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Performance analysis of cutting graphite-epoxy composite using a 90,000 PSI abrasive waterjet

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PERFORMANCE ANALYSIS OF CUTTING GRAPHITE-EPOXY COMPOSITE USING A 90,000PSI ABRASIVE WATERJET

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ABSTRACT

Graphite-epoxy composites are being widely used in many aerospace and structural applications because of their properties: which include lighter weight, higher strength to weight ratio and a greater flexibility in design. However, the inherent anisotropy of these composites makes it difficult to machine them using conventional methods. To overcome the major issues that develop with conventional machining such as fiber pull out, delamination, heat generation and high tooling costs, an effort is herein made to study abrasive waterjet machining of composites. An abrasive waterjet is used to cut 1” thick graphite epoxy composites based on baseline data obtained from the cutting of ¼” thick material. The objective of this project is to study the surface roughness of the cut surface with a focus on demonstrating the benefits of using higher pressures for cutting composites. The effects of major cutting parameters: jet pressure, traverse speed, abrasive feed rate and cutting head size are studied at different levels. Statistical analysis of the experimental data provides an understanding of the effect of the process parameters on surface roughness. Additionally, the effect of these parameters on the taper angle of the cut is studied. The data is analyzed to obtain a set of process parameters that optimize the cutting of 1” thick graphite-epoxy composite. The statistical analysis is used to validate the experimental data. Costs involved in the cutting process are investigated in term of abrasive consumed to better understand and illustrate the practical benefits of using higher pressures. It is demonstrated that, as pressure increased, ultra-high pressure waterjets produced a better surface quality at a faster traverse rate with lower costs.

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1. INTRODUCTION

1.1. INTRODUCTION TO ABRASIVE WATERJET CUTTING

In waterjet cutting, the kinetic energy of the water is used to cut the material. Water from a reservoir is pumped out through a small nozzle at high pressure and when this jet of high pressure strikes a material surface, material removal takes place. For harder materials, adding abrasives to the waterjet improves the ability to cut and the surface quality produced. These latter waterjets are known as abrasive waterjets(AWJ) [54]. In all applications it is critical, for optimal performance, to select the best operating parameters such as the fluid used, the size of the jet, the operating pressure, and the size, type and feed rate of the entrained abrasives.

The use of waterjets for various cutting operations has increased over the past six decades due to its inherent advantages. These include a minimum amount of dust or toxic fumes generated, no heat generation or deformation of the material surface, no thermal stresses as water itself cools down the work piece, lower tooling costs and no tool wear. However because of higher noise levels, lower material removal rates, the frequent difficulty in machining blind holes and pockets, questions of surface finish and the formation of a tapered cut surface have limited the acceptance of this non-conventional cutting technique [7].

1.2. RESEARCH FOCUS AND OBJECTIVES

Conventional machining of composites generates heat that has a negative effect on the cutting tool as well as on the mechanical properties of the work piece. Also, conventional machining introduces problems that include thermal stresses, fiber pull out, and has high tooling costs. The research is focused on overcoming these common problems by focusing on the application of an AWJ and improving the quality of the cut edges it produces. Both the benefits and the limitations of abrasive waterjet application in machining of composite will be examined.

Many new methods and techniques are being developed to improve the cutting performance of abrasive waterjets on composites. The development of high pressure pumps that can continuously operate at 90,000 psi, at power levels of 125Hp has widened the scope of this study of abrasive waterjet cutting of composites. Various cutting parameters are studied to better understand the cutting capabilities of abrasive waterjet cutting on composites. The experiments are carried out on ¼" and 1" thick graphite epoxy composites using baseline data generated for ¼" thick composite. This research is focused in defining optimal cutting conditions for an acceptable surface roughness of 400 μin. Thus, the study involves investigating the effect of different process parameters and optimizing their levels of operation for a 1" thick composite.

A systematic design of experiments is formulated and experiments are carried out to achieve this desired result. The results obtained are analyzed using various statistical methods. The effects of different process parameters are investigated and an explanatory mathematical model is developed to determine the influence of each of the process parameters. The experimental data is used to validate the explanatory model. From the experimental data, optimal cutting conditions that satisfy this specific application are suggested. To better identify these optimal cutting conditions, the economics associated with this process are studied and illustrates the cost savings while simultaneously achieving the required surface finish.

1.3. THESIS OUTLINE

This study is presented as a thesis consisting of 5 sections, of which this Introduction is Section 1. Section 2 is a review of previous work on composites and their applications, the machining of composites, non-conventional methods of machining, AWJ machining, AWJ cutting performance on various materials and AWJ machining of composites. Section 3 is a discussion on the experimental setup used, including the measurement technique used to determine surface roughness, an abrasive analysis and the outline of the design matrix. Section 4 is an analysis and discussion of the experimental data and results. Section 5 presents the conclusions and recommendations as a result of this research effort. Also, the scope of future work is discussed.

2. LITERATURE REVIEW

2.1. COMPOSITES AND THEIR APPLICATIONS

Composites are inhomogeneous combination of matrix and reinforcement material. Naturally found reinforcement materials include hemp, flaxmat, coir etc. The matrix material supports and holds together the reinforcement material. Mechanical and physical properties of the composite, including strength and stiffness are determined by the reinforcement material. Composites may contain combinations of many types of matrices and reinforcements. The selection of the appropriate constituent matrix and reinforcement is based on the desired properties of the resulting composite.

Composites are now widely used in many fields. They are replacing metals and alloys because of their light weight, a higher strength to weight ratio, a greater resistance to corrosion and fire and because they provide a flexibility in design. Because of these improved properties, composites are widely used in the aerospace industry, especially as materials that make up the fuselage, wings, and such infrastructure components as bridges, houses, and in the automotive industry and more recently for wind turbines. For example Beardmore and Johnson [1] investigated the applications of composites in the structural automotive industry. Fiber reinforced composites see a primary use in the making of semi-structural parts. E glass fiber is the composite with the greatest potential for use in the automobile industry and graphite fiber reinforcement is the composite most widely used in the aerospace industry. Composites fulfill many of the energy saving requirements and fatigue resistance standards needed in these industries.

Another example of a specific application of composites is described by Vasiliev, Barynin and Razin [21]. In their paper they discussed the development and aerospace application of anisogrid composites. These structures provide high bending stiffness and resistance to buckling under compression and shear. Also, lattice structures demonstrate shape stabilization under loading. Anisogrid composite lattice structure used as spacecraft structures are of two types based on the loading conditions. One group of the spacecraft bodies which are designed for minimum mass under strength and stiffness constraints to take up loads during launching, the other group does not experience loads during launching and operation.

A group of researchers Ramulu, Hashish, Kunaporn and Posinasetti [12] conducted experiments on different aerospace materials. They were using graphite/epoxy laminate, 7065-T6 aluminum alloy and Ti-6Al-4V, each 16mm thick. The variables in their study of the effects on kerf taper and surface finish were pressure, standoff distance, traverse rate and abrasive grit size. The material removed during cutting generates a difference between the width of cut at the top and the bottom, this difference is called the kerf taper. They varied the pressure at 138MPa, 172MPa and 207MPa, with standoff distances of 4mm, 2.5mm and 1mm, and traverse speed values of 0.7mm/s, 1.6mm/s and 2.4mm/s. Scanning electron microscopy was used for surface quality assessment. The machined surface was examined and three distinct cutting zones were identified. These are the initial damage region, the smooth cutting region and the rough cutting region. Surface waviness was observed to increase with depth of cut. It was also observed that higher pressure and lower standoff distances resulted in a smaller kerf ratio.

To meet the rising demand for waterjet use in the automotive industries, Knaupp and Dr.Ing [29] discussed the flexibility of 3D waterjet cutting systems for cutting 3D contours. Benefits such as easy programming, improved productivity, and the ability to quickly change the cutting head were also discussed. The cutting head can be designed for use with a double head. One table with one bridge and two separate cutting heads means that for a small additional cost the cutting power can be doubled. Between two cutting cycles, the jet quality was measured. High cut quality and reliability in performance was achieved.

Composites are also used in high temperature applications. One such high temperature application includes the manufacture of grips and molds. This application was described by Song, Wang and Zhou [22]. They investigated high temperature applications for reinforced tungsten composites. Although tungsten is a refractory material with good high temperature mechanical properties, its strength decreases with an increase in temperature. TiC is believed to provide a good reinforcement for tungsten. Particle reinforced tungsten based composites (TiC_p/W) showed excellent high temperature strength and good thermophysical properties. Experimentally it is shown that the elastic modulus and hardness of the product increased when TiC is added. Also, an increase in fracture toughness and flexural strength was seen. The strength and toughness gain with the composite is due to the fine grains of tungsten. As the thermal expansion coefficient of TiC is higher than tungsten, the thermal expansion coefficient of the composite increases. Increase in the thermal expansion coefficient and a decrease in thermal conductivity and diffusivity are seen with an increase in TiC content. Thus, with all these properties the TiC_p/W composite is more useful in high temperature applications.

2.2. MACHINING OF COMPOSITES

Composites can be tailored to cater to the needs of the application. The properties of composites are dependent on the type of fiber and matrix used. After fabrication of composites with the required properties, the pieces have to be machined to shape them to fit in real world applications. Aronson [6] has written on the machining of composites. Aronson describes the different kinds of composites and the appropriate tooling and cutting parameters when using conventional machining methods.

To meet the increasing demand for the production of better quality cuts, Palanikumar [49] investigated the effect of change in cutting parameters (speed, feed and depth of cut). Here, speed is the traverse rate of the cutting spindle, feed rate is the amount of material that is removed during cutting on surface roughness in machining a glass fibre reinforced polymer (GFRP) using a polycrystalline diamond cutting tool. He determined the optimum cutting conditions to minimize surface roughness. Experiments were carried according to Taguchi's orthogonal array model and he used the observed data to create a second order expression [Equation 1] that relates surface roughness with cutting parameters using response surface methodology. This expression gives an approximate surface roughness estimate for given cutting parameters without machining, thereby saving cost and time It was observed that feed is dominant parameter that effects the surface roughness followed by cutting speed, whereas, depth of cut plays a minimal role. To achieve a good surface finish on GFRP, a low feed and high cutting speed and shallow depth of cut are recommended.

$$Ra=1.9065 - 0.0103V + 11.1889f + 0.3283d + 0.000001V^2 - 7.1111f^2 + 0.0022d^2 + 0.0340Vf - 0.0015Vd - 4.433fd \quad (1)$$

Where, Ra is surface roughness, V is cutting speed (m/min), f is feed (mm/rev) and d is depth of cut (mm).

Conventional machining of composites can create various defects in the parts. Bhatnagar et al. [44] studied the damage induced while machining fiber reinforced plastics. Composites are replacing metals and alloys in many engineering sectors. Thus it is vital to be able to machine composites within tolerance limits. However the anisotropy and inhomogeneity of composites make it difficult to machine to those tolerances. Defects such as fiber pullout, surface fragmentation, delamination of layers, burning of the surface and other problems have been found. Figure 2.1.illustrates the problems of cutting in the negative and positive fiber direction. For positive fiber orientation, damage due to delamination and out of plane displacement can occur. For unidirectional GRFP composite laminates minimum damage will occur when the fiber orientation is 15□ - 30□ to the plane of the cut.

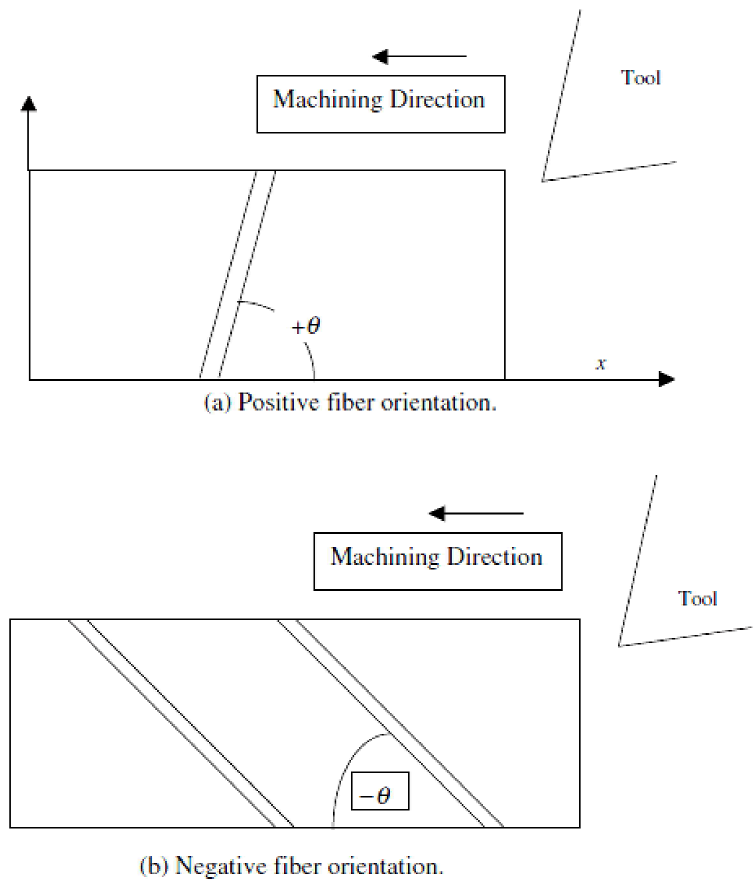


Figure 2.1. (a) Fiber orientation measured counter clockwise from x-axis to the fiber. (b) Negative fiber direction with respect to machining direction

Drilling is one of the common machining processes which creates holes in the piece. Birhan and Ergün [47] performed drilling tests on glass fiber-reinforced polymer (GFRP) using a CNC machine and studied the relation between the cutting parameters, tool parameters and the damage factor (DF). To quantitatively identify the impact of drilling using different cutting parameters, they used a MITUTOYO digital indicator microscope to measure the deformation at the hole entrance and the hole exit. Damage factor is calculated at the hole entrance and at the exit, as the ratio of the maximum deformation diameter to the hole diameter. Carbide drills of 8mm diameter with point angles (60°, 90°, and 120°) and flute numbers (2, 3 and 4) were used for the experiment. Cutting speeds (50, 70, and 90 m/min) and feed rates (0.06, 0.12, and 0.18 mm/rev) combinations were used in the tests. The DF was evaluated at both the hole entrance and hole exit. It was found that increasing the cutting speed decreases the DF at both the hole entrance and exit, whereas, increasing the feed rate decreases the DF at the hole entrance and increases the DF at the hole exit. Also, increasing the number of flutes on the drill decreases the DF at the entrance and increases the DF at the exit, while increasing the point angle increases the DF at both the entrance and exit.

Ramkumar et al. [48] studied the effect of work-piece vibration on drilling of glass fiber-reinforced polymer (GFRP) laminates. Laminates are subject to vibration using a variable frequency generator and performance parameters including thrust, tool wear, temperature and power were recorded. It was observed that providing a small amplitude low frequency vibration to the GFRP laminates resulted in better drilling performance, i.e. hole quality was improved and delamination reduced. Drilling was performed using tipped WC, 2-flute solid carbide and 3-flute solid carbide drills, of which 3-flute solid carbide drill yielded better results.

Machining composites includes processes such as edge trimming, and drilling, cutting, reaming within the parts. In the case of cylindrical work pieces turning is a key machining operation. Rajasekaran et al. [46] investigated turning of carbon fiber reinforced composites. In these experiments, the carbon fiber reinforced composite was machined on a CNC lathe using polycrystalline diamond (PCD) tools. Carbon fiber in the form of a roving filament, wound at +/- 45□, and reinforced with a polyester resin was used. The important cutting parameters of speed, feed and depth of cut were varied at three levels. A spindle power of 2.25 hp and a rotational speed of 54-1200 rpm were used to turn the composite. It was found that the amount of feed had the greatest influence on the cutting force.

2.3. NON-CONVENTIONAL METHODS OF MACHINING

As composites cannot be very easily machined with conventional machining methods their increasing use requires the development of new machining methods. Komanduri [7] compared the advantages and disadvantages of non-conventional and conventional machining. In conventional machining of composites, quality depends on many factors that include such properties of the fiber and matrix as fiber orientation, fiber volume fraction and matrix volume fraction. The inhomogeneity and anisotropy of composites makes conventional machining difficult. Issues in conventional machining such as rapid tool wear, high capital and operating costs, plastic deformation of parts, heat generation during cutting and layer delamination call for development of non-conventional methods such as laser machining, waterjet cutting, electric discharge machining and ultrasonic machining.

Jing et al. [50] studied the rotary ultrasonic elliptical machining (RUEM) of carbon fiber reinforced plastics (CRFP). In RUEM, a diamond core drill is vibrated in an elliptical mode during machining and the radial clearance between the tool and work piece is therefore greater during cutting than with conventional methods. This leads to advantages that include a better chip removal rate, a reduction in cutting force and reduced delamination at the hole exit, while providing better precision and higher surface quality. Experiments were conducted on a CA6140 lathe machine with CRFP panels. Only minor burrs were observed after cutting, delamination was reduced drastically, and there was an improvement in the internal surface of the hole.

To address the excessive tool wear and high tooling cost disadvantages of conventional machining , Dandekar, and Shin [45] investigated the effectiveness of laser assisted machining of high volume fraction metal matrix composites (MMCs). Despite the advantages of MMCs, conventionally machining the material brings challenges such as excessive tool wear and the risk of damage to the material subsurface. Laser assisted machining experiments were conducted using a CNC turret lathe and a 1.5kW CO_2 Coherent Everlase S51 laser. During the experiments, the cutting force, tool wear, depth of cut and surface roughness were measured. The effect of changes in the material removal temperature and the cutting condition on tool wear and the resulting surface were studied. In comparison to conventional machining, it was found that there was a reduction in specific cutting efficiency, a better quality surface was produced, and tool wear and fiber pullout was reduced.

As an attempt to minimize the thermal effects of laser machining Tangwarodomnukun, Wang, Huang, Zhu [40] developed a hybrid laser-waterjet ablation technology. In this, the waterjet was used to shear the softened work piece material and remove it by pressurized jet impingement. The experiment was carried on a 700µm thick single crystalline silicon wafer. In the experiment the waterjet was positioned next to the laser head and used to cool the work piece. The process parameters examined included laser pulse energy, pulse duration, pulse frequency, focal plane position and waterjet pressure, waterjet offset distance, waterjet impact angle, standoff distance and cutting head traverse speed. Two sets of experiments were conducted. In regard to the waterjet parameters, the offset was varied from 0 to 0.6mm in the first set of experiment, and the waterjet pressure and impact angle were varied in the second set of experiments from 5 MPa to 20MPa at angles ranging from 30º to 60º. Increases in laser pulse energy, pulse overlap, water pressure and waterjet impact angle increased the groove width. Groove width decreased with an increase in the offset distance between the laser beam and the waterjet stream. Also, the size of the Heat Affected Zone (HAZ) decreased with increases in offset distance and the position of the laser focal plane.

2.4. ABRASIVE WATERJET MACHINING

Abrasive waterjet machining is one of the most common non-conventional methods of machining. The concept of abrasive waterjet machining dates back to the 1980's. Since then many investigators have carried out relevant studies of abrasive waterjet machining. Trieb and Zamazal [16] investigated the difference between using a pure waterjet and an abrasive waterjet at pressures of 800 MPa on specimens of AlMgSi1 and stainless steel 1.4435. High pressure waterjet cutting showed an improved surface finish and cutting depth and was described as lowering the power required while increasing cutting speed and cut depth. High pressure abrasive waterjet cutting gave a much greater increase in cutting depth and cutting speed.

Ramulu, Jenkins and Guo [31] studied the effect of abrasive waterjet cutting and drilling on continuous fiber reinforced ceramic composites. A 3.7 mm thick CFCC material was used for their experiments. All drilling and cutting operations were performed using a high pressure jet at velocities above 900 m/s. A diamond grit saw was also used to cut the specimen allowing comparison of surface roughness, and waviness compared with that achieved using an abrasive waterjet. They concluded that micro mechanisms including bending, shearing, erosion and micro machining were taking place with the AWJ. Because of these, fiber pullout and delamination was found. Cleaner surfaces were produced at the jet entrance that at the jet exit. At the jet exit, fiber bending, and removal of the matrix from between the fibers occurred. Overall, the AWJ was a better rough cutting method than the use of either a pure waterjet or a diamond grit saw.

Over time the commercial use of waterjetting increased. Methods to improve the quality of the cut were developed. Renato Lombari [27] discussed the benefits of adding polymers to the cutting fluid in non-abrasive ultra-high pressure jetting. The addition of Super Water improved jet performance and reduced wear of consumable parts. Benefits included reduction in the striations along the cut, an increase in average cutting speed and better collimation of the jet leaving the nozzle.

Hashish [23] investigated using AWJ in machining operations that included turning, drilling and milling. The precision of the AWJ manipulator played a major role in the resulting accuracy of the cutting path. The cut surface was found to have a roughness due to the micro effects of each impacting particle and a waviness due to jet penetration and loss of stability as cut depth increased. The upper portion or shear zone was found to have relatively few striations. A smooth cut could be obtained by extending the shear zone through the entire thickness of material. . Surface waviness was reduced at lower traverse speeds, but the lower traverse speed did not improve taper and trailback. In turning with an AWJ, the volume removal rate increases as the depth of cut is increased. To improve the volume removal rate, turning and cutting can be combined. Experiments were conducted on 51mm diameter magnesium silicon carbide (20%) rod. Experiments were also conducted on 16mm thick Inconel plate and ceramic-coated metal. Holes with a standard deviation below 0.025mm were achieved. A variable depth milling of pockets was achieved using an AWJ varying the exposure time of the AWJ over different areas. An accuracy of 0.025mm was achieved in milling.

Zeng and Munoz [30] carried out tests to evaluate the surface finish in abrasive waterjet cutting. The surface finish was found to be similar to that of a sand blasted surface without thermal distortions. The cutting zone was divided into three distinct zones; a primary cutting zone, a secondary cutting zone which featured step cutting, and a pocket cutting zone. The surface roughness increased from the top to the bottom of the cut. Striations were also noted towards the lower section of the cut. Relations between surface deviation, quality index and cutting speed were found.

Researchers have developed various methods to improve cutting performance and surface quality. Lemma, Chen, Siores, Wang [42] conducted experiments on glass fiber reinforced polymer (GRFP) using a cutting head oscillation technique. They varied oscillation angle, frequency of oscillation, waterjet pressure, mass flow rate and nozzle traverse speed. Experiments were carried out to compare the surface roughness produced by normal AWJ and AWJ with cutting head oscillation. From these experiments, they concluded that for most combinations of oscillation angle and frequency the surface finish was improved over that cut with normal AWJ cutting. Improved surface quality was better at higher values of frequency and oscillation angle.

Shanmugam, Wang, Liu [37] introduced the concept of kerf-taper compensation by tilting the head to eliminate taper without compromising traverse speed. The experiment was carried out on an 87% alumina ceramic with dimensions of 150 x 100 x 12.7mm. A high pressure waterjet was collimated through a 0.254mm diameter sapphire orifice. Traverse speed, standoff distance, and water pressure were varied at four levels. Abrasive flow rate and compensation angle were varied at three and six levels respectively. Kerf taper angle decreased with an increase in compensation angle but the elimination of taper on one kerf wall led to an increase in taper on the opposing wall. when low traverse speed, high pressure of waterjet and kerf-taper compensation technique are combined a kerf taper angle of -0.7□ was achieved. . A mathematical model used dimensional analysis to include jet kinetic energy, properties of abrasive particles and material properties in describing the cutting process.

Jet pressure has a major effect on cut surface quality and Hashish [17] evaluated the performance of high pressure waterjets at pressures up to 690MPa. When commercial waterjet systems appeared in 1972 the available systems used 380MPa.This was followed by the development of 414 MPa intensifier pumps. As higher pressures are generated by industry, the effects of higher pressure on cutting are becoming increasingly important to know. Increasing pressure has been shown to greatly improve surface quality and reduce overall power requirements. Metals that included aluminum, and steel were used in Hashish's study. He found that increases in pressure lowered the consumption of abrasives and reduced kerf width. He also carried out an in-depth study of AWJ machining of composites.

Several researchers have looked into applications specific to ultra-high pressure waterjetting. Richard Schmid [28] discussed the use and advantages of ultra-high pressure waterjetting for surface preparation as an alternative to abrasive blasting. Abrasive blasting is used for many kinds of surface preparation including coating removal on bridges, storage tanks, ships and large complex shape steel structures. In comparison to grit blasting where airborne dust is generated causing health problems, ultra-high pressure waterjetting is accepted by environmental regulators. Removal rates are 80-100 sq. ft/hr for waterjetting compared to 90-120 sq. ft/hr for abrasive blast. Jetting also removes soluble salts. This method of surface preparation is used in shipyards and in the removal of lead based paints from steel structures.

Louis, Mohamed and Pude [18] investigated the cutting mechanisms and cutting efficiency of waterjets at pressures above 600 MPa. Cutting efficiency improved for both pure waterjet and abrasive waterjet machining. Also, for AWJ, there was a reduction in the consumption of abrasives. Increased jet pressure increased the depth of cut because of an increase in the jet hydraulic power. These experiments were performed on two metals with different crystalline structures, Aluminum and Zinc.

H.T. Zhu et al. [33] analyzed the ductile-erosion mechanism of hard-brittle materials when polished using an abrasive waterjet. The erosion process under a waterjet happens through impact of solid particles and the waterjet. For harder and brittle materials, material removal happens through erosion caused by the solid particles. Erosion can either be the direct impact of the particles or by shear as the lateral flow of the jet redirects the particles. A micromachining system was used to study precision surface machining by AWJ with silicate glass, 96% alumina and silicon nitride sample materials. Jet pressures of 15MPa at a diameter of 0.3mm were used. Both lapping and abrasive waterjet polishing were performed on all three materials using B_4C as the abrasive. It was found that the resulting lapped surface was coarse and contained some fractures. AWJ polishing produced a fine surface with no fractures that had good surface integrity.

Perec [39] studied the effect of abrasive particle size and particle size distribution on cutting efficiency. Abrasive particle fragmentation occurs when a jet passes through an orifice into the mixing chamber and then out of the focusing tube. Tests measured the abrasive particle size distribution of GMA80 and GMA120 abrasive, with three combinations of orifice/focusing tube diameter 0.25/0.75, 0.33/1.02 and 0.33/0.76 at five abrasive concentrations 15%, 17.5%, 20%, 22.5% and 25%. To capture the abrasives after exit a special receiver was built to prevent further disintegration of abrasive particles. The majority of the abrasive was fragmented below 53 microns during acceleration through the orifice and focusing tube. In the range tested the abrasive concentration and the orifice to focusing tube ratio had only a very small effect on fragmentation.

A computer program GRADISTAT was written by S J Blott and K Pye [51] to describe grain size statistics. The grain size affects entrainment, transport and deposition of sediment particles. Experiments to determine grain size included sieving, sedimentation, and use of a laser granulator together with the principle of division in sample analysis to describe the sample in size fractions divided by weight or volume percentage. The mean, standard deviation, skewness, kurtosis and range of cumulative percentile formulae are calculated from the user input.

Measurements of the surface roughness of a waterjet machined surface may not be accurate due to limitations of the measurement methods. Peter and Axel [53] studied roughness measurements using average roughness (Ra) and average peak to valley height (Rz). They concluded that as the traverse rate of the jet decreases, the jet cuts through the surface and produces a better surface finish at the bottom of the cut. The maximum cutting depth was inversely proportional to the surface quality Q. Experiments were conducted over 2in thick aluminum samples and surface roughness measurements were taken using a PocketSurf® PS1 surface profilometer with measurements taken over an inspection length of 0.6in. Striations started to become apparent at a depth of 0.29in and were prominent below 0.59in. They observed that the Rz values increased along the depth with a maximum peak to valley measurement Rt. As the depth increased the surface waviness increased, indicated by the rapidly increasing Rz values. Ra increased gradually and smoothly over the depth of cut. With a decrease in particle size the values of Ra and Rz decreased. Although both Ra and Rz are used for surface measurements, Rz provides a more accurate representation of the surface waviness than Ra. Rz measurements capture the surface waviness of the striations in the cut surface. It was concluded that the Ra values depend on the abrasive type, size and the location of the measurement and thus, Ra measurements were a poor quantifier of the surface quality whereas Rz values provide uniform, repeatable and traceable methods of surface finish measurement.

2.5. AWJ CUTTING PERFORMANCE ON VARIOUS MATERIALS

We have seen that pressure affects the surface roughness and depth of cut. High pressures have been used to achieve a better surface finish. The effects of all the process parameters including pressure on different materials are discussed below. Hascalik, Cayadas and Gurun [35] presented a study on the effect of traverse speed on Ti-6Al-4V. The machined surfaces, kerf geometries and micro structural features of the machined surfaces were studied. A 4.87mm thick Ti-6Al-4V was machined at traverse speeds of 60, 80, 120, 150, 200 and 250 mm/min. All other parameters were kept constant, pressure was at 150MPa, jet impact angle 90°, the abrasive flow rate (AFR) was 0.005kg/s and standoff distance 3mm. With an increase in traverse speed, the number of particles impinging on the exposed area decreased, reducing the width of the initial damage region. Also, with an increase in speed, the depth of penetration decreases in turn reducing the width of the smooth cutting region. The top of the taper was observed to be wider than the bottom of the cut. The change in kerf taper ratio with increase in traverse speed was less than 0.54°. Also, as the traverse speed increases, the cut had a narrower width and a greater kerf taper ratio. Increase in traverse speed decreased the size of the smooth cutting region and increased overall surface roughness.

Conner, Hashish and Ramulu [19] investigated the use of abrasive waterjet machining in the aerospace and automotive industries. The experiments were carried on on materials used extensively in those industries. Sample materials used were 1.6mm thick Inconel-718, Titanium (Ti6Al4V), 4mm thick 7075-T6 aluminum stock and 4-5mm thick graphite/ epoxy composed of 3501-6 resin and IM-6 fibers. The experiments were performed at 175-380 MPa, using a cutting head with 0.228-0.457mm orifice diameters and 0.79-1.69mm focusing tube diameters. They reported that the surface roughness and kerf characteristics were affected by the properties of the material being cut and the parameters of the cutting jet. In the materials that they tested, it was concluded slower traverse rates and finer abrasive size gave smoother surfaces.

Hard-brittle materials such as ceramics and glass are widely used in engineering applications and must be precisely machined Chen, Siores and Wong [32] cut ceramic materials using an abrasive waterjet and showed it to be more effective than conventional means. Experiments were carried out on 87% alumina ceramics with thickness varying from 12.7mm to 25.4mm. Design of experiments with a four factor design, at eight levels involving 64 runs to determine the effects of cutting variables on kerf quality. Pressure, traverse speed, abrasive flow rate and standoff distance were varied from 138 to 345 MPa, 20 to 50mm/min, 0.575 to 0.910 kg/min and 2 to 6 mm respectively. The surface finish was found to have three zones. The upper zone had a smooth surface, the middle zone contained striations and the lower zone contained lots of pits and the zones were defined as the cutting wear zone, the transition zone and the deformation zone respectively. Kerf curvature in the lower zones increases due to a ballooning effect. Increase in pressure or decrease in traverse speed could double the depth of penetration. Kerf taper angle increased with an increase in traverse speed and decreased with an increase in water pressure.

Wang and Liu [4] considered straight cutting and profile cutting of alumina ceramics using and AWJ. They developed performance models for kerf taper and the depth of cut, and found that kerf taper was greatly affected by the radius of curvature of the profile. Also, the depth of cut increased with an increase in the radius of curvature.

Two researchers, Hocheng and Chang [36] studied kerf formation in ceramic plates during AWJ cutting. Often, conventional ceramic cutting/machining involves higher tool wear and greater machining times because of the high strength and hardness of the ceramic, resulting in higher machining costs. To overcome this, non-conventional machining techniques such as AWJ cutting were studied. Slot cutting experiments examined the effect of changing machining parameters (pressure, traverse speed, abrasive flow rate and abrasive size) on the quality of machining (kerf width, taper ratio, surface roughness, material removal rate and through cut capability). The results are summarized in Table 2.1.

Table 2.1. Effect of different cutting parameters

Cutting Results	Cutting Parameters			
	Pressure(⬆)	Traverse Speed (⬆)	Abrasive Flow Rate (⬆)	Abrasive Size (⬆)
Kerf Width	Increase	Decrease	Increase	Increase
Taper Ratio	Decrease	Increase	Not Obvious	Decrease
Surface Roughness	Not Obvious	Increase	Decrease	Increase
Material Removal Rate	Increase	Increase	Increase	Increase
Through-Cut Capability	Increase	Decrease	Increase	Increase

⬆ - Increase

Later, Gudimetla, Wang and Wong [34] investigated kerf formation in industrial ceramics. 87% alumina plates 12.5mm and 25mm thick were used as samples. Pressure, abrasive flow rate and jet angle were varied from 290MPa to 380MPa, 300 to 800 g/min and 0° to 90° respectively. Traverse speed was varied from 5 to 20 mm/min and 60 to 140 mm/min. The kerf was wide at the entry and reduced in width over the thickness.

Higher abrasive flow rates produced a wider kerf. Taper angle was proportional to traverse speed and inversely proportional to water pressure and AFR. In ceramics, surface fracture and consequent crack propagation into the subsurface cause material removal. The kerf wall surface roughness increased with traverse speed. The kerf surface quality depended heavily on traverse speed and AFR.

When machining metallic coated sheet steels, non-conventional methods such as laser cutting have been employed but because of the high thermal conductivity of the material, this method has not been successful. Wang and Wong [38used an AWJ to cut metallic coated sheet steels. They experimented on 300 x 300 mm test specimens of Zincalume G300. An 80mm long slot 1mm thick was cut using a high pressure jet at 380 MPa. Three levels of waterjet pressure, traverse speed, AFR and standoff distance were tested. A three level four factor full factorial design experiment was performed and 81 slots were cut. The kerf geometry was studied and, hard burrs and loose hairline burrs were detected. Those burrs decreased in height with a decrease in traverse speed and increased with an increase in standoff distance. Small abrasive particles that are embedded in the cut surface were readily removed using compressed air. The summary of the effect of different cutting parameters on the surface quality is shown in Table 2.2.

Table 2.2. Effect of different process parameters on surface quality

	Water Pressure	Standoff distance	Abrasive flow rate	Traverse speed
Kerf width	Increase	Increase	Not significant	Decrease
Kerf taper	Not significant	Increase	Not Significant	Increase
Surface roughness	With a minimum	Increase	Decrease	Increase
Burr height	Decrease	Increase	Not Significant	Increase

Thomas [11] studied the formability and fatigue performance of edges cut by an abrasive waterjet in steel. The experiment was conducted at 360MPa, with traverse speeds varying from 250 mm/min to 1000mm/min. A 500g/min AFR with 80 mesh Garnet was used during the experiment. The surface roughness was influenced by traverse speed and abrasive particle size.

Cayadas, Hascalik [20] performed experiments to study surface roughness using artificial neural networks and regression analysis. before this ther had been little effort reported in using ANN for predicting surface roughness. The back propagation method in ANN was found to be successful for predicting surface roughness. AA 7075 T6 wrought alloy was used in the experimental studies. Five parameters were varied at three levels to create the design matrix. Taguchi's design of experiments was carried out. ANOVA and F-test were also used. Statistics showed that changing waterjet pressure had the greatest effect on surface roughness. Increase in pressure increased surface striations and waviness. Both ANN and regression analysis showed good correlation with the experimental results. Predictive models using regression analysis were however slightly better than ANN.

2.6. AWJ MACHINING OF COMPOSITES

Abrasive waterjet machining of composites overcomes some of the major problems that include rapid tool wear, and thermal deformation associated with conventional machining of composites. Komanduri [7] studied different forms of machining of composites. Composites included boron/epoxy, graphite/epoxy, aramid/epoxy and boron/polyester showed better results when machined using abrasive waterjet. At reduced cutting rates, the ceramic-matrix and metal-matrix can also be machined using abrasive waterjet cutting. Abrasive waterjet machining is a non-contact form of machining. Hence, there is no effect of the material being cut on the tool used. Ramulu and Arola [9] studied unidirectional graphite/epoxy composites machined by waterjet and abrasive waterjet cutting processes. The surface characteristics of the cuts in graphite/epoxy were different when cut by abrasive waterjet compared to those produced by a plain waterjet. The micromechanical behavior and material removal were strongly dependent on the fiber orientation.

Later, Arola and Ramulu [8] experimented on graphite/epoxy laminates 16mm and 19mm thick with a stacking sequence (0/90/45/-45). Along the cut depth, the surface roughness was divided into three regions, initial damage at jet entry, a smooth cutting region and a rough cutting region. High quality uniform cuts may be obtained by minimizing initial damage at the jet entry and by extending the smooth cutting region beyond the laminate thickness by selecting the appropriate choice of cutting parameters.

Geskin, Tisminetski, Verbitsky, Ossikou, Scotton and Schmitt [25] also evaluated the waterjet machining of composites. Waterjet machining removes material by plastic deformation and erosion and the energy transfer between the jet and the work piece is low. They found that the addition of abrasives to the waterjet improves the energy transfer efficiency and the flow diameter also increases performance . This increase in flow diameter increased the material removal rate and the size of kerf. They concluded that excessive kerf at the jet exit is caused by flow distortion due to changing resistance as the jet passed through the composite. They noted that a maximum jet distortion took place in cutting through honeycomb structured composites. Cutting was carried out at 340 MPa on 1.16mm and 18.3mm thick Kevlar, 22.4mm, 4.23mm and 3.45mm graphite epoxy, 1.03mm fiberglass and 26.7mm Kevlar honeycomb. For the graphite based composite, the optimal cutting conditions were at 300 MPa, 0.25mm nozzle diameter, 125mm/min cutting speed, 1.5mm standoff distance giving a defect free cut in both longitudinal and traverse directions. The addition of polymer to the cutting fluid helped reduce the kerf width.

Among different composites, graphite/epoxy is one that has wide commercial usage. Colligan, Ramulu and Arola [10] worked on graphite/epoxy laminates composed of IM-6 fibers and 3501-6 resin and hand laminated from pre-impregnated material with AWJ incorporating various feedrate and abrasive flow rate. They performed tests on two laminates one 4mm thick and the other 28.5mm thick, using a 25HP pump at 310MPa and a 100HP pump at 379MPa. Surface striations and waviness patterns were found to develop on the machined surface with combinations of low flow rate and high feedrate. The ply delamination was observed to increase with feed rate and with a decreasing abrasive flow rate.

Shanmugham and Masood [3] studied abrasive waterjet cutting of layered composites. Kerf characteristics and the effects of cutting parameters on pre-impregnated graphite woven fabric and glass epoxy were studied and a predictive model was developed.

Glass/epoxy (E-glass) is emerging as an increasingly important feed stock. Azmir, Ahsan [43] investigated the effect of different AWJ process parameters on two types of E-glass fibers, one with a woven TGF-800 and the other made with chopped strand mat TGFM-450. 5mm and 10mm thick samples were tested. A 20mm x 20mm square was cut out of the samples during the tests. Among the different process parameters, the parameters that affected the surface roughness the most were: the type of abrasive used, hydraulic pressure and traverse speed.

Later, Azmir, Ahsan [41] further studied the surface roughness and taper ratio of glass/epoxy composite materials cut using AWJ cutting. E-glass fibers and thermosetting epoxy resin matrix were combined to form the composite using hand lay-up. 9 plies of woven fibers were stacked to get a final thickness of 5.4mm. DOE was carried out with six different parameters. One two-level factor and five three level factors were considered. Aluminum oxide when used as the abrasive gave a better surface finish than garnet. The type of abrasive material used and the pressure were major factors affecting the surface roughness. Also, the better quality cuts were produced by increasing the kinetic energy of the process.

Abrasive waterjets are taken a step further by applying waterjet technology to drilling. Hashish and Craigen [24] developed a precision drilling process for composites. In this process, the jet pressure is gradually increased during drilling. A relatively low pressure at the start was employed so that no delamination or fracture is caused. The pressure was then increased continuously so that the surface of the material did not fracture or delaminate. The continuous increase of pressure was to maintain a sufficient drilling strength to penetrate the material.

Shaw and Tseng [26] analyzed composite plates drilled with an AWJ. The results showed that the most probable site for delamination is near the exit of the waterjet. Two mathematical models, a thin plate model and a double plate model were proposed. The paper described the formulation of the fracture mechanics parameters, strain energy release rate, different radii of delamination and different waterjet pressures using the two mathematical models. It concluded that higher water pressures have a higher strain energy release rate and thus lower pressure may improve the quality of drilling. The length of initial delamination may be constrained by using clamps on the laminate and improve the quality of drilling.

Another useful application of abrasive waterjets in composites is in piercing. Scott E. Krajca and M Ramulu [13] evaluated abrasive waterjet machining for piercing holes. Experiments were carried out on laminates of Toray 3K-70-PW unidirectional tape, Toray FGF-108 29M plain weave and a Toray 3900-2 toughened epoxy resin system. Parameters tested included material thickness, standoff distance and abrasive flow rate varied through three levels. The abrasive waterjet pressure was varied at three different levels, 69MPa, 207MPa and ramped pressures ranged from 69MPa to 380MPa.

Delamination is one of the major defects in abrasive waterjet machined materials. Shanmugham, Nguyen, Wang [2] used 6mm thick graphite/epoxy composites made up of graphite (GY70- carbon fibers) and epoxy (type 934) to study this and develop a predictive model. Also, Kok, Kanca and Eyercioglu [5] developed a genetic expression programming model to predict the average and the maximum surface roughness in abrasive waterjet machining of Aluminum alloy composites. Size and weight fraction of reinforced particles and depth of cut were considered as variables in developing the model.

AWJ trimming has evolved and is now proposed for trimming larger and smaller parts of the Airbus 350 and Boeing 787. Data for this application has been presented by Hashish [52]. The use of CRFP parts in the aerospace industry has become extensive over the past few years. Starting from CRFP manufacture of large parts like the plane fuselage to cutting the smaller parts such as clips and brackets. Conventional machining methods and use of solid tools gave problems such as fiber pull out, fiber breakage, matrix smearing and delamination. To overcome these problems the use of AWJ was proposed for composite trimming. These systems are divided into gantry and pedestal robotic systems. The end effector is designed to hold a catcher cup. Depending on the size of the part being cut, either a moving AWJ and stationary part setup is used or a moving part and stationary AWJ setup is used. Experiments were carried out on 5 different CRFP materials provided by an aircraft manufacturer. The taper angle and kerf width at the top of the cut was measured at various cutting speeds. Also, the surface finish and its effect were measured at the top and bottom of the cut surface. The effect of changing cutting speed was found to be insignificant on the top surface when compared to the effect on the bottom surface of the cut. As a remedy to trailback and jet deflection, a reduced cutting speed was suggested with use of the appropriate size and placement of the catcher cup. Parts such as stringers and fan blades have been trimmed using this technology. It was concluded that the AWJ is an ideal tool for trimming and robotic trimming is an emerging effective system for cutting where parts have loose tolerances. Sidefire cutting heads and smaller catcher cups have been developed for much more efficient and precise trimming of composites using AWJ.

3. EXPERIMENTATION METHODOLOGY

3.1 INTRODUCTION

In this section, a detailed discussion on the test material, equipment, instrumentation and the data acquisition method used during the experimentation is presented.

3.2 EXPERIMENTAL SETUP

Cutting is performed using a PaR 5-axis system coupled with a 90,000psi/125Hp intensifier provided by KMT Waterjet Systems, Inc. Figure 3.1. Control of the cutting, is through AutoCAD 2011 which is used to generate a panel configuration consisting of the required number of linear cuts and coupons for each test and SurfCAM 5.0 is used to generate the G-code. This CNC is designed to work with 5-axis milling systems and is adapted to work with an abrasive waterjet system. Thus, this system maintains a constant cutting head traverse rate, which is beneficial in this application since it eliminates cutting head acceleration and deceleration. Figure 3.2 shows the constant cutting head traverse rate achieved during cutting. The constant traverse rate allows use of linear cuts for performance analysis instead of using test coupons. Consequently, this allows more rapid testing.

Figure 3.1. The 5-axis PaR system coupled with the 125Hp intensifier

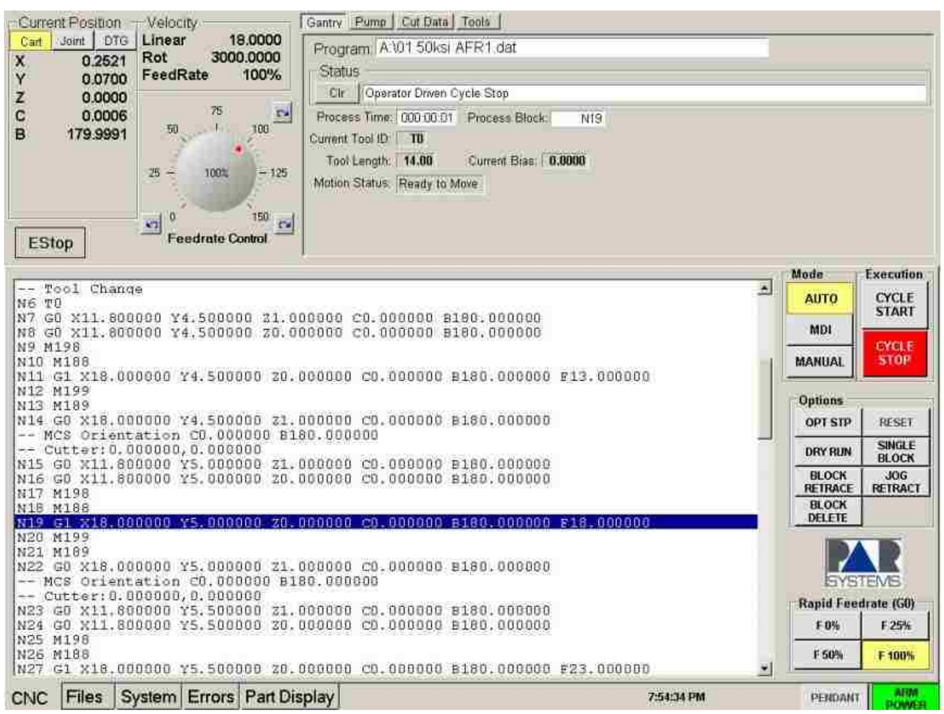


Figure 3.2. Screenshot showing constant cutting head traverse rate

Water is pressurized using the 125Hp intensifier and supplied to the cutting head. The piston is the pump traverses back and forth linearly to pressurize water. During this cycle, it is difficult to maintain a constant pressure throughout the test cutting period. Every cycle of movement of the piston depressurizes and re-pressurizes the water at the end of each stroke. This in turn, introduces a jet pulsation into the flow. The jet pulsation causes a pressure difference of - 10,000psi to +5,000psi. Because this fluctuation causes a difference in the surface roughness along the sample measurements are taken at three locations along the cut and an average of the three measurements is used in the analysis.

The graphite-epoxy composites used for the tests were specially manufactured for this program using an autoclave. The properties of the graphite/epoxy composite are given in Table 3.1.

No other properties other than those mentioned are known. The geometry of the cut path in the test coupon includes both internal and external semicircles to simulate real world applications and is shown in Figure 3.3. The figure shows the dimensions, the measurement locations and different curve diameters located along the coupon. The measurements on the coupon are taken on the linear parts of the coupon only. As the effect of acceleration and deceleration along the cutting head path were not found to be significant, to simplify the experimentation, all the treatment combinations of the test parameters are tested on a linear cut.

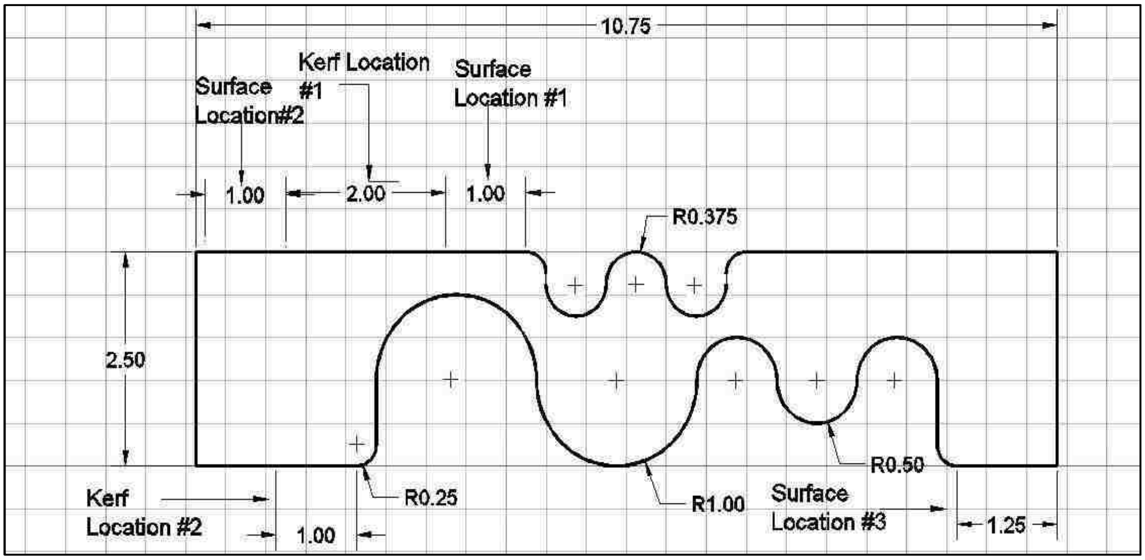


Figure 3.3. Schematic of test coupon with all the measurement locations. All dimensions are in inches.

Table 3.1. Composite Properties

No.	Property	
1	Fiber Orientation	0°,90°,+/- 45°
2	Fiber Diameter	5-6microns in a tow of 0.007”
3	Resin Volume fraction	0.355 (nominal)
4	Lamina Thickness	0.007”
5	Number of layers in each laminate	33

3.3 SURFACE ROUGHNESS AND TAPER ANGLE MEASUREMENT

A Mitutoyo surface profilometer model SJ-201, used for surface roughness assessment, is shown in Figure 3.4. The stylus tip of the profilometer is made of diamond which exerts a measuring force of 4mN. The measuring range of the surface profilometer along the X-axis and Z-axis are 0.5” and 13780 μin respectively. In accordance with the instrument requirements, a cut off length of 0.03”x5 is used for both the ¼” and 1” thick composites. The instrument is calibrated using a Brown & Sharpe precision roughness specimen. The surface roughness of the precision roughness specimen is 126 μin with a tolerance of ±4 μin.

Figure 3.4. Surface Profilometer

On the ¼” thick samples the surface roughness is measured at three locations as indicated in Figure 3.5. Measurements are taken on each sample at three different locations along the length of the sample and a mean surface roughness of the sample is obtained. Its standard deviation is also calculated. The measurements are taken along the direction of cut and perpendicular to the stream. All the measurements have a repeatability of ±50 Ra.

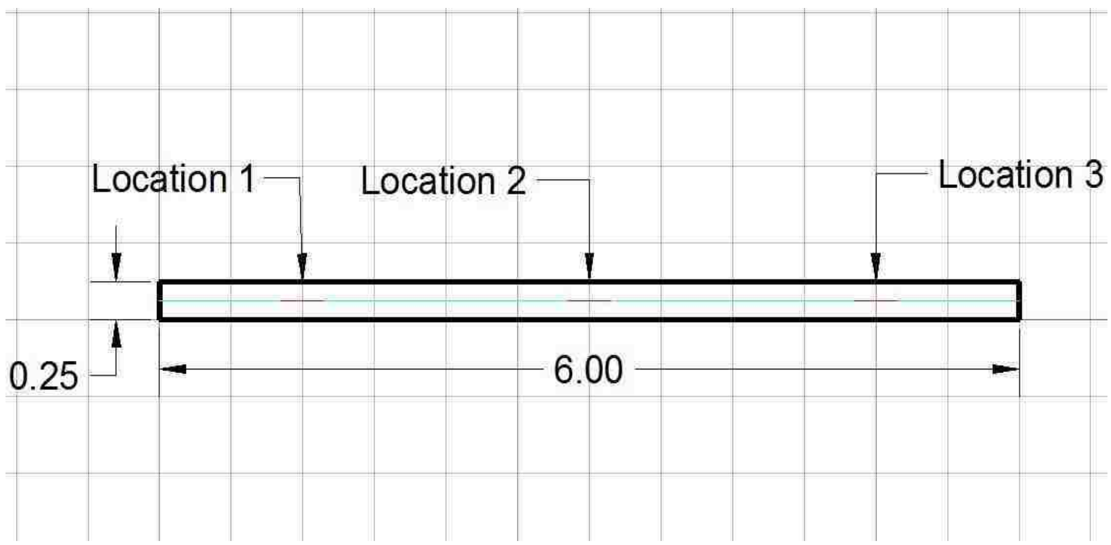


Figure 3.5. Schematic of measurement locations for 1/4" composite. All dimensions are in inches.

For the 1” thick composite, the surface roughness measurements are taken where the jet entered the composite, where the jet exited the composite, and in the middle half-way between the entrance and exit. The profilometer was oriented along the thickness of the composite. These measurements are repeated at three different locations along the cut direction. A schematic diagram of the measurements location is shown in Figure 3.6. The mean value of the surface roughness is calculated individually for the jet entrance, at the middle of the sample and at the jet exit from the piece.

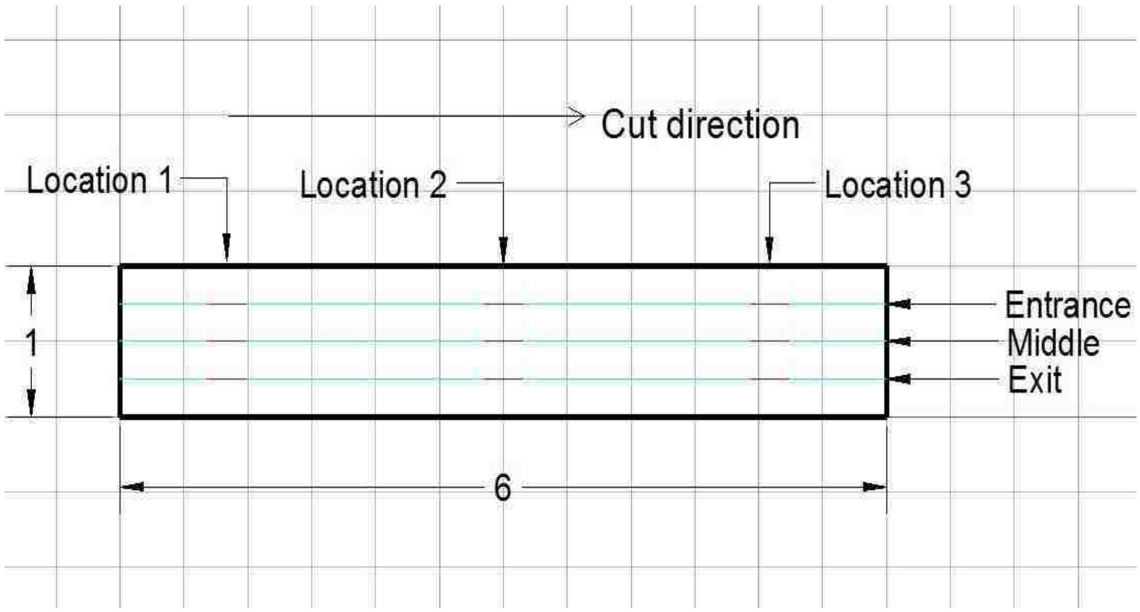


Figure 3.6. Schematic of measurement locations for 1" composite. All dimensions are in inches.

Taper is calculated using Mitutoyo digital calipers. Taper is the difference between the sample width at the top and bottom surface, which are the values measured. Figure 3.7 shows a schematic of taper angle measurements on 1” thick composite. The difference between the top and bottom surface is used to calculate the taper angle using simple trigonometry. The following equation holds true for a 1” thick material.

$$\alpha = tan^{-1}\left(\frac{\frac{b-t}{2}}{thickness}\right) \quad (2)$$

Here, α is the taper angle, t is the width of the top surface and b is the width of bottom surface.

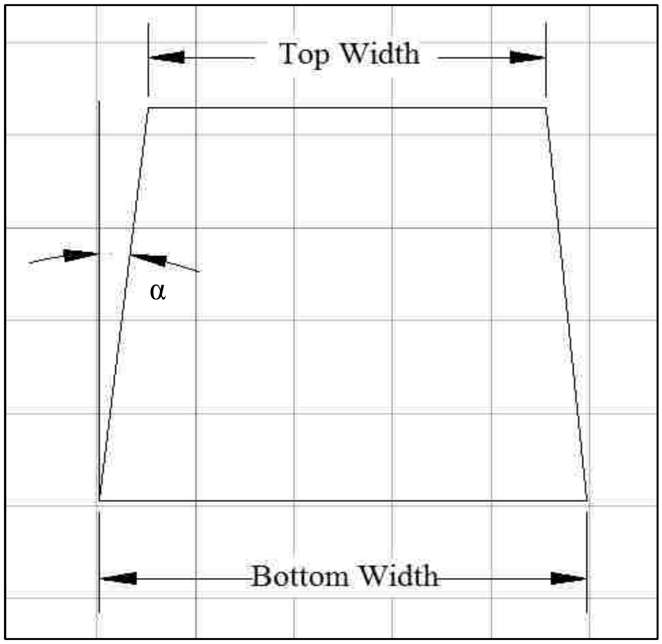


Figure 3.7. Schematic of Taper Angle Measurement on 1" Composite

3.4 ABRASIVE ANALYSIS

Barton 80HPX garnet is used as the cutting abrasive. Figure 3.8 shows the 80HPx garnet including the batch number for the material used. This abrasive grade was used throughout the cutting program. Two batches of garnet were used. Samples of the garnet from each of the batches were sieved to obtain the particle size distribution. The evaluation was performed twice using two trays of garnet each weighing approximately 11kgs. The average from these test results was used to obtain the particle size distribution. The test results were compared to the manufacturing size distribution provided by the Barton Company. Figure 3.9 shows the particle size distribution obtained from sieve analysis of the two sample batches.

Figure 3.8. 80HPx abrasive with batch number

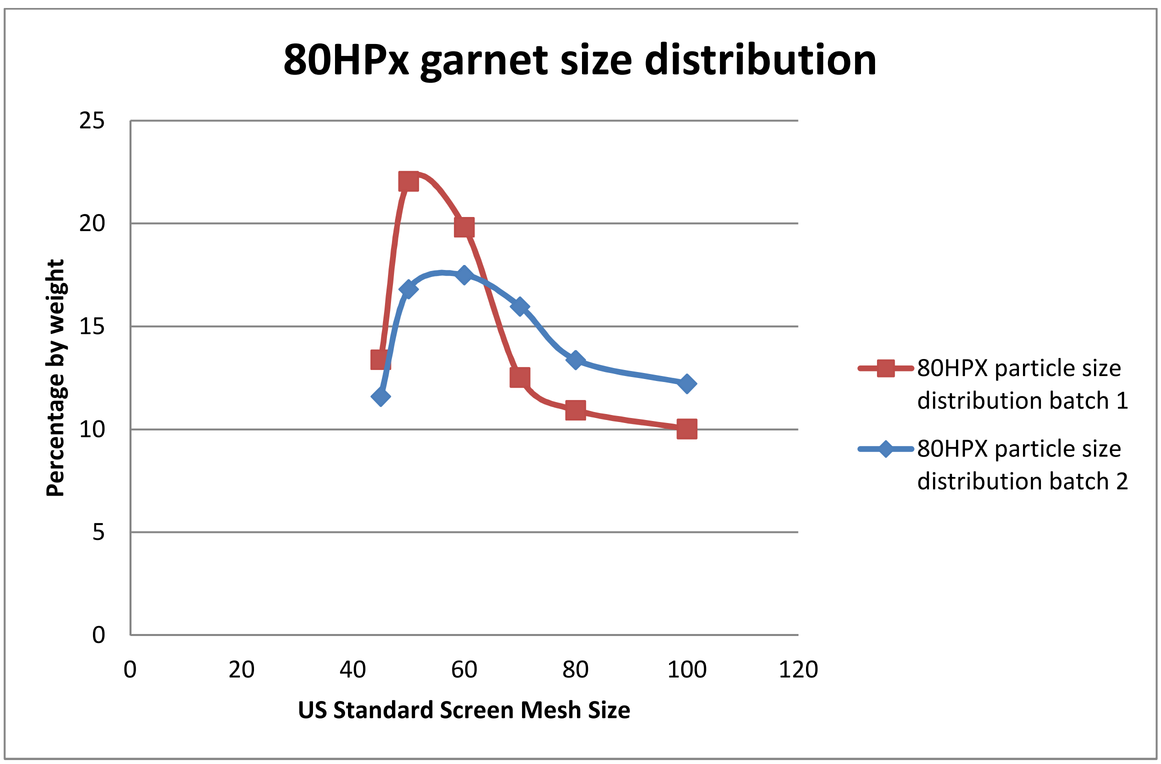


Figure 3.9. Particle size distribution for 80HPX garnet

3.5 DESIGN MATRIX

The literature review revealed that there are several factors that affect the surface quality of composites that have been machined to shape using abrasive waterjet cutting. To measure the impact of each factor on the response variables, a design of experiments (DOE) procedure was carried out. The object of the DOE was to determine the role of the most important factors and their optimal values. The different factors considered relevant to this experiment are: pressure, traverse speed, abrasive flow rate and cutting head configuration. Throughout these experiments, the standoff distance was maintained at 1/8" and the abrasive type, Barton,grade 80HPX, was kept constant. The baseline data which is achieved at an AFR of 1lb/min, with a 50ipm traverse speed under a jet at a pressure of 50,000psi and cutting ¼" stock was first verified, against an externally supplied result. This baseline data is considered as the start point identifying the state of the art in cutting this material, and the consequent experiments were carried out to determine how to improve on these surface characteristics

3.5.1 Variable Process Parameters for ¼" Composite. To verify the baseline data provided, initial tests were carried on ¼" thick composites. The cutting parameters were selected in such a way that they would define a zone of the different levels of that process parameters that would generate acceptable surface roughness levels for this application. The cutting parameters that were varied are traverse speed, pressure, and abrasive flow rate. The levels of the different factors are defined in Table 3.2. The baseline traverse speed for 50,000psi was obtained from the OMAX Feed Rate Calculator (OFRC) (which is used in conjunction with an OMAX waterjet cutting machine in another laboratory of the RMERC at Missouri S&T. It is recognized that different nozzle designs require different optimal operating parameters, however the use of the OMAX calculator, although it would give recognizably different optimal for use of the OMAX nozzles, rather than the KMT nozzles used in this program, did define the bounds of the parameters within which optimal values are likely to be found for both nozzle designs.

The AFR, orifice diameter, focusing tube diameter, material machinability rating and material thickness were input into the OFRC in order to obtain the recommended baseline traverse speed. The baseline AFR was set at 1 lb/minute, at a pressure of 50,000 psi, and surface quality was set at Quality 5 in the program.. Similarly, the baseline traverse speed for 75,000psi and 90,000psi were found using the OFRC. Figure 3.10 shows the recommended traverse speed as a function of pressure for the conditions of these tests. From the curve, the middle value of the traverse speed for a given pressure can be determined. The low and high traverse speeds are obtained by subtracting and adding 5ipm respectively to that middle value. The treatment combinations used for the tests that involve different process parameters are provided in

Table 3.3. The numbers 1,2, and 3 in the table represent the level1, level2, level3 values of the respective process parameters in Table 3.2. Each treatment combination is replicated three times and measurements are taken at three locations for each replication. A total of 81 tests were run and for each treatment combination nine surface roughness measurements were averaged to obtain the mean surface roughness measurement of the composite cut for each treatment combination.

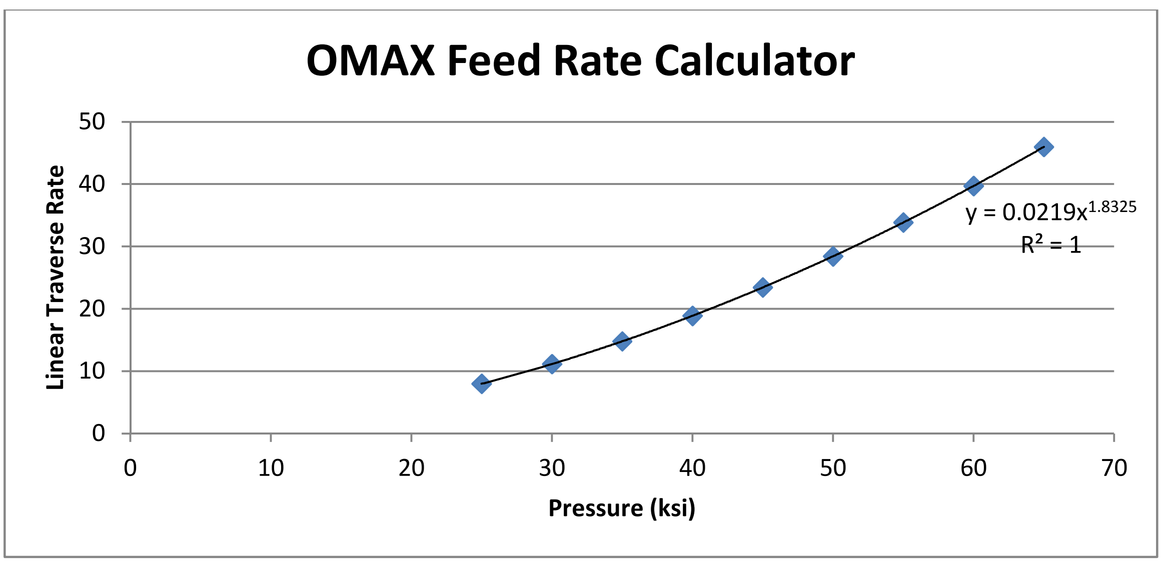


Figure 3.10. Linear traverse rate vs. pressure

Table 3.2. Process parameters for 1/4" thick composite

Parameter	**Level 1**	**Level 2**	**Level 3**
Composite thickness	1/4”	N/A	N/A
Pressure	50,000 psi	75,000 psi	90,000 psi
Abrasive flow rate	0.5lb/min	0.75lb/min	1lb/min
Traverse speed	Low	Mid	High

Table 3.3. Treatment combinations on 1/4" composite

Combinations #	**Pressure**	**Traverse Speed**	**Abrasive Feed Rate**
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3

Table 3.3.Treatment combinations on ¼" composite (cont.)

19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Additional experiments were carried out at 50,000psi at traverse speeds up to 98ipm to verify the function recommendations and and also to obtain the baseline traverse speed. All the cutting parameters other than the traverse speed were kept constant. At each traverse speed, three replications were made and the measurements taken as described above.

3.5.2. Variable Process Parameters for 1" Composite. The results obtained from the experiments on ¼" composites made it possible to estimate values for the process parameters to effectively cut through 1" composite and a design of experiments was formulated. Initially, linear cuts were performed to test all the parameters instead of using the cutting pattern of the test coupon. The coupon pattern was used once the optimal setting for the different parameters had been determined.

The linear cuts were carried out at three different pressures using waterjet orifice to focusing tube orifice diameters of 0.013"/0.040" and 0.016"/0.043" in the cutting head. An initial series of tests were carried out using the 0.013"/0.040" configuration. At each level of pressure, the traverse speed was varied at ten different levels starting at 5ipm, 8ipm and incrementing to 48ipm at intervals of 5ipm. Table 3.4 shows the levels of all the process parameters other than traverse speed used to test cut the 1" thick composite. At 50,000psi the samples were cut using 1lb/min, 1.25lb/min and 1.5lb/min AFR only. It is known that at the lower pressures of 50,000psi, increasing the abrasive feed rate beyond

1.0lbs/min will not change the surface roughness of the specimen significantly. The test combinations for the 1” composite, using the 0.013”/0.040” diameter ratio are given in Table 3.5. The numbers 1,2,3, and 4 in the Table 3.5 indicate the levels of the pressure and AFR given in Table 3.4. Traverse speeds 1-10 indicates the ten different levels of the traverse speed used during the experiment.

Two different cutting head configurations were evaluated to find the effect of changing the orifice diameters in the cutting head,. The tests performed using the cutting head with orifice ratio 0.016”/0.043” were similar to the tests performed with the earlier head, Only three abrasive feed rates were used at each pressure level. After the first cutting head results were analyzed, it was found that there was not much difference in cut quality when the AFR was increased above 1.5lb/min at 50,000psi. Thus, AFR levels of 1, 1.25, 1.5lbs/min were used in the tests at 50,000psi. At 75,000psi AFR values of 1.25, 1.5, 1.75lbs/min were used, and at 90,000psi AFR levels were 1.5, 1.75, 2lbs/min. Table 3.6 shows the test parameter levels used to cut 1” composite using the 0.016”/0.043” cutting head. The numbers 1, 2, and 3 indicate the levels of pressure and abrasive feed rate given in Table 3.4. The traverse speed values of 3-10 relate to the eight different traverse speeds used to cut the 1” composite. The slower traverse speeds 5ipm and 8ipm gave a very smooth surface finish throughout the depth of cut irrespective of the other process parameters used for cutting. Thus these slower traverse speeds were not tested further.

The design matrix formulated for 1” thick composite to test the effect of process parameters on the surface roughness using 0.013”/0.040” and 0.016”/0.043” heads was also used for taper angle analysis. Each treatment combination was repeated twice creating two parallel cuts so that each sample was cut with the same cutting conditions on both sides making it feasible to take effective taper angle measurements.

Table 3.4. Process parameters for 1" composite

Parameter	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Composite thickness	1”	N/A	N/A	N/A	N/A
Cutting Head	0.013”/0.040”	0.016”/0.043”	N/A	N/A	N/A
Pressure	50,000 psi	75,000 psi	90,000 psi	N/A	N/A
Abrasive flow rate	1lb/min	1.25lb/min	1.5lb/min	1.75lb/min	2lb/min

Table 3.5. Treatment combinations on 1" composite using 0.013”/0.040” cutting head

Combinations #	**Pressure**	**Abrasive Feed rate**	**Traverse Speed**
1-10	1	1	1-10
11-20	1	2	1-10
21-30	1	3	1-10
31-40	2	1	1-10
41-50	2	2	1-10

Table 3.5. Treatment Combinations on 1” thick composite using 0.013”/0.040” cutting head (cont.)

51-60	2	3	1-10
61-70	2	4	1-10
71-80	2	5	1-10
81-90	3	1	1-10
91-100	3	2	1-10
101-110	3	3	1-10
111-120	3	4	1-10
121-130	3	5	1-10

Table 3.6. Treatment combinations on 1" thick composite using 0.016"/0.043" cutting head

Combinations #	**Pressure**	**Abrasive Feed rate**	**Traverse Speed**
1-8	1	1	3-10
9-16	1	2	3-10

Table 3.6. Treatment combination on 1" thick composite using 0.016"/0.043" cutting head (cont.)

17-24	1	3	3-10
25-32	2	1	3-10
33-40	2	2	3-10
41-48	2	3	3-10
49-56	3	1	3-10
57-64	3	2	3-10
65-72	3	3	3-10

3.5.3. Variable Process Parameters for Underwater Cutting. In an effort to improve the surface quality when cutting 1”composite, underwater cutting was tested. The process parameters for underwater cutting were decided based on the optimal cutting parameters for 1” composite in air. The experiments were designed using only those treatment combinations that were likely to improve surface quality. Thus, two pressures: 75,000psi and 90,000psi were used and the abrasive feed rate was varied from 1.25lbs/min to 2lb/min. Table 3.7 shows the parameters used for underwater cutting. Table 3.8 shows the treatment combinations used to perform underwater cutting on 1”composite.

Table 3.7. Process parameters for underwater cutting

Parameter	Level 1	Level 2	Level 3	Level 4
Composite thickness	1”	X	X	X
Pressure	75,000 psi	90,000 psi	X	X
Abrasive flow rate	1.25lb/min	1.5lb/min	1.75lb/min	2lb/min

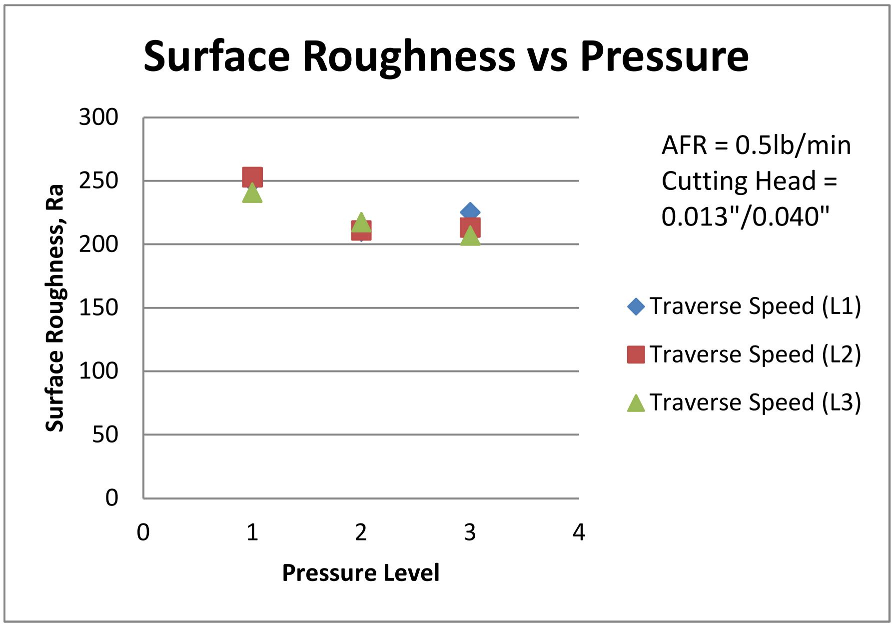
Table 3.8. Treatment combinations for underwater cutting

Combinations #	Pressure	Abrasive Feed rate	Traverse Speed
1	1	1	1-10
11	1	2	1-10
21	1	3	1-10
31	1	4	1-10
41	2	1	1-10
51	2	2	1-10
61	2	3	1-10
71	2	4	1-10

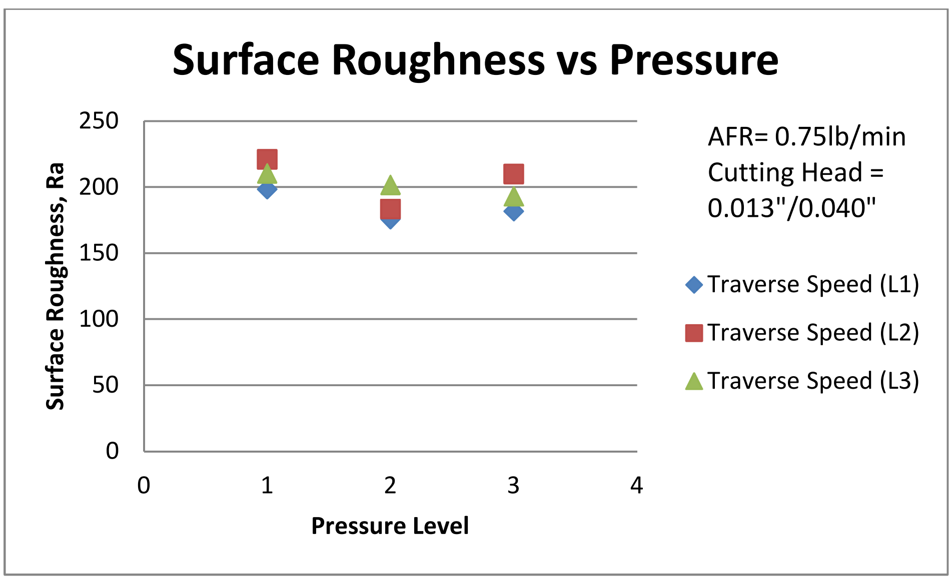
4. EXPERIMENTAL DESIGN AND DATA ANALYSIS

4.1. SURFACE FINISH OF THE MACHINED MATERIAL

4.1.1. Effect of Pressure on Surface Finish. The composite was cut at three different pressures, 50,000psi, 75,000psi and 90,000psi to find the effect of pressure on surface quality. Although surface roughness decreases with increase in pressure, the effect is predominantly seen in cutting 1” composite rather than in cutting ¼” composite. The effect of changing pressure on ¼” composite is shown in Figure 4.1. At 50,000psi and with traverse speeds above 33ipm delamination was found in the 1” thick composites particularly towards the exit of the jet, as shown in Figure 4.2. Most of the samples cut at faster traverse speeds also showed prominent jet striations that increased the surface roughness of the sample. In some cases, the notably high peaks and low dips were so disparate that the variation did not allow the surface profilometer to obtain measurements of the surface. At very high speeds the abrasive also penetrated into the material irregularly, leaving pits in the surface. Above all at 50,000psi and at the higher traverse speeds of 43ipm and 48ipm, the jet could not penetrate through the thickness of the material, and only partial cuts were achieved. The overall influence of pressure level on the cut quality in 1” composite is shown in Figure 4.3. As mentioned earlier, three abrasive feed rates were used at a jet pressure of 50,000psi, so only three graphs are presented to illustrate the difference in surface roughness.

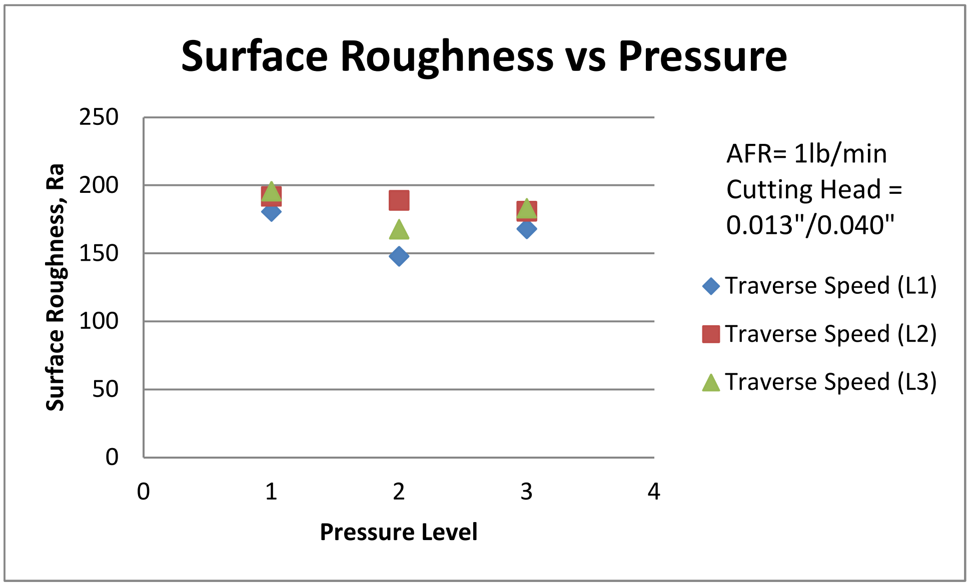


(a)



(b)

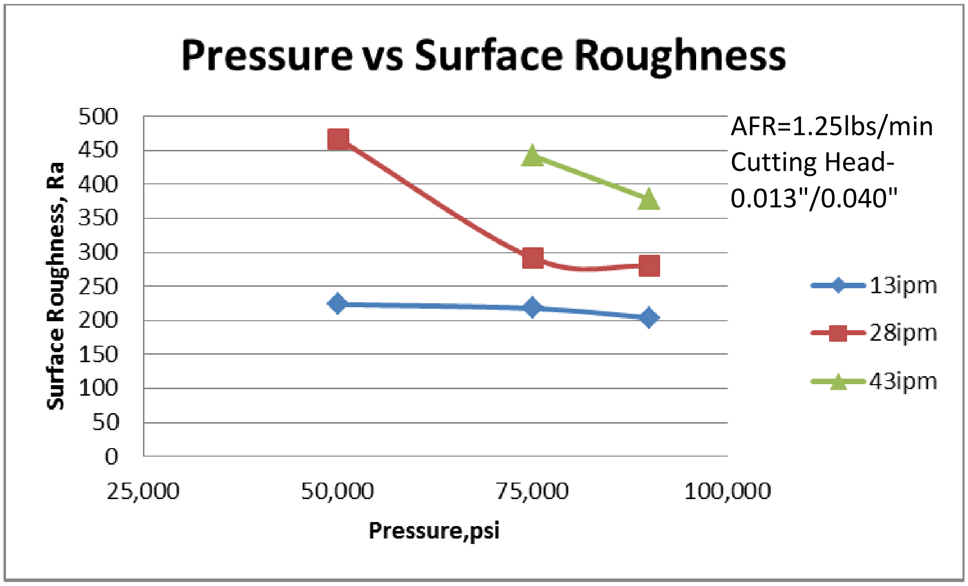
Figure 4.1. Comparison of surface roughness on ¼” composite cut at different pressures



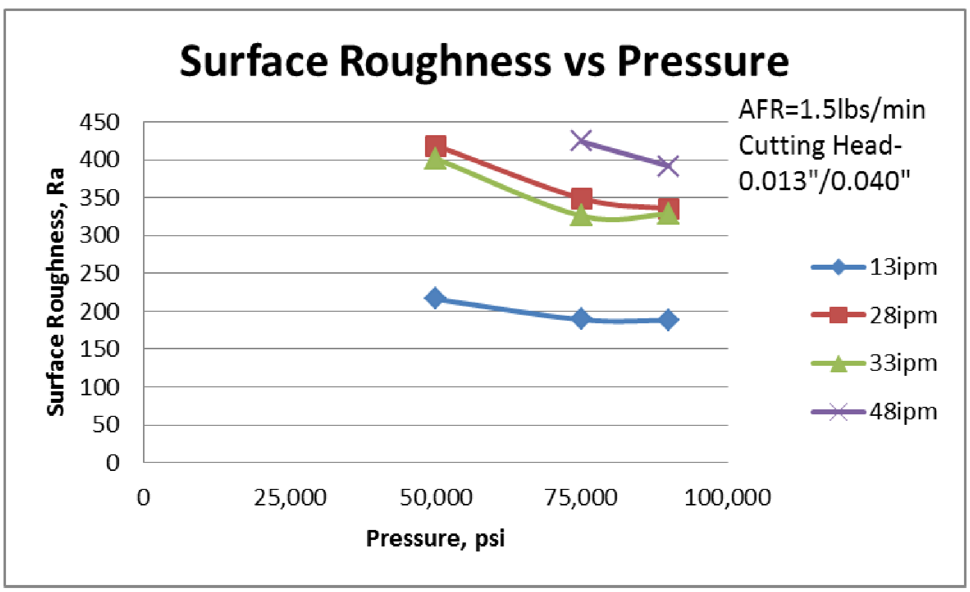
(c)

Figure 4.1. Comparison of surface roughness on ¼” composite cut at different pressures (cont.)

Figure 4.2. Delamination of 1" composite cut at 50,000psi (25x)

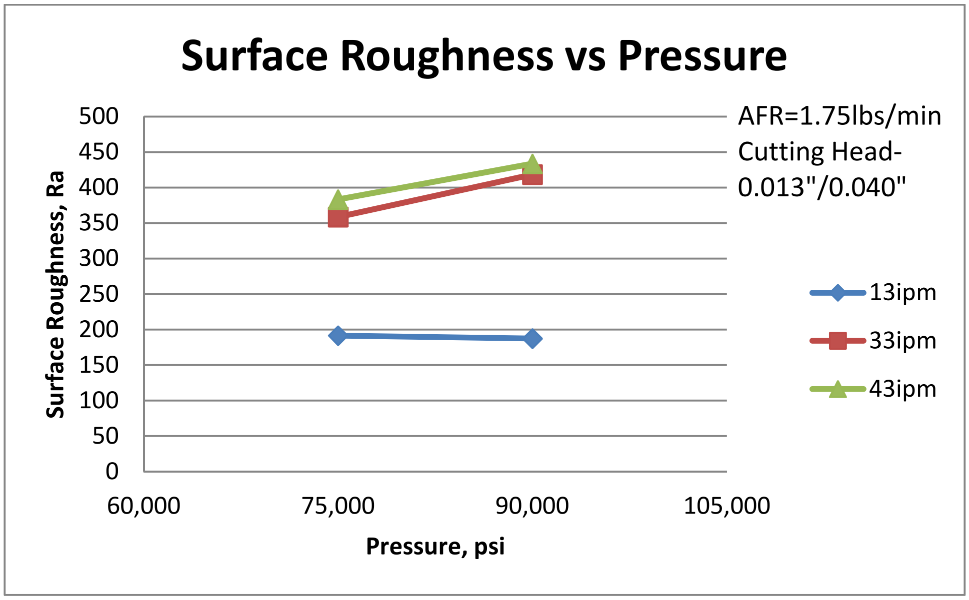


(a)



(b)

Figure 4.3. Comparison of surface roughness of 1" composite cut at different pressures



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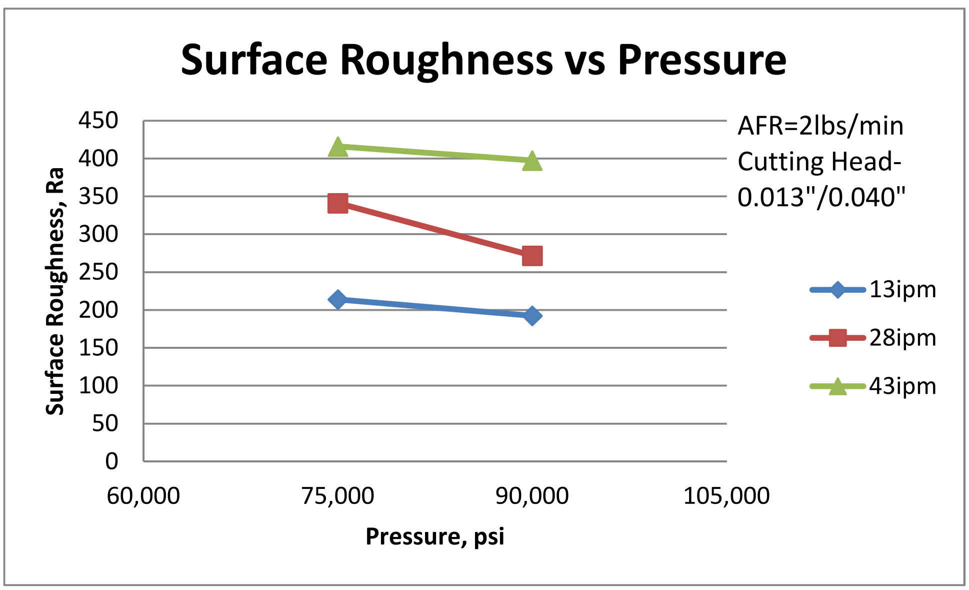


(d)

Figure 4.3. Comparison of surface roughness of 1" composite cut at different pressures (cont.)

The failure to cut through the composite at 50,000psi was overcome at higher pressures. Figure 4.4 shows a comparison between a delaminated sample cut at 50,000psi and a sample cut at 90,000psi using otherwise the same cutting parameters. It can be seen that, a better surface quality is obtained at higher pressures. But one of the problems noticed when using higher pressures is that bottom side erosion can occur. Although not all the samples showed this, a few samples were eroded on the underside of the coupon. Figure 4.5 show the bottom side erosion of one of the samples. It was found that the slats and support beams in the waterjet bed were causing splash back that led to the erosion. Cuts that happened to line up perfectly with the slats showed erosion along the length of the sample. Additionally, other samples showed regional erosion in areas where the cutting head crossed a slat perpendicularly. Thus, it was concluded that cut paths should be arranged to ensure that the jet did not pass over one of the support elements.

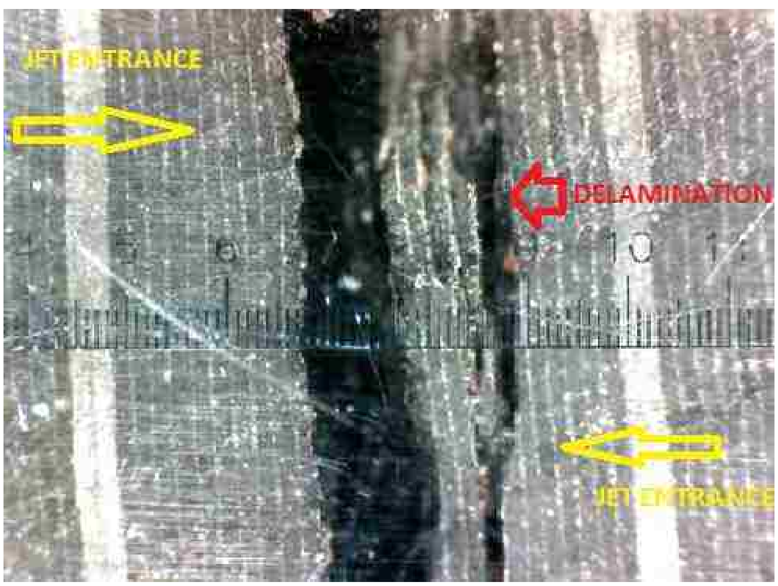


Figure 4.4.Comparison of Surface Quality at 90,000psi (left) and 50,000psi (right) cut at 33ipm, abrasive feed rate – 1.5lbs/min, cutting head- 0.013”/0.040”

Figure 4.5. Bottom side erosion on a 1" thick composite sample

Further testing was performed on test coupons at all pressures at a constant abrasive feed rate of 1.5lbs/min and at a traverse speed of 23ipm.in order to see how well the jets could follow the contour path of the earlier tests. As found when cutting the linear samples, at 50,000psi the jet could not separate the coupon from the panel. Also, because of jet lag the coupon did not separate along the exit cut. Other problems included delamination and fiber pull out of the composite. All these problems were eliminated when testing at higher pressures and as a result a better surface finish was obtained. Figure 4.6 and Figure 4.7 shows a comparison between a test coupon cut at 50,000psi and at 90,000psi.

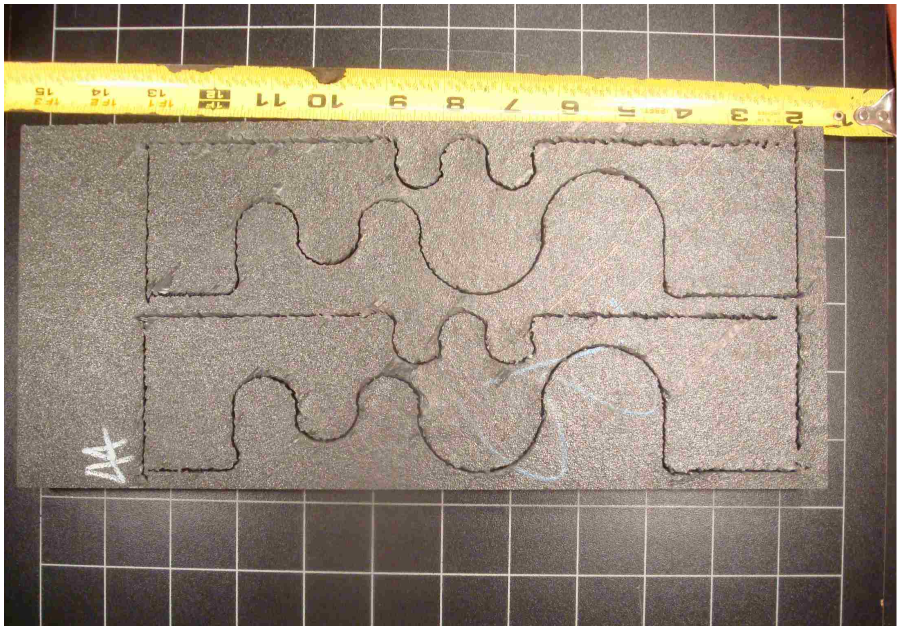


Figure 4.6. Coupon cut at 50,000psi, at a traverse rate of 23ipm, AFR 1.5lbs/min, cutting head 0.013”/0.040”, uniform perforations can be seen indicating a constant traverse rate regardless of coupon geometry

Figure 4.7. Coupon cut at 90,000psi at a traverse rate of 23ipm, AFR 1.5lbs/min, cutting head 0.013”/0.040”

4.1.2. Effect of Abrasive Feed Rate on Surface Finish. Abrasive selection has a great impact on the surface roughness of a machined material. Adding abrasives to waterjet increases the cutting efficiency, cutting depth and improves surface finish. Figure 4.8 shows a sample cut with an AWJ compared to a sample cut with plain water. The abrasive size (grade) and the AFR are the two major factors affecting the surface quality of the cut. Abrasive grade was constant (Barton 80HPX) throughout the tests and AFR was varied to determine its effect on the surface quality with varying pressure. AFR was found to have a major effect on surface roughness. For the ¼” thick composites, AFR was varied at three different levels, 0.5lb/min, 0.75lb/min and 1lb/min. A change in flow rate will change the optimal AFR, and so, at higher pressures that were used in cutting 1” composites, higher AFR have been used. The AFR was varied at five different levels from 1lb/min to 2lb/min at intervals of 0.25lb/min. Figure 4.9 and Figure 4.10 show the effect changing AFR in cutting ¼” and 1”composites respectively.

Three different traverse speeds were used at each pressure, and the graph for AFR vs. surface roughness was plotted. The graphs illustrate the surface roughness changes at the jet exit from the sample. The surface roughness measurements show that the roughness at the jet entrance and in the middle are better than the roughness at the jet exit though this was always within the acceptable limit of 400 micro inches. Thus, research was focused on improving surface quality at the jet exit. Thus, surface roughness values at the jet exit were chosen when plotting graphs showing factor effects since it was at this location that large differences were measured in the surface roughness. Thus the effect of changing parameters was more evident.

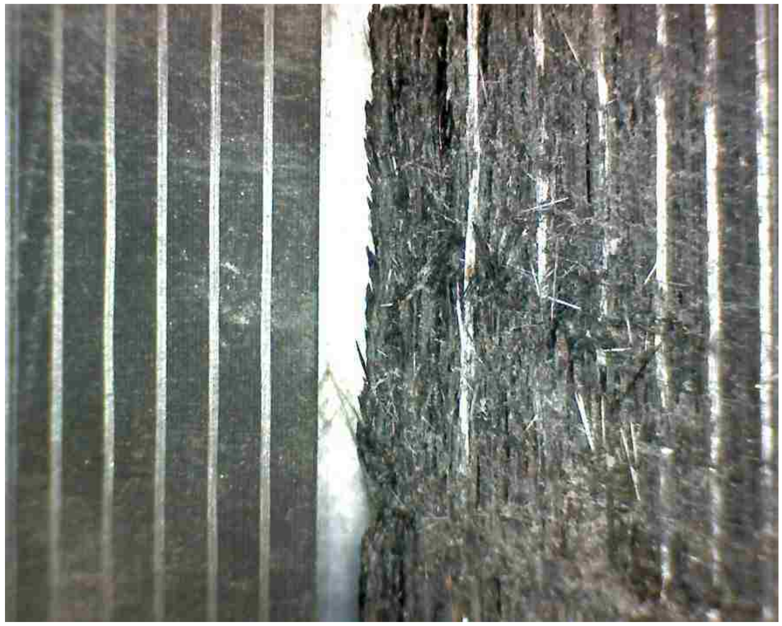
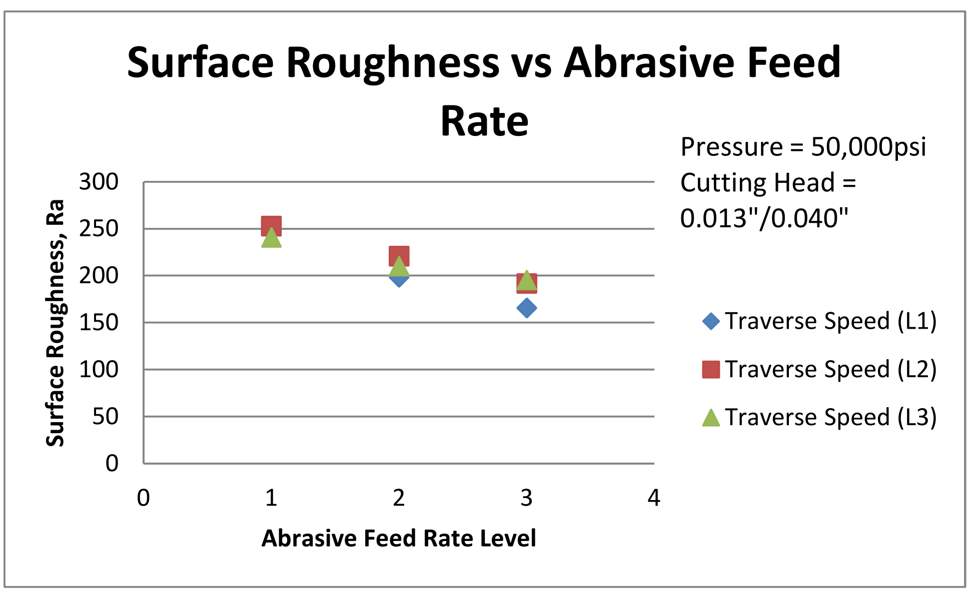
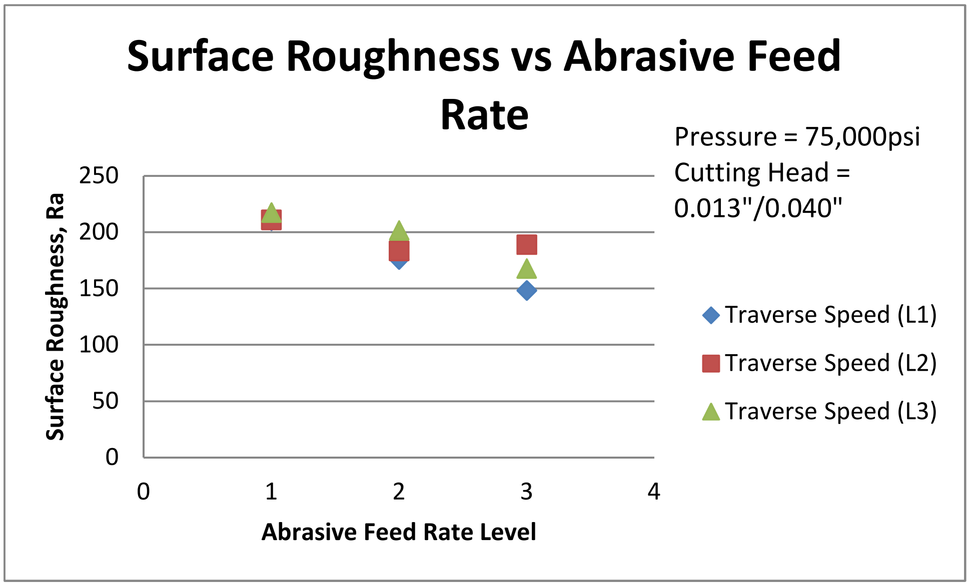


Figure 4.8. Comparison of a sample cut with abrasive waterjet (left) and plain waterjet (right)



(a)

Figure 4.9. Effect of abrasive feed rate on surface roughness in 1/4" composite



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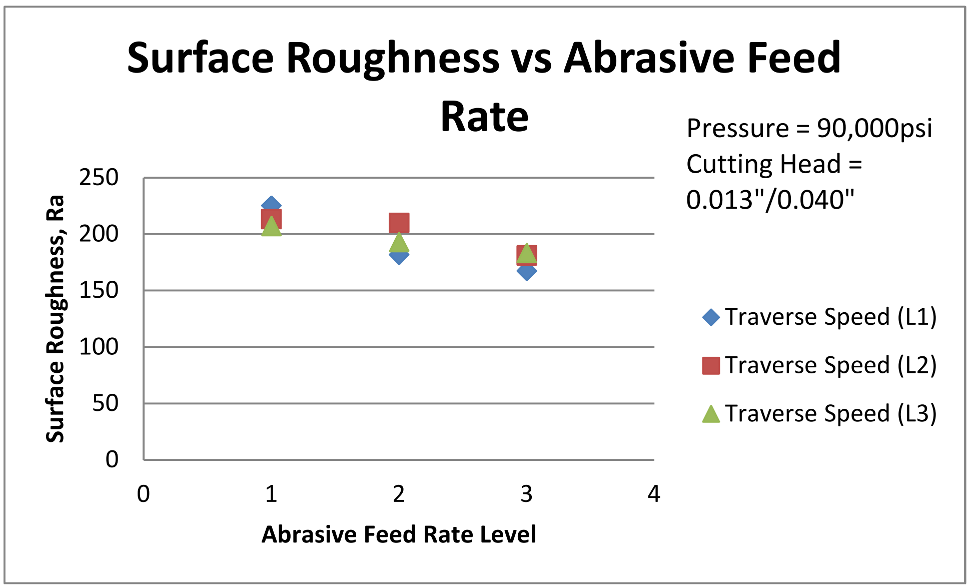
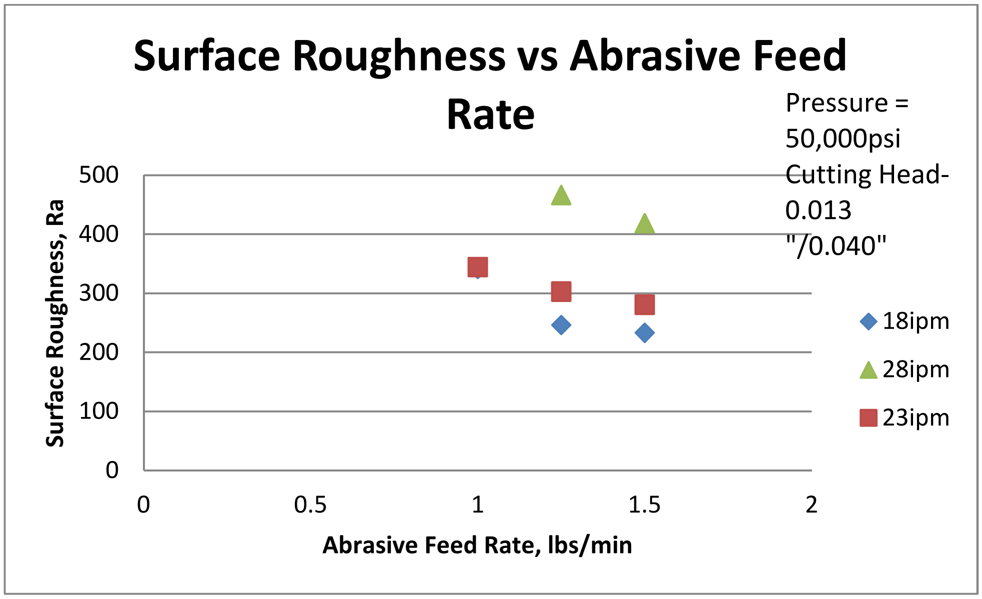
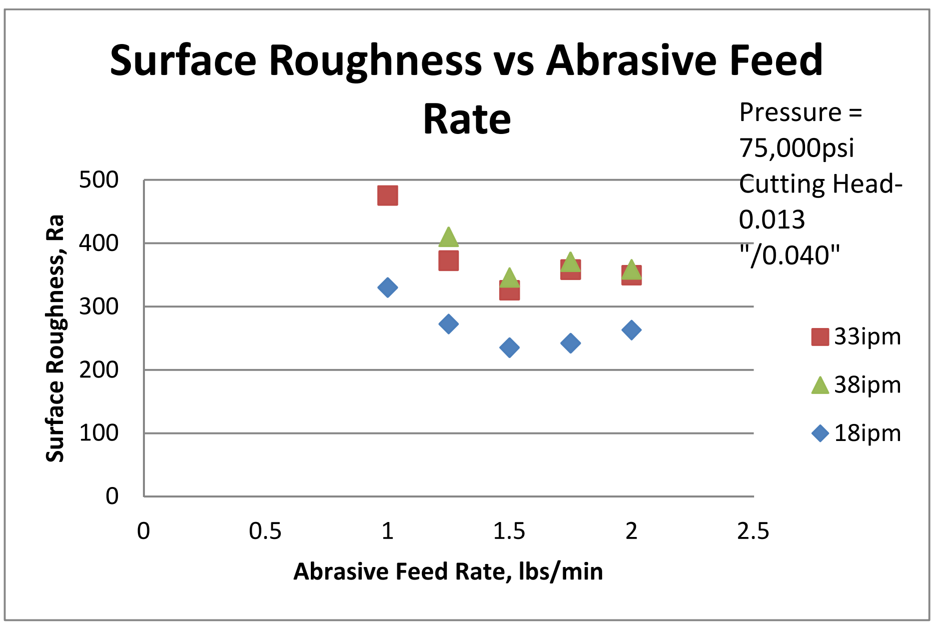


(c)

Figure 4.9. Effect of abrasive feed rate on surface roughness of 1/4" composite (cont.)

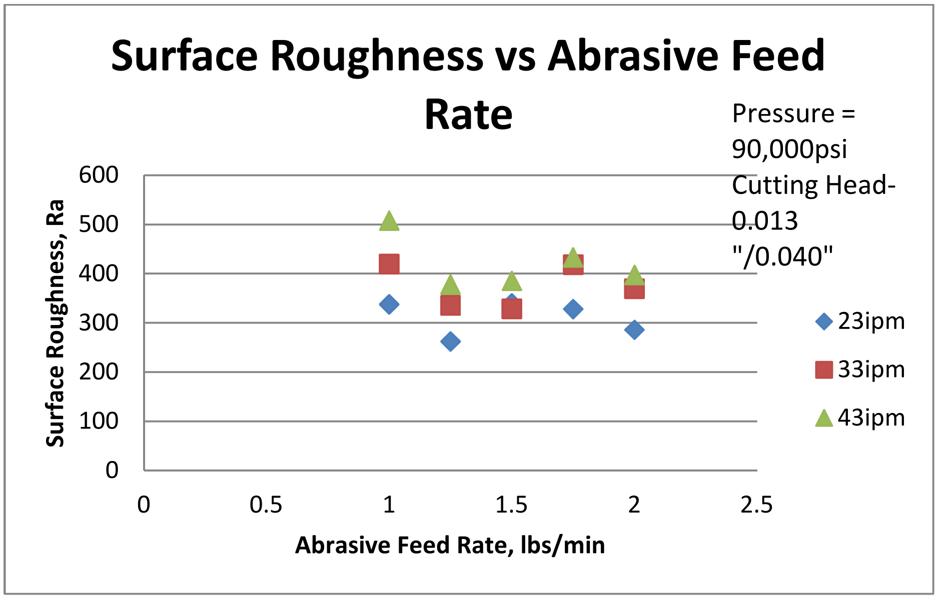


(a)



(b)

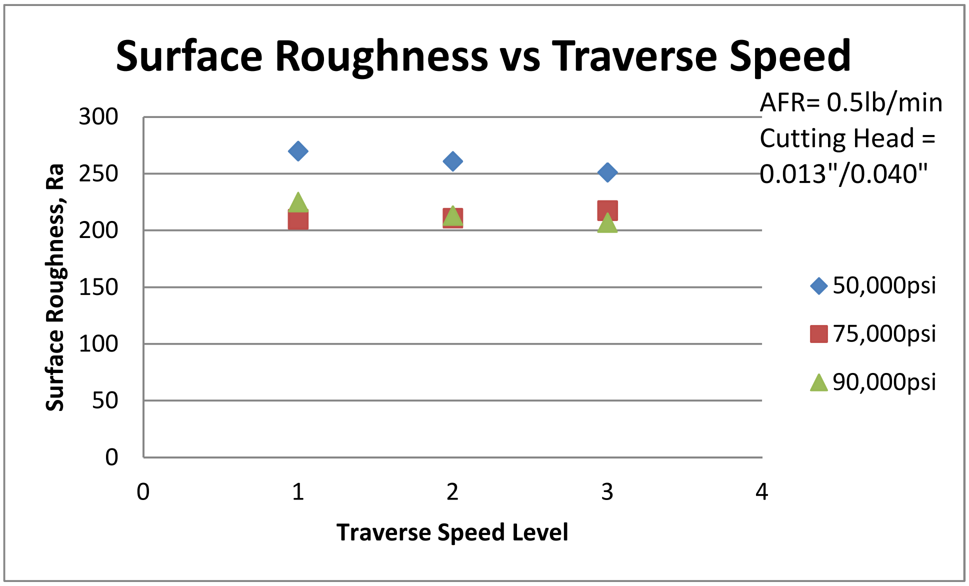
Figure 4.10. Effect of abrasive feed rate on surface roughness of 1" composite



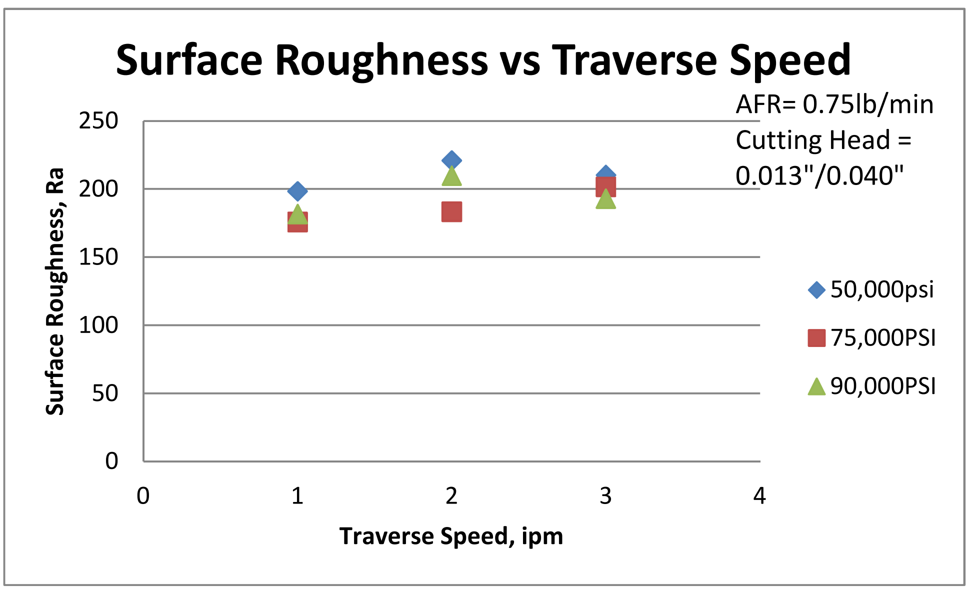
(c)

Figure 4.10. Effect of abrasive feed rate on surface roughness of 1" composite (cont.)

4.1.3. Effect of Traverse Rate on Surface Finish. Based on the design of experiments, the ¼" composite was cut at three different traverse rates. The effect of varying the traverse rate is shown in Figure 4.11. The surface roughness increases with increase in traverse speed. Similarly, following the design of experiments, cutting was performed on 1" composite at eight traverse speeds ranging from 5ipm to 48ipm. For a given pressure and AFR, a better surface quality was obtained using slower traverse speeds. Figure 4.12, shows the effect of various traverse speeds in cutting the 1" composite. Figure **4.13** shows that at higher speeds as the jet exits the composites, large striation marks became evident. The surface was divided into three different zones. The upper zone is at the entrance of the jet where the surface is very smooth. The middle zone is where the roughness began to increase and jet striations appear while the lower zone is at the exit of the jet where the jet striations are most prominent.

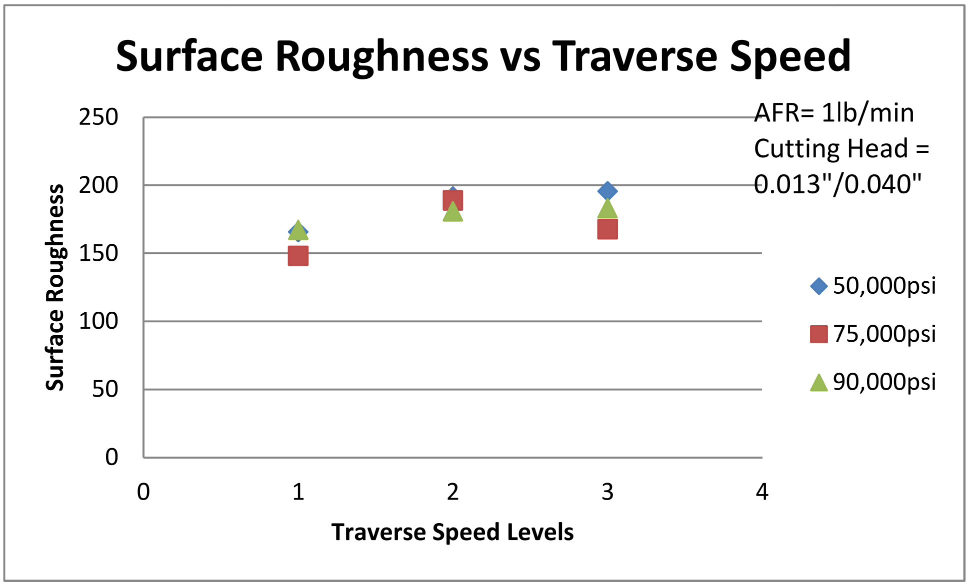


(a)



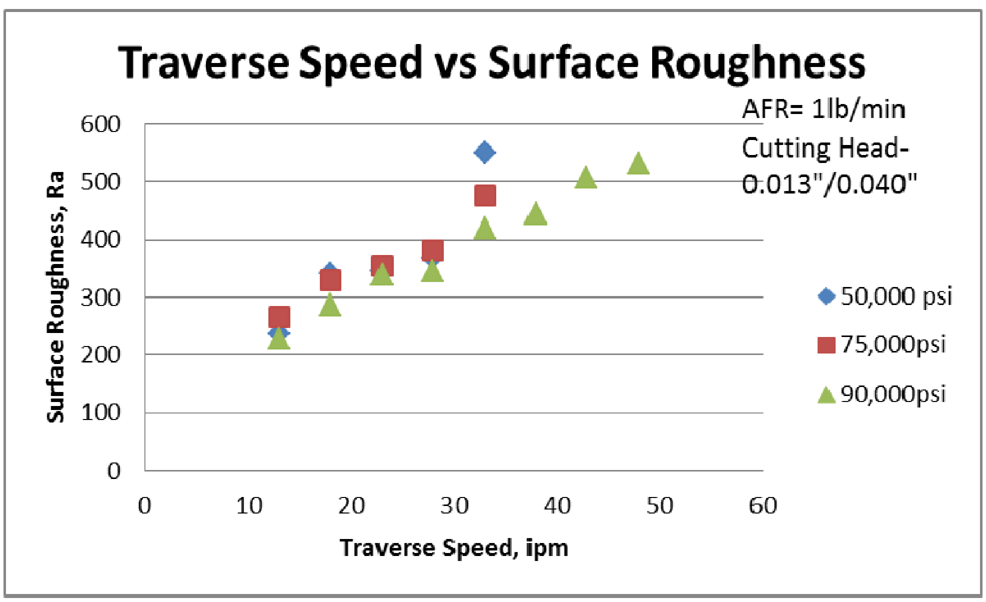
(b)

Figure 4.11. Effect of traverse speed on surface roughness of 1/4" composite



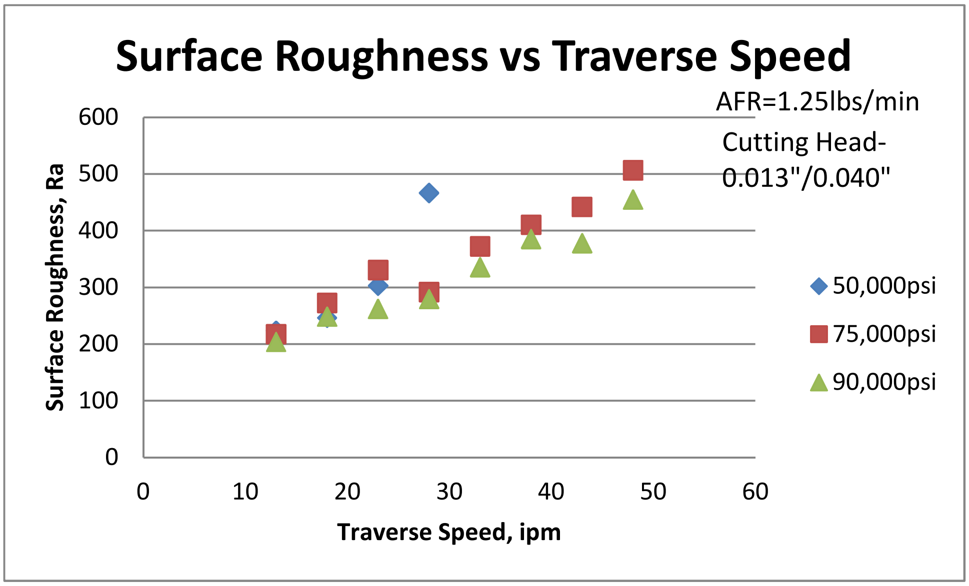
(c)

Figure 4.11. Effect of traverse speed on surface roughness of 1/4" composite (cont.)



(a)

Figure 4.12. Effect of traverse speed on surface roughness of 1" composite



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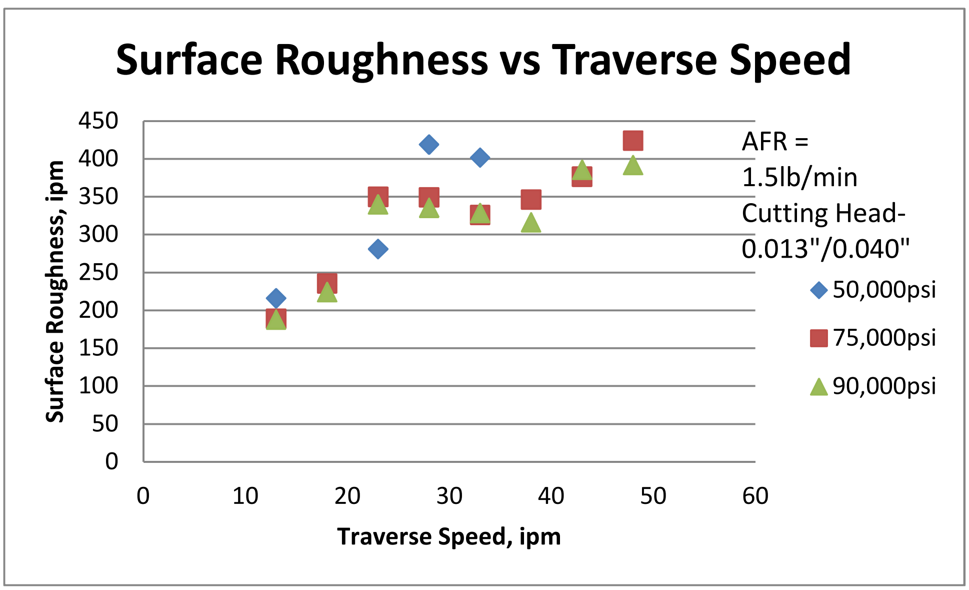
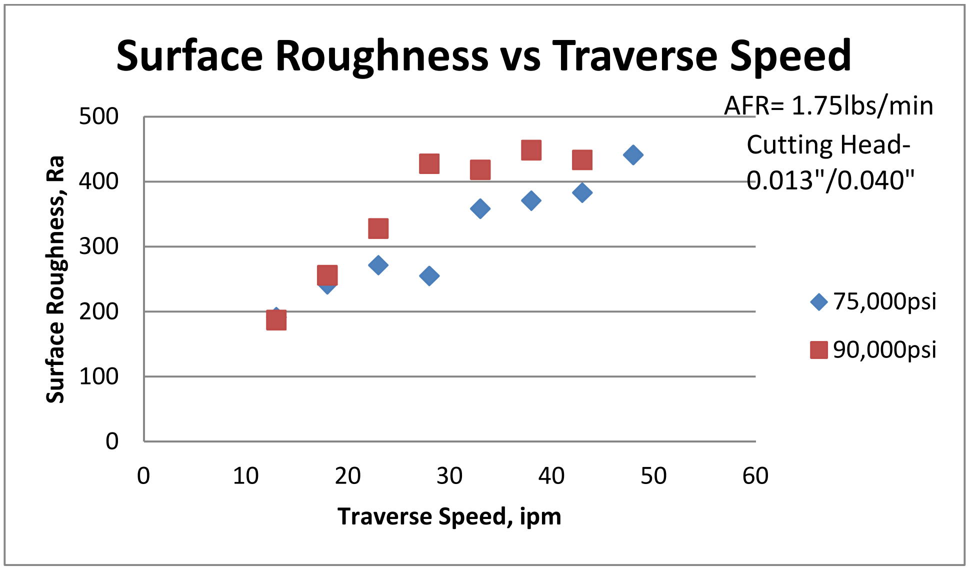


(c)

Figure 4.12. Effect of traverse speed on surface roughness of 1" composite (cont.)



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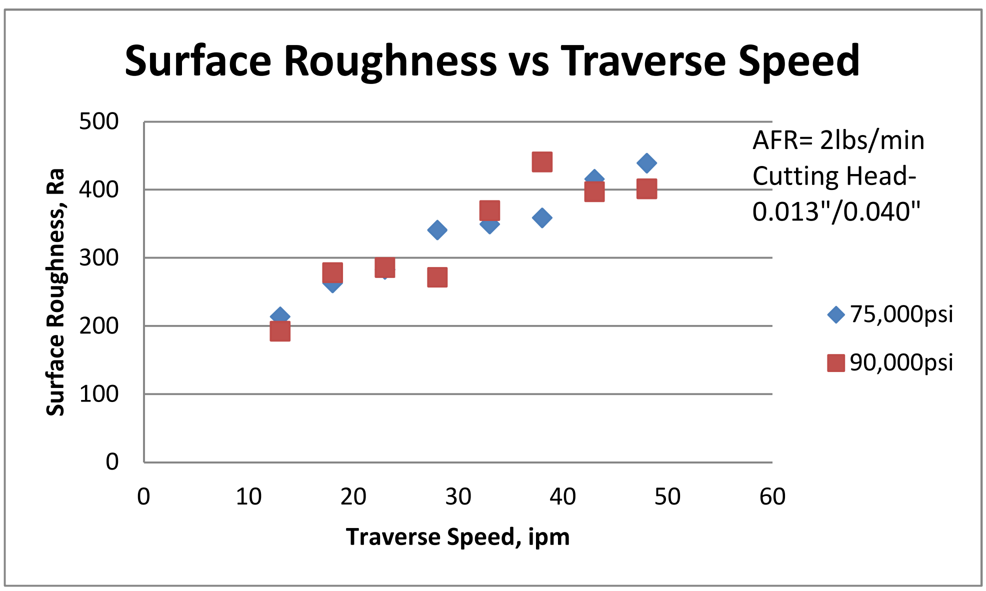
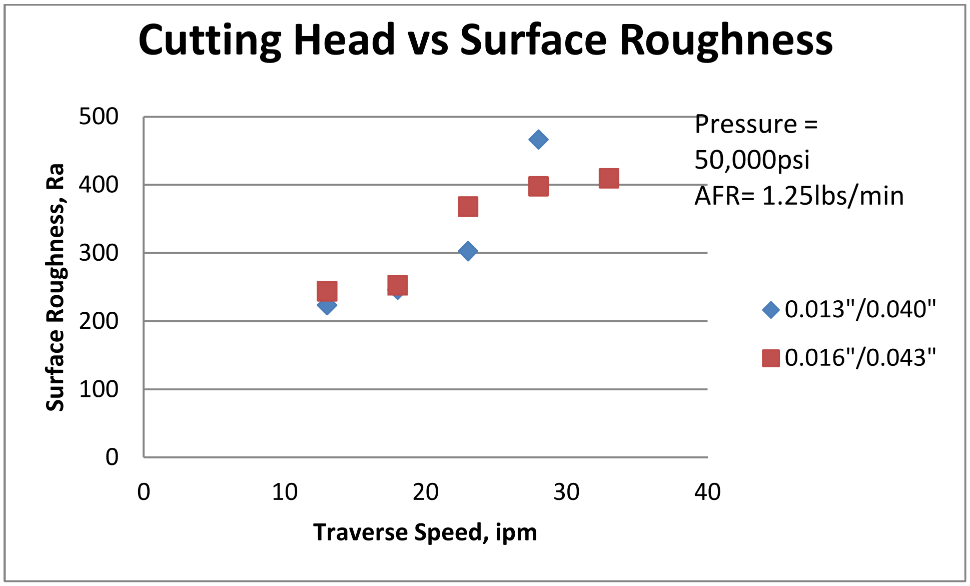


(e)

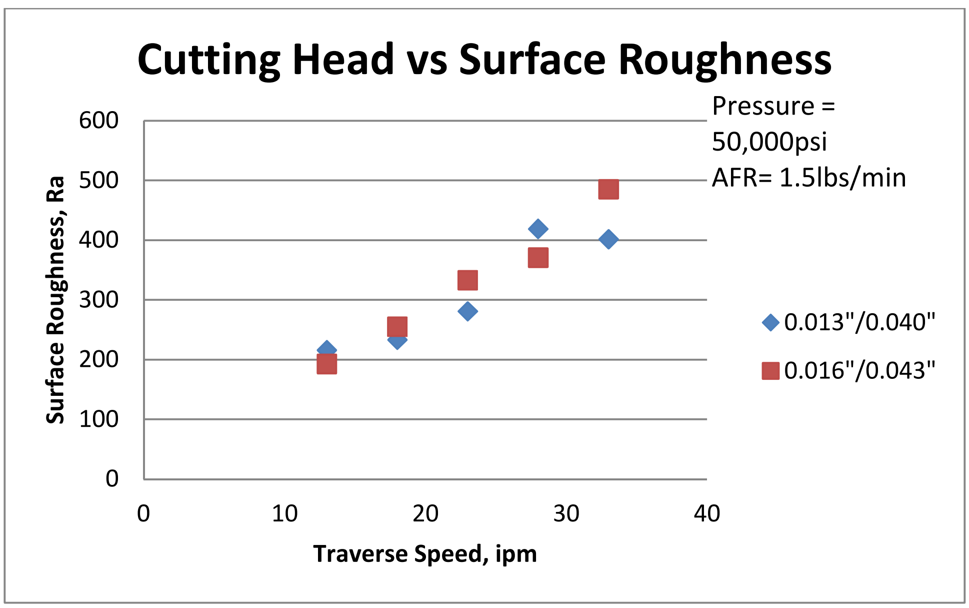
Figure 4.12. Effect of traverse speed on surface roughness of 1" composite (cont.)

Figure 4.13. Jet striations on a sample (15x)

4.1.4. Effect of Cutting Head Geometry on Surface Finish. The 1” graphite-epoxy panels were cut using two different cutting head configurations: 0.013”/0.040” and 0.016”/0.043”. The cutting head configuration gives the diameter of the waterjet orifice and the focusing tube inner diameter. The design of experiments was followed when cutting with both cutting heads. As the diameter of the cutting head increases the and the jet is more coherent, this leads to poor mixing of abrasive with the waterjet. Consequently, the jet is more diffuse without the fine focus of the smaller jet. Thus, the surface roughness using a larger diameter cutting head was greater than that of a smaller diameter cutting head. Also, more work and energy is needed to maintain a high of pressure on a cutting head with larger diameter. Because of the higher flow at the larger diameter cutting head 0.016”/0.043” the intensifier could not supply enough water to maintain pressures above 80.000psi. Thus, a comparative study of the cutting heads was performed at 50,000psi and 75,000psi only. The following Figure 4.14 compares the surface roughness of the sample cut by the two heads.

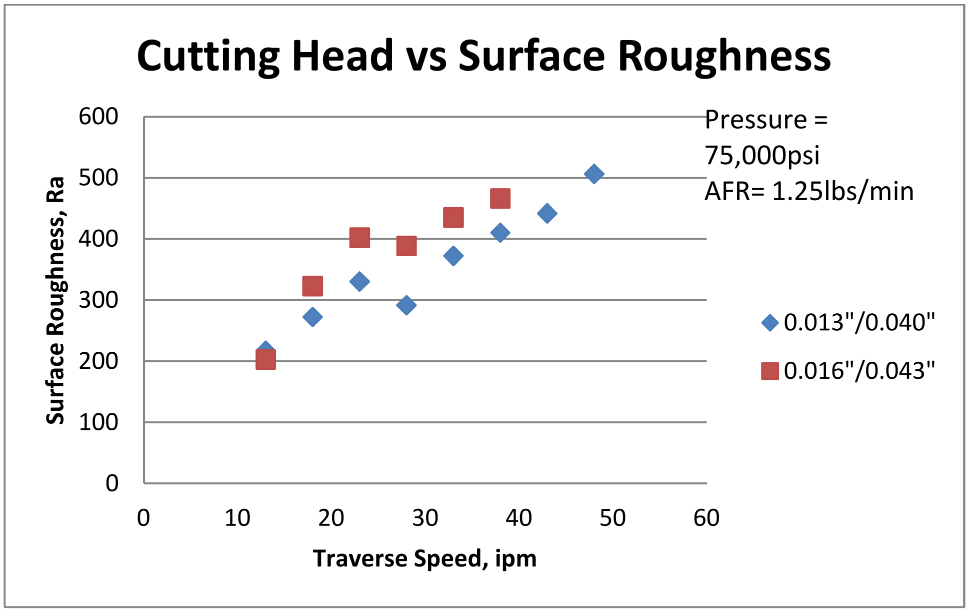


(a)



(b)

Figure 4.14. Effect of different cutting head configuration on the surface roughness of the sample



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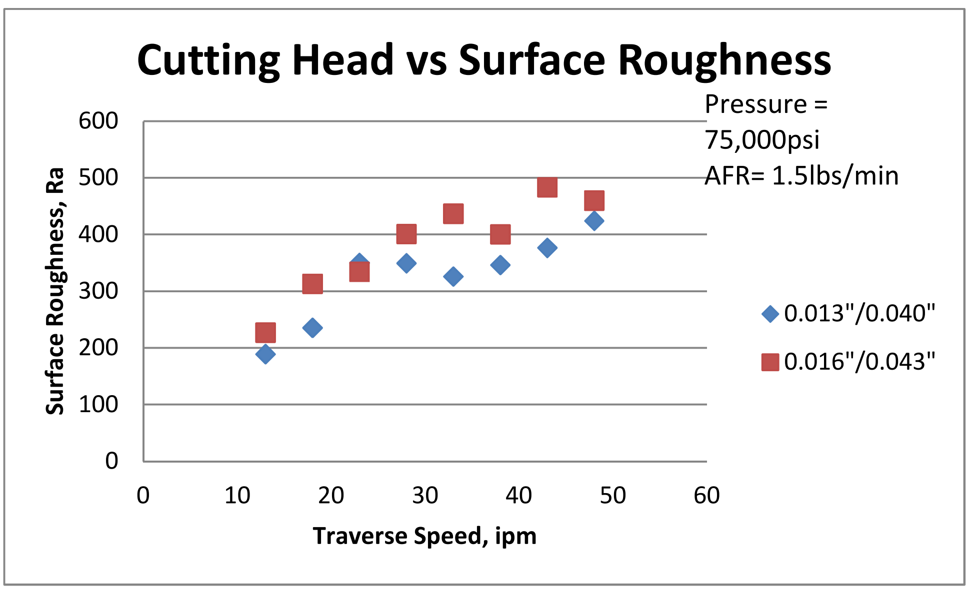

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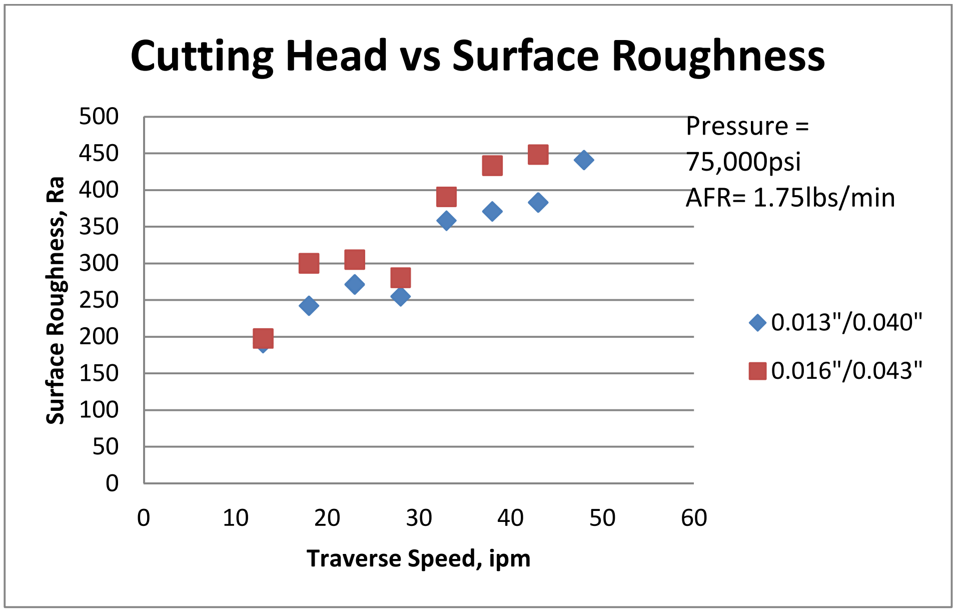
Figure 4.14. Effect of different cutting head configuration on the surface roughness of the sample (cont.)



(e)

Figure 4.14. Effect of different cutting head configuration on the surface roughness of the sample (cont.)

During the tests, one focusing tube was accidently damaged. This opportunity was taken to analyze the effect of cutting using a damaged nozzle. Figure 4.15 shows the damaged focusing tube. A summary of the results obtained using this damaged tube is shown in Figure 4.16. Under similar conditions, the surface roughness of samples cut using the damaged focusing tube was higher than with an undamaged nozzle. It was also noticed that the samples cut using the damaged focusing tube showed a slight burr along the upper surface due to excessive spraying from the nozzle.

Figure 4.15. Damaged Focusing Tube

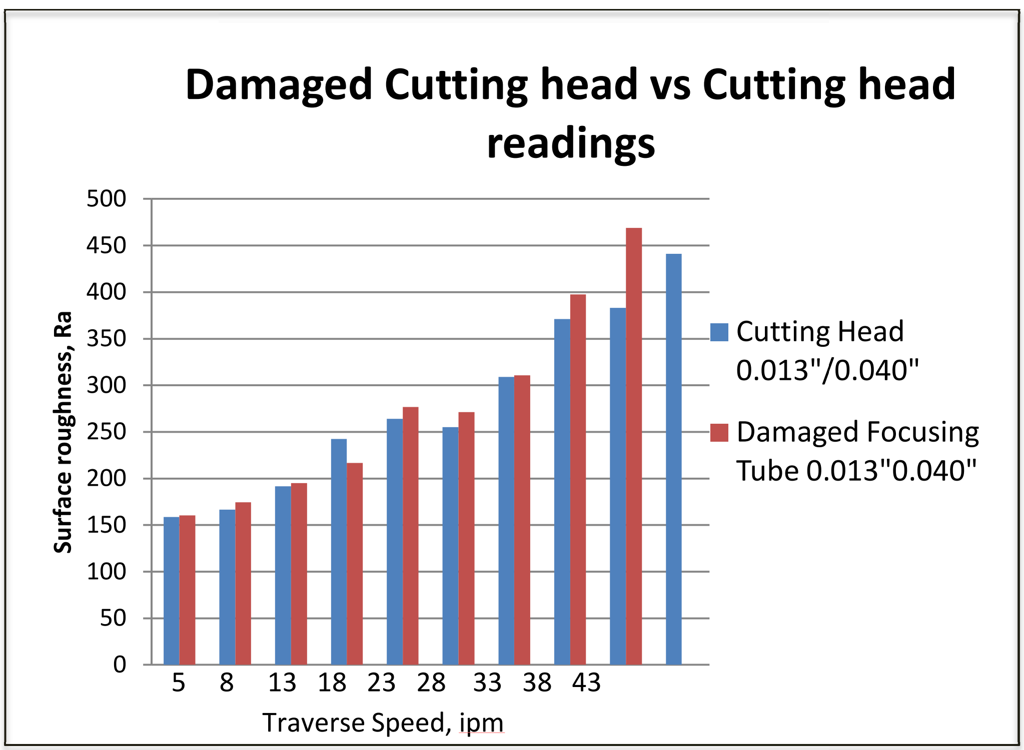
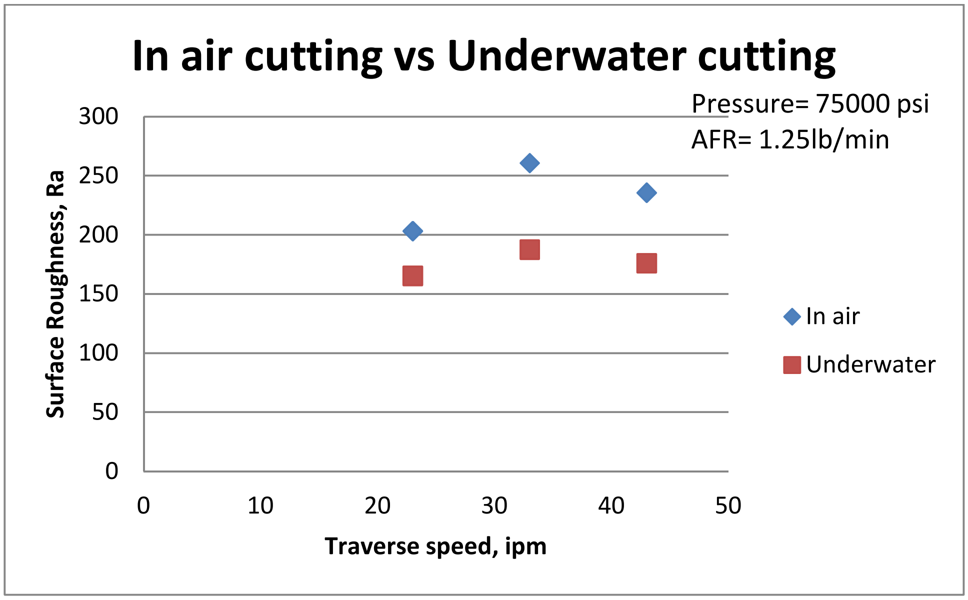
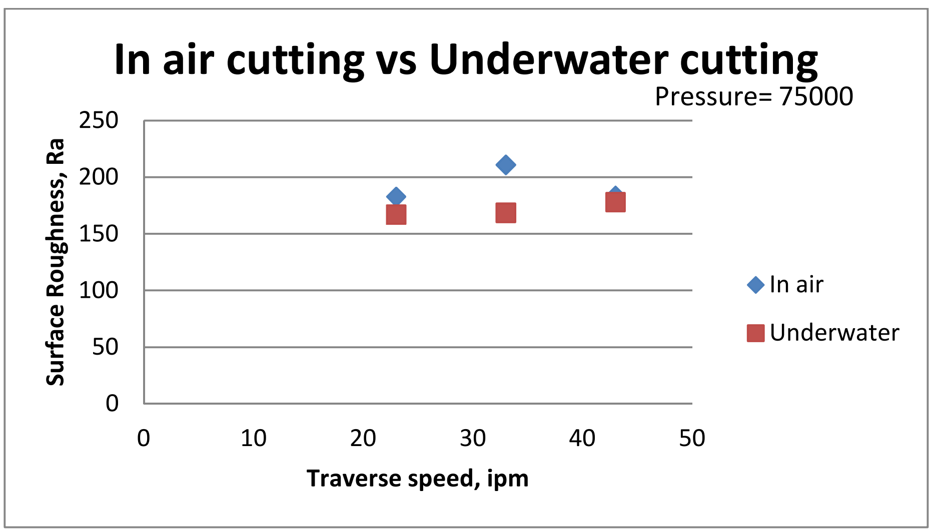


Figure 4.16. Surface roughness results obtained with a damaged focusing tube compared to those with an undamaged focusing tube

4.1.5. In Air and Underwater Conditions. Underwater cutting was performed in an attempt to improve the surface finish of 1” composite. The graphite-epoxy panel was completely submerged underwater to a depth of 1.5”. Tests were only carried out on 1” thick composite. Cutting parameters were varied as described in the design of experiments for underwater cutting. The surface roughness at the jet entrance was found to be smoother when compared to the composite cut in air. This technique improves surface finish to a limited extent. Figure 4.17. and Figure 4.18. show a comparison of surface roughness both underwater and in air conditions at 75,000psi and 90,000psi pressure and different AFR. Underwater cutting is effective in improving not only the surface roughness of the upper zone but it also reduces cutting noise significantly. One of the major problems associated with this technique is that the operator cannot see the tool path while the cutting is being performed. Although this method proved beneficial in improving surface finish at the jet entrance, the method may not be very advantageous for this application as the focus of this study remains in studying and optimizing cutting conditions at the jet exit where the surface roughness must be maintained within the specified limit of 400μin.

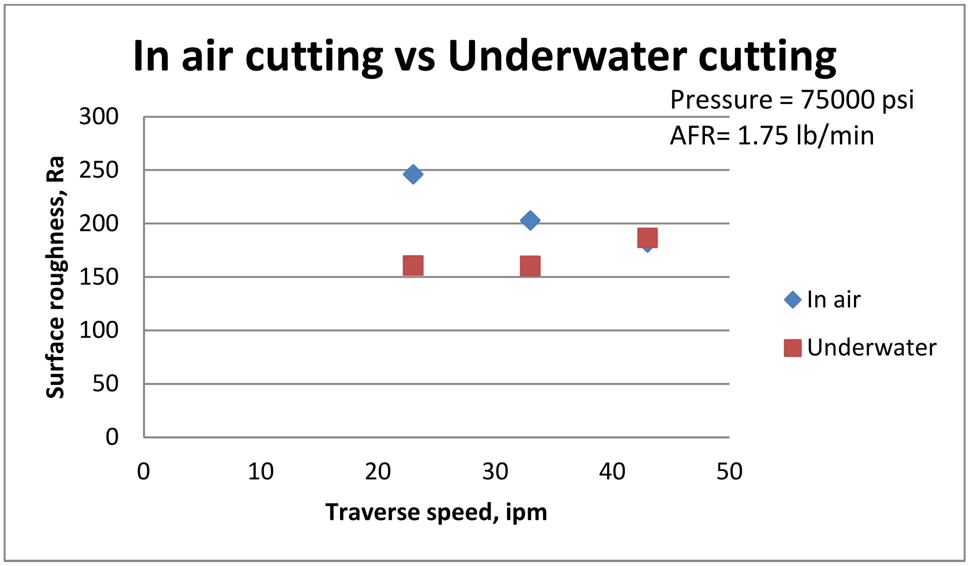


(a)



(b)

Figure 4.17. Effect of underwater cutting on the surface roughness at the jet entrance of samples cut at 75,000psi



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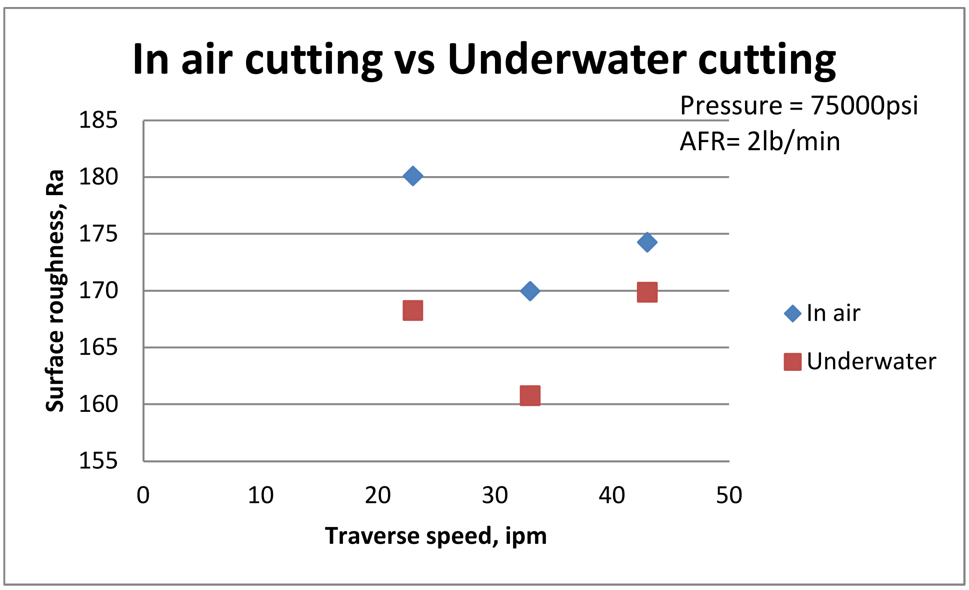
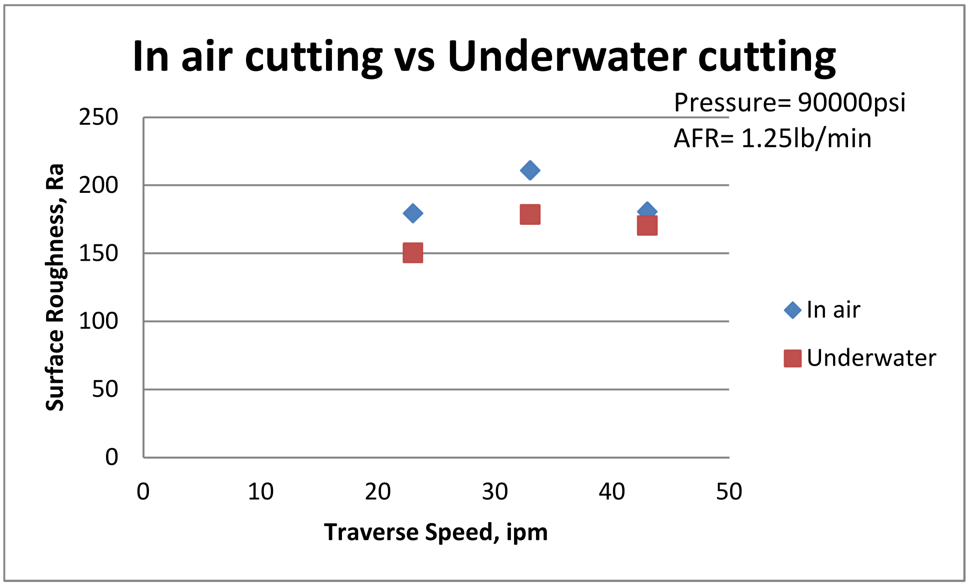
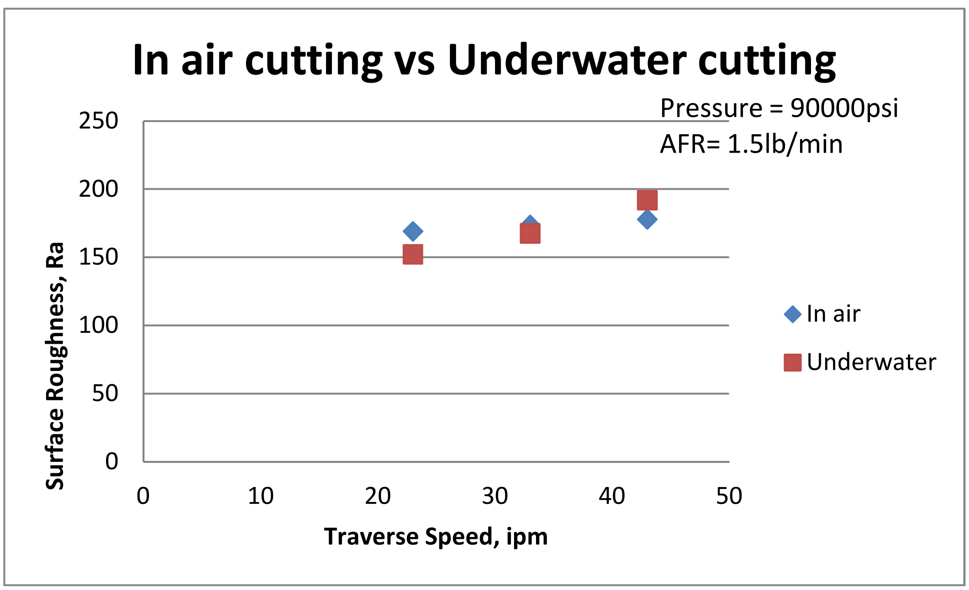


(d)

Figure 4.17. Effect of underwater cutting on the surface roughness at the jet entrance of samples cut at 75,000psi (cont.)

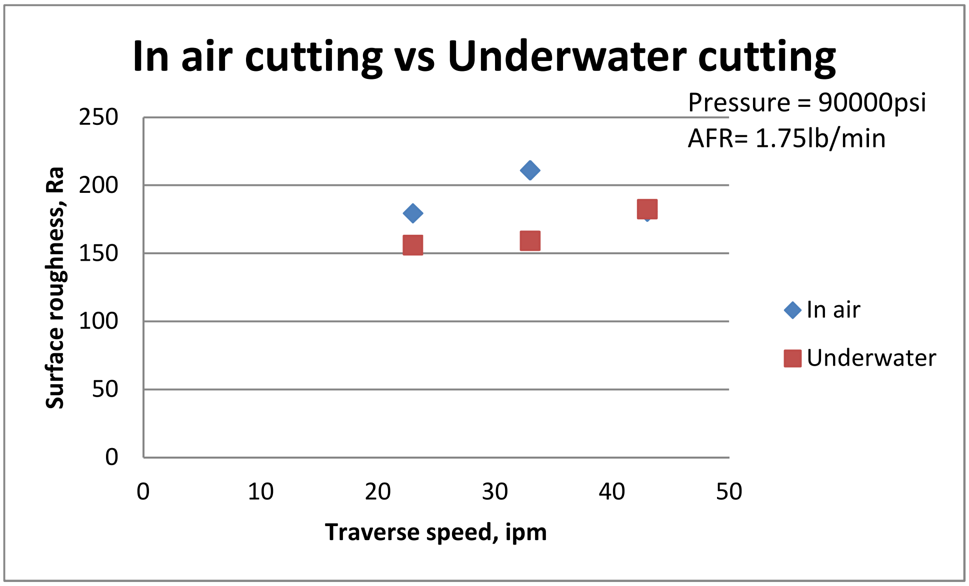


(a)



(b)

Figure 4.18. Effect of underwater cutting on the surface roughness at the jet entrance of samples cut at 90,000psi



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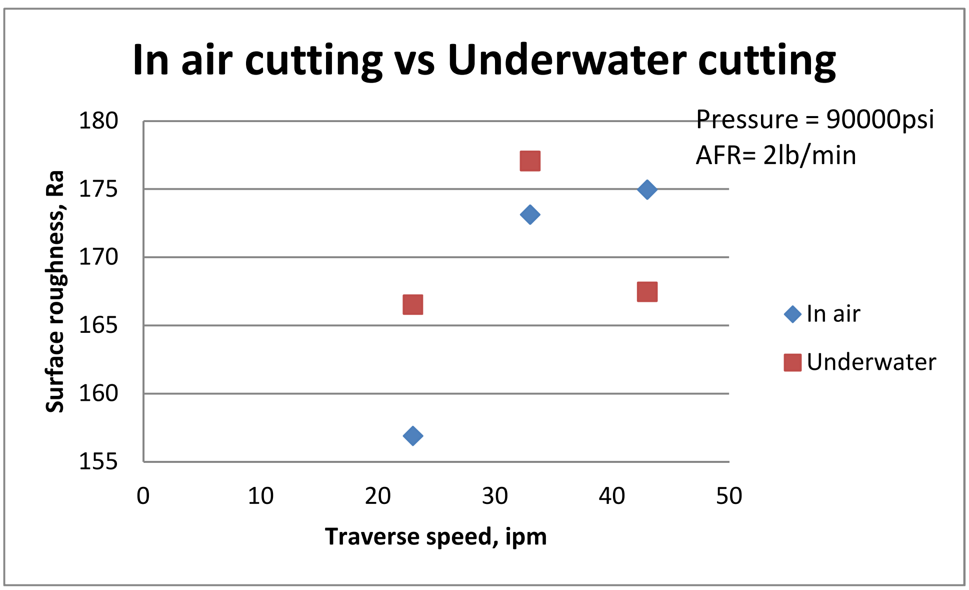


(d)

Figure 4.18. Effect of underwater cutting on the surface roughness at the jet entrance of samples cut at 90,000psi (cont.)

4.2. TAPER ANGLE ANALYSIS

Taper, the narrowing of the cut width with depth, is defined by the difference between the widths of the sample at the bottom surface and that at the top surface. Vernier calipers were used to measure these lengths. Simple trigonometry was used to calculate the taper angle using the difference in the widths. The DOE formulated for surface roughness was also used for taper angle analysis. To make the measurement more accurate, two parallel cuts were made using the same cutting parameters and taper angle was measured for the sample between these cuts. From the experimental results, it was found that slower traverse speeds can lead to a reverse taper angle while cutting faster gives a positive taper. Figure 4.19 illustrates reverse and positive taper. An increase in traverse speed increases the taper angle. Figure 4.20 shows a graph of the taper angle measured for samples cut at 90,000psi, AFR 1.75lbs/min using the 0.013”/0.040” cutting head. A similar trend was seen over all cutting conditions. For graphs of all the test cutting conditions, see Appendix C. The effect of change in pressure and AFR on taper angle were not very clear. To eliminate taper, speeds at which the taper transitions from reverse to positive taper were noted. As an alternate solution, the cutting head could be tilted to compensate for edge taper angle and thus to produce a zero degree taper on one side of the cut. Using this technique, the part can be cut at faster traverse speeds.

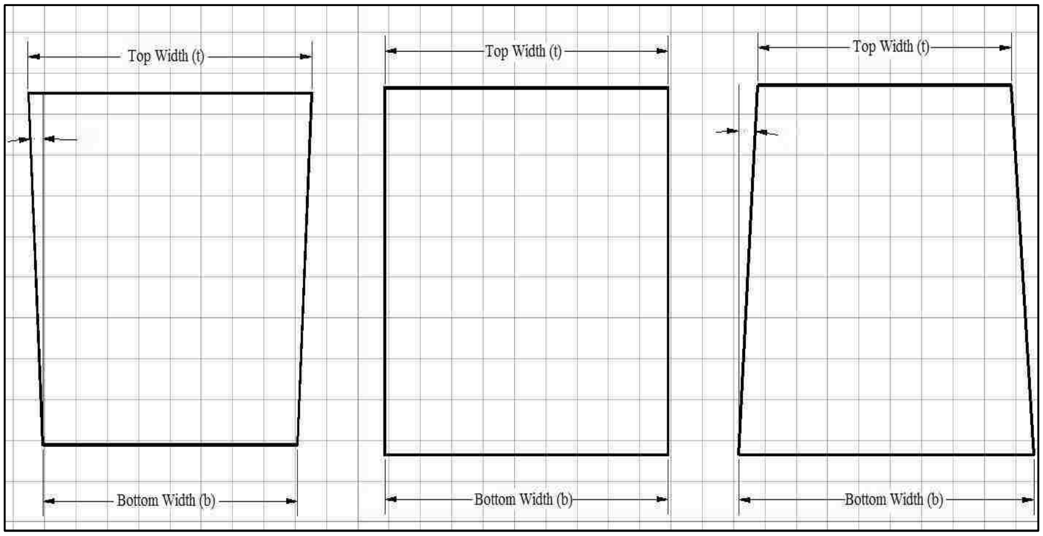


Figure 4.19. Reverse Taper, zero taper and Positive Taper

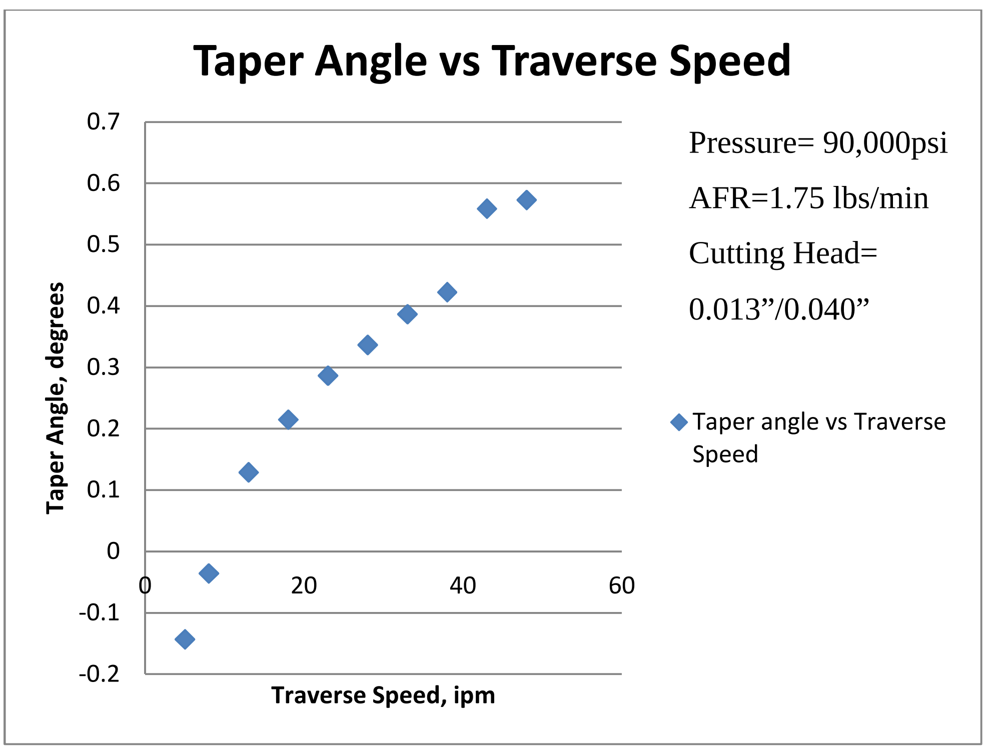


Figure 4.20. Effect of Traverse Speed on Taper Angle

4.3. STATISTICAL DATA ANALYSIS

A statistical data analysis was performed to identify the significance of the different cutting parameters. The computer program SAS 9.2 was used to perform the F-test and determine the significant cutting parameters at a significance level of 0.05. Surface roughness data was analyzed for both ¼” and 1” composites. Table 4.1 shows results for the ¼” composite. The p-value of pressure (0.0042) and traverse speed (<0.0001) were below the significance level. Thus, there is significant difference in the means of the surface roughness produced at different pressures and traverse speeds. Thus, for the cutting parameters tested changing pressure and traverse speed had the greatest impact on the surface roughness of a ¼” composite. For the ¼” thick composites, although there is a change in surface roughness with the change in pressure and traverse speeds, the surface roughness measurements were always within the specified tolerance of 400µin.

Tukey’s test was also carried out to analyze the test results. This test controls the experiment wise error rate. The Tukey grouping provides an estimate of the influence levels of each factor. All the abrasive levels were grouped into a single group indicating that the mean roughness values were not significantly different at different AFR as seen in the ANOVA table. The two higher pressure results were also grouped into the same Tukey group indicating that the mean surface roughness measurements for 50,000psi were different to those at 75,000psi and 90,000psi. See Appendix B for further test results and Tukey’s analysis.

ANOVA was also performed on the results obtained with the 1” thick composite. Table 4.2 shows that the p-value for all process parameters was below the significance level. This means that the change in surface roughness is sensitive to the change in abrasive feed rate, traverse speed and pressure. Type III p-values for pressure were greater than the significance level of 0.05 but Type I p-values for pressure were lower than the significance level of 0.05. Because, some samples showed delamination and others showed visually evident large jet striations too large for the surface profilometer to measure, the Type III p-value was considered the more accurate. Type III takes into account cases where results are missing and predicts the p-value. Also, the p-value of pressure is very close to the significance level. The decision on the effect of pressure may change with the significance level but it may have been due to the effect of experimental errors. The experimental data also validated this conclusion.

Tukey's test was carried out using the results from cutting 1" thick composite to estimate the mean values and also identify the different levels of process parameters at which significant differences in the mean are seen. For these thicker composites, the tests results showed a significant difference in mean surface roughness when the pressure is varied from 50,000psi to 90,000psi. There was also significant difference in the mean surface roughness when varying the traverse speed and the AFR. See Appendix B for further details.

Table 4.1. ANOVA results for 1/4" composite

Dependent Variable: roughness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	18703.01692	3117.16949	9.68	<.0001
Error	20	6443.14876	322.15744		
Corrected Total	26	25146.16568			

R-Square	Coeff Var	Root MSE	roughness Mean
0.743772	8.896192	17.94874	201.7576

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	2	4706.21948	2353.10974	7.30	0.0042
abrasive	2	332.73450	166.36725	0.52	0.6044
speed	2	13664.06295	6832.03147	21.21	<.0001

Table 4.2. ANOVA results for 1" composite

Additive Model

The GLM Procedure

Dependent Variable: roughness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	1126451.307	75096.754	49.94	<.0001
Error	100	150365.343	1503.653		
Corrected Total	115	1276816.650			

R-Square	Coeff Var	Root MSE	roughness Mean
0.882234	12.78639	38.77697	303.2676

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	2	9320.301	4660.150	3.10	0.0494
abrasive	4	30605.247	7651.312	5.09	0.0009
speed	9	1086525.760	120725.084	80.29	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
pressure	2	6889.292	3444.646	2.29	0.1065
abrasive	4	52380.691	13095.173	8.71	<.0001
speed	9	1086525.760	120725.084	80.29	<.0001

4.4. COST ANALYSIS

The economics involved in the process was studied to better identify the optimal cutting conditions. The cost of the process was measured in terms of the cost per unit area of material cut and was limited to an analysis based on abrasive consumption only, since abrasive forms the largest part of the cost of consumables. Later studies beyond this one may include the other overall costs including machining costs, power and other consumable costs and overhead costs.

The cost of abrasive was calculated as the abrasive consumed per unit area per minute. The area cut per minute is given as the product of the contour length cut in one minute and the thickness of the material. Thus, the area cut per minute is a product of traverse speed and thickness and is given below in equation (3). To calculate the cost involved, a new term called specific abrasive feed rate is introduced. Specific abrasive feed rate is defined as the amount of abrasive consumed per unit area per minute. Specific abrasive feed rate is mathematically defined as given in equation (5). Here, it is considered that the cost is directly proportional to the specific abrasive feed rate. As the specific abrasive feed rate increases, the cost involved increases.

$$Å= s \times t \tag{3}$$

$$Å=s \text{ for 1" thick} \tag{4}$$

$$SAFR= AFR/Å \tag{5}$$

Here,

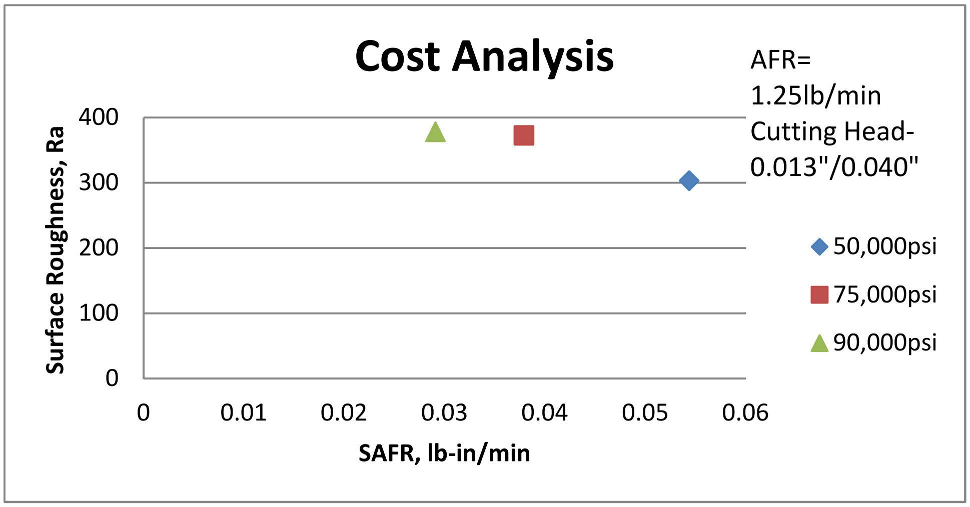
Å =Area cut per minute

s= Traverse speed

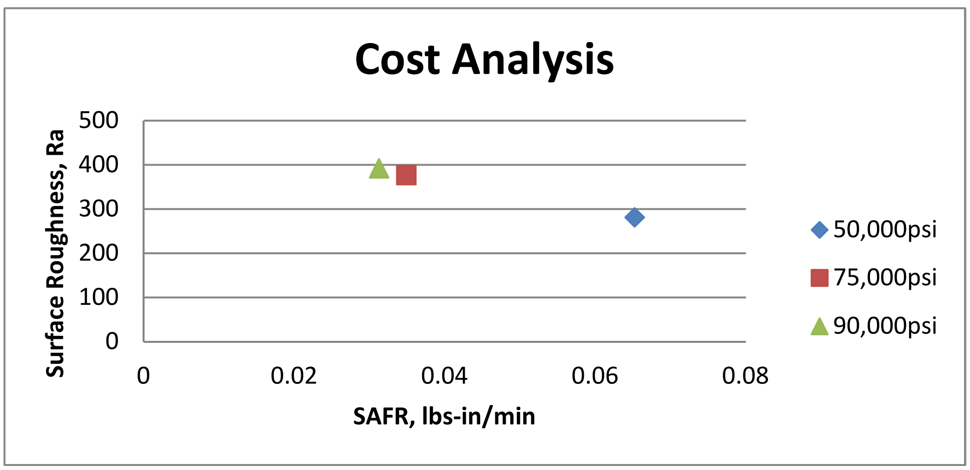
t= Thickness of the material

SAFR=Abrasive consumption per unit area per minute

The cutting costs play a vital role in the selection of the optimal cutting parameters. As an example Table 4.3 gives a summary of the costs associated with the the tests of samples cut using 0.013”/0.040” cutting head configuration at 1.25lbs/min abrasive feed rate. See appendix for tables giving a summary of cost involved in cutting using other AFR. From the table it can be seen that the specific AFR fell as traverse speeds increased, indicating a lower cost. Figure 4.21 shows the SAFR for the fastest traverse rate at each pressure. From both the table and the figure, it is clear that at a constant AFR, cutting at higher pressures involves less cost and provides a faster cutting ability.

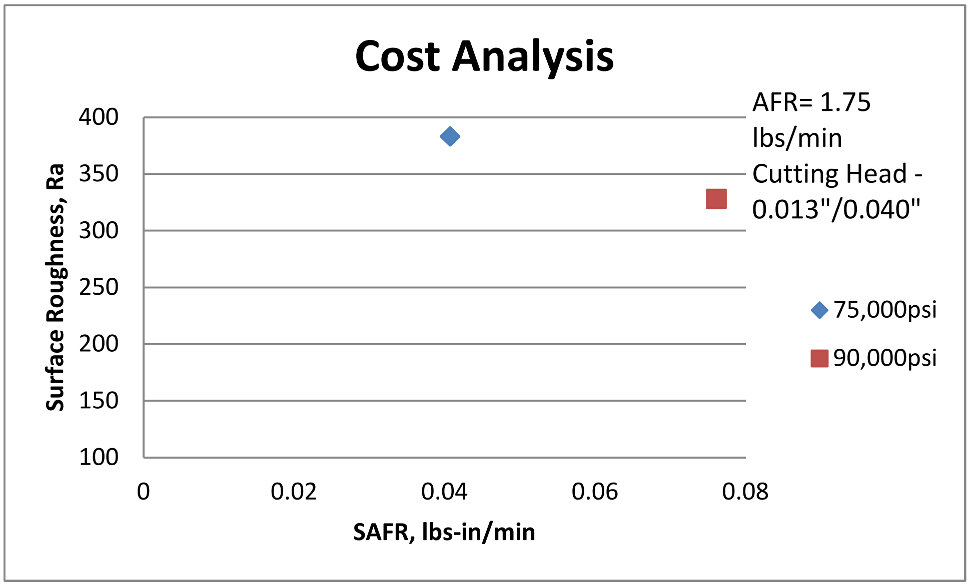


(a)

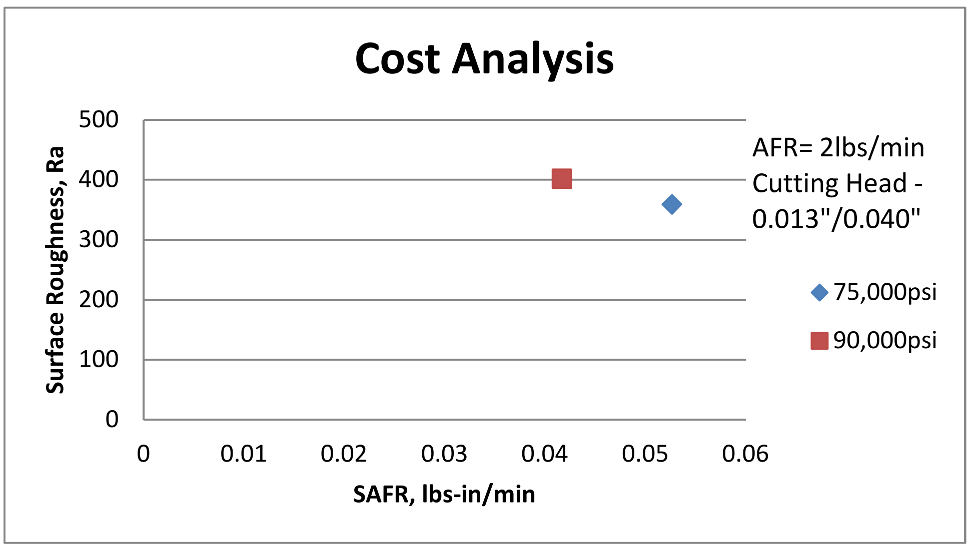


(b)

Figure 4.21. SAFR vs. Surface Roughness



(c)



(d)

Figure 4.21. SAFR vs. Surface Roughness (cont.)

Table 4.3. Cost Analysis at Abrasive Feed Rate of 1.25lbs/min

Traverse Speed (ipm)	13	18	23	28	33	38	43	48
A (in^2/min)	13	18	23	28	33	38	43	48
SAFR ($lb\text{-}in^2/min$)	0.096	0.069	0.054	0.044	0.037	0.032	0.029	0.026
Surface roughness at 50,000psi	223.8	246.43	303.1	466.7	Error	N/A	N/A	N/A
Surface roughness at 75,000psi	217.6	272.6	330.56	291.7	372.58	410.43	441.95	506.65
Surface roughness at 90,000psi	204.07	248.57	262.23	279.63	335.8	385.54	378	455.1

4.5. REGRESSION ANALYSIS

Regression analysis is a statistical data analysis tool consisting of fitting a response variable dependent on one or more independent variables. An explanatory model is fit to explain the trend of the response variable (surface roughness) in terms of the independent variables. Experimental data obtained by following the DOE was used to build this model. A multilinear regression was performed using the SAS 9.2 program. To generate the best possible regression model, tests were performed to find the highest R-square value, adjusted R-square value and for a low Cp value. After reviewing all the tests and examining the significance level of each parameter, an 8 variable model was chosen to best explain this data. The regression model developed is as follows:

$$Ra= \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3+ \beta_4X_{12} + \beta_5X_{13} + \beta_6X_{23} + \beta_7X_{22} + \beta_8X_{33} +\varepsilon_i \quad (6)$$

Here, Ra is the surface roughness, β_0 is the intercept, β_i's are the coefficient of the effect caused due to different process parameters and ε_i denotes the error at the i^{th}

observation. Here, i = 1, 2, 3, 4….n, where n is the total number of experimental observations. X_i's are the variables: pressure, abrasive feed rate, traverse speed. X_{ij}'s are the product of X_i and X_j.

The hypotheses that some of the variables were linearly related to the surface roughness were tested. The F-value of the tests indicates that there could be at least one process parameter that varies linearly with the response variable. Also, including all the process parameters improves the fit of the model by reducing the error. The multilinear regression model obtained was as follows:

$$Ra = 207.8 - 22.3 X_1 - 71.8 X_2 + 59.3 X_3 + 10.9X_{12} - 3X_{13} - 2.1X_{23} + 7.6X_{22} - 0.9X_{33} + \varepsilon_i \quad (7)$$

Table 4.4 shows the variables and their coefficients. It can be seen that the p-values for traverse speed and AFR are almost zero, which implies that both traverse speed and AFR have a significant effect on surface roughness. The R-square value and the adjusted R-square values are 87.07% and 86.1% respectively. This implies that this model well represents the experimental data and the experimental data fits the model well. To identify the outliers in the experimental data, a comparison between the experimental data and the results fit using the model was carried out using the program MINITAB 16. Five values were identified as outliers. These values were included in the analysis of the results. Thus any variation in the results from a true model could be caused by the presence of these outliers as well as through experimental error.

Table 4.4. Coefficients of independent variables

Minimum R-Square Improvement: Step 55

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1111705	138963	90.05	<.0001
Error	107	165111	1543.09693		
Corrected Total	115	1276817			

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	207.80658	36.51964	49964	32.38	<.0001
X1	-22.29463	14.41291	3692.24667	2.39	0.1249
X2	-71.85574	15.48405	33231	21.54	<.0001
X3	59.30426	7.14174	106404	68.95	<.0001
X12	10.93917	4.27585	10100	6.55	0.0119
X13	-3.01369	2.10637	3158.80764	2.05	0.1554
X23	-2.15070	1.00081	7126.08434	4.62	0.0339
X22	7.63692	2.23144	18074	11.71	0.0009
X33	-0.96210	0.53074	5070.80685	3.29	0.0727

Bounds on condition number: 34.036, 1371.1

The above model is the best 8-variable model found.

4.6. OPTIMAL CUTTING CONDITIONS

For each pressure, the fastest traverse speed at which the surface roughness was below 400µin is considered to be the optimal cutting condition for that application. Taper angle compensation technique was used to obtain 0º taper at those speeds. The taper angle compensation used under these optimal conditions is the negative taper angle obtained from the experimental results. To validate these conclusions, a final test was carried out using these defined optimal conditions and the surface quality and lack of taper were verified. Table 4.5. gives the summary of these test results and Figure 4.22 shows the sample cut under the optimal conditions.

Table 4.5. Optimal Cutting Conditions for 1” Thick Graphite-Composite

Pressure (psi)	Traverse Speed (ipm)	AFR (lbs/min)	SAFR (lbs-in/min)	Taper Angle Compensation (degrees)	Surface Roughness (Ra)
50,000	28	1	0.03571	0.264991	374.7667
75,000	43	1.5	0.034884	0.508487	386.7
90,000	48	1.5	0.03125	0.608745	383.3

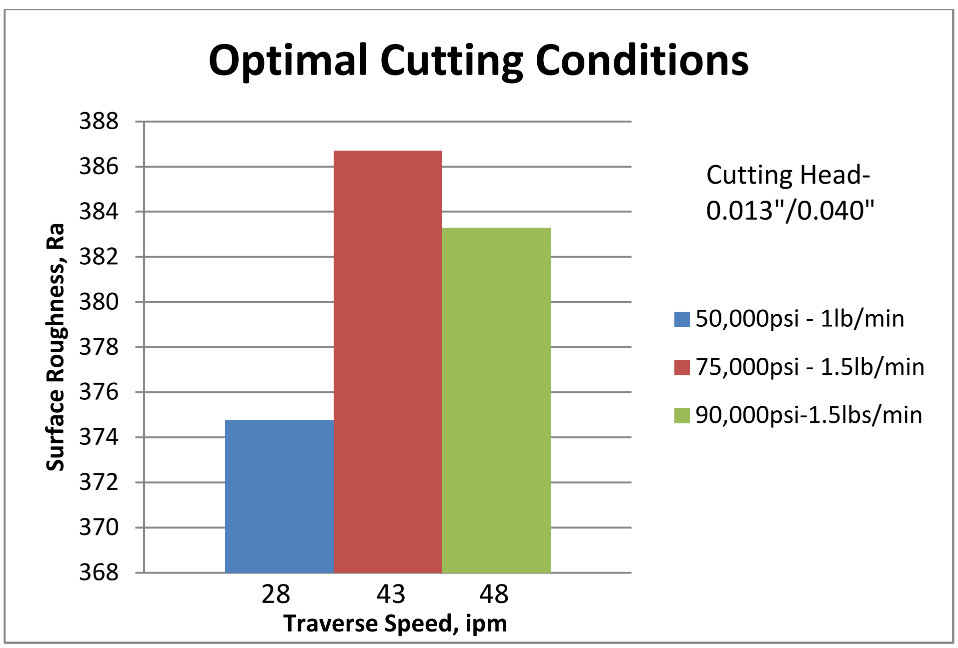


Figure 4.22. Optimal Cutting Conditions

5. CONCLUSIONS

The objective of this research, to study the benefits and limitations of cutting composites at ultra-high pressure up to 90,000psi was successfully accomplished. The objective of determining the parameters controlling surface roughness and their effects on surface roughness was successfully achieved. The study consisted of identifying the problems in cutting composites using abrasive waterjet and optimizing the process parameters to eliminate these problems. The process involved in waterjet cutting and the techniques to improve the surface quality using abrasive waterjets were studied. An in-depth literature review was carried out to understand the pre-existing technology. Composites and their uses in different fields were studied. Depending on usage, the machining process that best cuts the composite so that it can be used for a specified application was identified. The machining processes involved in processing composites were studied. The problems involved in conventional machining were identified and in an effort to eliminate these problems, non-conventional machining methods were reviewed. To understand the advantages and disadvantages of cutting composites using existing non-conventional machining methods, an in depth study was made, leading to an additional study focusing on the abrasive waterjet cutting of composites.

This research focused on machining graphite-epoxy composites using high pressure waterjets. Graphite-epoxy composites are widely used in the aerospace industries. These composites must be cut to a specified surface roughness with high surface quality. Experiments were carried out to achieve this specified surface roughness of 400μin. To perform the experiments, a DOE was formulated. The available equipment and the instrumentation were then used to their best levels to achieve the required results.

The experimental results were analyzed and the effect of each process parameter on surface roughness was successfully found. Problems included delamination and fiber pull out, and the inability of the waterjet to perform through cuts at 50,000psi were eliminated when cutting was carried out at the higher pressures of 75,000psi and 90,000psi. The effects of other process parameters, abrasive feed rate, traverse speed, and cutting head configuration (water flow rate) were also successfully studied. In an effort to improve the surface quality of the cut composites, underwater cutting was tested. Although underwater cutting improved the surface quality at the jet entrance to the cut, surface finish at the jet exit was not significantly affected. Thus, the use of underwater cutting for this application may not be beneficial. Taper angle of the cut slot was also reviewed. The effect of the process parameters on taper angle was successfully determined. It was found that an increase in traverse speed increased taper angle. To eliminate this taper, cutting head could be tilted to a compensating angle that eliminated taper on the useful side of the cut.

Statistical data analysis was carried out using the statistical program SAS 9.2 both to validate the experimental data and to determine the effects of each of the parameters. The surface roughness of the ¼" composite was most affected by changes in pressure and traverse speed. Increasing the pressure and decreasing the traverse speed produced a better surface quality. In case of the 1" thick composite, changes in abrasive feed rate, and traverse speed had the greatest affect on surface quality. Although a tremendous improvement in surface quality was seen when pressure was increased from 50,000psi to 90,000psi, the surface quality of cuts produced at 75,000psi and 90,000psi were not very different.

Use of ultra-high pressure to cut thicker composites allows a great increase in traverse speed, improved surface quality and allows a cutting ability to greater depth. Faster traverse speeds improve the productivity of the cutting process. At the ultra-high pressures of 90,000psi, the composite can be cut 53.5% faster than at lower pressures. Furthermore, a better surface quality at faster traverse speeds was achieved at the highest pressure. Although the traverse speed at higher pressures increases, the abrasive consumed with higher flow rates is also higher. To study the benefits of using higher pressures in real time situation, a cost analysis was performed defining the abrasive consumed for a given pressure and traverse speed. The cost involved in the process of cutting at higher pressure, higher abrasive feed rate, and at faster traverse speeds is much lower than the costs involved in cutting at lower pressures, lower abrasive feed rates, and at slower traverse speeds. Thus, the real time benefits of using higher pressures to cut composites were successfully demonstrated. The optimal cutting conditions for the process parameters of jet pressure, traverse speed, abrasive feed rate, taper compensation angle, cutting head configuration were successfully defined and validated for conditions which maintained the surface roughness below 400μin when cutting through 1” thick graphite-epoxy composites.

APPENDIX A.

COST ANALYSIS TABLES

AFR	1.5							
Cutting head configuration	0.013"/0.040"							
Traverse Speed	13	18	23	28	33	38	43	48
Å	13	18	23	28	33	38	43	48
SAFR	0.115	0.083	0.065	0.053	0.045	0.039	0.034	0.031
Surface roughness at 50,000psi	215.97	233.3	280.9	444.1	401.6	Error	N/A	N/A
Surface roughness at 75,000psi	189	235.4	349.9	349.2	325.9	346.2	376.5	424.1
Surface roughness at 90,000psi	188	224.17	339.9	335.4	328.6	316.3	385.6	391.8

AFR	1.75							
Cutting head configuration	0.013"/0.040"							
Traverse Speed	13	18	23	28	33	38	43	48
Å	13	18	23	28	33	38	43	48
SAFR	0.134	0.097	0.076	0.062	0.053	0.046	0.041	0.036
Surface roughness at 75,000psi	191.6	242.4	271.6	255.2	358.5	370.9	383.2	441.1
Surface roughness at 90,000psi	187.3	256.0	328.1	427.6	418.3	448.6	433.5	Error

AFR	2							
Cutting head configuration	0.013"/0.040"							
Traverse Speed	13	18	23	28	33	38	43	48
Å	13	18	23	28	33	38	43	48
SAFR	0.153	0.111	0.087	0.071	0.061	0.053	0.046	0.042
Surface roughness at 75,000psi	213.9	263.2	283.1	341.1	349.7	359.0	415.9	439.3
Surface roughness at 90,000psi	192.5	278.4	286.1	271.7	369.6	441.2	397.4	401.7

APPENDIX B.

SAS PROGRAM

SAS INPUT PROGRAM FOR ¼” COMPOSITES

```
optionsls=78;
data waterjet;
input pressure abrasive speed roughness;
datalines;
1 1 1 303.4111111
1 1 2 198.4444444
1 1 3 165.8222222
1 2 1 252.9222222
1 2 2 221.0111111
1 2 3 191.9
1 3 1 240.9222222
1 3 2 210.3888889
1 3 3 195.7111111
2 1 1 209.9555556
2 1 2 175.8777778
2 1 3 148.2555556
2 2 1 210.9666667
2 2 2 183.4555556
2 2 3 188.9444444
2 3 1 217.5888889
2 3 2 201.6888889
2 3 3 167.9222222
3 1 1 225.2222222
3 1 2 181.7888889
3 1 3 167.4444444
3 2 1 213.3
3 2 2 209.9777778
3 2 3 181.0666667
3 3 1 207.1111111
```

```
3 3 2 193.0666667
3 3 3 183.2888889
;
procglm data=waterjet;
class pressure abrasive speed;
title1 'Interactive model';
model roughness = pressure|abrasive|speed;
/*lsmeans a*c / pdiff;*/
run;
procglm;
class pressure abrasive speed;
title3 'Additive Model';
model roughness = pressure abrasive speed /solution;
means pressure abrasive speed /lsdtukey;
run;
```

SAS OUTPUT

Additive Model

The GLM Procedure

Class Level Information

Class	Levels	Values
pressure	3	1 2 3
abrasive	3	1 2 3
speed	3	1 2 3

Number of Observations Read	27
Number of Observations Used	27

The GLM Procedure

Dependent Variable: roughness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	18703.01692	3117.16949	9.68	<.0001
Error	20	6443.14876	322.15744		
Corrected Total	26	25146.16568			

R-Square	CoeffVar	Root MSE	roughness Mean
0.743772	8.896192	17.94874	201.7576

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	2	4706.21948	2353.10974	7.30	0.0042
abrasive	2	332.73450	166.36725	0.52	0.6044
speed	2	13664.06295	6832.03147	21.21	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
pressure	2	4706.21948	2353.10974	7.30	0.0042
abrasive	2	332.73450	166.36725	0.52	0.6044
speed	2	13664.06295	6832.03147	21.21	<.0001

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	322.1574
Critical Value of StudentizedRange	3.57793

Minimum Significant Difference 21.406

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	pressure
A	220.059	9	1
B	195.807	9	3
B			
B	189.406	9	2

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	322.1574
Critical Value of StudentizedRange	3.57793
Minimum Significant Difference	21.406

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	abrasive
A	205.949	9	2
A			
A	201.965	9	3
A			
A	197.358	9	1

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	322.1574
Critical Value of StudentizedRange	3.57793
Minimum Significant Difference	21.406

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	speed
A	231.267	9	1
B	197.300	9	2
B	176.706	9	3

SAS INPUT PROGRAM FOR 1” THICK COMPOSITE

```
optionsls=78;
datawaterjet;
input pressure abrasive speed roughness;
datalines;
1 1 1 197.7
1 1 2 201.23
1 1 3 238.27
1 1 4 341.67
1 1 5 344.67
1 1 6 358.567
1 1 7  550.767
1 1 8 .
1 1 9 .
1 1 10 .
1 2 1 176.1
1 2 2 198
1 2 3 223.8
1 2 4 246.43
1 2 5 303.1
1 2 6 466.7
1 2 7 .
1 2 8 .
1 2 9 .
1 2 10 .
1 3 1 138.7
1 3 2 164.33
1 3 3 215.9667
1 3 4 233.3667
1 3 5 280.9667
```

1 3 6 418.925

1 3 7 401.75

1 3 8 .

1 3 9 .

1 3 10 .

2 1 1 184.133

2 1 2 212.733

2 1 3 267.34

2 1 4 330.3667

2 1 5 354.933

2 1 6 381.6

2 1 7 475.5667

2 1 8 .

2 1 9 .

2 1 10 .

2 2 1 158.7667

2 2 2 192.6

2 2 3 217.6

2 2 4 272.6

2 2 5 376.58

2 2 6 291.7

2 2 7 372.275

2 2 8 410.4333

2 2 9 441.95

2 2 10 506.65

2 3 1 160.0667

2 3 2 169.3

2 3 3 189

2 3 4 235.4667

2 3 5 349.9

2 3 6 349.2

2 3 7 325.933

2 3 8 346.233

2 3 9 424.08

2 3 10 375.4

2 4 1 158.667

2 4 2 166.667

2 4 3 191.633

2 4 4 242.4667

2 4 5 264.1667

2 4 6 255.22

2 4 7 425.8

2 4 8 370.8

2 4 9 383.22

2 4 10 441.15

2 5 1 144.433

2 5 2 172.2667

2 5 3 213.9

2 5 4 263.2667

2 5 5 283.1333

2 5 6 341.08

2 5 7 349.68

2 5 8 359.0333

2 5 9 415.9

2 5 10 439.35

3 1 1 189.8667

3 1 2 186.4667

3 1 3 227.7333

3 1 4 286.6667

3 1 5 337.7

3 1 6 346.3333

3 1 7 419.6667

3 1 8 444.6

3 1 9 508.05

3 1 10 533.1

3 2 1 155.3667

3 2 2 181.4333

3 2 3 204.0667

3 2 4 248.5667

3 2 5 262.2333

3 2 6 279.6333

3 2 7 335.8

3 2 8 409.5333

3 2 9 378

3 2 10 455.1

3 3 1 149.2667

3 3 2 184.3333

3 3 3 188

3 3 4 224.1667

3 3 5 339.98

3 3 6 341.78

3 3 7 328.56

3 3 8 316.32

3 3 9 385.56

3 3 10 391.85

3 4 1 159.9333

3 4 2 159.9333

3 4 3 187.3333

3 4 4 256.0333

3 4 5 328.1333

3 4 6 492.94

3 4 7 418.3

3 4 8 488.22

```
3 4 9 433.5
3 4 10 .
3 5 1 173.8
3 5 2 203.233
3 5 3 192.5
3 5 4 278.433
3 5 5 328.7
3 5 6 271.7
3 5 7 369.5667
3 5 8 441.2
3 5 9 397.45
3 5 10 402.05
;
procglm data=waterjet;
class pressure abrasive speed;
title1 'Interactive model';
model roughness = pressure|abrasive|speed;
run;
procglm;
class pressure abrasive speed;
title3 'Additive Model';
model roughness = pressure abrasive speed /solution;
means pressure abrasive speed /lsdtukey;
run;
```

SAS OUTPUT FILE

The GLM Procedure

Class Level Information

Class	Levels	Values

pressure	3	1 2 3
abrasive	5	1 2 3 4 5
speed	10	1 2 3 4 5 6 7 8 9 10

Number of Observations Read	130
Number of Observations Used	116

Additive Model

The GLM Procedure

Dependent Variable: roughness

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	1126451.307	75096.754	49.94	<.0001
Error	100	150365.343	1503.653		
Corrected Total	115	1276816.650			

R-Square	Coeff Var	Root MSE	roughness Mean
0.882234	12.78639	38.77697	303.2676

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	2	9320.301	4660.150	3.10	0.0494
abrasive	4	30605.247	7651.312	5.09	0.0009
speed	9	1086525.760	120725.084	80.29	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
pressure	2	6889.292	3444.646	2.29	0.1065
abrasive	4	52380.691	13095.173	8.71	<.0001
speed	9	1086525.760	120725.084	80.29	<.0001

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate.

Alpha	0.05
Error Degrees of Freedom	100
Error Mean Square	1528.925
Critical Value of StudentizedRange	3.36457

Comparisons significant at the 0.05 level are indicated by ***.

pressure Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
3 - 2	8.398	-10.595	27.391	
3 - 1	25.617	0.933	50.301	***
2 - 3	-8.398	-27.391	10.595	
2 - 1	17.219	-7.617	42.055	
1 - 3	-25.617	-50.301	-0.933	***
1 - 2	-17.219	-42.055	7.617	

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate.

Alpha	0.05
Error Degrees of Freedom	100
Error Mean Square	1528.925
Critical Value of StudentizedRange	3.92894

Comparisons significant at the 0.05 level are indicated by ***.

abrasive Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
1 - 4	23.46	-9.90	56.81	
1 - 5	27.95	-4.93	60.84	
1 - 2	31.33	0.58	62.08	***
1 - 3	49.22	18.74	79.69	***
4 - 1	-23.46	-56.81	9.90	
4 - 5	4.50	-30.30	39.30	
4 - 2	7.88	-24.91	40.66	
4 - 3	25.76	-6.77	58.29	
5 - 1	-27.95	-60.84	4.93	
5 - 4	-4.50	-39.30	30.30	

5 - 2	3.38	-28.93	35.69	
5 - 3	21.26	-10.79	53.31	
2 - 1	-31.33	-62.08	-0.58	***
2 - 4	-7.88	-40.66	24.91	
2 - 5	-3.38	-35.69	28.93	
2 - 3	17.88	-11.97	47.73	
3 - 1	-49.22	-79.69	-18.74	***
3 - 4	-25.76	-58.29	6.77	
3 - 5	-21.26	-53.31	10.79	
3 - 2	-17.88	-47.73	11.97	

The GLM Procedure

Tukey'sStudentized Range (HSD) Test for roughness

NOTE: This test controls the Type I experiment wise error rate.

Alpha	0.05
Error Degrees of Freedom	100
Error Mean Square	1528.925
Critical Value of StudentizedRange	4.57678

Comparisons significant at the 0.05 level are indicated by ***.

speed Comparison	Difference Between Means	Simultaneous 95% Confidence Limits	
10 - 9	29.73	-31.76	91.22
10 - 8	44.60	-16.89	106.08

10 - 7	45.28	-12.48	103.03	
10 - 6	89.59	32.73	146.45	***
10 - 5	123.53	66.66	180.39	***
10 - 4	176.97	120.10	233.83	***
10 - 3	230.99	174.13	287.86	***
10 - 2	259.04	202.18	315.90	***
10 - 1	277.94	221.08	334.81	***
9 - 10	-29.73	-91.22	31.76	
9 - 8	14.86	-44.79	74.51	
9 - 7	15.54	-40.26	71.34	
9 - 6	59.86	4.98	114.73	***
9 - 5	93.79	38.92	148.67	***
9 - 4	147.23	92.36	202.11	***
9 - 3	201.26	146.39	256.13	***
9 - 2	229.31	174.43	284.18	***
9 - 1	248.21	193.34	303.08	***
8 - 10	-44.60	-106.08	16.89	
8 - 9	-14.86	-74.51	44.79	
8 - 7	0.68	-55.12	56.48	
8 - 6	45.00	-9.88	99.87	
8 - 5	78.93	24.06	133.81	***
8 - 4	132.37	77.50	187.24	***
8 - 3	186.40	131.53	241.27	***
8 - 2	214.45	159.57	269.32	***
8 - 1	233.35	178.47	288.22	***
7 - 10	-45.28	-103.03	12.48	
7 - 9	-15.54	-71.34	40.26	
7 - 8	-0.68	-56.48	55.12	
7 - 6	44.31	-6.34	94.97	
7 - 5	78.25	27.59	128.91	***
7 - 4	131.69	81.03	182.35	***

7 - 3	185.72	135.06	236.38	***
7 - 2	213.76	163.11	264.42	***
7 - 1	232.67	182.01	283.32	***
6 - 10	-89.59	-146.45	-32.73	***
6 - 9	-59.86	-114.73	-4.98	***
6 - 8	-45.00	-99.87	9.88	
6 - 7	-44.31	-94.97	6.34	
6 - 5	33.94	-15.70	83.57	
6 - 4	87.38	37.74	137.01	***
6 - 3	141.40	91.77	191.04	***
6 - 2	169.45	119.82	219.08	***
6 - 1	188.35	138.72	237.99	***
5 - 10	-123.53	-180.39	-66.66	***
5 - 9	-93.79	-148.67	-38.92	***
5 - 8	-78.93	-133.81	-24.06	***
5 - 7	-78.25	-128.91	-27.59	***
5 - 6	-33.94	-83.57	15.70	
5 - 4	53.44	3.80	103.07	***
5 - 3	107.47	57.83	157.10	***
5 - 2	135.51	85.88	185.15	***
5 - 1	154.42	104.78	204.05	***
4 - 10	-176.97	-233.83	-120.10	***
4 - 9	-147.23	-202.11	-92.36	***
4 - 8	-132.37	-187.24	-77.50	***
4 - 7	-131.69	-182.35	-81.03	***
4 - 6	-87.38	-137.01	-37.74	***
4 - 5	-53.44	-103.07	-3.80	***
4 - 3	54.03	4.39	103.66	***
4 - 2	82.07	32.44	131.71	***
4 - 1	100.98	51.34	150.61	***
3 - 10	-230.99	-287.86	-174.13	***

3 - 9	-201.26	-256.13	-146.39	***
3 - 8	-186.40	-241.27	-131.53	***
3 - 7	-185.72	-236.38	-135.06	***
3 - 6	-141.40	-191.04	-91.77	***
3 - 5	-107.47	-157.10	-57.83	***
3 - 4	-54.03	-103.66	-4.39	***
3 - 2	28.05	-21.59	77.68	
3 - 1	46.95	-2.68	96.58	
2 - 10	-259.04	-315.90	-202.18	***
2 - 9	-229.31	-284.18	-174.43	***
2 - 8	-214.45	-269.32	-159.57	***
2 - 7	-213.76	-264.42	-163.11	***
2 - 6	-169.45	-219.08	-119.82	***
2 - 5	-135.51	-185.15	-85.88	***
2 - 4	-82.07	-131.71	-32.44	***
2 - 3	-28.05	-77.68	21.59	
2 - 1	18.90	-30.73	68.54	
1 - 10	-277.94	-334.81	-221.08	***
1 - 9	-248.21	-303.08	-193.34	***
1 - 8	-233.35	-288.22	-178.47	***
1 - 7	-232.67	-283.32	-182.01	***
1 - 6	-188.35	-237.99	-138.72	***
1 - 5	-154.42	-204.05	-104.78	***
1 - 4	-100.98	-150.61	-51.34	***
1 - 3	-46.95	-96.58	2.68	
1 - 2	-18.90	-68.54	30.73	

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