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By

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ABSTRACT

Inconel 718 is a nickel-based heat resistant super-alloy (HRSA) that is widely used in many aerospace and automotive applications. It possesses good properties like corrosion resistance, high strength, and exceptional weld-ability but it is considered as one of the most difficult alloys to cut. Recently researchers have focused on employing many machining strategies to improve machinability of Inconel 718. This research work presents the experimentation of wet milling of Inconel 718 using a carbide tool with biodegradable oil. Surface quality is the major aspect of machinability. Hence input parameters such as depth of cut, cutting speed, and feed rate are considered to study their effect on surface quality. Nine experimental runs based on an L9 orthogonal array are performed. Additionally, analysis of variance (ANOVA) is applied to identify the most significant factors among cutting speed, feed rate, and depth of cut. Moreover, this research work presents the Artificial Neural Network (ANN) model for predicting the surface roughness based on experimental results. The ANN based-decision-making model is trained by using acquired experimental values. Visual Gene Developer 2.0 software package is used to study the efficiency of ANN. The presented ANN model demonstrates a very good statistical performance with a high correlation and extremely low error ratio between the actual and predicted values of surface roughness and tool wear.

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Analyzing and understanding cutting process mechanisms is a key issue in developing an economical, sustainable, and safe machining process. Beyond the adoption of machining technology, researchers should also consider the coolant behavior and machine tools. Industrial practitioners will only be willing to accept the new research if comprehensive solutions exist. In recent years, there has been growing interest in super-alloys as well as cutting materials such as ceramics, carbide and hybrid tools. There is also much importance given to sustainability when it comes to machining. So, all of these factors must be kept in mind when designing a machining operation. Super-alloys are widely used in the automotive, aeronautical, and power sectors because they provide the necessary strength at their operating temperature.

This research work aims towards sustainability and increasing productivity in the machining process by introducing biodegradable oil and an Artificial Neural Network. Biodegradable oil does not have harmful effects on the environment compared to non- biodegradable oils as it is easily decomposed by the living organisms while Artificial Neural Network provides the liberty to produce output values without performing the actual experimentation for the input parameters. Artificial Neural Network trains on the previous set of values and provides a new set of values.

1.1 Super-alloys:

The term “super-alloy” was first used shortly after World War II to describe a group of alloys developed for use in turbo-chargers, super-chargers, and aircraft turbine engines. Super-alloys are heat resistant alloys of nickel, nickel-iron, and cobalt-based alloys that frequently operate at temperatures exceeding 650°C. Nickel based super-alloys contain at least 50% nickel, whereas, in nickel-iron alloys, nickel is the major solute component. Other additives are chromium, aluminum, zirconium, magnesium, carbon, molybdenum, niobium, and tungsten, as shown in Table 1.1. The processing methods and tooling involved in the manufacturing of nickel alloy components are costly items. Nickel based super-alloys are especially popular in the manufacturing industries for high strength, good fatigue, corrosion, and creep resistance. However, some super-alloys are capable of being used in load bearing applications at temperatures in excess of 85% of their incipient melting temperatures. They have the ability to operate at elevated temperatures for extended periods. Their combination of strength at elevated temperature and resistance to surface degradation is unmatched by other metallic materials.

Table 1.1 Material composition of Inconel 718.

Elements	Content (Wt %)
Nickel	53.58
Chromium	17.52
Molybdenum	2.87
(Niobium +Tantalum)	5.19
Titanium	0.95
Aluminum	0.57
Cobalt	0.39
Carbon	0.034
Sulfur	0.002
Manganese	0.12
Silicon	0.07
Boron	0.004
Copper	0.05
Phosphorus	0.006

1.2 Applications of super-alloys:

Super-alloys have a broad range of applications. Aircraft engines are representative examples of high-temperature applications of super-alloys. The alloys used in aviation engines have traditionally been alloys of steel, nickel, titanium, and aluminum. Since aviation engines are limited by the weight and thermal capacity of the available materials, aluminum and steel have given way to super-alloys with properties and features adequate for extreme environments. The applications of super-alloys in different fields are discussed below (Rahul et al., 2017).

1.2.1 Aircraft Industry:

Super-alloys provide immense strength at extremely high temperatures, resistance to oxidation, creep resistance under high stress, and low expansion at high temperature. That is why they are routinely used in the exhaust section of an aircraft where burning jet fuel can cause parts to become immensely hot for extended periods of time. They are also used in disks, bolts, shafts, cases, blades, afterburners, and combustors of aircraft and industrial gas turbines (Ezugwu, 2005).

1.2.2 Medical Industry:

Super-alloys have remarkable strength and super resistance to corrosion so they are used to produce catheters, stylets, pacemaker leads, and orthopedic cables for medical purposes.

1.2.3 Space vehicle components:

Super-alloys have high strength, creep, and corrosion resistance so they are used to make fuel and oxygen turbo-pumps in space vehicles, as well as the backing structures within the wings. They are also used in the tail rudder speed brake of the wing's backing structure for the reinforced carbon outer shell (Ezugwu, 2005).

1.2.4 Nuclear power systems:

Super-alloys possess fatigue resistance and rupture strength so they are used in buckets, nozzles, combustion-liners, heat exchangers, gas ducting, and tubing in nuclear power plants.

1.2.5 Petrochemical industry:

Two types of super-alloys have been deployed for oil and gas applications. The first type is solid solution strengthened nickel-based alloys and the second type is age-hardened nickel-based alloys. Since they can operate on higher temperatures (>650°C) and high creep resistance, they are used in flow-lines, pipelines, valves, bolts, and reaction vessels.

1.3 Inconel 718:

Inconel 718 was developed in 1985 to meet the demands of high temperature applications. It is a nickel-based super-alloy that is widely used in the aerospace and automotive industries.

1.3.1 Metallurgy of Inconel 718:

The microstructure of Inconel 718 is comprised of an austenitic face-centered cubic (FCC) matrix phase, which is a solid solution of Fe, Cr, and Mo in nickel, together with other secondary phases (Ezugwu, 2005). Major phases present in nickel-based super-alloys are the gamma phase (γ), gamma prime phase ($\gamma^{/}$), and gamma double prime phase ($\gamma^{//}$). Gamma phase is a continuous matrix of a face centered cubic (FCC) nickel-based non-magnetic phase (Ezugwu, 2005). There is an addition of aluminum and titanium to precipitate FCC $\gamma^{/}$ Ni_3 (Al, Ti) phase in the $\gamma^{/}$ phase that is coherent with austenitic γ phase. Inconel 718 contains 5.1% niobium and smaller quantities of aluminum and titanium which leads to the formation of $\gamma^{/}$ Ni_3 (Al, Ti) phase. This phase is required for high temperature strength and creep resistance.

In the $\gamma^{//}$ phase, nickel and niobium combine in the presence of iron, as a catalyst, to form body centered tetragonal (BCT) Ni_3Nb, which is coherent with the γ phase (Ezugwu, 2005). This phase provides high strength at low and intermediate temperatures but is unstable above 650°C. Inconel is strengthened by the coherent (BCT) $\gamma^{//}$ phase (Ni_3Nb).

The principal characteristics of nickel as an alloy-base are high phase stability of the FCC nickel matrix and outstanding strength retention (Ezugwu, 2005). These characteristics encourage the use of Inconel 718 in a number of applications subjected to high temperatures. Table 1.2 shows the physical properties of Inconel 718.

Table 1.2 Physical properties of Inconel 718.

Hardness (HR_B)	89
Yield strength (GPa)	434
Tensile strength (MPa)	855
Boiling point (°C)	2197
Melting point (°C)	1260-1336
Density (g/cm^3)	8.19
Specific heat (J/ kg °C)	435
Coefficient of expansion (10^{-6} $°C^{-1}$)	130
Latent heat (kJ/kg)	272
Solidus temperature (°C)	1260
Liquidus temperature (°C)	1336
Thermal conductivity (W/m °C)	11.2
Thermal diffusivity (m^2/s)	2.94×10^{-6}

1.3.2 Applications of Inconel 718:

Materials in aircraft and automotive engines should provide high-temperature endurance properties, corrosion resistance, and high strength-to-weight ratio, resulting in efficient fuel consumption, and longer operational life. Nickel-based alloys can be used at a higher fraction of their melting temperature than any other materials. Following are the applications of Inconel 718 in the automotive and aerospace industry.

1.3.2.1 Inconel in aerospace industry:

1. The space shuttle used Inconel studs to secure the solid rocket boosters on the launch platform. Eight total studs were used to support the entire weight of the ready-to-fly shuttle system (Houston et al., 1998).
2. North American Aviation used Inconel to construct the skin of the North American X-15 Rocket-powered aircraft (Young, 2009).
3. Rocketdyne used Inconel for the thrust chamber of the F1 rocket engine. It was used in the first stage of the Saturn V booster (Kyle, 2018).
4. SpaceX used Inconel in the engine manifold of their Merlin rocket engine which powered the Falcon 9 launch vehicle (Kyle, 2018).

1.3.2.2 Inconel in automotive industry:

1. Tesla Motors is using Inconel, in place of steel, to upgrade the main battery pack contactor in its Model S, so it remains springy under the heat of heavy current. It allows upgraded vehicles to safely increase the maximum battery pack output from 1300 to 1500 amps, resulting in an increase in power output (Musk, 2015).
2. Ford Motor Company is using Inconel to make the turbine wheel in the turbocharger of its EcoBlue diesel engines that were introduced in 2016 (Kautonen, 2016).
3. BMW has started to use Inconel for BMW M5 E34 with the S38 engine. Inconel is used in the exhaust manifold of its high-performance luxury cars. It can easily withstand higher temperatures and reduce backpressure as compared to stainless steel (Mahwah, 2016).
4. Jaguar Cars have fit a new lightweight Inconel titanium exhaust system as standard in their Jaguar F-type SVR high performance sports car as compared to AJ-8 DHOC engines. It can withstand higher peak temperatures, reduce backpressure and eliminate 35lbs of mass from the vehicle (Mahwah, 2016).

1.4 Metal cutting:

The metal cutting process is the most universally employed metal shaping process to produce different profiles (Moufki et al., 2017). Metal cutting is defined as the removal of a thin layer of metal from a surface of a large work-piece with the help of a sharp edge tool (Trent & Wright, 2000). During any metal cutting process, the material is removed by the tool and work-piece motion relative to each other. The metal cutting process is a complex process since it involves friction, plastic flow, and fracture of materials under conditions more extreme than those normally found in materials subjected to testing or in other production processes. Machining processes share a major portion of its usage with industrial applications, e.g. aerospace/aircraft, automotive, and home appliances, etc. Machining processes start from the late 18^{th} century when tool manufacturing started from carbon steel (hardened) material. The hardened carbon steel tools were used to machine easy-to-cut materials (Trent & Wright, 2000). The continuous improvement in different aspects of machining technology such as machine tool structures, dynamics, power, sophisticated machine tool control (NC and CNC) have opened new dimensions to machining technologies.

1.4.1 Types of manufacturing processes:

The manufacturing process can be broadly divided into two groups; primary and secondary manufacturing processes. The former provides basic shape and size to the material as per the designer's requirement. Casting, molding, forming (hot and cold) are a few examples of primary manufacturing processes. Secondary manufacturing processes provide the final shape and size with tighter control over the dimensions, surface characteristics, etc. Material removal processes are mainly the secondary manufacturing processes (Mozammel & Dhar, 2016).

Material removal processes can be further divided into two groups; conventional machining such as turning, boring, milling, shaping, broaching, slotting, and grinding; and non-conventional machining such as abrasive jet machining, ultrasonic machining, and electro-discharge machining. Conventional machining usually involves changing the shape of a work-piece using a tool made of a harder material. Conventional machining uses mechanical motion energy while non-conventional machining uses other forms of energy such as electricity. Compared to non-conventional machining, conventional machining is economically suitable, has a lower capital cost, and is suitable for mass production (Devillez et al., 2007).

1.4.2 Milling:

Of all the conventional machining processes, milling is widely used in the aerospace and automotive applications. Milling is a metal removal process using a tool with one or more teeth rotating about a fixed axis. The milling process is a more complex operation owing to its intermittent nature and, thus, many factors affect the tool wear in this operation. In milling, the cutting forces periodically change as the chip thickness varies. The tooth periodically enters and exits from the work-piece; hence, it experiences stress and temperature cycling during the cutting process. As the tool enters the work-piece, it gets heated. The tool starts cooling when it exits from the work-piece. Milling is used for various applications such as machining of the impellers, support rails of seat frames, and control panels that are used in fixed wing, rotary wing, and simulator applications (Ezugwu et al., 1999).

1.5 Quality of machined surface:

Machining conditions are directly connected to the surface integrity of the final product. Surface integrity is the measure of quality of a machined surface. It describes the actual structure of both the surface and subsurface. Fatigue, creep, and stress corrosion cracking are responsible for severe failures in different applications. Therefore, it is necessary to satisfy the surface integrity requirements during machining process (Addona et al., 2017).

Many manufacturing processes involve some aspects of metal cutting operations. A determining factor in successful maximization of the manufacturing process is tool wear. Tool state alone, however, is not solely responsible for defining the limits of the cutting process. Other penalties can be incurred if attention is paid exclusively to the condition of the tool. Machine and tool parameters such as the cutting conditions, tool material and work-piece material are known to affect the tool wear.

Tool wear and surface roughness are often taken as a yardstick for comparing the behavior of tool and work-piece materials (Sun et al., 2013). The term "machinability' refers to the ease with which a given material can be machined. The criteria of machinability are tool wear, surface roughness, and cutting conditions (speed, feed, and depth of cut). The difficulty in predicting tool wear arises from the fact that tool wear is a very complex phenomenon and depends on many factors including the properties of the materials involved, the physical and chemical properties of the surfaces, temperature and cutting speed. In a complex machining process such as milling, an operation which involves several geometric cutter parameters and operating variables such as feed, speed, and depth of cut, the study of tool wear becomes more difficult. It is very difficult to select cutting parameters (cutting speed, feed, and depth of cut) without knowing the tool wear mechanisms. It is also well known that the prediction of tool life in the milling process is made difficult due to the complicated tool failure mechanisms.

Nickel based super-alloys contain additions of chromium, aluminum, titanium, cobalt, molybdenum, and other elements in varying quantities to give higher performance. With a material of such composition, the problem of tool wear and surface quality of the work-piece during machining appear more prominent if a proper cutting tool is not selected. Their outstanding high temperature strength and extreme toughness create difficulties during machining due to their work hardening tendency, which results in very high cutting forces and significant BUE (built-up-edge) formation during machining. Therefore, most of the major parameters including tool materials, tool geometry, machining method (up or down milling), chip formation, cutting speed, depth of cut and cutting environment (dry/coolant) should be studied during nickel material machining.

1.6 Tool selection:

Cutting nickel material is difficult due to its low thermal conductivity and the high chemical affinity to all known cutting tool materials. The machining of nickel material thus presents a challenge to produce new cutting tools that can be used to cut this material. On the other hand, higher tool wear, low permissible cutting speeds, and poor quality of machined surface present new challenges for the manufacturing industry. Cutting tools are subject to higher stress and higher temperature by modern machining technologies. All manufacturers in the metal machining industry face the same cutting tool dilemma determining what tool to adopt while keeping the cutting tool inventory and cost under control. The balance of cost versus productivity does not always yield the best possible manufacturing solutions or allow for the latest in cutting tool technology. There are various cutting tools that can be used for the milling operation of Inconel 718. Ceramic cutting tools have been used to increase the productivity of the machining process but they have a negative influence on the surface roughness. As a result, carbide tools are mostly used for the milling of Inconel 718. Carbide and ceramics cutting tools are either coated or uncoated. Most common coating for these tools are Al_2O_3, single layer physical vapor decomposition (PVD) TiAlN, multilayer PVD TiN/TiCN/TiN, TiN/AlTiN, nano-layer coatings of CrN/TiN. Other commonly used tools are micron grain ceramic tools (Al_2O_3+ SiC), cubic boron nitride (CBN), and whisker reinforced ceramic tools. The choice of cutting tool is dependent on the application and cutting parameters.

1.7 An overview of Analysis of Variance (ANOVA):

Sir Ronald Fisher established the ANOVA in 1930 to interpret experimental results in order to make optimized decisions. In ANOVA, the performance of input factors can be statistically examined on the dependent parameters by allocating the total variability into different parameters. ANOVA compares the total error of the experiment with the variation in the mean of each factor. It also forecasts the optimal combination of input parameters that can produce the required results. At the end, a confirmation trial is run to validate the estimation achieved from the analysis (Maghsoodloo et al., 2004).

1.8 An overview of Artificial Neural Network (ANN):

Artificial Neural Network (ANN) is a nonlinear mapping system inspired by the functions of a human brain as shown in Figure 1.1 (Krayel, 2009). A total of three layers, each populated by one or more neurons is the common structure of an ANN. Each neuron contains the weight and biases that are required to activate the function in the neuron of next layer. Some numerical values are presented to the network through the neurons of the input layer labeled as X_1, X_2, and X_3. Each neuron of input layer can take only one input value and this value is transferred to the hidden layers which are interconnected by synaptic weights to output layers in a way such that every neuron of a hidden layer is connected to every single neuron of the output layer labeled as Y_1. The output layer provides numerical values of responses.

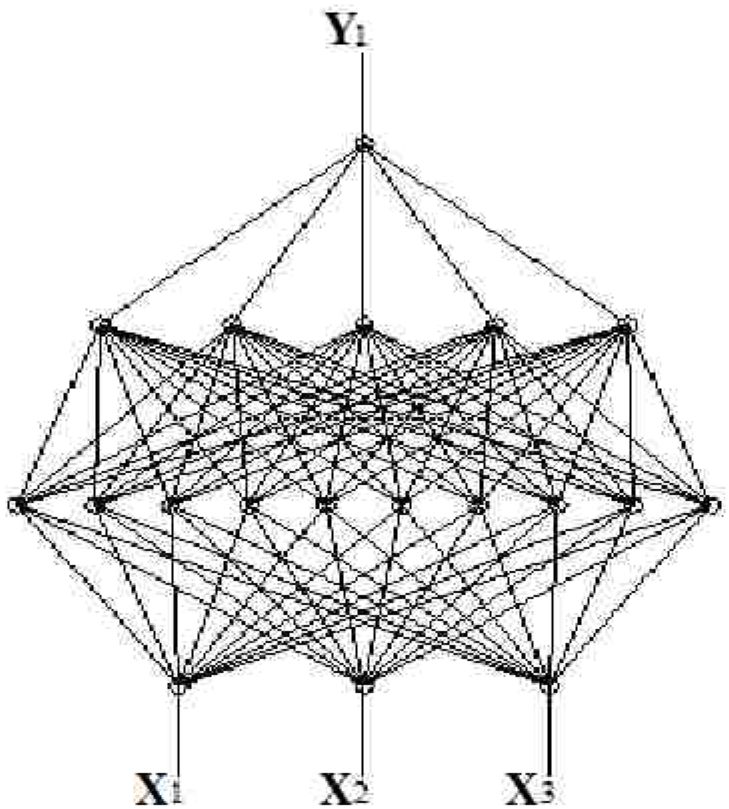


Figure 1.1 The structure of an artificial neuron.

The training of ANN is accomplished by adapting the strengths or weights of the connections among the inputs. Intermediate and output neurons are capable of storing memory and information. By achieving the learning ability, ANN produces the desired responses according to the given decision variables. A network can also be constructed with more than one hidden layer or without any hidden layers, which entirely depends on the input data, decision variables, the relationship among the input and output, and the number of process parameters (Krayel, 2009).

1.9 Outlook:

Chapter 1 provides the literature review on Inconel 718, the milling process and the basic concepts of tool wear, surface finish, ANOVA, and ANN. The review defines why Inconel 718 and milling operation is opted for this research work based on the physical properties and applications.

Moreover, these concepts are necessary to understand before starting the experimentation processes, as they will help set up the experimentation parameters as well as the post experiment simulations on ANOVA and ANN. The remainder of the thesis is organized as follows: Chapter 2 gives a literature overview of the research papers related to the milling of Inconel 718 and using ANN to predict output values. Chapter 3 presents the equipment and instrumentation, working assumptions, and design of experiments. Chapter 4 shows the results and discussion of the surface roughness during the milling operation based on ANOVA and Artificial Neural Network. Finally, conclusions and recommendations for future research are presented in Chapter 5.

Chapter 2 Literature review:

Chapter 2 presents the literature related to this research work. A thorough review of the literature is conducted to get the necessary knowledge required to determine the gaps in published work. Section 2.1 briefly explains the different concepts related to machining processes including surface roughness and tool wear. It helps to establish a base for the further research on the specific milling operation while section 2.2 shows the gaps found in literature. The following topics are considered while briefly studying the literature to understand the solution approaches:

i. Machining of Inconel 718,
ii. Methodologies from literature.

2.1 Machining of Inconel 718:

The development of government pollution pre-venting initiatives and increasing consumer focus on environmentally conscious products has placed increased pressure on industries to minimize their waste streams. For this purpose, the ISO 14000 international environmental management system standards have been developed to help industries control the impact of their activities on the environment. In the metal-working sector, which includes the automotive and aerospace industries, attention is being directed to the role of cutting fluids in machining and machine tool energy efficiency.

2.1.1 Tool wear and tool life:

Due to the low machinability of Inconel 718, the worked surface and subsurface are easily affected or damaged during machining operations. To ensure better surface integrity, a special care must be taken when choosing cutting conditions, tool material, geometry, and tool coating.

Sharman et al. (2006) carry out a series of experiments in which they performed turning operation on Inconel 718, using coated and uncoated tools. They evaluate the effects of geometry, wear level, and operating parameters (the tested cutting speed, and feed rate are 40, 80, 120 m/min and 0.15, 0.25 mm/rev) on surface integrity. When cutting with a new tool, relatively, little plastic deformation of the grain boundaries occurred and all the samples are strain hardened in the near-surface layer. The residual stress profile is tensile near the surface layer before rapidly dropping to compressive values. When the same operating conditions are used for cutting, the surface produced with the coated tool has higher tensile stress (up to 747 MPa) than the corresponding surface cut with the uncoated tool. This increase of tensile stress is due to the fact that the coated tool has a multi-layer coating containing a thermal barrier of Al_2O_3. This leads to an increase of work-piece surface temperature, causing higher tensile residual stresses. When the cutting speed is increased, the peak tensile stress is reduced and the greatest reduction is obtained between 40 and 80 m/min. The increase of feed rate results in increased stress levels. The same authors perform, in a next study, (Sharman et al., 2008), a series of experiments examining the effects of varying cutting fluid supply pressure when finish turning Inconel 718. The cooling fluid is supplied at various pressures to the rake face, the flank face, or both simultaneously. Surprisingly, no increase in tool life is observed when using a high pressure, up to 450 bar. In addition, cutting fluid supply pressure and the direction of the jet have relatively little influence on the level of surface integrity. More precisely, in comparison with conventional flood cooling (5 bar), cutting with 450 bar supplied to the rake face increased the tensile stress in the near-surface layer. Nevertheless, it must be noted that a significant reduction in the level of this tensile stress is observed when the 450 bar coolant is directed at the flank face. This suggests that lower work-piece temperatures are developed in this case.

Ezugwu et al. (2002) report a 50 min tool life when single layer physical vapor deposition (PVD) TiAlN and multilayer PVD TiN/TiCN/TiN coated carbide tools are employed at a cutting speed of 54 m/min and a 0.635 mm depth cut. The tool rejection criterion is average flank wear (400 μm). However, at a higher depth cut of 2.54 mm, the triple layer TiN/TiCN/TiN coated tools outperformed the single-layer TiAlN coated tools by about four times, in terms of tool life. Even at higher speeds, the triple-layer tool performed better than the single-layer tool.

Ducros et al. (2003) study the TiN/AlTiN and CrN/TiN nano-layer coatings deposited on a cemented carbide tool that used lubrication while cutting Inconel 718. The performance of the nano-layer coated tool is compared to multilayer coated and uncoated tools. The researchers report a 7.5 min tool life when a Nano-layer coated carbide tool is employed at a cutting speed of 40 m/min, a 0.2 mm/rev feed, and a 1.5 mm depth of cut. Again, the tool rejection criterion is uniform flank wear below a predefined value.

Ezugwu et al. (2002) report a 7 min tool life for a micron grain ceramic tool (Al_2O_3+SiC) used to machine Inconel 718 at a cutting speed of 230 m/min and a 0.125 mm/rev feed. The tool failure criterion is uniform flank wear.

Ezuguw et al. (2005) report on tool life for whisker-reinforced ceramic tools at different coolant pressures and found that with increasing coolant pressure up to 15 MPa, the tool life is gradually improved. A tool life increase of up to 71% is observed when machining Inconel 718 at a cutting speed of 250 m/min and a feed rate of 0.2 mm/rev. The researchers also observe that doubling the feed rate from 0.1 to 0.2 mm/ rev has no adverse effect on tool performance.

Arunachalam et al. (2004) report a 6.6 min tool life for a cubic boron nitride (CBN) cutting tool used to machine Inconel 718 at a cutting speed of 150 m/min and a 0.15 mm/rev feed. The tool failure criterion is uniform flank wear. The major cause of tool rejection in most of the tests is a crater on the rake face, which breaks through the cutting edge in the flank face, especially at the depth of cut notch wear region.

Several wear mechanisms have been identified as responsible for the deterioration of ceramic and carbide tools when machining Inconel 718. The main tool wear is flank wear, which is characterized by the plastic flow towards the side of the chip, and a burr on the work-piece formed by the major edge at a specific cutting speed.

Li et al. (2014) studies the effect of tool wear on surface integrity and its impact on fatigue performance of Inconel 718 alloy by end milling using physical vapor deposition (PVD) coated tools. Three levels of tool flank wear (VB) at 0, 0.01 mm, 0.2 mm are used to characterize the surface integrity including surface roughness, micro-structure, and micro-hardness. The effects of cutting speed, feed rate, and radial depth of cut on surface integrity are investigated on all three levels of tool flank wear.

Li et al. (2014) investigates the surface integrity and tests four-point bending fatigue to determine the fatigue life of Inconel 718. Flank wear, surface integrity, and fatigue performance of the work-piece are studied together and an optimum value with acceptable tool flank wear is determined. Before performing the milling operations, the top and bottom surfaces of work-piece are pre-prepared by faced milling process to remove the heat treatment induced surface defects. Pre-preparing the work-piece ensure flatness to eliminate machining errors during the experiments. The work-pieces are also degreased by ultrasonic cleaning in acetone and then rinsed with DI-water. Then, the work-piece samples are cross-sectioned with an abrasive cut-off saw at low cutting conditions to avoid modification of surface integrity. At the end, the work-piece samples are polished and then mounted in cold setting epoxy thus ensuring that surface quality of work-piece is not altered before the actual milling of Inconel 718.

This research involves an L7 experimentation approach with a total of 21 experiments to study the effect of input parameters such as depth of cut, cutting speed, and feed per tooth on surface roughness. An L7 experiment approach is not enough to study the effects of the above-mentioned input parameters on the surface roughness. Moreover, only medium cutting speeds are used, ranging from 60 to 80 m/min. The experiments should have been performed for a wider range of input values. In addition, no statistical analysis is done to study the comparative effectiveness of input parameters on the surface roughness.

The work by Li et al. (2014) focuses on the basic relationships between tool wear, surface integrity, and fatigue in the end milling of Inconel 718. It is concluded that higher tool wear produces less surface roughness and vice versa. The machined surface is hardened due to the mechanical loading of cutting tool resulting in higher micro-hardness values at the milled work-piece surface.

Sugihara et al. (2016) use cubic boron nitride tools for the high-speed machining of Inconel 718 They perform an orthogonal cutting experiment over a wide range of cutting speeds in order to study the wear mechanism of CBN tools in continuous cutting operation. The study is done to extend the tool life of CBN tools in high-speed machining over 100 m/min as CBN tools are much more expensive than conventional tools. They examine the influence of the surface topography of the tool rake face on crater wear and the relationship between the surface roughness of the rake face, and the wear resistance. In this research, cutting speed is the sole input factor that has been considered to study the tool topography during the high-speed machining of Inconel 718. Other environmental and input parameters that play an important role in the tool wear, such as depth of cut, and feed rate, have been ignored. Moreover, no data collection sheets comprising the information about the machine and environmental conditions are mentioned to study the accuracy of the experiments.

The study concludes that the crater wear increases due to the cycle of adhesions of work-piece material and their removals at low speed. In addition, the crater wear also occurs when the cutting tool substrate is flaked from the work-piece material after the experiment is performed. At a cutting speed of over 100 m/min, diffusion of the cutting tool and work-piece material is the major factor for the increased crater wear as a result of high cutting temperatures. The crater wear increases proportionally to the cutting length of cutting tool. During the high-speed machining process, the micro-surface topography of CBN tools is dependent on the crater wear resistance.

(Devillez et al. (2011) perform dry and wet-turning tests using a coated carbide tool at various cutting speeds, with semi-finishing conditions (0.5 mm depth of cut and 0.1 mm/rev feed rate). The cutting force is measured, the machined surface is observed, and residual stress profiles are determined for each cutting test. Additional measurements and observations are performed at an optimum cutting speed of 60 m/min. After the experiment, micro-hardness of the work-piece increases and the microstructure changes as well. These changes are also analyzed beneath the machined surface using an electron microscope. The research work focuses on the surface integrity during the wet and dry machining. Three experiments are performed accordingly with dry machining as well as wet machining. The results are then compared to investigate the optimum input parameters such as depth of cut, and speed of cut for attaining surface integrity. The research work compares the surface roughness values for both wet and dry machining showing which machining process yields better surface roughness values at given input parameters.

There is no care taken about the use of oil during the wet milling process. They did not compare the results of using flood coolant and minimum quantity coolant. Moreover, different coolants have different effects on the wet milling process, so one cannot decide which milling process is better than the other without using different types of lubricants.

Devillez et al. (2011) conclude that the wet and dry-conditions produces same cutting force levels. In dry conditions, the deposition of residual built up edge of the cutting tool to the machined surface is due to the higher generated temperatures. It is also responsible for the change in surface quality of the work-piece. During dry and wet conditions, material side flow is also observed in the area of feed marks. Residual stresses profiles are analyzed, showing a thin layer near the machined surface. This thing layer exhibits that residual stresses are present near the machined surface followed by the maximum tensile stress at the surface of the work-piece. After the thin layer, a compressive stresses zone is present which is several times thicker than the tensile layer.

2.1.2 Surface roughness:

Surface topography is of great importance in specifying the function of a surface. A significant proportion of component failure starts at the surface due to either an isolated manufacturing discontinuity or a gradual deterioration of the surface quality. Surface roughness is an important parameter when describing surface. In the manufacturing industry, a surface must be within certain limits of roughness. Therefore, measuring surface roughness is vital to the quality control of machining the work-piece.

Arunachalam et al. (2003) report the results of their investigation into the surface integrity of age-hardened Inconel 718 parts, which focus on surface finish and residual stresses while facing Inconel 718. A TiAlN coated cemented carbide tool with rhomboid and square shaped geometries is used in both dry and wet conditions. Three cutting parameters tested are: (i) cutting speed ranges from 40 m/min to 60 m/min, (ii) feed ranges from 0.1 mm/rev to 0.15 mm/rev, and (iii) a constant depth of cut of 0.5 mm. Lower values of surface roughness and tensile residual stresses (300MPa) are obtained while facing with a coolant as compared to those values obtained when facing with identical cutting data but without a coolant.

Ezugwu et al. (2002) also investigate the effect of cutting speed on the surface of Inconel 718 when using Nano-ceramic cutting tools for the roughing operation. They found that surface finish deteriorates with prolonged machining, and an increase in the feed rate does not produce any significant change in the surface finish. The Si_3N_4-based tool produces the worst surface roughness value of 8 µm when machining at a feed rate of 0.125 mm/rev and a speed of 270 m/min.

Darwish (2003) measures the surface roughness of Inconel 718 when carrying out the roughing operation with ceramic and CBN cutting tools under dry cutting conditions. From the experiments performed, Darwish finds that the cutting speed has little effect on surface roughness, at both low and high speed; whereas, feed rate and depth of cut have a major effect on surface roughness. As for the effect of tool material, ceramic tools produce a 7% improvement of surface quality (surface roughness) at a high feed rate, and an average improvement of 10% at low feeds (as compared to the CBN cutting tool).

Ezugwu et al. (2005) investigate surface roughness for Inconel 718 using whisker-reinforced ceramic tools under conventional and high-pressure coolant supplies. The researchers found that the surface roughness is very low when a round tool is used. With a round tool, a large contact radius is produced with the work-piece material, thus they are able to produce a high-quality surface finish.

Arunachalam et al. (2004) measure surface roughness (after the first pass and at the end of tool life) when facing age hardened Inconel 718 with CBN and ceramic cutting tools having round geometries. Low surface roughness values are obtained when using a round tool, and a surface roughness as low as 0.20 µm is obtained with the cutting parameters tested during the course of experiments at the cutting speed of 150 m/min, the feed of 0.15 mm/rev and a 0.5 mm depth of cut.

Akhtar et al. (2016) analyze surface roughness, micro-hardness, and residual stresses. Since surface roughness, micro-hardness, and residual stresses are the most important aspects of surface integrity so they are studied by varying the cutting parameters (cutting speed, feed rate, and depth of cut). Coated cemented carbide and whisker-reinforced coated ceramic inserts are used for finish milling of Inconel 718. This work shows that cutting speed, feed rate, and depth of cut have a substantial effect on the surface integrity of the finished part.

The research work focuses on the finish milling process of Inconel 718. The ceramic insert grades have not been utilized properly for the milling of Inconel 718 in previous studies due to which there exists a difference in the findings of different studies. So, this work focuses on the issue of the surface integrity characterization in the high-speed finish milling process that arises by using coated cemented carbide and silicon carbide whisker-reinforced ceramic inserts. The results are then compared to investigate the effect of two different coatings on the surface integrity.

This paper provides limited information about the behavior of cemented carbide and silicon carbide whisker-reinforced ceramic during the dry or wet milling process. Hybrid inserts are a new technology that has not been addressed in this paper as hybrid inserts are less expensive and they play a role in sustainability, by saving more material.

The study concluded that all three cutting parameters have a significant effect on surface characteristics of the finished product. It is considered that cutting speed and feed rate has a substantial effect on surface integrity as compared to the depth of cut. This study shows that the depth of cut also has a significant impact on surface integrity. The optimum values of surface integrity all the used cutting inserts are observed at medium cutting speed, minimum cutting feed, and medium depth of cut. In comparison to ceramic inserts, carbide inserts generated better surface integrity of the work-piece. Although, ceramic inserts gave better productivity than carbide inserts. The downside of using ceramic inserts is they always produced high tensile residual stresses during the machining process, resulting in a poor surface finish.

2.1.3 Coolant for machining:

The demands for environment-friendly cutting processes impose new techniques like the use of a minimal quantity, or even the complete omission of, cutting fluids (Fratila & Caizar, 2011). The most promising solution to these requirements is the use of minimum-quantity-lubrication (MQL) machining or biodegradable lubricants. MQL machining consists of the application of a very small amount of cutting oil, delivered in a compressed air stream, directed at the cutting zone (Ezugwu, 2005). Sanchez et al. (2010) accepts MQL machining as a practical way toward cleaner manufacturing in the context of more sustainable production, based on environmental preservation and conformity with the ISO 14000 standard of environmental management. MQL machining can be successfully applied without affecting the machining process results, such as surface roughness, tool life, and cutting power (Obikawa et al., 2006; Liao et al., 2007; Fratila & Caizar, 2011). The combination of tool coating technique and MQL represents an interesting opportunity in machining difficult-to-machine materials (Settineri et al., 2008). Kamata & Obikawa (2007) present the cutting performances of coated tools in MQL cutting of Inconel 718, in terms of tool life and surface finish, and they find that there is an optimum air pressure in finish-turning Inconel 718 with MQL. However, machining of Inconel 718 remains a difficult problem because the air has relatively poor cooling capacity compared to liquids (Ahmad et al., 2010). In order to compensate for the low cooling capacity of the traditional MQL technique, the compressed air is refrigerated and then jetted to the cutting zone to remove the heat from the cutting zone. This minimum quantity cooling lubrication (MQCL) system combines the advantages of cryogenic air and MQL (Obikawa et al., 2006).

Biodegradability of lubricants is an additional environmental factor to consider. Esters and vegetable oils are readily biodegradable, in contrast to the mineral and synthetic cutting fluids (Shashidhara & Jayaram, 2010).

2.2 Gaps in literature:

A summary of the literature review is presented in Table 2.1. By examining the literature, it is concluded that milling operations have been performed on Inconel 718 using either carbide or ceramic tools and the effect of depth of cut, cutting speed, and feed rate on surface integrity has been studied. The literature shows two main challenges in machining of Inconel 718. Firstly, there is very short tool life because of the work hardening and abrasion properties of Inconel 718. Secondly, due to very high cutting pressure, temperature, and lower thermal conductivity (11.2 W/m °C), there is metallurgical and surface damages to the work-piece which also contributes towards work hardening, surface tearing, and deformation.

In the published work that we examined, mineral and non-biodegradable synthetic oil has been used for the machining process and not much importance is given to semi-synthetic or bio-degradable oil. Moreover, ANOVA has been applied for either low cutting speeds or high speed machining and interaction between the input parameters using L-9 orthogonal array has not been studied. In addition, the examined past research work does not involve the application of artificial neural network to predict the output values. There is no work done for the automation of machining process that can bring researchers one step closer to the green machining.

Since Inconel 718 is mainly used in the automotive and aircraft industries, mass production is needed to meet the demand. Sustainability should be considered in the process of milling of Inconel 718 for mass production. Mostly, synthetic lubrication is used for wet milling operations which is unsustainable and harmful for the environment. For that reason, in this research work, biodegradable oil will be used instead of synthetic oil countering the sustainability issues as biodegradable oil can be easily decomposed by the living organisms since they have low toxicity levels.

Inconel 718 is very expensive and since its application demands high accuracy, one cannot use a trial-and-error method for finding the optimum input parameters to meet the surface finish requirements. There is a need for finding the optimum values of input parameters as well as investigate them to find the most significant parameter. In this research work, ANOVA is used to study the comparative effects of feed rate, depth of cut, and cutting speed. In addition, Artificial Neural Network will be used to verify the experimental values and train the system on the basis of those values. As a result, one can predict the output values based on input data sets without the need for experimentation. Visual Gene Developer 2.0 software package will be used for the Artificial Neural Network simulation.

Table 2.1 Summary of literature review

Author	**Year**	**Turning**	**Milling**		**Tools**		**Oil**		**ANN**
			Dry	Wet	Carbide	Ceramic	Synthetic	Biodegradable	
Khorasani & Yazdi.	2017		☒	☒	☒		☒		☒
Sugihara et al.	2016		☒		☒				
Akhter et al.	2016	☒			☒	☒			
Li et al.	2014		☒						
Maiyar et al.	2013		☒		☒				
Zhang et al.	2012		☒	☒	☒		☒		
Devillez.	2011		☒	☒		☒	☒		
Kaya et al.	2011		☒		☒				☒
Al-Ahmari	2007	☒			☒				
Cus & Zuperi.	2006	☒			☒				☒
Oktem et al.	2006		☒			☒			☒
Li et al.	2006		☒		☒				
Ezugwu et al.	2005		☒		☒				☒
Kohli & Dixit.	2005	☒			☒				☒
Ezugwu et al.	2005	☒			☒				☒
Dudzinski et al.	2004		☒	☒		☒	☒		
Present research	**2018**			☒	☒			☒	☒

Chapter 3 Instrumentation and design of experiment:

A benefit offered by all forms of computer numerical control (CNC) machines is improved automation. A CNC machine is used in this research work to machine a nickel-based, super-alloy (Inconel 718) material. Inconel 718 is a high strength, thermal resistant nickel-based super-alloy, as shown in Figure 3.1. This alloy is used in applications such as aircraft gas turbines, space vehicles, and nuclear power systems. Instruments, cutting tools, and the design of experiment (D.O.E) are described in the following chapter.

Figure 3.1 Work-piece material (Inconel 718).

3.1 Equipment for machining:

In this work, cutting tests are performed by a Hartford LG-500 three-axis CNC milling machine. The inspection of the surface roughness is carried out using a surface profilometer (Wyko NT 1100). The equipment and instrumentation are discussed below.

3.1.1 CNC milling machine:

The characteristic features of most processed work-pieces in tools, forms, and models include large dimensions (length and width), increasingly complex free-form surfaces, and the need for high quality when it comes to surface and precision. Figure 3.2 shows the CNC milling machine used for the experimentation.

Figure 3.2 CNC milling machine.

The CNC milling machine (Hartford LG-500) is a new type of compact universal milling machine. The maximum spindle speed is 15,000 rpm with a table size of 620 × 420 mm. The table capacity is 300 kg. The enhanced range provides accuracy, precision, and high surface finish. It has three axes that provide a large range of motions. X-axis travel is 520 mm, the Y-axis travel is 420 mm, and the Z-axis travel is 450 mm. The CNC milling machine (Hartford LG-500) has a universal machining center that provides constant precision while working at low, medium and high loads ensuring an economic production.

3.1.2 Cutting fluid:

Coolant has been used to reduce tool wear during the machining operation. The use of cutting fluids is often considered a solution rather than a problem in machining. They serve many useful functions, including cooling of the cutting tool at higher cutting speeds, lubricating the tool at low speeds and high loads, increasing the tool life, improving surface finish, and reducing cutting forces, power consumption, and the distortion due to the temperature rise in the work-piece. It provides a protective layer on the machined surface from oxidation and protection of the machine tool components from rust. Figure 3.3 shows nozzles for supplying coolant during the machining operation. Two nozzles have been used to provide lubrication during the milling process. A through coolant process has been used that runs right through the tool, one nozzle per insert.

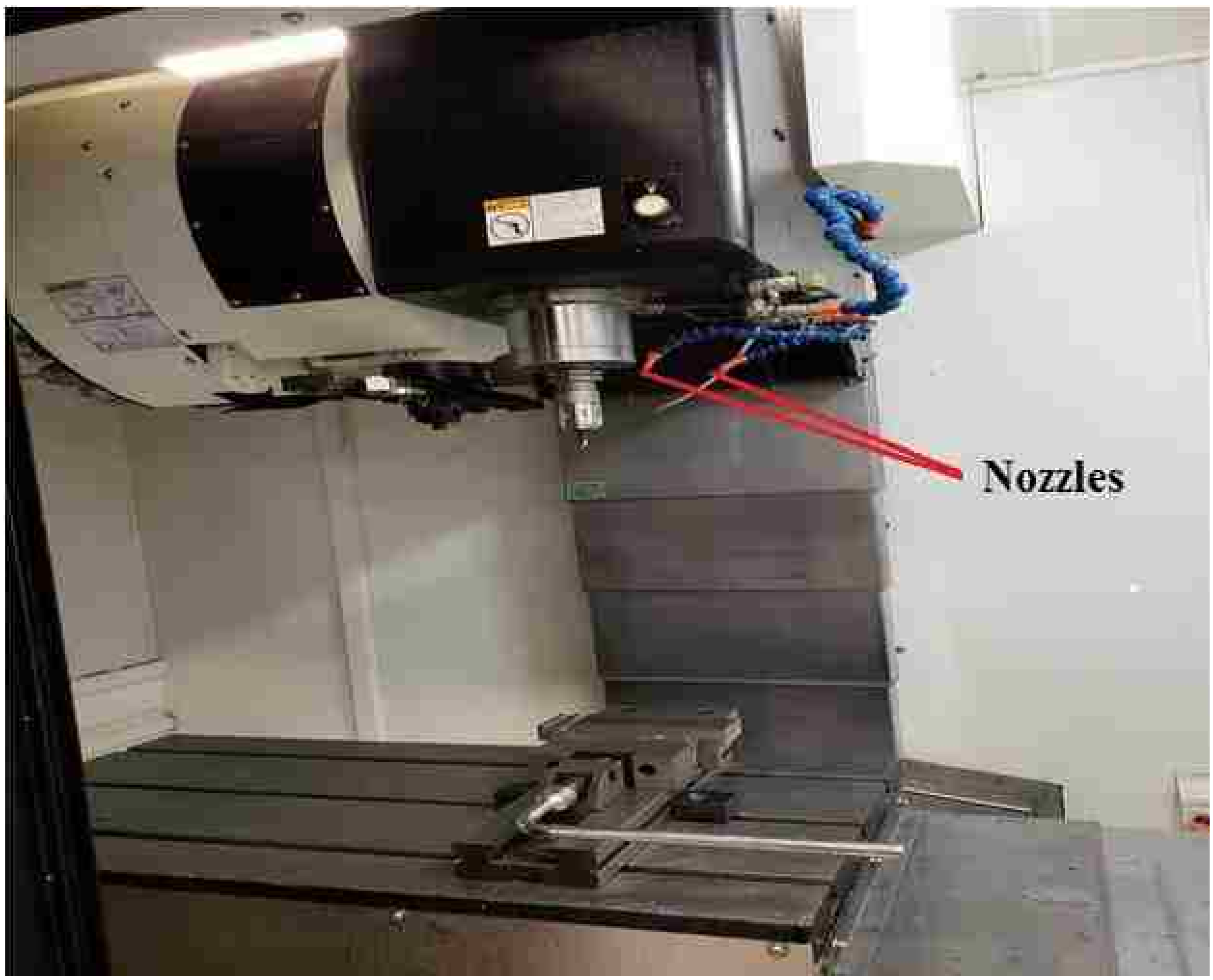


Figure 3.3 Coolant supplied through nozzles in CNC milling machine.

3.1.3 Surface roughness machine:

The surface profilometer, Wyko NT 1100 (Veeco Instruments Inc.), is used for the measurement of surface roughness during the machining operation. Figure 3.4 shows the surface profilometer.

Figure 3.4 Surface profilometer.

The surface profilometer is quite fast and utilizes white light interferometry for high resolution 3-D surface measurements. Profilometer stores the light reflected from a reference mirror and combines it with the light reflected from the sample work-piece. The system records the intensity of resulting interference pattern and provide the resultant values. Surface profilometer has the ability to measure from sub-nanometer roughness to millimeter-high steps. The surface profilometer can measure surface features for process control, wear and failure analysis on smooth as well as rough surfaces. The WYKO Vision analytical software package is used to quantify and visualize surface data by stitching the observed surface.

3.1.4 Cutting tools:

Micro-grains carbide is considered a reliable material for cutting tools because it is relatively insensitive to changes in cutting parameters due to its smaller grain size. These tools have a lower affinity with Inconel 718 compared to tungsten carbide materials thus exhibiting a good resistance to wear. In this study, the carbide tools used for milling of Inconel 718 is Sandvik (US) 390R-070204E-MM S30T. These tools are super-alloy coated with titanium aluminum nitride (TiAlN). The wiper edge length (BS), insert width (W1), cutting edge effective length (LE), corner radius (RE), and insert thickness (W) is 0.7 mm, 4.06 mm, 5.9 mm, 0.4 mm, and 2.4 mm respectively. Each insert has two cutting edges and two inserts are used at a time. Figure 3.5 shows the carbide tool used for experimentation.

(a) (b)

Figure 3.5 Carbide tools used for the milling of Inconel 718.

The inserts are rigidly clamped in a specially designed tool holder (R390-0097A 10-07L) as shown in Figure 3.6. The cutter diameter of the tool holder is 9.7 mm.

Figure 3.6 Tool holder for the inserts.

3.2 Design of experiments:

In recent years, the Taguchi method has become a powerful tool for improving productivity by investigating the input parameters during research and development. It is being utilized so that high-quality products can be produced quickly at a low cost (Maghsoodloo et al., 2004). Taguchi's parameter design is robust that uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The methodology of Taguchi for three factors at three levels is used for the implementation of the plan of experiments. The degree of freedom required for the study is six and Taguchi's L9 orthogonal array is used to define the nine trial conditions. Only the main effects are of interest and factor interactions are not studied. The process levels and parameters are listed in Table 3.1 while Table 3.2 shows the experimental layout..

Table 3.1 Process parameters and their levels.

Parameter	Unit	Level 1	Level 2	Level 3
Cutting speed (v) *	m/min	65	80	95
Feed rate (f)**	mm/tooth	0.10	0.15	0.20
Depth of cut (d)	mm	0.20	0.30	0.40

Table 3.2 Experimental layout using an L9 orthogonal array.

Experiment	Cutting speed	Feed rate	Depth of cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

There are certain cutting parameters (Cutting speed, feed rate, and depth of cut) that should be considered, before setting up any work-piece for machining process higher finish and accuracy is required. These cutting parameters can be selected either by literature review or using the following equations.

*Cutting Speed (v) m/min = $\frac{d \times 3.14 \times n}{1000}$ (3.1)

Where "d" is the tool diameter and "n" is the spindle speed. Spindle speed can be find out using equation 3.2.

Spindle Speed (n) in rpm = $\frac{v \times 1000}{3.14 \times d}$ (3.2)

Feed rate is calculated using the equation 3.3 where “N” is the number of flutes for cutting tool, “cpt” is the chip load which is defined as the amount of material removed by each tooth of the cutter as it rotates and advances into the work-piece.

$$**\text{Feed rate} = N \times cpt \times \text{spindle speed} \quad (3.3)$$

Chapter 4 Experimental results and discussion:

During the milling test, wear gradually develops on the flank faces of the cutting tool. For the cutting of Inconel 718, flank wear is the primary concern; therefore, its width is taken as the criterion of tool life. In order to understand the development of tool wear, the work tools are examined thoroughly under the tool wear measuring microscope. The surface profilometer is used to measure the surface roughness of Inconel 718.

4.1 Surface roughness:

The principal consideration of a surface condition produced during the manufacturing process is linked with safety, reliability, and service life as good surface roughness guarantees safety and surface life (Trent & Wright, 2000). It requires the study of surface quality resulting from the different machining processes. Surface quality concerns the geometric irregularities of the surface and the metallurgical alternations of the surface as during the machining process, the tool material at times stick on the work-piece surface. Surface roughness is widely used to denote the general quality of a surface. However, good finish guarantees low roughness value (Trent & Wright, 2000). Roughness is of significant interest in manufacturing because it is the roughness value that determines its friction in contact with another surface. The roughness of a surface defines how that surface feels, how it looks, how it behaves in contact with another surface and is denoted by "Ra". Table 4.1 shows the input parameters used during the experiments along with the surface roughness and time taken for each experiment in an L9 orthogonal array.

Table 4.1 Experiment layout of milling of Inconel 718.

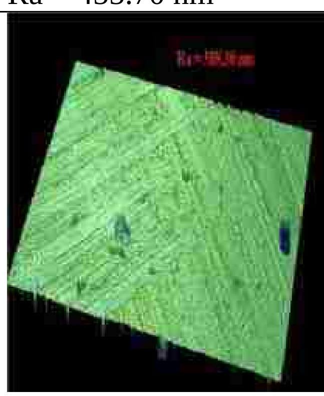
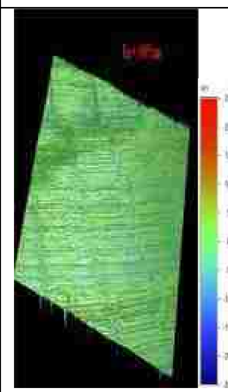
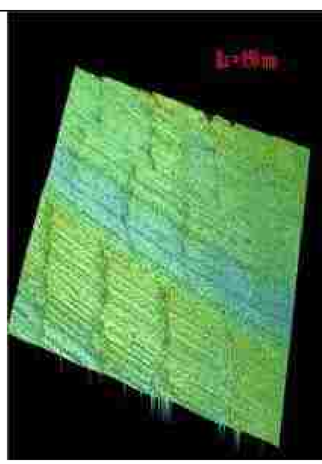
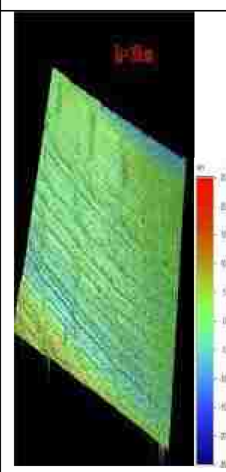
Experiment	Cutting speed	Feed rate	Depth of cut	Surface roughness (microns)	Time to machine (sec)
1	65	0.10	0.20	0.544	192
2	65	0.15	0.30	0.819	101
3	65	0.20	0.40	0.998	66
4	80	0.10	0.30	1.038	116
5	80	0.15	0.40	1.546	71
6	80	0.20	0.20	1.690	105
7	95	0.10	0.40	1.596	83
8	95	0.15	0.20	1.835	111
9	95	0.20	0.30	1.920	64

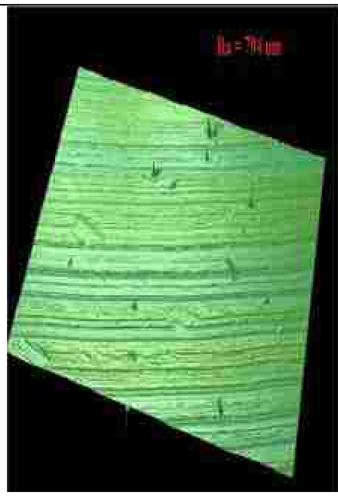
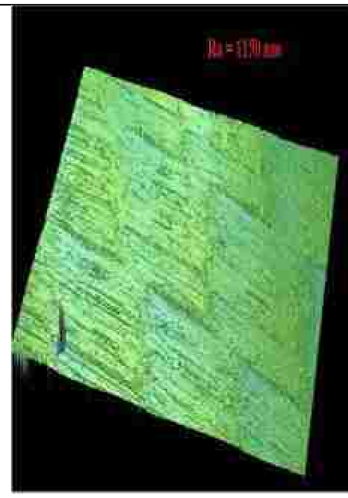
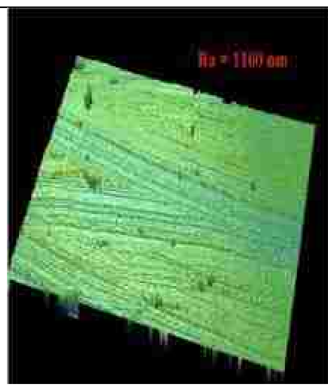
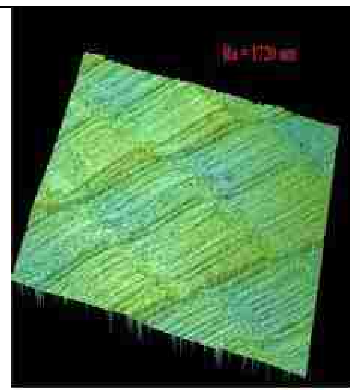
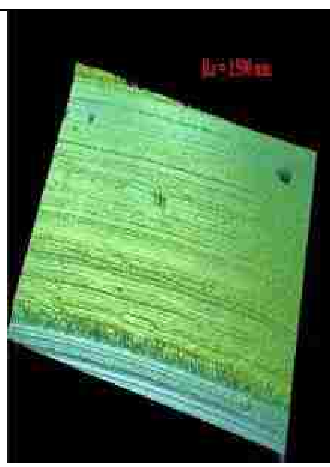
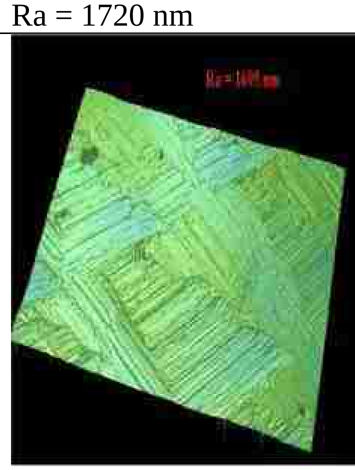
Three points have been marked to measure the surface roughness of Inconel 718 as shown in Figure 4.1. The starting point of the contact between the tool and the work-piece, middle point, and the end point are considered. The final surface roughness value is the average of those three values.

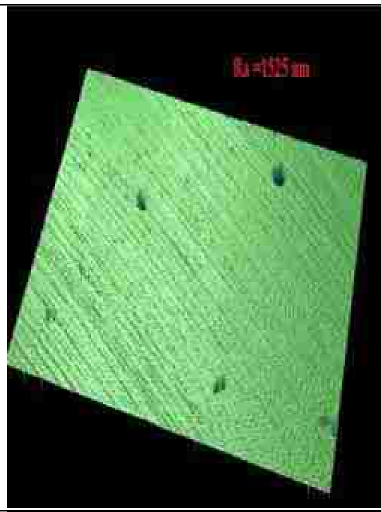
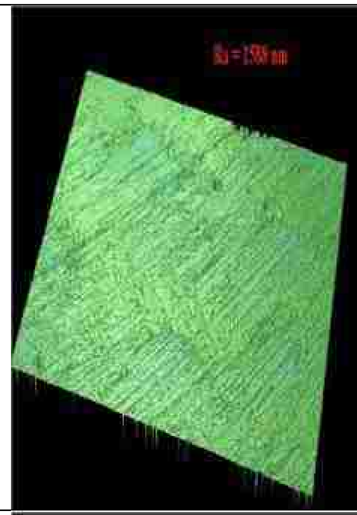
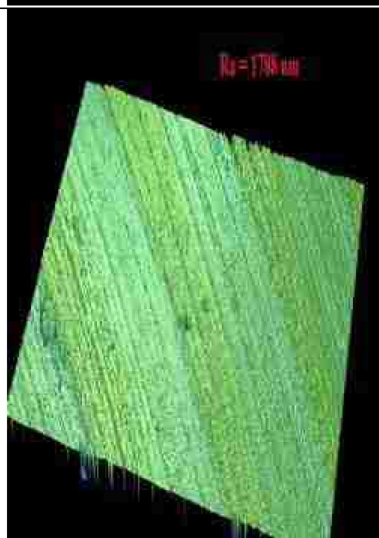
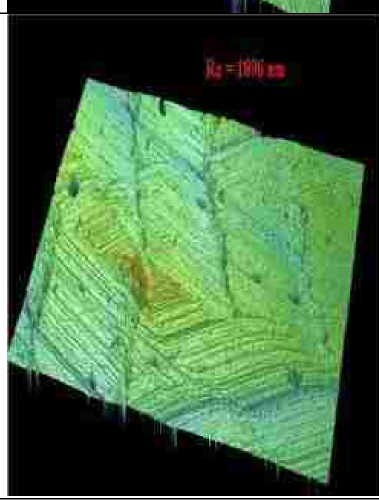
Figure 4.1 Marked bar of Inconel 718 for measuring of surface roughness.

Table 4.2 shows the 3-D plots for the surface roughness of three points (start, middle, and end) for the nine experiments.

Table 4.2 Surface roughness plots obtained from surface profilometer.

Experiment	**Start**	**Middle**	**End**
1 ((CS = 65, FR = 0.1, DOC = 0.2)	 Ra = 455.70 nm	 Ra = 570.58 nm	 Ra = 606.15 nm
2 (CS = 65, FR = 0.15, DOC = 0.3)	 Ra = 588.30 nm	 Ra = 865 nm	 Ra = 1005 nm
3 (CS = 65, FR = 0.2, DOC = 0.4)	 Ra = 950 nm	 Ra = 1010 nm	 Ra = 1036 nm

4 (CS = 80, FR = 0.1, DOC = 0.3)	 Ra = 794 nm	 Ra = 1150 nm	 Ra = 1170 nm
5 (CS = 80, FR = 0.15, DOC = 0.4)	 Ra = 1160 nm	 Ra = 1720 nm	 Ra = 1760 nm
6 (CS = 80, FR = 0.2, DOC = 0.2)	 Ra = 1590 nm	 Ra = 1695 nm	 Ra = 1784 nm

7 (CS = 95, FR = 0.1, DOC = 0.4)			
8 (CS = 95, FR = 0.15, DOC = 0.2)			
9 (CS = 95, FR = 0.2, DOC = 0.3)			

4.1.1 Analysis of Variance:

In this study, the purpose of analysis of variance is to investigate which machining parameters (cutting speed, feed rate, and depth of cut) significantly affect the performance characteristic (surface roughness) for in the machining of Inconel 718. This is accomplished by performing a regression analysis. First, the total sum of the squared deviations (SS_T) from the total mean of the grey relational grade (γ_M) can be calculated. The total sum of the squared deviations (SS_T) is divided into two sources: the sum of the squared deviations (SS_d) due to each machining parameter and the sum of the squared error (SS_e). The percentage contribution of each of the machining parameter in the total sum of the squared deviations (SS_T) can be used to evaluate the importance of the machining parameter change on the performance characteristic (Maghsoodloo et al., 2004). In addition, Fisher's F-test can also be used along with P test to determine the most significant machining parameter. Minitab 2018 is used to perform the analysis of variance (ANOVA). The cutting parameters have a significant effect if the F-value is large and p-value is low. Table 4.3 shows the results of ANOVA where CS, FR, and DOC are cutting speed, feed rate, and depth of cut respectively.

Table 4.3 Results of analysis of variance.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
CS	2	1528844	764422	165.57	0.006
FR	2	361761	180880	39.18	0.025
DOC	2	24675	12337	2.67	0.272
Error	2	9234	4617		
Total	8	1924514			

Figure 4.2 shows the main plots obtained by using Minitab. These main plots show the behavior of surface roughness with respect to the cutting speed, feed rate, and depth of cut. As you can see from Figure 4.2, if you increase the cutting speed and feed rate, the surface roughness increases. The Surface roughness decreases while increasing the depth of cut until 0.3 mm and then it starts to increase again. This behavior can be described by the working limitation of cutting tools. If the depth of cut is increased beyond a specific value, the surface roughness increases drastically as there will be high temperature generated at the point of contact between the work-piece and cutting

tool, consequently, breaking the cutting edge (Akhtar et al., 2016). Similarly, if the depth of cut is decreased below a specific value, the cutting tool will start to rub against the surface of work-piece rather than cutting the work-piece. This will induce more stress on the point of contact, consequently, breaking the cutting edge.

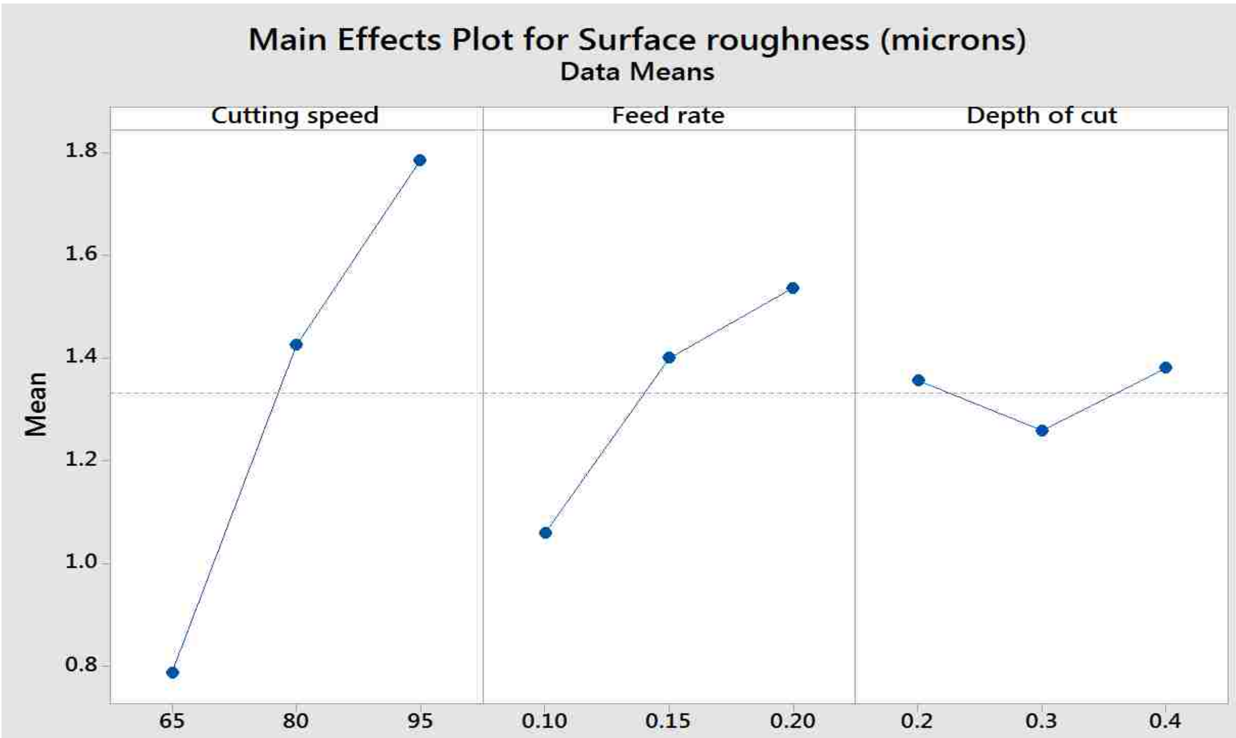
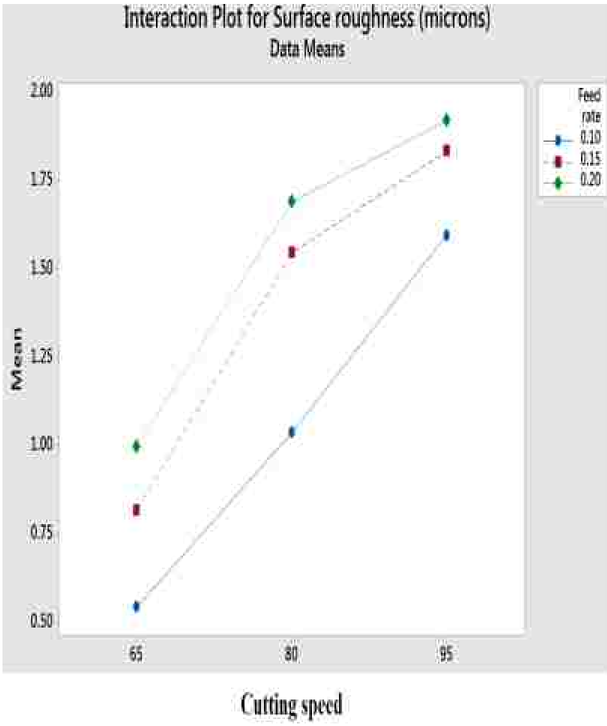
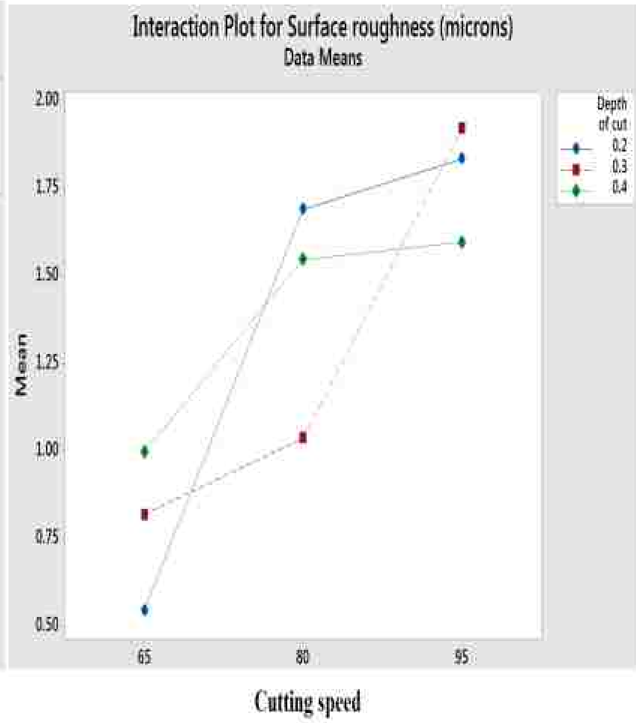


Figure 4.2 Main plots for cutting speed, feed rate, and depth of cut.

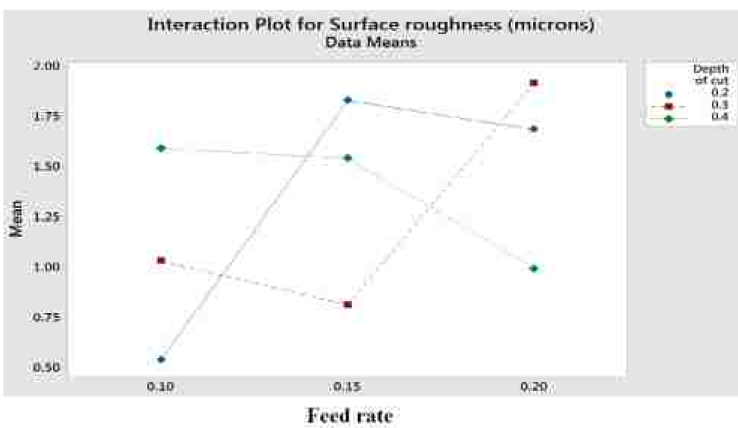
Figure 4.3 shows the interaction plots between cutting speed, feed rate, and depth of cut. An interaction effect is the simultaneous effect of two or more independent variables on at least one dependent variable in which their joint effect is significantly greater (or significantly less) than the sum of the parts. Figure 4.3 shows the interaction between all three input parameters showing that cutting speed and depth of cut have main effect while depth of cut does not have a main effect, further verifying the results obtained from the analysis of variance.



(a)



(b)



(c)

Figure 4.3 Interaction plots between cutting speed, feed rate, and depth of cut.

4.1.2 Artificial Neural Network:

Artificial Neural Network (ANN) is a nonlinear mapping system inspired by the functions of a human brain. Visual Gene Developer 2.0 is used to train the system for a particular data set and consequently predict values for a different data set. A total of three input neurons (Cutting speed, feed rate, and depth of cut) are selected in the topology settings along with one output neuron (surface roughness). The maximum number of training cycles are set to be 1 million along with the target error of 0.00001 percent. The learning rate value is set to 0.01. The learning rate is defined in terms of decreasing the average error in each output value.

4.1.2.1 Validation of analysis:

The input values are recorded in the neural network and the system is set to train with the target error of 0.00001 percent. The system takes 1 hour and 25 minutes to train on the particular data set. This simulation is performed on an Intel Core 2 Duo 3.4 GHz system with a 4.0 Giga Bites of random access memory (RAM). The correlation coefficient is 0.9999. Figure 4.4 shows the graph for the slope between actual and trained values.

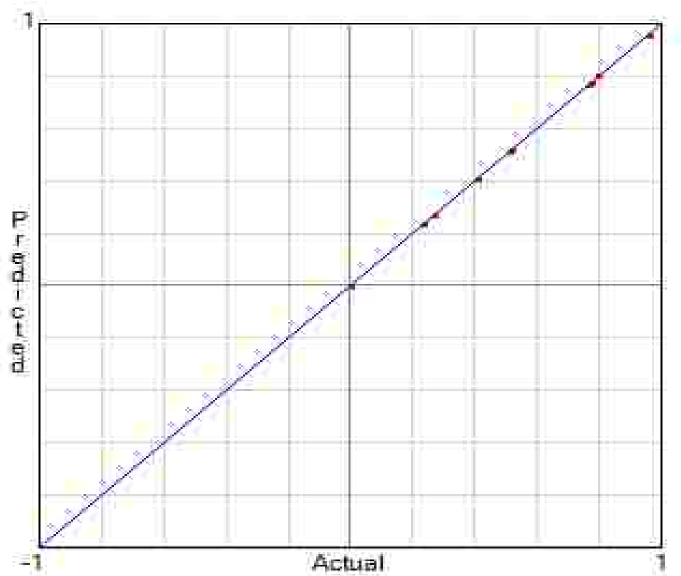


Figure 4.4 Graphical representation of actual and trained values.

Table 4.4 shows the input parameters used in the milling of Inconel 718 along with the machined and trained surface roughness values after training in the neural network.

Table 4.4 Experimented and trained values of surface roughness.

Experiment	Cutting speed	Feed rate	Depth of cut	Experimented surface roughness (microns)	ANN trained surface roughness (microns)
1	65	0.10	0.20	0.544	0.54391
2	65	0.15	0.30	0.819	0.8195
3	65	0.20	0.40	0.998	0.9993
4	80	0.10	0.30	1.038	1.0375
5	80	0.15	0.40	1.546	1.5455
6	80	0.20	0.20	1.690	1.704
7	95	0.10	0.40	1.596	1.603
8	95	0.15	0.20	1.835	1.8154
9	95	0.20	0.30	1.920	1.924

4.1.2.2 Prediction of values:

As the Artificial Neural Network is trained on the input values, backward propagation is done to predict the surface roughness values with a different set of input parameters. Table 4.5 shows the cutting parameters and corresponding predicted surface roughness values obtained through the Artificial Neural Network. Two sets of input parameters are chosen to verify the predicted values obtained from ANN as shown in Table 4.6. Milling tests have been performed again for the two data sets. The percentage error between the predicted and experimented values for (cutting speed = 45 m/min, feed rate = 0.13 mm/tooth, and depth of cut = 0.35 mm) comes out to be 0.77% while the % error for (cutting speed = 70 m/min, feed rate = 0.12 mm/tooth, and depth of cut = 0.25 mm) comes out to be 0.68%.

Table 4.5 Prediction of surface roughness using Artificial Neural Network.

Experiment	Cutting speed	Feed rate	Depth of cut	Predicted surface roughness (microns)
1	45	0.05	0.15	0.7145
2	45	0.09	0.25	0.6689
3	45	0.13	0.35	0.7100
4	70	0.12	0.25	0.9063
5	85	0.18	0.33	1.7934
6	90	0.22	0.42	1.9209

Table 4.6 Predicted and experimented values for the validation.

Experiment	Cutting speed	Feed rate	Depth of cut	Predicted surface roughness (microns)	Re-experimented surface roughness (microns)
1	45	0.13	0.35	0.7100	0.7045
2	70	0.12	0.25	0.9063	0.9001

This neural network is the possible 500,000 combinations of three input parameters that the system performed for learning. After learning from all the possible combinations, it predicts the output values. Thickest line shows the highest weights and biases for the first input parameter (cutting speed) while thin lines show lesser values of weights and biases for the other two input parameters (feed rate and depth of cut) in Figure 4.5.

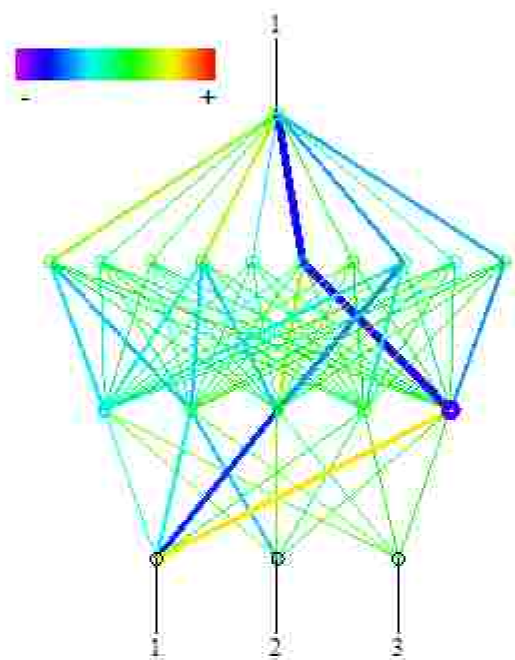


Figure 4.5 The neural network after analysis.

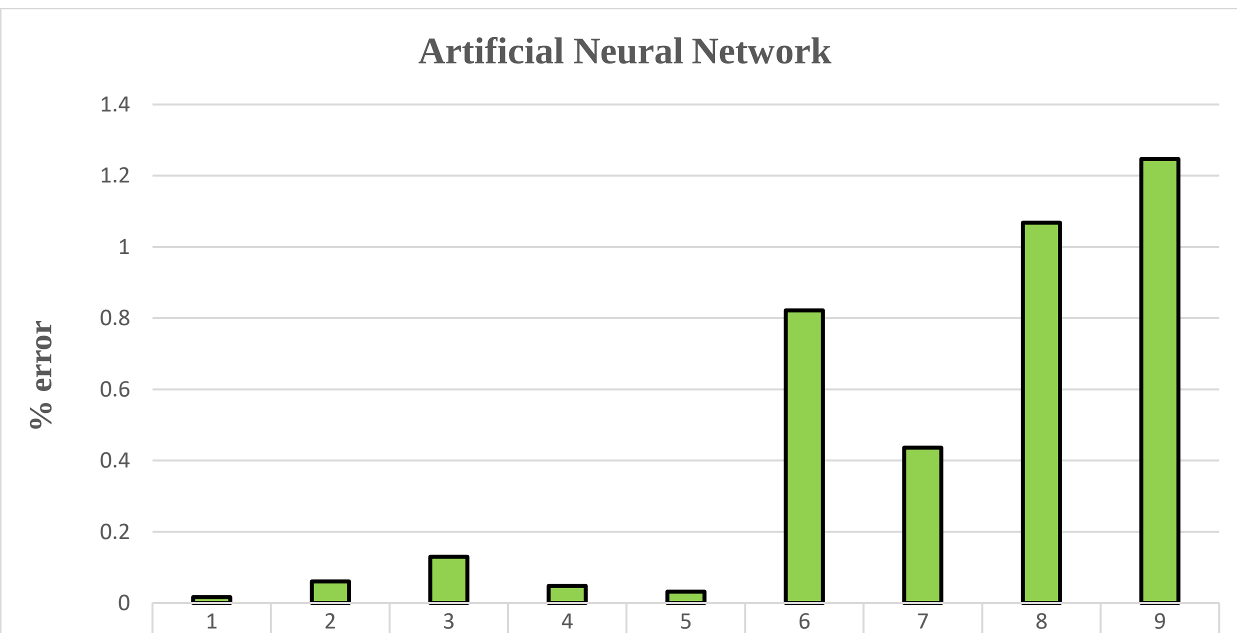
4.1.3 Discussion of results:

It is well understood that the quality of the surface plays a very important role in the performance of such parts as airfoils machined by milling. Although many factors affect the surface condition of a machined part, cutting parameters such as feed rate and cutting speed have a significant influence on the surface roughness for a given machine tool and work-piece. A quality milled surface significantly improves fatigue strength, corrosion resistance, and creep life. Thus, it is necessary to know how to control the machining parameters to produce a fine surface quality for a machined work-piece.

It can be seen from Table 4.2 that an increase in feed rate (0.10-0.20) accelerates the higher values of surface roughness while keeping the cutting speed constant. As it is an L9 orthogonal array, each experiment has a different combination of input values. It is obvious from Table 4.2 that, as you accelerate towards the higher values of cutting speed, feed rate, and depth of cut, the values of surface roughness increase. However, the chip load (feed) must be kept below a maximum value, to avoid mechanical load on cutting tool, and above a minimum value, to avoid rubbing of tool and work-piece. Arunachalan et al. (2004) also report that surface roughness increases with increasing feed rate.

Table 4.3 shows the analysis of variance (ANOVA) indicating that cutting speed is the most significant factor followed by feed rate when it comes to the milling of Inconel 718. The α-value should be under 0.05 to determine if a certain factor is significant or not. Table 4.3 shows that the p-value for feed rate is 0.025, and cutting speed is 0.006, showing that these two factors have a significant effect on the surface roughness of the machined work-piece. A similar trend can also be seen in Table 4.1. Moreover, the p-value for depth of cutting is 0.272 indicating that for this range (0.2-0.4), depth of cut does not have a significant effect on the surface roughness.

After the analysis of variance (ANOVA), Visual Gene Developer is used to develop the Artificial Neural Network to predict the future values. The six basic steps used in the general application of a neural network are adopted in the development of the model: assembly or collection of the data, analysis and pre-processing of the data, design of the network object, training and testing of the network, performing simulation with the trained network, and post-processing of the results. The performance capability of the network is examined based on the correlation coefficient between the network predictions and the experimental values. The neural network is trained on 500,000 different sets of combinations. The learning rate is set to be 0.01 with a target error of 0.00001. The system is trained on the input parameters and surface roughness values. The values are recalled every 15 minutes to check the correlation coefficient. The correlation coefficient of 0.99 is obtained between the entire data set and the model predictions. The percentage error of the model prediction is also calculated as the percentage difference between the experimental and predicted value relative to the experimental value. The error distribution of the model for the prediction of surface roughness using the entire data set is shown in Figure 4.6. The neural network takes 1 hour and 25 minutes to reach an error value of 0.00001. Once it is assured that the system is well trained, backward propagation is done. The system is fed with six different sets of input parameters, as shown in Table 4.5, and the new set of values for surface roughness are collected.



	1	2	3	4	5	6	7	8	9
% error	0.0165	0.061	0.13	0.0481	0.0323	0.8215	0.4366	1.0681	1.2471

Figure 4.6 Graphical representation of % error.

Figure 4.7 shows the interaction of feed rate and cutting speed on surface roughness. As can be seen, by increasing the feed rate and cutting speed, the roughness is increased. Tracing the boundary of contour colors indicates the effect of cutting speed on the surface roughness is stronger than feed rate. If you move close to 1 on both axis, the surface roughness increases.

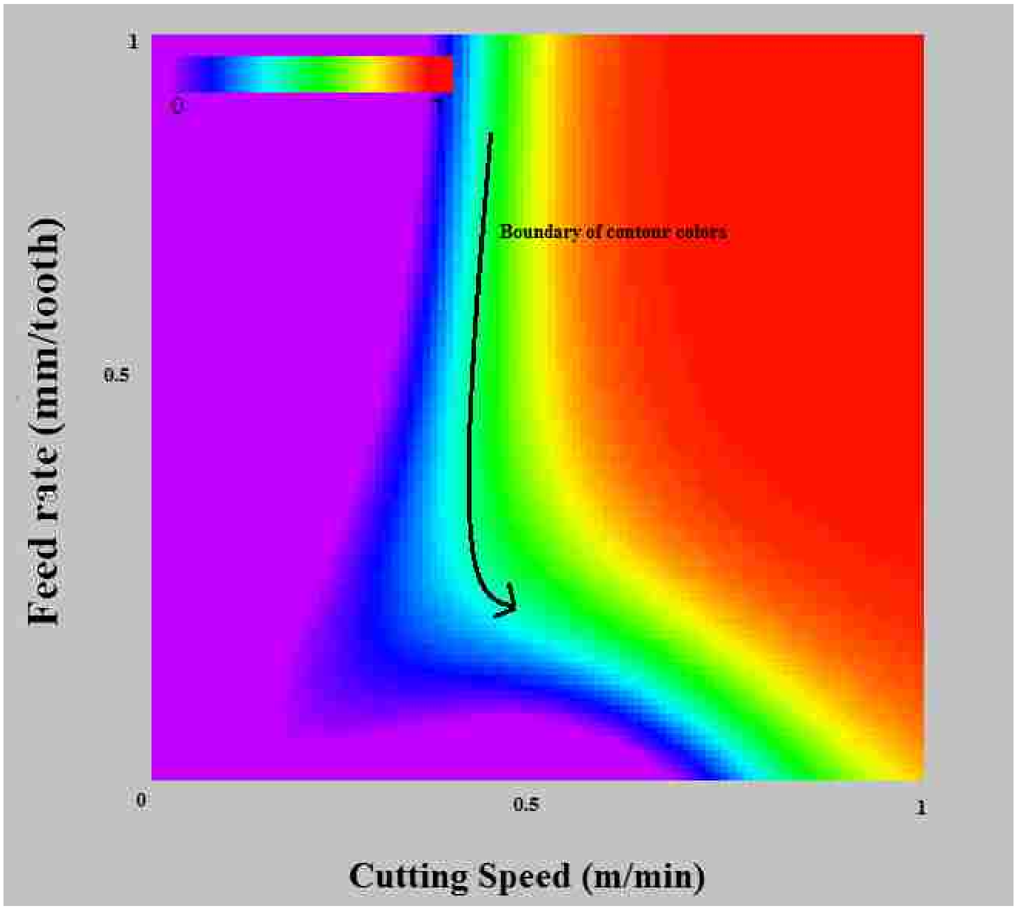


Figure 4.7 Interaction of cutting speed and feed rate on surface roughness.

It is concluded that for the given set of input parameters, the value of surface roughness increases as the cutting speed and feed rate increase. ANOVA shows that the feed rate and cutting speed are significant factors while the depth of cut is not a significant factor for surface roughness. Cutting speed and feed rate should be given consideration while milling Inconel 718. In addition to ANOVA, ANN increases the productivity as it enables you to predict the surface roughness for the input parameters of any range once you train the system on a specific machining operation. ANN enables one to choose the optimum input parameters without the need for actual experimentation, thus saving raw material, man-hours, and consequently increasing the productivity and taking a step forward toward green manufacturing.

Chapter 5 Conclusions and recommendations for future work:

This thesis has explored milling of a nickel-based super-alloy, Inconel 718, using carbide tools. In this chapter the conclusions and recommendations for future work are presented.

Nickel based super-alloys have been widely used in the aerospace, automotive, and nuclear industries due to their exceptional thermal resistance and their ability to retain mechanical properties at high temperatures. However, surface quality is a key issue in nickel-based super-alloy machining operations. Therefore, this work studied the surface roughness of machined Inconel 718 while varying the process parameters of depth of cut, feed rate, and cutting speed.

Based on the detailed discussion of the results presented in previous chapters, it is concluded that the Sandvik (US) 390R-070204E-MM S30T carbide tools showed satisfactory results while milling Inconel 718 work-pieces. The tools did not wear out beyond the limit or break during the machining process. Hence, carbide tools performed satisfactorily given the average and maximum tool wear limitations under the studied input parameters.

In this research work, L-9 orthogonal array is used and most influential parameter among cutting speed, feed rate, and depth of cut is determined. Using L-9 orthogonal array, each experiment is repeated three times and average surface roughness values are taken. As seen from Table 4.1, the machining parameters (cutting speed = 65, feed rate = 0.1, and depth of cut = 0.2) for the first experiment yields the best surface quality of 0.544 microns whereas the machining parameters (cutting speed = 65, feed rate = 0.1, and depth of cut = 0.2) for the ninth experiment resulted into the highest value of surface roughness and lowest machining time. This fact is confirmed in Table 4.3, where cutting speed is the most significant parameter and the depth of cut is the least significant parameter.

Finally, ANN eliminated the trial and error method of selecting the input parameters to achieve a certain output value. ANN has been used to reduce the need for future experiments. ANN method has been used to predict values and then additional experiments are performed to compare and validate the ANN results that we obtained. The error between predicted and experimental values is insignificant which helped validating the ANN method. This way, the predicted values can be advantageously used for machining purposes. In addition, the biodegradable oil has contributed to a working environment that is free of contaminants and unwanted pollution which normally exists in wet machining process with mineral oils. Thus, this research paves a path to save workable hours and raw material, contributing to greener machining and less environmental pollution.

There are many input parameters that can be varied to further research the surface quality of milling of Inconel 718. Those input parameters are different types of lubrication oils, lubrication oil pressure, lubrication supply rate, different cutting tools, and different coatings of the cutting tools. The recommendations for future work are as follows:

- This study used wet cutting for all experiments. Few research works have been conducted in order to determine the effect of the MQL system on surface quality, tool wear, and chip formation during the machining operation. Studies should compare MQL, dry cutting, and wet cutting (coolant) and their effect based on surface quality, tool wear, and chip formation.

- Experiments were conducted for nickel-based super-alloys with carbide tools during medium cutting speed operation. Ceramics and Polycrystalline cubic boron nitride (PCBN) tools can be used to machine nickel-based super-alloys in low-speed and high-speed machining. Therefore, a detailed study of surface quality should be performed using ceramics and PCBN cutting tools.

- This study investigated the surface roughness of a nickel-based material machined with carbide tools. Tool wear is also a factor that affects the surface roughness of machined components. Therefore, wear mechanics for carbide, ceramic, and PCBN cutting tools should be investigated.

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