
420 Stainless Steel	24.9 W/m - K	173 BTU-in/hr-ft^2 - ˚F
D2 Tool Steel 25-30 RC	20.9 W/m – K @ 95˚C	145 BTU-in/hr-ft^2 - ˚F
D2 Tool Steel 60-65 RC	20.9 W/m – K @ 95˚C	145 BTU-in/hr-ft^2 - ˚F

The CTE is important to consider because it will dictate the degree to which the overall part temperature needs to be controlled in order to achieve the desired part accuracy. The CTE is the change in the material's size due to a change in the temperature of the part. Table 3.4 lists the CTE of the test materials.

Table 3.4 - Coefficient of Thermal Expansion (CTE) of the Test Materials

Materials	Coefficient of Thermal Expansion (CTE)	
Aluminum 6061 T6	23.6 µm/m-˚C at 20˚C	13.1 µin/in-˚F at 68˚F
Yellow Brass SS360	20.5 µm/m-˚C at 20˚C	11.4 µin/in-˚F at 68˚F
420 Stainless Steel	10.3 µm/m-˚C at 20˚C	5.72 µin/in-˚F at 68˚F
D2 Tool Steel 25-30 RC	10.3 µm/m-˚C at 20˚C	5.72 µin/in-˚F at 68˚F
D2 Tool Steel 60-65 RC	10.3 µm/m-˚C at 20˚C	5.72 µin/in-˚F at 68˚F

In contrast to the data listed above, the hardness of the five test materials was obtained through testing each of the different materials. The material hardness was measured using a Rockwell hardness tester. In order to measure the hardness of the D2 heat-treated tool steel a 1.524 mm (0.06 inch) Brale diamond cone indicator was used with a force of 980.7 N (1000 Kgf). For the remainder of the materials a 1.587 mm (0.0625 inch) tungsten carbide ball was used with a force of 147.1 N (150 KGF). Each of the materials was tested five times. The three median test values were averaged in order to determine the hardness of each material. This data is documented in the appendix (see Appendix B). Table 3.5 shows the average of the three median test values and their conversion into Brinell Hardness for each of the test materials.

Table 3.5 - Conversion of HRC and HRB to Brinell Hardness for the Test Materials

Materials	Average	Brinell Hardness
Aluminum 6061 T6	57.5 HRB	98
Yellow Brass SS360	74.2 HRB	126
420 Stainless Steel	86.5 HRB	167
D2 Tool Steel 25-30 RC	95.7 HRB	212
D2 Tool Steel 60-65 RC	62.8 HRC	701

3.3 Test Blank Design

The test blanks for this study are hexahedron cuboids that measure 76.2 millimeters (3 inches) long by 25.4 milimeters (1 inch) square. This allowed sufficient material for each of the thin-walled sections to be cut, and sufficient space between them so that they could be measured. Figure 3.1 is an isometric drawing showing the size and shape of the test blanks.

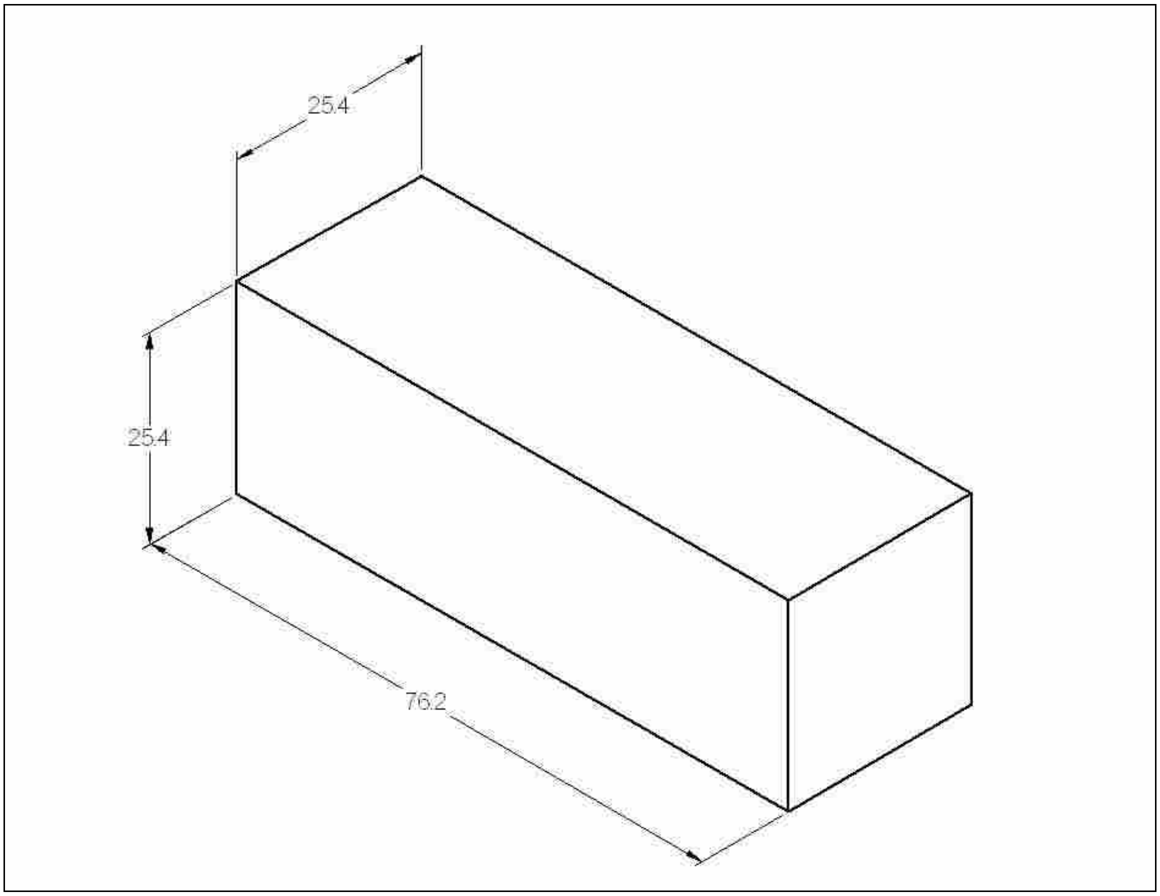

Figure 3.1 - Size and Shape of Test Blanks (units: mm)

In order to enable the wire to be threaded through the test blank, 3.175 mm (.125 inch) holes were drilled through the center of each of the sections which were cut out of the blanks. Figure 3.2 is a drawing that shows the location and diameter of each of the thread holes.

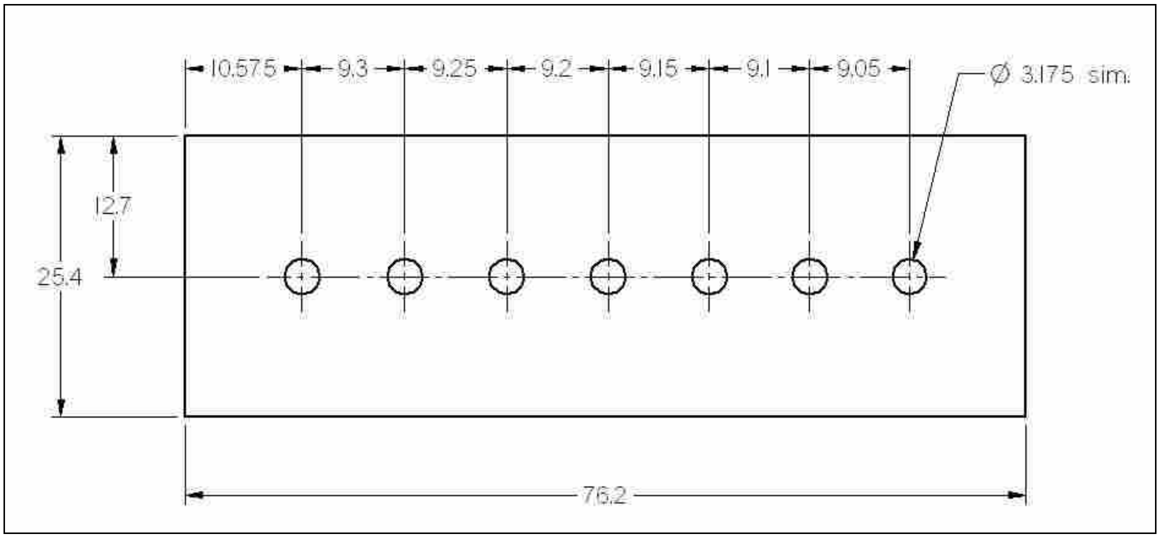

Figure 3.2 - Layout of Thread Holes for the Test Blanks (units: mm)

A CNC program was created in Gibbs CAM, and the holes were drilled with one of the Hurco milling machines located in the Crabtree building. Due to the different materials, several CNC programs were generated to accommodate the different feed rates and are documented in the appendix (see Appendix C). Also, the holes were drilled in the D2 Tool Steel blanks before those requiring heat treating were hardened.

Six different thicknesses of thin-walled sections increasing incrementally in thickness by 0.05 millimeters (0.002 inches) from 0.05 millimeters (0.002 inches) to 0.30 millimeters (0.012 inches) were cut. This was achieved by cutting a line of hexahedron cuboids out of the center of the test blank leaving a thin-walled section between each of the cutouts. Both ends of the thin-walled sections remained attached to the parent material thus constraining them as required. Figure 3.3 is a drawing indicating the layout of the thin-walled sections and the target thickness for each.

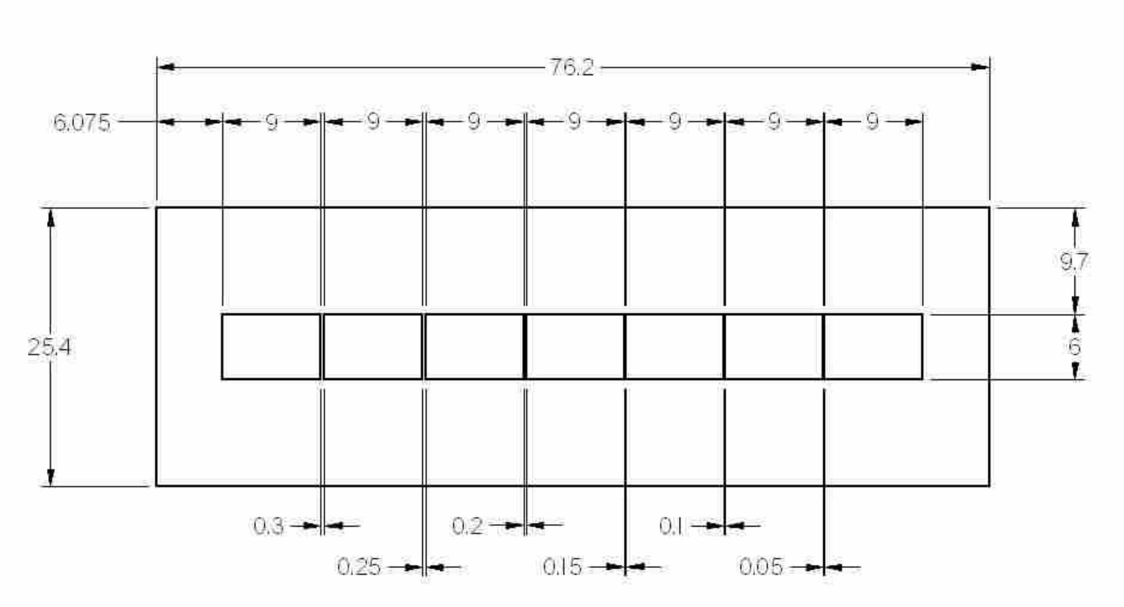

Figure 3.3 - Drawing Indicating Layout of Thin-walled Sections and their Target Thickness

The target measurements for each of the thin-walled sections are represented in Figure 3.3. These target dimensions were used in the analysis of the specimens which is discussed in Chapter 4 of this thesis.

3.4 Machine Parameters

The machine parameters encompass those factors that dictate the operation of the machine and conditions within which it operates. The topics of discussion within this section are machine settings, cutting conditions, machining programs, and wire offset.

3.4.1 Machine Settings

The power settings utilized by the Sodick AQ325L were different for each of the different types of materials that were cut. These settings were defined at the beginning of each of the CNC programs and can be seen in the appendix (see Appendix D).

3.4.2 Cutting Conditions

The cutting conditions are the factors relative to the part being machined and the environment within which the machine exists and operates. Those factors listed in Table 3.6 are the cutting conditions selected from the machine's operating parameters during the setup prior to cutting each part.

Table 3.6 - Cutting Conditions for Sodick AQ325L wire-EDM Machine

Machine Dielectric Fluid	Deionized Water
Wire Diameter	0.24892 mm (0.0098 inches)
Wire Type	Brass (Intech Super Brass 900)
Work Setting	Al, Cu (for Brass), Steel (for D2 Tool Steel and Stainless Steel)
Work Thickness	29.972 mm (1.18 inches)
Machine	Punch
Nozzle Position	Open-U
Number of Passes	1,2, or 4

3.4.3 Machining Programs

Part of the object of this thesis is to observe the effects which a variation of roughing and finishing passes have with regard to a wire-EDM machine cutting thin-walled sections. Three different combinations of these passes were utilized; namely:

- Rough Cut with no Finishing Passes

- Rough Cut with one Finishing Pass
- Rough Cut with three Finishing Passes

As stated earlier, the difference in each subsequent pass is a reduction in the voltage and spark on-time resulting in a better surface finish and a thinner heat affected zone.

The cutting parameter of a roughing cut with two finishing passes was not run for two reasons. First, in some research performed by Mundt, there was very little difference observed between the results when comparing a roughing cut with two finishing passes to a roughing cut with three finishing passes. Second, in order to maintain the similarity to the research performed by Kim, a roughing cut with two finishing passes was omitted.

In order to run these three different cutting sequences it was necessary to write a CNC program for each of the sequences. Each of the programs is a compilation of the X Y cutting path and the machine settings. The three different CNC programs can be seen in the appendix (see Appendix E).

3.4.4 Wire Offset

Wire offset is defined as the distance from the center of the wire to the finished edge of the workpiece plus the arc gap. The arc gap is the distance between the electrode (in our case the wire) and workpiece during arcing when the dielectric fluid is in an ionized condition. In order to leave material to be removed by subsequent passes the wire offset needs to be increased with regards to the desired number of finishing passes and the type of material being machined. Table 3.7 lists the wire offsets which were used. The measurements which are reported in this table were converted from English units to metric due to the fact that the Sodick AQ 325L operates in English units.

Table 3.7 - Offset Distances Used for Each Material and Required Passes (units: mm)

Materials	Roughing Cut	Roughing Cut and one Finishing Pass	Roughing Cut and three Finishing Passes
Aluminum 6061 T6	Roughing 0.1930	Roughing 0.2360 Finishing 0.1461	Roughing 0.2570 1st Finishing 0.1669 2nd Finishing 0.1369 3rd Finishing 0.1321
Yellow Brass SS360	Roughing 0.1971	Roughing 0.2339 Finishing 0.1491	Roughing 0.2551 1st Finishing 0.1600 2nd Finishing 0.1349 3rd Finishing 0.1331
420 Stainless Steel	Roughing 0.1661	Roughing 0.2009 Finishing 0.1359	Roughing 0.2179 1st Finishing 0.1529 2nd Finishing 0.1331 3rd Finishing 0.1311
D2 Tool Steel 25-30 RC	Roughing 0.1661	Roughing 0.2009 Finishing 0.1359	Roughing 0.2179 1st Finishing 0.1529 2nd Finishing 0.1331 3rd Finishing 0.1311
D2 Tool Steel 60-65 RC	Roughing 0.1661	Roughing 0.2009 Finishing 0.1359	Roughing 0.2179 1st Finishing 0.1529 2nd Finishing 0.1331 3rd Finishing 0.1311

The same wire offsets were used for the 420 Stainless Steel, D2 Tool Steel 25-30 RC, and D2 Tool Steel 60-65 RC because the machine setting for steel was utilized.

3.4.5 Modification to Machine Default Settings

In beginning to cut the test specimens, utilizing the default settings of the wire-EDM machine, the EDM wire kept breaking. The rupture of the wire would occur during the first seconds of operation. This occurred on each of the three material settings used to machine the five metal types. In order to overcome this problem an adjustment of some of the default settings was required. Upon inspection of the CNC program documented in appendix C of *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* by Sangseop Kim, Kim indicated that setting adjustments were necessary to perform his research. Spark on-time was lowered and the MAO changed for the lead in and rouging pass.

> [MAO] is the parameter for establishing the criteria for machining stability. [‘M’] defines the voltage level for judging stability in machining. [‘A’] specifies how many number of times the OFF time should automatically be extended when the state of machining is judged unstable from the level defined by ‘M’. [‘O’] specifies a duration for the ON time which should be used when the state of machining is judged unstable from the level defined by ‘M’ [when running in TM pulse machining].[64]

The wire tension and wire speed were also reduced; however in contrast to the previous changes, the reduction of these parameters was made on all of the passes made by the wire. Tables displaying all of the machine settings used in this study for the three material settings used – aluminum, copper, and steel – can be seen in the appendix (see Appendix D).

3.5 Measurement Methods

Two types of data were gathered from each of the test specimens. First, numerical data was obtained by measuring the thicknesses of each of the thin-walled sections. A Brown and Sharp Coordinate Measuring Machine (CMM) was used to measure each of the sections. The sensor head consisted of two pieces the Renishaw PH10MQ and the Renishaw SP600M. A 10 millimeter long tip was used which had a one millimeter diameter ball on the end. The software used to run the CMM was PC-DMIS version 3.7.3. The CNC program that was written to measure each of the test

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[64] Sodick Co., Ltd, *Sodick Wire Cut-EDM AQ Series with LN1W Power Supply Ver. 1.0 (Instruction Manual)*, 2-2-5.

specimens can be seen in the appendix (see Appendix F). Measurements were taken in six different locations on each of the thin-walled sections; three on the top and three on the bottom. A measurement was taken close to each end of the section where it is attached to the parent material, and the other was taken close to the center of the section approximately three millimeters in from each end. The measurements taken at each end of the sections were acquired at a sufficient distance from the end in order to ensure that the inside corner radius left by the EDM wire did not affect the data. Figure 3.4 is a diagram showing a blown-up section of a test specimen with a red X indicating the approximate locations where measurements were taken on the top and bottom of one of the thin-walled sections.

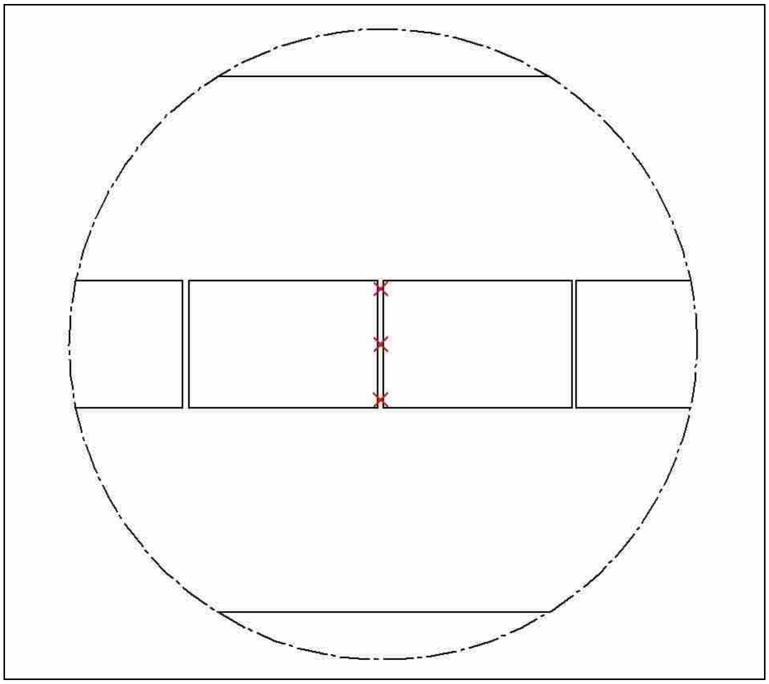

Figure 3.4 - Approximate Location where Measurements were Taken

The CNC program that was written for the CMM and used to measure each of the sections followed the same sequence for each of the test specimens. Each location where a measurement was taken in the sequence was documented. Figure 3.5 is a drawing depicting of the end view of a test specimen. The numbers indicated on the drawing represent the sequence in which the measurements were taken on a given web and are also used in the documentation of the data obtained.

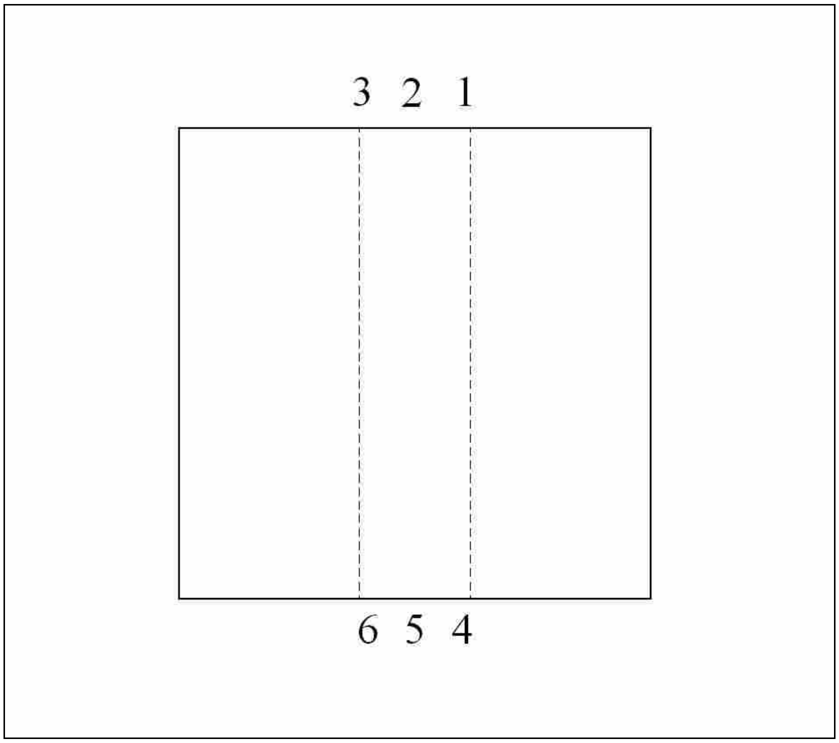

Figure 3.5 - Sequence in which Measurements were Taken

This drawing depicting the test specimen is oriented so that you are looking at the end closest to the web with a target thickness of .30 millimeters. Numbers 1 – 3 were taken on the top of the test specimen and numbers 4 – 6 were taken on the bottom.

The second type of data obtained was a visual inspection of each of the thin-walled sections. The visual inspection was used to look for any material that was obviously missing from the center or edges of each of the sections or any bending/deflection of the web. Defects that were looked for were holes eroded through the center of the sections, and/or material that was eroded away from the top or bottom of the sections. The data obtained through this inspection was recorder as pass or fail. If either of the defects existed then that thin-walled section was recorded as a failure.

3.6 Experimental Design

Due to the nature of the machining and measuring processes there are several issues which constrained and dictated the experimental design. The factors being studied were not constrained to high/low settings, so they would not fit into a factorial design. Also, in order to keep run times and number of test specimens to a reasonable level and in order to simulate industrial operations to a greater degree, an entire set of the six sizes of thin-walled section were cut from each test blank. The measurements of the resultant thicknesses of the thin-walled sections were taken in a similar manor through the application of the same reasoning. The order in which each of the test specimens were machined and measured was randomized in order to increase the statistical confidence of the experiment. Each of the test specimens was assigned a number, and then a random number generator was used to select the run order. This was performed twice so that a different randomized run order could be used for the machining and measuring processes. All of this information can be seen in Table 3.8.

Table 3.8 - Run Order for Machining and Measuring Processes

Part #	Material	Passes	Random Number	EDM Run Order	Random Number	Measure Run Order
1	Aluminum 6061 T6	Rough, 0 Finish	0.379196	13	0.289062	9
2			0.400696	17	0.788150	31
3			0.069573	3	0.920496	40
4		Rough, 1 Finish	0.570704	28	0.349893	15
5			0.208069	8	0.874471	36
6			0.991150	45	0.112356	2
7		Rough, 3 Finish	0.516545	25	0.489187	22
8			0.589384	30	0.639066	28
9			0.137788	6	0.882520	38
10	Yellow Brass SS360	Rough, 0 Finish	0.741350	32	0.884409	39
11			0.834438	40	0.404693	16
12			0.985437	44	0.262720	8
13		Rough, 1 Finish	0.828998	38	0.473000	20
14			0.132738	5	0.823829	33
15			0.931927	42	0.432578	18
16		Rough, 3 Finish	0.196552	7	0.059588	1
17			0.785868	36	0.722216	29
18			0.010870	1	0.408485	17
19	420 Stainless Steel	Rough, 0 Finish	0.412140	19	0.331628	13
20			0.400650	16	0.504737	23
21			0.504690	23	0.637009	27
22		Rough, 1 Finish	0.742025	33	0.524870	24
23			0.542877	26	0.995588	44
24			0.285657	11	0.260593	7
25		Rough, 3 Finish	0.421377	20	0.197123	5
26			0.381974	15	0.837847	34
27			0.480584	22	0.476208	21
28	D2 Tool Steel 25-30 RC	Rough, 0 Finish	0.092238	4	0.132047	4
29			0.786365	37	0.999010	45
30			0.295017	12	0.224889	6
31		Rough, 1 Finish	0.510127	24	0.343309	14
32			0.833413	39	0.767175	30
33			0.269216	10	0.309160	10
34		Rough, 3 Finish	0.263871	9	0.310990	11
35			0.641014	31	0.980044	43
36			0.060569	2	0.855267	35
37	D2 Tool Steel 60-65 RC	Rough, 0 Finish	0.570113	27	0.321029	12
38			0.433286	21	0.453287	19
39			0.867007	41	0.127822	3
40		Rough, 1 Finish	0.581824	29	0.590736	26
41			0.380528	14	0.875332	37
42			0.403539	18	0.803872	32
43		Rough, 3 Finish	0.753522	34	0.977714	42
44			0.961134	43	0.960180	41
45			0.765459	35	0.532579	25

4 Results and Analysis

4.1 Introduction

The sections in this chapter discuss the data that was obtained through the experiment and its subsequent analysis. In section 4.2 the data obtained through visual inspection and its subsequent analysis is presented. Definitions of the types of failures are delineated and then used in the analysis. The data is separated and discussed according to the different material types. In section 4.3 the numerical data which was obtained is presented and analyzed. Several statistical values – the mean, average difference from target, standard deviation, C_p, and C_{pk} – were calculated in order to describe the data. ANOVA tests were also performed on the data in order to facilitate comparisons between the materials according to the cutting parameters utilized. In section 4.4 the C_p and C_{pk} values that were calculated for each data set were used to compare the distribution of the data values for each of the different materials. It is important to note that these values are used for comparison only and only have significance to the comparisons made in this thesis. C_p and C_{pk} formulas require specification limits in their calculations, so specification limits of ± 0.03 millimeters (.0012 inches) were arbitrarily chosen. To facilitate the desired comparison the only requirement was that the specification limits be the same in all the calculations. The designated limits were chosen because they enabled a positive C_{pk} value to be calculated for virtually all of the data sets.

4.2 Visual Inspection Test of Thin-Walled Sections

A visual inspection test was performed on each of the thin-walled sections in order to determine if portions of the sections had been eroded away or if permanent deflection of the section had occurred. It should be noted that deflection of the thin-walled sections was likely caused by stresses introduced into the material through the machining process. Kim performed test on similar stock in order to determine if there were any residual forces in the materials. He observed bending which occurred in the direction of the last side cut by the wire-EDM machine. He thus concluded that there were no residual stresses in the parent material.[65] The tests for this thesis were performed under the same assumption. Four terms were used in order to describe defects which occurred while machining the thin-walled sections: depleted, notch, bent/notch, and bent. Each of these terms if further defined bellow.

- Depleted – this describes a thin-walled section which was completely eroded away. Often there were small tabs left on the parent material where the section should be attached due to the corner radius left by the round wire. Pictures of test specimens depicting this type of defect are shown in Figure 4.1.
- Notch – this describes a thin-walled section which had a major portion of the thin-walled section missing, and occurred in several different forms. Sometimes the center of the section was missing so that there were only tabs extending out from the parent material on each side, while at other times a ‘U’ or ‘V’ shaped notch was cut out of the top and/or bottom of the section. The difference between this

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[65] Sangseop Kim, *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* (School of Technology, Brigham Young University, Thesis. April 2005), 35-40.

Figure 4.1 - Test Specimens Demonstrating a Defect where a Thin-walled Section is Depleted

type of defect and the "depleted" description is that with the "notch" there was a sufficient amount of material left in order to obtain a measurement of the thickness of the thin-walled section. Figure 4.2 shows pictures of test specimens illustrating this type of defect.

Figure 4.2 - Test Specimens Demonstrating a Notch Defect in the Thin-walled Section

- Bent/Notch – this describes a thin-walled section where a notch was present and where the entire section or portions of the section had deflected. Often, the deflection was confined to a small portion of the thin-walled section or the deflection was evenly spread across the web so that it resembled a parenthesis when looked at directly from the top or bottom. In these cases it was possible to obtain a measurement where there was not a notch present in the section. At times, in conjunction with a notch the edge created by the notch curled or bent to a degree such that it was not possible to take a measurement. Figure 4.3 shows pictures of these types of defects.

Figure 4.3 - Test Specimens Demonstrating a Bent/Notch Defect

- Bent – this describes a thin-walled section which had deflected but was not missing any portions of the section. It was noted that the deflection always occurred away from the final cut, or in other words the deflection occurred in a direction that moved the section away from the wire as it was cutting the second side of the web. Figure 4.4 is a picture of this type of defect.

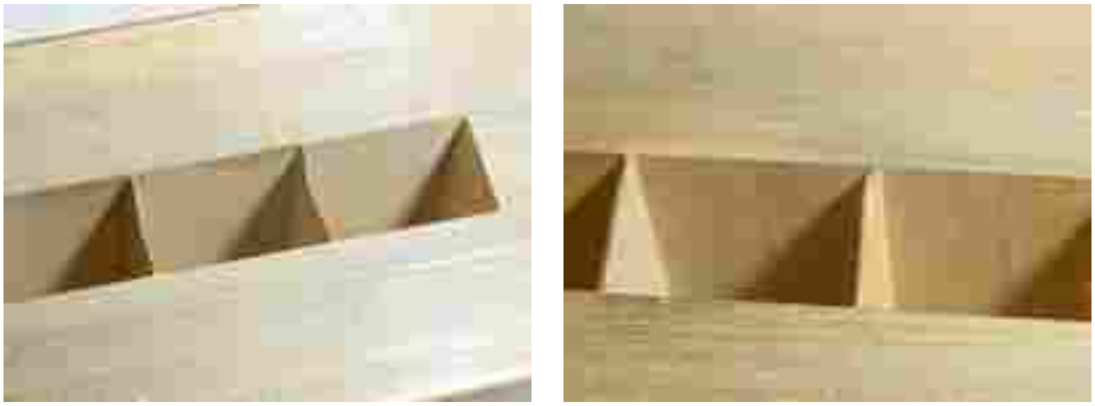

Figure 4.4 - Test Specimens Demonstrating a Bent Failure for the Thin-walled Sections

Each of the thin-walled sections was evaluated and records were generated when any of the four visual inspection failures just described was observed. This data was compiled and can be seen in its entirety in the appendix (see Appendix G).

An analysis of the visual inspection data, which follows, is separated into sections by material type and by the number of finishing passes that were used. Three replications for each of the cutting parameters were performed in this study, so each of the graphs in this section represents the compilation of the data for those replications.

4.2.1 Aluminum 6061 T6 – Visual Inspection Data and Analysis

Figure 4.5 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Aluminum 6061 T6 while utilizing the machining parameters of a roughing pass with no finishing passes. As indicated by the chart, the thin-walled sections with target thicknesses of 0.10 and 0.05 millimeters (.004 and .002 inches) were almost totally vaporized during the machining process. The sections with a target thickness of 0.15 millimeters (.006 inches) demonstrated a significant difference in quality between the top and the bottom of the sections. The top of these sections were slightly bent, but the bottom of each also had significant notches in them. The sections with a target thickness of 0.20 millimeters (.008 inches) did not have any defects on the top of the sections, but the bottom of the sections each had slight defects, either a bend or a slight notch.

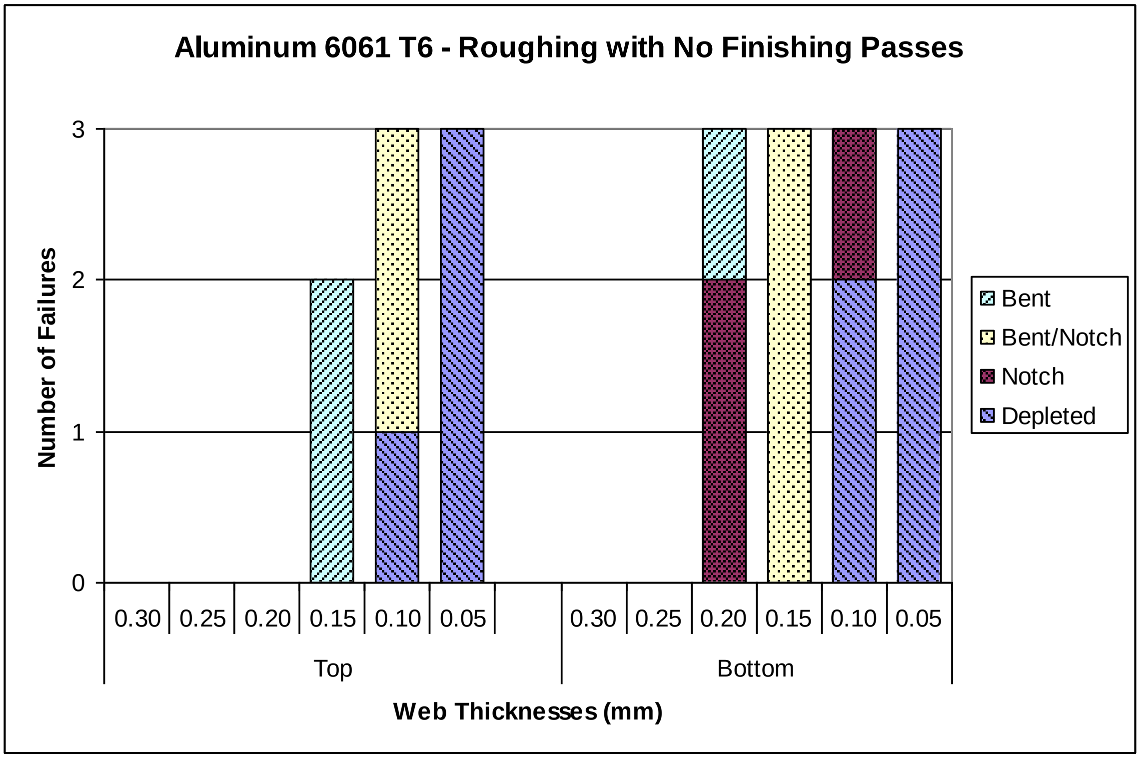

Figure 4.5 - Visual Inspection Failures of Thin-walled Sections of Aluminum 6061 T6 – Roughing with No Finishing Passes

Figure 4.6 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Aluminum 6061 T6 while utilizing the machining parameters of a roughing pass with one finishing pass. As indicated by the chart, the thin-walled sections with a target thickness of 0.05 millimeter (.002 inch) were almost entirely vaporized. Only one of the sections with a target thickness of 0.10 millimeter (.004 inch)

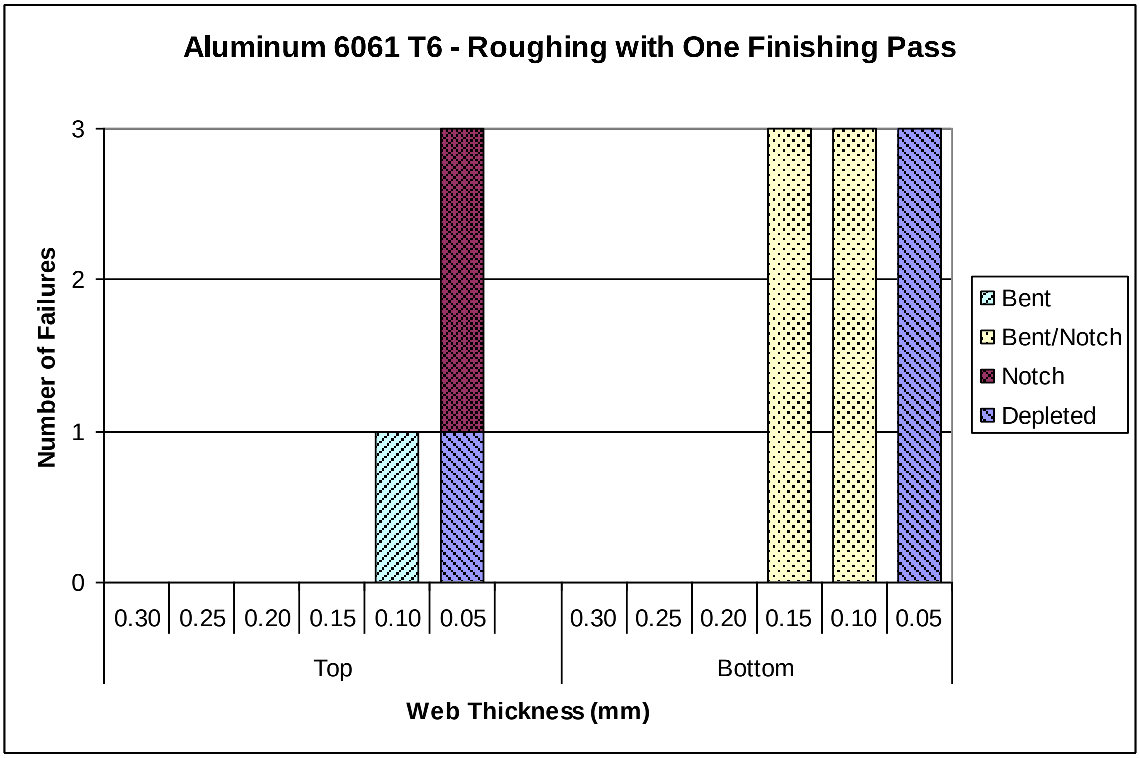

Figure 4.6 - Visual Inspection Failures of Thin-walled Sections of Aluminum 6061 T6 – Roughing with One Finishing Pass

had a defect on the top of the section – a slight bend – , but the bottom of the sections had significant notches and had deflected significantly. The bottom of each of the sections with a target thickness of 0.15 millimeter (.006 inch) had a small notch in it and was slightly bent.

Figure 4.7 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Aluminum 6061 T6 while utilizing the machining parameters of a roughing pass with three finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were each slightly bent on the top of the sections while each section had a large notch in the bottom where some of the section had been eroded. The

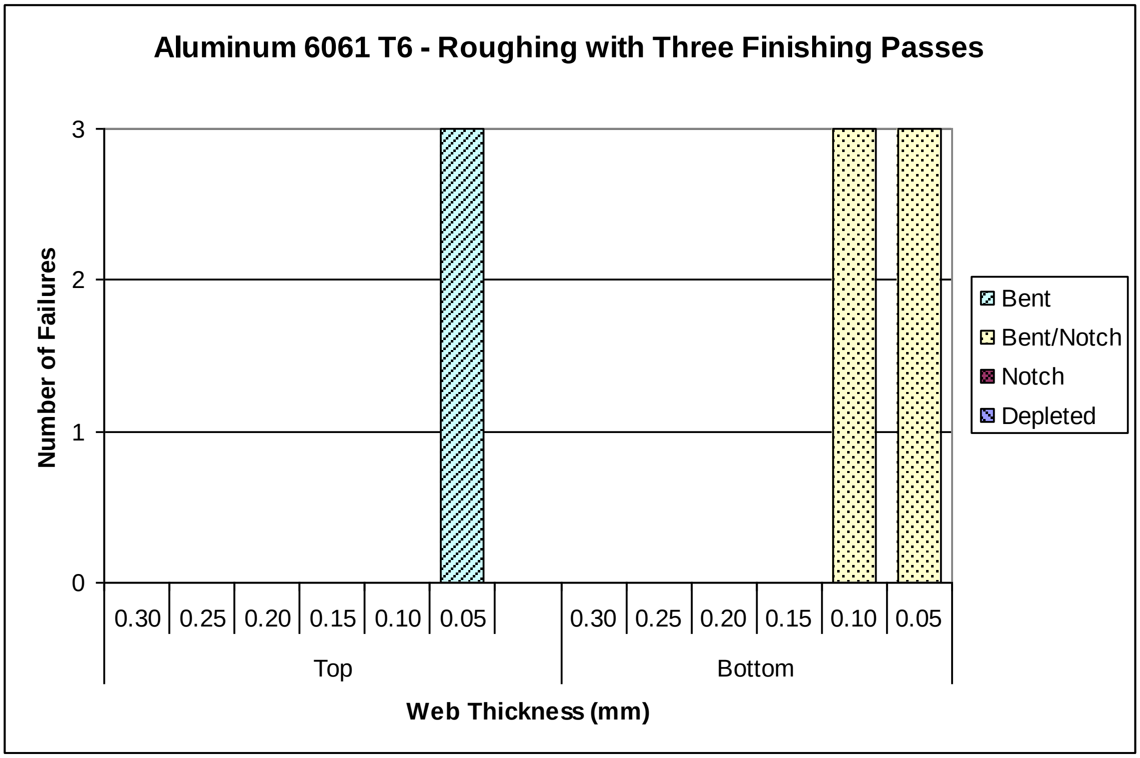

Figure 4.7 - Visual Inspection Failures of Thin-walled Sections of Aluminum 6061 T6 – Roughing with Three Finishing Passes

bottom of each of the sections with a target thickness of 0.10 millimeter (.004 inch) was slightly bent and also exhibited small notches.

By comparing the data depicted in the three proceeding charts, which represent failures determined through visual inspection while cutting thin-walled section from Aluminum 6061 T6, it can be seen that both the number and degree of failure decreased when the number of finishing passes was increased. Thus, a roughing pass and three finishing passes obtained the best results. Also, it is interesting to note that all of the test specimens exhibited a greater number and more drastic failures on the bottom of the thin-walled sections as compared to those found on the top of the corresponding sections. Although the data clearly exhibits this pattern, the cause of this phenomenon is unknown.

4.2.2 Yellow Brass 360 – Visual Inspection Data and Analysis

Figure 4.8 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Yellow Brass SS360 while utilizing the machining parameters of a roughing pass with no finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were totally eroded during the machining process. The top of the sections with a target thickness of 0.10 millimeter (.004 inch) were bent while the bottom of each of the corresponding sections also had a large notch where part of it had been eroded. While the top of the sections with a target thickness of 0.15 millimeter (.006 inch) exhibited no defects the bottom of these same sections were slightly bent.

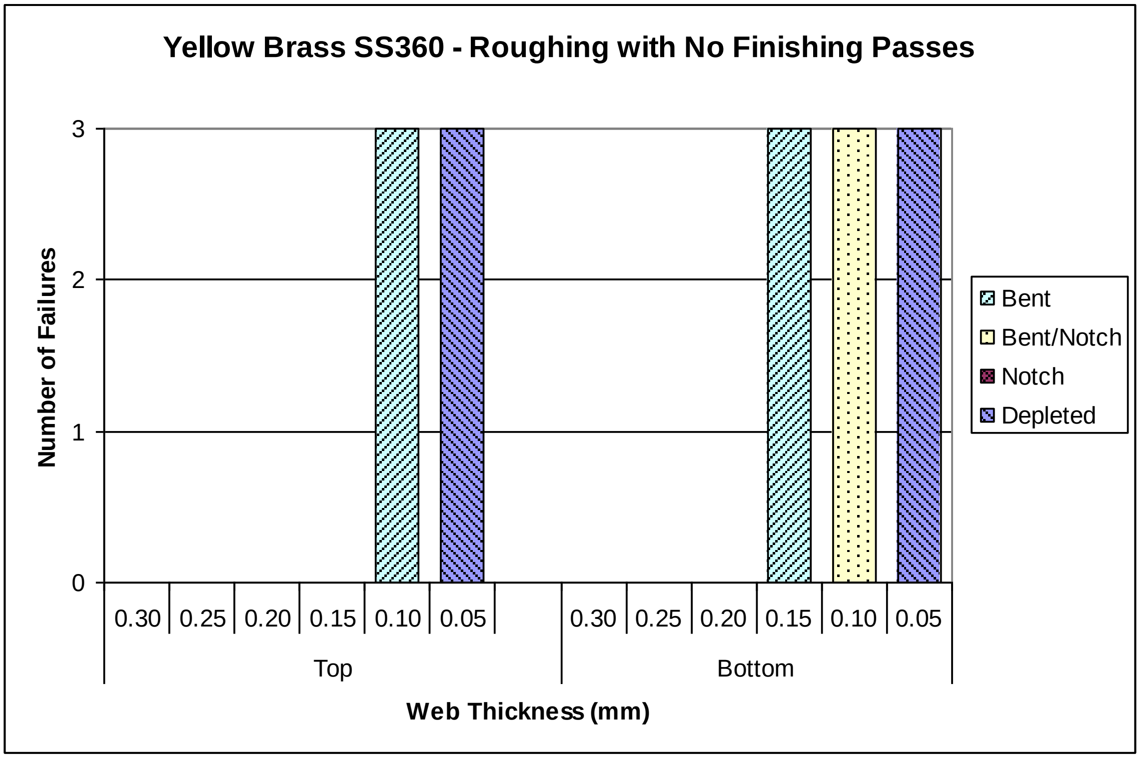

Figure 4.8 - Visual Inspection Failures of Thin-walled Sections of Yellow Brass SS360 – Roughing with No Finishing Passes

Figure 4.9 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Yellow Brass SS360 while utilizing the machining parameters of a roughing pass with one finishing pass. Each of the sections with a target thickness of 0.05 millimeter (.002 inch) was bent and contained a notch, but the degree of bending and size of the notches was significantly greater in the bottom of each section. The sections with a target thickness of 0.10 millimeter (.004 inch) were slightly bent on the top of the sections and exhibited a slightly greater degree of bending on the bottom of the corresponding sections.

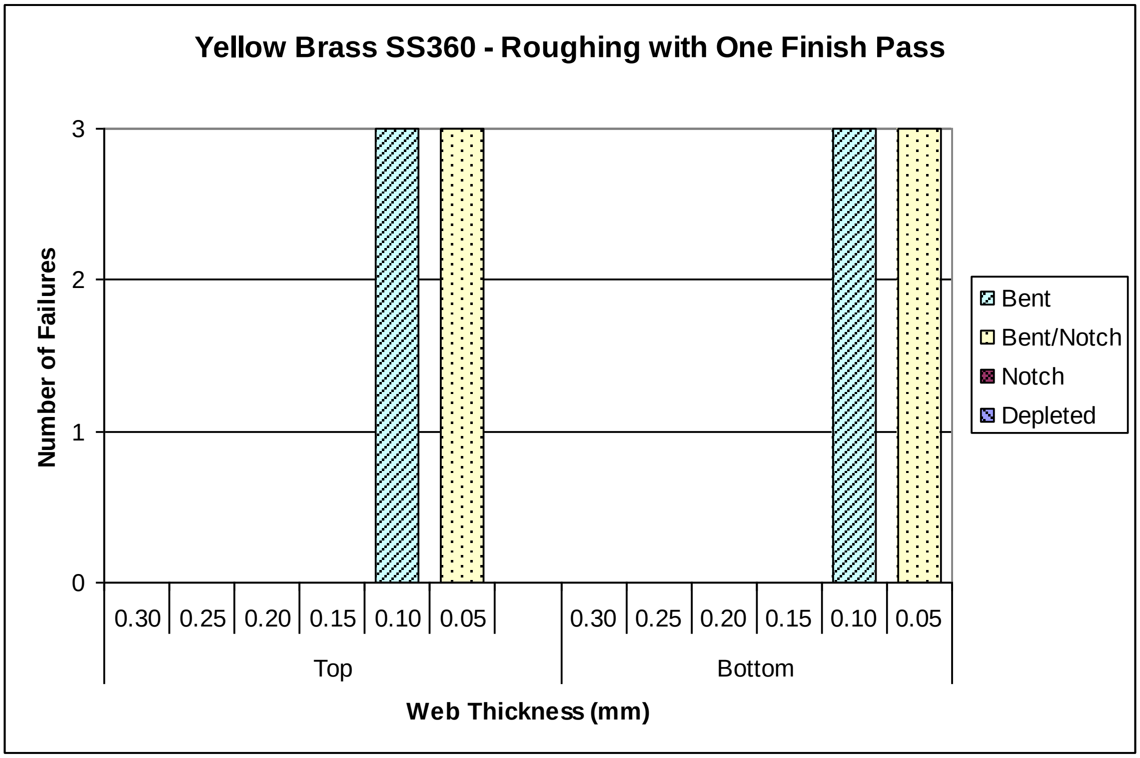

Figure 4.9 - Visual Inspection Failures of Thin-walled Sections of Yellow Brass SS360 – Roughing with One Finishing Pass

Figure 4.10 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from Yellow Brass SS360 while utilizing the machining parameters of a roughing pass with three finishing passes. The top of the sections with a target thickness of 0.05 millimeter (.002 inch) were bent while the bottom of two of the sections were both bent and notched. Unlike the other two, the bottom of the third section was only bent. The sections with a target thickness of 0.10 millimeter (.004 inch) exhibited a similar degree of slight bending on both the top and bottom of the sections.

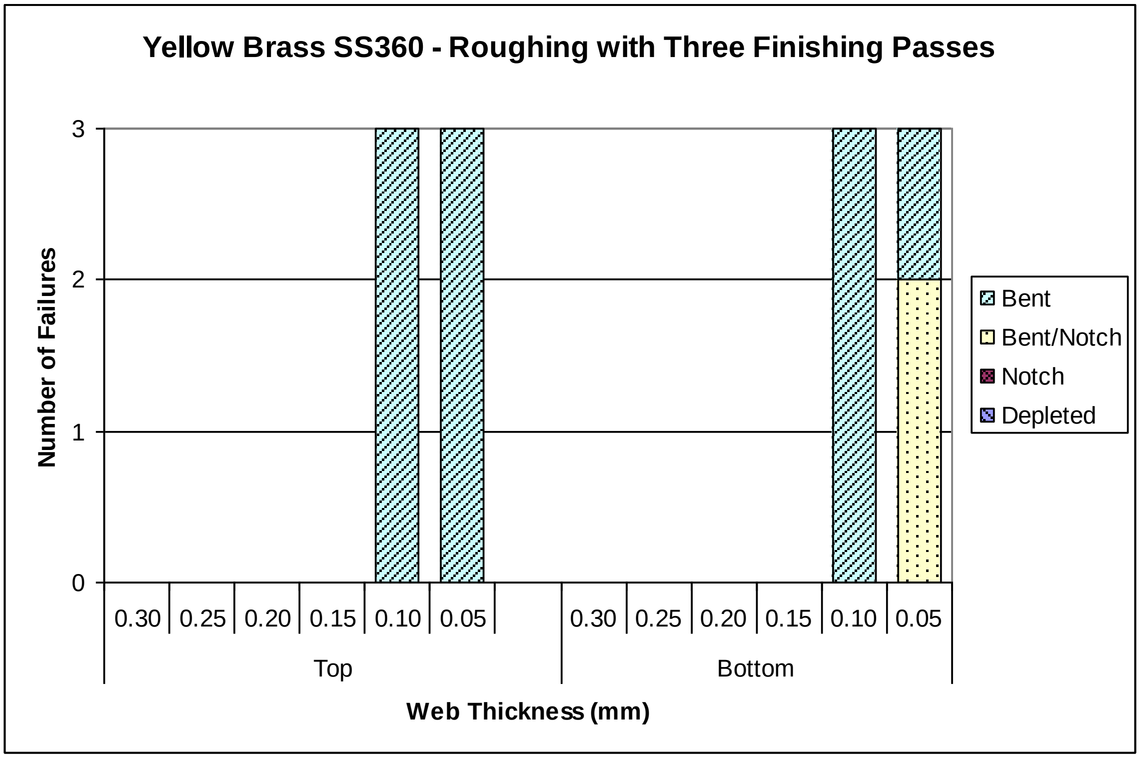

Figure 4.10 - Visual Inspection Failures of Thin-walled Sections of Yellow Brass SS360 – Roughing with Three Finishing Passes

By comparing the data depicted in the three preceding charts, which represent failures determined through visual inspection while cutting thin-walled sections from

Yellow Brass SS360, it can be seen that both the number and degree of failures decreased when the number of finishing passes was increased. Thus, a roughing pass and three finishing passes obtained the best results. Although not as pronounced as the failures in Aluminum 6061 T6, the bottoms of the thin-walled sections cut from Yellow Brass SS360 also displayed a greater number and more dramatic failures than did the tops of the same sections.

4.2.3 420 Stainless Steel – Visual Inspection Data and Analysis

Figure 4.11 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from 420 Stainless Steel while utilizing the machining parameters of

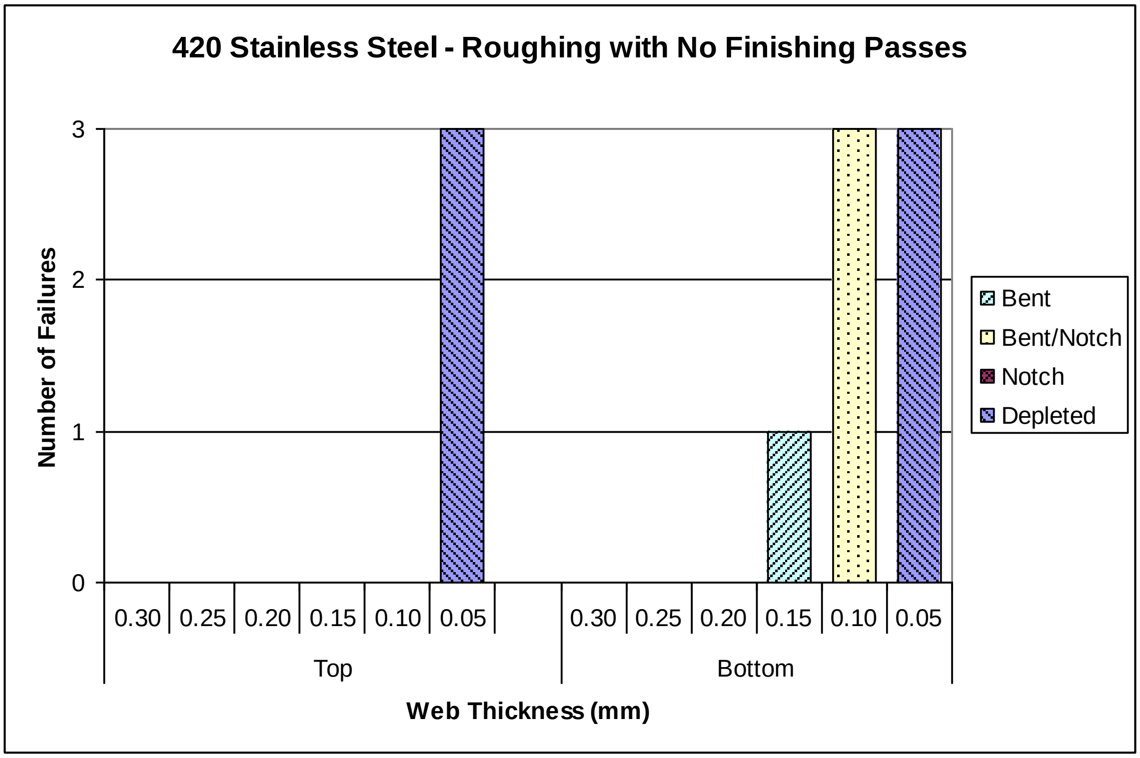

Figure 4.11 - Visual Inspection Failures of Thin-walled Sections of 420 Stainless Steel – Roughing with No Finishing Passes

a roughing pass with no finishing passes. As indicated by the chart, the sections with a target thickness of 0.05 millimeter (.002 inch) were completely eroded during the machining process. The top of the sections with a target thickness of 0.10 millimeter (.004 inch) were free of defects, but the bottom of the sections were each bent and had fairly large notches in them where some of the material had been consumed during the machining process. The bottom of one of the sections with a target thickness of 0.15 millimeter (.006 inch) was slightly bent while the other sections with the same target thickness were free of defects.

Figure 4.12 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from 420 Stainless Steel while utilizing the machining parameters of

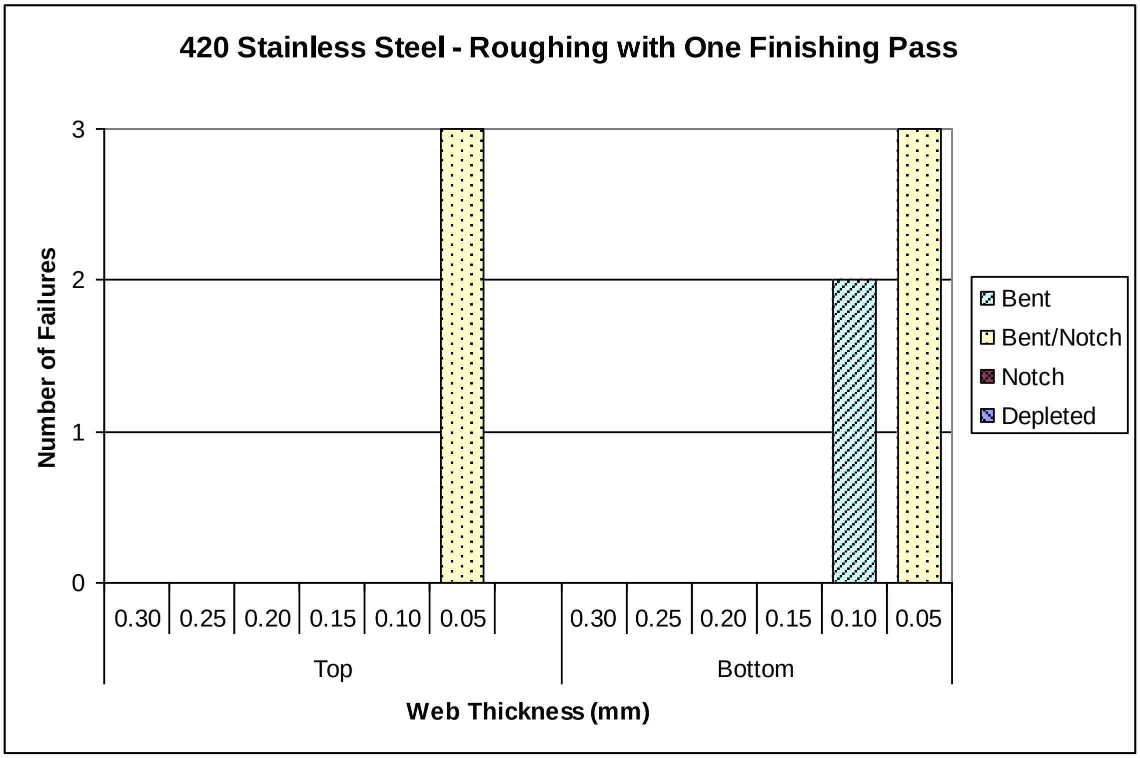

Figure 4.12 - Visual Inspection Failures of Thin-walled Sections of 420 Stainless Steel – Roughing with One Finishing Pass

a roughing pass with one finishing pass. Both the top and bottom of the sections with a target thickness of 0.05 millimeter (.002 inch) were slightly bent and contained fairly large notches which were comparable in size on the top and bottom. Two of the sections with at target thickness of 0.10 millimeter (.004 inch) displayed very slight bending on the bottom of the sections.

Figure 4.13 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from 420 Stainless Steel while utilizing the machining parameters of a roughing pass with three finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were the only sections that displayed any defects. The top of the

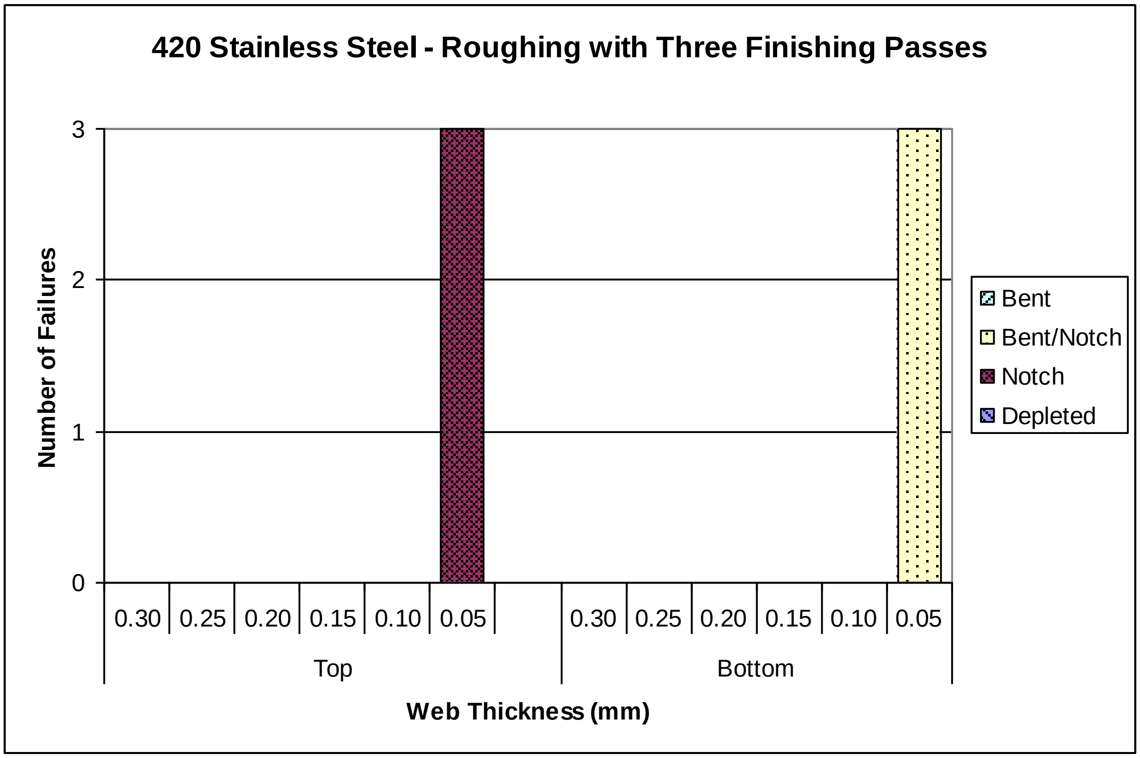

Figure 4.13 - Visual Inspection Failures of Thin-walled Sections of 420 Stainless Steel – Roughing with Three Finishing Passes

sections each had large notches in them while the bottom of the sections had small notches and were very slightly bent.

By comparing the data depicted in the three proceeding charts, which represent failures determined through visual inspection while cutting sections from 420 Stainless Steel, it can be seen that both the number and degree of failures decreases when the number of finishing passes was increased. While the first two cutting parameters discussed, roughing with no finishing passes and roughing with one finishing pass, exhibited the same characteristic of having more dramatic failures on the bottoms of the thin-walled sections as compared with those found on the tops of the sections, the third cutting parameter, roughing with three finishing passes, demonstrated the opposite tendency. That is, the tops of the sections had more dramatic failures than did the bottoms of the same sections.

4.2.4 D2 Tool Steel 25-30 RC – Visual Inspection Data and Analysis

Figure 4.14 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 25 to 30 RC while utilizing the machining parameters of a roughing pass with no finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were completely eroded during the machining process. The tops of the sections with a target thickness of 0.10 millimeter (.004 inch) did not contain any defects, but the bottom of those sections each had a large notch in them where some of the material had been eroded during the machining process.

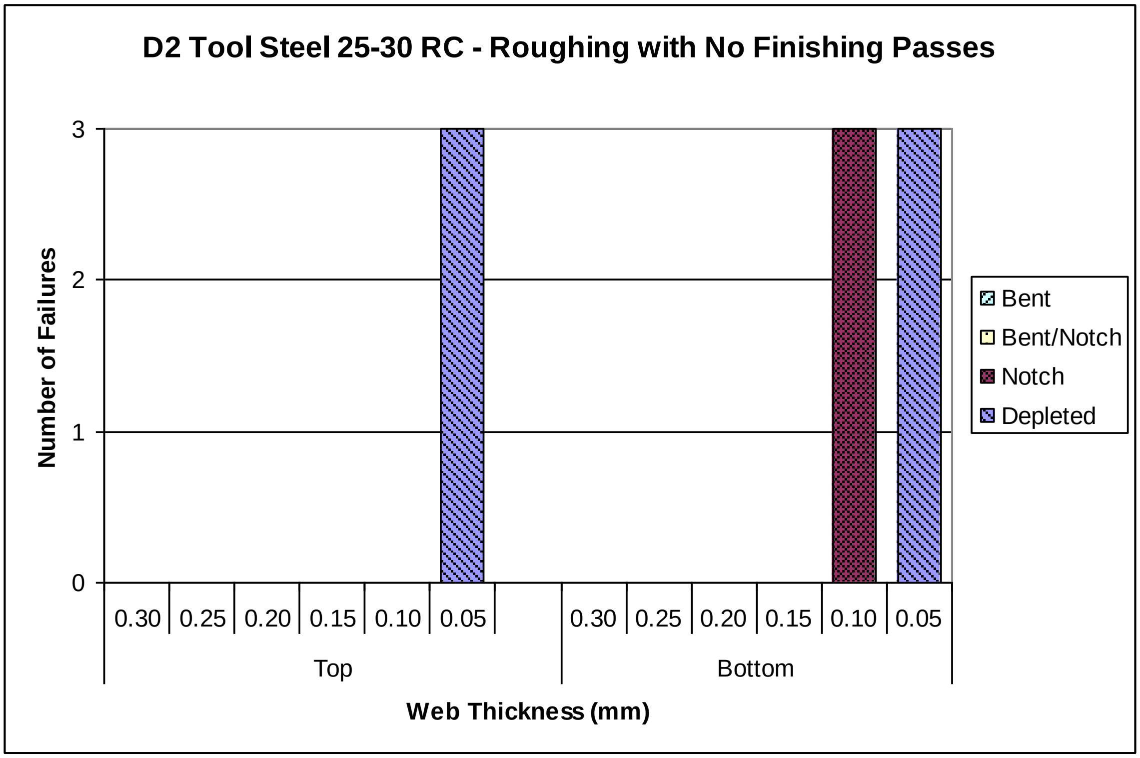

Figure 4.14 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 25-30 RC – Roughing with No Finishing Passes

Figure 4.15 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 25 to 30 RC while utilizing the machining parameters of a roughing pass with one finishing pass. The only defective sections observed with this material were the sections with a target thickness of 0.05 millimeter (.002 inch). Each of the sections had a notch in both the top and the bottom of the section. The bending of these sections refers to curling of the material around the edges of the notch. In all of the observed cases the direction of the curling was toward the side of the web that was cut last. This being the case, the curling had to have occurred on the final pass of the wire, but the cause of the curling could not be determined from this research.

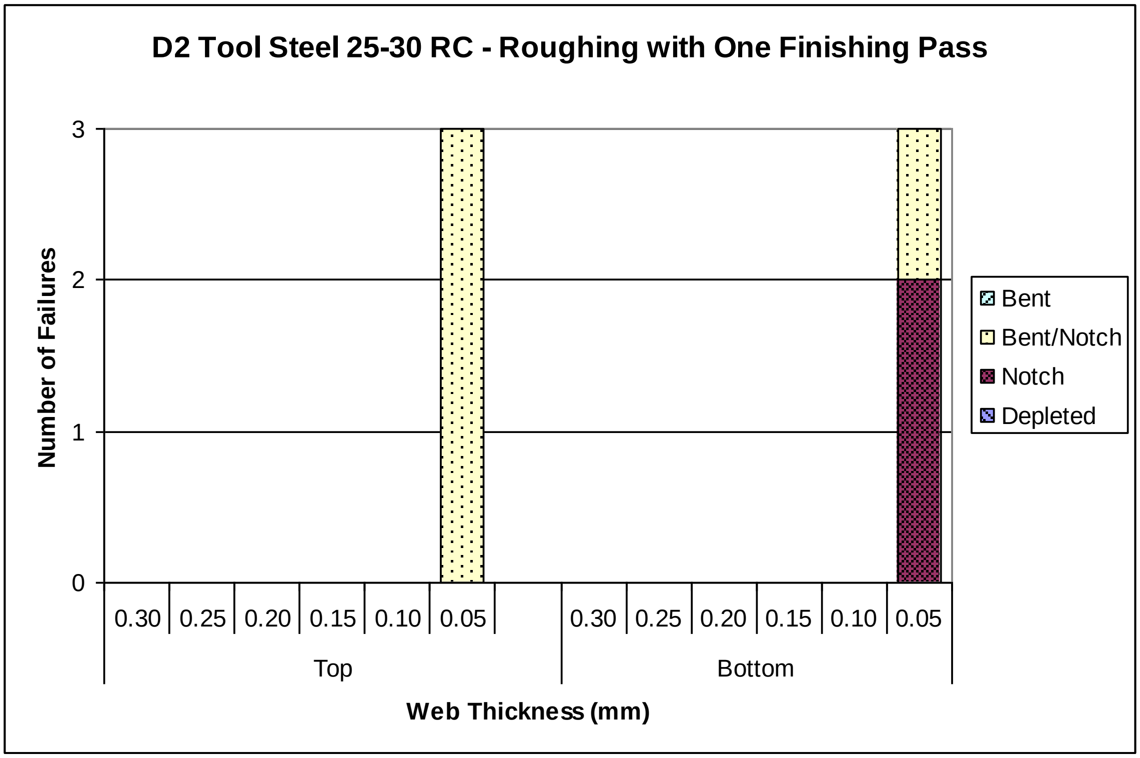

Figure 4.15 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 25-30 RC – Roughing with One Finishing Pass

Figure 4.16 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 25 to 30 RC while utilizing the machining parameters of a roughing pass with three finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were the only sections containing defects while utilizing the specified machining parameters. The top of the sections each had a large notch in them while the bottom of the sections each had two smaller notches.

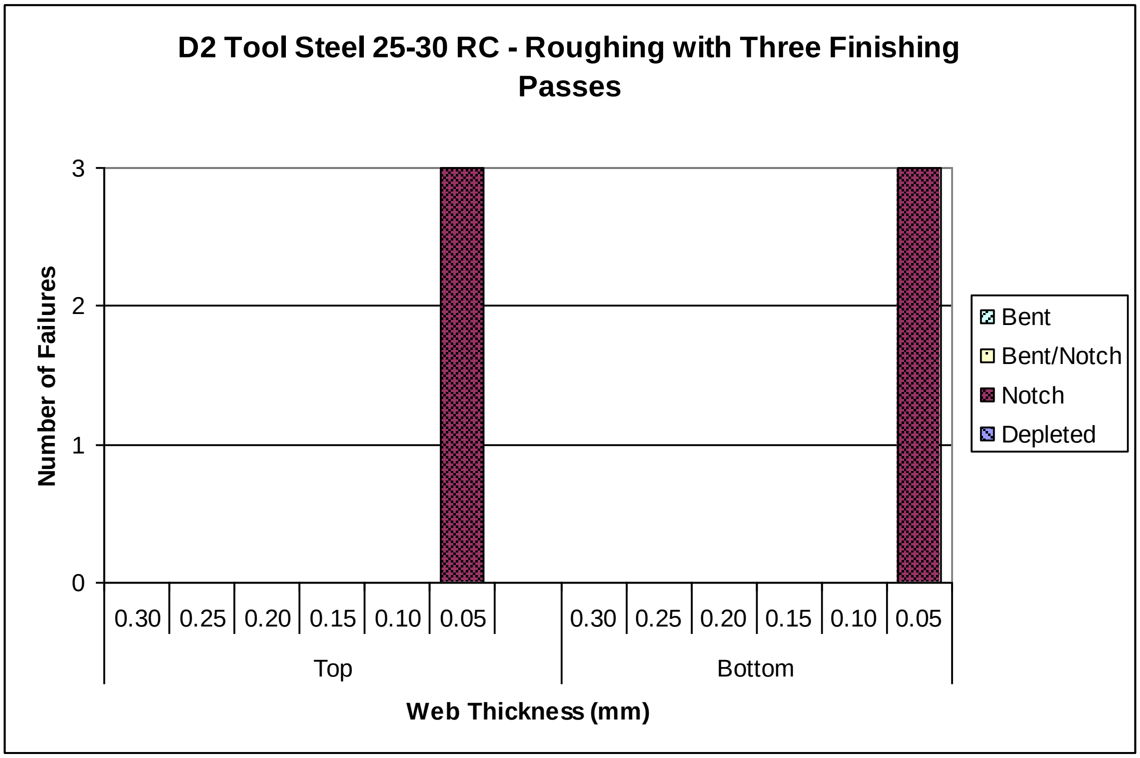

Figure 4.16 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 25-30 RC – Roughing with Three Finishing Passes

By comparing the data depicted in the three proceeding charts, which represent failures determined through visual inspection while cutting thin-walled sections from D2 Tool Steel at 25 to 30 RC, it can be seen that both the number and degree of failures decreased when the number of finishing passes was increased. The bottoms of the defective sections demonstrated a greater number and degree of failure while utilizing a roughing with no finishing passes. The failures observed between the tops and bottoms of the sections while utilizing a roughing with one finishing pass were relatively equal. While utilizing a roughing with three finishing passes the failures on the tops of the sections were more significant than those on the bottoms of the sections.

4.2.5 D2 Tool Steel 60-65 RC – Visual Inspection Data and Analysis

Figure 4.17 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 60 to 65 RC while utilizing the machining parameters of a roughing pass with no finishing passes. The sections with a target thickness of 0.05 millimeter (.002 inch) were totally eroded during the machining process. Two of the sections with a target thickness of 0.10 millimeter (.004 inch) exhibited relatively small notches on the bottom of the sections while the third and the top of all the sections did not exhibit any defects.

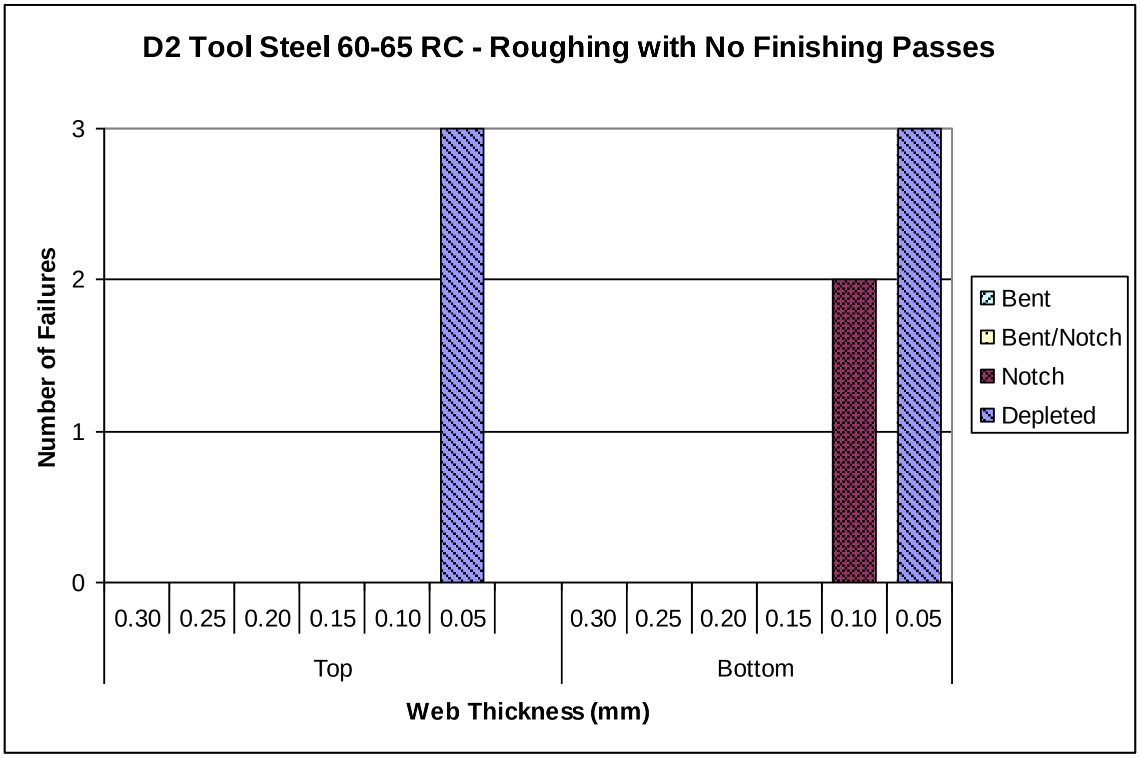

Figure 4.17 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 60-65 RC – Roughing with No Finishing Passes

Figure 4.18 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 60 to 65 RC while utilizing the machining parameters of a roughing pass with one finishing pass. As can be seen from the chart, the only sections that exhibited any defects were those that had a target thickness of 0.05 millimeters (.002 inches). Each of these sections had a large notch in both the top and bottom of the section. In some cases, the entire center of the section was missing from the top to the bottom leaving large tabs on each side attached to the parent material.

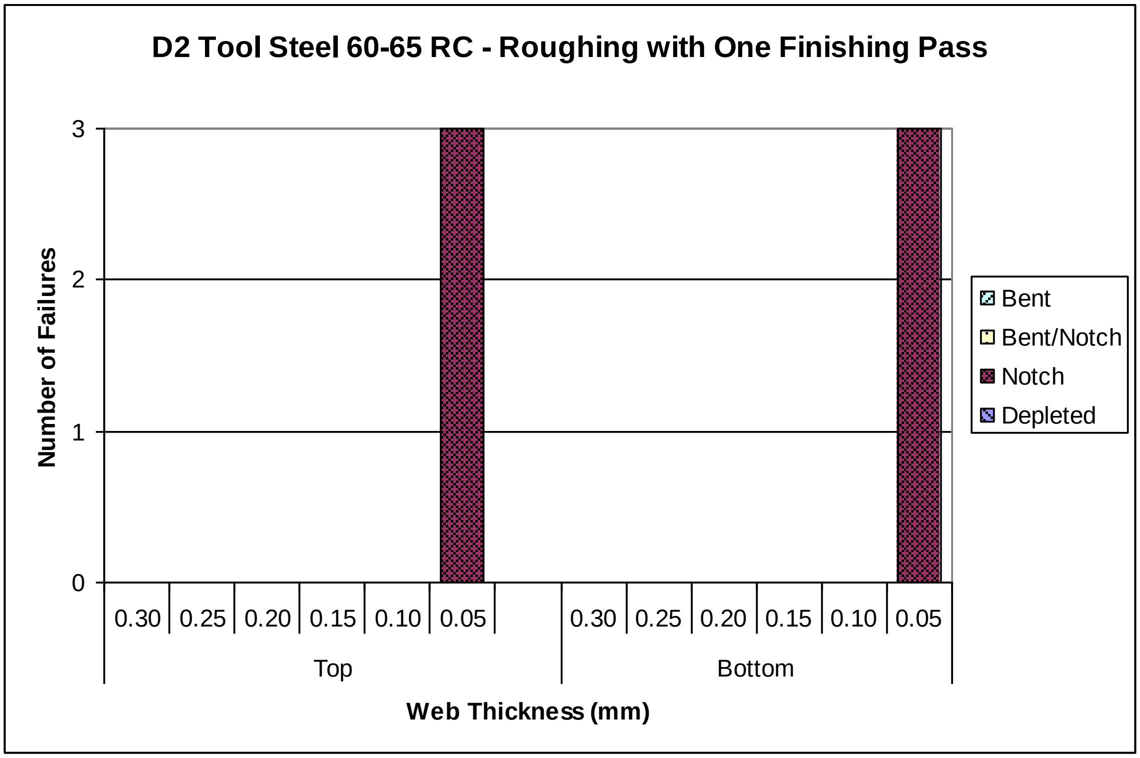

Figure 4.18 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 60-65 RC – Roughing with One Finishing Pass

Figure 4.19 is a chart depicting the visual inspection data obtained after cutting thin-walled sections from D2 Tool Steel at 60 to 65 RC while utilizing the machining

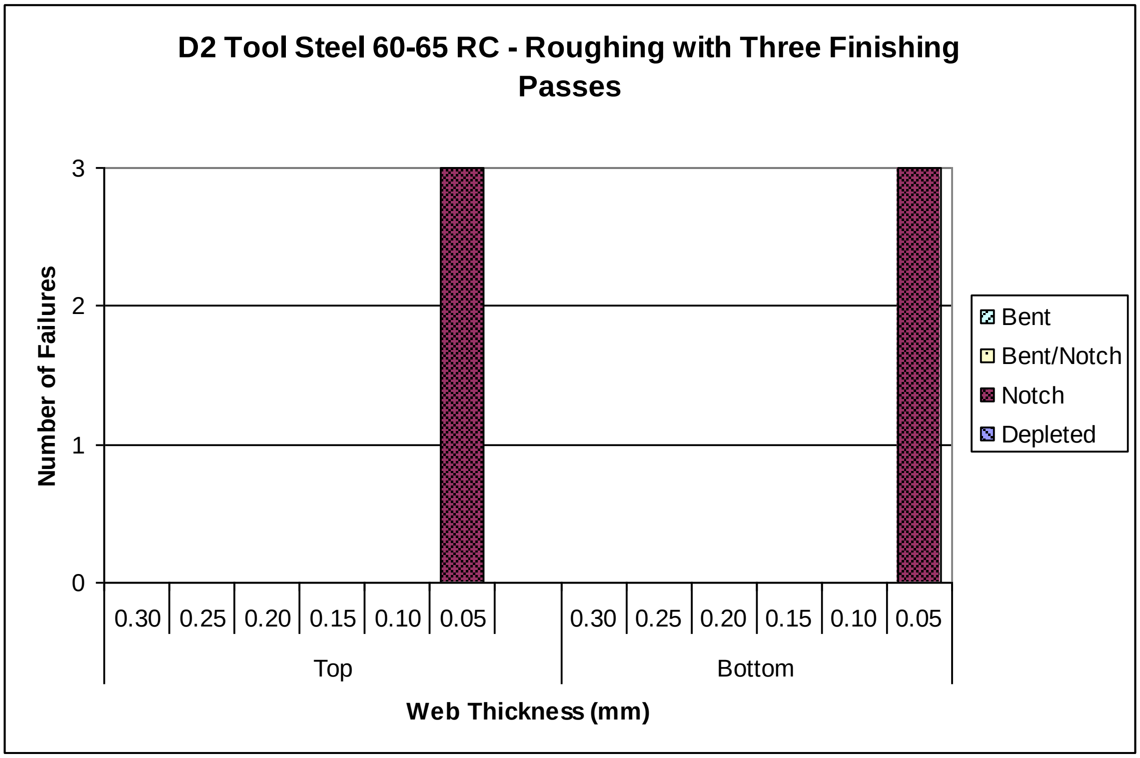

Figure 4.19 - Visual Inspection Failures of Thin-walled Sections of D2 Tool Steel 60-65 RC – Roughing with Three Finishing Passes

parameters of a roughing pass with three finishing passes. The only sections containing defects while utilizing the aforementioned cutting parameters were those that had a target thickness of 0.05 millimeters (.002 inches). One of the sections had a large notch in both the top and the bottom and a hole in the center. The other two sections were missing the entire center from the top to the bottom of the specimens.

By comparing the data depicted in the tree proceeding charts, which represent failures determined through visual inspection while cutting thin-walled sections from D2 Tool Steel at 60 to 65 RC, it can be observed that better results are achieved through the use of finishing passes. As to failures observed through visual inspection of the thin-walled sections, there is no difference in the number of failures observed while using one or three finishing passes. However, while utilizing a roughing with no finishing passes both the degree and number of failures increased. Also, while utilizing a roughing with no finishing passes the number and degree of failures was greater on the bottoms of the sections as compared to those observed on the tops of the same sections. While utilizing a roughing with one finishing pass and a roughing with three finishing passes there is no observable difference between the failures on the tops and the bottoms of the thin-walled sections.

4.3 Measurement of Thin-Walled Sections and Statistical Analysis

The following sections contain the analysis of the numerical data which was obtained from the test specimens. The analysis of the data is separated according to the material types that were tested. Charts indicating each of the data sets used and their distributions are given. Black dots were used on these graphs to indicate each data point, and a red diamond was used to indicate the target thickness for each thin-walled section. Tables follow each of these charts which list the mean, the mean's difference from target, standard deviation, C_p, and C_{pk} for each individual data set. In order to increase the reliability of the statistical analysis, any measurements that were taken on a thin-walled section which failed the visual inspection test was eliminated from the data set.

An ANOVA test was performed on the numerical data that was obtained by measuring the thickness of each of the thin-walled sections with a CMM. The complete statistical report of this analysis can be seen in the appendix (see Appendix H). Three different aspects of each data set were tested as to its significance: the number of finishing passes used, the thicknesses of the thin-walled sections, and the location from which the measurements were taken – in reference to the top and bottom of the test specimen. A second ANOVA test was performed in order to compare the data sets obtained for the three different cutting parameters according to the material that was cut. The complete statistical report for this test can be seen in the appendix (see Appendix I). Tables, according to material type, listing the P-values obtained from this statistical analysis are displayed in the following sections. A third ANOVA test was performed in order to compare the data sets obtained for the five different materials according to the cutting parameters that were used to cut the materials. The complete statistical report for this ANOVA test can be seen in the appendix (see Appendix J). A table containing the P-values for each of these comparisons is given followed by a graph giving a visual interpretation of this data.

4.3.1 Aluminum 6061 T6 – Statistical Analysis

Figure 4.20 indicates the data set that was used in the statistical analysis for Aluminum 6061 T6 while utilizing cutting parameters of a roughing with no finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) and 0.10 millimeters (.004 inches) failed the visual inspection test, so there are no data points represented at these thicknesses. Also, several of the 0.15 millimeter (.006 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

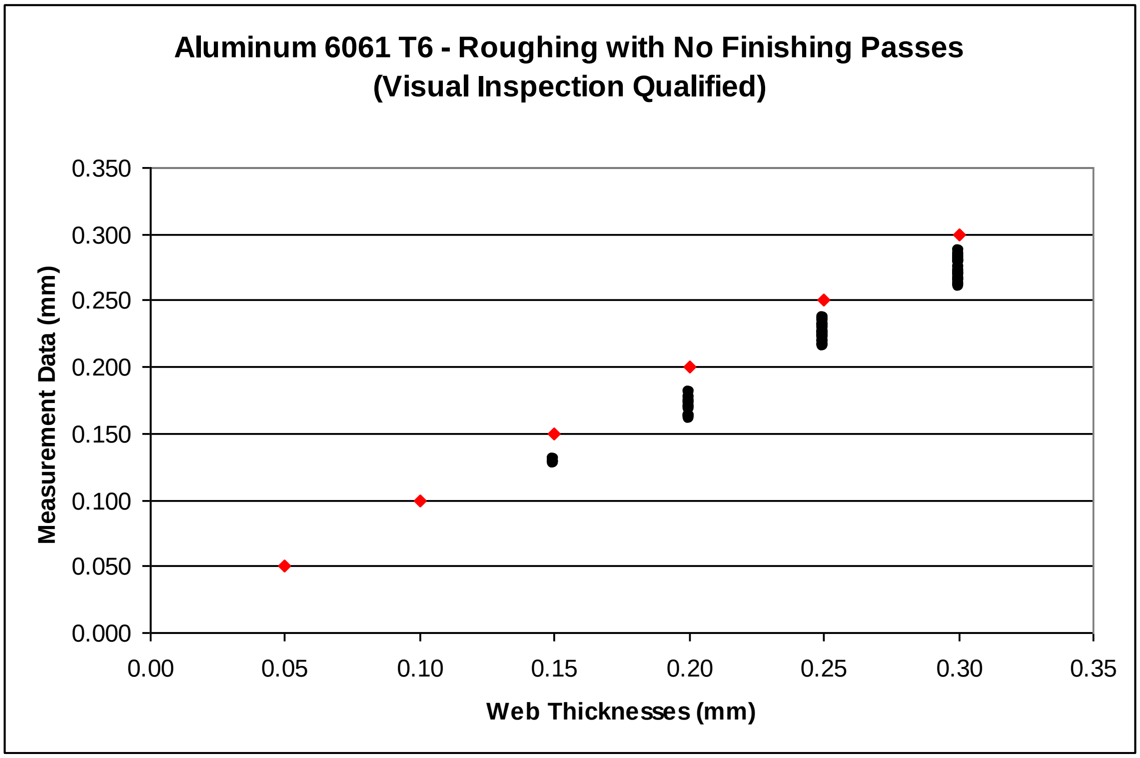

Figure 4.20 - Data Set Used for Aluminum 6061 T6 - Roughing with No Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.1. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is

Table 4.1 - Aluminum 6061 T6 - Statistics for Roughing with No Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.273	-0.027	0.008238	1.2139	0.1326
0.250	0.226	-0.024	0.006582	1.5193	0.2814
0.200	0.170	-0.030	0.006708	1.4907	-0.0166
0.150	0.128	-0.022	0.001528	6.5465	1.8185
0.100	-	-	-	-	-
0.050	-	-	-	-	-

statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Figure 4.21 indicates the data set that was used in the statistical analysis for Aluminum 6061 T6 while utilizing cutting parameters of a roughing with one finishing pass. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at that thickness. Also, several of the 0.10 millimeter (.004 inch) and 0.15 millimeter (.006 inch) sections failed the visual inspection test thus reducing the number of data points indicated at those thicknesses.

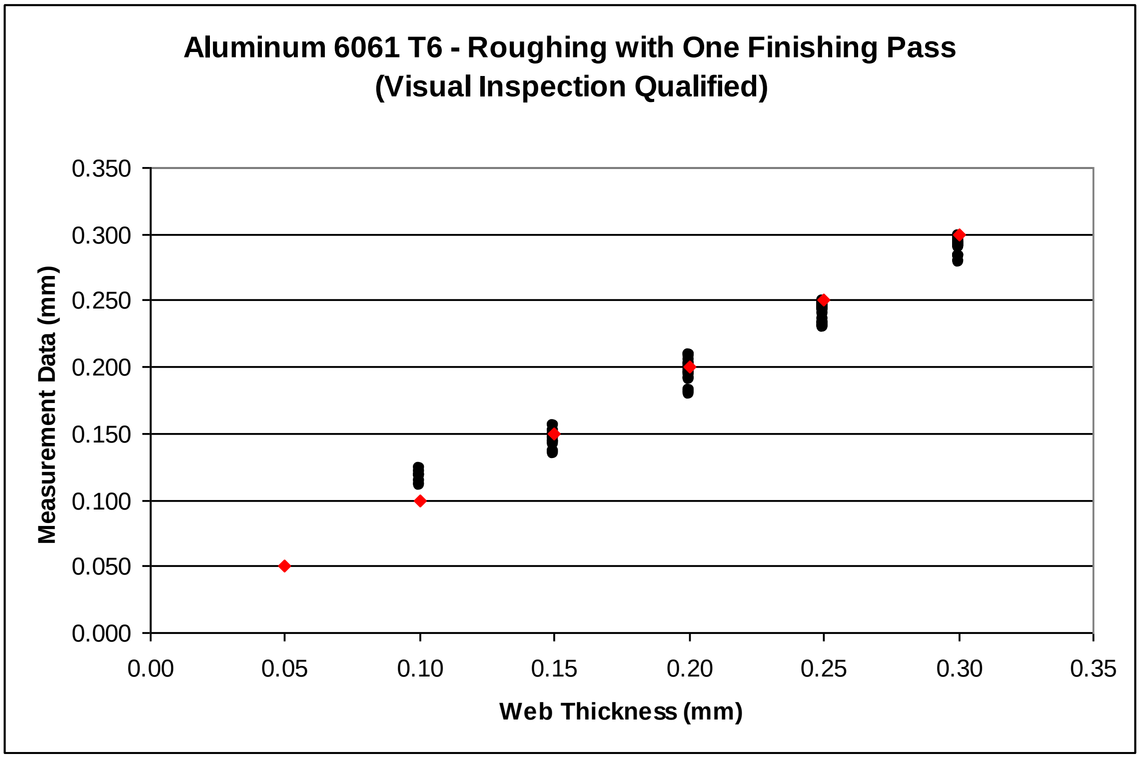

Figure 4.21 - Data Set Used for Aluminum 6061 T6 - Roughing with One Finishing Pass

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.2. The mean for each data set representing target thicknesses from 0.30 to 0.15 millimeters (.012 to .006 inches) is smaller than the respective target value while the mean for the data set with a target value of 0.10 millimeters (.004 inches) is greater than the target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of 0.0025 for the specified parameters.

Table 4.2 - Aluminum 6061 T6 - Statistics for Roughing with One Finishing Pass Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.290	-0.010	0.005237	1.9094	1.2977
0.250	0.241	-0.009	0.006964	1.4360	0.9839
0.200	0.196	-0.004	0.009149	1.0930	0.9453
0.150	0.144	-0.006	0.006572	1.5215	1.2285
0.100	0.117	0.017	0.004561	2.1926	0.9501
0.050	-	-	-	-	-

Figure 4.22 indicates the data set that was used in the statistical analysis for Aluminum 6061 T6 while utilizing cutting parameters of a roughing with three finishing passes. All of the sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at that thickness. Several of the 0.10 millimeter (.004 inch) sections failed the visual inspection test thus reducing the number of data points indicated at this thickness.

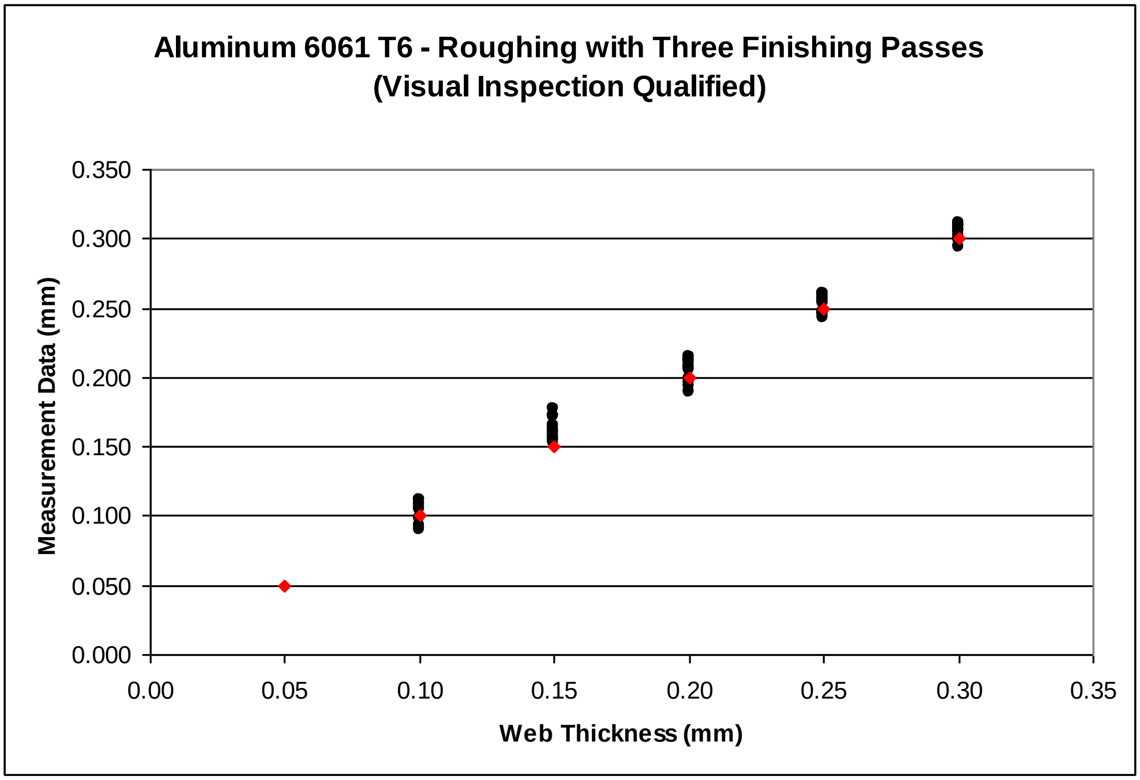

Figure 4.22 - Data Set Used for Aluminum 6061 T6 - Roughing with Three Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.3. The mean for each data set is larger than each of the respective target values. The ANOVA test indicated that this data

Table 4.3 - Aluminum 6061 T6 - Statistics for Roughing with Three Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.305	0.005	0.004840	2.0660	1.6949
0.250	0.253	0.003	0.006082	1.6441	1.4766
0.200	0.207	0.007	0.007617	1.3129	1.0236
0.150	0.161	0.011	0.007302	1.3694	0.8597
0.100	0.103	0.003	0.007672	1.3034	1.1683
0.050	-	-	-	-	-

is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

The ANOVA test further indicated that there was a significant difference in the data when the measurements that were taken from the tops of the thin-walled sections were compared to those taken from the bottoms of the sections. A t-value of 0.0031 was observed.

Figure 4.23 is a graph depicting the accuracy of cutting thin-walled sections from Aluminum 6061 T6 while utilizing the three cutting parameters previously specified. Each of the calculated mean values for the respective target thicknesses and cutting parameters were subtracted from the target value in order to generate the values represented on this graph. This effectually makes 0.00 the target. Upper and lower

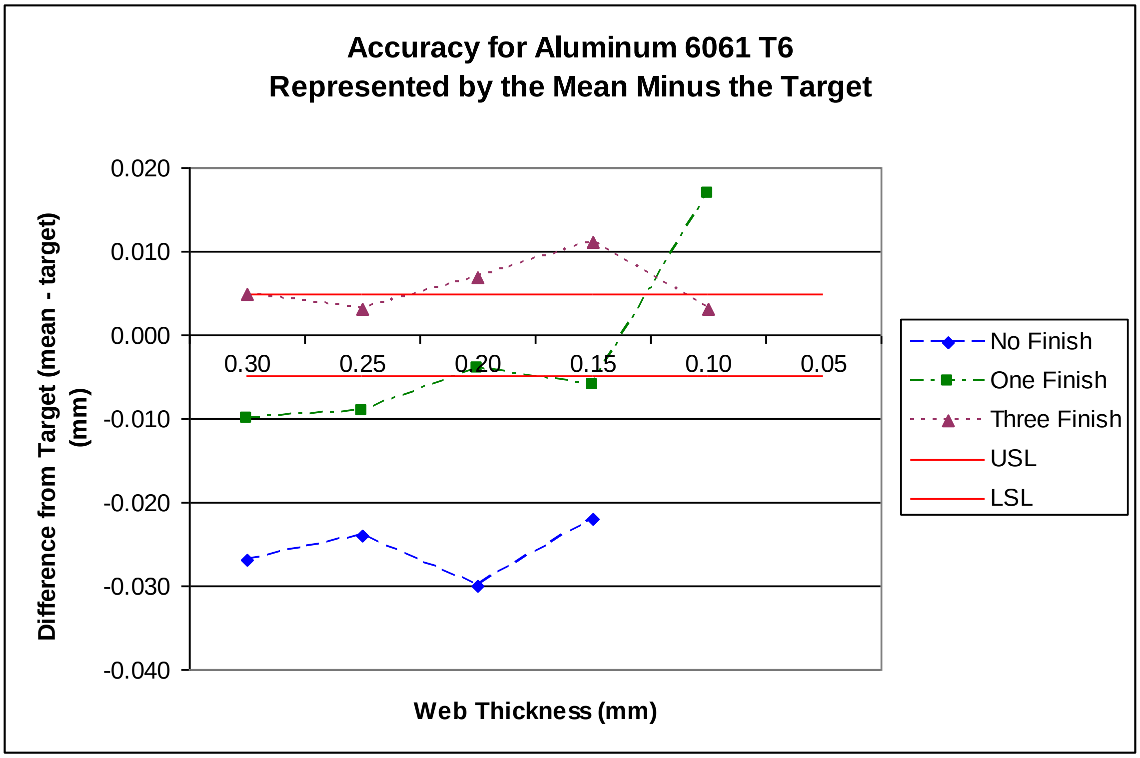

Figure 4.23 - Aluminum 6061 T6 - Accuracy in Cutting Thin-walled Sections (mean minus target)

specification limits were also indicated at ±0.005 millimeters. The accuracy obtainable by each of the cutting parameters can be readily seen along with a comparison of the cutting parameters.

A second ANOVA test was performed in order to determine the statistical significance between cutting parameters when machining the same material type. Table 4.4 lists the P-values that were generated from the ANOVA test. Any P-value which is greater than 0.05 indicates that there is not a statistically significant difference between the data sets being compared. Therefore, there is no statistical difference between the data obtained when comparing any of the cutting parameters utilized for any of the section target thicknesses when cutting Aluminum 6061 T6.

Table 4.4 - Aluminum 6061 T6 - P-values of Comparisons between Cutting Parameters

Target Thickness	No Finishing to One Finishing	No Finishing to Three Finishing	One Finishing to Three Finishing
0.30	0.4860001703	0.3618320789	0.6930152117
0.25	0.5131348044	0.3878437887	0.7094943847
0.20	0.7938636543	0.6391734601	0.7221205947
0.15	0.9607255287	0.9183661278	0.9383849382
0.10	-	-	0.9871155440
0.05	-	-	-

Figure 4.24 is a graph of the calculated P-values for the comparisons between cutting parameters while machining Aluminum 6061 T6. None of the P-values are located below the line indicating statistical significance which is at 0.05. Therefore, statistically, there exists no significant difference between the data sets generated by the three different cutting parameters used in this study.

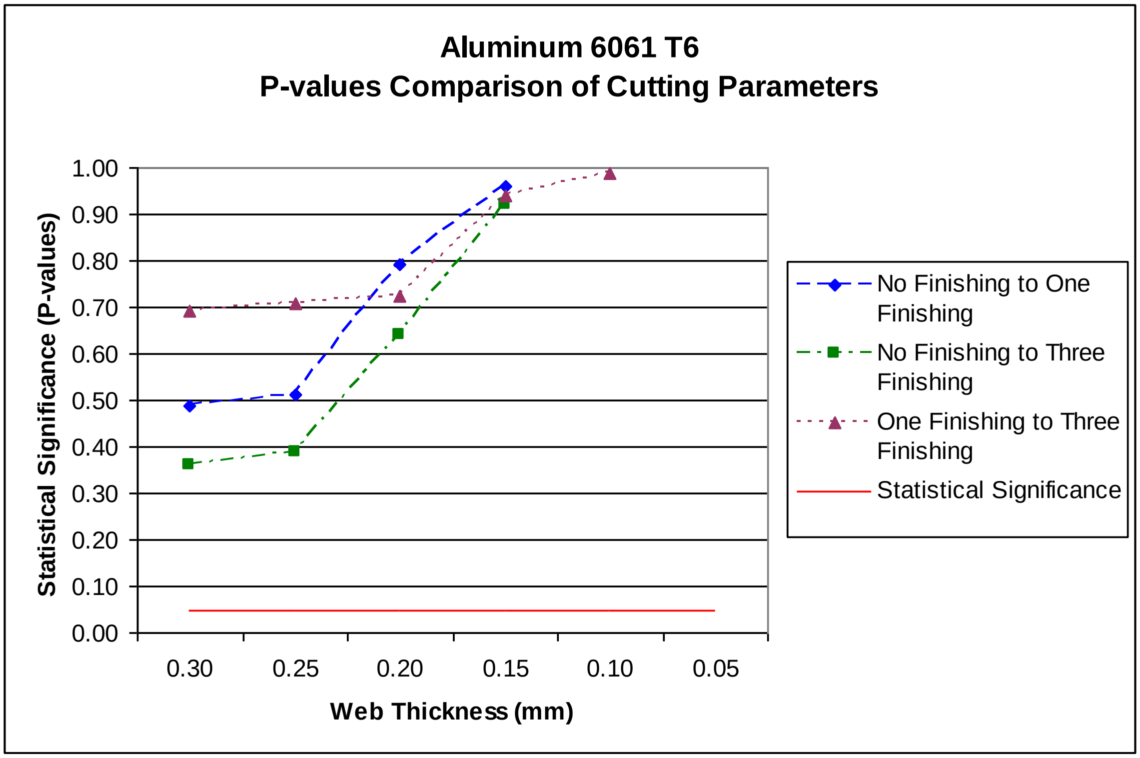

Figure 4.24 - Aluminum 6061 T6 – Statistical Significance Comparison of Cutting Parameters by P-values

A third ANOVA test was performed on each data set of a thin-walled section according to the number of finishing passes that were utilized in order to compare the effect of material type. This test generated a P-value which indicates if there is a statistically significant difference between the data sets of the five different materials. Table 4.5 lists all of the P-values obtained through the ANOVA test in comparing the data sets for Aluminum 6061 T6 to the data sets for the other four materials.

Table 4.5 - P-values Indicating Statistical Significance between Aluminum 6061 T6 and ...

	Target Thickness	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
Roughing with No Finishing Passes	0.30	0.0000038572	0.0002911954	0.1191170943	0.0001863499
	0.25	0.0002039253	0.0012120027	0.7123788079	0.0027739700
	0.20	0.0001520229	0.0000000229	0.0978853903	0.0000003847
	0.15	0.6759058442	0.1435173447	0.5278811871	0.0165226643
	0.10	-	-	-	-
	0.05	-	-	-	-
Roughing with One Finishing Pass	0.30	0.0000001474	0.4376391946	0.5502159928	0.2232230948
	0.25	0.0000082635	0.7059711579	0.6892050026	0.7249130607
	0.20	0.0000162978	0.2237618341	0.1305754806	0.0058350527
	0.15	0.1230860174	0.2724377251	0.1211740256	0.0790816756
	0.10	-	0.0000711693	0.0000252616	0.0000001357
	0.05	-	-	-	-
Roughing with Three Finishing Passes	0.30	0.0000000004	0.0044339346	0.0012160995	0.0009779895
	0.25	0.0000000029	0.0032983520	0.1919323004	0.0098430943
	0.20	0.0000000938	0.0036404531	0.0668523185	0.0031581498
	0.15	0.0000000367	0.0000168709	0.0000069160	0.0000004849
	0.10	-	0.575902024	0.071468704	0.077330044
	0.05	-	-	-	-

A graph depicting the relationships between each of the P-values can be seen in Figure 4.25. Included in this graph is a pink line with a P-value of 0.05. Any of the values above this line indicate that there is no statistical difference between the data sets while all of the values located below the line demonstrate that there is a statistical difference between the data sets.

When utilizing the machining parameters of a roughing with no finishing passes it can be seen that there is no statistical difference between the data sets for Aluminum 6061 T6 and D2 Tool Steel at 25 to 30 RC. There is also no significant statistical difference between the data sets with a section target thickness of 0.15 millimeters (.006 inches) for the Yellow Brass SS360 and the 420 Stainless Steel. All other data sets exhibited a statistically significant difference.

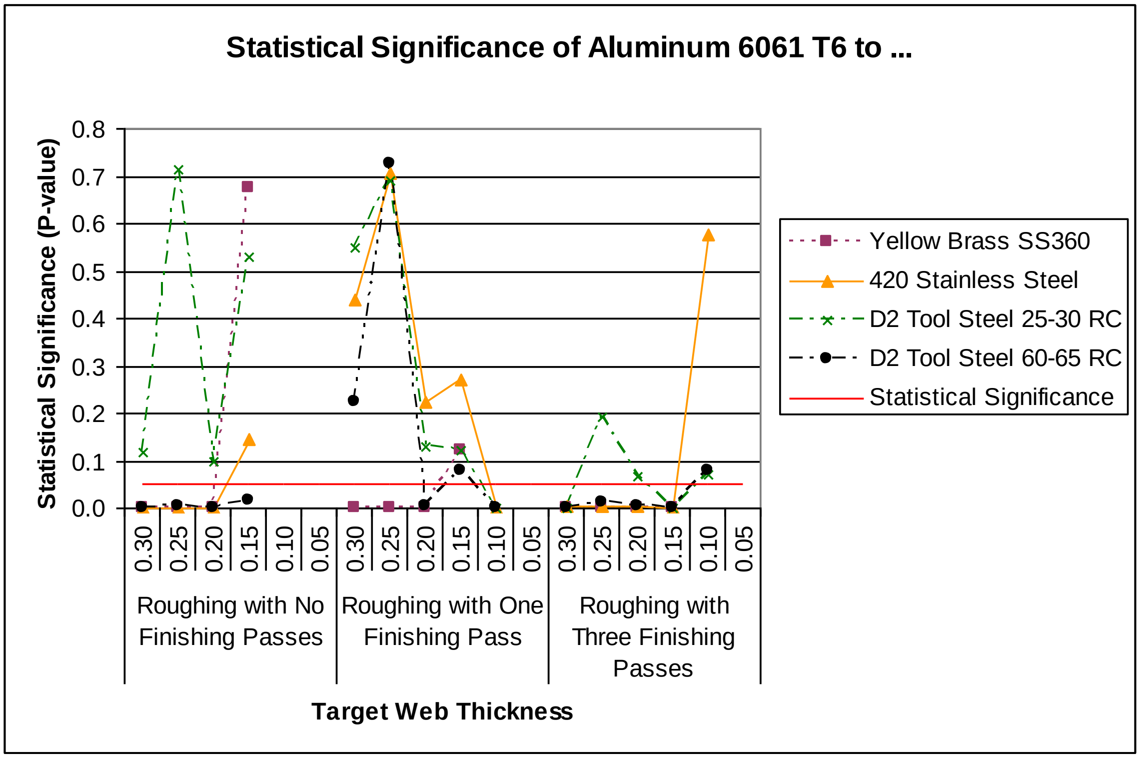

Figure 4.25 - Statistical Significance of Aluminum 6061 T6 to the Other Four Materials

When utilizing the machining parameters of a roughing with one finishing pass there was no statistically significant difference for the majority of the comparative data sets. For the section thicknesses with a target value of 0.30 and 0.25 millimeters (.012 and .010 inches) the only material that exhibited a statistically significant difference is the Yellow Brass SS360. Both the Yellow Brass SS360 and the D2 Tool Steel at 60 to 65 RC had statistically significant data sets at the target section thickness of 0.20 millimeters (.008 inches). None of the data sets with a target thickness of 0.15 millimeters (.006 inches) demonstrated statistical significance, but all of the materials with data exhibited statistical significance when the target section thickness was 0.10 millimeters (.004 inches).

When utilizing the machining parameters of a roughing with three finishing passes the majority of the comparative data sets demonstrated statistical significance. The only exceptions to this being the D2 Tool Steel at 25 to 30 RC with section target thicknesses of 0.25, 0.20, and 0.10 millimeters (.010, .008, and .004 inches). The 420 Stainless Steel and the D2 Tool Steel at 60 to 65 RC data sets were also not significant with a section target thickness of 0.10 millimeters (.004 inches).

4.3.2 Yellow Brass SS360 – Statistical Analysis

Figure 4.26 indicates the data set that was used in the statistical analysis for Yellow Brass SS360 while utilizing cutting parameters of a roughing with no finishing

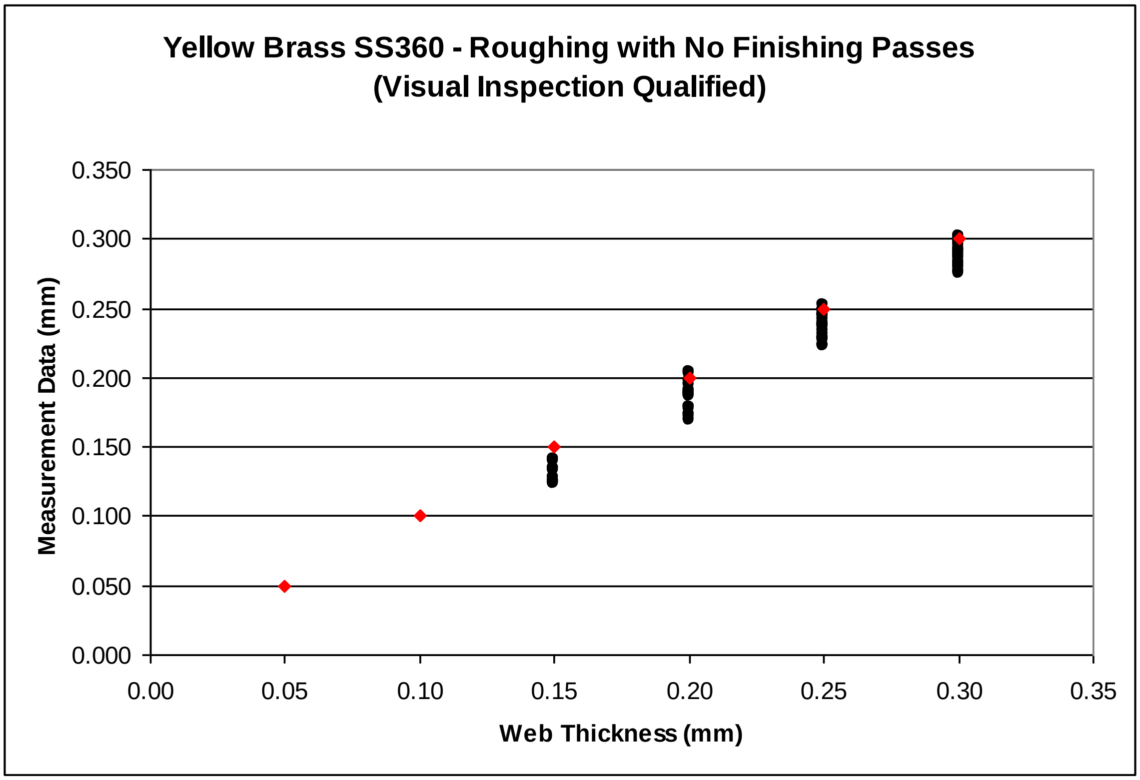

Figure 4.26 - Data Set Used for Yellow Brass SS360 - Roughing with No Finishing Passes

passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) and 0.10 millimeters (.004 inches) failed the visual inspection test, so there are no data points represented at these thicknesses. Also, several of the 0.15 millimeter (.006 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.6. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Table 4.6 - Yellow Brass SS360 - Statistics for Roughing with No Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.288	-0.012	0.008189	1.2212	0.7463
0.250	0.237	-0.013	0.009223	1.0843	0.6024
0.200	0.186	-0.014	0.010027	0.9973	0.5393
0.150	0.130	-0.020	0.006882	1.4531	0.4897
0.100	-	-	-	-	-
0.050	-	-	-	-	-

Figure 4.27 indicates the data set that was used in the statistical analysis for Yellow Brass SS360 while utilizing cutting parameters of a roughing with one finishing pass. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) and 0.10 millimeters (.004 inches) failed the visual inspection test, so there are no data points represented at these thicknesses.

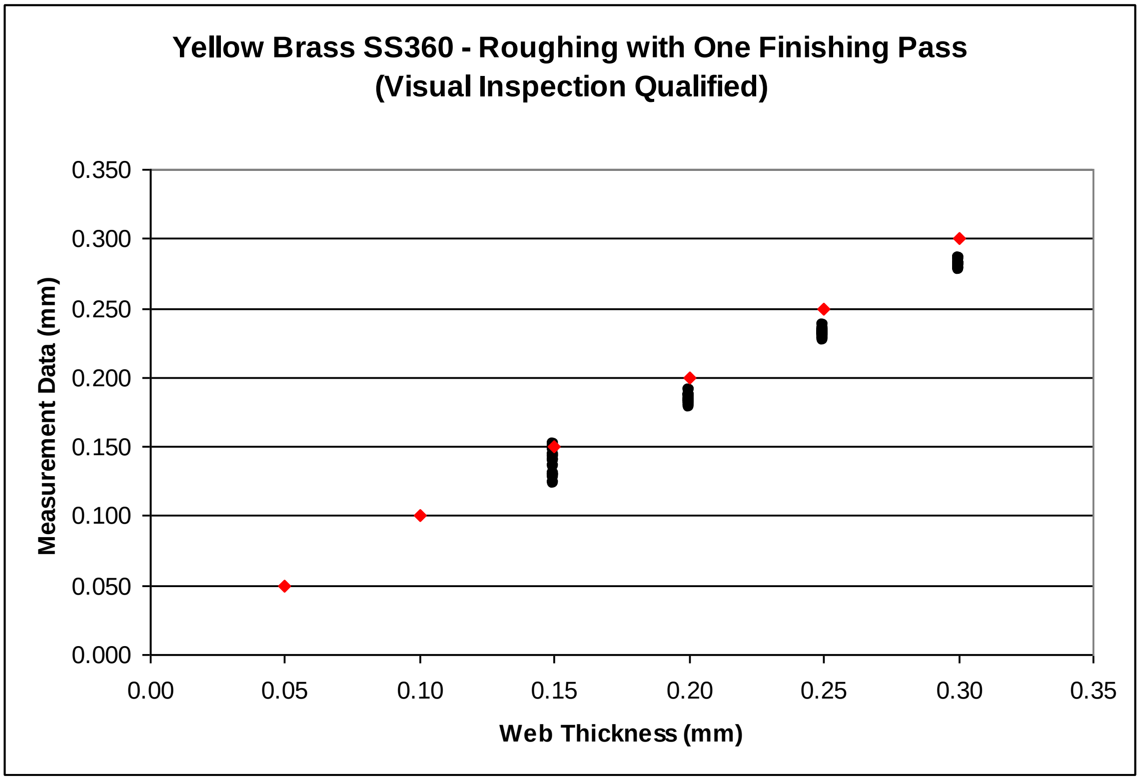

Figure 4.27 - Data Set Used for Yellow Brass SS360 - Roughing with One Finishing Pass

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.7. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is

Table 4.7 - Yellow Brass SS360 - Statistics for Roughing with One Finishing Pass Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.281	-0.019	0.002713	3.6862	1.3789
0.250	0.231	-0.019	0.002547	3.9263	1.4905
0.200	0.184	-0.016	0.003294	3.0359	1.4617
0.150	0.139	-0.011	0.008844	1.1307	0.7119
0.100	-	-	-	-	-
0.050	-	-	-	-	-

statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Figure 4.28 indicates the data set that was used in the statistical analysis for Yellow Brass SS360 while utilizing cutting parameters of a roughing with three finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) and 0.10 millimeters (.004 inches) failed the visual inspection test, so there are no data points indicated at these thicknesses.

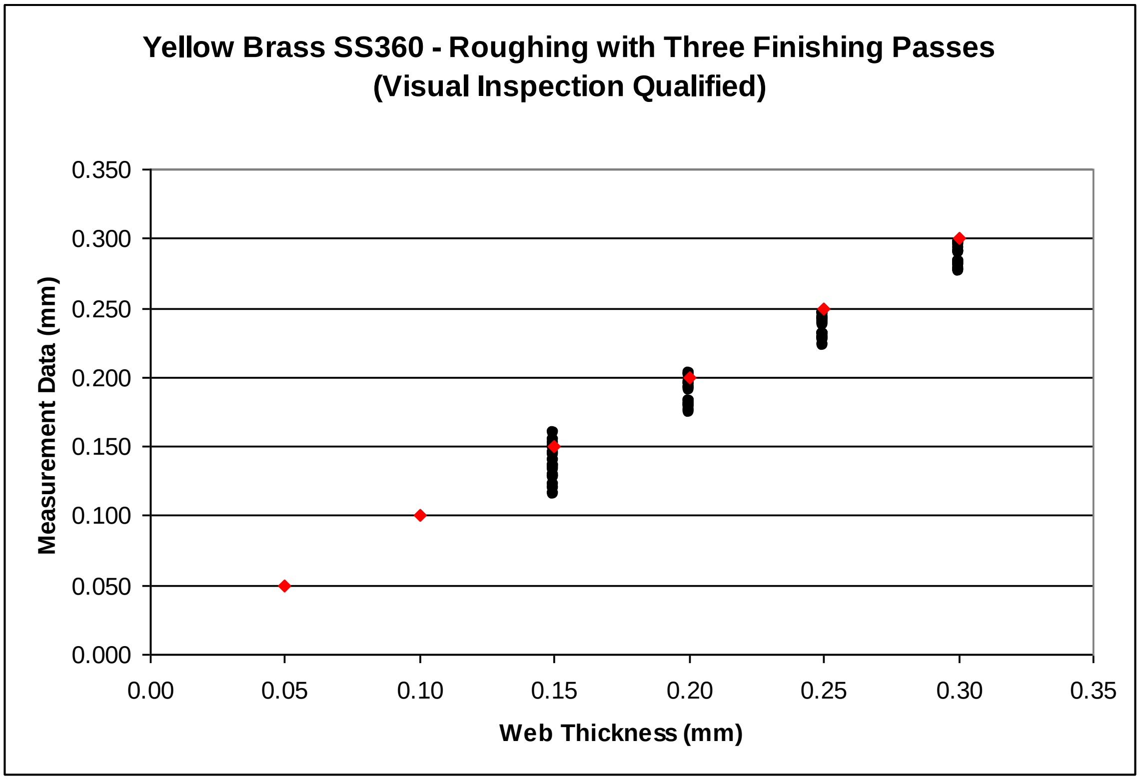

Figure 4.28 - Data Set Used for Yellow Brass SS360 - Roughing with Three Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.8. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Table 4.8 - Yellow Brass SS360 - Statistics for Roughing with Three Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.287	-0.013	0.007737	1.2925	0.7205
0.250	0.235	-0.015	0.007475	1.3377	0.6689
0.200	0.188	-0.012	0.009204	1.0864	0.6378
0.150	0.137	-0.013	0.012420	0.8051	0.4607
0.100	-	-	-	-	-
0.050	-	-	-	-	-

The ANOVA test further indicated that there was a significant difference in the data when the measurements that were taken from the tops of the thin-walled sections were compared to those taken from the bottoms of the sections. A t-value of less than 0.0001 was observed.

Figure 4.29 is a graph depicting the accuracy of cutting thin-walled sections from Yellow Brass SS360 while utilizing the three cutting parameters previously specified. Each of the calculated mean values for the respective target thicknesses and cutting parameters were subtracted from the target value in order to generate the values represented on this graph. This effectually makes 0.00 the target. Upper and lower specification limits were also indicated at ±0.005 millimeters. The accuracy obtainable by each of the cutting parameters can be readily seen along with a comparison of the cutting parameters.

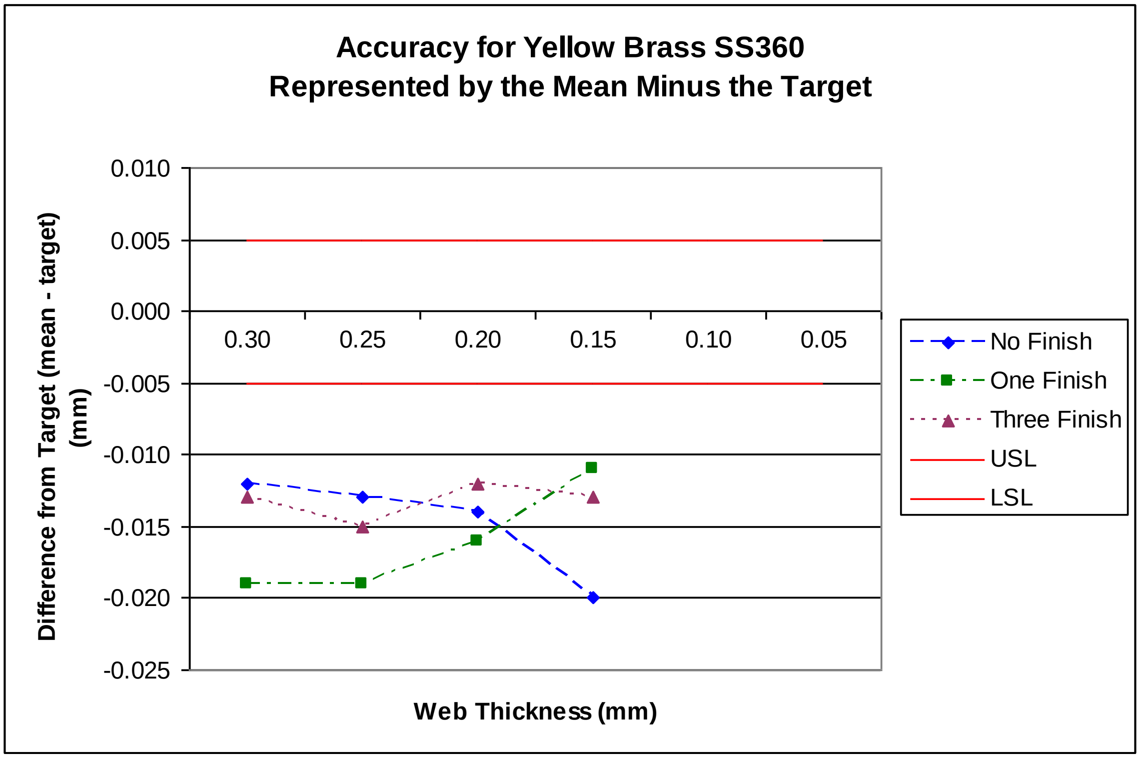

Figure 4.29 - Yellow Brass SS360 - Accuracy in Cutting Thin-walled Sections (mean minus target)

A second ANOVA test was performed in order to determine the statistical significance between cutting parameters when machining the same material type. Table 4.9 lists the P-values that were generated from the ANOVA test. Any P-value which is greater than 0.05 indicates that there is not a statistically significant difference between the data sets being compared. Therefore, there is no statistical difference between the data obtained when comparing any of the cutting parameters utilized for any of the section target thicknesses when cutting Yellow Brass SS360.

Table 4.9 - Yellow Brass SS360 - P-values of Comparisons between Cutting Parameters

Target Thickness	No Finishing to One Finishing	No Finishing to Three Finishing	One Finishing to Three Finishing
0.30	0.6421421453	0.4868496955	0.7342283808
0.25	0.6413974068	0.4966835251	0.7474713961
0.20	0.6296252066	0.4936736734	0.7540279236
0.15	0.8960576221	0.7486562725	0.7782427710
0.10	-	-	-
0.05	-	-	-

Figure 4.30 is a graph of the calculated P-values for the comparisons between cutting parameters while machining Yellow Brass SS360. None of the P-values are located below the line indicating statistical significance. Therefore, statistically speaking,

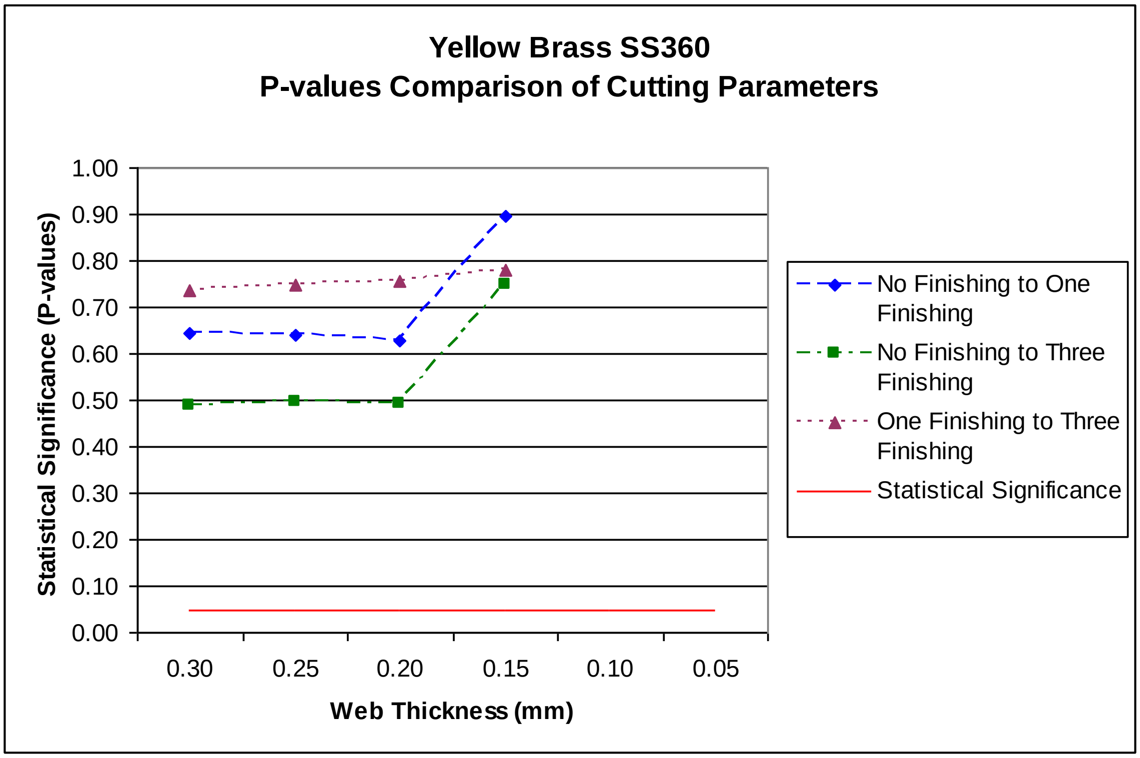

Figure 4.30 - Yellow Brass SS360 – Statistical Significance Comparison of Cutting Parameters by P-values

there exists no significant difference between the data sets generated by the three different cutting parameters used in this study.

A third ANOVA test was performed on each data set of a thin-walled section according to the number of finishing passes that were utilized in order to compare the effect of material type. This test generated a P-value which indicates if there is a statistically significant difference between the data sets of the five different materials. Table 4.10 lists all of the P-values obtained through the ANOVA test in comparing the data sets for Yellow Brass SS360 to the data sets for the other four materials.

Table 4.10 - P-values Indicating Statistical Significance between Yellow Brass SS360 and ...

	Target Thickness	Aluminum 6061 T6	420 Stainless Steel	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
Roughing with No Finishing Passes	0.30	0.0000038572	0.0024430719	0.0003548463	0.0061351144
	0.25	0.0002039253	0.0371639207	0.0006118921	0.0133669478
	0.20	0.0001520229	0.4209285900	0.0240047053	0.3115954826
	0.15	0.6759058442	0.3878788406	0.1540753461	0.1304528395
	0.10	-	-	-	-
	0.05	-	-	-	-
Roughing with One Finishing Pass	0.30	0.0000001474	0.0000001068	0.0000014920	0.0009996591
	0.25	0.0000082635	0.0000068157	0.0000008825	0.0000000048
	0.20	0.0000162978	0.0000323065	0.0000028133	0.0007800752
	0.15	0.1230860174	0.3902627836	0.4756017927	0.4864522245
	0.10	-	-	-	-
	0.05	-	-	-	-
Roughing with Three Finishing Passes	0.30	0.0000000004	0.0000000027	0.0000000361	0.0000000059
	0.25	0.0000000029	0.0000000431	0.0000000001	0.0000000049
	0.20	0.0000000938	0.0000016730	0.0000000329	0.0000009250
	0.15	0.0000000367	0.0000430732	0.0000222788	0.0000821502
	0.10	-	-	-	-
	0.05	-	-	-	-

A graph depicting the relationships between each of the P-values can be seen in Figure 4.31. Included in this graph is a pink line with a P-value of 0.05. Any of the values above this line indicate that there is no statistical difference between the data sets

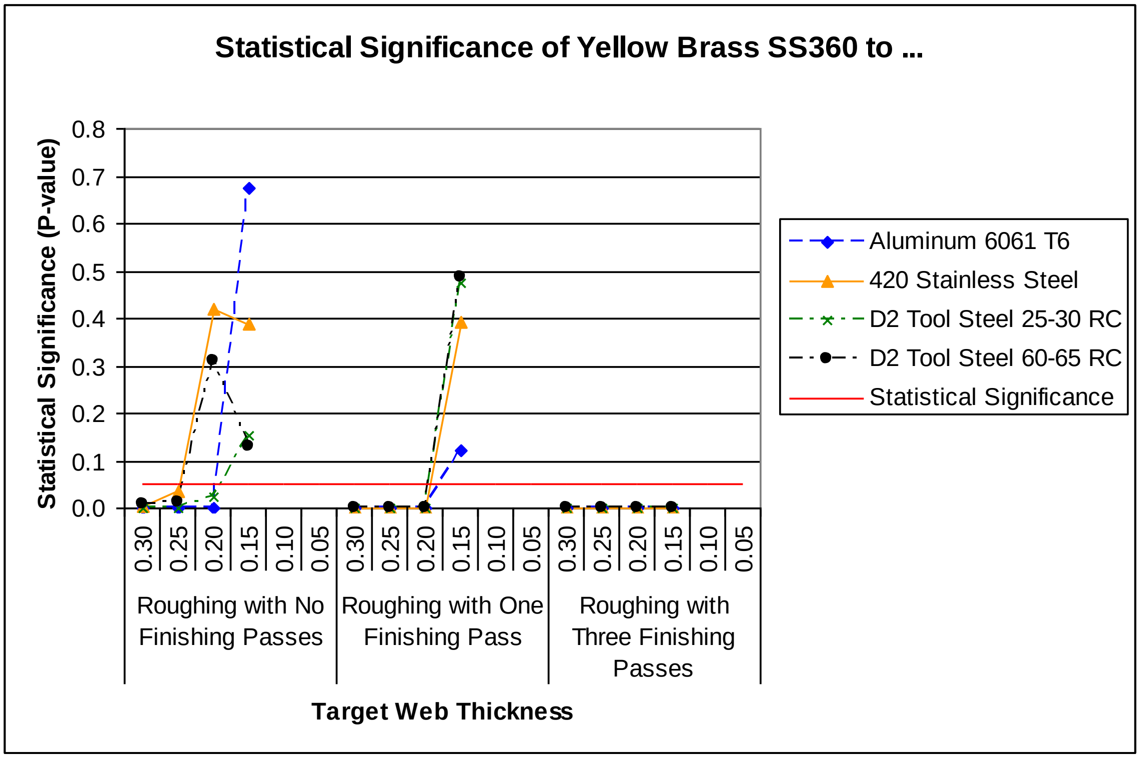

Figure 4.31 - Statistical Significance of Yellow Brass SS360 to the Other Four Materials

while all of the values located below the line demonstrate that there is a statistical difference between the data sets.

When utilizing the machining parameters of a roughing with no finishing passes it can be seen that there is a statistically significant difference between the data sets with section target thicknesses of 0.30 and 0.25 millimeters (.012 and .010 inches) when comparing Yellow Brass SS360 to the remainder of the materials. When the section target thickness was 0.20 millimeters (.008 inches) the data sets for both the Aluminum 6061 T6 and the D2 Tool Steel at 25 to 30 RC demonstrated statistical significance while the data sets for the 420 Stainless Steel and the D2 Tool Steel at 60 to 65 RC did not demonstrate statistical significance. None of the data sets for any of the materials demonstrated statistical significance when the section target thickness was 0.15 millimeters (.006 inches).

When utilizing the machining parameters of a roughing with one finishing pass the data sets for all of the materials demonstrated statistical significance for the section target thicknesses of 0.30, 0.25, and 0.20 millimeters (.012, .010, and .008 inches) while none of the data sets for all of the materials were not statistically significant for the sections with a target thickness of 0.15 millimeters (.006 inches).

When utilizing the machining parameters of a roughing with three finishing passes the data sets for all of the materials demonstrated statistical significance.

4.3.3 420 Stainless Steel – Statistical Analysis

Figure 4.32 indicates the data set that was used in the statistical analysis for 420 Stainless Steel while utilizing cutting parameters of a roughing with no finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness. Also, several of the 0.10 millimeter (.004 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

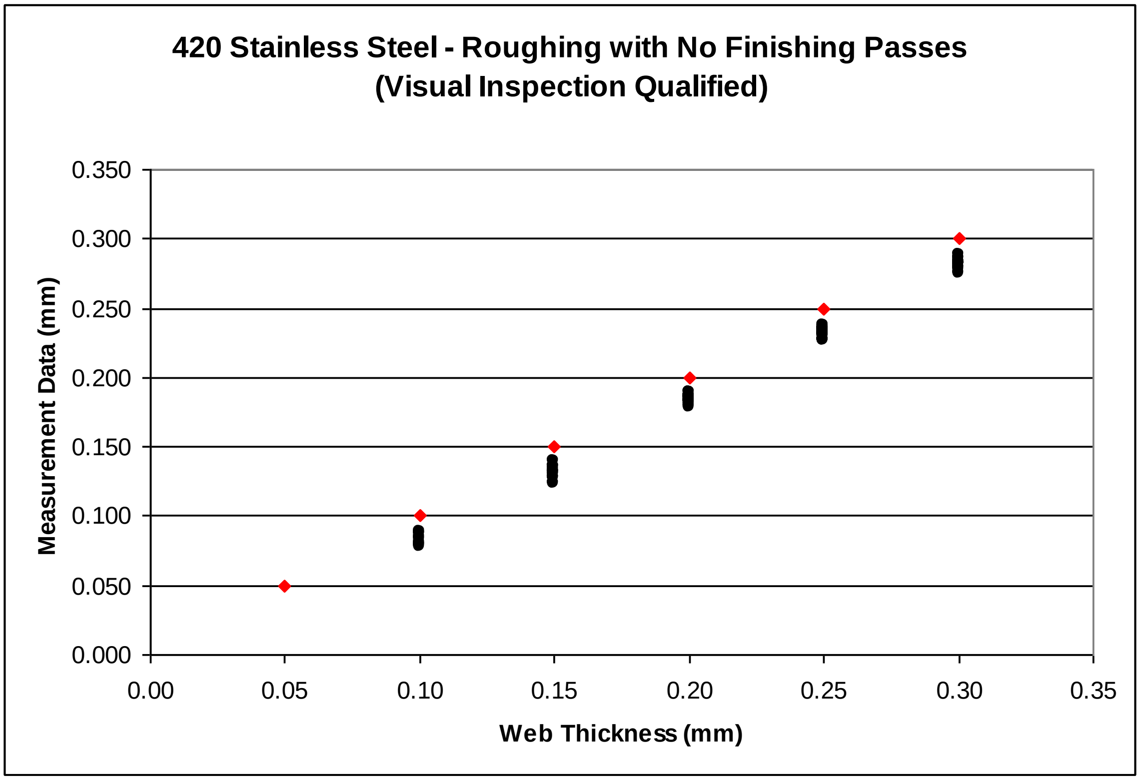

Figure 4.32 - Data Set Used for 420 Stainless Steel - Roughing with No Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.11. The mean for each data set is smaller than the respective target value and very consistent to the others in this group.

Table 4.11 - 420 Stainless Steel - Statistics for Roughing with No Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.282	-0.018	0.002973	3.3634	1.3018
0.250	0.232	-0.018	0.003254	3.0732	1.1951
0.200	0.184	-0.016	0.002819	3.5471	1.6816
0.150	0.132	-0.018	0.004061	2.4622	0.9903
0.100	0.083	-0.017	0.003905	2.5607	1.1097
0.050	-	-	-	-	-

The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Figure 4.33 indicates the data set that was used in the statistical analysis for 420 Stainless Steel while utilizing cutting parameters of a roughing with one finishing pass. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness. Also, several of the 0.10 millimeter (.004 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

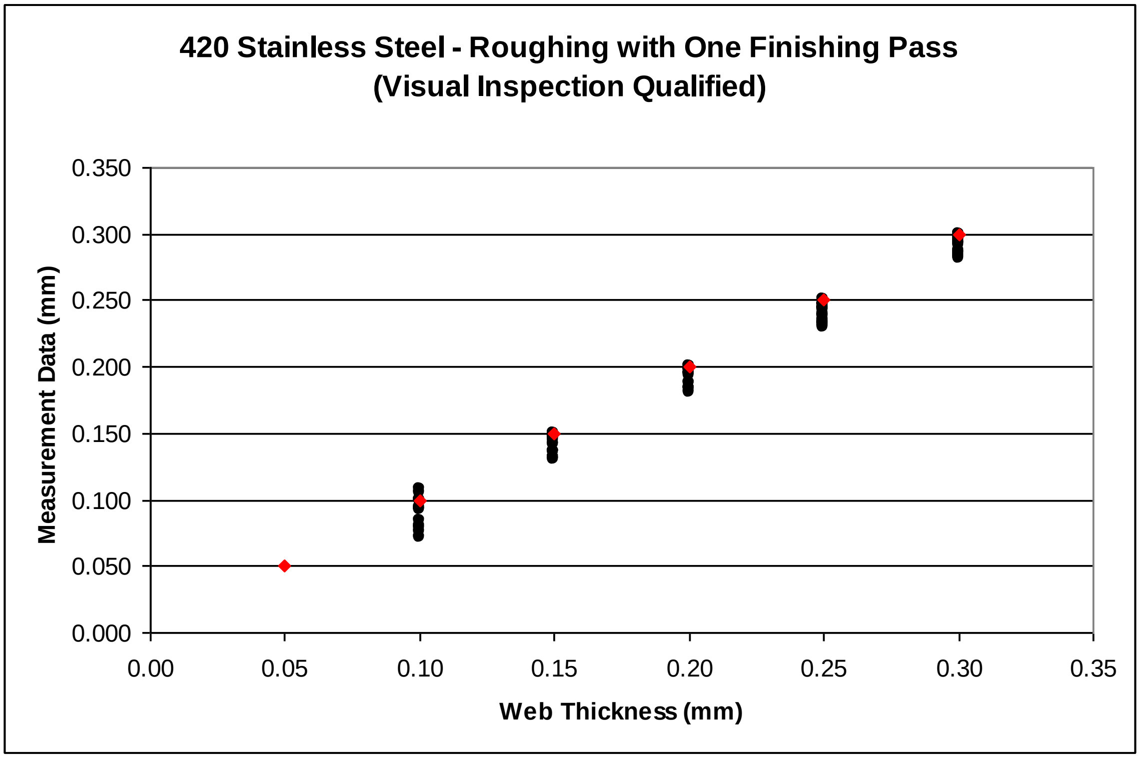

Figure 4.33 - Data Set Used for 420 Stainless Steel - Roughing with One Finishing Pass

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.12. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Table 4.12 - 420 Stainless Steel - Statistics for Roughing with One Finishing Pass Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.292	-0.008	0.006182	1.6175	1.1802
0.250	0.240	-0.010	0.006153	1.6252	1.0684
0.200	0.193	-0.007	0.006499	1.5387	1.1626
0.150	0.141	-0.009	0.006715	1.4893	1.0508
0.100	0.090	-0.010	0.011886	0.8413	0.5609
0.050	-	-	-	-	-

Figure 4.34 indicates the data set that was used in the statistical analysis for 420 Stainless Steel while utilizing cutting parameters of a roughing with three finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness.

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.13. The mean for each data set except that with a target of 0.25 millimeters (.010 inches) is larger than the respective target value. The mean of the data set with a target thickness of 0.25 millimeters (.010 inches) is less than that target value. The ANOVA test indicated that this data is not statistically significant from the target values and has a combined t-value of 0.2922 for the specified parameters.

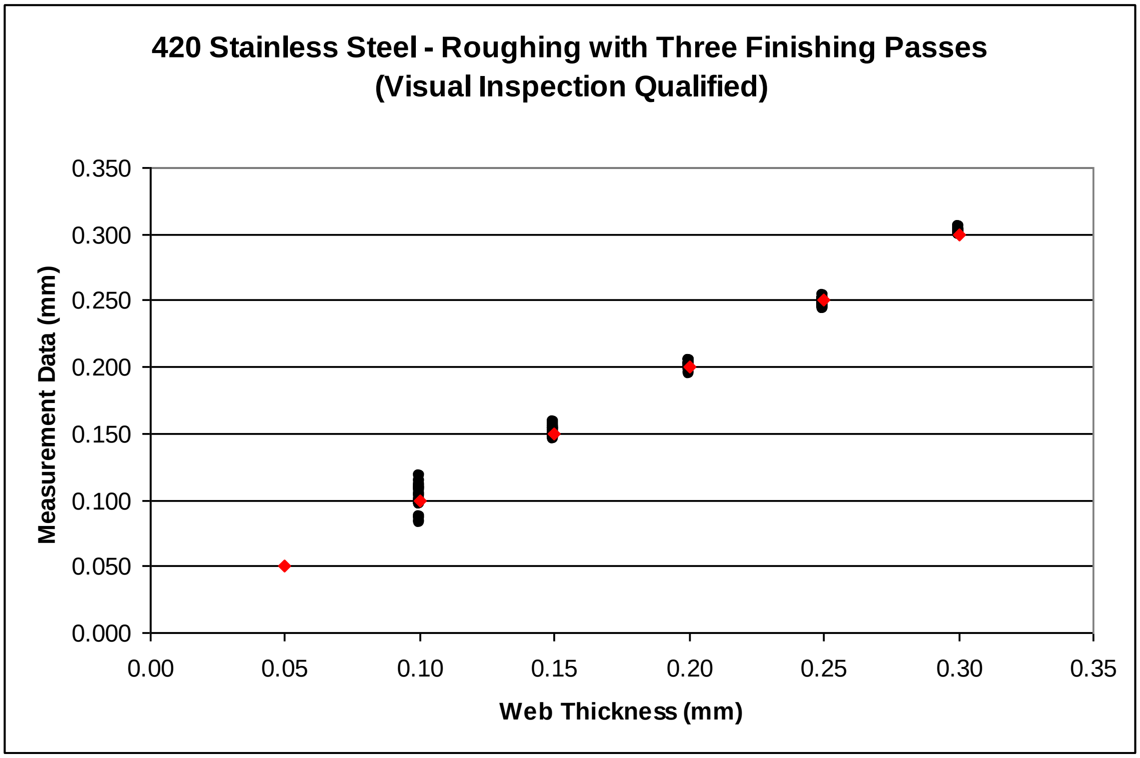

Figure 4.34 - Data Set Used for 420 Stainless Steel - Roughing with Three Finishing Passes

Table 4.13 - 420 Stainless Steel - Statistics for Roughing with Three Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.302	0.002	0.001847	5.4139	5.1131
0.250	0.248	-0.002	0.002654	3.7674	3.5301
0.200	0.201	0.001	0.002679	3.7329	3.6499
0.150	0.152	0.002	0.003714	2.6925	2.5579
0.100	0.101	0.001	0.009732	1.0276	0.9933
0.050	-	-	-	-	-

The ANOVA test further indicated that there was a significant difference in the data when the measurements that were taken from the tops of the thin-walled sections were compared to those taken from the bottoms of the sections. A t-value of less than 0.0001 was observed.

Figure 4.35 is a graph depicting the accuracy of cutting thin-walled sections from 420 Stainless Steel while utilizing the three cutting parameters previously specified. Each of the calculated mean values for the respective target thicknesses and cutting parameters were subtracted from the target value in order to generate the values represented on this graph. This effectually makes 0.00 the target. Upper and lower specification limits were also indicated at ±0.005 millimeters. The accuracy obtainable by each of the cutting parameters can be readily seen along with a comparison of the cutting parameters.

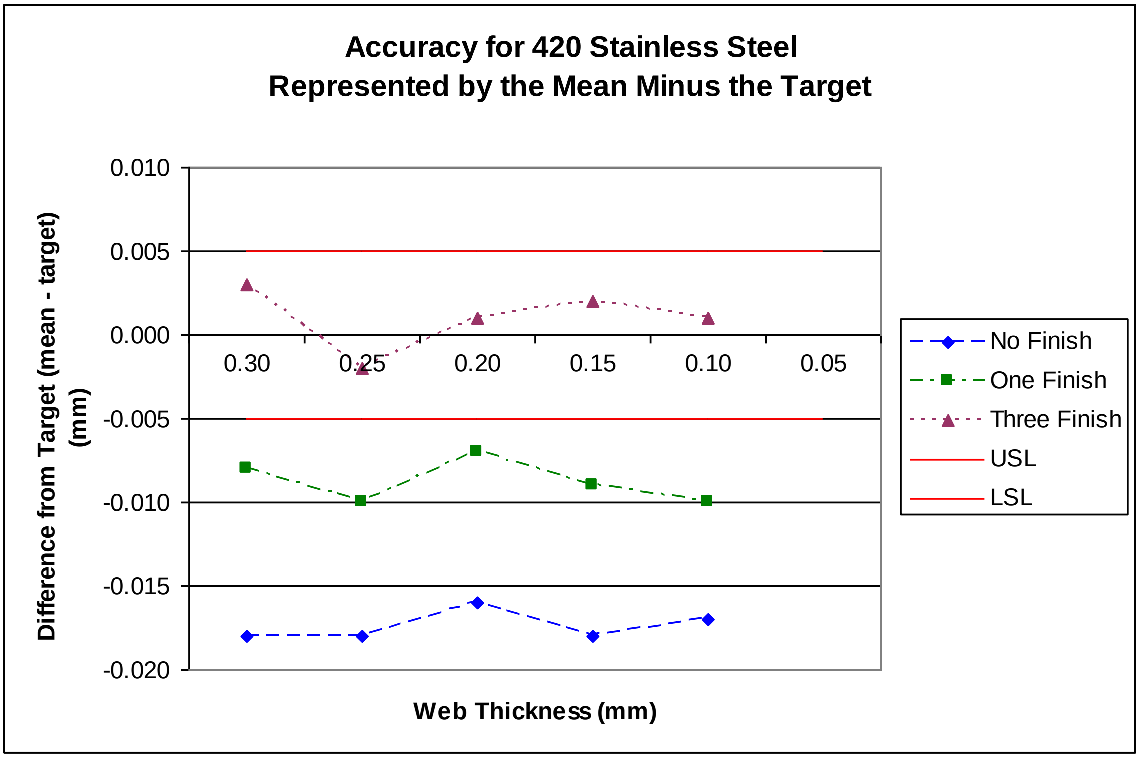

Figure 4.35 - 420 Stainless Steel - Accuracy in Cutting Thin-walled Sections (mean minus target)

A second ANOVA test was performed in order to determine the statistical significance between cutting parameters when machining the same material type. Table

4.14 lists the P-values that were generated from the ANOVA test. Any P-value which is greater than 0.05 indicates that there is not a statistically significant difference between the data sets being compared. Therefore, there is no statistical difference between the data obtained when comparing any of the cutting parameters utilized for any of the section target thicknesses when cutting 420 Stainless Steel.

Table 4.14 - 420 Stainless Steel - P-values of Comparisons between Cutting Parameters

Target Thickness	No Finishing to One Finishing	No Finishing to Three Finishing	One Finishing to Three Finishing
0.30	0.5266018304	0.4034056519	0.7148576019
0.25	0.5548510289	0.4269103403	0.7266468512
0.20	0.5649292938	0.4361855871	0.7333577090
0.15	0.6577334101	0.5058490493	0.7293690461
0.10	0.7418862291	0.7251514615	0.9404836756
0.05	-	-	-

Figure 4.36 is a graph of the calculated P-values for the comparisons between cutting parameters while machining 420 Stainless Steel. None of the P-values are located below the line indicating statistical significance. Therefore, statistically speaking, there exists no significant difference between the data sets generated by the three different cutting parameters used in this study.

A third ANOVA test was performed on each data set of a thin-walled section according to the number of finishing passes that were utilized in order to compare the effect of material type. This test generated a P-value which indicates if there is a statistically significant difference between the data sets of the five different materials. Table 4.15 lists all of the P-values obtained through the ANOVA test in comparing the data sets for 420 Stainless Steel to the data sets for the other four materials.

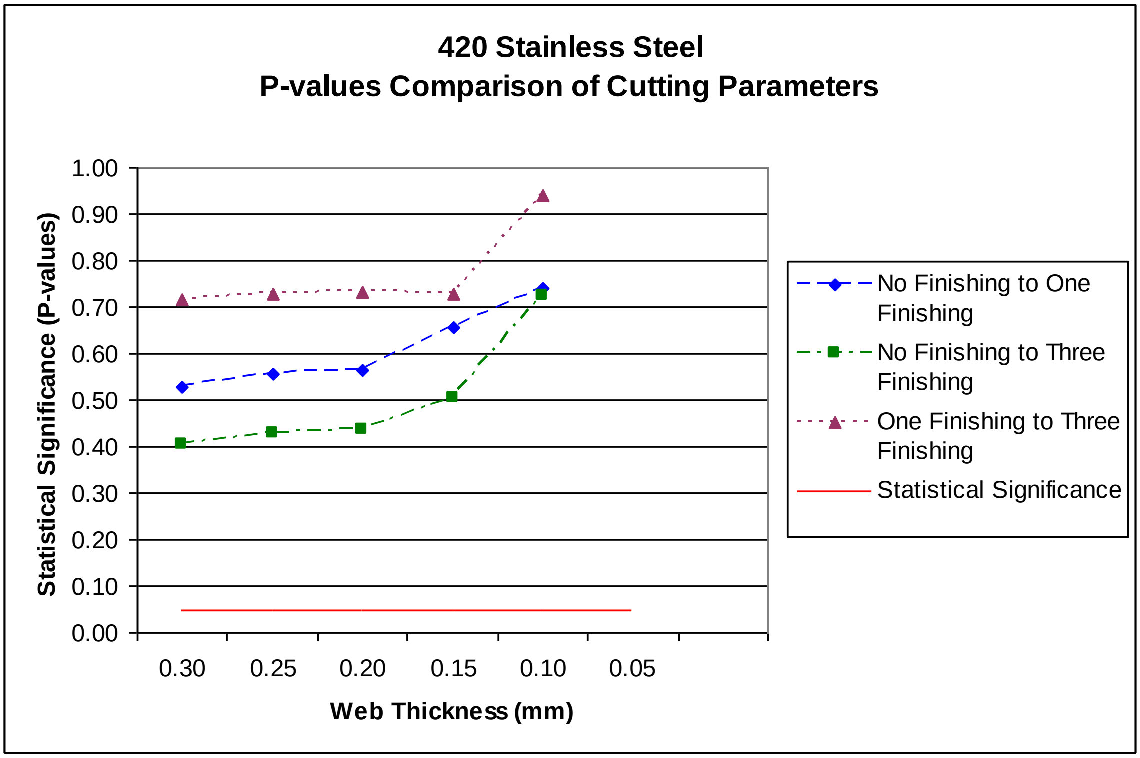

Figure 4.36 - 420 Stainless Steel – Statistical Significance Comparison of Cutting Parameters by P-values

Table 4.15 - P-values Indicating Statistical Significance between 420 Stainless Steel and ...

	Target Thickness	Aluminum 6061 T6	Yellow Brass SS360	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
Roughing with No Finishing Passes	0.30	0.0002911954	0.0024430719	0.0554442904	0.6179693748
	0.25	0.0012120027	0.0371639207	0.0070440682	0.3745896767
	0.20	0.0000000229	0.4209285900	0.0280299280	0.5980114209
	0.15	0.1435173447	0.3878788406	0.0142150908	0.4276242120
	0.10	-	-	0.1166572258	0.7923250913
	0.05	-	-	-	-
Roughing with One Finishing Pass	0.30	0.4376391946	0.0000001068	0.1904494479	0.0755366301
	0.25	0.7059711579	0.0000068157	1.0000000000	0.9231260490
	0.20	0.2237618341	0.0000323065	0.7949071841	0.0504217640
	0.15	0.2724377251	0.3902627836	0.7790325603	0.7200021732
	0.10	0.0000711693	-	0.3617758096	0.1941318677
	0.05	-	-	-	-
Roughing with Three Finishing Passes	0.30	0.0044339346	0.0000000027	0.2219704523	0.2948293968
	0.25	0.0032983520	0.0000000431	0.0001076297	0.2327318989
	0.20	0.0036404531	0.0000016730	0.0010339015	0.8813736318
	0.15	0.0000168709	0.0000430732	0.823215517	0.218087636
	0.10	0.575902024	-	0.204302052	0.321286478
	0.05	-	-	-	-

A graph depicting the relationships between each of the P-values can be seen in Figure 4.37. Included in this graph is a pink line with a P-value of 0.05. Any of the values above this line indicate that there is no statistical difference between the data sets while all of the values located below the line demonstrate that there is a statistical difference between the data sets.

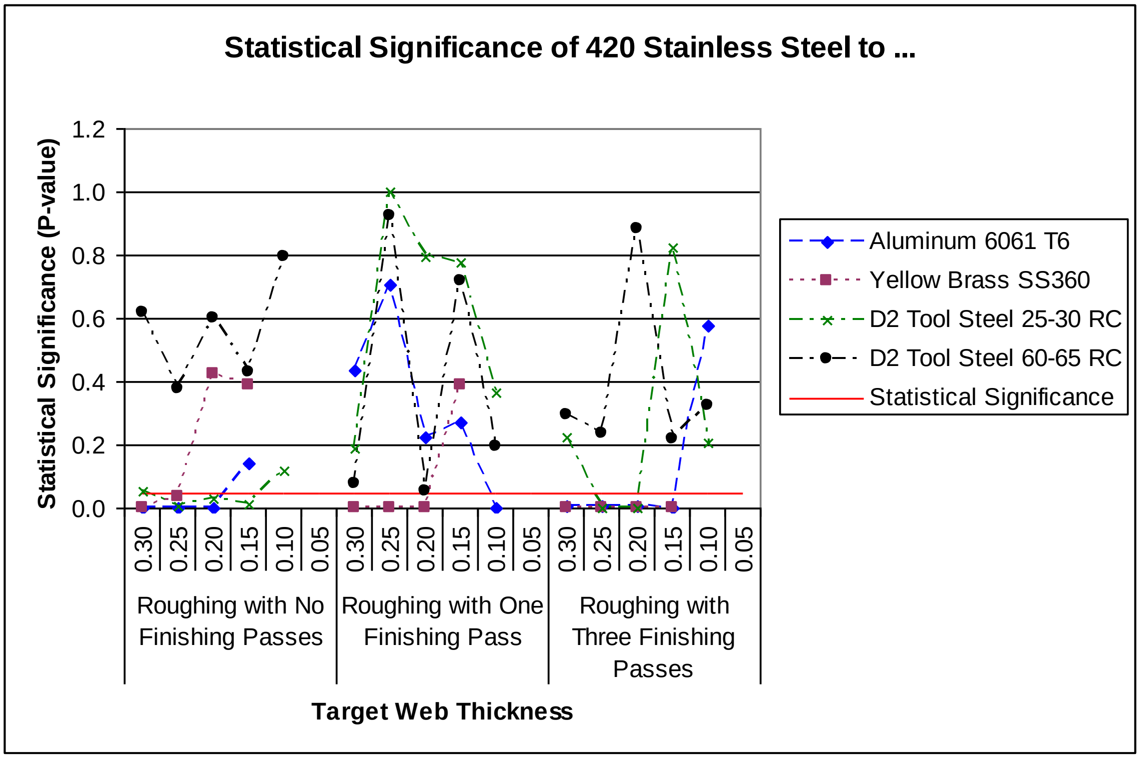

Figure 4.37 - Statistical Significance for 420 Stainless Steel to the Other Four Materials

In comparing the data sets for the 420 Stainless Steel, while utilizing the machining parameters of a roughing with no finishing passes, with the data sets for the Aluminum 6061 T6 it can be seen that there is a statistically significant difference between them when cutting sections with target thicknesses of 0.30, 0.25, and 0.20 millimeters (.012, .010, and .008 inches), but there is no significant statistical difference for the sections with a target thickness of 0.15 millimeters (.006 inches). A comparison with the Yellow Brass SS360 demonstrates a statistical difference for the sections with target thicknesses of 0.30 and 0.25 millimeters (.012 and .010 inches), but no statistically significant difference for the sections with target thicknesses of 0.20 and 0.15 millimeters (.008 and .006 inches). In comparing the D2 Tool Steel at 25 to 30 RC statistical significance was observed for the sections with target thicknesses of 0.25, 0.20, and 0.15 millimeters (.010, .008, and .006 inches), but there was no statistical significance observed for the sections with target thicknesses of 0.30 and 0.10 millimeters (.012 and .004 inches). There was no statistical significance observed between any of the data sets when compared with the D2 Tool Steel at 60 to 65 RC.

When utilizing the machining parameters of a roughing with one finishing pass there was no statistical significance observed when comparing the data sets for 420 Stainless Steel to those of the D2 Tool Steel at 25 to 30 RC and the D2 Tool Steel at 60 to 65 RC. When compared with the Aluminum 6061 T6 none of the data sets demonstrated statistical significance except those for the section with a target thickness of 0.10 millimeters (.004 inches). A comparison with the data sets for Yellow Brass SS360 demonstrated a statistical significance for all of the section thicknesses except that with a target thickness of 0.15 millimeters (.006 inches).

In comparing the data sets for the 420 Stainless Steel, when utilizing the machining parameters of a roughing with three finishing passes, with those of the Aluminum 6061 T6 it was observed that there was a statistical significance for all of the section thicknesses except that with a target thickness of 0.10 millimeters (.004 inches). All of the data sets for the Yellow Brass SS360 demonstrated a statistical significance. A comparison with the data sets for the D2 Tool Steel at 25 to 30 RC showed a statistical significance for those with target thicknesses of 0.25 and 0.20 millimeters (.010 and .008 inches), while there was no statistical significance observed for the sections with target thicknesses of 0.30, 0.15, and 0.10 millimeters (.012, .006, and .004 inches). When compared with the data sets for the D2 Tool Steel at 60 to 65 RC there was no statistical significance found.

4.3.4 D2 Tool Steel 25-30 RC – Statistical Analysis

Figure 4.38 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 25 to 30 RC while utilizing cutting parameters of a roughing with no finishing passes. All of the thin-walled sections which had a target thickness of 0.05

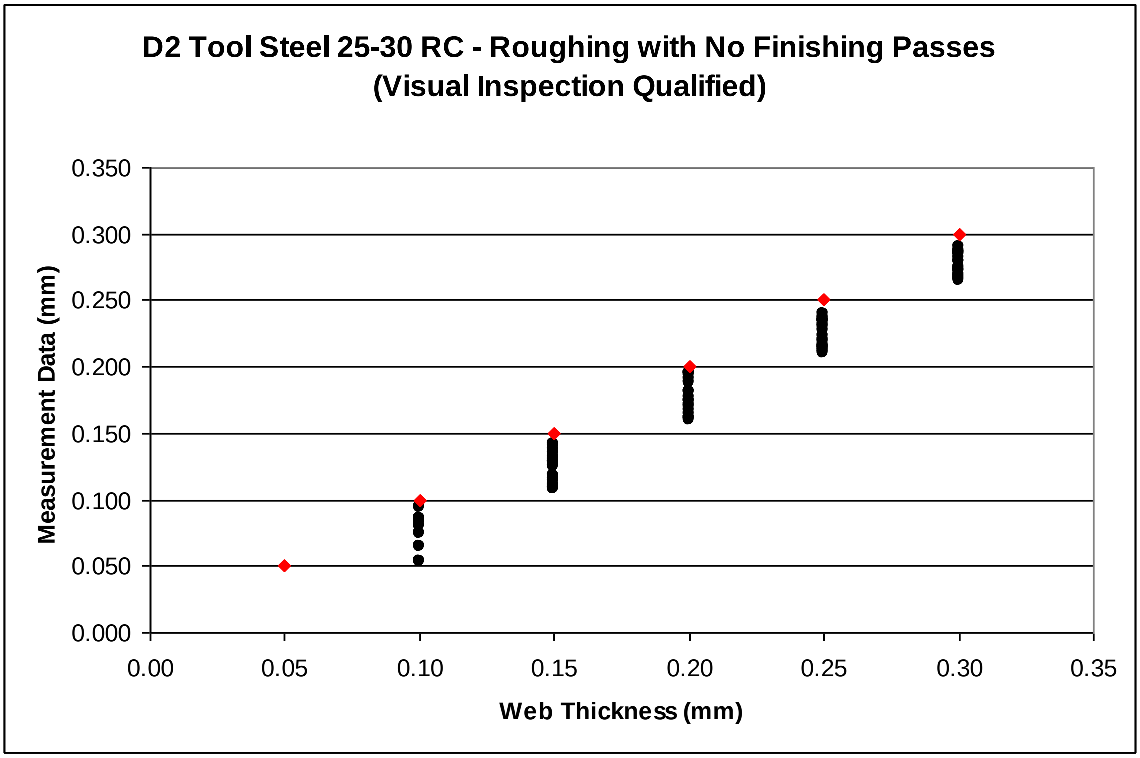

Figure 4.38 - Data Set Used for D2 Tool Steel 25-30 RC - Roughing with No Finishing Passes

millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness. Also, several of the 0.10 millimeter (.004 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.16. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Table 4.16 - D2 Tool Steel 25-30 RC - Statistics for Roughing with No Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.278	-0.022	0.008023	1.2464	0.3162
0.250	0.225	-0.026	0.010089	0.9911	0.1487
0.200	0.177	-0.023	0.012419	0.8052	0.1968
0.150	0.124	-0.026	0.011412	0.8763	0.1168
0.100	0.075	-0.025	0.014766	0.6772	0.1028
0.050	-	-	-	-	-

Figure 4.39 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 25 to 30 RC while utilizing cutting parameters of a roughing with one finishing pass. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness.

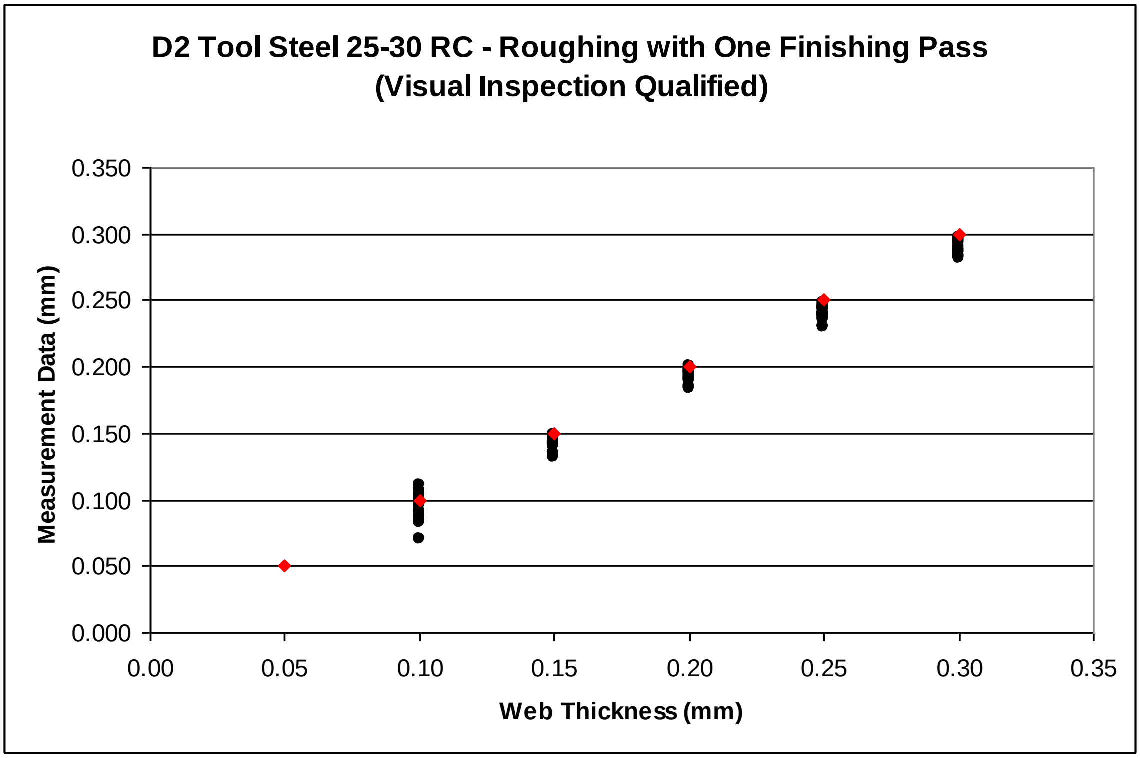

Figure 4.39 - Data Set Used for D2 Tool Steel 25-30 RC - Roughing with One Finishing Pass

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.17. The mean for each data set is smaller than the respective target value.

Table 4.17 - D2 Tool Steel 25-30 RC - Statistics for Roughing with One Finishing Pass Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.289	-0.011	0.005258	1.9018	1.2256
0.250	0.240	-0.010	0.005323	1.8788	1.2351
0.200	0.192	-0.008	0.004829	2.0706	1.5300
0.150	0.141	-0.009	0.004937	2.0257	1.3917
0.100	0.094	-0.006	0.010270	0.9737	0.7717
0.050	-	-	-	-	-

The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Figure 4.40 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 25 to 30 RC while utilizing cutting parameters of a roughing with three finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness.

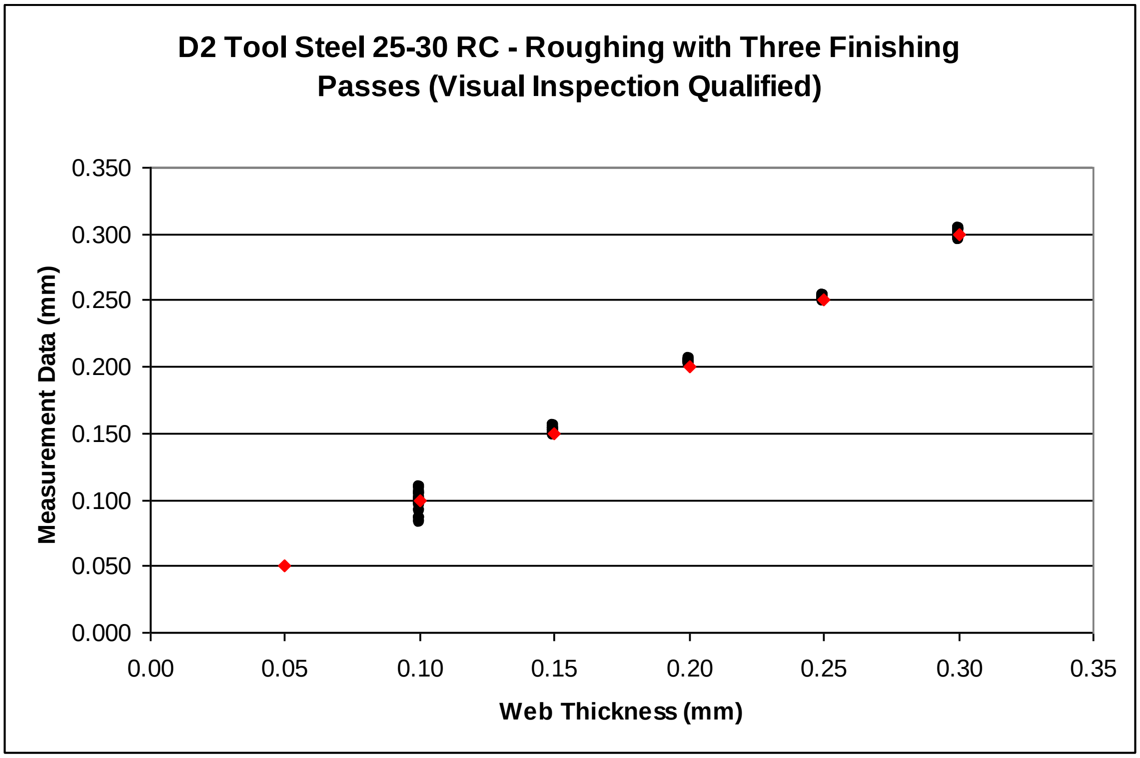

Figure 4.40 - Data Set Used for D2 Tool Steel 25-30 RC - Roughing with Three Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.18. The mean for each data set except that with a target value of 0.10 millimeters (.004 inches) is larger than the

Table 4.18 - D2 Tool Steel 25-30 RC - Statistics for Roughing with Three Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.301	0.001	0.003090	3.2366	3.1707
0.250	0.251	0.001	0.001183	8.4555	8.1423
0.200	0.203	0.003	0.001249	8.0094	7.1640
0.150	0.152	0.002	0.001934	5.1696	4.8728
0.100	0.097	-0.003	0.007659	1.3057	1.1848
0.050	-	-	-	-	-

respective target value. The mean for the data set with a target value of 0.10 millimeters (.004 inches) is smaller than the target value. The ANOVA test indicated that this data is not statistically significant from the target values and has a combined t-value of 0.3465 for the specified parameters.

For the D2 Tool Steel at 25 to 30 RC, the ANOVA test indicated that, in contrast to the previous materials discussed, there was no significant difference in the data when the measurements that were taken from the tops of the thin-walled sections were compared to those taken from the bottoms of the sections. A t-value of 0.2261 was observed.

Figure 4.41 is a graph depicting the accuracy of cutting thin-walled sections from D2 Tool Steel at 25 to 30 RC while utilizing the three cutting parameters previously specified. Each of the calculated mean values for the respective target thicknesses and cutting parameters were subtracted from the target value in order to generate the values represented on this graph. This effectually makes 0.00 the target. Upper and lower specification limits were also indicated at ±0.005 millimeters. The accuracy obtainable by each of the cutting parameters can be readily seen along with a comparison of the cutting parameters.

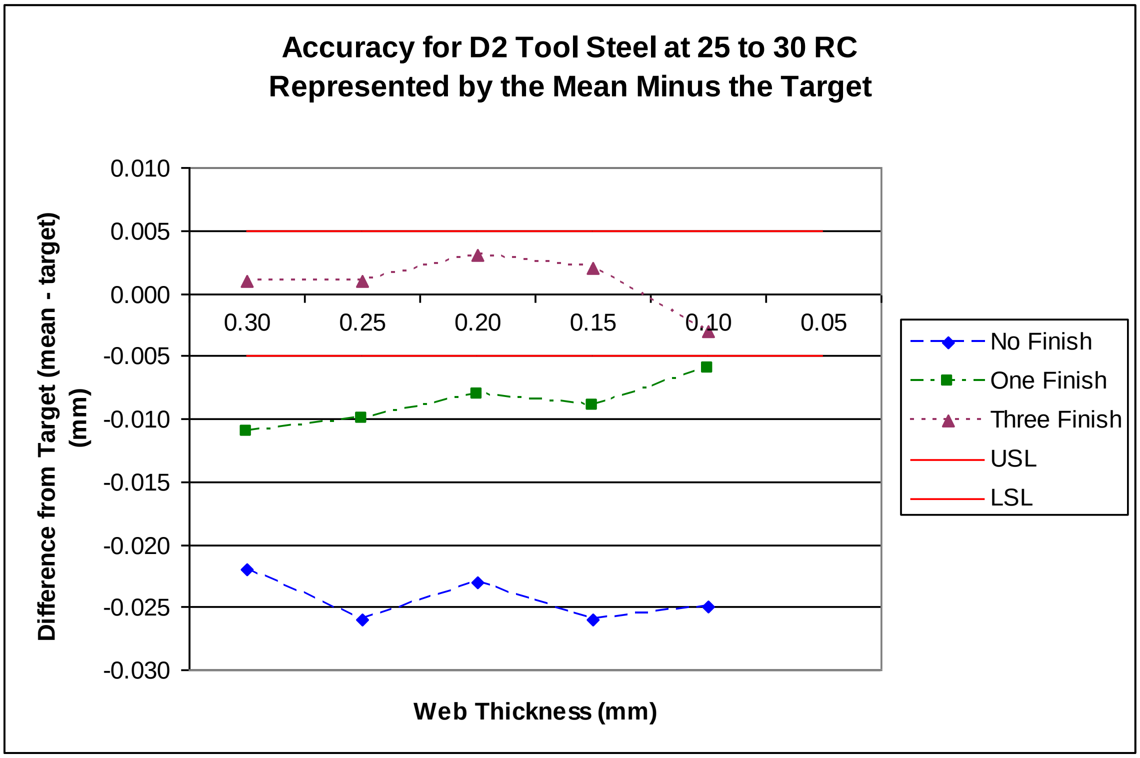

Figure 4.41 - D2 Tool Steel 25-30 RC - Accuracy in Cutting Thin-walled Sections (mean minus target)

A second ANOVA test was performed in order to determine the statistical significance between cutting parameters when machining the same material type. Table 4.19 lists the P-values that were generated from the ANOVA test. Any P-value which is greater than 0.05 indicates that there is not a statistically significant difference between

Table 4.19 - D2 Tool Steel 25-30 RC - P-values of Comparisons between Cutting Parameters

Target Thickness	No Finishing to One Finishing	No Finishing to Three Finishing	One Finishing to Three Finishing
0.30	0.5185476356	0.3934144598	0.7088139305
0.25	0.5121146184	0.3912289610	0.7141800778
0.20	0.5277431492	0.4034738276	0.7211538106
0.15	0.5315199307	0.4072869829	0.7263100696
0.10	0.8624544080	0.7123463043	0.7615375244
0.05	-	-	-

the data sets being compared. Therefore, there is no statistical difference between the data obtained when comparing any of the cutting parameters utilized for any of the section target thicknesses when cutting D2 Tool Steel at 25 to 30 RC.

Figure 4.42 is a graph of the calculated P-values for the comparisons between cutting parameters while machining D2 Tool Steel at 25 to 30 RC. None of the P-values are located below the line indicating statistical significance. Therefore, statistically speaking, there exists no significant difference between the data sets generated by the three different cutting parameters used in this study.

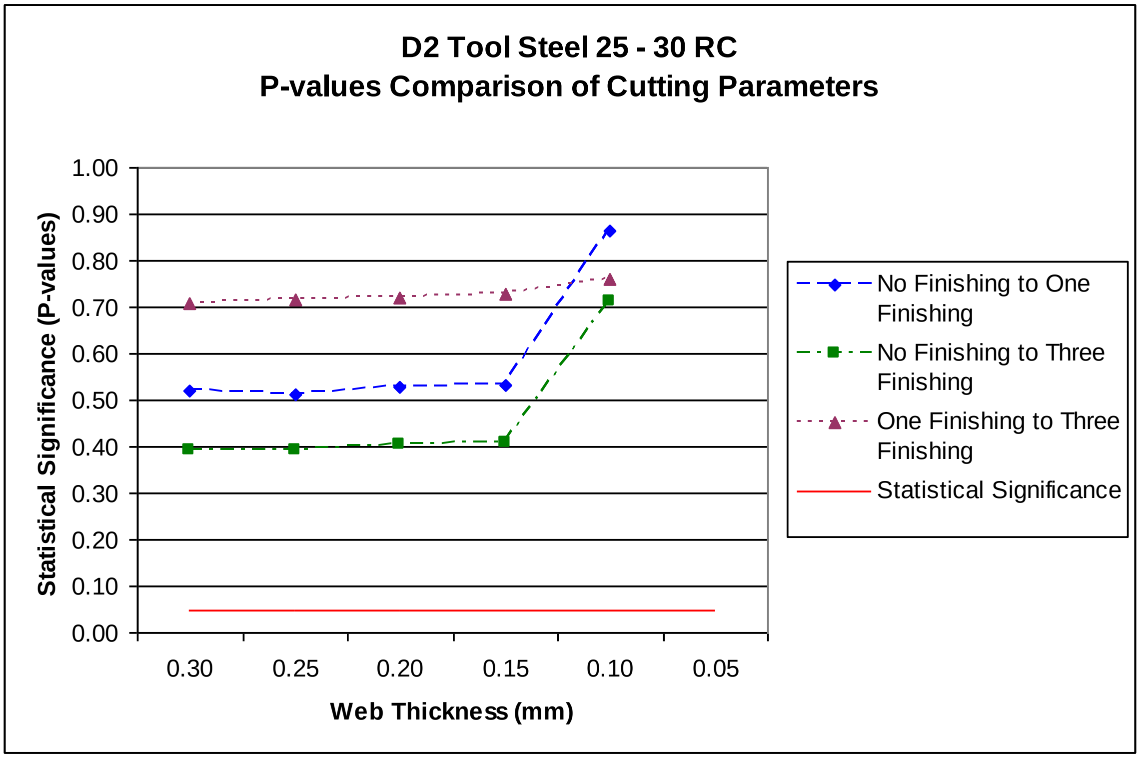

Figure 4.42 - D2 Tool Steel 25-30 RC – Statistical Significance Comparison of Cutting Parameters by P-values

A third ANOVA test was performed on each data set of a thin-walled section according to the number of finishing passes that were utilized in order to compare the effect of material type. This test generated a P-value which indicates if there is a statistically significant difference between the data sets of the five different materials. Table 4.20 lists all of the P-values obtained through the ANOVA test in comparing the data sets for D2 Tool Steel at 25 to 30 RC to the data sets for the other four materials.

Table 4.20 - P-values Indicating Statistical Significance between D2 Tool Steel at 25 - 30 RC and ...

	Target Thickness	Aluminum 6061 T6	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 60-65 RC
Roughing with No Finishing Passes	0.30	0.1191170943	0.0003548463	0.0554442904	0.0350069777
	0.25	0.7123788079	0.0006118921	0.0070440682	0.0136320786
	0.20	0.0978853903	0.0240047053	0.0280299280	0.0489008208
	0.15	0.5278811871	0.1540753461	0.0142150908	0.0025614931
	0.10	-	-	0.1166572258	0.1544807380
	0.05	-	-	-	-
Roughing with One Finishing Pass	0.30	0.5502159928	0.0000014920	0.1904494479	0.4655144182
	0.25	0.6892050026	0.0000008825	1.0000000000	0.9151307801
	0.20	0.1305754806	0.0000028133	0.7949071841	0.0407918741
	0.15	0.1211740256	0.4756017927	0.7790325603	0.9413973416
	0.10	0.0000252616	-	0.3617758096	0.0106721303
	0.05	-	-	-	-
Roughing with Three Finishing Passes	0.30	0.0012160995	0.0000000361	0.2219704523	0.5908711585
	0.25	0.1919323004	0.0000000001	0.0001076297	0.0000789291
	0.20	0.0668523185	0.0000000329	0.0010339015	0.0000206555
	0.15	0.0000069160	0.0000222788	0.823215517	0.016953102
	0.10	0.071468704	-	0.204302052	0.623032562
	0.05	-	-	-	-

A graph depicting the relationships between each of the P-values can be seen in Figure 4.43. Included in this graph is a pink line with a P-value of 0.05. Any of the values above this line indicate that there is no statistical difference between the data sets while all of the values located below the line demonstrate that there is a statistical difference between the data sets.

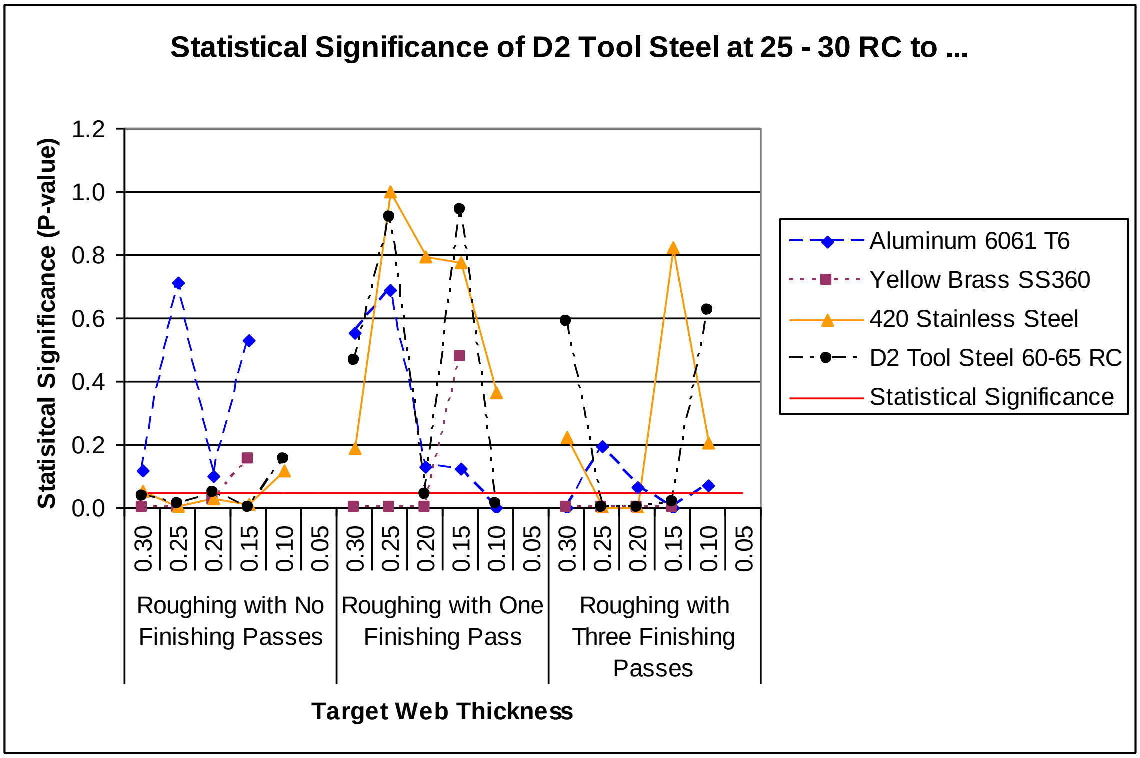

Figure 4.43 - Statistical Significance of D2 Tool Steel at 25 - 30 RC to the Other Four Materials

In comparing the data sets for the D2 Tool Steel at 25 to 30 RC, while utilizing the machining parameters of a roughing with no finishing passes, with the data sets for the Aluminum 6061 T6 it can be seen that there is not a statistically significant difference for any of the sections. In a comparison with the data sets for the Yellow Brass SS360 it was observed that there is a statistical difference for the sections with target thicknesses of 0.30, 0.25, and 0.20 millimeters (.012, .010, and .008 inches), but there is not a statistically significant difference for the data sets with a target thickness of 0.15 millimeters (.006 inches). The data sets for the 420 Stainless Steel are statistically significant for the section target thicknesses of 0.25, 0.20, and 0.15 millimeters (.010, .008, and .006 inches), but they are not statistically different for the section target thicknesses of 0.30 and 0.10 millimeters (.012 and .004 inches). In comparison with the data sets for the D2 Tool Steel at 60 to 65 RC it was observed that there was a statistically significant difference for the sections with target thicknesses of 0.30, 0.25, 0.20, and 0.15 millimeters (.012, .010, .008, and .006 inches), but they are not statistically different for the section target thickness of 0.10 millimeters (.004 inches).

When utilizing the machining parameters of a roughing with one finishing pass, it was observed that the majority of the comparisons with the D2 Tool Steel at 25 to 30 RC were not statistically significant. The data sets for the Yellow Brass SS360 were the only ones that demonstrated statistical significance when the section target thicknesses were 0.30 and 0.25 millimeters (.012 and .010 inches). A comparison with the data sets for the section target thickness of 0.20 millimeters (.008 inches) revealed that Yellow Brass SS360 and D2 Tool Steel at 60 to 65 RC demonstrated statistical significance. A comparison with the data sets for the section target thickness of 0.10 millimeters (.004 inches) revealed that Aluminum 6061 T6 and D2 Tool Steel at 60 to 65 RC demonstrated statistical significance.

In comparing the data sets for the D2 Tool Steel at 25 to 30 RC, while utilizing the machining parameters of a roughing with three finishing passes, with the data sets for the Aluminum 6061 T6 it can be seen that there is a statistically significant difference when cutting sections with target thicknesses of 0.30 and 0.15 millimeters (.012 and .006 inches), but there is no significant statistical difference for the sections with target thicknesses of 0.25, 0.20, and 0.10 millimeters (.010, .008, and .004 inches). A comparison with the Yellow Brass SS360 demonstrates a statistical difference for all of the data sets. In comparing the 420 Stainless Steel statistical significance was observed for the sections with target thicknesses of 0.25 and 0.20 millimeters (.010 and .008

inches), but there was no statistical significance observed for the sections with target thicknesses of 0.30, 0.15, and 0.10 millimeters (.012, .006, and .004 inches). In comparing the data sets with those of the D2 Tool Steel at 60 to 65 RC it was observed that there was a statistically significant difference for those with target thicknesses of 0.25, 0.20, and 0.15 millimeters (.010, .008, and .006 inches), but there was no statistically significant difference for those sections with target thicknesses of 0.30 and 0.10 millimeters (.012 and .004 inches).

4.3.5 D2 Tool Steel 60-65 RC – Statistical Analysis

Figure 4.44 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 60 to 65 RC while utilizing cutting parameters of a roughing with no

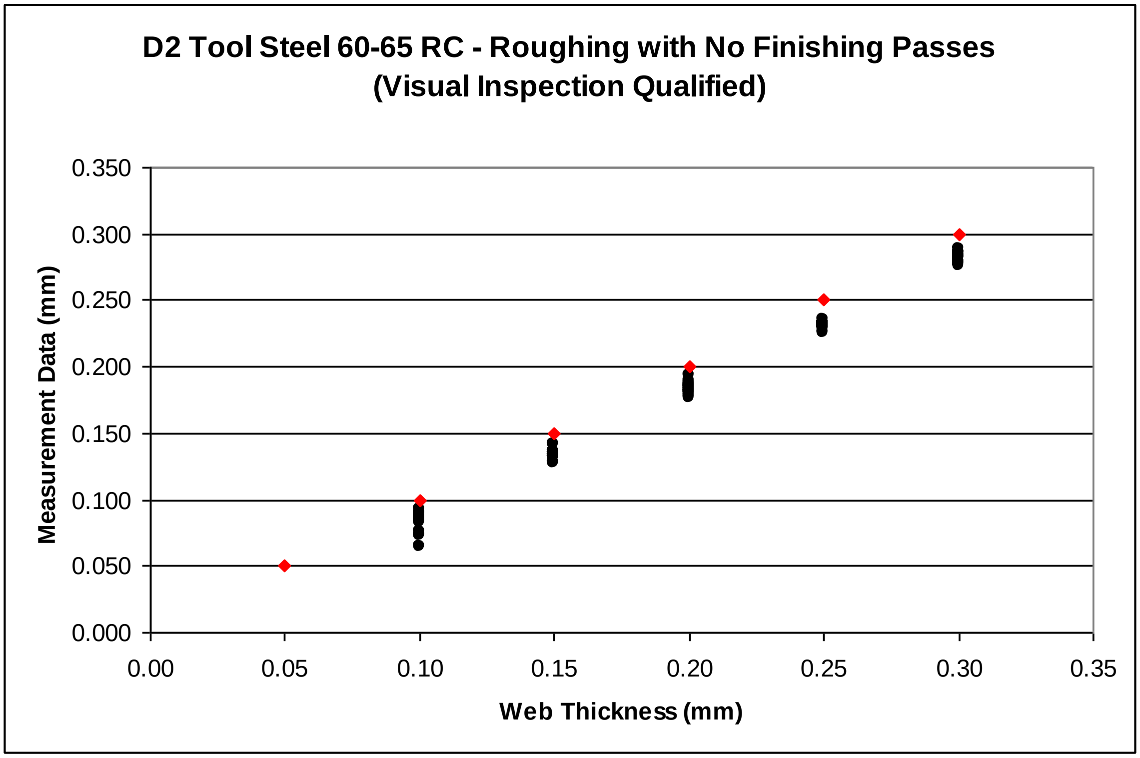

Figure 4.44 - Data Set Used for D2 Tool Steel 60-65 RC - Roughing with No Finishing Passes

finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness. Also, several of the 0.10 millimeter (.004 inch) sections failed the visual inspection test thus reducing the number of data points indicated at that thickness.

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.21. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Table 4.21 - D2 Tool Steel 60-65 RC - Statistics for Roughing with No Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.282	-0.018	0.003618	2.7641	1.1210
0.250	0.231	-0.019	0.002203	4.5394	1.6392
0.200	0.184	-0.016	0.003973	2.5173	1.1421
0.150	0.133	-0.017	0.002999	3.3339	1.4509
0.100	0.082	-0.018	0.008685	1.1514	0.4670
0.050	-	-	-	-	-

Figure 4.45 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 60 to 65 RC while utilizing cutting parameters of a roughing with one finishing pass. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness.

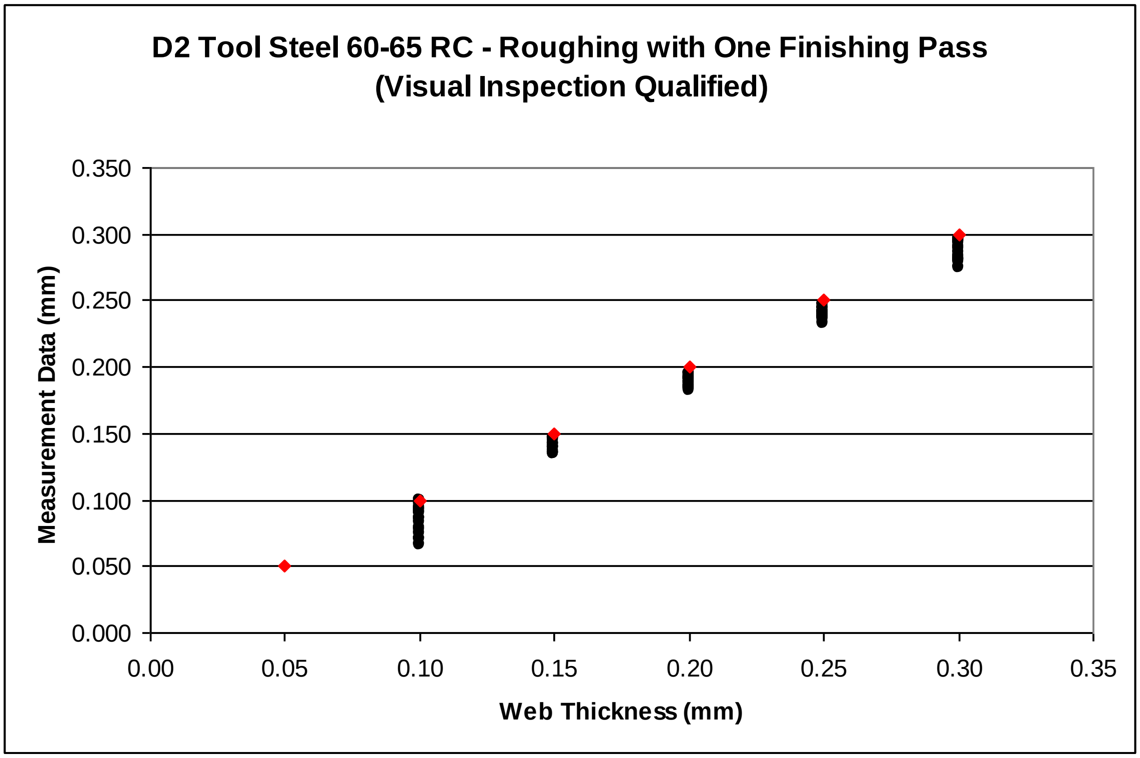

Figure 4.45 - Data Set Used for D2 Tool Steel 60-65 RC - Roughing with One Finishing Pass

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.22. The mean for each data set is smaller than the respective target value. The ANOVA test indicated that this data is

Table 4.22 - D2 Tool Steel 60-65 RC - Statistics for Roughing with One Finishing Pass Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.288	-0.012	0.007232	1.3828	0.8194
0.250	0.240	-0.010	0.003879	2.5781	1.7092
0.200	0.189	-0.011	0.004073	2.4553	1.5550
0.150	0.141	-0.010	0.004018	2.4886	1.7005
0.100	0.085	-0.015	0.009959	1.0041	0.4909
0.050	-	-	-	-	-

statistically significant from the target values and has a combined t-value of less than 0.0001 for the specified parameters.

Figure 4.46 indicates the data set that was used in the statistical analysis for D2 Tool Steel at 60 to 65 RC while utilizing cutting parameters of a roughing with three finishing passes. All of the thin-walled sections which had a target thickness of 0.05 millimeters (.002 inches) failed the visual inspection test, so there are no data points represented at this thickness.

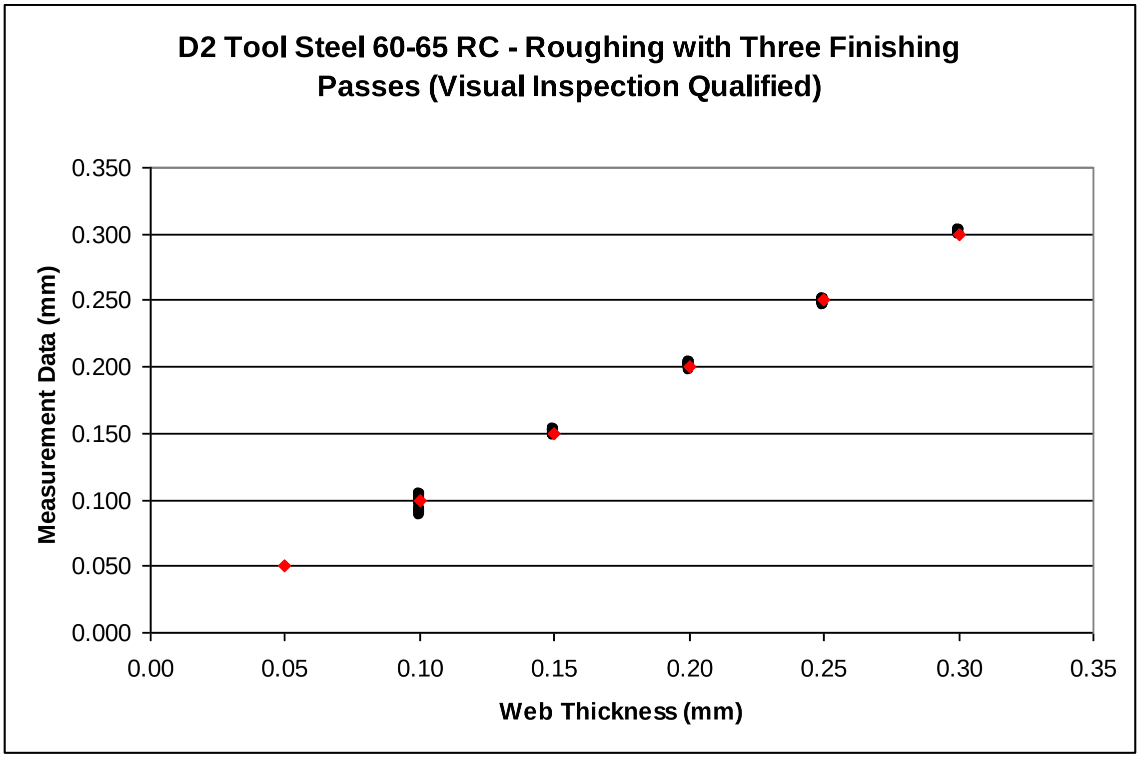

Figure 4.46 - Data Set Used for D2 Tool Steel 60-65 RC - Roughing with Three Finishing Passes

The arithmetic mean, mean's difference from target, standard deviation, C_p, and C_{pk} for each data set indicated above is shown in Table 4.23. The mean for the data sets with target values of 0.30 and 0.200 millimeters (.012 and .008 inches) are larger than the

Table 4.23 - D2 Tool Steel 60-65 RC - Statistics for Roughing with Three Finishing Passes Data Set

Web Thickness (mm)	Mean (mm)	μ - Target Thickness (mm)	Standard Deviation	C_p	C_{pk}
0.300	0.301	0.001	0.001589	6.2917	6.0704
0.250	0.249	-0.001	0.001609	6.2158	6.0086
0.200	0.201	0.001	0.001629	6.1388	5.9796
0.150	0.150	0.000	0.001328	7.5277	7.4441
0.100	0.098	-0.002	0.005626	1.7776	1.6788
0.050	-	-	-	-	-

respective target value. The mean for the data sets with target values of 0.25 and 0.10 millimeters (.010 and .004 inches) are smaller than their respective target value while the mean for the data set with a target value of 0.15 millimeters (.006 inches) is equal to the target value. The ANOVA test indicated that this data is not statistically significant from the target values and has a combined t-value of 0.8441 for the specified parameters.

For the D2 Tool Steel at 60 to 65 RC, the ANOVA test indicated that, in contrast to the first three materials discussed yet equivalent to the D2 Tool Steel as 35 to 30 RC, there was no significant difference in the data when the measurements that were taken from the tops of the thin-walled sections were compared to those taken from the bottoms of the sections. A t-value of 0.4404 was observed.

Figure 4.47 is a graph depicting the accuracy of cutting thin-walled sections from D2 Tool Steel at 60 to 65 RC while utilizing the three cutting parameters previously specified. Each of the calculated mean values for the respective target thicknesses and cutting parameters were subtracted from the target value in order to generate the values represented on this graph. This effectually makes 0.00 the target. Upper and lower specification limits were also indicated at ±0.005 millimeters. The accuracy obtainable

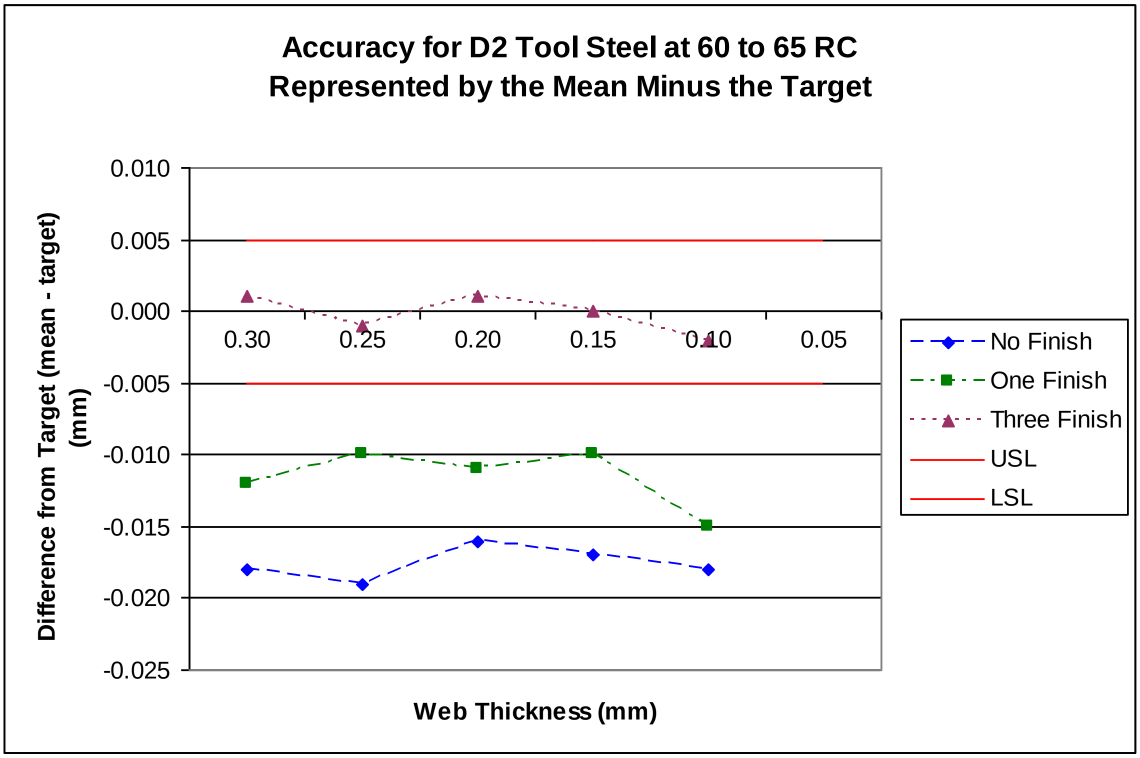

Figure 4.47 - D2 Tool Steel 60-65 RC - Accuracy in Cutting Thin-walled Sections (mean minus target)

by each of the cutting parameters can be readily seen along with a comparison of the cutting parameters.

A second ANOVA test was performed in order to determine the statistical significance between cutting parameters when machining the same material type. Table 4.24 lists the P-values that were generated from the ANOVA test. Any P-value which is greater than 0.05 indicates that there is not a statistically significant difference between the data sets being compared. Therefore, there is no statistical difference between the data obtained when comparing any of the cutting parameters utilized for any of the section target thicknesses when cutting D2 Tool Steel at 60 to 65 RC.

Table 4.24 - D2 Tool Steel 60-65 RC - P-values of Comparisons between Cutting Parameters

Target Thickness	No Finishing to One Finishing	No Finishing to Three Finishing	One Finishing to Three Finishing
0.30	0.5569437666	0.4076369144	0.7005773010
0.25	0.5486871300	0.4206432641	0.7236164208
0.20	0.5842338658	0.4336260607	0.7183390700
0.15	0.5838901385	0.4429028542	0.7314331690
0.10	0.8110045583	0.6169402445	0.7221815447
0.05	-	-	-

Figure 4.48 is a graph of the calculated P-values for the comparisons between cutting parameters while machining D2 Tool Steel at 60 to 65 RC. None of the P-values are located below the line indicating statistical significance. Therefore, statistically,

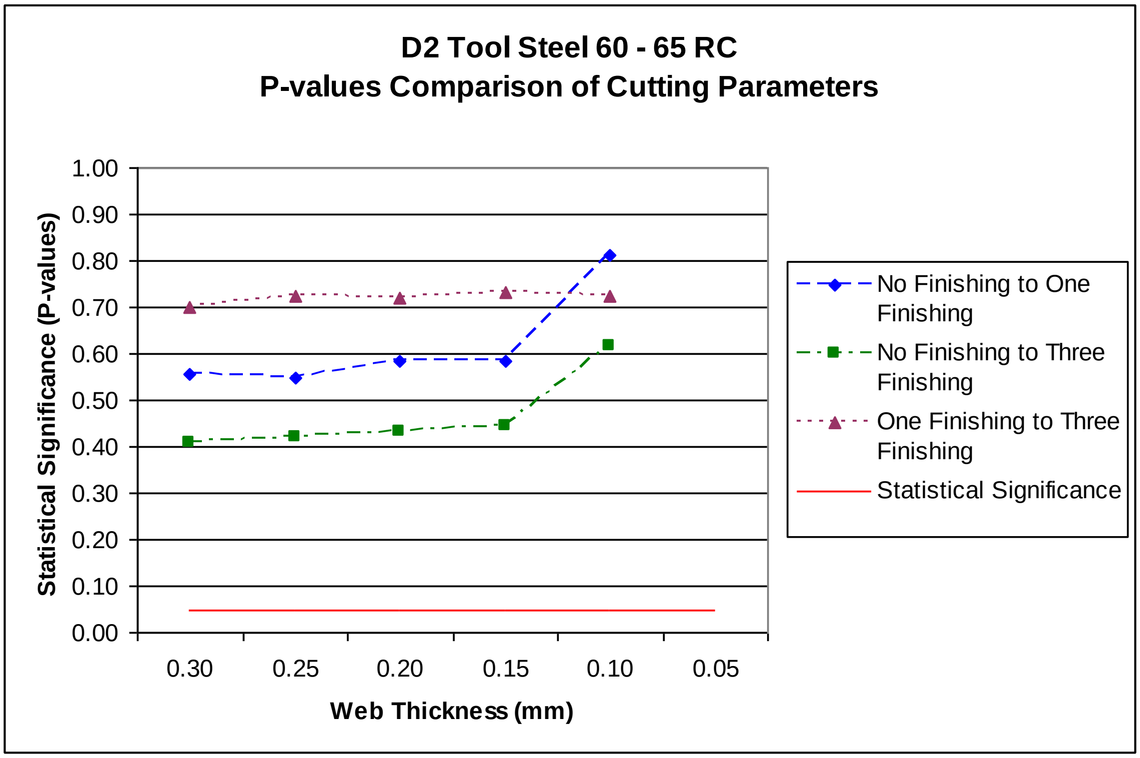

Figure 4.48 - D2 Tool Steel 60-65 RC – Statistical Significance Comparison of Cutting Parameters by P-values

there exists no significant difference between the data sets generated by the three different cutting parameters used in this study.

A third ANOVA test was performed on each data set of a thin-walled section according to the number of finishing passes that were utilized in order to compare the effect of material type. This test generated a P-value which indicates if there is a statistically significant difference between the data sets of the five different materials. Table 4.25 lists all of the P-values obtained through the ANOVA test in comparing the data sets for D2 Tool Steel at 60 to 65 RC to the data sets for the other four materials.

Table 4.25 - P-values Indicating Statistical Significance between D2 Tool Steel at 60 - 65 RC and ...

	Target Thickness	Aluminum 6061 T6	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 25-30 RC
Roughing with No Finishing Passes	0.30	0.0001863499	0.0061351144	0.6179693748	0.0350069777
	0.25	0.0027739700	0.0133669478	0.3745896767	0.0136320786
	0.20	0.0000003847	0.3115954826	0.5980114209	0.0489008208
	0.15	0.0165226643	0.1304528395	0.4276242120	0.0025614931
	0.10	-	-	0.7923250913	0.1544807380
	0.05	-	-	-	-
Roughing with One Finishing Pass	0.30	0.2232230948	0.0009996591	0.0755366301	0.4655144182
	0.25	0.7249130607	0.0000000048	0.9231260490	0.9151307801
	0.20	0.0058350527	0.0007800752	0.0504217640	0.0407918741
	0.15	0.0790816756	0.4864522245	0.7200021732	0.9413973416
	0.10	0.0000001357	-	0.1941318677	0.0106721303
	0.05	-	-	-	-
Roughing with Three Finishing Passes	0.30	0.0009779895	0.0000000059	0.2948293968	0.5908711585
	0.25	0.0098430943	0.0000000049	0.2327318989	0.0000789291
	0.20	0.0031581498	0.0000009250	0.8813736318	0.0000206555
	0.15	0.0000004849	0.0000821502	0.218087636	0.016953102
	0.10	0.077330044	-	0.321286478	0.623032562
	0.05	-	-	-	-

A graph depicting the relationships between each of the P-values can be seen in Figure 4.49. Included in this graph is a pink line with a P-value of 0.05. Any of the values above this line indicate that there is no statistical difference between the data sets

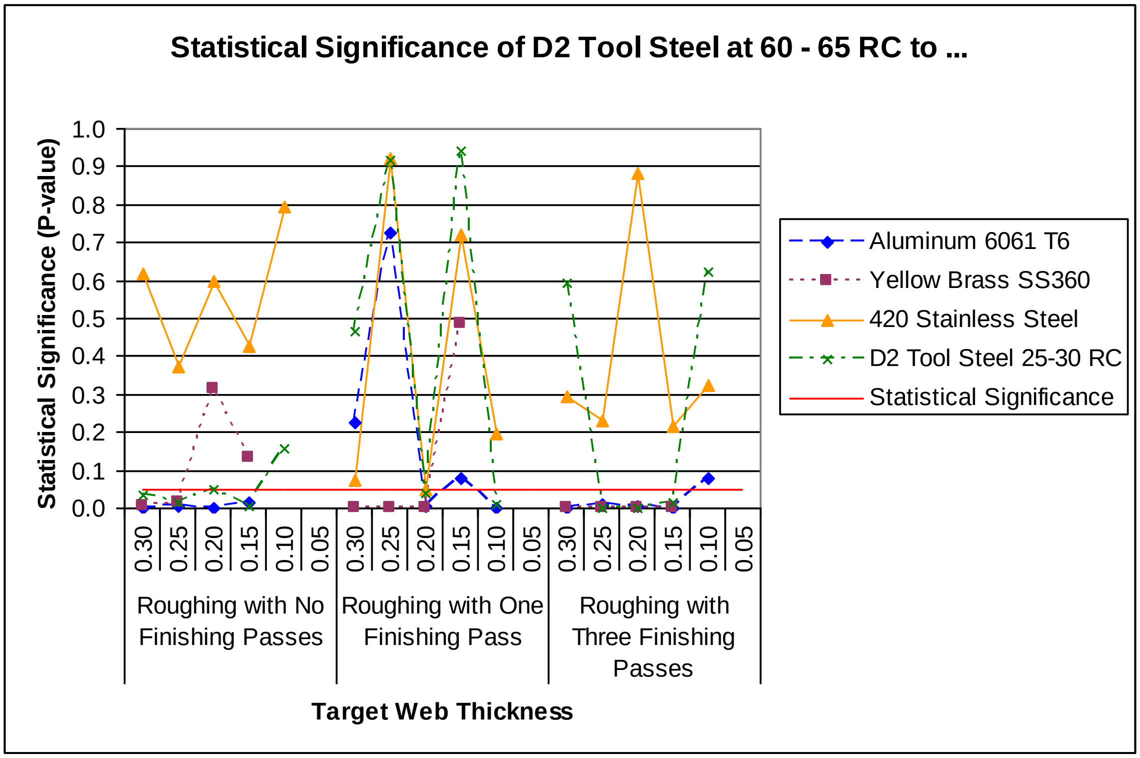

Figure 4.49 - Statistical Significance of D2 Tool Steel at 60 - 65 RC to the Other Four Materials

while all of the values located below the line demonstrate that there is a statistical difference between the data sets.

In comparing the data sets for the D2 Tool Steel at 60 to 65 RC, while utilizing the machining parameters of a roughing with no finishing passes, with the data sets for the 420 Stainless Steel it was observed that there was not a statistically significant difference for any of the sections, but a comparison with the remainder of the materials demonstrated statistical significance with the majority of these data sets. The exceptions to this being the Yellow Brass SS360 with section target thicknesses of 0.20 and 0.15 millimeters (.008 and .006 inches), and the D2 Tool Steel at 25 to 30 RC with a section target thickness of 0.10 millimeters (.004 inches).

In comparing the data sets for the D2 Tool Steel at 60 to 65 RC, when utilizing the machining parameters of a roughing with one finishing pass, it was observed that the data sets for the Yellow Brass SS360 were the only ones that demonstrated statistical significance for the sections with target thicknesses of 0.30 and 0.25 millimeters (.012 and .010 inches). A comparison of the data sets for the section target thickness of 0.20 millimeters (.008 inches) demonstrated that all of the material except 420 Stainless Steel were statistically significant. None of the data sets for any of the materials were statistically significant for the section target thickness of 0.15 millimeters (.006 inches). A comparison of the data sets for the section target thickness of 0.10 millimeters (.004 inches) demonstrated that the Aluminum 6061 T6 and the D2 Tool Steel at 25 to 30 RC were statistically significant while the 420 Stainless Steel was not statistically significant.

In comparing the data sets for the D2 Tool Steel at 60 to 65 RC, when utilizing the machining parameters of a roughing with three finishing passes, with those of the Aluminum 6061 T6 it was observed that there was a statistical significance for all of the section thicknesses except that with a target thickness of 0.10 millimeters (.004 inches). All of the data sets for the Yellow Brass SS360 demonstrated a statistical significance. When compared with the data sets for the 420 Stainless Steel there was no statistical significance found. A comparison with the data sets for the D2 Tool Steel at 25 to 30 RC showed a statistical significance for those with target thicknesses of 0.25, 0.20, and 0.15 millimeters (.010, .008, and .006 inches), while there was no statistical significance observed for the sections with target thicknesses of 0.30 and 0.10 millimeters (.012 and .004 inches).

4.4 Statistical Comparisons of the Data Distribution Between Materials

As discussed in the introduction to this section, a C_p and C_{pk} value was calculated for each data set using a common set of specification limits so that comparisons and trends for the data distribution could be evaluated between the five materials tested in this experiment. These comparisons were separated into a trichotomy according to the number of finishing passes used.

Table 4.26 is a compilation of all the calculated C_p and C_{pk} values for the five different materials studied while utilizing cutting parameters of a roughing with no finishing passes. These values are delineated by material type and by the thin-walled section target thickness.

Table 4.26 - C_p and C_{pk} Comparisons while Utilizing a Roughing with No Finishing Passes

Web Thickness		Aluminum 6061 T6	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
C_p	0.300	1.2139	1.2212	3.3634	1.2464	2.7641
	0.250	1.5193	1.0843	3.0732	0.9911	4.5394
	0.200	1.4907	0.9973	3.5471	0.8052	2.5173
	0.150	6.5465	1.4531	2.4622	0.8763	3.3339
	0.100	-	-	2.5607	0.6772	1.1514
	0.050	-	-	-	-	-
C_{pk}	0.300	0.1326	0.7463	1.3018	0.3162	1.1210
	0.250	0.2814	0.6024	1.1951	0.1487	1.6392
	0.200	-0.0166	0.5393	1.6816	0.1968	1.1421
	0.150	1.8185	0.4897	0.9903	0.1168	1.4509
	0.100	-	-	1.1097	0.1028	0.4670
	0.050	-	-	-	-	-

Figure 4.50 is a graph depicting the C_p and C_{pk} values that are listed in the previous table and illustrate the data with the independent variable being the material

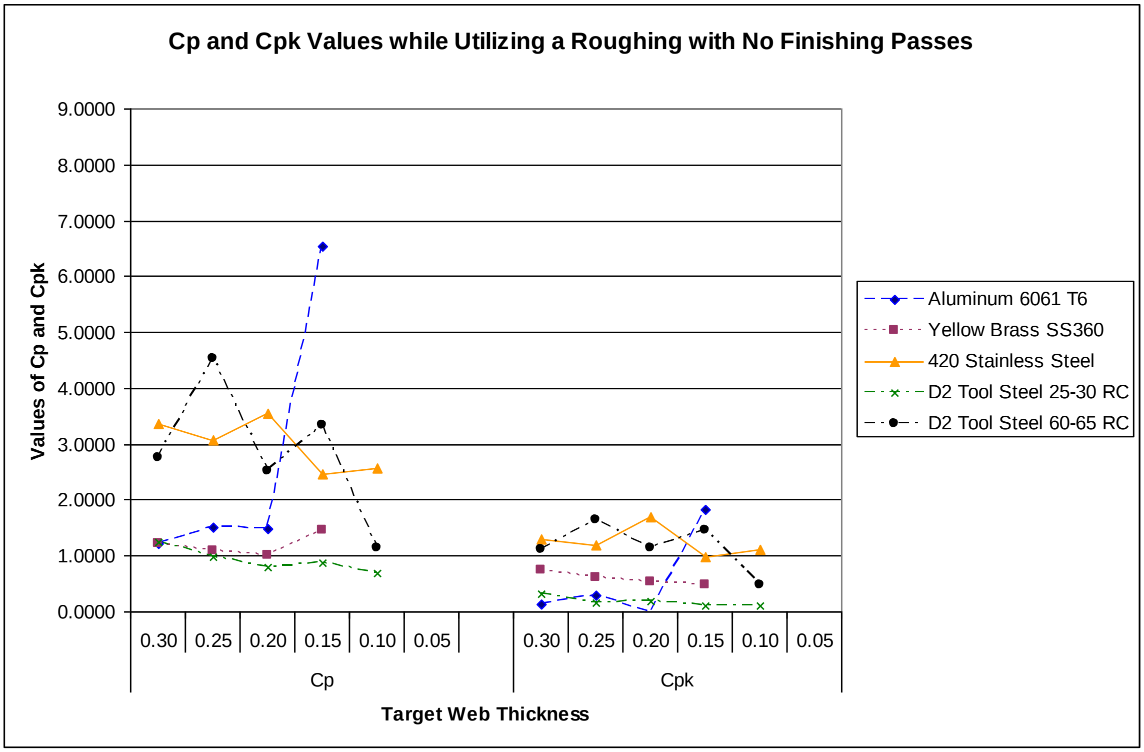

Figure 4.50 – C_p and C_{pk} Values Depicting the Data Distributions while Utilizing a Roughing with No Finishing Passes

types. The size of the distribution of each data set as it relates to those of the other materials shown can be observed with the size of the distribution decreasing as the numbers on the y-axis increase.

Table 4.27 is a compilation of all the calculated C_p and C_{pk} values for the five different materials studied while utilizing cutting parameters of a roughing with one finishing pass. These values are delineated by material type and by the thin-walled section target thickness.

Figure 4.51 is a graph depicting the C_p and C_{pk} values that are listed in the previous table and illustrate the data with the independent variable being the material types. The size of the distribution of each data set as it relates to those of the other

Table 4.27 - C_p and C_{pk} Comparisons while Utilizing a Roughing with One Finishing Pass

Web Thickness		Aluminum 6061 T6	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
C_p	0.300	1.9094	3.6862	1.6175	1.9018	1.3828
	0.250	1.4360	3.9263	1.6252	1.8788	2.5781
	0.200	1.0930	3.0359	1.5387	2.0706	2.4553
	0.150	1.5215	1.1307	1.4893	2.0257	2.4886
	0.100	2.1926	-	0.8413	0.9737	1.0041
	0.050	-	-	-	-	-
C_{pk}	0.300	1.2977	1.3789	1.1802	1.2256	0.8194
	0.250	0.9839	1.4905	1.0684	1.2351	1.7092
	0.200	0.9453	1.4617	1.1626	1.5300	1.5550
	0.150	1.2285	0.7119	1.0508	1.3917	1.7005
	0.100	0.9501	-	0.5609	0.7717	0.4909
	0.050	-	-	-	-	-

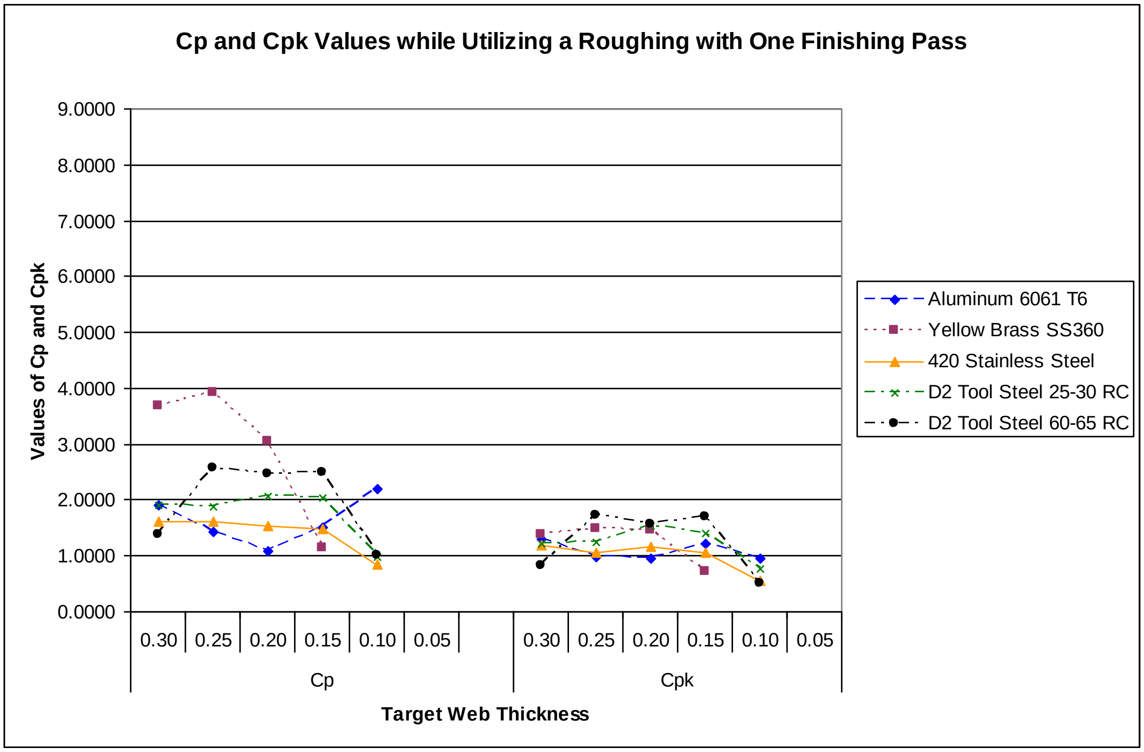

Figure 4.51 – C_p and C_{pk} Values Depicting the Data Distributions while Utilizing a Roughing with One Finishing Pass

materials shown can be observed with the size of the distribution decreasing as the numbers on the y-axis increase.

In comparing these values to those obtained while utilizing a roughing pass with no finishing passes there were slight change observed for both the Aluminum 6061 T6 and the D2 Tool Steel at 60 to 65 RC, but there were no noticeable trends. There is a significant increase in the capability for the Yellow Brass SS360. The D2 Tool Steel at 25 to 30 RC demonstrated a slight increase over all of the values while the 420 Stainless Steel demonstrated a significant decrease in capability.

Table 4.28 is a compilation of all the calculated C_p and C_{pk} values for the five different materials studied while utilizing cutting parameters of a roughing with three finishing passes.

Table 4.28 - C_p and C_{pk} Comparisons while Utilizing a Roughing with Three Finishing Passes

Web Thickness		Aluminum 6061 T6	Yellow Brass SS360	420 Stainless Steel	D2 Tool Steel 25-30 RC	D2 Tool Steel 60-65 RC
C_p	0.300	2.0660	1.2925	5.4139	3.2366	6.2917
	0.250	1.6441	1.3377	3.7674	8.4555	6.2158
	0.200	1.3129	1.0864	3.7329	8.0094	6.1388
	0.150	1.3694	0.8051	2.6925	5.1696	7.5277
	0.100	1.3034	-	1.0276	1.3057	1.7776
	0.050	-	-	-	-	-
C_{pk}	0.300	1.6949	0.7205	5.1131	3.1707	6.0704
	0.250	1.4766	0.6689	3.5301	8.1423	6.0086
	0.200	1.0236	0.6378	3.6499	7.1640	5.9796
	0.150	0.8597	0.4607	2.5579	4.8728	7.4441
	0.100	1.1683	-	0.9933	1.1848	1.6788
	0.050	-	-	-	-	-

Figure 4.52 is a graph depicting the C_p and C_{pk} values that are listed in the previous table and illustrate the data with the independent variable being the material types. The size of the distribution of each data set as it relates to those of the other materials shown can be observed with the size of the distribution decreasing as the numbers on the y-axis increase.

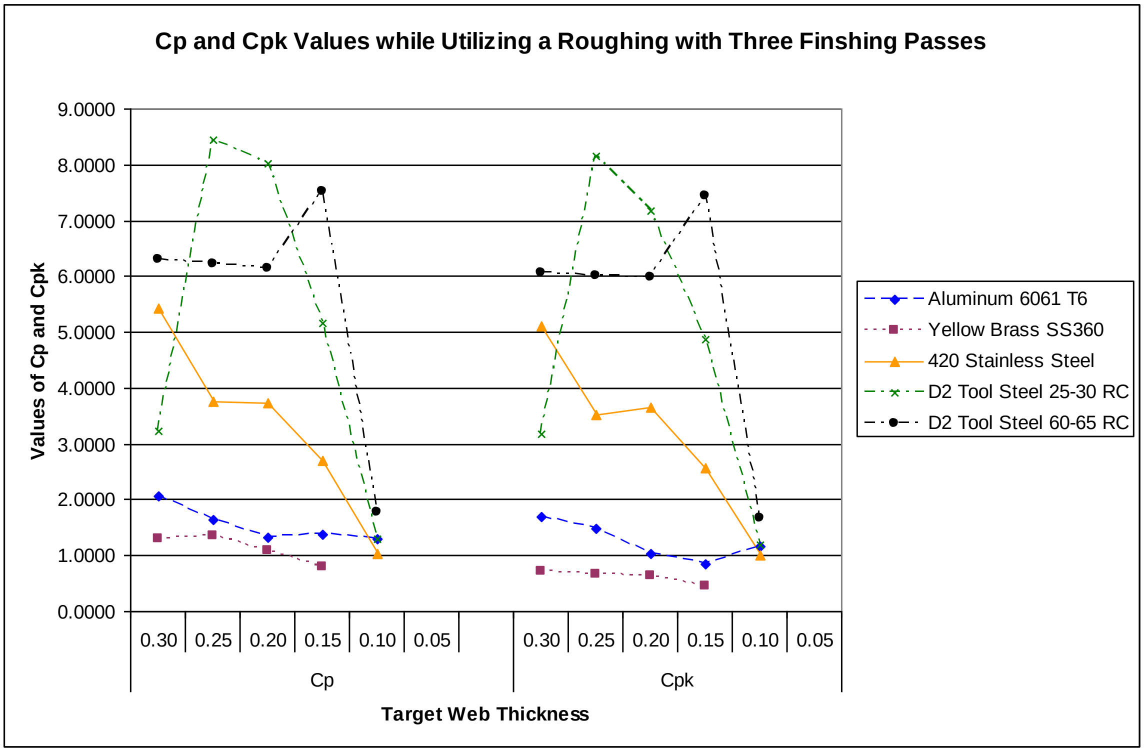

Figure 4.52 – C_p and C_{pk} Values Depicting the Data Distributions while Utilizing a Roughing with Three Finishing Passes

With the exception of the Yellow Brass SS360, all of the materials demonstrated an overall improvement in both capability and accuracy when utilizing a roughing with three finishing passes. The Yellow Brass SS360 demonstrated similar values to those seen when utilizing a roughing with no finishing passes.

5 Conclusions and Recommendations

5.1 Introduction

Wire Electric Discharge Machining (wire-EDM) is a nontraditional manufacturing process which uses successive sparks to vaporize a kerf in a workpiece. The path along which the machine cuts is programmed and uploaded into the CNC machine. In wire-EDM, a wire is used as the agent in order to position the sparks in the desired area. This wire is typically brass, an alloy of copper and zinc. A dielectric fluid, typically deionized water, is used to help control the spark gap by: creating a controllable electrical barrier, flushing away contaminants in the kerf, and creating a temperature controlled environment. Modern machines use linear motors to move the wire along the desired cut path described by the NC code.

Although this process is relatively new, it is being used extensively in the industrial sector. The process has improved dramatically throughout its existence, but very little research has been performed in cutting thin-walled sections utilizing the default parameters of a conventional wire-EDM machine.

5.2 Hypothesis

The purpose of this study was to observe the limitations in cutting thin-walled sections, which are constrained on each end, from five different commonly used metals with a conventional wire-EDM machine while utilizing the machine’s default settings for different combinations of the roughing and finishing passes. The null hypothesis for this study states that there is no significant difference of wire-EDM cutting performance of thin-walled sections in five different commonly used metals while utilizing a variation of the rough and finishing parameters of the Sodick AQ325L wire-EDM machine.

5.3 Conclusions

The data obtained from this study was first separated according to material type and comparisons were made between the three sets of cutting parameters, and second according to cutting parameters so that comparisons could be made between the five metals. The test specimens were analyzed by two different methods – visual inspection and measurements of the thin-walled sections with a CMM in order to test accuracy. ANOVA tests were also performed in order to determine if there were statistically significant differences between the data sets being compared. Conclusions were drawn from this data in order to reject or fail to reject the null hypothesis.

In comparing the results of this study to those obtained by Kim in his thesis *Determination of Wall Thickness and Height Limits when Cutting Various Materials with Wire Electric Discharge Machining Process* it was observed that both the accuracy and number of defect free parts was greater in this study. This is attributed to each of the thin-walled sections being constrained on both ends as opposed to only being constrained on one end.

5.3.1 Aluminum 6061 T6 – Visual and Statistical Conclusions

The analysis indicates that differences exist between the respective data sets obtained when utilizing the three sets of cutting parameters specified in Chapter 3. Due to these differences, which are discussed below, the null hypothesis was rejected as it relates to the comparison of these cutting parameters while machining Aluminum 6061 T6.

When machining Aluminum 6061 T6 with the cutting parameters of a roughing with no finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.25 millimeters (.010 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.027 millimeters (.0011 inches) under target to 0.024 millimeters (.0009 inches) under target.

When machining Aluminum 6061 T6 with the cutting parameters of a roughing with one finishing pass the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.20 millimeters (.008 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.010 millimeters (.0004 inches) under target to 0.004 millimeters (.0002 inches) under target.

When machining Aluminum 6061 T6 with the cutting parameters of a roughing with three finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.003 millimeters (.0001 inches) over target to 0.011 millimeters (.0004 inches) over target.

5.3.2 Yellow Brass SS360 – Visual and Statistical Conclusions

The analysis indicates that the only differences that exist are when a comparison is made to the data obtained when utilizing the cutting parameters of a roughing with no finishing passes. Due to the observed differences, which are discussed below, the null hypothesis was rejected as it relates to comparisons with the cutting parameter of a roughing with no finishing passes, but the data failed to reject the null hypothesis for comparisons between the two remaining cutting parameters while machining Yellow Brass SS360.

When machining Yellow Brass SS360 with the cutting parameters of a roughing with no finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.20 millimeters (.008 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.014 millimeters (.0006 inches) under target to 0.012 millimeters (.0005 inches) under target.

When machining Yellow Brass SS360 with the cutting parameters of a roughing with one finishing pass the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.019 millimeters (.0007 inches) under target to 0.011 millimeters (.0004 inches) under target.

When machining Yellow Brass SS360 with the cutting parameters of a roughing with three finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.015 millimeters (.0006 inches) under target to 0.012 millimeters (.0005 inches) under target.

5.3.3 420 Stainless Steel – Visual and Statistical Conclusions

The analysis indicates that differences exist between the respective data sets obtained when utilizing the three sets of cutting parameters specified in Chapter 3. Due to these differences, which are discussed below, the null hypothesis was rejected as it relates to the comparison of these cutting parameters while machining 420 Stainless Steel.

When machining 420 Stainless Steel with the cutting parameters of a roughing with no finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.20 millimeters (.008 inches) without any defects, but some of the sections cut to a thickness of 0.15 millimeters (.006 inches) were also free of defects.

- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.018 millimeters (.0007 inches) under target to 0.016 millimeters (.0006 inches) under target.

When machining 420 Stainless Steel with the cutting parameters of a roughing with one finishing pass the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches) without any defects, but some of the sections cut to a thickness of 0.10 millimeters (.004 inches) were also free of defects.
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.010 millimeters (.0004 inches) under target to 0.007 millimeters (.0003 inches) under target.

When machining 420 Stainless Steel with the cutting parameters of a roughing with three finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.10 millimeters (.004 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.002 millimeters (.0001 inches) under target to 0.003 millimeters (.0001 inches) over target.

5.3.4 D2 Tool Steel at 25 to 30 RC – Visual and Statistical Conclusions

The analysis indicates that differences exist between the respective data sets obtained when utilizing the three sets of cutting parameters specified in Chapter 3. Due to these differences, which are discussed below, the null hypothesis was rejected as it relates to the comparison of these cutting parameters while machining D2 Tool Steel at 25 to 30 RC.

When machining D2 Tool Steel at 25 to 30 RC with the cutting parameters of a roughing with no finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.026 millimeters (.0010 inches) under target to 0.022 millimeters (.0009 inches) under target.

When machining D2 Tool Steel at 25 to 30 RC with the cutting parameters of a roughing with one finishing pass the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.10 millimeters (.004 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.011 millimeters (.0004 inches) under target to 0.006 millimeters (.0002 inches) under target.

When machining D2 Tool Steel at 25 to 30 RC with the cutting parameters of a roughing with three finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.10 millimeters (.004 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.003 millimeters (.0001 inches) under target to 0.003 millimeters (.0001 inches) over target.

5.3.5 D2 Tool Steel at 60 to 65 RC – Visual and Statistical Conclusions

The analysis indicates that differences exist between the respective data sets obtained when utilizing the three sets of cutting parameters specified in Chapter 3. Due to these differences, which are discussed below, the null hypothesis was rejected as it relates to the comparison of these cutting parameters while machining D2 Tool Steel at 60 to 65 RC.

When machining D2 Tool Steel at 60 to 65 RC with the cutting parameters of a roughing with no finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.15 millimeters (.006 inches) without any defects, but some of the sections cut to a thickness of 0.10 millimeters (.004 inches) were also free of defects.
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.019 millimeters (.0007 inches) under target to 0.016 millimeters (.0006 inches) under target.

When machining D2 Tool Steel at 60 to 65 RC with the cutting parameters of a roughing with one finishing pass the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.10 millimeters (.004 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.015 millimeters (.0006 inches) under target to 0.010 millimeters (.0004 inches) under target.

When machining D2 Tool Steel at 60 to 65 RC with the cutting parameters of a roughing with three finishing passes the following observations were made:

- Thin-walled sections could be successfully cut to a thickness equal to and greater than 0.10 millimeters (.004 inches).
- The mean values of the data sets obtained from the thin-walled sections which passed the visual inspection ranged from 0.002 millimeters (.0001 inches) under target to 0.001 millimeters (.00004 inches) over target.

5.3.6 Roughing with No Finishing Passes – Visual and Statistical Conclusions

The analysis indicates that differences exist between some of the data sets for the five metals when utilizing the cutting parameters of a roughing with no finishing passes. These differences were observed in both the visual inspection and the numerical data. Due to the differences in data the null hypothesis was rejected for the following materials when utilizing a roughing with no finishing passes:

- Aluminum 6061 T6
- Yellow Brass SS360
- D2 Tool Steel at 25 to 30 RC

The data failed to reject the null hypothesis due to the similarity of the data for the following materials when utilizing a roughing with no finishing passes:

- 420 Stainless Steel
- D2 Tool Steel at 60 to 65 RC

5.3.7 Roughing with One Finishing Pass – Visual and Statistical Conclusions

The analysis indicates that differences exist between some of the data sets for the five metals when utilizing the cutting parameters of a roughing with one finishing pass.

These differences were observed in both the visual inspection and the numerical data. Due to the differences in data the null hypothesis was rejected for the following materials when utilizing a roughing with one finishing pass:

- Aluminum 6061 T6
- Yellow Brass SS360
- 420 Stainless Steel

The data failed to reject the null hypothesis due to the similarity of the data for the following materials when utilizing a roughing with one finishing pass:

- D2 Tool Steel at 25 to 30 RC
- D2 Tool Steel at 60 to 65 RC

5.3.8 Roughing with Three Finishing Passes – Visual and Statistical Conclusions

The analysis indicates that differences exist between some of the data sets for the five metals when utilizing the cutting parameters of a roughing with three finishing passes. These differences were observed in both the visual inspection and the numerical data. Due to the differences in data the null hypothesis was rejected for the following materials when utilizing a roughing with three finishing passes:

- Aluminum 6061 T6
- Yellow Brass SS360

The data failed to reject the null hypothesis due to the similarity of the data for the following materials when utilizing a roughing with three finishing passes:

- 420 Stainless Steel

- D2 Tool Steel at 25 to 30 RC
- D2 Tool Steel at 60 to 65 RC

5.4 Recommendations for Further Study

While performing the review of literature for this study and while performing the study itself there were several areas of further study that became apparent. Further study in these areas would enhance the research that has already been done and help to further the use and capabilities of wire-EDM. These areas for further study are presented below.

- Perform the study that has been documented in this thesis, but use coated EDM wire to perform the cutting. With the increased flushing capabilities of the coated EDM wire and the change in electrical conductivity, the results may be different from those obtained through the use of conventional brass EDM wire.
- We observed bending of the webs for all of the metals, but at different thicknesses of the thin-walled sections. In thin-walled sections where bending did not occur increase the length of the webs in order to observe if bending will occur with the thicker webs or if the webs will continue to be straight over longer distances.
- There may be some residual stresses that are introduced into webs due to the thermal effect of the EDM process. Webs could be cut as is described in this thesis after which one end of the web could be freed. The amount of deflection could then be measured. Tests would have to be run on the parent material in order to determine if there are any residual stresses in the materials prior to their being cut on the wire-EDM machine. The cutting direction of the wire-EDM

machine would be an important factor to consider throughout the experiment and its setup.

- During this study it was observed that both the severity and number of defects were greater on the bottoms of the thin-walled sections in comparison to those observed on the tops of the sections. The reason for this is unknown, so a study could be performed in order to determine the cause.
- There is an occurrence which is depicted in Figure 4.52; a chart comparing the C_p and C_{pk} values of the five materials tested when utilizing the cutting parameters of a roughing with three finishing passes. Both the D2 Tool Steel at 25 to 30 RC and the D2 Tool Steel at 60 to 65 RC show an improvement and subsequent decline in capability. The capability of the process being reflective of the spread of the data set and therefore described by the C_p and C_{pk} values. By contrast, the other three materials show a steady decline in capability starting at the thickest sections and proceeding to the thinnest. It is not known what causes this increase in capability, so a study should be performed in order to determine the cause of this increase in capability.

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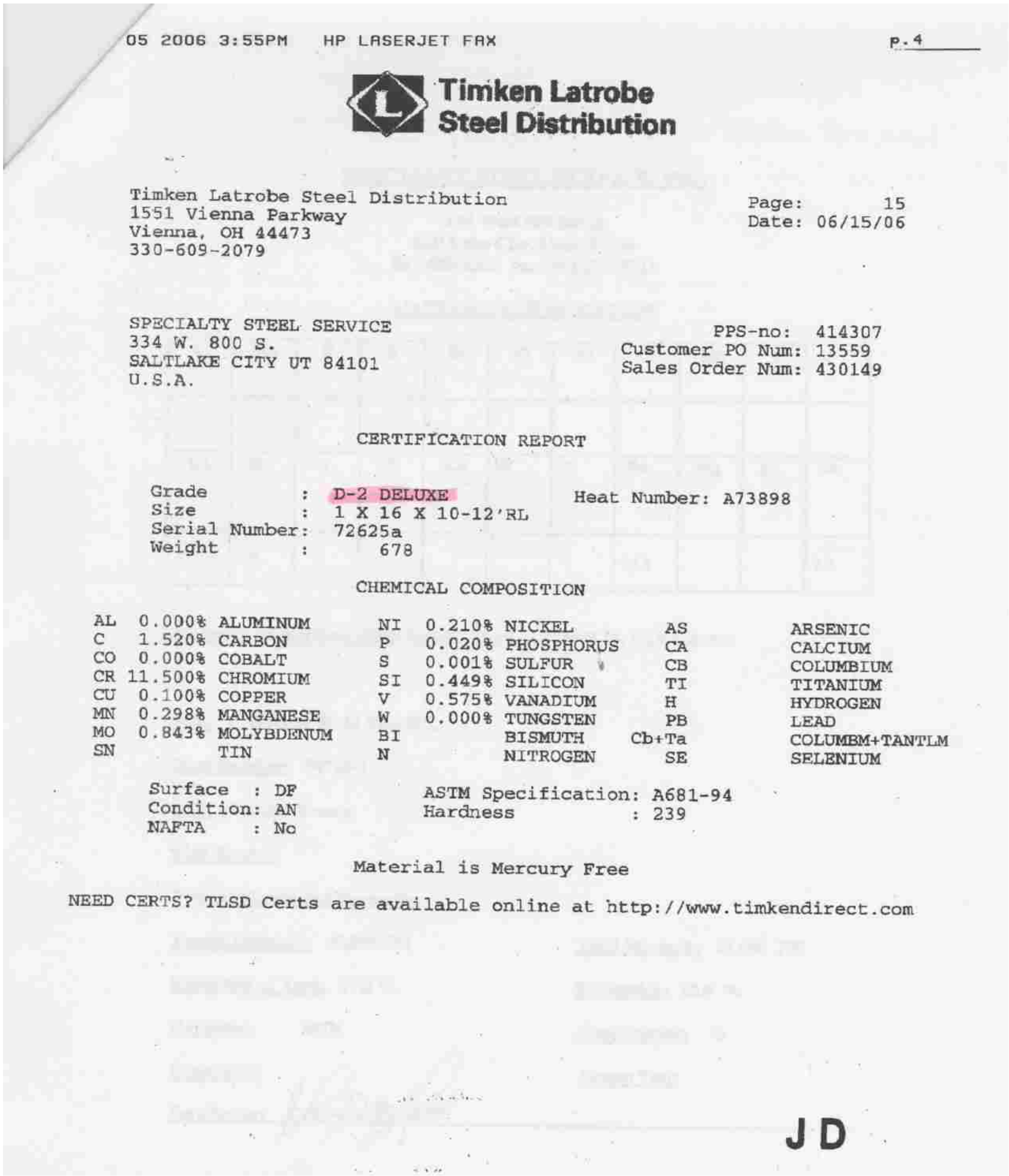
Appendices

Appendix A. Material Data Sheets



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Timken Latrobe Steel Distribution

Timken Latrobe Steel Distribution
1551 Vienna Parkway
Vienna, OH 44473
330-609-2079

Page: 15
Date: 06/15/06

SPECIALTY STEEL SERVICE
334 W. 800 S.
SALTLAKE CITY UT 84101
U.S.A.

PPS-no: 414307
Customer PO Num: 13559
Sales Order Num: 430149

CERTIFICATION REPORT

Grade : D-2 DELUXE
Size : 1 X 16 X 10-12'RL
Serial Number: 72625a
Weight : 678

Heat Number: A73898

CHEMICAL COMPOSITION

AL	0.000%	ALUMINUM	NI	0.210%	NICKEL	AS		ARSENIC
C	1.520%	CARBON	P	0.020%	PHOSPHORUS	CA		CALCIUM
CO	0.000%	COBALT	S	0.001%	SULFUR	CB		COLUMBIUM
CR	11.500%	CHROMIUM	SI	0.449%	SILICON	TI		TITANIUM
CU	0.100%	COPPER	V	0.575%	VANADIUM	H		HYDROGEN
MN	0.298%	MANGANESE	W	0.000%	TUNGSTEN	PB		LEAD
MO	0.843%	MOLYBDENUM	BI		BISMUTH	Cb+Ta		COLUMBM+TANTLM
SN		TIN	N		NITROGEN	SE		SELENIUM

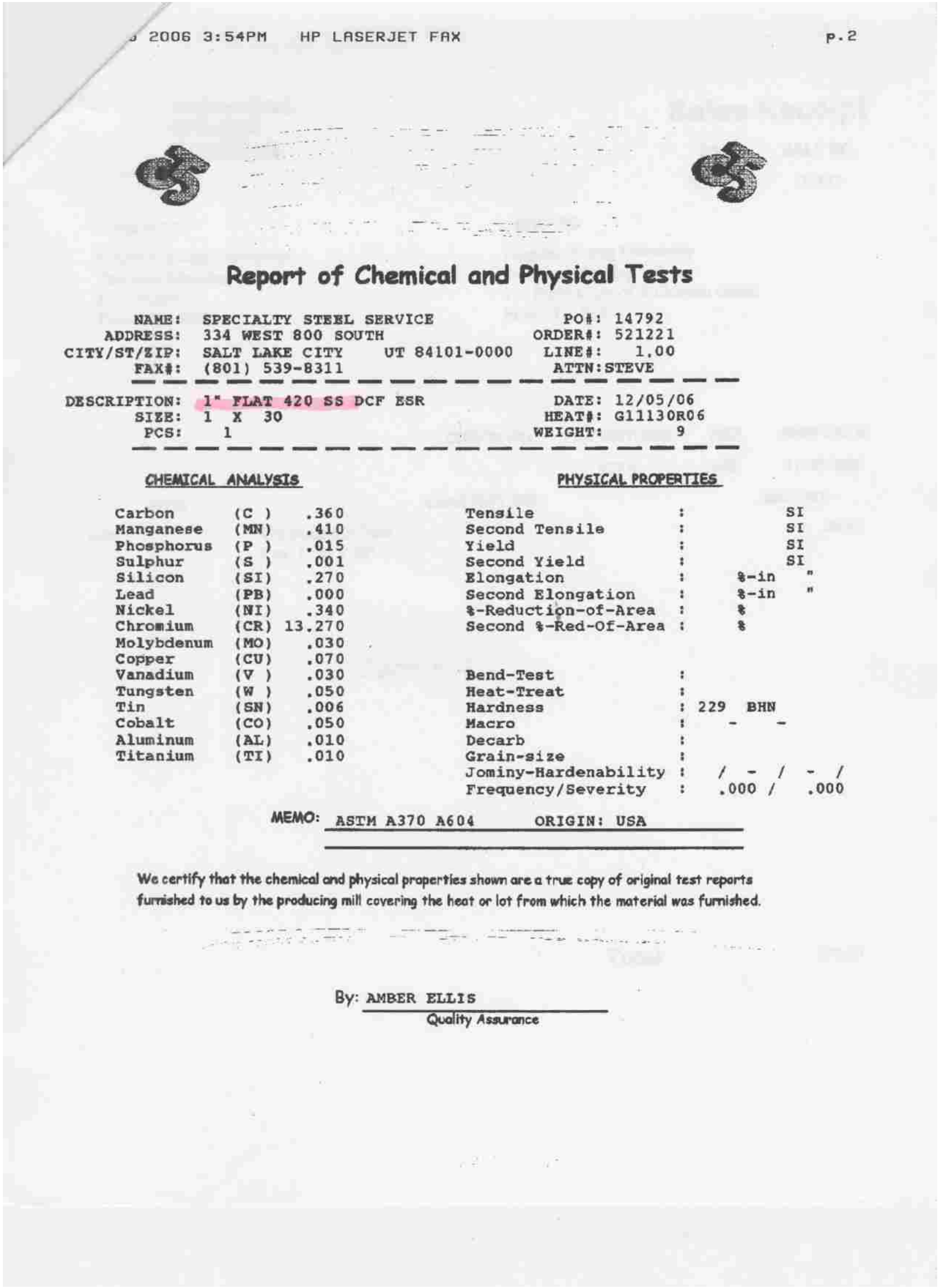
Surface : DF
Condition: AN
NAFTA : No

ASTM Specification: A681-94
Hardness : 239

Material is Mercury Free

NEED CERTS? TLSD Certs are available online at http://www.timkendirect.com

JD



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Report of Chemical and Physical Tests

NAME: SPECIALTY STEEL SERVICE
ADDRESS: 334 WEST 800 SOUTH
CITY/ST/ZIP: SALT LAKE CITY UT 84101-0000
FAX#: (801) 539-8311

PO#: 14792
ORDER#: 521221
LINE#: 1.00
ATTN:STEVE

DESCRIPTION: 1" FLAT 420 SS DCF ESR
SIZE: 1 X 30
PCS: 1

DATE: 12/05/06
HEAT#: G11130R06
WEIGHT: 9

CHEMICAL ANALYSIS

Carbon	(C)	.360
Manganese	(MN)	.410
Phosphorus	(P)	.015
Sulphur	(S)	.001
Silicon	(SI)	.270
Lead	(PB)	.000
Nickel	(NI)	.340
Chromium	(CR)	13.270
Molybdenum	(MO)	.030
Copper	(CU)	.070
Vanadium	(V)	.030
Tungsten	(W)	.050
Tin	(SN)	.006
Cobalt	(CO)	.050
Aluminum	(AL)	.010
Titanium	(TI)	.010

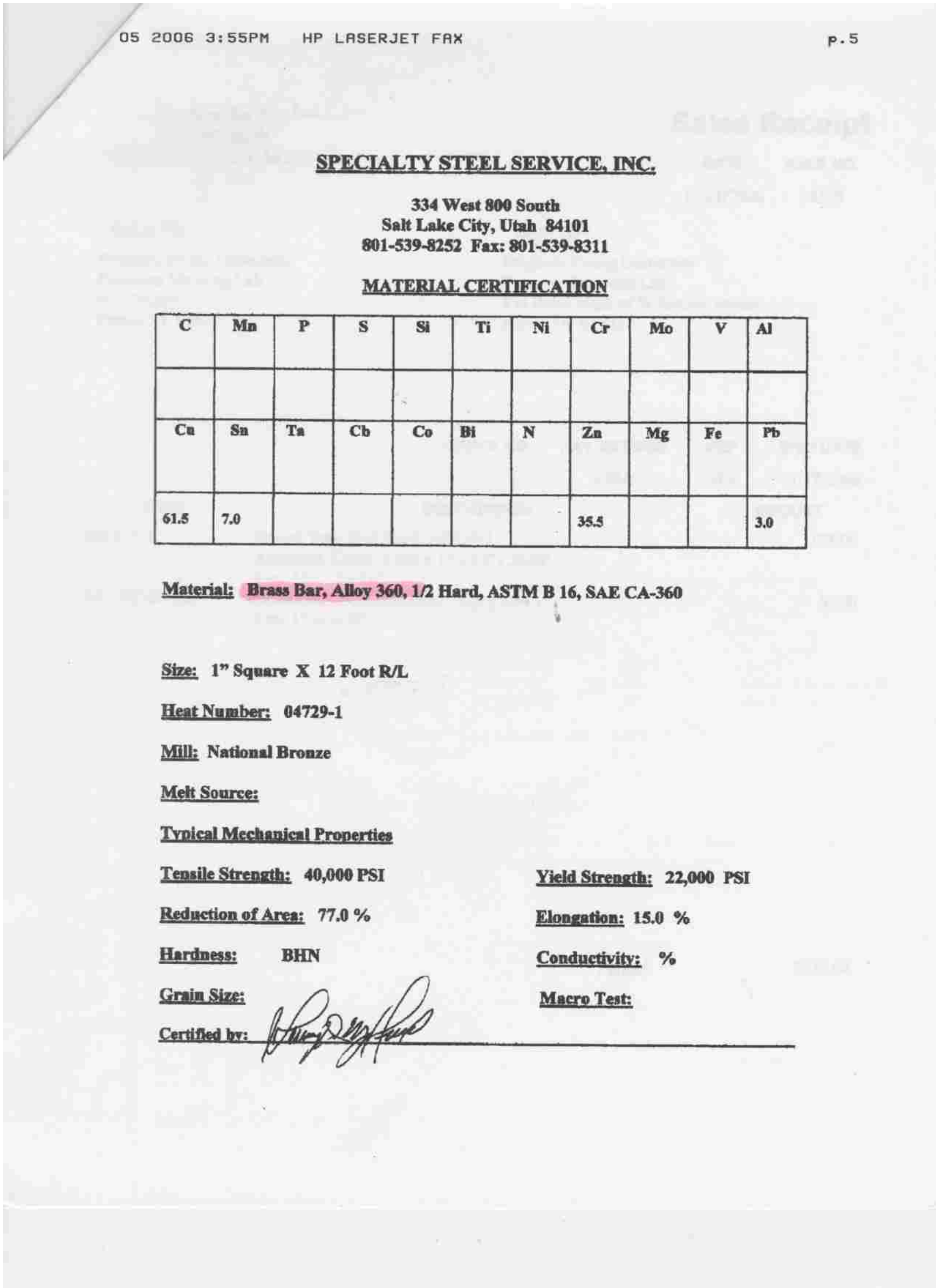
PHYSICAL PROPERTIES

Tensile	:	SI
Second Tensile	:	SI
Yield	:	SI
Second Yield	:	SI
Elongation	:	%-in "
Second Elongation	:	%-in "
%-Reduction-of-Area	:	%
Second %-Red-Of-Area	:	%
Bend-Test	:	
Heat-Treat	:	
Hardness	:	229 BHN
Macro	:	- -
Decarb	:	
Grain-size	:	
Jominy-Hardenability	:	/ - / - /
Frequency/Severity	:	.000 / .000

MEMO: ASTM A370 A604 ORIGIN: USA

We certify that the chemical and physical properties shown are a true copy of original test reports furnished to us by the producing mill covering the heat or lot from which the material was furnished.

By: AMBER ELLIS
Quality Assurance



05 2006 3:55PM HP LASERJET FAX p.5

SPECIALTY STEEL SERVICE, INC.

334 West 800 South
Salt Lake City, Utah 84101
801-539-8252 Fax: 801-539-8311

MATERIAL CERTIFICATION

C	Mn	P	S	Si	Ti	Ni	Cr	Mo	V	Al
Cu	Sn	Ta	Cb	Co	Bi	N	Zn	Mg	Fe	Pb
61.5	7.0						35.5			3.0

Material: Brass Bar, Alloy 360, 1/2 Hard, ASTM B 16, SAE CA-360

Size: 1" Square X 12 Foot R/L

Heat Number: 04729-1

Mill: National Bronze

Melt Source:

Typical Mechanical Properties

Tensile Strength: 40,000 PSI

Yield Strength: 22,000 PSI

Reduction of Area: 77.0 %

Elongation: 15.0 %

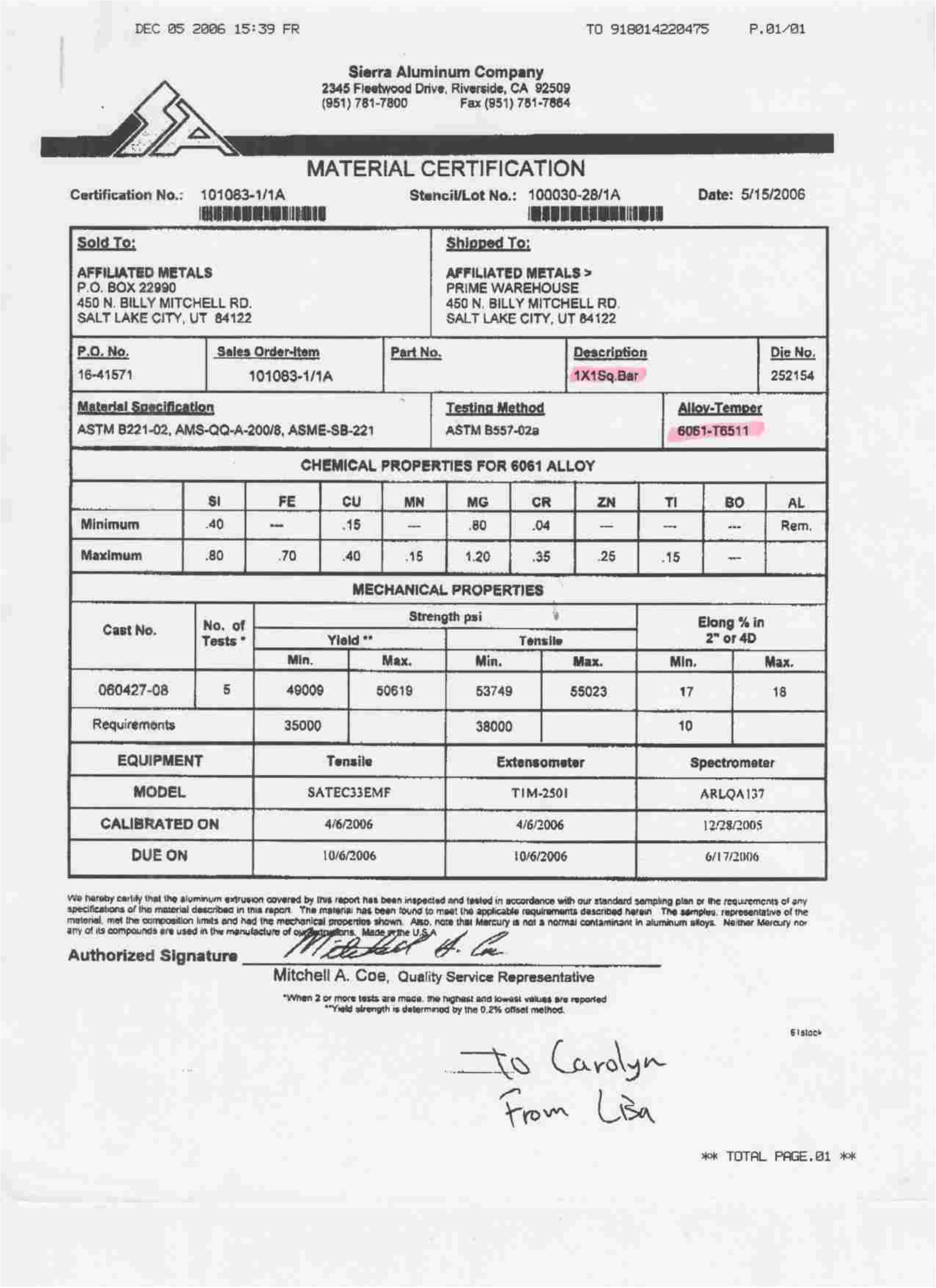
Hardness: BHN

Conductivity: %

Grain Size:

Macro Test:

Certified by:



DEC 05 2006 15:39 FR TO 918014220475 P.01/01

Sierra Aluminum Company
2345 Fleetwood Drive, Riverside, CA 92509
(951) 781-7800 Fax (951) 781-7864

MATERIAL CERTIFICATION

Certification No.: 101083-1/1A
Stencil/Lot No.: 100030-28/1A
Date: 5/15/2006

Sold To:	**Shipped To:**
AFFILIATED METALS P.O. BOX 22990 450 N. BILLY MITCHELL RD. SALT LAKE CITY, UT 84122	**AFFILIATED METALS >** PRIME WAREHOUSE 450 N. BILLY MITCHELL RD. SALT LAKE CITY, UT 84122

P.O. No.	Sales Order-Item	Part No.	Description	Die No.
16-41571	101083-1/1A		1X1Sq.Bar	252154

Material Specification	Testing Method	Alloy-Temper
ASTM B221-02, AMS-QQ-A-200/8, ASME-SB-221	ASTM B557-02a	6061-T6511

CHEMICAL PROPERTIES FOR 6061 ALLOY

	SI	FE	CU	MN	MG	CR	ZN	TI	BO	AL
Minimum	.40	---	.15	---	.80	.04	---	---	---	Rem.
Maximum	.80	.70	.40	.15	1.20	.35	.25	.15	---	

MECHANICAL PROPERTIES

Cast No.	No. of Tests *	Strength psi				Elong % in 2" or 4D	
		Yield **		Tensile			
		Min.	Max.	Min.	Max.	Min.	Max.
060427-08	5	49009	50619	53749	55023	17	18
Requirements		35000		38000		10	

EQUIPMENT	Tensile	Extensometer	Spectrometer
MODEL	SATEC33EMF	TIM-2501	ARLQA137
CALIBRATED ON	4/6/2006	4/6/2006	12/28/2005
DUE ON	10/6/2006	10/6/2006	6/17/2006

We hereby certify that the aluminum extrusion covered by this report has been inspected and tested in accordance with our standard sampling plan or the requirements of any specifications of the material described in this report. The material has been found to meet the applicable requirements described herein. The samples, representative of the material, met the composition limits and had the mechanical properties shown. Also, note that Mercury is not a normal contaminant in aluminum alloys. Neither Mercury nor any of its compounds are used in the manufacture of our extrusions. Made in the U.S.A.

Authorized Signature ____________________
Mitchell A. Coe, Quality Service Representative

*When 2 or more tests are made, the highest and lowest values are reported
**Yield strength is determined by the 0.2% offset method.

61stock

To Carolyn
From Lisa

** TOTAL PAGE.01 **

Appendix B. Brinell Hardness Measurements

Table B. 1 - Data from Measurements for Brinell Hardness

Materials	Test 1	Test 2	Test 3	Test 4	Test 5	Average	Brinell Hardness
Aluminum 6061 T6	56.7	57.3	58.4	56.2	58.5	HRB 57.5	98
Yellow Brass SS360	76.0	72.4	75.5	72.1	74.8	HRB 74.2	126
420 Stainless Steel	85.9	86.4	85.5	87.2	87.7	HRB 86.5	167
D2 Non-Heat-Treated Tool Steel	95.8	96.2	94.9	96.0	95.4	HRB 95.7	212
D2 Heat-Treated Tool Steel	63.1	62.8	62.7	61.0	63.0	HRC 62.8	701

Appendix C. CNC Programs for Thread Holes

Aluminum 6061 T6

```
%
O1( ALUMINUM 6061 T6.NCF )
N1( FORMAT: HURCO ULTMX 4 [CTD] NMK32.16.3.PST )
N2( 1/12/07 AT  3:27 PM )
N3( OUTPUT IN ABSOLUTE INCHES )
N4( PARTS PROGRAMMED: 1 )
N5( FIRST TOOL NOT IN SPINDLE )
N6G17
N7G00
N8G70
N9G90
N10M25
N11T1M06
N12M25
N13( OPERATION 1: HOLES )
N14( WORKGROUP )
N15( TOOL 1: .0781 CENTER DRILL )
N16S3700M03
N17X-.164Y-.8
N18Z.1
N19G81X-.164Y-.8Z.13F6.85
N20G00G80Z.1
N21( OPERATION 2: HOLES )
N22( WORKGROUP )
N23( TOOL 1: .0781 CENTER DRILL )
N24G00
N25X-.4163Y-.5
N26Z.1
N27G81X-.4163Y-.5Z.2F6.85
N28G00G80
N29Z.1
N30X-.7825
N31G81X-.7825Y-.5Z.2F6.85
N32G00G80
N33Z.1
N34X-1.1467
```

```
N35G81X-1.1467Y-.5Z.2F6.85
N36G00G80
N37Z.1
N38X-1.5089
N39G81X-1.5089Y-.5Z.2F6.85
N40G00G80
N41Z.1
N42X-1.8691
N43G81X-1.8691Y-.5Z.2F6.85
N44G00G80
N45Z.1
N46X-2.2274
N47G81X-2.2274Y-.5Z.2F6.85
N48G00G80
N49Z.1
N50X-2.5837
N51G81X-2.5837Y-.5Z.2F6.85
N52G00G80Z.1M09
N53M25
N54M01
N55G00
N56T2M06
N57M25
N58( OPERATION 3: HOLES )
N59( WORKGROUP )
N60( TOOL 2: .125 DRILL )
N61S3700M03
N62X-.4163Y-.5
N63Z.1
N64G83X-.4163Y-.5Z1.1876Z.05F4.28
N65G00G80
N66Z.1
N67X-.7825
N68G83X-.7825Y-.5Z1.1876Z.05F4.28
N69G00G80
N70Z.1
N71X-1.1467
N72G83X-1.1467Y-.5Z1.1876Z.05F4.28
N73G00G80
N74Z.1
N75X-1.5089
N76G83X-1.5089Y-.5Z1.1876Z.05F4.28
N77G00G80
N78Z.1
N79X-1.8691
N80G83X-1.8691Y-.5Z1.1876Z.05F4.28
```

```
N81G00G80
N82Z.1
N83X-2.2274
N84G83X-2.2274Y-.5Z1.1876Z.05F4.28
N85G00G80
N86Z.1
N87X-2.5837
N88G83X-2.5837Y-.5Z1.1876Z.05F4.28
N89G00G80Z.1M09
N90M25
N91M05
N92M02
E
N93( FILE LENGTH: 1562 CHARACTERS )
N94( FILE LENGTH: 13.33 FEET )
N95( FILE LENGTH: 4.14 METERS )
```

Yellow Brass SS360

```
%
O1( YELLOW BRASS SS360.NCF )
N1( FORMAT: HURCO ULTMX 4 [CTD] NMK32.16.3.PST )
N2( 12/15/06 AT  3:12 PM )
N3( OUTPUT IN ABSOLUTE INCHES )
N4( PARTS PROGRAMMED: 1 )
N5( FIRST TOOL NOT IN SPINDLE )
N6G17
N7G00
N8G70
N9G90
N10M25
N11T1M06
N12M25
N13( OPERATION 1: HOLES )
N14( WORKGROUP )
N15( TOOL 1: .0781 CENTER DRILL )
N16S2445M03
N17X-.164Y-.8
N18Z.1
N19G81X-.164Y-.8Z.13F2.44
N20G00G80Z.1
N21( OPERATION 2: HOLES )
N22( WORKGROUP )
N23( TOOL 1: .0781 CENTER DRILL )
```

```
N24G00
N25X-.4163Y-.5
N26Z.1
N27G81X-.4163Y-.5Z.2F2.44
N28G00G80
N29Z.1
N30X-.7825
N31G81X-.7825Y-.5Z.2F2.44
N32G00G80
N33Z.1
N34X-1.1467
N35G81X-1.1467Y-.5Z.2F2.44
N36G00G80
N37Z.1
N38X-1.5089
N39G81X-1.5089Y-.5Z.2F2.44
N40G00G80
N41Z.1
N42X-1.8691
N43G81X-1.8691Y-.5Z.2F2.44
N44G00G80
N45Z.1
N46X-2.2274
N47G81X-2.2274Y-.5Z.2F2.44
N48G00G80
N49Z.1
N50X-2.5837
N51G81X-2.5837Y-.5Z.2F2.44
N52G00G80Z.1M09
N53M25
N54M01
N55G00
N56T2M06
N57M25
N58( OPERATION 3: HOLES )
N59( WORKGROUP )
N60( TOOL 2: .125 DRILL )
N61S1528M03
N62X-.4163Y-.5
N63Z.1
N64G83X-.4163Y-.5Z1.1876Z.125F1.53
N65G00G80
N66Z.1
N67X-.7825
N68G83X-.7825Y-.5Z1.1876Z.125F1.53
N69G00G80
```

```
N70Z.1
N71X-1.1467
N72G83X-1.1467Y-.5Z1.1876Z.125F1.53
N73G00G80
N74Z.1
N75X-1.5089
N76G83X-1.5089Y-.5Z1.1876Z.125F1.53
N77G00G80
N78Z.1
N79X-1.8691
N80G83X-1.8691Y-.5Z1.1876Z.125F1.53
N81G00G80
N82Z.1
N83X-2.2274
N84G83X-2.2274Y-.5Z1.1876Z.125F1.53
N85G00G80
N86Z.1
N87X-2.5837
N88G83X-2.5837Y-.5Z1.1876Z.125F1.53
N89G00G80Z.1M09
N90M25
N91M05
N92M02
E
N93( FILE LENGTH: 1572 CHARACTERS )
N94( FILE LENGTH: 13.41 FEET )
N95( FILE LENGTH: 4.17 METERS )
```

<u>420 Stainless Steel</u>

```
%
O1( STAINLESS STEEL.NCF )
N1( FORMAT: HURCO ULTMX 4 [CTD] NMK32.16.3.PST )
N2( 12/15/06 AT  3:11 PM )
N3( OUTPUT IN ABSOLUTE INCHES )
N4( PARTS PROGRAMMED: 1 )
N5( FIRST TOOL NOT IN SPINDLE )
N6G17
N7G00
N8G70
N9G90
N10M25
N11T1M06
N12M25
```

```
N13( OPERATION 1: HOLES )
N14( WORKGROUP )
N15( TOOL 1: .0781 CENTER DRILL )
N16S2445M03
N17X-.164Y-.8
N18Z.1
N19G81X-.164Y-.8Z.13F2.44
N20G00G80Z.1
N21( OPERATION 2: HOLES )
N22( WORKGROUP )
N23( TOOL 1: .0781 CENTER DRILL )
N24G00
N25X-.4163Y-.5
N26Z.1
N27G81X-.4163Y-.5Z.2F2.44
N28G00G80
N29Z.1
N30X-.7825
N31G81X-.7825Y-.5Z.2F2.44
N32G00G80
N33Z.1
N34X-1.1467
N35G81X-1.1467Y-.5Z.2F2.44
N36G00G80
N37Z.1
N38X-1.5089
N39G81X-1.5089Y-.5Z.2F2.44
N40G00G80
N41Z.1
N42X-1.8691
N43G81X-1.8691Y-.5Z.2F2.44
N44G00G80
N45Z.1
N46X-2.2274
N47G81X-2.2274Y-.5Z.2F2.44
N48G00G80
N49Z.1
N50X-2.5837
N51G81X-2.5837Y-.5Z.2F2.44
N52G00G80Z.1M09
N53M25
N54M01
N55G00
N56T2M06
N57M25
N58( OPERATION 3: HOLES )
```

```
N59( WORKGROUP )
N60( TOOL 2: .125 DRILL )
N61S1528M03
N62X-.4163Y-.5
N63Z.1
N64G83X-.4163Y-.5Z1.1876Z.125F1.53
N65G00G80
N66Z.1
N67X-.7825
N68G83X-.7825Y-.5Z1.1876Z.125F1.53
N69G00G80
N70Z.1
N71X-1.1467
N72G83X-1.1467Y-.5Z1.1876Z.125F1.53
N73G00G80
N74Z.1
N75X-1.5089
N76G83X-1.5089Y-.5Z1.1876Z.125F1.53
N77G00G80
N78Z.1
N79X-1.8691
N80G83X-1.8691Y-.5Z1.1876Z.125F1.53
N81G00G80
N82Z.1
N83X-2.2274
N84G83X-2.2274Y-.5Z1.1876Z.125F1.53
N85G00G80
N86Z.1
N87X-2.5837
N88G83X-2.5837Y-.5Z1.1876Z.125F1.53
N89G00G80Z.1M09
N90M25
N91M05
N92M02
E
N93( FILE LENGTH: 1569 CHARACTERS )
N94( FILE LENGTH: 13.38 FEET )
N95( FILE LENGTH: 4.16 METERS )
```

D2 Tool Steel

```
%
O1( D2 TOOL STEEL.NCF )
N1( FORMAT: HURCO ULTMX 4 [CTD] NMK32.16.3.PST )
```

```
N2( 12/15/06 AT 12:37 PM )
N3( OUTPUT IN ABSOLUTE INCHES )
N4( PARTS PROGRAMMED: 1 )
N5( FIRST TOOL NOT IN SPINDLE )
N6G17
N7G00
N8G70
N9G90
N10M25
N11T1M06
N12M25
N13( OPERATION 1: HOLES )
N14( WORKGROUP )
N15( TOOL 1: .0781 CENTER DRILL )
N16S1467M03
N17X-.164Y-.8
N18Z.1
N19G81X-.164Y-.8Z.13F1.47
N20G00G80Z.1
N21( OPERATION 2: HOLES )
N22( WORKGROUP )
N23( TOOL 1: .0781 CENTER DRILL )
N24G00
N25X-.4163Y-.5
N26Z.1
N27G81X-.4163Y-.5Z.2F1.47
N28G00G80
N29Z.1
N30X-.7825
N31G81X-.7825Y-.5Z.2F1.47
N32G00G80
N33Z.1
N34X-1.1467
N35G81X-1.1467Y-.5Z.2F1.47
N36G00G80
N37Z.1
N38X-1.5089
N39G81X-1.5089Y-.5Z.2F1.47
N40G00G80
N41Z.1
N42X-1.8691
N43G81X-1.8691Y-.5Z.2F1.47
N44G00G80
N45Z.1
N46X-2.2274
N47G81X-2.2274Y-.5Z.2F1.47
```

```
N48G00G80
N49Z.1
N50X-2.5837
N51G81X-2.5837Y-.5Z.2F1.47
N52G00G80Z.1M09
N53M25
N54M01
N55G00
N56T2M06
N57M25
N58( OPERATION 3: HOLES )
N59( WORKGROUP )
N60( TOOL 2: .125 DRILL )
N61S917M03
N62X-.4163Y-.5
N63Z.1
N64G83X-.4163Y-.5Z1.1876Z.125F.92
N65G00G80
N66Z.1
N67X-.7825
N68G83X-.7825Y-.5Z1.1876Z.125F.92
N69G00G80
N70Z.1
N71X-1.1467
N72G83X-1.1467Y-.5Z1.1876Z.125F.92
N73G00G80
N74Z.1
N75X-1.5089
N76G83X-1.5089Y-.5Z1.1876Z.125F.92
N77G00G80
N78Z.1
N79X-1.8691
N80G83X-1.8691Y-.5Z1.1876Z.125F.92
N81G00G80
N82Z.1
N83X-2.2274
N84G83X-2.2274Y-.5Z1.1876Z.125F.92
N85G00G80
N86Z.1
N87X-2.5837
N88G83X-2.5837Y-.5Z1.1876Z.125F.92
N89G00G80Z.1M09
N90M25
N91M05
N92M02
E
```

N93(FILE LENGTH: 1559 CHARACTERS)
N94(FILE LENGTH: 13.30 FEET)
N95(FILE LENGTH: 4.14 METERS)

Appendix D. Machine Settings for the Sodick AQ325L

Table D. 1 - Sodick AQ325L Machine Settings for Aluminum 6061 T6

Roughing, No Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0047	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0047	0	000	0000	025	100	100	055
Roughing, One Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0047	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0047	0	000	0000	025	100	100	055
C002	002	023	2215	000	750	053	8	6028	0	000	0000	025	100	100	012
Roughing, Three Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0047	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0047	0	000	0000	025	100	100	055
C002	002	023	2215	000	750	053	8	6028	0	000	0000	025	100	100	012
C903	000	001	1015	000	000	030	6	7024	0	008	0000	025	100	100	012
C904	000	001	1015	000	000	018	2	7028	0	009	0000	025	100	060	012

Table D. 2 - Sodick AQ325L Machine Settings for Yellow Brass SS360

Roughing, No Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0028	0	000	0000	025	100	100	055
Roughing, One Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0028	0	000	0000	025	100	100	055
C002	003	023	2215	000	750	053	8	6016	0	000	0000	025	100	100	012
Roughing, Three Finishing															
	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	014	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	014	2215	000	251	035	8	0028	0	000	0000	025	100	100	055
C002	003	023	2215	000	750	053	8	6016	0	000	0000	025	100	100	012
C903	000	001	1015	000	000	030	7	7020	0	008	0000	025	100	100	012
C904	000	001	1015	000	000	018	2	7024	0	009	0000	025	100	060	012

Table D. 3 - Sodick AQ325L Machine Settings for 420 Stainless Steel, D2 Tool Steel at 25 - 30 RC, and D2 Tool Steel at 60 - 65 RC

Roughing, No Finishing

	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	013	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	013	2215	000	251	028	8	0028	0	000	0000	025	100	100	055

Roughing, One Finishing

	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	013	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	013	2215	000	251	028	8	0028	0	000	0000	025	100	100	055
C002	002	023	2215	000	750	053	8	6020	0	000	0000	025	100	100	012

Roughing, Three Finishing

	ON	OFF	IP	HRP	MAO	SV	V	SF	C	PIK	CTRL	WK	WT	WS	WP
C000	009	013	2215	000	250	040	8	0028	0	000	0000	025	100	100	045
C001	011	013	2215	000	251	028	8	0028	0	000	0000	025	100	100	055
C002	002	023	2215	000	750	053	8	6020	0	000	0000	025	100	100	012
C903	000	001	1015	000	000	030	7	7020	0	008	0000	025	100	100	012
C904	000	001	1015	000	000	018	2	7024	0	009	0000	025	100	060	012

Appendix E. CNC Programs for Sodick AQ325L

Roughing with No Finishing Passes

```
"G90;"
"G54;"
"G92X0Y0(1ST POCKET);"
"G29;"
"T82;"
"T96;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y.3661(2ND POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y.7303(3RD POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
```

```
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
"Y.7303;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y1.0925(4TH POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y1.4528(5TH POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y1.8110(6TH POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.6339;"
"X-.1181;"
```

```
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"M00;"
"G40X.0681;"
"T90;"
"G00X0Y2.1673(7TH POCKET);"
"G29;"
"T91;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"M00;"
"G40X.0681;"
"T85;"
"T87;"
"T97;"
"T83;"
"T90;"
"M02;"
```

Roughing with One Finishing Pass

```
"G90;"
"G54;"
"G92X0Y0(1ST POCKET);"
"G29;"
"T82;"
"T96;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"M00;"
```

```
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"G40X.0681;"
"T90;"
"G00X0Y.3661(2ND POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"G40X.0681;"
"T90;"
"G00X0Y.7303(3RD POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
```

```
"Y.7303;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
"Y.7303;"
"G40X.0681;"
"T90;"
"G00X0Y1.0925(4TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"G40X.0681;"
"T90;"
"G00X0Y1.4528(5TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.2756;"
"X-.1181;"
```

```
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"G40X.0681;"
"T90;"
"G00X0Y1.8110(6TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"G40X.0681;"
"T90;"
"G00X0Y2.1673(7TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
```

```
"G01Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"G40X.0681;"
"T87;"
"T97;"
"T83;"
"T90;"
"M02;"
```

Roughing with Three Finishing Passes

```
"G90;"
"G54;"
"G92X0Y0(1ST POCKET);"
"G29;"
"T82;"
"T96;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
```

```
"Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y-.1772;"
"X-.1181;"
"Y.1772;"
"X.1181;"
"Y0;"
"G40X.0681;"
"T90;"
"G00X0Y.3661(2ND POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"G40X.0681;"
```

```
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y.1890;"
"X-.1181;"
"Y.5433;"
"X.1181;"
"Y.3661;"
"G40X.0681;"
"T90;"
"G00X0Y.7303(3RD POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
"Y.7303;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
"Y.7303;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
```

```
"Y.7303;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y.5531;"
"X-.1181;"
"Y.9075;"
"X.1181;"
"Y.7303;"
"G40X.0681;"
"T90;"
"G00X0Y1.0925(4TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y.9154;"
"X-.1181;"
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y.9154;"
"X-.1181;"
```

```
"Y1.2697;"
"X.1181;"
"Y1.0925;"
"G40X.0681;"
"T90;"
"G00X0Y1.4528(5TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y1.2756;"
"X-.1181;"
"Y1.6299;"
"X.1181;"
"Y1.4528;"
"G40X.0681;"
"T90;"
"G00X0Y1.8110(6TH POCKET);"
```

```
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y1.6339;"
"X-.1181;"
"Y1.9882;"
"X.1181;"
"Y1.8110;"
"G40X.0681;"
"T90;"
"G00X0Y2.1673(7TH POCKET);"
"G29;"
"T91;"
"T84;"
"C000H001(LEAD IN CONDITIONS H&C);"
"G01G42X.1181(WIRE OFFSET RIGHT);"
"C001(ROUGH PASS CONDITIONS H&C);"
```

```
"G01Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"M00;"
"T85;"
"G40X.0681;"
"C002H002(FIRST FINISH PASS);"
"G01G42X.1181;"
"Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"G40X.0681;"
"C903H003(SECOND FINISH PASS);"
"G01G42X.1181;"
"Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"G40X.0681;"
"C904H004(THIRD FINISH PASS);"
"G01G42X.1181;"
"Y1.9902;"
"X-.1181;"
"Y2.3445;"
"X.1181;"
"Y2.1673;"
"G40X.0681;"
"T87;"
"T97;"
"T83;"
"T90;"
"M02;"
```

Appendix F. CNC Program for CMM

```
PART NAME  : EDM_2
REV NUMBER :
SER NUMBER :
STATS COUNT : 1

STARTUP    =ALIGNMENT/START,RECALL:, LIST= YES
           ALIGNMENT/END
           MODE/MANUAL
           LOADPROBE/EDM
           TIP/T1A0B0, SHANKIJK=0, 0, 1, ANGLE=0
           FORMAT/TEXT,OPTIONS, ,HEADINGS,SYMBOLS, ;MEAS, , , , , ,
PLN1       =FEAT/PLANE,RECT,TRIANGLE
           THEO/185.453,76.967,-513.211,0.0005534,0.000334,0.9999998
           ACTL/185.453,76.967,-513.211,0.0005534,0.000334,0.9999998
           MEAS/PLANE,3
           HIT/BASIC,NORMAL,212.892,81.722,-
           513.227,0.0005534,0.000334,0.9999998,212.892,81.722,-513.227,USE THEO =
           YES
           HIT/BASIC,NORMAL,188.219,66.047,
           513.209,0.0005534,0.000334,0.9999998,188.219,66.047,-513.209,USE THEO =
           YES
           HIT/BASIC,NORMAL,155.248,83.133,-
           513.196,0.0005534,0.000334,0.9999998,155.248,83.133,-513.196,USE THEO =
           YES
           ENDMEAS/
LIN1       =FEAT/LINE,RECT,UNBND
           THEO/155.571,88.218,-515.812,0.9999104,0.013383,0
           ACTL/155.571,88.218,-515.812,0.9999104,0.013383,0
           MEAS/LINE,2,WORKPLANE
           HIT/BASIC,NORMAL,155.571,88.218,-515.812,-
           0.013383,0.9999104,0,155.571,88.218,-515.812,USE THEO = YES
           HIT/BASIC,NORMAL,216.38,89.032,-515.804,-
           0.013383,0.9999104,0,216.38,89.032,-515.804,USE THEO = YES
           ENDMEAS/
MANPNT1    =FEAT/POINT,RECT
           THEO/222.392,76.163,-515.582,1,0,0
           ACTL/222.392,76.163,-515.582,1,0,0
           MEAS/POINT,1
```

```
          HIT/BASIC,NORMAL,222.392,76.163,-515.582,1,0,0,222.392,76.163,-
          515.582,USE THEO = YES
          ENDMEAS/
A2          =ALIGNMENT/START,RECALL:STARTUP, LIST= YES
          ALIGNMENT/LEVEL,ZPLUS,PLN1
          ALIGNMENT/ROTATE,XPLUS,TO,LIN1,ABOUT,ZPLUS
          ALIGNMENT/TRANS,XAXIS,MANPNT1
          ALIGNMENT/TRANS,YAXIS,LIN1
          ALIGNMENT/TRANS,ZAXIS,PLN1
          ALIGNMENT/END
          WORKPLANE/ZPLUS
          CLEARP/ZPLUS,6,ZPLUS,0
          MODE/DCC
          MOVE/CLEARPLANE
PLN2        =FEAT/PLANE,RECT,TRIANGLE
          THEO/-36.926,-11.651,0,0,0,1
          ACTL/-36.97,-11.619,-0.265,-0.0002164,-0.0097751,0.9999522
          MEAS/PLANE,3
          HIT/BASIC,NORMAL,-9.426,-7.264,0,0,0,1,-9.473,-7.231,-0.216,USE THEO =
          YES
          HIT/BASIC,NORMAL,-34.307,-22.607,0,0,0,1,-34.348,-22.572,-0.371,USE
          THEO = YES
          HIT/BASIC,NORMAL,-67.046,-5.081,0,0,0,1,-67.088,-5.056,-0.207,USE THEO
          = YES
          ENDMEAS/
          MOVE/CLEARPLANE
LIN2        =FEAT/LINE,RECT,UNBND
          THEO/-66.653,0,-2.614,0.9999998,0,0.0005578
          ACTL/-66.642,-0.167,-2.643,0.9999995,-0.0009527,0
          MEAS/LINE,2,WORKPLANE
          HIT/BASIC,NORMAL,-66.653,0,-2.614,-0.0000002,0.9999999,0.0003266,-
          66.642,-0.167,-2.643,USE THEO = YES
          HIT/BASIC,NORMAL,-5.84,0,-2.572,-0.0000002,0.9999999,0.0003266,-5.83,-
          0.225,-2.602,USE THEO = YES
          ENDMEAS/
          MOVE/CLEARPLANE
AUTOPNT2   =FEAT/POINT,RECT
          THEO/0,-12.948,-2.351,0.9999103,-0.013383,0.0005534
          ACTL/-0.143,-12.937,-2.355,0.9999103,-0.013383,0.0005534
          MEAS/POINT,1
          HIT/BASIC,NORMAL,0,-12.948,-2.351,0.9999103,-0.013383,0.0005534,-
          0.143,-12.937,-2.355,USE THEO = YES
          ENDMEAS/
A3          =ALIGNMENT/START,RECALL:A2, LIST= YES
          ALIGNMENT/LEVEL,ZPLUS,PLN2
          ALIGNMENT/ROTATE,XPLUS,TO,LIN2,ABOUT,ZPLUS
```

```
            ALIGNMENT/TRANS,XAXIS,AUTOPNT2
            ALIGNMENT/TRANS,YAXIS,LIN2
            ALIGNMENT/TRANS,ZAXIS,PLN2
            ALIGNMENT/END
            PREHIT/ 1.5
            RETRACT/ 1.5
            TOUCHSPEED/ 1
            MOVE/CLEARPLANE
C1          =COMMENT/INPUT,YES,'Part Number ='
C2          =COMMENT/INPUT,YES,'Top or Bottum?'
V1          =LOOP/START, ID = YES, NUMBER = 6, START = 1, SKIP = ,
             OFFSET: XAXIS = -9, YAXIS = 0, ZAXIS = 0, ANGLE = 0
PNT1        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15,-11,-0.75,1,0,0
            ACTL/-16.287,-11.044,-0.75,1,0,0
            TARG/-15,-11,-0.75,1,0,0
PNT2        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15,-12.7,-0.75,1,0,0
            ACTL/-16.077,-12.693,-0.752,1,0,0
            TARG/-15,-12.7,-0.75,1,0,0
PNT3        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15,-14.4,-0.75,1,0,0
            ACTL/-16.14,-14.39,-0.752,1,0,0
            TARG/-15,-14.4,-0.75,1,0,0
            MOVE/CLEARPLANE
PNT4        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15.3,-14.4,-0.75,-1,0,0
            ACTL/-16.18,-14.377,-0.778,-1,0,0
            TARG/-15.3,-14.4,-0.75,-1,0,0
PNT5        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15.3,-12.7,-0.75,-1,0,0
            ACTL/-16.159,-12.683,-0.78,-1,0,0
            TARG/-15.3,-12.7,-0.75,-1,0,0
PNT6        =AUTO/VECTOR POINT,SHOWALLPARAMS = NO
            THEO/-15.3,-11,-0.75,-1,0,0
            ACTL/-16.114,-11.044,-0.768,-1,0,0
            TARG/-15.3,-11,-0.75,-1,0,0
DIM DIST1= 2D DISTANCE FROM POINT PNT1 TO POINT PNT6    (CENTER TO
CENTER), NO_RADIUS  UNITS=MM ,$
GRAPH=OFF  TEXT=OFF  MULT=10.00  OUTPUT=BOTH
AX    MEAS
DIM DIST2= 2D DISTANCE FROM POINT PNT2 TO POINT PNT5    (CENTER TO
CENTER), NO_RADIUS  UNITS=MM ,$
GRAPH=OFF  TEXT=OFF  MULT=10.00  OUTPUT=BOTH
AX    MEAS
```

```
DIM DIST3= 2D DISTANCE FROM POINT PNT3 TO POINT PNT4     (CENTER TO
CENTER), NO_RADIUS  UNITS=MM ,$
GRAPH=OFF  TEXT=OFF  MULT=10.00  OUTPUT=BOTH
AX    MEAS
          LOOP/END
          MOVE/CLEARPLANE
```

Appendix G. Thin-wall Section Thickness Measurements and Defects

Table G. 1 - Aluminum 6061 T6 Thin-wall Section Thickness Measurements and Defects

Part #	Web Thickness	Measurements of Web Thicknesses (mm)						Notes	
		1	2	3	4	5	6	Top	Bottom
1	0.30	0.264	0.275	0.264	0.281	0.287	0.278		
	0.25	0.223	0.218	0.226	0.230	0.231	0.235		
	0.20	0.168	0.174	0.181	0.182	0.182	0.185		Notch
	0.15	0.130	0.127	0.128	Notch	Notch	Bent		Bent/Notch
	0.10	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
2	0.30	0.260	0.262	0.269	0.278	0.271	0.269		
	0.25	0.215	0.219	0.215	0.223	0.225	0.221		
	0.20	0.163	0.163	0.161	Notch	0.182	0.177		Notch
	0.15	0.118	0.113	0.119	Notch	Notch	0.146	Bent	Bent/Notch
	0.10	Bent	Depleted	Depleted	Depleted	Depleted	Depleted	Bent/Notch	Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
3	0.30	0.270	0.280	0.266	0.283	0.284	0.278		
	0.25	0.224	0.228	0.225	0.234	0.237	0.231		
	0.20	0.176	0.169	0.172	0.191	0.183	0.188		Bent
	0.15	0.133	0.118	0.132	Notch	Notch	0.152	Bent	Bent/Notch
	0.10	0.054	Notch	Notch	Notch	Notch	Notch	Bent/Notch	Depleted
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
4	0.30	0.283	0.279	0.283	0.283	0.291	0.290		
	0.25	0.229	0.230	0.235	0.231	0.232	0.233		
	0.20	0.179	0.180	0.182	0.190	0.195	0.193		
	0.15	0.136	0.135	0.143	0.163	0.161	0.161		Bent/Notch
	0.10	0.105	0.108	0.118	Notch	0.147	0.144	Bent	Bent/Notch
	0.05	0.049	Notch	Notch	Depleted	Depleted	Depleted	Notch	Depleted
5	0.30	0.291	0.292	0.290	0.290	0.297	0.292		
	0.25	0.240	0.243	0.244	0.242	0.247	0.245		
	0.20	0.190	0.194	0.196	0.208	0.209	0.202		
	0.15	0.141	0.143	0.151	Bent	0.178	0.170		Bent/Notch
	0.10	0.110	0.114	0.120	Notch	Notch	Bent		Bent/Notch
	0.05	0.057	Notch	Notch	Depleted	Depleted	Depleted	Notch	Depleted

6	0.30	0.296	0.293	0.294	0.291	0.298	0.294		
	0.25	0.245	0.248	0.247	0.242	0.249	0.248		
	0.20	0.197	0.200	0.199	0.202	0.207	0.204		
	0.15	0.148	0.146	0.155	0.179	0.177	0.172		Bent/Notch
	0.10	0.118	0.117	0.123	Depleted	Bent	0.162		Bent/Notch
	0.05	0.060	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
7	0.30	0.311	0.309	0.309	0.309	0.310	0.310		
	0.25	0.259	0.259	0.258	0.260	0.260	0.260		
	0.20	0.212	0.212	0.210	0.215	0.214	0.213		
	0.15	0.161	0.158	0.159	0.177	0.171	0.165		
	0.10	0.111	0.098	0.111	0.172	0.157	0.144		Bent/Notch
	0.05	0.106	0.111	0.111	0.106	0.111	0.167	Bent	Bent/Notch
8	0.30	0.308	0.306	0.306	0.309	0.302	0.294		
	0.25	0.256	0.256	0.255	0.246	0.246	0.247		
	0.20	0.207	0.206	0.205	0.196	0.193	0.189		
	0.15	0.157	0.154	0.154	0.171	0.161	0.153		
	0.10	0.105	0.093	0.108	Bent	0.146	0.131		Bent/Notch
	0.05	0.100	0.097	0.110	Notch	Notch	Bent	Bent	Bent/Notch
9	0.30	0.306	0.306	0.305	0.299	0.299	0.299		
	0.25	0.253	0.253	0.254	0.245	0.245	0.243		
	0.20	0.208	0.211	0.212	0.212	0.205	0.199		
	0.15	0.154	0.155	0.159	0.172	0.164	0.156		
	0.10	0.105	0.090	0.107	0.171	0.150	Notch		Bent/Notch
	0.05	0.099	0.102	0.103	Bent	Notch	Bent	Bent	Bent/Notch

Table G. 2 - Yellow Brass SS360 Thin-wall Section Thickness Measurements and Defects

Part #	Web Thickness	Measurements of Web Thicknesses (mm)						Notes	
		1	2	3	4	5	6	Top	Bottom
10	0.30	0.283	0.279	0.275	0.298	0.295	0.291		
	0.25	0.222	0.222	0.226	0.244	0.241	0.244		
	0.20	0.173	0.169	0.177	0.189	0.186	0.190		
	0.15	0.123	0.123	0.125	0.136	0.134	0.138		Bent
	0.10	0.093	0.083	0.103	Bent	Notch	0.112	Bent	Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
11	0.30	0.290	0.287	0.293	0.302	0.300	0.296		
	0.25	0.236	0.237	0.239	0.248	0.252	0.248		
	0.20	0.188	0.189	0.195	0.204	0.197	0.203		
	0.15	0.139	0.134	0.141	0.150	0.147	0.148		Bent
	0.10	0.101	0.091	0.108	0.092	Bent	0.112	Bent	Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted

12	0.30	0.281	0.276	0.280	0.291	0.285	0.288		
	0.25	0.228	0.230	0.228	0.237	0.233	0.245		
	0.20	0.179	0.172	0.178	0.187	0.188	0.188		
	0.15	0.133	0.125	0.128	0.132	0.130	0.142		Bent
	0.10	0.088	0.082	0.100	0.091	0.094	0.099	Bent	Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
13	0.30	0.277	0.284	0.277	0.284	0.285	0.280		
	0.25	0.230	0.230	0.232	0.232	0.231	0.232		
	0.20	0.178	0.184	0.185	0.190	0.190	0.187		
	0.15	0.129	0.124	0.135	0.150	0.143	0.142		
	0.10	0.114	0.115	0.107	0.127	0.125	0.123	Bent	Bent
	0.05	0.051	0.061	Bent	0.053	Notch	Bent	Bent/Notch	Bent/Notch
14	0.30	0.278	0.281	0.281	0.281	0.286	0.285		
	0.25	0.228	0.231	0.234	0.234	0.237	0.235		
	0.20	0.181	0.182	0.183	0.186	0.186	0.187		
	0.15	0.129	0.129	0.139	0.151	0.149	0.148		
	0.10	0.102	0.119	0.110	0.120	0.123	0.130	Bent	Bent
	0.05	0.137	Bent	0.106	Notch	Notch	Bent	Bent/Notch	Bent/Notch
15	0.30	0.280	0.280	0.282	0.279	0.282	0.280		
	0.25	0.226	0.231	0.229	0.231	0.231	0.231		
	0.20	0.180	0.181	0.183	0.184	0.187	0.186		
	0.15	0.128	0.130	0.140	0.148	0.144	0.142		
	0.10	0.107	0.118	0.105	0.139	0.131	0.126	Bent	Bent
	0.05	0.091	0.045	0.189	Notch	Notch	0.076	Bent/Notch	Bent/Notch
16	0.30	0.280	0.281	0.282	0.289	0.290	0.290		
	0.25	0.230	0.231	0.231	0.237	0.240	0.239		
	0.20	0.180	0.180	0.182	0.192	0.190	0.192		
	0.15	0.129	0.120	0.133	0.149	0.143	0.145		
	0.10	0.090	0.093	0.083	0.141	0.137	0.117	Bent	Bent
	0.05	0.089	0.083	0.123	Notch	Notch	Notch	Bent	Bent/Notch
17	0.30	0.276	0.277	0.276	0.280	0.283	0.283		
	0.25	0.223	0.226	0.227	0.228	0.228	0.230		
	0.20	0.175	0.176	0.179	0.181	0.179	0.182		
	0.15	0.122	0.115	0.128	0.135	0.128	0.134		
	0.10	0.086	0.080	0.077	0.134	0.124	0.102	Bent	Bent
	0.05	0.083	0.071	0.117	0.115	0.104	0.100	Bent	Bent/Notch
18	0.30	0.295	0.295	0.293	0.297	0.297	0.297		
	0.25	0.241	0.243	0.241	0.245	0.245	0.245		
	0.20	0.194	0.195	0.196	0.201	0.201	0.202		
	0.15	0.140	0.135	0.151	0.159	0.149	0.154		
	0.10	0.107	0.101	0.108	0.144	0.141	0.129	Bent	Bent
	0.05	0.089	0.082	0.092	0.096	0.088	0.101	Bent	Bent

Table G. 3 - 420 Stainless Steel Thin-wall Section Thickness Measurements and Defects

Part #	Web Thickness	Measurements of Web Thicknesses (mm)						Notes	
		1	2	3	4	5	6	Top	Bottom
19	0.30	0.281	0.281	0.283	0.285	0.281	0.283		
	0.25	0.235	0.230	0.234	0.235	0.226	0.235		
	0.20	0.185	0.185	0.182	0.189	0.184	0.189		
	0.15	0.133	0.132	0.132	0.136	0.132	0.140		
	0.10	0.088	0.079	0.085	Notch	Notch	0.097		Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
20	0.30	0.283	0.282	0.279	0.281	0.275	0.281		
	0.25	0.230	0.227	0.232	0.236	0.233	0.231		
	0.20	0.180	0.182	0.187	0.184	0.179	0.183		
	0.15	0.135	0.132	0.128	0.130	0.130	0.134		
	0.10	0.087	0.078	0.087	0.087	Notch	0.096		Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
21	0.30	0.282	0.286	0.278	0.279	0.288	0.281		
	0.25	0.232	0.231	0.230	0.237	0.227	0.229		
	0.20	0.185	0.181	0.186	0.185	0.183	0.187		
	0.15	0.128	0.123	0.136	0.130	0.123	0.133		Bent
	0.10	0.079	0.081	0.083	Notch	Bent	0.095		Bent/Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
22	0.30	0.296	0.300	0.295	0.297	0.300	0.300		
	0.25	0.246	0.244	0.246	0.243	0.250	0.244		
	0.20	0.193	0.197	0.200	0.198	0.200	0.198		
	0.15	0.144	0.142	0.147	0.147	0.145	0.148		
	0.10	0.094	0.080	0.099	0.118	0.110	0.108		Bent
	0.05	Notch	Notch	Bent	Notch	Bent	0.082	Bent/Notch	Bent/Notch
23	0.30	0.297	0.293	0.291	0.292	0.294	0.293		
	0.25	0.238	0.238	0.243	0.242	0.247	0.239		
	0.20	0.195	0.194	0.195	0.200	0.195	0.197		
	0.15	0.141	0.136	0.145	0.149	0.147	0.150		
	0.10	0.092	0.078	0.092	0.116	0.110	0.107		Bent
	0.05	0.021	Notch	Bent	Notch	Notch	0.066	Bent/Notch	Bent/Notch
24	0.30	0.287	0.286	0.281	0.283	0.284	0.285		
	0.25	0.233	0.231	0.233	0.235	0.229	0.234		
	0.20	0.181	0.183	0.184	0.184	0.187	0.187		
	0.15	0.130	0.132	0.136	0.136	0.130	0.136		
	0.10	0.076	0.072	0.084	0.108	0.100	0.105		
	0.05	Depleted	Depleted	0.057	Bent	Depleted	0.052	Bent/Notch	Bent/Notch
25	0.30	0.301	0.299	0.299	0.301	0.300	0.300		
	0.25	0.249	0.247	0.248	0.250	0.249	0.249		
	0.20	0.202	0.197	0.199	0.202	0.201	0.201		
	0.15	0.151	0.145	0.146	0.154	0.149	0.151		
	0.10	0.097	0.082	0.097	0.110	0.102	0.104		
	0.05	Notch	Notch	0.042	Notch	0.044	0.064	Notch	Bent/Notch

26	0.30	0.303	0.301	0.301	0.300	0.302	0.303		
	0.25	0.251	0.248	0.250	0.251	0.250	0.253		
	0.20	0.204	0.199	0.201	0.204	0.204	0.205		
	0.15	0.153	0.148	0.150	0.156	0.153	0.157		
	0.10	0.100	0.085	0.096	0.114	0.107	0.109		
	0.05	Notch	Notch	0.046	Notch	0.072	0.069	Notch	Bent/Notch
27	0.30	0.304	0.302	0.301	0.305	0.303	0.305		
	0.25	0.245	0.243	0.244	0.247	0.245	0.247		
	0.20	0.200	0.197	0.195	0.201	0.200	0.200		
	0.15	0.153	0.147	0.149	0.158	0.153	0.154		
	0.10	0.097	0.087	0.098	0.117	0.108	0.108		
	0.05	Notch	Notch	0.049	Bent	0.058	0.066	Notch	Bent/Notch

Table G. 4 - D2 Tool Steel at 25 - 30 RC Thin-wall Section Thickness Measurements and Defects

Part #	Web Thickness	Measurements of Web Thicknesses (mm)						Notes	
		1	2	3	4	5	6	Top	Bottom
28	0.30	0.272	0.265	0.267	0.266	0.269	0.273		
	0.25	0.214	0.213	0.211	0.216	0.210	0.214		
	0.20	0.160	0.161	0.161	0.164	0.167	0.170		
	0.15	0.108	0.108	0.110	0.109	0.113	0.115		
	0.10	0.053	0.053	0.064	Notch	Notch	0.099		Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
29	0.30	0.284	0.285	0.284	0.290	0.287	0.285		
	0.25	0.234	0.234	0.240	0.237	0.230	0.234		
	0.20	0.193	0.194	0.187	0.194	0.191	0.194		
	0.15	0.135	0.132	0.137	0.140	0.129	0.142		
	0.10	0.086	0.080	0.094	0.086	Notch	Notch		Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
30	0.30	0.286	0.281	0.279	0.278	0.272	0.274		
	0.25	0.235	0.231	0.227	0.220	0.219	0.222		
	0.20	0.180	0.181	0.177	0.174	0.171	0.173		
	0.15	0.127	0.130	0.128	0.125	0.117	0.127		
	0.10	0.082	0.074	0.085	Depleted	Depleted	0.076		Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
31	0.30	0.296	0.294	0.297	0.288	0.285	0.287		
	0.25	0.244	0.248	0.247	0.243	0.239	0.240		
	0.20	0.196	0.196	0.200	0.192	0.192	0.197		
	0.15	0.141	0.143	0.147	0.146	0.142	0.143		
	0.10	0.087	0.084	0.097	0.104	0.099	0.102		
	0.05	Notch	Notch	Notch	Notch	Notch	0.058	Bent/Notch	Notch
32	0.30	0.285	0.287	0.282	0.282	0.283	0.283		
	0.25	0.235	0.238	0.235	0.230	0.229	0.236		
	0.20	0.183	0.190	0.189	0.185	0.184	0.189		
	0.15	0.135	0.132	0.134	0.133	0.135	0.140		
	0.10	0.083	0.070	0.086	0.099	0.091	0.095		
	0.05	Notch	Notch	Bent	Notch	Notch	0.060	Bent/Notch	Bent/Notch

33	0.30	0.294	0.295	0.293	0.292	0.295	0.290		
	0.25	0.238	0.245	0.242	0.240	0.244	0.242		
	0.20	0.193	0.198	0.195	0.194	0.191	0.195		
	0.15	0.142	0.143	0.149	0.142	0.140	0.144		
	0.10	0.090	0.083	0.099	0.110	0.102	0.107		
	0.05	Notch	Notch	0.074	Notch	Notch	Notch	Bent/Notch	Notch
34	0.30	0.303	0.301	0.302	0.303	0.302	0.303		
	0.25	0.252	0.252	0.251	0.253	0.252	0.253		
	0.20	0.204	0.201	0.201	0.206	0.202	0.204		
	0.15	0.152	0.148	0.153	0.155	0.151	0.155		
	0.10	0.097	0.085	0.100	0.108	0.097	0.104		
	0.05	Notch	Notch	0.025	0.060	Notch	0.046	Notch	Notch
35	0.30	0.303	0.302	0.302	0.304	0.302	0.304		
	0.25	0.251	0.250	0.251	0.252	0.251	0.252		
	0.20	0.204	0.203	0.203	0.204	0.203	0.203		
	0.15	0.152	0.149	0.151	0.154	0.151	0.151		
	0.10	0.096	0.085	0.095	0.109	0.099	0.101		
	0.05	Notch	Notch	Notch	0.063	Notch	0.041	Notch	Notch
36	0.30	0.295	0.295	0.296	0.298	0.297	0.299		
	0.25	0.249	0.249	0.250	0.250	0.251	0.251		
	0.20	0.202	0.203	0.203	0.203	0.203	0.205		
	0.15	0.151	0.150	0.150	0.154	0.152	0.152		
	0.10	0.091	0.082	0.097	0.105	0.096	0.103		
	0.05	Notch	Notch	0.026	Notch	0.032	0.045	Notch	Notch

Table G. 5 – D2 Tool Steel at 60 – 65 RC Thin-wall Section Thickness Measurements and Defects

Part #	Web Thickness	Measurements of Web Thicknesses (mm)						Notes	
		1	2	3	4	5	6	Top	Bottom
37	0.30	0.286	0.282	0.285	0.288	0.277	0.277		
	0.25	0.233	0.229	0.230	0.232	0.229	0.233		
	0.20	0.193	0.189	0.182	0.186	0.178	0.184		
	0.15	0.136	0.133	0.134	0.133	0.131	0.134		
	0.10	0.090	0.073	0.086	0.063	0.042	0.082		Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
38	0.30	0.283	0.282	0.283	0.284	0.276	0.286		
	0.25	0.228	0.235	0.232	0.233	0.229	0.231		
	0.20	0.181	0.187	0.184	0.185	0.185	0.182		
	0.15	0.133	0.128	0.141	0.136	0.131	0.135		
	0.10	0.087	0.075	0.090	Notch	0.041	0.090		Notch
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted

39	0.30	0.278	0.278	0.284	0.286	0.283	0.281		
	0.25	0.229	0.232	0.232	0.231	0.226	0.231		
	0.20	0.179	0.177	0.181	0.186	0.181	0.185		
	0.15	0.133	0.128	0.132	0.132	0.134	0.131		
	0.10	0.084	0.073	0.093	0.082	0.065	0.088		
	0.05	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted	Depleted
40	0.30	0.275	0.280	0.280	0.279	0.280	0.281		
	0.25	0.241	0.241	0.246	0.239	0.241	0.241		
	0.20	0.195	0.193	0.192	0.189	0.191	0.191		
	0.15	0.145	0.145	0.146	0.145	0.136	0.142		
	0.10	0.093	0.079	0.094	0.092	0.074	0.086		
	0.05	Notch	Notch	0.036	Notch	Notch	0.055	Notch	Notch
41	0.30	0.296	0.296	0.296	0.294	0.295	0.292		
	0.25	0.243	0.247	0.239	0.244	0.243	0.237		
	0.20	0.186	0.188	0.185	0.185	0.183	0.182		
	0.15	0.145	0.140	0.142	0.144	0.138	0.142		
	0.10	0.097	0.077	0.091	0.100	0.070	0.090		
	0.05	0.045	Notch	Notch	Notch	Notch	Notch	Notch	Notch
42	0.30	0.283	0.286	0.290	0.289	0.294	0.294		
	0.25	0.235	0.232	0.238	0.236	0.237	0.238		
	0.20	0.188	0.190	0.184	0.192	0.194	0.194		
	0.15	0.135	0.134	0.135	0.138	0.139	0.138		
	0.10	0.086	0.070	0.086	0.083	0.066	0.090		
	0.05	Notch	Notch	Bent	Notch	Notch	Notch	Notch	Notch
43	0.30	0.300	0.299	0.300	0.303	0.303	0.303		
	0.25	0.248	0.249	0.247	0.250	0.251	0.249		
	0.20	0.200	0.199	0.197	0.202	0.202	0.201		
	0.15	0.151	0.148	0.148	0.153	0.150	0.151		
	0.10	0.104	0.091	0.099	0.103	0.092	0.102		
	0.05	0.025	Notch	Notch	Notch	Notch	Notch	Notch	Notch
44	0.30	0.300	0.301	0.300	0.303	0.302	0.302		
	0.25	0.250	0.251	0.250	0.251	0.250	0.251		
	0.20	0.202	0.202	0.203	0.203	0.201	0.203		
	0.15	0.151	0.151	0.150	0.151	0.149	0.150		
	0.10	0.103	0.101	0.104	0.102	0.088	0.097		
	0.05	0.022	Notch	0.034	0.030	Notch	0.047	Notch	Notch
45	0.30	0.303	0.302	0.301	0.299	0.299	0.299		
	0.25	0.248	0.247	0.249	0.247	0.246	0.248		
	0.20	0.200	0.200	0.200	0.200	0.199	0.200		
	0.15	0.152	0.151	0.151	0.151	0.149	0.149		
	0.10	0.104	0.090	0.098	0.103	0.090	0.099		
	0.05	0.029	Notch	Notch	0.030	Notch	Notch	Notch	Notch

Appendix H. ANOVA Test for Number of Passes and Location

Aluminum 6061 T6

```
                          The SAS System     15:30 Friday, March 9, 2007
                        the material is alum

                         The Mixed Procedure

                         Model Information

      Data Set                      WORK.ALUML
      Dependent Variable            diff
      Covariance Structure          Variance Components
      Subject Effect                id
      Estimation Method             REML
      Residual Variance Method      Parameter
      Fixed Effects SE Method       Model-Based
      Degrees of Freedom Method     Between-Within

            Class Level Information

      Class            Levels    Values

      passes                3    aroughing one finish three
                                                       finish
      loc                   2    B T
      Web_Thickness         6    0.05 0.1 0.15 0.2 0.25 0.3
      id                   54    1.05 1.1 1.15 1.2 1.25 1.3
                                 2.05 2.1 2.15 2.2 2.25 2.3
                                 3.05 3.1 3.15 3.2 3.25 3.3
                                 4.05 4.1 4.15 4.2 4.25 4.3
                                 5.05 5.1 5.15 5.2 5.25 5.3
                                 6.05 6.1 6.15 6.2 6.25 6.3
                                 7.05 7.1 7.15 7.2 7.25 7.3
                                 8.05 8.1 8.15 8.2 8.25 8.3
                                 9.05 9.1 9.15 9.2 9.25 9.3


                                        Dimensions

      Covariance Parameters            1
      Columns in X                    11
      Columns in Z                     0
      Subjects                        54
```

```
               The SAS System      15:30 Friday, March 9, 2007
            the material is alum

             The Mixed Procedure

                  Dimensions

                  Max Obs Per Subject               6


                  Number of Observations

         Number of Observations Read             324
         Number of Observations Used             198
         Number of Observations Not Used         126


                     Iteration History

Iteration    Evaluations    -2 Res Log Like       Criterion

        0              1     -1281.23376891
        1              1     -1281.23376891      0.00000000


                  Convergence criteria met.


                Covariance Parameter Estimates

               Cov Parm     Subject    Estimate

               Residual     id         0.000059


                       Fit Statistics

               -2 Res Log Likelihood         -1281.2
               AIC (smaller is better)       -1279.2
               AICC (smaller is better)      -1279.2
               BIC (smaller is better)       -1277.2
```

```
                     the material is alum

                      The Mixed Procedure

                Null Model Likelihood Ratio Test

                 DF    Chi-Square      Pr > ChiSq

                 0          0.00          1.0000


                  Type 3 Tests of Fixed Effects

                          Num     Den
        Effect             DF      DF    F Value    Pr > F

        passes              2      32     203.06    <.0001
        loc                 1      26      10.64    0.0031
        Web_Thickness       4      32       8.64    <.0001


                      Least Squares Means

                                        Web_
Row    Effect        passes        loc  Thickness  Estimate
 1     Passes        aroughing                     -0.02248
 2     passes        one finish                    -0.00326
 3     passes        three finish                  0.007223
 4     loc                         B               -0.00426
 5     loc                         T               -0.00808
 6     Web_Thickness                     0.1       0.001373
 7     Web_Thickness                    0.15       -0.00372
 8     Web_Thickness                     0.2       -0.00792
 9     Web_Thickness                    0.25       -0.01028
10     Web_Thickness                     0.3       -0.01031



                     Least Squares Means (continued)

       Standard
Row       Error    DF   t Value   Pr > |t|


 1     0.001272    32    -17.67    <.0001
 2     0.000991    32     -3.29    0.0025
 3     0.000883    32      8.18    <.0001
 4     0.001027    26     -4.15    0.0003
 5     0.000744    26    -10.86    <.0001
 6     0.002140    32      0.64    0.5257
 7     0.001479    32     -2.51    0.0172
 8     0.001170    32     -6.78    <.0001
 9     0.001048    32     -9.81    <.0001
10     0.001048    32     -9.84    <.0001
```

```
                     the material is alum

                      The Mixed Procedure

               Differences of Least Squares Means

                                         Web_
Row    Effect         passes        loc  Thickness  passes        _loc

 1     passes         aroughing                     one finish
 2     passes         aroughing                     three finish
 3     passes         one finish                    three finish
 4     loc                          B                             T
 5     Web_Thickness                      0.1
 6     Web_Thickness                      0.1
 7     Web_Thickness                      0.1
 8     Web_Thickness                      0.1
 9     Web_Thickness                     0.15
10     Web_Thickness                     0.15
11     Web_Thickness                     0.15
12     Web_Thickness                      0.2
13     Web_Thickness                      0.2
14     Web_Thickness                     0.25


        Differences of Least Squares Means (continued)

       Web_       Standard
Row    Thickness  Estimate     Error    DF  t Value  Pr > |t|

 1                -0.01923  0.001479    32   -13.00    <.0001
 2                -0.02971  0.001475    32   -20.15    <.0001
 3                -0.01048  0.001276    32    -8.22    <.0001
 4                0.003821  0.001171    26     3.26    0.0031
 5     0.15       0.005090  0.002467    32     2.06    0.0472
 6      0.2       0.009298  0.002370    32     3.92    0.0004
 7     0.25        0.01165  0.002383    32     4.89    <.0001
 8      0.3        0.01169  0.002383    32     4.90    <.0001
 9      0.2       0.004208  0.001836    32     2.29    0.0286
10     0.25       0.006561  0.001813    32     3.62    0.0010
11      0.3       0.006598  0.001813    32     3.64    0.0010
12     0.25       0.002353  0.001570    32     1.50    0.1438
13      0.3       0.002390  0.001570    32     1.52    0.1378
14      0.3       0.000037  0.001482    32     0.02    0.9802
```

Yellow Brass SS360

```
                    The SAS System      15:30 Friday, March 9, 2007
                 the material is yb

                  The Mixed Procedure

                   Model Information

Data Set                     WORK.YBL
Dependent Variable           diff
Covariance Structure         Variance Components
Subject Effect               id
Estimation Method            REML
Residual Variance Method     Parameter
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Between-Within


                 Class Level Information

Class            Levels    Values

passes                3    aroughing one finish three
                           finish
loc                   2    B T
Web_Thickness         6    0.05 0.1 0.15 0.2 0.25 0.3
id                   54    10.05 10.1 10.15 10.2 10.25
                           10.3 11.05 11.1 11.15 11.2
                           11.25 11.3 12.05 12.1 12.15
                           12.2 12.25 12.3 13.05 13.1
                           13.15 13.2 13.25 13.3 14.05
                           14.1 14.15 14.2 14.25 14.3
                           15.05 15.1 15.15 15.2 15.25
                           15.3 16.05 16.1 16.15 16.2
                           16.25 16.3 17.05 17.1 17.15
                           17.2 17.25 17.3 18.05 18.1
                           18.15 18.2 18.25 18.3


                        Dimensions

             Covariance Parameters             1
             Columns in X                     10
```

```
                 The SAS System      15:30 Friday, March 9, 2007
              the material is yb

               The Mixed Procedure

                   Dimensions

       Columns in Z                       0
       Subjects                          54
       Max Obs Per Subject                6


              Number of Observations

   Number of Observations Read              324
   Number of Observations Used              207
   Number of Observations Not Used          117


                 Iteration History

Iteration    Evaluations    -2 Res Log Like       Criterion

        0              1     -1397.14606233
        1              1     -1397.14606233      0.00000000


              Convergence criteria met.


            Covariance Parameter Estimates

            Cov Parm     Subject    Estimate

            Residual     id         0.000047


                   Fit Statistics

        -2 Res Log Likelihood        -1397.1
        AIC (smaller is better)      -1395.1
        AICC (smaller is better)     -1395.1
```

```
                        The SAS System      15:30 Friday, March 9, 2007
                     the material is yb

                      The Mixed Procedure

                        Fit Statistics

             BIC (smaller is better)       -1393.2


                Null Model Likelihood Ratio Test

                  DF    Chi-Square      Pr > ChiSq

                  0          0.00          1.0000


                   Type 3 Tests of Fixed Effects

                          Num     Den
        Effect             DF      DF    F Value    Pr > F

        passes              2      30       3.89    0.0315
        loc                 1      32      85.35    <.0001
        Web_Thickness       3      30       1.83    0.1629


                       Least Squares Means

                                        Web_
Row    Effect        passes        loc  Thickness  Estimate

 1     Passes        aroughing                     -0.01304
 2     Passes        one finish                    -0.01601
 3     passes        three finish                  -0.01337
 4     loc                         B               -0.00969
 5     loc                         T               -0.01859
 6     Web_Thickness                    0.15       -0.01245
 7     Web_Thickness                     0.2       -0.01391
 8     Web_Thickness                    0.25       -0.01565
 9     Web_Thickness                     0.3       -0.01457


                   Least Squares Means (continued)

       Standard
Row       Error    DF   t Value   Pr > |t|
 1     0.000879    30    -14.83    <.0001
 2     0.000811    30    -19.76    <.0001
 3     0.000811    30    -16.50    <.0001
 4     0.000700    32    -13.86    <.0001
 5     0.000662    32    -28.09    <.0001
 6     0.001040    30    -11.96    <.0001
 7     0.000936    30    -14.86    <.0001
 8     0.000936    30    -16.72    <.0001
 9     0.000936    30    -15.57    <.0001
                        The SAS System      15:30 Friday, March 9, 2007
```

```
                     the material is yb

                      The Mixed Procedure

               Differences of Least Squares Means

                                  Web_
Row    Effect         passes        loc  Thickness  passes        _loc

 1     passes         aroughing                     one finish
 2     passes         aroughing                     three finish
 3     passes         one finish                    three finish
 4     loc                          B                             T
 5     Web_Thickness                     0.15
 6     Web_Thickness                     0.15
 7     Web_Thickness                     0.15
 8     Web_Thickness                      0.2
 9     Web_Thickness                      0.2
10     Web_Thickness                     0.25


        Differences of Least Squares Means (continued)

       Web_                   Standard
Row    Thickness   Estimate      Error    DF  t Value  Pr > |t|
 1                0.002971    0.001196    30     2.48    0.0188
 2                0.000333    0.001196    30     0.28    0.7829
 3                -0.00264    0.001146    30    -2.30    0.0285
 4                0.008898    0.000963    32     9.24    <.0001
 5     0.2        0.001462    0.001399    30     1.04    0.3045
 6    0.25        0.003203    0.001399    30     2.29    0.0293
 7     0.3        0.002129    0.001399    30     1.52    0.1387
 8    0.25        0.001741    0.001324    30     1.32    0.1984
 9     0.3        0.000667    0.001324    30     0.50    0.6182
10     0.3        -0.00107    0.001324    30    -0.81    0.4235
```

420 Stainless Steel

```
                    The SAS System      15:30 Friday, March 9, 2007
                 the material is ss420

                  The Mixed Procedure

                   Model Information

      Data Set                     WORK.SS420L
      Dependent Variable           diff
      Covariance Structure         Variance Components
      Subject Effect               id
      Estimation Method            REML
      Residual Variance Method     Parameter
      Fixed Effects SE Method      Model-Based
      Degrees of Freedom Method    Between-Within


                 Class Level Information

      Class            Levels    Values

      passes                3    aroughing one finish three
                                 finish
      loc                   2    B T
      Web_Thickness         6    0.05 0.1 0.15 0.2 0.25 0.3
      id                   54    19.05 19.1 19.15 19.2 19.25
                                 19.3 20.05 20.1 20.15 20.2
                                 20.25 20.3 21.05 21.1 21.15
                                 21.2 21.25 21.3 22.05 22.1
                                 22.15 22.2 22.25 22.3 23.05
                                 23.1 23.15 23.2 23.25 23.3
                                 24.05 24.1 24.15 24.2 24.25
                                 24.3 25.05 25.1 25.15 25.2
                                 25.25 25.3 26.05 26.1 26.15
                                 26.2 26.25 26.3 27.05 27.1
                                 27.15 27.2 27.25 27.3


                       Dimensions

       Covariance Parameters              1
       Columns in X                      11
```

```
                  The SAS System      15:30 Friday, March 9, 2007
               the material is ss420

                The Mixed Procedure

                    Dimensions

          Columns in Z                         0
          Subjects                            54
          Max Obs Per Subject                  6


              Number of Observations

      Number of Observations Read             324
      Number of Observations Used             252
      Number of Observations Not Used          72


                 Iteration History

 Iteration    Evaluations    -2 Res Log Like       Criterion

         0              1     -1839.77761105
         1              1     -1839.77761105      0.00000000


             Convergence criteria met.


           Covariance Parameter Estimates

            Cov Parm     Subject    Estimate

            Residual     id         0.000027


                  Fit Statistics

         -2 Res Log Likelihood         -1839.8
         AIC (smaller is better)       -1837.8
         AICC (smaller is better)      -1837.8
```

```
              the material is ss420

               The Mixed Procedure

                 Fit Statistics

       BIC (smaller is better)       -1835.8


          Null Model Likelihood Ratio Test

            DF    Chi-Square      Pr > ChiSq

             0          0.00          1.0000

           Type 3 Tests of Fixed Effects

                   Num     Den
Effect              DF      DF    F Value    Pr > F

passes               2      38     238.66    <.0001
loc                  1      38      27.46    <.0001
Web_Thickness        4      38       2.04    0.1082

               Least Squares Means

                                           Web_
Row    Effect         passes         loc  Thickness  Estimate

 1     Passes         aroughing                      -0.01719
 2     passes         one finish                     -0.00867
 3     passes         three finish                   0.000589
 4     loc                           B               -0.00667
 5     loc                           T               -0.01018
 6     Web_Thickness                        0.1      -0.00793
 7     Web_Thickness                       0.15      -0.00828
 8     Web_Thickness                        0.2      -0.00748
 9     Web_Thickness                       0.25      -0.01017
10     Web_Thickness                        0.3      -0.00828

          Least Squares Means (continued)

       Standard
Row       Error    DF   t Value   Pr > |t|

 1     0.000601    38    -28.61    <.0001
 2     0.000574    38    -15.11    <.0001
 3     0.000551    38      1.07    0.2922
 4     0.000495    38    -13.49    <.0001
 5     0.000450    38    -22.61    <.0001
 6     0.000854    38     -9.28    <.0001
 7     0.000733    38    -11.29    <.0001
 8     0.000712    38    -10.51    <.0001
 9     0.000712    38    -14.29    <.0001
10     0.000712    38    -11.63    <.0001
```

```
                   the material is ss420

                    The Mixed Procedure

              Differences of Least Squares Means

                                           Web_
Row    Effect         passes        loc  Thickness  passes        _loc

 1     passes         aroughing                     one finish
 2     passes         aroughing                     three finish
 3     passes         one finish                    three finish
 4     loc                          B                             T
 5     Web_Thickness                       0.1
 6     Web_Thickness                       0.1
 7     Web_Thickness                       0.1
 8     Web_Thickness                       0.1
 9     Web_Thickness                      0.15
10     Web_Thickness                      0.15
11     Web_Thickness                      0.15
12     Web_Thickness                       0.2
13     Web_Thickness                       0.2
14     Web_Thickness                      0.25


        Differences of Least Squares Means (continued)

       Web_                 Standard
Row    Thickness  Estimate     Error    DF  t Value  Pr > |t|

 1                -0.00852  0.000824    38   -10.34    <.0001
 2                -0.01778  0.000816    38   -21.80    <.0001
 3                -0.00926  0.000796    38   -11.64    <.0001
 4                0.003505  0.000669    38     5.24    <.0001
 5     0.15       0.000350  0.001121    38     0.31    0.7568
 6      0.2       -0.00044  0.001111    38    -0.40    0.6916
 7     0.25       0.002241  0.001111    38     2.02    0.0509
 8      0.3       0.000352  0.001111    38     0.32    0.7531
 9      0.2       -0.00079  0.001022    38    -0.78    0.4420
10     0.25       0.001891  0.001022    38     1.85    0.0720
11      0.3       2.395E-6  0.001022    38     0.00    0.9981
12     0.25       0.002685  0.001006    38     2.67    0.0112
13      0.3       0.000796  0.001006    38     0.79    0.4338
14      0.3       -0.00189  0.001006    38    -1.88    0.0683
```

D2 Tool Steel at 25 – 30 RC

```
                   The SAS System      15:30 Friday, March 9, 2007
                the material is ts25

                 The Mixed Procedure

                  Model Information

Data Set                     WORK.TS25L
Dependent Variable           diff
Covariance Structure         Variance Components
Subject Effect               id
Estimation Method            REML
Residual Variance Method     Parameter
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Between-Within


                Class Level Information

Class            Levels    Values

passes                3    aroughing one finish three
                           finish
loc                   2    B T
Web_Thickness         6    0.05 0.1 0.15 0.2 0.25 0.3
id                   54    28.05 28.1 28.15 28.2 28.25
                           28.3 29.05 29.1 29.15 29.2
                           29.25 29.3 30.05 30.1 30.15
                           30.2 30.25 30.3 31.05 31.1
                           31.15 31.2 31.25 31.3 32.05
                           32.1 32.15 32.2 32.25 32.3
                           33.05 33.1 33.15 33.2 33.25
                           33.3 34.05 34.1 34.15 34.2
                           34.25 34.3 35.05 35.1 35.15
                           35.2 35.25 35.3 36.05 36.1
                           36.15 36.2 36.25 36.3


                       Dimensions

Covariance Parameters            1
Columns in X                    11
```

```
                 The SAS System      15:30 Friday, March 9, 2007
              the material is ts25

               The Mixed Procedure

                   Dimensions

        Columns in Z                       0
        Subjects                          54
        Max Obs Per Subject                6


             Number of Observations

    Number of Observations Read             324
    Number of Observations Used             261
    Number of Observations Not Used          63


                Iteration History

Iteration    Evaluations    -2 Res Log Like       Criterion

        0              1     -1717.30113495
        1              1     -1717.30113495      0.00000000


            Convergence criteria met.


          Covariance Parameter Estimates

         Cov Parm     Subject    Estimate

         Residual     id         0.000058


                 Fit Statistics

       -2 Res Log Likelihood         -1717.3
       AIC (smaller is better)       -1715.3
       AICC (smaller is better)      -1715.3
```

```
                 the material is ts25

                  The Mixed Procedure

                    Fit Statistics

           BIC (smaller is better)       -1713.3


               Null Model Likelihood Ratio Test

               DF    Chi-Square      Pr > ChiSq

                0          0.00          1.0000

                 Type 3 Tests of Fixed Effects

                           Num     Den
         Effect             DF      DF    F Value    Pr > F

         passes              2      38     228.95    <.0001
         loc                 1      41       1.51    0.2261
         Web_Thickness       4      38       0.88    0.4875

                     Least Squares Means

                                                Web_
 Row    Effect        passes         loc  Thickness  Estimate

  1     Passes        aroughing                      -0.02427
  2     passes        one finish                     -0.00888
  3     passes        three finish                   0.000767
  4     loc                          B               -0.01021
  5     loc                          T               -0.01138
  6     Web_Thickness                          0.1   -0.01127
  7     Web_Thickness                         0.15   -0.01122
  8     Web_Thickness                          0.2   -0.00911
  9     Web_Thickness                         0.25   -0.01156
 10     Web_Thickness                          0.3   -0.01081

                Least Squares Means (continued)

        Standard
 Row       Error    DF   t Value   Pr > |t|

  1     0.000857    38    -28.31    <.0001
  2     0.000804    38    -11.04    <.0001
  3     0.000804    38      0.95    0.3465
  4     0.000686    41    -14.89    <.0001
  5     0.000657    41    -17.32    <.0001
  6     0.001150    38     -9.79    <.0001
  7     0.001038    38    -10.81    <.0001
  8     0.001038    38     -8.77    <.0001
  9     0.001038    38    -11.13    <.0001
 10     0.001038    38    -10.41    <.0001
```

```
                    the material is ts25

                     The Mixed Procedure

              Differences of Least Squares Means

                                              Web_
Row    Effect          passes         loc  Thickness  passes        _loc

 1     passes          aroughing                      one finish
 2     passes          aroughing                      three finish
 3     passes          one finish                     three finish
 4     loc                            B                              T
 5     Web_Thickness                        0.1
 6     Web_Thickness                        0.1
 7     Web_Thickness                        0.1
 8     Web_Thickness                        0.1
 9     Web_Thickness                       0.15
10     Web_Thickness                       0.15
11     Web_Thickness                       0.15
12     Web_Thickness                        0.2
13     Web_Thickness                        0.2
14     Web_Thickness                       0.25


          Differences of Least Squares Means (continued)

       Web_                Standard
Row    Thickness  Estimate     Error    DF  t Value  Pr > |t|

 1                -0.01539  0.001176    38   -13.09    <.0001
 2                -0.02504  0.001176    38   -21.30    <.0001
 3                -0.00964  0.001138    38    -8.48    <.0001
 4                0.001167  0.000950    41     1.23    0.2261
 5     0.15       -0.00005  0.001550    38    -0.03    0.9768
 6      0.2       -0.00216  0.001550    38    -1.39    0.1722
 7     0.25       0.000288  0.001550    38     0.19    0.8536
 8      0.3       -0.00045  0.001550    38    -0.29    0.7717
 9      0.2       -0.00211  0.001469    38    -1.44    0.1587
10     0.25       0.000333  0.001469    38     0.23    0.8217
11      0.3       -0.00041  0.001469    38    -0.28    0.7830
12     0.25       0.002444  0.001469    38     1.66    0.1042
13      0.3       0.001704  0.001469    38     1.16    0.2532
14      0.3       -0.00074  0.001469    38    -0.50    0.6169
```

D2 Tool Steel at 60 – 65 RC

```
                    The SAS System      15:30 Friday, March 9, 2007
                 the material is ts60

                  The Mixed Procedure

                   Model Information

Data Set                     WORK.TS60L
Dependent Variable           diff
Covariance Structure         Variance Components
Subject Effect               id
Estimation Method            REML
Residual Variance Method     Parameter
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Between-Within


               Class Level Information

Class            Levels    Values

passes                3    aroughing one finish three
                           finish
loc                   2    B T
Web_Thickness         6    0.05 0.1 0.15 0.2 0.25 0.3
id                   54    37.05 37.1 37.15 37.2 37.25
                           37.3 38.05 38.1 38.15 38.2
                           38.25 38.3 39.05 39.1 39.15
                           39.2 39.25 39.3 40.05 40.1
                           40.15 40.2 40.25 40.3 41.05
                           41.1 41.15 41.2 41.25 41.3
                           42.05 42.1 42.15 42.2 42.25
                           42.3 43.05 43.1 43.15 43.2
                           43.25 43.3 44.05 44.1 44.15
                           44.2 44.25 44.3 45.05 45.1
                           45.15 45.2 45.25 45.3


                       Dimensions

Covariance Parameters             1
Columns in X                     11
```

```
                       The SAS System      15:30 Friday, March 9, 2007
                    the material is ts60

                     The Mixed Procedure

                         Dimensions

            Columns in Z                      0
            Subjects                         54
            Max Obs Per Subject               6


                  Number of Observations

        Number of Observations Read             324
        Number of Observations Used             264
        Number of Observations Not Used          60


                     Iteration History

Iteration    Evaluations    -2 Res Log Like       Criterion

        0              1     -1976.06517889
        1              1     -1976.06517889      0.00000000


                Convergence criteria met.


              Covariance Parameter Estimates

             Cov Parm     Subject    Estimate

             Residual     id         0.000023


                      Fit Statistics

           -2 Res Log Likelihood         -1976.1
           AIC (smaller is better)       -1974.1
           AICC (smaller is better)      -1974.0
```

```
                     the material is ts60

                      The Mixed Procedure

                        Fit Statistics

             BIC (smaller is better)       -1972.1


               Null Model Likelihood Ratio Test

               DF    Chi-Square      Pr > ChiSq

                0          0.00          1.0000

                 Type 3 Tests of Fixed Effects

                         Num     Den
       Effect             DF      DF    F Value    Pr > F

       passes              2      38     306.15    <.0001
       loc                 1      42       0.61    0.4404
       Web_Thickness       4      38       3.46    0.0166

                      Least Squares Means

                                        Web_
Row    Effect        passes        loc  Thickness  Estimate

 1     Passes        aroughing                     -0.01778
 2     passes        one finish                    -0.01163
 3     passes        three finish                  -0.00010
 4     loc                         B               -0.01007
 5     loc                         T               -0.00961
 6     Web_Thickness                     0.1       -0.01185
 7     Web_Thickness                    0.15       -0.00870
 8     Web_Thickness                     0.2       -0.00887
 9     Web_Thickness                    0.25       -0.01009
10     Web_Thickness                     0.3       -0.00967

                 Least Squares Means (continued)

       Standard
Row    Error       DF   t Value   Pr > |t|

 1     0.000525    38    -33.85    <.0001
 2     0.000505    38    -23.03    <.0001
 3     0.000505    38     -0.20    0.8441
 4     0.000423    42    -23.77    <.0001
 5     0.000412    42    -23.29    <.0001
 6     0.000695    38    -17.06    <.0001
 7     0.000652    38    -13.35    <.0001
 8     0.000652    38    -13.60    <.0001
 9     0.000652    38    -15.47    <.0001
10     0.000652    38    -14.82    <.0001
```

```
                      the material is ts60

                       The Mixed Procedure

                Differences of Least Squares Means

                                         Web_
Row    Effect         passes        loc  Thickness  passes        _loc

 1     passes         aroughing                     one finish
 2     passes         aroughing                     three finish
 3     passes         one finish                    three finish
 4     loc                          B                              T
 5     Web_Thickness                          0.1
 6     Web_Thickness                          0.1
 7     Web_Thickness                          0.1
 8     Web_Thickness                          0.1
 9     Web_Thickness                         0.15
10     Web_Thickness                         0.15
11     Web_Thickness                         0.15
12     Web_Thickness                          0.2
13     Web_Thickness                          0.2
14     Web_Thickness                         0.25


              Differences of Least Squares Means (continued)

       Web_                 Standard
Row    Thickness  Estimate     Error    DF  t Value  Pr > |t|

 1                -0.00615  0.000729    38    -8.43    <.0001
 2                -0.01768  0.000729    38   -24.26    <.0001
 3                -0.01153  0.000714    38   -16.14    <.0001
 4                -0.00046  0.000591    42    -0.78    0.4404
 5     0.15       -0.00315  0.000953    38    -3.31    0.0021
 6      0.2       -0.00298  0.000953    38    -3.13    0.0033
 7     0.25       -0.00176  0.000953    38    -1.85    0.0722
 8      0.3       -0.00219  0.000953    38    -2.30    0.0273
 9      0.2       0.000167  0.000922    38     0.18    0.8576
10     0.25       0.001389  0.000922    38     1.51    0.1404
11      0.3       0.000963  0.000922    38     1.04    0.3031
12     0.25       0.001222  0.000922    38     1.33    0.1930
13      0.3       0.000796  0.000922    38     0.86    0.3934
14      0.3       -0.00043  0.000922    38    -0.46    0.6469
```

Appendix I. ANOVA Test for Cutting Parameters

Legend for Cutting Parameters

1 Roughing with No Finishing Passes
2 Roughing with One Finishing Pass
3 Roughing with Three Finishing Passes

Aluminum 6061 T6

0.30 mm Target Thickness

	Param. 1	Param. 2
1, 4	0.264	0.283
	0.275	0.279
	0.264	0.283
	0.281	0.283
	0.287	0.291
	0.278	0.290
2, 5	0.260	0.291
	0.262	0.292
	0.269	0.290
	0.278	0.290
	0.271	0.297
	0.269	0.292
3, 6	0.270	0.296
	0.280	0.293
	0.266	0.294
	0.283	0.291
	0.284	0.298
	0.278	0.294

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.92	0.31153	0.02786
Column 2	19	7.23	0.38037	0.15386

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.045	1	0.04502	0.49553	0.48600017	4.113
Within Groups	3.2709	36	0.09086			
Total	3.3159	37				

	Param.	
	1	3
1, 7	0.264	0.311
	0.275	0.309
	0.264	0.309
	0.281	0.309
	0.287	0.310
2, 8	0.278	0.310
	0.260	0.308
	0.262	0.306
	0.269	0.306
	0.278	0.309
	0.271	0.302
	0.269	0.294
	0.270	0.306
3, 9	0.280	0.306
	0.266	0.305
	0.283	0.299
	0.284	0.299
	0.278	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.92	0.31153	0.02786
Column 2	19	8.5	0.44721	0.38218

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1749	1	0.1749	0.85308	0.361832079	4.113
Within Groups	7.3807	36	0.20502			
Total	7.5556	37				

	Param.	
	2	3
4, 7	0.283	0.311
	0.279	0.309
	0.283	0.309
	0.283	0.309
	0.291	0.310
5, 8	0.290	0.310
	0.291	0.308
	0.292	0.306
	0.290	0.306
	0.290	0.309
	0.297	0.302
	0.292	0.294
	0.296	0.306
6, 9	0.293	0.306
	0.294	0.305
	0.291	0.299
	0.298	0.299
	0.294	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	7.23	0.38037	0.15386
Column 2	19	8.5	0.44721	0.38218

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0424	1	0.04244	0.15837	0.693015212	4.113
Within Groups	9.6486	36	0.26802			
Total	9.691	37				

0.25 mm Target Thickness

	Param.	
	1	2
1, 4	0.223	0.229
	0.218	0.230
	0.226	0.235
	0.230	0.231
	0.231	0.232
	0.235	0.233
2, 5	0.215	0.240
	0.219	0.243
	0.215	0.244
	0.223	0.242
	0.225	0.247
	0.221	0.245
3, 6	0.224	0.245
	0.228	0.248
	0.225	0.247
	0.234	0.242
	0.237	0.249
	0.231	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.06	0.26632	0.03161
Column 2	19	6.33	0.33316	0.16297

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0424	1	0.04244	0.43627	0.513134804	4.113
Within Groups	3.5025	36	0.09729			
Total	3.5449	37				

	Param.	
	1	3
1, 7	0.223	0.259
	0.218	0.259
	0.226	0.258
	0.230	0.260
	0.231	0.260
	0.235	0.260
2, 8	0.215	0.256
	0.219	0.256
	0.215	0.255
	0.223	0.246
	0.225	0.246
	0.221	0.247
3, 9	0.224	0.253
	0.228	0.253
	0.225	0.254
	0.234	0.245
	0.237	0.245
	0.231	0.243

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.06	0.26632	0.03161
Column 2	19	7.56	0.39763	0.39718

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1638	1	0.16382	0.7641	0.387843789	4.113
Within Groups	7.7181	36	0.21439			
Total	7.8819	37				

	Param. 2	Param. 3
4, 7	0.229	0.259
	0.230	0.259
	0.235	0.258
	0.231	0.260
	0.232	0.260
	0.233	0.260
5, 8	0.240	0.256
	0.243	0.256
	0.244	0.255
	0.242	0.246
	0.247	0.246
	0.245	0.247
6, 9	0.245	0.253
	0.248	0.253
	0.247	0.254
	0.242	0.245
	0.249	0.245
	0.248	0.243

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.33	0.33316	0.16297
Column 2	19	7.56	0.39763	0.39718

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0395	1	0.03949	0.141	0.709494385	4.113
Within Groups	10.083	36	0.28008			
Total	10.122	37				

0.20 mm Target Thickness

	Param. 1	Param. 2
1, 4	0.168	0.179
	0.174	0.180
	0.181	0.182
		0.190
		0.195
		0.193
2, 5	0.163	0.190
	0.163	0.194
	0.161	0.196
		0.208
		0.209
		0.202
3, 6	0.176	0.197
	0.169	0.200
	0.172	0.199
		0.202
		0.207
		0.204

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	2.53	0.2527	0.06899
Column 2	19	5.53	0.29089	0.17137

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0096	1	0.00956	0.06964	0.793863654	4.21
Within Groups	3.7056	27	0.13724			
Total	3.7152	28				

	Param.	
	1	3
1, 7	0.168	0.212
	0.174	0.212
	0.181	0.210
		0.215
		0.214
		0.213
2, 8	0.163	0.207
	0.163	0.206
	0.161	0.205
		0.196
		0.193
		0.189
3, 9	0.176	0.208
	0.169	0.211
	0.172	0.212
		0.212
		0.205
		0.199

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	2.53	0.2527	0.06899
Column 2	19	6.72	0.35363	0.41074

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0667	1	0.06674	0.22486	0.63917346	4.21
Within Groups	8.0142	27	0.29682			
Total	8.0809	28				

	Param.	
	2	3
4, 7	0.179	0.212
	0.180	0.212
	0.182	0.210
	0.190	0.215
	0.195	0.214
	0.193	0.213
5, 8	0.190	0.207
	0.194	0.206
	0.196	0.205
	0.208	0.196
	0.209	0.193
	0.202	0.189
6, 9	0.197	0.208
	0.200	0.211
	0.199	0.212
	0.202	0.212
	0.207	0.205
	0.204	0.199

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.53	0.29089	0.17137
Column 2	19	6.72	0.35363	0.41074

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0374	1	0.03739	0.12847	0.722120595	4.113
Within Groups	10.478	36	0.29106			
Total	10.515	37				

0.15 mm Target Thickness

	Param.	
	1	2
	0.130	0.136
	0.127	0.135
1, 4	0.128	0.143
		0.141
		0.143
2, 5		0.151
		0.148
		0.146
3, 6		0.155

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	4	1.39	0.34625	0.18995
Column 2	10	3.3	0.3298	0.34443

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0008	1	0.00077	0.00253	0.960725529	4.747
Within Groups	3.6697	12	0.30581			
Total	3.6705	13				

	Param.	
	1	3
	0.130	0.161
	0.127	0.158
1, 7	0.128	0.159
		0.177
		0.171
		0.165
		0.157
		0.154
2, 8		0.154
		0.171
		0.161
		0.153
		0.154
		0.155
3, 9		0.159
		0.172
		0.164
		0.156

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	4	1.39	0.34625	0.18995
Column 2	19	5.9	0.31058	0.42421

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0042	1	0.0042	0.01076	0.918366128	4.325
Within Groups	8.2056	21	0.39074			
Total	8.2098	22				

	Param. 2	Param. 3
4, 7	0.136	0.161
	0.135	0.158
	0.143	0.159
		0.177
		0.171
		0.165
5, 8	0.141	0.157
	0.143	0.154
	0.151	0.154
		0.171
		0.161
		0.153
6, 9	0.148	0.154
	0.146	0.155
	0.155	0.159
		0.172
		0.164
		0.156

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	3.3	0.3298	0.34443
Column 2	19	5.9	0.31058	0.42421

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0024	1	0.00242	0.00609	0.938384938	4.21
Within Groups	10.736	27	0.39761			
Total	10.738	28				

0.10 mm Target Thickness

	Param. 2	Param. 3
4, 7		0.111
		0.098
		0.111
5, 8	0.110	0.105
	0.114	0.093
	0.120	0.108
6, 9	0.118	0.105
	0.117	0.090
	0.123	0.107

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	7	2.7	0.386	0.50654
Column 2	10	3.93	0.3928	0.83925

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00019	0.00027	0.987115544	4.543
Within Groups	10.593	15	0.70617			
Total	10.593	16				

Yellow Brass SS360

0.30 mm Target Thickness

	Param.	
	1	2
10, 13	0.283	0.277
	0.279	0.284
	0.275	0.277
	0.298	0.284
	0.295	0.285
	0.291	0.280
11, 14	0.290	0.278
	0.287	0.281
	0.293	0.281
	0.302	0.281
	0.300	0.286
	0.296	0.285
12, 15	0.281	0.280
	0.276	0.280
	0.280	0.282
	0.291	0.279
	0.285	0.282
	0.288	0.280

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.19	0.32579	0.02672
Column 2	19	7.06	0.37168	0.15549

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02	1	0.02001	0.21964	0.642142145	4.113
Within Groups	3.2798	36	0.09111			
Total	3.2998	37				

	Param.	
	1	3
10, 16	0.283	0.280
	0.279	0.281
	0.275	0.282
	0.298	0.289
	0.295	0.290
	0.291	0.290
11, 17	0.290	0.276
	0.287	0.277
	0.293	0.276
	0.302	0.280
	0.300	0.283
	0.296	0.283
12, 18	0.281	0.295
	0.276	0.295
	0.280	0.293
	0.291	0.297
	0.285	0.297
	0.288	0.297

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.19	0.32579	0.02672
Column 2	19	8.16	0.42953	0.38752

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1022	1	0.10223	0.49359	0.486849695	4.113
Within Groups	7.4564	36	0.20712			
Total	7.5586	37				

	Param.	
	2	3
13, 16	0.277	0.280
	0.284	0.281
	0.277	0.282
	0.284	0.289
	0.285	0.290
	0.280	0.290
14, 17	0.278	0.276
	0.281	0.277
	0.281	0.276
	0.281	0.280
	0.286	0.283
	0.285	0.283
15, 18	0.280	0.295
	0.280	0.295
	0.282	0.293
	0.279	0.297
	0.282	0.297
	0.280	0.297

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	7.06	0.37168	0.15549
Column 2	19	8.16	0.42953	0.38752

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0318	1	0.03178	0.11707	0.734228381	4.113
Within Groups	9.7743	36	0.27151			
Total	9.806	37				

0.25 mm Target Thickness

	Param.	
	1	2
10, 13	0.222	0.230
	0.222	0.230
	0.226	0.232
	0.244	0.232
	0.241	0.231
	0.244	0.232
11, 14	0.236	0.228
	0.237	0.231
	0.239	0.234
	0.248	0.234
	0.252	0.237
	0.248	0.235
12, 15	0.228	0.226
	0.230	0.231
	0.228	0.229
	0.237	0.231
	0.233	0.231
	0.245	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.26	0.27684	0.03075
Column 2	19	6.17	0.32447	0.16464

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0216	1	0.02155	0.22062	0.641397407	4.113
Within Groups	3.5169	36	0.09769			
Total	3.5385	37				

	Param.	
	1	3
10, 16	0.222	0.230
	0.222	0.231
	0.226	0.231
	0.244	0.237
	0.241	0.240
	0.244	0.239
11, 17	0.236	0.223
	0.237	0.226
	0.239	0.227
	0.248	0.228
	0.252	0.228
	0.248	0.230
12, 18	0.228	0.241
	0.230	0.243
	0.228	0.241
	0.237	0.245
	0.233	0.245
	0.245	0.245

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.26	0.27684	0.03075
Column 2	19	7.23	0.38053	0.40243

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1021	1	0.10213	0.47153	0.496683525	4.113
Within Groups	7.7973	36	0.21659			
Total	7.8994	37				

	Param.	
	2	3
13, 16	0.230	0.230
	0.230	0.231
	0.232	0.231
	0.232	0.237
	0.231	0.240
	0.232	0.239
14, 17	0.228	0.223
	0.231	0.226
	0.234	0.227
	0.234	0.228
	0.237	0.228
	0.235	0.230
15, 18	0.226	0.241
	0.231	0.243
	0.229	0.241
	0.231	0.245
	0.231	0.245
	0.231	0.245

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.17	0.32447	0.16464
Column 2	19	7.23	0.38053	0.40243

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0298	1	0.02985	0.10527	0.747471396	4.113
Within Groups	10.207	36	0.28353			
Total	10.237	37				

0.20 mm Target Thickness

	Param. 1	Param. 2
	0.173	0.178
	0.169	0.184
10, 13	0.177	0.185
	0.189	0.190
	0.186	0.190
	0.190	0.187
	0.188	0.181
	0.189	0.182
11, 14	0.195	0.183
	0.204	0.186
	0.197	0.186
	0.203	0.187
	0.179	0.180
	0.172	0.181
12, 15	0.178	0.183
	0.187	0.184
	0.188	0.187
	0.188	0.186

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.35	0.22905	0.03495
Column 2	19	5.32	0.28	0.1735

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0247	1	0.02466	0.23659	0.629625207	4.113
Within Groups	3.752	36	0.10422			
Total	3.7767	37				

	Param. 1	Param. 3
	0.173	0.180
	0.169	0.180
10, 16	0.177	0.182
	0.189	0.192
	0.186	0.190
	0.190	0.192
	0.188	0.175
	0.189	0.176
11, 17	0.195	0.179
	0.204	0.181
	0.197	0.179
	0.203	0.182
	0.179	0.194
	0.172	0.195
12, 18	0.178	0.196
	0.187	0.201
	0.188	0.201
	0.188	0.202

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.35	0.22905	0.03495
Column 2	19	6.38	0.33563	0.41637

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1079	1	0.10791	0.4782	0.493673673	4.113
Within Groups	8.1238	36	0.22566			
Total	8.2317	37				

	Param.	
	2	3
13, 16	0.178	0.180
	0.184	0.180
	0.185	0.182
	0.190	0.192
	0.190	0.190
	0.187	0.192
14, 17	0.181	0.175
	0.182	0.176
	0.183	0.179
	0.186	0.181
	0.186	0.179
	0.187	0.182
15, 18	0.180	0.194
	0.181	0.195
	0.183	0.196
	0.184	0.201
	0.187	0.201
	0.186	0.202

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	19	5.32	0.28	0.1735
Column 2	19	6.38	0.33563	0.41637

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0294	1	0.0294	0.09969	0.754027924	4.113
Within Groups	10.618	36	0.29493			
Total	10.647	37				

0.15 mm Target Thickness

	Param.	
	1	2
10, 13	0.123	0.129
	0.123	0.124
	0.125	0.135
		0.150
		0.143
		0.142
11, 14	0.139	0.129
	0.134	0.129
	0.141	0.139
		0.151
		0.149
		0.148
12, 15	0.133	0.128
	0.125	0.130
	0.128	0.140
		0.148
		0.144
		0.142

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	10	2.17	0.2171	0.07571
Column 2	19	4.5	0.23684	0.18238

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0026	1	0.00255	0.01739	0.896057622	4.21
Within Groups	3.9642	27	0.14682			
Total	3.9667	28				

	Param. 1	3
10, 16	0.123	0.129
	0.123	0.120
	0.125	0.133
		0.149
		0.143
		0.145
11, 17	0.139	0.122
	0.134	0.115
	0.141	0.128
		0.135
		0.128
		0.134
12, 18	0.133	0.140
	0.125	0.135
	0.128	0.151
		0.159
		0.149
		0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	2.17	0.2171	0.07571
Column 2	19	5.47	0.28784	0.4315

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0328	1	0.03279	0.10478	0.748656273	4.21
Within Groups	8.4485	27	0.31291			
Total	8.4813	28				

	Param. 2	3
13, 16	0.129	0.129
	0.124	0.120
	0.135	0.133
	0.150	0.149
	0.143	0.143
	0.142	0.145
14, 17	0.129	0.122
	0.129	0.115
	0.139	0.128
	0.151	0.135
	0.149	0.128
	0.148	0.134
15, 18	0.128	0.140
	0.130	0.135
	0.140	0.151
	0.148	0.159
	0.144	0.149
	0.142	0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.5	0.23684	0.18238
Column 2	19	5.47	0.28784	0.4315

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0247	1	0.02471	0.0805	0.778242771	4.113
Within Groups	11.05	36	0.30694			
Total	11.075	37				

420 Stainless Steel

0.30 mm Target Thickness

	Param.	
	1	2
19, 22	0.281	0.296
	0.281	0.300
	0.283	0.295
	0.285	0.297
	0.281	0.300
	0.283	0.300
20, 23	0.283	0.297
	0.282	0.293
	0.279	0.291
	0.281	0.292
	0.275	0.294
	0.281	0.293
21, 24	0.282	0.287
	0.286	0.286
	0.278	0.281
	0.279	0.283
	0.288	0.284
	0.281	0.285

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.07	0.31942	0.02717
Column 2	19	7.25	0.38179	0.1536

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.037	1	0.03695	0.40885	0.52660183	4.113
Within Groups	3.2538	36	0.09038			
Total	3.2908	37				

	Param.	
	1	3
19, 25	0.281	0.301
	0.281	0.299
	0.283	0.299
	0.285	0.301
	0.281	0.300
	0.283	0.300
20, 26	0.283	0.303
	0.282	0.301
	0.279	0.301
	0.281	0.300
	0.275	0.302
	0.281	0.303
21, 27	0.282	0.304
	0.286	0.302
	0.278	0.301
	0.279	0.305
	0.288	0.303
	0.281	0.305

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.07	0.31942	0.02717
Column 2	19	8.43	0.44368	0.38321

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1467	1	0.14669	0.7149	0.403405652	4.113
Within Groups	7.3869	36	0.20519			
Total	7.5336	37				

	Param.	
	2	3
	0.296	0.301
	0.300	0.299
22, 25	0.295	0.299
	0.297	0.301
	0.300	0.300
	0.300	0.300
	0.297	0.303
	0.293	0.301
23, 26	0.291	0.301
	0.292	0.300
	0.294	0.302
	0.293	0.303
	0.287	0.304
	0.286	0.302
24, 27	0.281	0.301
	0.283	0.305
	0.284	0.303
	0.285	0.305

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	7.25	0.38179	0.1536
Column 2	19	8.43	0.44368	0.38321

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0364	1	0.03639	0.13559	0.714857602	4.113
Within Groups	9.6626	36	0.26841			
Total	9.699	37				

0.25 mm Target Thickness

	Param.	
	1	2
	0.235	0.246
	0.230	0.244
19, 22	0.234	0.246
	0.235	0.243
	0.226	0.250
	0.235	0.244
	0.230	0.238
	0.227	0.238
20, 23	0.232	0.243
	0.236	0.242
	0.233	0.247
	0.231	0.239
	0.232	0.233
	0.231	0.231
21, 24	0.230	0.233
	0.237	0.235
	0.227	0.229
	0.229	0.234

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.17	0.27211	0.03108
Column 2	19	6.32	0.33237	0.16312

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0345	1	0.0345	0.35531	0.554851029	4.113
Within Groups	3.4956	36	0.0971			
Total	3.5301	37				

	Param.	
	1	3
19, 25	0.235	0.249
	0.230	0.247
	0.234	0.248
	0.235	0.250
	0.226	0.249
20, 26	0.235	0.249
	0.230	0.251
	0.227	0.248
	0.232	0.250
	0.236	0.251
	0.233	0.250
	0.231	0.253
	0.232	0.245
21, 27	0.231	0.243
	0.230	0.244
	0.237	0.247
	0.227	0.245
	0.229	0.247

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.17	0.27211	0.03108
Column 2	19	7.47	0.39295	0.39858

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1387	1	0.13873	0.64575	0.42691034	4.113
Within Groups	7.7339	36	0.21483			
Total	7.8726	37				

	Param.	
	2	3
22, 25	0.246	0.249
	0.244	0.247
	0.246	0.248
	0.243	0.250
	0.250	0.249
23, 26	0.244	0.249
	0.238	0.251
	0.238	0.248
	0.243	0.250
	0.242	0.251
	0.247	0.250
	0.239	0.253
	0.233	0.245
24, 27	0.231	0.243
	0.233	0.244
	0.235	0.247
	0.229	0.245
	0.234	0.247

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.32	0.33237	0.16312
Column 2	19	7.47	0.39295	0.39858

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0349	1	0.03486	0.12413	0.726646851	4.113
Within Groups	10.111	36	0.28085			
Total	10.145	37				

0.20 mm Target Thickness

	Param.	
	1	2
19, 22	0.185	0.193
	0.185	0.197
	0.182	0.200
	0.189	0.198
	0.184	0.200
	0.189	0.198
20, 23	0.180	0.195
	0.182	0.194
	0.187	0.195
	0.184	0.200
	0.179	0.195
	0.183	0.197
21, 24	0.185	0.181
	0.181	0.183
	0.186	0.184
	0.185	0.184
	0.183	0.187
	0.187	0.187

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.32	0.22716	0.03503
Column 2	19	5.47	0.28779	0.17196

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0349	1	0.03492	0.33744	0.564929294	4.113
Within Groups	3.7259	36	0.1035			
Total	3.7608	37				

	Param.	
	1	3
19, 25	0.185	0.202
	0.185	0.197
	0.182	0.199
	0.189	0.202
	0.184	0.201
	0.189	0.201
20, 26	0.180	0.204
	0.182	0.199
	0.187	0.201
	0.184	0.204
	0.179	0.204
	0.183	0.205
21, 27	0.185	0.200
	0.181	0.197
	0.186	0.195
	0.185	0.201
	0.183	0.200
	0.187	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.32	0.22716	0.03503
Column 2	19	6.61	0.348	0.41244

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1387	1	0.13873	0.62004	0.436185587	4.113
Within Groups	8.0546	36	0.22374			
Total	8.1933	37				

	Param. 2	Param. 3
	0.193	0.202
	0.197	0.197
22, 25	0.200	0.199
	0.198	0.202
	0.200	0.201
	0.198	0.201
	0.195	0.204
	0.194	0.199
23, 26	0.195	0.201
	0.200	0.204
	0.195	0.204
	0.197	0.205
	0.181	0.200
	0.183	0.197
24, 27	0.184	0.195
	0.184	0.201
	0.187	0.200
	0.187	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.47	0.28779	0.17196
Column 2	19	6.61	0.348	0.41244

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0344	1	0.03444	0.11787	0.733357709	4.113
Within Groups	10.519	36	0.2922			
Total	10.554	37				

0.15 mm Target Thickness

	Param. 1	Param. 2
	0.133	0.144
	0.132	0.142
19, 22	0.132	0.147
	0.136	0.147
	0.132	0.145
	0.140	0.148
	0.135	0.141
	0.132	0.136
20, 23	0.128	0.145
	0.130	0.149
	0.130	0.147
	0.134	0.150
	0.128	0.130
	0.123	0.132
21, 24	0.136	0.136
		0.136
		0.130
		0.136

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	16	2.98	0.18631	0.0471
Column 2	19	4.54	0.239	0.1819

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0241	1	0.02411	0.19989	0.65773341	4.139
Within Groups	3.9806	33	0.12063			
Total	4.0047	34				

	Param. 1	Param. 3
19, 25	0.133	0.151
	0.132	0.145
	0.132	0.146
	0.136	0.154
	0.132	0.149
20, 26	0.140	0.151
	0.135	0.153
	0.132	0.148
	0.128	0.150
	0.130	0.156
	0.130	0.153
	0.134	0.157
	0.128	0.153
21, 27	0.123	0.147
	0.136	0.149
		0.158
		0.153
		0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	16	2.98	0.18631	0.0471
Column 2	19	5.73	0.30142	0.42706

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1151	1	0.11509	0.45247	0.505849049	4.139
Within Groups	8.3936	33	0.25435			
Total	8.5087	34				

	Param. 2	Param. 3
22, 25	0.144	0.151
	0.142	0.145
	0.147	0.146
	0.147	0.154
	0.145	0.149
23, 26	0.148	0.151
	0.141	0.153
	0.136	0.148
	0.145	0.150
	0.149	0.156
	0.147	0.153
	0.150	0.157
	0.130	0.153
24, 27	0.132	0.147
	0.136	0.149
	0.136	0.158
	0.130	0.153
	0.136	0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.54	0.239	0.1819
Column 2	19	5.73	0.30142	0.42706

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.037	1	0.03702	0.12157	0.729369046	4.113
Within Groups	10.961	36	0.30448			
Total	10.998	37				

0.10 mm Target Thickness

	Param. 1	Param. 2
19, 22	0.088	0.094
	0.079	0.080
	0.085	0.099
20, 23	0.087	0.092
	0.078	0.078
	0.087	0.092
21, 24	0.079	0.076
	0.081	0.072
	0.083	0.084
		0.108
		0.100
		0.105

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	1.75	0.1747	0.0841
Column 2	13	3.08	0.23692	0.28075

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0219	1	0.02188	0.11138	0.741886229	4.325
Within Groups	4.126	21	0.19647			
Total	4.1478	22				

	Param. 1	Param. 3
19, 25	0.088	0.097
	0.079	0.082
	0.085	0.097
		0.110
		0.102
		0.104
20, 26	0.087	0.100
	0.078	0.085
	0.087	0.096
		0.114
		0.107
		0.109
21, 27	0.079	0.097
	0.081	0.087
	0.083	0.098
		0.117
		0.108
		0.108

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	1.75	0.1747	0.0841
Column 2	19	4.82	0.25358	0.44242

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0408	1	0.04076	0.12621	0.725151462	4.21
Within Groups	8.7204	27	0.32298			
Total	8.7612	28				

	Param. 2	Param. 3
22, 25	0.094	0.097
	0.080	0.082
	0.099	0.097
		0.110
		0.102
		0.104
23, 26	0.092	0.100
	0.078	0.085
	0.092	0.096
		0.114
		0.107
		0.109
24, 27	0.076	0.097
	0.072	0.087
	0.084	0.098
	0.108	0.117
	0.100	0.108
	0.105	0.108

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	13	3.08	0.23692	0.28075
Column 2	19	4.82	0.25358	0.44242

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0021	1	0.00214	0.00567	0.940483676	4.171
Within Groups	11.333	30	0.37775			
Total	11.335	31				

D2 Tool Steel 25-30 RC

0.30 mm Target Thickness

	Param. 1	Param. 2
28, 31	0.272	0.296
	0.265	0.294
	0.267	0.297
	0.266	0.288
	0.269	0.285
29, 32	0.273	0.287
	0.284	0.285
	0.285	0.287
	0.284	0.282
	0.290	0.282
	0.287	0.283
	0.285	0.283
30, 33	0.286	0.294
	0.281	0.295
	0.279	0.293
	0.278	0.292
	0.272	0.295
	0.274	0.290

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6	0.31563	0.02753
Column 2	19	7.21	0.37937	0.15405

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0386	1	0.03859	0.42509	0.518547636	4.113
Within Groups	3.2683	36	0.09079			
Total	3.3069	37				

	Param. 1	Param. 3
28, 34	0.272	0.303
	0.265	0.301
	0.267	0.302
	0.266	0.303
	0.269	0.302
29, 35	0.273	0.303
	0.284	0.303
	0.285	0.302
	0.284	0.302
	0.290	0.304
	0.287	0.302
	0.285	0.304
30, 36	0.286	0.295
	0.281	0.295
	0.279	0.296
	0.278	0.298
	0.272	0.297
	0.274	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6	0.31563	0.02753
Column 2	19	8.41	0.44268	0.38352

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1534	1	0.15335	0.74616	0.39341446	4.113
Within Groups	7.3988	36	0.20552			
Total	7.5522	37				

	Param.	
	2	3
	0.296	0.303
	0.294	0.301
31, 34	0.297	0.302
	0.288	0.303
	0.285	0.302
	0.287	0.303
	0.285	0.303
	0.287	0.302
32, 35	0.282	0.302
	0.282	0.304
	0.283	0.302
	0.283	0.304
	0.294	0.295
	0.295	0.295
33, 36	0.293	0.296
	0.292	0.298
	0.295	0.297
	0.290	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	7.21	0.37937	0.15405
Column 2	19	8.41	0.44268	0.38352

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0381	1	0.03808	0.14169	0.708813931	4.113
Within Groups	9.6762	36	0.26878			
Total	9.7143	37				

0.25 mm Target Thickness

	Param.	
	1	2
	0.214	0.244
	0.213	0.248
28, 31	0.211	0.247
	0.216	0.243
	0.210	0.239
	0.214	0.240
	0.234	0.235
	0.234	0.238
29, 32	0.240	0.235
	0.237	0.230
	0.230	0.229
	0.234	0.236
	0.235	0.238
	0.231	0.245
30, 33	0.227	0.242
	0.220	0.240
	0.219	0.244
	0.222	0.242

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.04	0.26532	0.03175
Column 2	19	6.32	0.33237	0.16311

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0427	1	0.04271	0.4384	0.512114618	4.113
Within Groups	3.5075	36	0.09743			
Total	3.5502	37				

	Param. 1	Param. 3
28, 34	0.214	0.252
	0.213	0.252
	0.211	0.251
	0.216	0.253
	0.210	0.252
	0.214	0.253
29, 35	0.234	0.251
	0.234	0.250
	0.240	0.251
	0.237	0.252
	0.230	0.251
	0.234	0.252
30, 36	0.235	0.249
	0.231	0.249
	0.227	0.250
	0.220	0.250
	0.219	0.251
	0.222	0.251

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.04	0.26532	0.03175
Column 2	19	7.52	0.39579	0.39771

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1617	1	0.16172	0.75315	0.391228961	4.113
Within Groups	7.7302	36	0.21473			
Total	7.8919	37				

	Param. 2	Param. 3
31, 34	0.244	0.252
	0.248	0.252
	0.247	0.251
	0.243	0.253
	0.239	0.252
	0.240	0.253
32, 35	0.235	0.251
	0.238	0.250
	0.235	0.251
	0.230	0.252
	0.229	0.251
	0.236	0.252
33, 36	0.238	0.249
	0.245	0.249
	0.242	0.250
	0.240	0.250
	0.244	0.251
	0.242	0.251

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.32	0.33237	0.16311
Column 2	19	7.52	0.39579	0.39771

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0382	1	0.03821	0.13627	0.714180078	4.113
Within Groups	10.095	36	0.28041			
Total	10.133	37				

0.20 mm Target Thickness

	Param. 1	Param. 2
28, 31	0.160	0.196
	0.161	0.196
	0.161	0.200
	0.164	0.192
	0.167	0.192
	0.170	0.197
29, 32	0.193	0.183
	0.194	0.190
	0.187	0.189
	0.194	0.185
	0.191	0.184
	0.194	0.189
30, 33	0.180	0.193
	0.181	0.198
	0.177	0.195
	0.174	0.194
	0.171	0.191
	0.173	0.195

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.19	0.22063	0.03577
Column 2	19	5.46	0.28732	0.17204

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0422	1	0.04224	0.40658	0.527743149	4.113
Within Groups	3.7404	36	0.1039			
Total	3.7827	37				

	Param. 1	Param. 3
28, 34	0.160	0.204
	0.161	0.201
	0.161	0.201
	0.164	0.206
	0.167	0.202
	0.170	0.204
29, 35	0.193	0.204
	0.194	0.203
	0.187	0.203
	0.194	0.204
	0.191	0.203
	0.194	0.203
30, 36	0.180	0.202
	0.181	0.203
	0.177	0.203
	0.174	0.203
	0.171	0.203
	0.173	0.205

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.19	0.22063	0.03577
Column 2	19	6.66	0.35037	0.4117

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1599	1	0.1599	0.71469	0.403473828	4.113
Within Groups	8.0544	36	0.22373			
Total	8.2143	37				

	Param. 2	Param. 3
31, 34	0.196	0.204
	0.196	0.201
	0.200	0.201
	0.192	0.206
	0.192	0.202
	0.197	0.204
32, 35	0.183	0.204
	0.190	0.203
	0.189	0.203
	0.185	0.204
	0.184	0.203
	0.189	0.203
	0.193	0.202
33, 36	0.198	0.203
	0.195	0.203
	0.194	0.203
	0.191	0.203
	0.195	0.205

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.46	0.28732	0.17204
Column 2	19	6.66	0.35037	0.4117

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0378	1	0.03777	0.1294	0.721153811	4.113
Within Groups	10.507	36	0.29187			
Total	10.545	37				

0.15 mm Target Thickness

	Param. 1	Param. 2
28, 31	0.108	0.141
	0.108	0.143
	0.110	0.147
	0.109	0.146
	0.113	0.142
	0.115	0.143
29, 32	0.135	0.135
	0.132	0.132
	0.137	0.134
	0.140	0.133
	0.129	0.135
	0.142	0.140
	0.127	0.142
30, 33	0.130	0.143
	0.128	0.149
	0.125	0.142
	0.117	0.140
	0.127	0.144

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.23	0.17011	0.04051
Column 2	19	4.53	0.23847	0.18199

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0444	1	0.04441	0.39915	0.531519931	4.113
Within Groups	4.005	36	0.11125			
Total	4.0494	37				

	Param. 1	Param. 3
	0.108	0.152
	0.108	0.148
28, 34	0.110	0.153
	0.109	0.155
	0.113	0.151
	0.115	0.155
	0.135	0.152
	0.132	0.149
29, 35	0.137	0.151
	0.140	0.154
	0.129	0.151
	0.142	0.151
	0.127	0.151
	0.130	0.150
30, 36	0.128	0.150
	0.125	0.154
	0.117	0.152
	0.127	0.152

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.23	0.17011	0.04051
Column 2	19	5.73	0.30163	0.42699

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1643	1	0.16434	0.70307	0.407286983	4.113
Within Groups	8.415	36	0.23375			
Total	8.5793	37				

	Param. 2	Param. 3
	0.141	0.152
	0.143	0.148
31, 34	0.147	0.153
	0.146	0.155
	0.142	0.151
	0.143	0.155
	0.135	0.152
	0.132	0.149
32, 35	0.134	0.151
	0.133	0.154
	0.135	0.151
	0.140	0.151
	0.142	0.151
	0.143	0.150
33, 36	0.149	0.150
	0.142	0.154
	0.140	0.152
	0.144	0.152

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.53	0.23847	0.18199
Column 2	19	5.73	0.30163	0.42699

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0379	1	0.03789	0.12445	0.72631007	4.113
Within Groups	10.962	36	0.30449			
Total	10.999	37				

0.10 mm Target Thickness

	Param.	
	1	2
28, 31	0.053	0.087
	0.053	0.084
	0.064	0.097
		0.104
		0.099
		0.102
29, 32	0.086	0.083
	0.080	0.070
	0.094	0.086
		0.099
		0.091
		0.095
30, 33	0.082	0.090
	0.074	0.083
	0.085	0.099
		0.110
		0.102
		0.107

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	1.67	0.1671	0.08584
Column 2	19	3.69	0.19411	0.19135

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0048	1	0.00478	0.03059	0.862454408	4.21
Within Groups	4.2168	27	0.15618			
Total	4.2216	28				

	Param.	
	1	3
28, 34	0.053	0.097
	0.053	0.085
	0.064	0.100
		0.108
		0.097
		0.104
29, 35	0.086	0.096
	0.080	0.085
	0.094	0.095
		0.109
		0.099
		0.101
30, 36	0.082	0.091
	0.074	0.082
	0.085	0.097
		0.105
		0.096
		0.103

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	1.67	0.1671	0.08584
Column 2	19	4.75	0.25	0.44354

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.045	1	0.04503	0.13884	0.712346304	4.21
Within Groups	8.7562	27	0.3243			
Total	8.8012	28				

	Param.	
	2	3
31, 34	0.087	0.097
	0.084	0.085
	0.097	0.100
	0.104	0.108
	0.099	0.097
	0.102	0.104
32, 35	0.083	0.096
	0.070	0.085
	0.086	0.095
	0.099	0.109
	0.091	0.099
	0.095	0.101
33, 36	0.090	0.091
	0.083	0.082
	0.099	0.097
	0.110	0.105
	0.102	0.096
	0.107	0.103

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.69	0.19411	0.19135
Column 2	19	4.75	0.25	0.44354

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0297	1	0.02968	0.0935	0.761537524	4.113
Within Groups	11.428	36	0.31744			
Total	11.458	37				

D2 Tool Steel 60-65 RC

0.30 mm Target Thickness

	Param. 1	Param. 2
37, 40	0.286	0.275
	0.282	0.280
	0.285	0.280
	0.288	0.279
	0.277	0.280
	0.277	0.281
38, 41	0.283	0.296
	0.282	0.296
	0.283	0.296
	0.284	0.294
	0.276	0.295
	0.286	0.292
39, 42	0.278	0.283
	0.278	0.286
	0.284	0.290
	0.286	0.289
	0.283	0.294
	0.281	0.294

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.08	0.31995	0.02713
Column 2	19	7.18	0.37789	0.15435

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0319	1	0.0319	0.35155	0.556943767	4.113
Within Groups	3.2667	36	0.09074			
Total	3.2986	37				

	Param. 1	Param. 3
37, 43	0.286	0.300
	0.282	0.299
	0.285	0.300
	0.288	0.303
	0.277	0.303
	0.277	0.303
38, 44	0.283	0.300
	0.282	0.301
	0.283	0.300
	0.284	0.303
	0.276	0.302
	0.286	0.302
39, 45	0.278	0.303
	0.278	0.302
	0.284	0.301
	0.286	0.299
	0.283	0.299
	0.281	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.08	0.31995	0.02713
Column 2	19	8.42	0.44311	0.38339

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1441	1	0.14409	0.70201	0.407636914	4.113
Within Groups	7.3893	36	0.20526			
Total	7.5334	37				

	Param.	
	2	3
40, 43	0.275	0.300
	0.280	0.299
	0.280	0.300
	0.279	0.303
	0.280	0.303
	0.281	0.303
41, 44	0.296	0.300
	0.296	0.301
	0.296	0.300
	0.294	0.303
	0.295	0.302
	0.292	0.302
42, 45	0.283	0.303
	0.286	0.302
	0.290	0.301
	0.289	0.299
	0.294	0.299
	0.294	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	7.18	0.37789	0.15435
Column 2	19	8.42	0.44311	0.38339

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0404	1	0.0404	0.15025	0.700577301	4.113
Within Groups	9.6793	36	0.26887			
Total	9.7197	37				

0.25 mm Target Thickness

	Param.	
	1	2
37, 40	0.233	0.241
	0.229	0.241
	0.230	0.246
	0.232	0.239
	0.229	0.241
	0.233	0.241
38, 41	0.228	0.243
	0.235	0.247
	0.232	0.239
	0.233	0.244
	0.229	0.243
	0.231	0.237
39, 42	0.229	0.235
	0.232	0.232
	0.232	0.238
	0.231	0.236
	0.226	0.237
	0.231	0.238

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.16	0.27132	0.03114
Column 2	19	6.32	0.33253	0.16307

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0356	1	0.03559	0.36655	0.54868713	4.113
Within Groups	3.4958	36	0.0971			
Total	3.5314	37				

	Param.	
	1	3
37, 43	0.233	0.248
	0.229	0.249
	0.230	0.247
	0.232	0.250
	0.229	0.251
38, 44	0.233	0.249
	0.228	0.250
	0.235	0.251
	0.232	0.250
	0.233	0.251
	0.229	0.250
	0.231	0.251
	0.229	0.248
39, 45	0.232	0.247
	0.232	0.249
	0.231	0.247
	0.226	0.246
	0.231	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.16	0.27132	0.03114
Column 2	19	7.48	0.39379	0.39832

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1425	1	0.1425	0.66361	0.420643264	4.113
Within Groups	7.7303	36	0.21473			
Total	7.8728	37				

	Param.	
	2	3
40, 43	0.241	0.248
	0.241	0.249
	0.246	0.247
	0.239	0.250
	0.241	0.251
41, 44	0.241	0.249
	0.243	0.250
	0.247	0.251
	0.239	0.250
	0.244	0.251
	0.243	0.250
	0.237	0.251
	0.235	0.248
42, 45	0.232	0.247
	0.238	0.249
	0.236	0.247
	0.237	0.246
	0.238	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	6.32	0.33253	0.16307
Column 2	19	7.48	0.39379	0.39832

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0357	1	0.03566	0.12703	0.723616421	4.113
Within Groups	10.105	36	0.28069			
Total	10.141	37				

0.20 mm Target Thickness

	Param.	
	1	2
37, 40	0.193	0.195
	0.189	0.193
	0.182	0.192
	0.186	0.189
	0.178	0.191
	0.184	0.191
38, 41	0.181	0.186
	0.187	0.188
	0.184	0.185
	0.185	0.185
	0.185	0.183
	0.182	0.182
39, 42	0.179	0.188
	0.177	0.190
	0.181	0.184
	0.186	0.192
	0.181	0.194
	0.185	0.194

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.31	0.22658	0.03509
Column 2	19	5.4	0.28432	0.17263

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0317	1	0.03167	0.30491	0.584233866	4.113
Within Groups	3.7391	36	0.10386			
Total	3.7707	37				

	Param.	
	1	3
37, 43	0.193	0.200
	0.189	0.199
	0.182	0.197
	0.186	0.202
	0.178	0.202
	0.184	0.201
38, 44	0.181	0.202
	0.187	0.202
	0.184	0.203
	0.185	0.203
	0.185	0.201
	0.182	0.203
39, 45	0.179	0.200
	0.177	0.200
	0.181	0.200
	0.186	0.200
	0.181	0.199
	0.185	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.31	0.22658	0.03509
Column 2	19	6.61	0.34811	0.4124

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1403	1	0.1403	0.62705	0.433626061	4.113
Within Groups	8.055	36	0.22375			
Total	8.1953	37				

	Param.	
	2	3
40, 43	0.195	0.200
	0.193	0.199
	0.192	0.197
	0.189	0.202
	0.191	0.202
	0.191	0.201
41, 44	0.186	0.202
	0.188	0.202
	0.185	0.203
	0.185	0.203
	0.183	0.201
	0.182	0.203
	0.188	0.200
42, 45	0.190	0.200
	0.184	0.200
	0.192	0.200
	0.194	0.199
	0.194	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	5.4	0.28432	0.17263
Column 2	19	6.61	0.34811	0.4124

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0387	1	0.03866	0.13215	0.71833907	4.113
Within Groups	10.531	36	0.29252			
Total	10.569	37				

0.15 mm Target Thickness

	Param.	
	1	2
37, 40	0.136	0.145
	0.133	0.145
	0.134	0.146
	0.133	0.145
	0.131	0.136
	0.134	0.142
38, 41	0.133	0.145
	0.128	0.140
	0.141	0.142
	0.136	0.144
	0.131	0.138
	0.135	0.142
	0.133	0.135
39, 42	0.128	0.134
	0.132	0.135
	0.132	0.138
	0.134	0.139
	0.131	0.138

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.4	0.17868	0.03957
Column 2	19	4.53	0.23837	0.182

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0338	1	0.03384	0.30547	0.583890139	4.113
Within Groups	3.9882	36	0.11078			
Total	4.0221	37				

	Param.	
	1	3
	0.136	0.151
	0.133	0.148
37, 43	0.134	0.148
	0.133	0.153
	0.131	0.150
	0.134	0.151
	0.133	0.151
	0.128	0.151
38, 44	0.141	0.150
	0.136	0.151
	0.131	0.149
	0.135	0.150
	0.133	0.152
	0.128	0.151
39, 45	0.132	0.151
	0.132	0.151
	0.134	0.149
	0.131	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.4	0.17868	0.03957
Column 2	19	5.71	0.30032	0.4274

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.1405	1	0.14055	0.60195	0.442902854	4.113
Within Groups	8.4054	36	0.23348			
Total	8.546	37				

	Param.	
	2	3
	0.145	0.151
	0.145	0.148
40, 43	0.146	0.148
	0.145	0.153
	0.136	0.150
	0.142	0.151
	0.145	0.151
	0.140	0.151
41, 44	0.142	0.150
	0.144	0.151
	0.138	0.149
	0.142	0.150
	0.135	0.152
	0.134	0.151
42, 45	0.135	0.151
	0.138	0.151
	0.139	0.149
	0.138	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	4.53	0.23837	0.182
Column 2	19	5.71	0.30032	0.4274

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0365	1	0.03646	0.11965	0.731433169	4.113
Within Groups	10.969	36	0.3047			
Total	11.006	37				

0.10 mm Target Thickness

	Param.	
	1	2
37, 40	0.090	0.093
	0.073	0.079
	0.086	0.094
		0.092
		0.074
		0.086
38, 41	0.087	0.097
	0.075	0.077
	0.090	0.091
		0.100
		0.070
		0.090
39, 42	0.084	0.086
	0.073	0.070
	0.093	0.086
	0.082	0.083
	0.065	0.066
	0.088	0.090

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	13	1.99	0.15277	0.06487
Column 2	19	3.52	0.18547	0.19317

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0083	1	0.00826	0.0582	0.811004558	4.171
Within Groups	4.2556	30	0.14185			
Total	4.2638	31				

	Param.	
	1	3
37, 43	0.090	0.104
	0.073	0.091
	0.086	0.099
		0.103
		0.092
		0.102
38, 44	0.087	0.103
	0.075	0.101
	0.090	0.104
		0.102
		0.088
		0.097
39, 45	0.084	0.104
	0.073	0.090
	0.093	0.098
	0.082	0.103
	0.065	0.090
	0.088	0.099

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	13	1.99	0.15277	0.06487
Column 2	19	4.77	0.25105	0.44317

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0746	1	0.07456	0.25547	0.616940244	4.171
Within Groups	8.7555	30	0.29185			
Total	8.8301	31				

	Param.	
	2	3
	0.093	0.104
	0.079	0.091
40, 43	0.094	0.099
	0.092	0.103
	0.074	0.092
	0.086	0.102
	0.097	0.103
	0.077	0.101
41, 44	0.091	0.104
	0.100	0.102
	0.070	0.088
	0.090	0.097
	0.086	0.104
	0.070	0.090
42, 45	0.086	0.098
	0.083	0.103
	0.066	0.090
	0.090	0.099

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	19	3.52	0.18547	0.19317
Column 2	19	4.77	0.25105	0.44317

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0409	1	0.04086	0.12841	0.722181545	4.113
Within Groups	11.454	36	0.31817			
Total	11.495	37				

Appendix J. ANOVA Test for Materials

Legend for Metals

1	Aluminum 6061 T6
2	Yellow Brass SS360
3	420 Stainless Steel
4	D2 Tool Steel 25-30 RC
5	D2 Tool Steel 60-65 RC

0.30 Roughing with No Finishing Passes

	Metals	
	1	2
1, 10	0.264	0.283
	0.275	0.279
	0.264	0.275
	0.281	0.298
	0.287	0.295
	0.278	0.291
2, 11	0.260	0.290
	0.262	0.287
	0.269	0.293
	0.278	0.302
	0.271	0.300
	0.269	0.296
3, 12	0.270	0.281
	0.280	0.276
	0.266	0.280
	0.283	0.291
	0.284	0.285
	0.278	0.288

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.92	0.27328	6.8E-05
2	18	5.19	0.28833	6.7E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002	1	0.00204	30.2409	0.0000038572	4.13
Within Groups	0.0023	34	6.7E-05			
Total	0.0043	35				

	Metals	
	1	3
1, 19	0.264	0.281
	0.275	0.281
	0.264	0.283
	0.281	0.285
	0.287	0.281
	0.278	0.283
2, 20	0.260	0.283
	0.262	0.282
	0.269	0.279
	0.278	0.281
	0.271	0.275
	0.269	0.281
3, 21	0.270	0.282
	0.280	0.286
	0.266	0.278
	0.283	0.279
	0.284	0.288
	0.278	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.92	0.27328	6.8E-05
3	18	5.07	0.28161	8.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0006	1	0.00062	16.2974	0.0002911954	4.13
Within Groups	0.0013	34	3.8E-05			
Total	0.0019	35				

	Metals	
	1	4
1, 28	0.264	0.272
	0.275	0.265
	0.264	0.267
	0.281	0.266
	0.287	0.269
	0.278	0.273
2, 29	0.260	0.284
	0.262	0.285
	0.269	0.284
	0.278	0.290
	0.271	0.287
	0.269	0.285
3, 30	0.270	0.286
	0.280	0.281
	0.266	0.279
	0.283	0.278
	0.284	0.272
	0.278	0.274

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.92	0.27328	6.8E-05
4	18	5	0.27761	6.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00017	2.55618	0.1191170943	4.13
Within Groups	0.0022	34	6.6E-05			
Total	0.0024	35				

	Metals	
	1	5
1, 37	0.264	0.286
	0.275	0.282
	0.264	0.285
	0.281	0.288
	0.287	0.277
	0.278	0.277
2, 38	0.260	0.283
	0.262	0.282
	0.269	0.283
	0.278	0.284
	0.271	0.276
	0.269	0.286
3, 39	0.270	0.278
	0.280	0.278
	0.266	0.284
	0.283	0.286
	0.284	0.283
	0.278	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.92	0.27328	6.8E-05
5	18	5.08	0.28217	1.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0007	1	0.00071	17.5696	0.0001863499	4.13
Within Groups	0.0014	34	4E-05			
Total	0.0021	35				

	Metals	
	2	3
10, 19	0.283	0.281
	0.279	0.281
	0.275	0.283
	0.298	0.285
	0.295	0.281
	0.291	0.283
11, 20	0.290	0.283
	0.287	0.282
	0.293	0.279
	0.302	0.281
	0.300	0.275
	0.296	0.281
12, 21	0.281	0.282
	0.276	0.286
	0.280	0.278
	0.291	0.279
	0.285	0.288
	0.288	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.19	0.28833	6.7E-05
3	18	5.07	0.28161	8.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00041	10.7168	0.0024430719	4.13
Within Groups	0.0013	34	3.8E-05			
Total	0.0017	35				

	Metals	
	2	4
10, 28	0.283	0.272
	0.279	0.265
	0.275	0.267
	0.298	0.266
	0.295	0.269
	0.291	0.273
11, 29	0.290	0.284
	0.287	0.285
	0.293	0.284
	0.302	0.290
	0.300	0.287
	0.296	0.285
12, 30	0.281	0.286
	0.276	0.281
	0.280	0.279
	0.291	0.278
	0.285	0.272
	0.288	0.274

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.19	0.28833	6.7E-05
4	18	5	0.27761	6.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001	1	0.00103	15.7454	0.0003548463	4.13
Within Groups	0.0022	34	6.6E-05			
Total	0.0033	35				

	Metals	
	2	5
10, 37	0.283	0.286
	0.279	0.282
	0.275	0.285
	0.298	0.288
	0.295	0.277
	0.291	0.277
11, 38	0.290	0.283
	0.287	0.282
	0.293	0.283
	0.302	0.284
	0.300	0.276
	0.296	0.286
12, 39	0.281	0.278
	0.276	0.278
	0.280	0.284
	0.291	0.286
	0.285	0.283
	0.288	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.19	0.28833	6.7E-05
5	18	5.08	0.28217	1.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00034	8.54055	0.0061351144	4.13
Within Groups	0.0014	34	4E-05			
Total	0.0017	35				

	Metals	
	3	4
19, 28	0.281	0.272
	0.281	0.265
	0.283	0.267
	0.285	0.266
	0.281	0.269
	0.283	0.273
20, 29	0.283	0.284
	0.282	0.285
	0.279	0.284
	0.281	0.290
	0.275	0.287
	0.281	0.285
21, 30	0.282	0.286
	0.286	0.281
	0.278	0.279
	0.279	0.278
	0.288	0.272
	0.281	0.274

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.07	0.28161	8.8E-06
4	18	5	0.27761	6.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00014	3.93393	0.0554442904	4.13
Within Groups	0.0012	34	3.7E-05			
Total	0.0014	35				

	Metals	
	3	5
19, 37	0.281	0.286
	0.281	0.282
	0.283	0.285
	0.285	0.288
	0.281	0.277
	0.283	0.277
20, 38	0.283	0.283
	0.282	0.282
	0.279	0.283
	0.281	0.284
	0.275	0.276
	0.281	0.286
21, 39	0.282	0.278
	0.286	0.278
	0.278	0.284
	0.279	0.286
	0.288	0.283
	0.281	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.07	0.28161	8.8E-06
5	18	5.08	0.28217	1.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-06	1	2.8E-06	0.25335	0.6179693748	4.13
Within Groups	0.0004	34	1.1E-05			
Total	0.0004	35				

	Metals	
	4	5
28, 37	0.272	0.286
	0.265	0.282
	0.267	0.285
	0.266	0.288
	0.269	0.277
	0.273	0.277
29, 38	0.284	0.283
	0.285	0.282
	0.284	0.283
	0.290	0.284
	0.287	0.276
	0.285	0.286
30, 39	0.286	0.278
	0.281	0.278
	0.279	0.284
	0.278	0.286
	0.272	0.283
	0.274	0.281

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	5	0.27761	6.4E-05
5	18	5.08	0.28217	1.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00019	4.82272	0.0350069777	4.13
Within Groups	0.0013	34	3.9E-05			
Total	0.0015	35				

0.25 Roughing with No Finishing Passes

	Metals	
	1	2
1, 10	0.223	0.222
	0.218	0.222
	0.226	0.226
	0.230	0.244
	0.231	0.241
	0.235	0.244
2, 11	0.215	0.236
	0.219	0.237
	0.215	0.239
	0.223	0.248
	0.225	0.252
	0.221	0.248
3, 12	0.224	0.228
	0.228	0.230
	0.225	0.228
	0.234	0.237
	0.237	0.233
	0.231	0.245

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.06	0.22556	4.3E-05
2	18	4.26	0.23667	8.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0011	1	0.00111	17.3098	0.0002039253	4.13
Within Groups	0.0022	34	6.4E-05			
Total	0.0033	35				

	Metals	
	1	3
1, 19	0.223	0.235
	0.218	0.230
	0.226	0.234
	0.230	0.235
	0.231	0.226
	0.235	0.235
2, 20	0.215	0.230
	0.219	0.227
	0.215	0.232
	0.223	0.236
	0.225	0.233
	0.221	0.231
3, 21	0.224	0.232
	0.228	0.231
	0.225	0.230
	0.234	0.237
	0.237	0.227
	0.231	0.229

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.06	0.22556	4.3E-05
3	18	4.17	0.23167	1.1E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00034	12.4697	0.0012120027	4.13
Within Groups	0.0009	34	2.7E-05			
Total	0.0013	35				

	Metals	
	1	4
1, 28	0.223	0.214
	0.218	0.213
	0.226	0.211
	0.230	0.216
	0.231	0.210
	0.235	0.214
2, 29	0.215	0.234
	0.219	0.234
	0.215	0.240
	0.223	0.237
	0.225	0.230
	0.221	0.234
3, 30	0.224	0.235
	0.228	0.231
	0.225	0.227
	0.234	0.220
	0.237	0.219
	0.231	0.222

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.06	0.22556	4.3E-05
4	18	4.04	0.2245	0.0001

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-05	1	1E-05	0.13821	0.7123788079	4.13
Within Groups	0.0025	34	7.3E-05			
Total	0.0025	35				

	Metals	
	1	5
1, 37	0.223	0.233
	0.218	0.229
	0.226	0.230
	0.230	0.232
	0.231	0.229
	0.235	0.233
2, 38	0.215	0.228
	0.219	0.235
	0.215	0.232
	0.223	0.233
	0.225	0.229
	0.221	0.231
3, 39	0.224	0.229
	0.228	0.232
	0.225	0.232
	0.234	0.231
	0.237	0.226
	0.231	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.06	0.22556	4.3E-05
5	18	4.16	0.23083	4.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00025	10.408	0.0027739700	4.13
Within Groups	0.0008	34	2.4E-05			
Total	0.0011	35				

	Metals	
	2	3
10, 19	0.222	0.235
	0.222	0.230
	0.226	0.234
	0.244	0.235
	0.241	0.226
	0.244	0.235
11, 20	0.236	0.230
	0.237	0.227
	0.239	0.232
	0.248	0.236
	0.252	0.233
	0.248	0.231
12, 21	0.228	0.232
	0.230	0.231
	0.228	0.230
	0.237	0.237
	0.233	0.227
	0.245	0.229

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.26	0.23667	8.5E-05
3	18	4.17	0.23167	1.1E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00022	4.7048	0.0371639207	4.13
Within Groups	0.0016	34	4.8E-05			
Total	0.0019	35				

	Metals	
	2	4
10, 28	0.222	0.214
	0.222	0.213
	0.226	0.211
	0.244	0.216
	0.241	0.210
	0.244	0.214
11, 29	0.236	0.234
	0.237	0.234
	0.239	0.240
	0.248	0.237
	0.252	0.230
	0.248	0.234
12, 30	0.228	0.235
	0.230	0.231
	0.228	0.227
	0.237	0.220
	0.233	0.219
	0.245	0.222

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.26	0.23667	8.5E-05
4	18	4.04	0.2245	0.0001

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0013	1	0.00133	14.2599	0.0006118921	4.13
Within Groups	0.0032	34	9.3E-05			
Total	0.0045	35				

	Metals	
	2	5
10, 37	0.222	0.233
	0.222	0.229
	0.226	0.230
	0.244	0.232
	0.241	0.229
	0.244	0.233
11, 38	0.236	0.228
	0.237	0.235
	0.239	0.232
	0.248	0.233
	0.252	0.229
	0.248	0.231
12, 39	0.228	0.229
	0.230	0.232
	0.228	0.232
	0.237	0.231
	0.233	0.226
	0.245	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.26	0.23667	8.5E-05
5	18	4.16	0.23083	4.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00031	6.81223	0.0133669478	4.13
Within Groups	0.0015	34	4.5E-05			
Total	0.0018	35				

	Metals	
	3	4
19, 28	0.235	0.214
	0.230	0.213
	0.234	0.211
	0.235	0.216
	0.226	0.210
	0.235	0.214
20, 29	0.230	0.234
	0.227	0.234
	0.232	0.240
	0.236	0.237
	0.233	0.230
	0.231	0.234
21, 30	0.232	0.235
	0.231	0.231
	0.230	0.227
	0.237	0.220
	0.227	0.219
	0.229	0.222

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.17	0.23167	1.1E-05
4	18	4.04	0.2245	0.0001

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0005	1	0.00046	8.22638	0.0070440682	4.13
Within Groups	0.0019	34	5.6E-05			
Total	0.0024	35				

	Metals	
	3	5
19, 37	0.235	0.233
	0.230	0.229
	0.234	0.230
	0.235	0.232
	0.226	0.229
	0.235	0.233
20, 38	0.230	0.228
	0.227	0.235
	0.232	0.232
	0.236	0.233
	0.233	0.229
	0.231	0.231
21, 39	0.232	0.229
	0.231	0.232
	0.230	0.232
	0.237	0.231
	0.227	0.226
	0.229	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.17	0.23167	1.1E-05
5	18	4.16	0.23083	4.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-06	1	6.2E-06	0.80952	0.3745896767	4.13
Within Groups	0.0003	34	7.7E-06			
Total	0.0003	35				

	Metals	
	4	5
28, 37	0.214	0.233
	0.213	0.229
	0.211	0.230
	0.216	0.232
	0.210	0.229
	0.214	0.233
29, 38	0.234	0.228
	0.234	0.235
	0.240	0.232
	0.237	0.233
	0.230	0.229
	0.234	0.231
30, 39	0.235	0.229
	0.231	0.232
	0.227	0.232
	0.220	0.231
	0.219	0.226
	0.222	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	4.04	0.2245	0.0001
5	18	4.16	0.23083	4.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00036	6.76999	0.0136320786	4.13
Within Groups	0.0018	34	5.3E-05			
Total	0.0022	35				

0.20 Roughing with No Finishing Passes

	Metals	
	1	2
1, 10	0.168	0.173
	0.174	0.169
	0.181	0.177
		0.189
		0.186
		0.190
2, 11	0.163	0.188
	0.163	0.189
	0.161	0.195
		0.204
		0.197
		0.203
3, 12	0.176	0.179
	0.169	0.172
	0.172	0.178
		0.187
		0.188
		0.188

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.53	0.16967	4.5E-05
2	18	3.35	0.18622	0.0001

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0016	1	0.00164	19.8699	0.0001520229	4.242
Within Groups	0.0021	25	8.3E-05			
Total	0.0037	26				

	Metals	
	1	3
1, 19	0.168	0.185
	0.174	0.185
	0.181	0.182
		0.189
		0.184
		0.189
2, 20	0.163	0.180
	0.163	0.182
	0.161	0.187
		0.184
		0.179
		0.183
3, 21	0.176	0.185
	0.169	0.181
	0.172	0.186
		0.185
		0.183
		0.187

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.53	0.16967	4.5E-05
3	18	3.32	0.18422	7.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0013	1	0.00127	64.1869	0.0000000229	4.242
Within Groups	0.0005	25	2E-05			
Total	0.0018	26				

	Metals	
	1	4
1, 28	0.168	0.160
	0.174	0.161
	0.181	0.161
		0.164
		0.167
		0.170
2, 29	0.163	0.193
	0.163	0.194
	0.161	0.187
		0.194
		0.191
		0.194
3, 30	0.176	0.180
	0.169	0.181
	0.172	0.177
		0.174
		0.171
		0.173

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.53	0.16967	4.5E-05
4	18	3.19	0.17733	0.00015

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00035	2.95663	0.0978853903	4.242
Within Groups	0.003	25	0.00012			
Total	0.0033	26				

	Metals	
	1	5
1, 37	0.168	0.193
	0.174	0.189
	0.181	0.182
		0.186
		0.178
		0.184
2, 38	0.163	0.181
	0.163	0.187
	0.161	0.184
		0.185
		0.185
		0.182
3, 39	0.176	0.179
	0.169	0.177
	0.172	0.181
		0.186
		0.181
		0.185

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.53	0.16967	4.5E-05
5	18	3.31	0.18361	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0012	1	0.00117	46.4239	0.0000003847	4.242
Within Groups	0.0006	25	2.5E-05			
Total	0.0018	26				

	Metals	
	2	3
10, 19	0.173	0.185
	0.169	0.185
	0.177	0.182
	0.189	0.189
	0.186	0.184
	0.190	0.189
11, 20	0.188	0.180
	0.189	0.182
	0.195	0.187
	0.204	0.184
	0.197	0.179
	0.203	0.183
12, 21	0.179	0.185
	0.172	0.181
	0.178	0.186
	0.187	0.185
	0.188	0.183
	0.188	0.187

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.35	0.18622	0.0001
3	18	3.32	0.18422	7.9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-05	1	3.6E-05	0.66369	0.4209285900	4.13
Within Groups	0.0018	34	5.4E-05			
Total	0.0019	35				

	Metals	
	2	4
10, 28	0.173	0.160
	0.169	0.161
	0.177	0.161
	0.189	0.164
	0.186	0.167
	0.190	0.170
11, 29	0.188	0.193
	0.189	0.194
	0.195	0.187
	0.204	0.194
	0.197	0.191
	0.203	0.194
12, 30	0.179	0.180
	0.172	0.181
	0.178	0.177
	0.187	0.174
	0.188	0.171
	0.188	0.173

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.35	0.18622	0.0001
4	18	3.19	0.17733	0.00015

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0007	1	0.00071	5.58235	0.0240047053	4.13
Within Groups	0.0043	34	0.00013			
Total	0.005	35				

	Metals	
	2	5
10, 37	0.173	0.193
	0.169	0.189
	0.177	0.182
	0.189	0.186
	0.186	0.178
	0.190	0.184
11, 38	0.188	0.181
	0.189	0.187
	0.195	0.184
	0.204	0.185
	0.197	0.185
	0.203	0.182
12, 39	0.179	0.179
	0.172	0.177
	0.178	0.181
	0.187	0.186
	0.188	0.181
	0.188	0.185

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.35	0.18622	0.0001
5	18	3.31	0.18361	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	6.1E-05	1.05507	0.3115954826	4.13
Within Groups	0.002	34	5.8E-05			
Total	0.002	35				

	Metals	
	3	4
19, 28	0.185	0.160
	0.185	0.161
	0.182	0.161
	0.189	0.164
	0.184	0.167
	0.189	0.170
20, 29	0.180	0.193
	0.182	0.194
	0.187	0.187
	0.184	0.194
	0.179	0.191
	0.183	0.194
21, 30	0.185	0.180
	0.181	0.181
	0.186	0.177
	0.185	0.174
	0.183	0.171
	0.187	0.173

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.32	0.18422	7.9E-06
4	18	3.19	0.17733	0.00015

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00043	5.26703	0.0280299280	4.13
Within Groups	0.0028	34	8.1E-05			
Total	0.0032	35				

	Metals	
	3	5
19, 37	0.185	0.193
	0.185	0.189
	0.182	0.182
	0.189	0.186
	0.184	0.178
	0.189	0.184
20, 38	0.180	0.181
	0.182	0.187
	0.187	0.184
	0.184	0.185
	0.179	0.185
	0.183	0.182
21, 39	0.185	0.179
	0.181	0.177
	0.186	0.181
	0.185	0.186
	0.183	0.181
	0.187	0.185

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.32	0.18422	7.9E-06
5	18	3.31	0.18361	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-06	1	3.4E-06	0.28329	0.5980114209	4.13
Within Groups	0.0004	34	1.2E-05			
Total	0.0004	35				

	Metals	
	4	5
28, 37	0.160	0.193
	0.161	0.189
	0.161	0.182
	0.164	0.186
	0.167	0.178
	0.170	0.184
29, 38	0.193	0.181
	0.194	0.187
	0.187	0.184
	0.194	0.185
	0.191	0.185
	0.194	0.182
30, 39	0.180	0.179
	0.181	0.177
	0.177	0.181
	0.174	0.186
	0.171	0.181
	0.173	0.185

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	3.19	0.17733	0.00015
5	18	3.31	0.18361	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00035	4.17247	0.0489008208	4.13
Within Groups	0.0029	34	8.5E-05			
Total	0.0032	35				

0.15 Roughing with No Finishing Passes

	Metals	
	1	2
	0.130	0.123
	0.127	0.123
1, 10	0.128	0.125
		0.139
		0.134
2, 11		0.141
		0.133
		0.125
3, 12		0.128

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	3	0.39	0.12833	2.3E-06
2	9	1.17	0.13011	4.7E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7E-06	1	7.1E-06	0.1854	0.6759058442	4.965
Within Groups	0.0004	10	3.8E-05			
Total	0.0004	11				

	Metals	
	1	3
	0.130	0.133
	0.127	0.132
1, 19	0.128	0.132
		0.136
		0.132
		0.140
		0.135
		0.132
2, 20		0.128
		0.130
		0.130
		0.134
		0.128
		0.123
3, 21		0.136

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	3	0.39	0.12833	2.3E-06
3	15	1.98	0.13207	1.6E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3E-05	1	3.5E-05	2.36635	0.1435173447	4.494
Within Groups	0.0002	16	1.5E-05			
Total	0.0003	17				

	Metals	
	1	4
1, 28	0.130	0.108
	0.127	0.108
	0.128	0.110
		0.109
		0.113
		0.115
2, 29		0.135
		0.132
		0.137
		0.140
		0.129
		0.142
3, 30		0.127
		0.130
		0.128
		0.125
		0.117
		0.127

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	3	0.39	0.12833	2.3E-06
4	18	2.23	0.124	0.00013

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5E-05	1	4.8E-05	0.4135	0.5278811871	4.381
Within Groups	0.0022	19	0.00012			
Total	0.0023	20				

	Metals	
	1	5
1, 37	0.130	0.136
	0.127	0.133
	0.128	0.134
		0.133
		0.131
		0.134
2, 38		0.133
		0.128
		0.141
		0.136
		0.131
		0.135
3, 39		0.133
		0.128
		0.132
		0.132
		0.134
		0.131

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	3	0.39	0.12833	2.3E-06
5	18	2.4	0.13306	9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	5.7E-05	6.91248	0.0165226643	4.381
Within Groups	0.0002	19	8.3E-06			
Total	0.0002	20				

	Metals	
	2	3
10, 19	0.123	0.133
	0.123	0.132
	0.125	0.132
		0.136
		0.132
		0.140
11, 20	0.139	0.135
	0.134	0.132
	0.141	0.128
		0.130
		0.130
		0.134
12, 21	0.133	0.128
	0.125	0.123
	0.128	0.136

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
2	9	1.17	0.13011	4.7E-05
3	15	1.98	0.13207	1.6E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2E-05	1	2.2E-05	0.77604	0.3878788406	4.301
Within Groups	0.0006	22	2.8E-05			
Total	0.0006	23				

	Metals	
	2	4
10, 28	0.123	0.108
	0.123	0.108
	0.125	0.110
		0.109
		0.113
		0.115
11, 29	0.139	0.135
	0.134	0.132
	0.141	0.137
		0.140
		0.129
		0.142
12, 30	0.133	0.127
	0.125	0.130
	0.128	0.128
		0.125
		0.117
		0.127

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
2	9	1.17	0.13011	4.7E-05
4	18	2.23	0.124	0.00013

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0002	1	0.00022	2.16047	0.1540753461	4.242
Within Groups	0.0026	25	0.0001			
Total	0.0028	26				

	Metals	
	2	5
10, 37	0.123	0.136
	0.123	0.133
	0.125	0.134
		0.133
		0.131
		0.134
11, 38	0.139	0.133
	0.134	0.128
	0.141	0.141
		0.136
		0.131
		0.135
12, 39	0.133	0.133
	0.125	0.128
	0.128	0.132
		0.132
		0.134
		0.131

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	9	1.17	0.13011	4.7E-05
5	18	2.4	0.13306	9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5E-05	1	5.2E-05	2.44525	0.1304528395	4.242
Within Groups	0.0005	25	2.1E-05			
Total	0.0006	26				

	Metals	
	3	4
19, 28	0.133	0.108
	0.132	0.108
	0.132	0.110
	0.136	0.109
	0.132	0.113
	0.140	0.115
20, 29	0.135	0.135
	0.132	0.132
	0.128	0.137
	0.130	0.140
	0.130	0.129
	0.134	0.142
21, 30	0.128	0.127
	0.123	0.130
	0.136	0.128
		0.125
		0.117
		0.127

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	15	1.98	0.13207	1.6E-05
4	18	2.23	0.124	0.00013

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0005	1	0.00053	6.75045	0.0142150908	4.16
Within Groups	0.0024	31	7.9E-05			
Total	0.003	32				

	Metals	
	3	5
19, 37	0.133	0.136
	0.132	0.133
	0.132	0.134
	0.136	0.133
	0.132	0.131
	0.140	0.134
20, 38	0.135	0.133
	0.132	0.128
	0.128	0.141
	0.130	0.136
	0.130	0.131
	0.134	0.135
21, 39	0.128	0.133
	0.123	0.128
	0.136	0.132
		0.132
		0.134
		0.131

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	15	1.98	0.13207	1.6E-05
5	18	2.4	0.13306	9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8E-06	1	8E-06	0.64612	0.4276242120	4.16
Within Groups	0.0004	31	1.2E-05			
Total	0.0004	32				

	Metals	
	4	5
28, 37	0.108	0.136
	0.108	0.133
	0.110	0.134
	0.109	0.133
	0.113	0.131
	0.115	0.134
29, 38	0.135	0.133
	0.132	0.128
	0.137	0.141
	0.140	0.136
	0.129	0.131
	0.142	0.135
30, 39	0.127	0.133
	0.130	0.128
	0.128	0.132
	0.125	0.132
	0.117	0.134
	0.127	0.131

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	2.23	0.124	0.00013
5	18	2.4	0.13306	9E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0007	1	0.00074	10.6014	0.0025614931	4.13
Within Groups	0.0024	34	7E-05			
Total	0.0031	35				

0.10 Roughing with No Finishing Passes

	Metals	
	3	4
19, 28	0.088	0.053
	0.079	0.053
	0.085	0.064
20, 29	0.087	0.086
	0.078	0.080
	0.087	0.094
21, 30	0.079	0.082
	0.081	0.074
	0.083	0.085

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	9	0.75	0.083	1.5E-05
4	9	0.67	0.07456	0.00022

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00032	2.75113	0.1166572258	4.494
Within Groups	0.0019	16	0.00012			
Total	0.0022	17				

	Metals	
	3	5
19, 37	0.088	0.090
	0.079	0.073
	0.085	0.086
20, 38	0.087	0.087
	0.078	0.075
	0.087	0.090
21, 39	0.079	0.084
	0.081	0.073
	0.083	0.093
		0.082
		0.065
		0.088

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	9	0.75	0.083	1.5E-05
5	12	0.99	0.08217	7.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-06	1	3.6E-06	0.0713	0.7923250913	4.381
Within Groups	0.001	19	5E-05			
Total	0.001	20				

	Metals	
	4	5
28, 37	0.053	0.090
	0.053	0.073
	0.064	0.086
29, 38	0.086	0.087
	0.080	0.075
	0.094	0.090
30, 39	0.082	0.084
	0.074	0.073
	0.085	0.093
		0.082
		0.065
		0.088

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	9	0.67	0.07456	0.00022
5	12	0.99	0.08217	7.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.0003	2.1992	0.1544807380	4.381
Within Groups	0.0026	19	0.00014			
Total	0.0029	20				

0.30 Roughing with One Finishing Pass

	Metals	
	1	2
4, 13	0.283	0.277
	0.279	0.284
	0.283	0.277
	0.283	0.284
	0.291	0.285
	0.290	0.280
5, 14	0.291	0.278
	0.292	0.281
	0.290	0.281
	0.290	0.281
	0.297	0.286
	0.292	0.285
6, 15	0.296	0.280
	0.293	0.280
	0.294	0.282
	0.291	0.279
	0.298	0.282
	0.294	0.280

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.23	0.29039	2.7E-05
2	18	5.06	0.28122	7.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0008	1	0.00076	43.4782	0.0000001474	4.13
Within Groups	0.0006	34	1.7E-05			
Total	0.0013	35				

	Metals	
	1	3
4, 22	0.283	0.296
	0.279	0.300
	0.283	0.295
	0.283	0.297
	0.291	0.300
	0.290	0.300
5, 23	0.291	0.297
	0.292	0.293
	0.290	0.291
	0.290	0.292
	0.297	0.294
	0.292	0.293
6, 24	0.296	0.287
	0.293	0.286
	0.294	0.281
	0.291	0.283
	0.298	0.284
	0.294	0.285

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.23	0.29039	2.7E-05
3	18	5.25	0.29189	3.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-05	1	2E-05	0.6169	0.4376391946	4.13
Within Groups	0.0011	34	3.3E-05			
Total	0.0011	35				

	Metals	
	1	4
4, 31	0.283	0.296
	0.279	0.294
	0.283	0.297
	0.283	0.288
	0.291	0.285
	0.290	0.287
5, 32	0.291	0.285
	0.292	0.287
	0.290	0.282
	0.290	0.282
	0.297	0.283
	0.292	0.283
6, 33	0.296	0.294
	0.293	0.295
	0.294	0.293
	0.291	0.292
	0.298	0.295
	0.294	0.290

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	18	5.23	0.29039	2.7E-05
4	18	5.21	0.28933	2.8E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1E-05	1	1E-05	0.36415	0.5502159928	4.13
Within Groups	0.0009	34	2.8E-05			
Total	0.0009	35				

	Metals	
	1	5
4, 40	0.283	0.275
	0.279	0.280
	0.283	0.280
	0.283	0.279
	0.291	0.280
	0.290	0.281
5, 41	0.291	0.296
	0.292	0.296
	0.290	0.296
	0.290	0.294
	0.297	0.295
	0.292	0.292
6, 42	0.296	0.283
	0.293	0.286
	0.294	0.290
	0.291	0.289
	0.298	0.294
	0.294	0.294

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	18	5.23	0.29039	2.7E-05
5	18	5.18	0.28778	5.2E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6E-05	1	6.1E-05	1.53925	0.2232230948	4.13
Within Groups	0.0014	34	4E-05			
Total	0.0014	35				

	Metals	
	2	3
13, 22	0.277	0.296
	0.284	0.300
	0.277	0.295
	0.284	0.297
	0.285	0.300
	0.280	0.300
14, 23	0.278	0.297
	0.281	0.293
	0.281	0.291
	0.281	0.292
	0.286	0.294
	0.285	0.293
15, 24	0.280	0.287
	0.280	0.286
	0.282	0.281
	0.279	0.283
	0.282	0.284
	0.280	0.285

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.06	0.28122	7.4E-06
3	18	5.25	0.29189	3.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001	1	0.00102	44.9303	0.0000001068	4.13
Within Groups	0.0008	34	2.3E-05			
Total	0.0018	35				

	Metals	
	2	4
13, 31	0.277	0.296
	0.284	0.294
	0.277	0.297
	0.284	0.288
	0.285	0.285
	0.280	0.287
14, 32	0.278	0.285
	0.281	0.287
	0.281	0.282
	0.281	0.282
	0.286	0.283
	0.285	0.283
15, 33	0.280	0.294
	0.280	0.295
	0.282	0.293
	0.279	0.292
	0.282	0.295
	0.280	0.290

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.06	0.28122	7.4E-06
4	18	5.21	0.28933	2.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0006	1	0.00059	33.8286	0.0000014920	4.13
Within Groups	0.0006	34	1.8E-05			
Total	0.0012	35				

	Metals	
	2	5
13, 40	0.277	0.275
	0.284	0.280
	0.277	0.280
	0.284	0.279
	0.285	0.280
	0.280	0.281
14, 41	0.278	0.296
	0.281	0.296
	0.281	0.296
	0.281	0.294
	0.286	0.295
	0.285	0.292
15, 42	0.280	0.283
	0.280	0.286
	0.282	0.290
	0.279	0.289
	0.282	0.294
	0.280	0.294

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.06	0.28122	7.4E-06
5	18	5.18	0.28778	5.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00039	12.966	0.0009996591	4.13
Within Groups	0.001	34	3E-05			
Total	0.0014	35				

	Metals	
	3	4
22, 31	0.296	0.296
	0.300	0.294
	0.295	0.297
	0.297	0.288
	0.300	0.285
	0.300	0.287
23, 32	0.297	0.285
	0.293	0.287
	0.291	0.282
	0.292	0.282
	0.294	0.283
	0.293	0.283
24, 33	0.287	0.294
	0.286	0.295
	0.281	0.293
	0.283	0.292
	0.284	0.295
	0.285	0.290

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.25	0.29189	3.8E-05
4	18	5.21	0.28933	2.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	5.9E-05	1.78468	0.1904494479	4.13
Within Groups	0.0011	34	3.3E-05			
Total	0.0012	35				

	Metals	
	3	5
22, 40	0.296	0.275
	0.300	0.280
	0.295	0.280
	0.297	0.279
	0.300	0.280
	0.300	0.281
23, 41	0.297	0.296
	0.293	0.296
	0.291	0.296
	0.292	0.294
	0.294	0.295
	0.293	0.292
24, 42	0.287	0.283
	0.286	0.286
	0.281	0.290
	0.283	0.289
	0.284	0.294
	0.285	0.294

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.25	0.29189	3.8E-05
5	18	5.18	0.28778	5.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00015	3.36072	0.0755366301	4.13
Within Groups	0.0015	34	4.5E-05			
Total	0.0017	35				

	Metals	
	4	5
31, 40	0.296	0.275
	0.294	0.280
	0.297	0.280
	0.288	0.279
	0.285	0.280
	0.287	0.281
32, 41	0.285	0.296
	0.287	0.296
	0.282	0.296
	0.282	0.294
	0.283	0.295
	0.283	0.292
33, 42	0.294	0.283
	0.295	0.286
	0.293	0.290
	0.292	0.289
	0.295	0.294
	0.290	0.294

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	5.21	0.28933	2.8E-05
5	18	5.18	0.28778	5.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-05	1	2.2E-05	0.5448	0.4655144182	4.13
Within Groups	0.0014	34	4E-05			
Total	0.0014	35				

0.25 Roughing with One Finishing Pass

	Metals	
	1	2
4, 13	0.229	0.230
	0.230	0.230
	0.235	0.232
	0.231	0.232
	0.232	0.231
	0.233	0.232
5, 14	0.240	0.228
	0.243	0.231
	0.244	0.234
	0.242	0.234
	0.247	0.237
	0.245	0.235
6, 15	0.245	0.226
	0.248	0.231
	0.247	0.229
	0.242	0.231
	0.249	0.231
	0.248	0.231

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.33	0.24056	4.8E-05
2	18	4.17	0.23139	6.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0008	1	0.00076	27.5082	0.0000082635	4.13
Within Groups	0.0009	34	2.7E-05			
Total	0.0017	35				

	Metals	
	1	3
4, 22	0.229	0.246
	0.230	0.244
	0.235	0.246
	0.231	0.243
	0.232	0.250
	0.233	0.244
5, 23	0.240	0.238
	0.243	0.238
	0.244	0.243
	0.242	0.242
	0.247	0.247
	0.245	0.239
6, 24	0.245	0.233
	0.248	0.231
	0.247	0.233
	0.242	0.235
	0.249	0.229
	0.248	0.234

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.33	0.24056	4.8E-05
3	18	4.32	0.23972	3.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-06	1	6.3E-06	0.14475	0.7059711579	4.13
Within Groups	0.0015	34	4.3E-05			
Total	0.0015	35				

	Metals	
	1	4
4, 31	0.229	0.244
	0.230	0.248
	0.235	0.247
	0.231	0.243
	0.232	0.239
	0.233	0.240
5, 32	0.240	0.235
	0.243	0.238
	0.244	0.235
	0.242	0.230
	0.247	0.229
	0.245	0.236
6, 33	0.245	0.238
	0.248	0.245
	0.247	0.242
	0.242	0.240
	0.249	0.244
	0.248	0.242

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.33	0.24056	4.8E-05
4	18	4.32	0.23972	2.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-06	1	6.3E-06	0.1627	0.6892050026	4.13
Within Groups	0.0013	34	3.8E-05			
Total	0.0013	35				

	Metals	
	1	5
4, 40	0.229	0.241
	0.230	0.241
	0.235	0.246
	0.231	0.239
	0.232	0.241
	0.233	0.241
5, 41	0.240	0.243
	0.243	0.247
	0.244	0.239
	0.242	0.244
	0.247	0.243
	0.245	0.237
6, 42	0.245	0.235
	0.248	0.232
	0.247	0.238
	0.242	0.236
	0.249	0.237
	0.248	0.238

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.33	0.24056	4.8E-05
5	18	4.32	0.23989	1.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-06	1	4E-06	0.1259	0.7249130607	4.13
Within Groups	0.0011	34	3.2E-05			
Total	0.0011	35				

	Metals	
	2	3
13, 22	0.230	0.246
	0.230	0.244
	0.232	0.246
	0.232	0.243
	0.231	0.250
	0.232	0.244
14, 23	0.228	0.238
	0.231	0.238
	0.234	0.243
	0.234	0.242
	0.237	0.247
	0.235	0.239
15, 24	0.226	0.233
	0.231	0.231
	0.229	0.233
	0.231	0.235
	0.231	0.229
	0.231	0.234

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.17	0.23139	6.5E-06
3	18	4.32	0.23972	3.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0006	1	0.00062	28.1872	0.0000068157	4.13
Within Groups	0.0008	34	2.2E-05			
Total	0.0014	35				

	Metals	
	2	4
13, 31	0.230	0.244
	0.230	0.248
	0.232	0.247
	0.232	0.243
	0.231	0.239
	0.232	0.240
14, 32	0.228	0.235
	0.231	0.238
	0.234	0.235
	0.234	0.230
	0.237	0.229
	0.235	0.236
15, 33	0.226	0.238
	0.231	0.245
	0.229	0.242
	0.231	0.240
	0.231	0.244
	0.231	0.242

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.17	0.23139	6.5E-06
4	18	4.32	0.23972	2.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0006	1	0.00062	35.902	0.0000008825	4.13
Within Groups	0.0006	34	1.7E-05			
Total	0.0012	35				

	Metals	
	2	5
13, 40	0.230	0.241
	0.230	0.241
	0.232	0.246
	0.232	0.239
	0.231	0.241
	0.232	0.241
14, 41	0.228	0.243
	0.231	0.247
	0.234	0.239
	0.234	0.244
	0.237	0.243
	0.235	0.237
15, 42	0.226	0.235
	0.231	0.232
	0.229	0.238
	0.231	0.236
	0.231	0.237
	0.231	0.238

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.17	0.23139	6.5E-06
5	18	4.32	0.23989	1.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0007	1	0.00065	60.3966	0.0000000048	4.13
Within Groups	0.0004	34	1.1E-05			
Total	0.001	35				

	Metals	
	3	4
22, 31	0.246	0.244
	0.244	0.248
	0.246	0.247
	0.243	0.243
	0.250	0.239
	0.244	0.240
23, 32	0.238	0.235
	0.238	0.238
	0.243	0.235
	0.242	0.230
	0.247	0.229
	0.239	0.236
24, 33	0.233	0.238
	0.231	0.245
	0.233	0.242
	0.235	0.240
	0.229	0.244
	0.234	0.242

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.32	0.23972	3.8E-05
4	18	4.32	0.23972	2.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0	1	0	0	1.0000000000	4.13
Within Groups	0.0011	34	3.3E-05			
Total	0.0011	35				

	Metals	
	3	5
22, 40	0.246	0.241
	0.244	0.241
	0.246	0.246
	0.243	0.239
	0.250	0.241
	0.244	0.241
23, 41	0.238	0.243
	0.238	0.247
	0.243	0.239
	0.242	0.244
	0.247	0.243
	0.239	0.237
24, 42	0.233	0.235
	0.231	0.232
	0.233	0.238
	0.235	0.236
	0.229	0.237
	0.234	0.238

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.32	0.23972	3.8E-05
5	18	4.32	0.23989	1.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-07	1	2.5E-07	0.00945	0.9231260490	4.13
Within Groups	0.0009	34	2.6E-05			
Total	0.0009	35				

	Metals	
	4	5
31, 40	0.244	0.241
	0.248	0.241
	0.247	0.246
	0.243	0.239
	0.239	0.241
	0.240	0.241
32, 41	0.235	0.243
	0.238	0.247
	0.235	0.239
	0.230	0.244
	0.229	0.243
	0.236	0.237
33, 42	0.238	0.235
	0.245	0.232
	0.242	0.238
	0.240	0.236
	0.244	0.237
	0.242	0.238

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	4.32	0.23972	2.8E-05
5	18	4.32	0.23989	1.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-07	1	2.5E-07	0.01153	0.9151307801	4.13
Within Groups	0.0007	34	2.2E-05			
Total	0.0007	35				

0.20 Roughing with One Finishing Pass

	Metals	
	1	2
4, 13	0.179	0.178
	0.180	0.184
	0.182	0.185
	0.190	0.190
	0.195	0.190
	0.193	0.187
5, 14	0.190	0.181
	0.194	0.182
	0.196	0.183
	0.208	0.186
	0.209	0.186
	0.202	0.187
6, 15	0.197	0.180
	0.200	0.181
	0.199	0.183
	0.202	0.184
	0.207	0.187
	0.204	0.186

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	18	3.53	0.19594	8.4E-05
2	18	3.32	0.18444	1.1E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0012	1	0.00119	25.1765	0.0000162978	4.13
Within Groups	0.0016	34	4.7E-05			
Total	0.0028	35				

	Metals	
	1	3
4, 22	0.179	0.193
	0.180	0.197
	0.182	0.200
	0.190	0.198
	0.195	0.200
	0.193	0.198
5, 23	0.190	0.195
	0.194	0.194
	0.196	0.195
	0.208	0.200
	0.209	0.195
	0.202	0.197
6, 24	0.197	0.181
	0.200	0.183
	0.199	0.184
	0.202	0.184
	0.207	0.187
	0.204	0.187

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	18	3.53	0.19594	8.4E-05
3	18	3.47	0.19267	4.2E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1E-04	1	9.7E-05	1.53559	0.2237618341	4.13
Within Groups	0.0021	34	6.3E-05			
Total	0.0022	35				

	Metals	
	1	4
4, 31	0.179	0.196
	0.180	0.196
	0.182	0.200
	0.190	0.192
	0.195	0.192
	0.193	0.197
5, 32	0.190	0.183
	0.194	0.190
	0.196	0.189
	0.208	0.185
	0.209	0.184
	0.202	0.189
6, 33	0.197	0.193
	0.200	0.198
	0.199	0.195
	0.202	0.194
	0.207	0.191
	0.204	0.195

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.53	0.19594	8.4E-05
4	18	3.46	0.19217	2.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00013	2.40024	0.1305754806	4.13
Within Groups	0.0018	34	5.4E-05			
Total	0.0019	35				

	Metals	
	1	5
4, 40	0.179	0.195
	0.180	0.193
	0.182	0.192
	0.190	0.189
	0.195	0.191
	0.193	0.191
5, 41	0.190	0.186
	0.194	0.188
	0.196	0.185
	0.208	0.185
	0.209	0.183
	0.202	0.182
6, 42	0.197	0.188
	0.200	0.190
	0.199	0.184
	0.202	0.192
	0.207	0.194
	0.204	0.194

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.53	0.19594	8.4E-05
5	18	3.4	0.189	1.7E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0004	1	0.00043	8.65538	0.0058350527	4.13
Within Groups	0.0017	34	5E-05			
Total	0.0021	35				

	Metals	
	2	3
13, 22	0.178	0.193
	0.184	0.197
	0.185	0.200
	0.190	0.198
	0.190	0.200
	0.187	0.198
14, 23	0.181	0.195
	0.182	0.194
	0.183	0.195
	0.186	0.200
	0.186	0.195
	0.187	0.197
15, 24	0.180	0.181
	0.181	0.183
	0.183	0.184
	0.184	0.184
	0.187	0.187
	0.186	0.187

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.32	0.18444	1.1E-05
3	18	3.47	0.19267	4.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0006	1	0.00061	22.9234	0.0000323065	4.13
Within Groups	0.0009	34	2.7E-05			
Total	0.0015	35				

	Metals	
	2	4
13, 31	0.178	0.196
	0.184	0.196
	0.185	0.200
	0.190	0.192
	0.190	0.192
	0.187	0.197
14, 32	0.181	0.183
	0.182	0.190
	0.183	0.189
	0.186	0.185
	0.186	0.184
	0.187	0.189
15, 33	0.180	0.193
	0.181	0.198
	0.183	0.195
	0.184	0.194
	0.187	0.191
	0.186	0.195

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.32	0.18444	1.1E-05
4	18	3.46	0.19217	2.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0005	1	0.00054	31.4103	0.0000028133	4.13
Within Groups	0.0006	34	1.7E-05			
Total	0.0011	35				

	Metals	
	2	5
13, 40	0.178	0.195
	0.184	0.193
	0.185	0.192
	0.190	0.189
	0.190	0.191
	0.187	0.191
14, 41	0.181	0.186
	0.182	0.188
	0.183	0.185
	0.186	0.185
	0.186	0.183
	0.187	0.182
15, 42	0.180	0.188
	0.181	0.190
	0.183	0.184
	0.184	0.192
	0.187	0.194
	0.186	0.194

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.32	0.18444	1.1E-05
5	18	3.4	0.189	1.7E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00019	13.6146	0.0007800752	4.13
Within Groups	0.0005	34	1.4E-05			
Total	0.0007	35				

	Metals	
	3	4
22, 31	0.193	0.196
	0.197	0.196
	0.200	0.200
	0.198	0.192
	0.200	0.192
	0.198	0.197
23, 32	0.195	0.183
	0.194	0.190
	0.195	0.189
	0.200	0.185
	0.195	0.184
	0.197	0.189
24, 33	0.181	0.193
	0.183	0.198
	0.184	0.195
	0.184	0.194
	0.187	0.191
	0.187	0.195

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.47	0.19267	4.2E-05
4	18	3.46	0.19217	2.3E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-06	1	2.3E-06	0.06864	0.7949071841	4.13
Within Groups	0.0011	34	3.3E-05			
Total	0.0011	35				

	Metals	
	3	5
22, 40	0.193	0.195
	0.197	0.193
	0.200	0.192
	0.198	0.189
	0.200	0.191
	0.198	0.191
23, 41	0.195	0.186
	0.194	0.188
	0.195	0.185
	0.200	0.185
	0.195	0.183
	0.197	0.182
24, 42	0.181	0.188
	0.183	0.190
	0.184	0.184
	0.184	0.192
	0.187	0.194
	0.187	0.194

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.47	0.19267	4.2E-05
5	18	3.4	0.189	1.7E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00012	4.114	0.0504217640	4.13
Within Groups	0.001	34	2.9E-05			
Total	0.0011	35				

	Metals	
	4	5
31, 40	0.196	0.195
	0.196	0.193
	0.200	0.192
	0.192	0.189
	0.192	0.191
	0.197	0.191
32, 41	0.183	0.186
	0.190	0.188
	0.189	0.185
	0.185	0.185
	0.184	0.183
	0.189	0.182
33, 42	0.193	0.188
	0.198	0.190
	0.195	0.184
	0.194	0.192
	0.191	0.194
	0.195	0.194

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	3.46	0.19217	2.3E-05
5	18	3.4	0.189	1.7E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9E-05	1	9E-05	4.52248	0.0407918741	4.13
Within Groups	0.0007	34	2E-05			
Total	0.0008	35				

0.15 Roughing with One Finishing Pass

	Metals	
	1	2
4, 13	0.136	0.129
	0.135	0.124
	0.143	0.135
		0.150
		0.143
		0.142
5, 14	0.141	0.129
	0.143	0.129
	0.151	0.139
		0.151
		0.149
		0.148
6, 15	0.148	0.128
	0.146	0.130
	0.155	0.140
		0.148
		0.144
		0.142

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.3	0.14422	4.3E-05
2	18	2.5	0.13889	7.8E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00017	2.54676	0.1230860174	4.242
Within Groups	0.0017	25	6.7E-05			
Total	0.0018	26				

	Metals	
	1	3
4, 22	0.136	0.144
	0.135	0.142
	0.143	0.147
		0.147
		0.145
		0.148
5, 23	0.141	0.141
	0.143	0.136
	0.151	0.145
		0.149
		0.147
		0.150
6, 24	0.148	0.130
	0.146	0.132
	0.155	0.136
		0.136
		0.130
		0.136

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	1.3	0.14422	4.3E-05
3	18	2.54	0.14117	4.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	5.6E-05	1.25935	0.2724377251	4.242
Within Groups	0.0011	25	4.4E-05			
Total	0.0012	26				

	Metals	
	1	4
4, 31	0.136	0.141
	0.135	0.143
	0.143	0.147
		0.146
		0.142
		0.143
5, 32	0.141	0.135
	0.143	0.132
	0.151	0.134
		0.133
		0.135
		0.140
6, 33	0.148	0.142
	0.146	0.143
	0.155	0.149
		0.142
		0.140
		0.144

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	9	1.3	0.14422	4.3E-05
4	18	2.53	0.14061	2.4E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8E-05	1	7.8E-05	2.57427	0.1211740256	4.242
Within Groups	0.0008	25	3E-05			
Total	0.0008	26				

	Metals	
	1	5
4, 40	0.136	0.145
	0.135	0.145
	0.143	0.146
		0.145
		0.136
		0.142
5, 41	0.141	0.145
	0.143	0.140
	0.151	0.142
		0.144
		0.138
		0.142
6, 42	0.148	0.135
	0.146	0.134
	0.155	0.135
		0.138
		0.139
		0.138

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	9	1.3	0.14422	4.3E-05
5	18	2.53	0.1405	1.6E-05

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8E-05	1	8.3E-05	3.3517	0.0790816756	4.242
Within Groups	0.0006	25	2.5E-05			
Total	0.0007	26				

	Metals	
	2	3
13, 22	0.129	0.144
	0.124	0.142
	0.135	0.147
	0.150	0.147
	0.143	0.145
	0.142	0.148
14, 23	0.129	0.141
	0.129	0.136
	0.139	0.145
	0.151	0.149
	0.149	0.147
	0.148	0.150
15, 24	0.128	0.130
	0.130	0.132
	0.140	0.136
	0.148	0.136
	0.144	0.130
	0.142	0.136

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.5	0.13889	7.8E-05
3	18	2.54	0.14117	4.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5E-05	1	4.7E-05	0.75735	0.3902627836	4.13
Within Groups	0.0021	34	6.2E-05			
Total	0.0021	35				

	Metals	
	2	4
13, 31	0.129	0.141
	0.124	0.143
	0.135	0.147
	0.150	0.146
	0.143	0.142
	0.142	0.143
14, 32	0.129	0.135
	0.129	0.132
	0.139	0.134
	0.151	0.133
	0.149	0.135
	0.148	0.140
15, 33	0.128	0.142
	0.130	0.143
	0.140	0.149
	0.148	0.142
	0.144	0.140
	0.142	0.144

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.5	0.13889	7.8E-05
4	18	2.53	0.14061	2.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-05	1	2.7E-05	0.5204	0.4756017927	4.13
Within Groups	0.0017	34	5.1E-05			
Total	0.0018	35				

	Metals	
	2	5
13, 40	0.129	0.145
	0.124	0.145
	0.135	0.146
	0.150	0.145
	0.143	0.136
	0.142	0.142
14, 41	0.129	0.145
	0.129	0.140
	0.139	0.142
	0.151	0.144
	0.149	0.138
	0.148	0.142
15, 42	0.128	0.135
	0.130	0.134
	0.140	0.135
	0.148	0.138
	0.144	0.139
	0.142	0.138

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.5	0.13889	7.8E-05
5	18	2.53	0.1405	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-05	1	2.3E-05	0.4951	0.4864522245	4.13
Within Groups	0.0016	34	4.7E-05			
Total	0.0016	35				

	Metals	
	3	4
22, 31	0.144	0.141
	0.142	0.143
	0.147	0.147
	0.147	0.146
	0.145	0.142
	0.148	0.143
23, 32	0.141	0.135
	0.136	0.132
	0.145	0.134
	0.149	0.133
	0.147	0.135
	0.150	0.140
24, 33	0.130	0.142
	0.132	0.143
	0.136	0.149
	0.136	0.142
	0.130	0.140
	0.136	0.144

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	2.54	0.14117	4.5E-05
4	18	2.53	0.14061	2.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-06	1	2.8E-06	0.07998	0.7790325603	4.13
Within Groups	0.0012	34	3.5E-05			
Total	0.0012	35				

	Metals	
	3	5
22, 40	0.144	0.145
	0.142	0.145
	0.147	0.146
	0.147	0.145
	0.145	0.136
	0.148	0.142
23, 41	0.141	0.145
	0.136	0.140
	0.145	0.142
	0.149	0.144
	0.147	0.138
	0.150	0.142
24, 42	0.130	0.135
	0.132	0.134
	0.136	0.135
	0.136	0.138
	0.130	0.139
	0.136	0.138

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	2.54	0.14117	4.5E-05
5	18	2.53	0.1405	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-06	1	4E-06	0.13064	0.7200021732	4.13
Within Groups	0.001	34	3.1E-05			
Total	0.001	35				

	Metals	
	4	5
31, 40	0.141	0.145
	0.143	0.145
	0.147	0.146
	0.146	0.145
	0.142	0.136
	0.143	0.142
32, 41	0.135	0.145
	0.132	0.140
	0.134	0.142
	0.133	0.144
	0.135	0.138
	0.140	0.142
33, 42	0.142	0.135
	0.143	0.134
	0.149	0.135
	0.142	0.138
	0.140	0.139
	0.144	0.138

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	2.53	0.14061	2.4E-05
5	18	2.53	0.1405	1.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-07	1	1.1E-07	0.00548	0.9413973416	4.13
Within Groups	0.0007	34	2E-05			
Total	0.0007	35				

0.10 Roughing with One Finishing Pass

	Metals	
	1	3
		0.094
		0.080
4, 22		0.099
	0.110	0.092
	0.114	0.078
5, 23	0.120	0.092
	0.118	0.076
	0.117	0.072
6, 24	0.123	0.084
		0.108
		0.100
		0.105

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	6	0.7	0.117	2.1E-05
3	12	1.08	0.09	0.00014

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0029	1	0.00292	28.1399	0.0000711693	4.494
Within Groups	0.0017	16	0.0001			
Total	0.0046	17				

	Metals	
	1	4
		0.087
		0.084
4, 31		0.097
		0.104
		0.099
		0.102
	0.110	0.083
	0.114	0.070
5, 32	0.120	0.086
		0.099
		0.091
		0.095
	0.118	0.090
	0.117	0.083
6, 33	0.123	0.099
		0.110
		0.102
		0.107

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
1	6	0.7	0.117	2.1E-05
4	18	1.69	0.09378	0.00011

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0024	1	0.00243	28.1417	0.0000252616	4.301
Within Groups	0.0019	22	8.6E-05			
Total	0.0043	23				

	Metals	
	1	5
4, 40		0.093
		0.079
		0.094
		0.092
		0.074
		0.086
5, 41	0.110	0.097
	0.114	0.077
	0.120	0.091
		0.100
		0.070
		0.090
6, 42	0.118	0.086
	0.117	0.070
	0.123	0.086
		0.083
		0.066
		0.090

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	6	0.7	0.117	2.1E-05
5	18	1.52	0.08467	9.9E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0047	1	0.0047	57.8207	0.0000001357	4.301
Within Groups	0.0018	22	8.1E-05			
Total	0.0065	23				

	Metals	
	3	4
22, 31	0.094	0.087
	0.080	0.084
	0.099	0.097
		0.104
		0.099
		0.102
23, 32	0.092	0.083
	0.078	0.070
	0.092	0.086
		0.099
		0.091
		0.095
24, 33	0.076	0.090
	0.072	0.083
	0.084	0.099
	0.108	0.110
	0.100	0.102
	0.105	0.107

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	12	1.08	0.09	0.00014
4	18	1.69	0.09378	0.00011

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.0001	0.85959	0.3617758096	4.196
Within Groups	0.0033	28	0.00012			
Total	0.0034	29				

	Metals	
	3	5
22, 40	0.094	0.093
	0.080	0.079
	0.099	0.094
		0.092
		0.074
		0.086
23, 41	0.092	0.097
	0.078	0.077
	0.092	0.091
		0.100
		0.070
		0.090
24, 42	0.076	0.086
	0.072	0.070
	0.084	0.086
	0.108	0.083
	0.100	0.066
	0.105	0.090

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	12	1.08	0.09	0.00014
5	18	1.52	0.08467	9.9E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.0002	1.76988	0.1941318677	4.196
Within Groups	0.0032	28	0.00012			
Total	0.0034	29				

	Metals	
	4	5
31, 40	0.087	0.093
	0.084	0.079
	0.097	0.094
	0.104	0.092
	0.099	0.074
	0.102	0.086
32, 41	0.083	0.097
	0.070	0.077
	0.086	0.091
	0.099	0.100
	0.091	0.070
	0.095	0.090
33, 42	0.090	0.086
	0.083	0.070
	0.099	0.086
	0.110	0.083
	0.102	0.066
	0.107	0.090

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	1.69	0.09378	0.00011
5	18	1.52	0.08467	9.9E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0007	1	0.00075	7.30123	0.0106721303	4.13
Within Groups	0.0035	34	0.0001			
Total	0.0042	35				

0.30 Roughing with Three Finishing Passes

	Metals	
	1	2
7, 16	0.311	0.280
	0.309	0.281
	0.309	0.282
	0.309	0.289
	0.310	0.290
	0.310	0.290
8, 17	0.308	0.276
	0.306	0.277
	0.306	0.276
	0.309	0.280
	0.302	0.283
	0.294	0.283
9, 19	0.306	0.295
	0.306	0.295
	0.305	0.293
	0.299	0.297
	0.299	0.297
	0.299	0.297

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.5	0.30539	2.3E-05
2	18	5.16	0.28672	6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0031	1	0.00314	75.3053	0.0000000004	4.13
Within Groups	0.0014	34	4.2E-05			
Total	0.0046	35				

	Metals	
	1	3
7, 25	0.311	0.301
	0.309	0.299
	0.309	0.299
	0.309	0.301
	0.310	0.300
	0.310	0.300
8, 26	0.308	0.303
	0.306	0.301
	0.306	0.301
	0.309	0.300
	0.302	0.302
	0.294	0.303
9, 27	0.306	0.304
	0.306	0.302
	0.305	0.301
	0.299	0.305
	0.299	0.303
	0.299	0.305

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.5	0.30539	2.3E-05
3	18	5.43	0.30167	3.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00012	9.29173	0.0044339346	4.13
Within Groups	0.0005	34	1.3E-05			
Total	0.0006	35				

	Metals	
	1	4
7, 34	0.311	0.303
	0.309	0.301
	0.309	0.302
	0.309	0.303
	0.310	0.302
	0.310	0.303
8, 35	0.308	0.303
	0.306	0.302
	0.306	0.302
	0.309	0.304
	0.302	0.302
	0.294	0.304
9, 36	0.306	0.295
	0.306	0.295
	0.305	0.296
	0.299	0.298
	0.299	0.297
	0.299	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.5	0.30539	2.3E-05
4	18	5.41	0.30061	9.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00021	12.4611	0.0012160995	4.13
Within Groups	0.0006	34	1.6E-05			
Total	0.0008	35				

	Metals	
	1	5
7, 43	0.311	0.300
	0.309	0.299
	0.309	0.300
	0.309	0.303
	0.310	0.303
	0.310	0.303
8, 44	0.308	0.300
	0.306	0.301
	0.306	0.300
	0.309	0.303
	0.302	0.302
	0.294	0.302
9, 45	0.306	0.303
	0.306	0.302
	0.305	0.301
	0.299	0.299
	0.299	0.299
	0.299	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	5.5	0.30539	2.3E-05
5	18	5.42	0.30106	2.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00017	13.0229	0.0009779895	4.13
Within Groups	0.0004	34	1.3E-05			
Total	0.0006	35				

	Metals	
	2	3
16, 25	0.280	0.301
	0.281	0.299
	0.282	0.299
	0.289	0.301
	0.290	0.300
	0.290	0.300
17, 26	0.276	0.303
	0.277	0.301
	0.276	0.301
	0.280	0.300
	0.283	0.302
	0.283	0.303
18, 27	0.295	0.304
	0.295	0.302
	0.293	0.301
	0.297	0.305
	0.297	0.303
	0.297	0.305

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.16	0.28672	6E-05
3	18	5.43	0.30167	3.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002	1	0.00201	63.5369	0.0000000027	4.13
Within Groups	0.0011	34	3.2E-05			
Total	0.0031	35				

	Metals	
	2	4
16, 34	0.280	0.303
	0.281	0.301
	0.282	0.302
	0.289	0.303
	0.290	0.302
	0.290	0.303
17, 35	0.276	0.303
	0.277	0.302
	0.276	0.302
	0.280	0.304
	0.283	0.302
	0.283	0.304
18, 36	0.295	0.295
	0.295	0.295
	0.293	0.296
	0.297	0.298
	0.297	0.297
	0.297	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.16	0.28672	6E-05
4	18	5.41	0.30061	9.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0017	1	0.00174	50.0283	0.0000000361	4.13
Within Groups	0.0012	34	3.5E-05			
Total	0.0029	35				

	Metals	
	2	5
16, 43	0.280	0.300
	0.281	0.299
	0.282	0.300
	0.289	0.303
	0.290	0.303
	0.290	0.303
17, 44	0.276	0.300
	0.277	0.301
	0.276	0.300
	0.280	0.303
	0.283	0.302
	0.283	0.302
18, 45	0.295	0.303
	0.295	0.302
	0.293	0.301
	0.297	0.299
	0.297	0.299
	0.297	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	5.16	0.28672	6E-05
5	18	5.42	0.30106	2.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0018	1	0.00185	59.2765	0.0000000059	4.13
Within Groups	0.0011	34	3.1E-05			
Total	0.0029	35				

	Metals	
	3	4
25, 34	0.301	0.303
	0.299	0.301
	0.299	0.302
	0.301	0.303
	0.300	0.302
	0.300	0.303
26, 35	0.303	0.303
	0.301	0.302
	0.301	0.302
	0.300	0.304
	0.302	0.302
	0.303	0.304
27, 36	0.304	0.295
	0.302	0.295
	0.301	0.296
	0.305	0.298
	0.303	0.297
	0.305	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.43	0.30167	3.4E-06
4	18	5.41	0.30061	9.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-05	1	1E-05	1.54779	0.2219704523	4.13
Within Groups	0.0002	34	6.5E-06			
Total	0.0002	35				

	Metals	
	3	5
25, 43	0.301	0.300
	0.299	0.299
	0.299	0.300
	0.301	0.303
	0.300	0.303
	0.300	0.303
26, 44	0.303	0.300
	0.301	0.301
	0.301	0.300
	0.300	0.303
	0.302	0.302
	0.303	0.302
27, 45	0.304	0.303
	0.302	0.302
	0.301	0.301
	0.305	0.299
	0.303	0.299
	0.305	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	5.43	0.30167	3.4E-06
5	18	5.42	0.30106	2.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-06	1	3.4E-06	1.13209	0.2948293968	4.13
Within Groups	0.0001	34	3E-06			
Total	0.0001	35				

	Metals	
	4	5
34, 43	0.303	0.300
	0.301	0.299
	0.302	0.300
	0.303	0.303
	0.302	0.303
	0.303	0.303
35, 44	0.303	0.300
	0.302	0.301
	0.302	0.300
	0.304	0.303
	0.302	0.302
	0.304	0.302
36, 45	0.295	0.303
	0.295	0.302
	0.296	0.301
	0.298	0.299
	0.297	0.299
	0.299	0.299

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	5.41	0.30061	9.5E-06
5	18	5.42	0.30106	2.5E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-06	1	1.8E-06	0.29453	0.5908711585	4.13
Within Groups	0.0002	34	6E-06			
Total	0.0002	35				

0.25 Roughing with Three Finishing Passes

	Metals	
	1	2
7, 16	0.259	0.230
	0.259	0.231
	0.258	0.231
	0.260	0.237
	0.260	0.240
	0.260	0.239
8, 17	0.256	0.223
	0.256	0.226
	0.255	0.227
	0.246	0.228
	0.246	0.228
	0.247	0.230
9, 19	0.253	0.241
	0.253	0.243
	0.254	0.241
	0.245	0.245
	0.245	0.245
	0.243	0.245

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.56	0.25306	3.7E-05
2	18	4.23	0.235	5.6E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0029	1	0.00293	63.1795	0.0000000029	4.13
Within Groups	0.0016	34	4.6E-05			
Total	0.0045	35				

	Metals	
	1	3
7, 25	0.259	0.249
	0.259	0.247
	0.258	0.248
	0.260	0.250
	0.260	0.249
	0.260	0.249
8, 26	0.256	0.251
	0.256	0.248
	0.255	0.250
	0.246	0.251
	0.246	0.250
	0.247	0.253
9, 27	0.253	0.245
	0.253	0.243
	0.254	0.244
	0.245	0.247
	0.245	0.245
	0.243	0.247

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.56	0.25306	3.7E-05
3	18	4.47	0.24811	7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00022	9.99162	0.0032983520	4.13
Within Groups	0.0007	34	2.2E-05			
Total	0.001	35				

	Metals	
	1	4
7, 34	0.259	0.252
	0.259	0.252
	0.258	0.251
	0.260	0.253
	0.260	0.252
	0.260	0.253
8, 35	0.256	0.251
	0.256	0.250
	0.255	0.251
	0.246	0.252
	0.246	0.251
	0.247	0.252
9, 36	0.253	0.249
	0.253	0.249
	0.254	0.250
	0.245	0.250
	0.245	0.251
	0.243	0.251

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.56	0.25306	3.7E-05
4	18	4.52	0.25111	1.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-05	1	3.4E-05	1.77249	0.1919323004	4.13
Within Groups	0.0007	34	1.9E-05			
Total	0.0007	35				

	Metals	
	1	5
7, 43	0.259	0.248
	0.259	0.249
	0.258	0.247
	0.260	0.250
	0.260	0.251
	0.260	0.249
8, 44	0.256	0.250
	0.256	0.251
	0.255	0.250
	0.246	0.251
	0.246	0.250
	0.247	0.251
9, 45	0.253	0.248
	0.253	0.247
	0.254	0.249
	0.245	0.247
	0.245	0.246
	0.243	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	4.56	0.25306	3.7E-05
5	18	4.48	0.249	2.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00015	7.47899	0.0098430943	4.13
Within Groups	0.0007	34	2E-05			
Total	0.0008	35				

	Metals	
	2	3
16, 25	0.230	0.249
	0.231	0.247
	0.231	0.248
	0.237	0.250
	0.240	0.249
	0.239	0.249
17, 26	0.223	0.251
	0.226	0.248
	0.227	0.250
	0.228	0.251
	0.228	0.250
	0.230	0.253
18, 27	0.241	0.245
	0.243	0.243
	0.241	0.244
	0.245	0.247
	0.245	0.245
	0.245	0.247

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.23	0.235	5.6E-05
3	18	4.47	0.24811	7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0015	1	0.00155	49.1708	0.0000000431	4.13
Within Groups	0.0011	34	3.1E-05			
Total	0.0026	35				

	Metals	
	2	4
16, 34	0.230	0.252
	0.231	0.252
	0.231	0.251
	0.237	0.253
	0.240	0.252
	0.239	0.253
17, 35	0.223	0.251
	0.226	0.250
	0.227	0.251
	0.228	0.252
	0.228	0.251
	0.230	0.252
18, 36	0.241	0.249
	0.243	0.249
	0.241	0.250
	0.245	0.250
	0.245	0.251
	0.245	0.251

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.23	0.235	5.6E-05
4	18	4.52	0.25111	1.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0023	1	0.00234	81.5666	0.0000000001	4.13
Within Groups	0.001	34	2.9E-05			
Total	0.0033	35				

	Metals	
	2	5
16, 43	0.230	0.248
	0.231	0.249
	0.231	0.247
	0.237	0.250
	0.240	0.251
	0.239	0.249
17, 44	0.223	0.250
	0.226	0.251
	0.227	0.250
	0.228	0.251
	0.228	0.250
	0.230	0.251
18, 45	0.241	0.248
	0.243	0.247
	0.241	0.249
	0.245	0.247
	0.245	0.246
	0.245	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	4.23	0.235	5.6E-05
5	18	4.48	0.249	2.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0018	1	0.00176	60.338	0.0000000049	4.13
Within Groups	0.001	34	2.9E-05			
Total	0.0028	35				

	Metals	
	3	4
25, 34	0.249	0.252
	0.247	0.252
	0.248	0.251
	0.250	0.253
	0.249	0.252
	0.249	0.253
26, 35	0.251	0.251
	0.248	0.250
	0.250	0.251
	0.251	0.252
	0.250	0.251
	0.253	0.252
27, 36	0.245	0.249
	0.243	0.249
	0.244	0.250
	0.247	0.250
	0.245	0.251
	0.247	0.251

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.47	0.24811	7E-06
4	18	4.52	0.25111	1.4E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8E-05	1	8.1E-05	19.1842	0.0001076297	4.13
Within Groups	0.0001	34	4.2E-06			
Total	0.0002	35				

	Metals	
	3	5
25, 43	0.249	0.248
	0.247	0.249
	0.248	0.247
	0.250	0.250
	0.249	0.251
	0.249	0.249
26, 44	0.251	0.250
	0.248	0.251
	0.250	0.250
	0.251	0.251
	0.250	0.250
	0.253	0.251
27, 45	0.245	0.248
	0.243	0.247
	0.244	0.249
	0.247	0.247
	0.245	0.246
	0.247	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	4.47	0.24811	7E-06
5	18	4.48	0.249	2.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7E-06	1	7.1E-06	1.47626	0.2327318989	4.13
Within Groups	0.0002	34	4.8E-06			
Total	0.0002	35				

	Metals	
	4	5
34, 43	0.252	0.248
	0.252	0.249
	0.251	0.247
	0.253	0.250
	0.252	0.251
	0.253	0.249
35, 44	0.251	0.250
	0.250	0.251
	0.251	0.250
	0.252	0.251
	0.251	0.250
	0.252	0.251
36, 45	0.249	0.248
	0.249	0.247
	0.250	0.249
	0.250	0.247
	0.251	0.246
	0.251	0.248

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	4.52	0.25111	1.4E-06
5	18	4.48	0.249	2.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-05	1	4E-05	20.1213	0.0000789291	4.13
Within Groups	7E-05	34	2E-06			
Total	0.0001	35				

0.20 Roughing with Three Finishing Passes

	Metals	
	1	2
7, 16	0.212	0.180
	0.212	0.180
	0.210	0.182
	0.215	0.192
	0.214	0.190
	0.213	0.192
8, 17	0.207	0.175
	0.206	0.176
	0.205	0.179
	0.196	0.181
	0.193	0.179
	0.189	0.182
9, 19	0.208	0.194
	0.211	0.195
	0.212	0.196
	0.212	0.201
	0.205	0.201
	0.199	0.202

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.72	0.20661	5.8E-05
2	18	3.38	0.18761	8.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0032	1	0.00325	45.5238	0.0000000938	4.13
Within Groups	0.0024	34	7.1E-05			
Total	0.0057	35				

	Metals	
	1	3
7, 25	0.212	0.202
	0.212	0.197
	0.210	0.199
	0.215	0.202
	0.214	0.201
	0.213	0.201
8, 26	0.207	0.204
	0.206	0.199
	0.205	0.201
	0.196	0.204
	0.193	0.204
	0.189	0.205
9, 27	0.208	0.200
	0.211	0.197
	0.212	0.195
	0.212	0.201
	0.205	0.200
	0.199	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.72	0.20661	5.8E-05
3	18	3.61	0.20067	7.2E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00032	9.75653	0.0036404531	4.13
Within Groups	0.0011	34	3.3E-05			
Total	0.0014	35				

Metals

	1	4
	0.212	0.204
	0.212	0.201
7, 34	0.210	0.201
	0.215	0.206
	0.214	0.202
	0.213	0.204
	0.207	0.204
	0.206	0.203
8, 35	0.205	0.203
	0.196	0.204
	0.193	0.203
	0.189	0.203
	0.208	0.202
	0.211	0.203
9, 36	0.212	0.203
	0.212	0.203
	0.205	0.203
	0.199	0.205

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.72	0.20661	5.8E-05
4	18	3.66	0.20317	1.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00011	3.58464	0.0668523185	4.13
Within Groups	0.001	34	3E-05			
Total	0.0011	35				

Metals

	1	5
	0.212	0.200
	0.212	0.199
7, 43	0.210	0.197
	0.215	0.202
	0.214	0.202
	0.213	0.201
	0.207	0.202
	0.206	0.202
8, 44	0.205	0.203
	0.196	0.203
	0.193	0.201
	0.189	0.203
	0.208	0.200
	0.211	0.200
9, 45	0.212	0.200
	0.212	0.200
	0.205	0.199
	0.199	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	3.72	0.20661	5.8E-05
5	18	3.61	0.20078	2.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003	1	0.00031	10.0956	0.0031581498	4.13
Within Groups	0.001	34	3E-05			
Total	0.0013	35				

	Metals	
	2	3
16, 25	0.180	0.202
	0.180	0.197
	0.182	0.199
	0.192	0.202
	0.190	0.201
	0.192	0.201
17, 26	0.175	0.204
	0.176	0.199
	0.179	0.201
	0.181	0.204
	0.179	0.204
	0.182	0.205
18, 27	0.194	0.200
	0.195	0.197
	0.196	0.195
	0.201	0.201
	0.201	0.200
	0.202	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.38	0.18761	8.5E-05
3	18	3.61	0.20067	7.2E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0015	1	0.00153	33.3852	0.0000016730	4.13
Within Groups	0.0016	34	4.6E-05			
Total	0.0031	35				

	Metals	
	2	4
16, 34	0.180	0.204
	0.180	0.201
	0.182	0.201
	0.192	0.206
	0.190	0.202
	0.192	0.204
17, 35	0.175	0.204
	0.176	0.203
	0.179	0.203
	0.181	0.204
	0.179	0.203
	0.182	0.203
18, 36	0.194	0.202
	0.195	0.203
	0.196	0.203
	0.201	0.203
	0.201	0.203
	0.202	0.205

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.38	0.18761	8.5E-05
4	18	3.66	0.20317	1.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0022	1	0.00218	50.481	0.0000000329	4.13
Within Groups	0.0015	34	4.3E-05			
Total	0.0036	35				

	Metals	
	2	5
16, 43	0.180	0.200
	0.180	0.199
	0.182	0.197
	0.192	0.202
	0.190	0.202
	0.192	0.201
17, 44	0.175	0.202
	0.176	0.202
	0.179	0.203
	0.181	0.203
	0.179	0.201
	0.182	0.203
18, 45	0.194	0.200
	0.195	0.200
	0.196	0.200
	0.201	0.200
	0.201	0.199
	0.202	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	3.38	0.18761	8.5E-05
5	18	3.61	0.20078	2.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0016	1	0.00156	35.7135	0.0000009250	4.13
Within Groups	0.0015	34	4.4E-05			
Total	0.003	35				

	Metals	
	3	4
25, 34	0.202	0.204
	0.197	0.201
	0.199	0.201
	0.202	0.206
	0.201	0.202
	0.201	0.204
26, 35	0.204	0.204
	0.199	0.203
	0.201	0.203
	0.204	0.204
	0.204	0.203
	0.205	0.203
27, 36	0.200	0.202
	0.197	0.203
	0.195	0.203
	0.201	0.203
	0.200	0.203
	0.200	0.205

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.61	0.20067	7.2E-06
4	18	3.66	0.20317	1.6E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	5.6E-05	12.8788	0.0010339015	4.13
Within Groups	0.0001	34	4.4E-06			
Total	0.0002	35				

	Metals	
	3	5
25, 43	0.202	0.200
	0.197	0.199
	0.199	0.197
	0.202	0.202
	0.201	0.202
	0.201	0.201
26, 44	0.204	0.202
	0.199	0.202
	0.201	0.203
	0.204	0.203
	0.204	0.201
	0.205	0.203
27, 45	0.200	0.200
	0.197	0.200
	0.195	0.200
	0.201	0.200
	0.200	0.199
	0.200	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	3.61	0.20067	7.2E-06
5	18	3.61	0.20078	2.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-07	1	1.1E-07	0.02261	0.8813736318	4.13
Within Groups	0.0002	34	4.9E-06			
Total	0.0002	35				

	Metals	
	4	5
34, 43	0.204	0.200
	0.201	0.199
	0.201	0.197
	0.206	0.202
	0.202	0.202
	0.204	0.201
35, 44	0.204	0.202
	0.203	0.202
	0.203	0.203
	0.204	0.203
	0.203	0.201
	0.203	0.203
36, 45	0.202	0.200
	0.203	0.200
	0.203	0.200
	0.203	0.200
	0.203	0.199
	0.205	0.200

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	3.66	0.20317	1.6E-06
5	18	3.61	0.20078	2.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5E-05	1	5.1E-05	24.3856	0.0000206555	4.13
Within Groups	7E-05	34	2.1E-06			
Total	0.0001	35				

0.15 Roughing with Three Finishing Passes

	Metals	
	1	2
7, 16	0.161	0.129
	0.158	0.120
	0.159	0.133
	0.177	0.149
	0.171	0.143
	0.165	0.145
8, 17	0.157	0.122
	0.154	0.115
	0.154	0.128
	0.171	0.135
	0.161	0.128
	0.153	0.134
9, 19	0.154	0.140
	0.155	0.135
	0.159	0.151
	0.172	0.159
	0.164	0.149
	0.156	0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	2.9	0.16117	5.3E-05
2	18	2.47	0.13717	0.00015

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0052	1	0.00518	49.945	0.0000000367	4.13
Within Groups	0.0035	34	0.0001			
Total	0.0087	35				

	Metals	
	1	3
7, 25	0.161	0.151
	0.158	0.145
	0.159	0.146
	0.177	0.154
	0.171	0.149
	0.165	0.151
8, 26	0.157	0.153
	0.154	0.148
	0.154	0.150
	0.171	0.156
	0.161	0.153
	0.153	0.157
9, 27	0.154	0.153
	0.155	0.147
	0.159	0.149
	0.172	0.158
	0.164	0.153
	0.156	0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	2.9	0.16117	5.3E-05
3	18	2.73	0.1515	1.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0008	1	0.00084	25.0605	0.0000168709	4.13
Within Groups	0.0011	34	3.4E-05			
Total	0.002	35				

	Metals	
	1	4
7, 34	0.161	0.152
	0.158	0.148
	0.159	0.153
	0.177	0.155
	0.171	0.151
	0.165	0.155
8, 35	0.157	0.152
	0.154	0.149
	0.154	0.151
	0.171	0.154
	0.161	0.151
	0.153	0.151
9, 36	0.154	0.151
	0.155	0.150
	0.159	0.150
	0.172	0.154
	0.164	0.152
	0.156	0.152

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	2.9	0.16117	5.3E-05
4	18	2.73	0.15172	3.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0008	1	0.0008	28.1354	0.0000069160	4.13
Within Groups	0.001	34	2.9E-05			
Total	0.0018	35				

	Metals	
	1	5
7, 43	0.161	0.151
	0.158	0.148
	0.159	0.148
	0.177	0.153
	0.171	0.150
	0.165	0.151
8, 44	0.157	0.151
	0.154	0.151
	0.154	0.150
	0.171	0.151
	0.161	0.149
	0.153	0.150
9, 45	0.154	0.152
	0.155	0.151
	0.159	0.151
	0.172	0.151
	0.164	0.149
	0.156	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	18	2.9	0.16117	5.3E-05
5	18	2.71	0.15033	1.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0011	1	0.00106	38.3476	0.0000004849	4.13
Within Groups	0.0009	34	2.8E-05			
Total	0.002	35				

	Metals	
	2	3
16, 25	0.129	0.151
	0.120	0.145
	0.133	0.146
	0.149	0.154
	0.143	0.149
	0.145	0.151
17, 26	0.122	0.153
	0.115	0.148
	0.128	0.150
	0.135	0.156
	0.128	0.153
	0.134	0.157
18, 27	0.140	0.153
	0.135	0.147
	0.151	0.149
	0.159	0.158
	0.149	0.153
	0.154	0.154

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.47	0.13717	0.00015
3	18	2.73	0.1515	1.4E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0018	1	0.00185	22.0042	0.0000430732	4.13
Within Groups	0.0029	34	8.4E-05			
Total	0.0047	35				

	Metals	
	2	4
16, 34	0.129	0.152
	0.120	0.148
	0.133	0.153
	0.149	0.155
	0.143	0.151
	0.145	0.155
17, 35	0.122	0.152
	0.115	0.149
	0.128	0.151
	0.135	0.154
	0.128	0.151
	0.134	0.151
18, 36	0.140	0.151
	0.135	0.150
	0.151	0.150
	0.159	0.154
	0.149	0.152
	0.154	0.152

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.47	0.13717	0.00015
4	18	2.73	0.15172	3.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0019	1	0.00191	24.1354	0.0000222788	4.13
Within Groups	0.0027	34	7.9E-05			
Total	0.0046	35				

	Metals	
	2	5
16, 43	0.129	0.151
	0.120	0.148
	0.133	0.148
	0.149	0.153
	0.143	0.150
	0.145	0.151
17, 44	0.122	0.151
	0.115	0.151
	0.128	0.150
	0.135	0.151
	0.128	0.149
	0.134	0.150
18, 45	0.140	0.152
	0.135	0.151
	0.151	0.151
	0.159	0.151
	0.149	0.149
	0.154	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2	18	2.47	0.13717	0.00015
5	18	2.71	0.15033	1.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0016	1	0.00156	19.9994	0.0000821502	4.13
Within Groups	0.0027	34	7.8E-05			
Total	0.0042	35				

	Metals	
	3	4
25, 34	0.151	0.152
	0.145	0.148
	0.146	0.153
	0.154	0.155
	0.149	0.151
	0.151	0.155
26, 35	0.153	0.152
	0.148	0.149
	0.150	0.151
	0.156	0.154
	0.153	0.151
	0.157	0.151
27, 36	0.153	0.151
	0.147	0.150
	0.149	0.150
	0.158	0.154
	0.153	0.152
	0.154	0.152

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	2.73	0.1515	1.4E-05
4	18	2.73	0.15172	3.7E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E-07	1	4.4E-07	0.05069	0.823215517	4.13
Within Groups	0.0003	34	8.8E-06			
Total	0.0003	35				

	Metals	
	3	5
25, 43	0.151	0.151
	0.145	0.148
	0.146	0.148
	0.154	0.153
	0.149	0.150
	0.151	0.151
26, 44	0.153	0.151
	0.148	0.151
	0.150	0.150
	0.156	0.151
	0.153	0.149
	0.157	0.150
27, 45	0.153	0.152
	0.147	0.151
	0.149	0.151
	0.158	0.151
	0.153	0.149
	0.154	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	2.73	0.1515	1.4E-05
5	18	2.71	0.15033	1.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-05	1	1.2E-05	1.57467	0.218087636	4.13
Within Groups	0.0003	34	7.8E-06			
Total	0.0003	35				

	Metals	
	4	5
34, 43	0.152	0.151
	0.148	0.148
	0.153	0.148
	0.155	0.153
	0.151	0.150
	0.155	0.151
35, 44	0.152	0.151
	0.149	0.151
	0.151	0.150
	0.154	0.151
	0.151	0.149
	0.151	0.150
36, 45	0.151	0.152
	0.150	0.151
	0.150	0.151
	0.154	0.151
	0.152	0.149
	0.152	0.149

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	2.73	0.15172	3.7E-06
5	18	2.71	0.15033	1.8E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E-05	1	1.7E-05	6.30564	0.016953102	4.13
Within Groups	9E-05	34	2.8E-06			
Total	0.0001	35				

0.10 Roughing with Three Finishing Passes

	Metals	
	1	3
7, 25	0.111	0.097
	0.098	0.082
	0.111	0.097
		0.110
		0.102
		0.104
8, 26	0.105	0.100
	0.093	0.085
	0.108	0.096
		0.114
		0.107
		0.109
9, 27	0.105	0.097
	0.090	0.087
	0.107	0.098
		0.117
		0.108
		0.108

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	0.93	0.10311	5.9E-05
3	18	1.82	0.101	9.5E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3E-05	1	2.7E-05	0.32127	0.575902024	4.242
Within Groups	0.0021	25	8.3E-05			
Total	0.0021	26				

	Metals	
	1	4
7, 34	0.111	0.097
	0.098	0.085
	0.111	0.100
		0.108
		0.097
		0.104
8, 35	0.105	0.096
	0.093	0.085
	0.108	0.095
		0.109
		0.099
		0.101
9, 36	0.105	0.091
	0.090	0.082
	0.107	0.097
		0.105
		0.096
		0.103

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	0.93	0.10311	5.9E-05
4	18	1.75	0.09722	5.9E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	1	0.00021	3.5435	0.071468704	4.242
Within Groups	0.0015	25	5.9E-05			
Total	0.0017	26				

Metals

	1	5
7, 43	0.111	0.104
	0.098	0.091
	0.111	0.099
		0.103
		0.092
		0.102
8, 44	0.105	0.103
	0.093	0.101
	0.108	0.104
		0.102
		0.088
		0.097
9, 45	0.105	0.104
	0.090	0.090
	0.107	0.098
		0.103
		0.090
		0.099

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	9	0.93	0.10311	5.9E-05
5	18	1.77	0.09833	3.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00014	3.39391	0.077330044	4.242
Within Groups	0.001	25	4E-05			
Total	0.0011	26				

Metals

	3	4
25, 34	0.097	0.097
	0.082	0.085
	0.097	0.100
	0.110	0.108
	0.102	0.097
	0.104	0.104
26, 35	0.100	0.096
	0.085	0.085
	0.096	0.095
	0.114	0.109
	0.107	0.099
	0.109	0.101
27, 36	0.097	0.091
	0.087	0.082
	0.098	0.097
	0.117	0.105
	0.108	0.096
	0.108	0.103

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	1.82	0.101	9.5E-05
4	18	1.75	0.09722	5.9E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	1	0.00013	1.67508	0.204302052	4.13
Within Groups	0.0026	34	7.7E-05			
Total	0.0027	35				

	Metals	
	3	5
25, 43	0.097	0.104
	0.082	0.091
	0.097	0.099
	0.110	0.103
	0.102	0.092
	0.104	0.102
26, 44	0.100	0.103
	0.085	0.101
	0.096	0.104
	0.114	0.102
	0.107	0.088
	0.109	0.097
27, 45	0.097	0.104
	0.087	0.090
	0.098	0.098
	0.117	0.103
	0.108	0.090
	0.108	0.099

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
3	18	1.82	0.101	9.5E-05
5	18	1.77	0.09833	3.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6E-05	1	6.4E-05	1.01304	0.321286478	4.13
Within Groups	0.0021	34	6.3E-05			
Total	0.0022	35				

	Metals	
	4	5
34, 43	0.097	0.104
	0.085	0.091
	0.100	0.099
	0.108	0.103
	0.097	0.092
	0.104	0.102
35, 44	0.096	0.103
	0.085	0.101
	0.095	0.104
	0.109	0.102
	0.099	0.088
	0.101	0.097
36, 45	0.091	0.104
	0.082	0.090
	0.097	0.098
	0.105	0.103
	0.096	0.090
	0.103	0.099

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
4	18	1.75	0.09722	5.9E-05
5	18	1.77	0.09833	3.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E-05	1	1.1E-05	0.24609	0.623032562	4.13
Within Groups	0.0015	34	4.5E-05			
Total	0.0015	35				