JULY 2014 M.Sc. Thesis in Mechanical Engineering MUHANNAD AKRAM HASAN

GAZIANTEP UNIVERSITY
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AN EXPERIMENTAL STUDY ON TURNING WITH ABRASIVE WATERJET

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MUHANNAD AKRAM HASAN
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An Experimental Study on Turning with Abrasive Water jet

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Prof. Dr. İ. HüseyinFiliz

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Muhannad A. Hasan

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ABSTRACT

AN EXPERIMENTAL STUDY ON TURNING WITH ABRASIVE WATERJET

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In this study an experimental turning set up is designed, constructed and coupled with abrasive water jet cutting machine and the effect of turning process parameters on surface roughness (Ra), material removal rate(MRR) and final diameter (df), have been investigated through a series of experiments. Aliminum alloy (Al 7075-T6) which is frequently used in automotive and aerospace industries is used as the workpiece material. Experiments are performed on three different diameters. Specimens from 20 mm, 25mm and 30mm diameters are prepared.

Water jet pressure (p), feed rate (f), waterjet impact distance (e) are the three cutting parameters. Diameter of the workpiece (d) is considered as another factor in this study. A total of 81 AWJ turning experiments are conducted basing on three-level full factorial design of experiment for the four factors. The effects of process parameters on Ra, MRR and final diameter have been investigated by Minitab software®. From the results of these experiments it is noticed that waterjet impact distance and the feed rate are the most effective parameters on the material removal rate and surface quality and final diameter.

Keywords: Aluminum alloy, abrasive water jet turning, material removal rate, surface roughness.

ÖZET

AŞINDIRICILI SUJETİ İLE TORNALAMA ÜZERİNE DENEYSEL BİR ÇALIŞMA

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Temmuz 2014
89sayfa

Bu çalışmadadeneyselbirtornalamasistemitasarlanmış, imaledilmişveaşındırıcılısujetimakinesiylebirleştirilerekişlemparametrelerininyüzeyp ürüzlülüğü(Ra), malzemekaldırmahızı(MRR) veparçanınişlemdensonraki son çapı(df) üzerindekietkilerideneylerlearaştırılmıştır. ÖrneklerdahaziyadesıklıklaotomotivveuçakendüstrilerindekullanılanAluminum alaşımdan (Al 7075-T6) hazırlanmıştır. Deneylerüçfarklıçaptakimalzemelerleyapılmıştır. 20mm, 25mm ve 30 mm çaplarındaörneklerhazırlanmıştır.

Su jetibasıncı(p), ilerlemehızı (f) vesujetiçarpmamesafesiişlemparametrelerioIarakalnmıştır. Bu çalışmadaörnekparçaçapları da diğerbir factor olarakelealınmıştır. Bu dört factor içinüçseviyeli tam faktöryeldeneytasarımına gore toplam 81 deneygerçekleştirilmiştir. İşlemparametrelerinin Ra, MRR vedfüzerindekietkileri Minitab® yazılımıileeldeedilmiştir. Deneylerinsonucuna gore, ilerlemehızınınvesujetiçarpmamesafesininyüzeykalitesine, malzemekaldırmahızıve son çapdeğeriüzerinde en etkiliparametreleroldugugözlemlenmiştir.

AnahtarKelimeler: Aluminyumalaşım, aşındırıcılısujetiyletornalama, malzemekaldırmahızı, yüzeypürüzlülüğü.

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Last but not least, I dedicate this work to my first teacher in life, my father who passed away, I am gratefully indebted to my mother, she is always asking about me, my study, and care of me from my remote hometown. Finally, I wish to acknowledge all of my parent's members, my brothers, sisters, and their families, and all friends for their warm support.

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AWJ	Abrasive water jet machine
MRR	Material removal rate
Ra	Surface roughness
p	Water jet pressure
f	Nozzle feed rate
e	Jet impact distance
h	Stand off distance
d_i	Initial diameter
d_f	Final diameter
d_n	Nozzle diameter
d_c	Depth of cut
d_{Avg}	Average of diameter
N	Work piece rotational speed
t_c	Cutting time
L	Length of cut
V	Surface speed
ρ	Material density
α	Impact angle
Rw	The roughness waviness
Rq	The root mean square average of the surface roughness profile
Rzi	The vertical distance between the highest peak and the deepest valley.

Rp	The highest peak of the roughness profile
Rv	The deepest profile of the roughness
Rmax	The maximum roughness depth
Rt	The maximum height of the profile

CHAPTER 1

INTRODUCTION

1.1 Introduction

Abrasive water jet processing technology has been found to be one of the most recently developed non-traditional technology used in industry for material machining with the distinct advantages of no heat stresses and thermal distortion; high flexibility; high machining versatility and small values of cutting forces. Also, itis low sensitive to material properties, therefore, does not cause noise or chatter.Additionally, because of water jets do not rely on or produce heat when cutting, it will leave the target material undamaged. Other technologies such as laser cuttinginduce a heat affected zone (HAZ) that often needs to be treated after the initial cutting.

In the conventional process of machining, a solid tool, made of higher hardened material than the work piece material, makes a direct contact with the work piece. Several untraditional machining processes, electro-discharge machining, electro-chemical machining, ultrasonic machining, chemical machining, abrasive water jet machining and laser beam machining are the most popular processes. In all these processes,there is no solid tool which will contact with the work piece.The abrasive water jet machining process is gaining a lot of popularity because of its ability to process a wide range of materials in different ways. In the abrasive water jet, normally the water exits the nozzle at a high speed and the abrasive is mixed and injected into the water jet stream. The purpose of the abrasive water jet is for penetrating the material of work piece to perform some machining process or finishing operation such as cutting, turning, drilling, boring etc.Abrasive water jet machines are extensively employed to machining or cutting a wide range of materials from soft and ductile to hard and brittle [1].

The abrasive materials are the particles of a kind of special materials like silicon carbide, garnet, aluminum oxide, dolomite, and sodium bicarbonate with different forms of varying grain sizes. The added abrasives drastically increase the process energy by accelerating the range of impacting particle materials that can be penetrated with a water jet. Materials like ceramics, super alloys, glass, kinds of stainless steel, and refractory material are typically machined by this process. The abrasive water jet is characterized by numbers of process parameters that determine the quality of the final product respect to efficiency, economy, and finishing of the entire process. The parameters in the abrasive water-jet can be grouped into four categories;the first group includes;hydraulic parameters, (water pressure, orifice diameter, and the water flow rate), the second group consist ofacceleration and mixing parameters (focus length,focus diameter). Cutting parameters (traverse speed,standoff distance, number of passes, impact angle, and rotational speed) are included in the third group, and the fourth group is made up ofabrasive parameters (abrasive mass flow-rate,abrasive particle size distribution, abrasive particle diameter, andabrasive particle shape.

The form of abrasive water jet in turningprosses is almost similar to conventional lathe, except that an abrasive water jet is used as a cutting tool. An AWJ is formed by the mixture of the abrasive material particles with high speed water jet into a chamber of specially designed nozzle assembly. The high speed of the water jet stream is obtained by running water at very higher (up to 400 MPa) pressure to a value of approximately 400 MPa through a small sapphire of special material orifice less than one millimeter in diameter. Impact the mixture of high velocity water -abrasive particles with the work piece results removal of material, which can broadly be classified as an erosive wear process.

Abrasive water jet is highly used in automotive, aerospace, and electronics industries. For example, engine components (heat resistant alloys, aluminum, titanium), titanium structures for military aircrafts, aluminum body parts and interior cabin parts in aerospace industries, interior trim (head liners, trunk liners, door panels), bumpers in automotive industries, fiberglass body components, circuit boards and cable stripping in electronics industries are generally made by using this technology .

However, turning process by abrasive water jet is new technology and still under development. There are a lot of aspects of abrasive water jet turning process which need for deeper research and more study to be fully understood. The quality of AWJ turning such as surface finishing and material removal rate depends on the input turning process parameters such as water jet pressure, jet traverse speed, and impact distance.These parameters play the main roles on effecting of turning quality.

In this study, a series of experiments are performed in order to investigate the effects of cutting parameters water jet pressure (p), jet feed rate (traverse speed) (f), water jet impact distance (e)] on the surface roughness and the material removal rate of three different diameters of aluminum alloy (Al 7075-T6). The diameter of the work piece (d) is considered as another factor in this study. A total of 81 AWJ turning experiments are conducted based on a three-level full factorial design of experiment for the four factors. The effects of abrasive water jet turning parameters are investigated experimentally and predictive analysis of surface roughness and material removal rate for each diameter by keeping the values of rotational speed, abrasive flow rate, and stand off distance constant. By using Minitab software - full factorial design method, the main effect and the interaction effect plot of the process parameters on surface roughness (Ra) and material removal rate (MRR) have been presented.

Literature survey is presented in Chapter 2, Chapter 3 is devoted to the review and brief explanation of AWJ machine, the mechanism of abrasive water jet turning process,the design of the experimental setupis given in Chapter 4. Experimental work and evaluation of the effects of process parameters (water jet pressure p, jet impact distance e, nozzle traverse speed f, and diameter of work piece d) on surface roughness (Ra), material removal rate (MRR) and thefinal diameter (d_f) are presented in Chapter 5. Finally, discussion and final conclusions are stated in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents literature most relevant to this thesis. A study on kerf geometry is given in section 2.2. Section 2.3 is devoted to the literature on erosion and material removal. Modeling studies on abrasive water jet process are presented in section 2.4. Abrasive water jet parameters affecting, cutting qualityand studies on abrasive water jet turning process are presented in sections 2.5 and 2.6 respectively.

2.2 Kerfs Geometry

Chen et al [2], in his experimental study of kerfs geometry for AWJ cutting process of ceramic found that there are three cutting zones, while the two upperzones resemble that of a through cut, but a later cut at the bottom causes the kerf to widen forming an enlarged with an irregular shape. The upper zone has a smooth surface. In the lower zone which is characterized by numerous pits, the penetration process occurs to jet upward deflection. The middle zone, which has obvious striation but no pits, marks the transition form the upper smooth zone to the lower enlarge zone. The width of kerf tapers in the upper zone and the width at the end of this zone is equal to the least width of the cut. In the middle zone the kerf width remains unchanged and is also equal to the least width. In the lower zone the kerf curvature changing greatly and a ballooning formation is observed. As the depth penetration increases, such formation becomes enlarged.

Shanmugam and Masood [3] presented an investigation on the kerf taper angle generated by abrasive water jet (AWJ) technique in machining two types of composites: epoxy pre-impregnated graphite woven fabric and glass epoxy. Comprehensive factorial design of experiments was carried out in varying the traverse speed, abrasive flow rate, standoff distance and water pressure. Using the dimensional technique and adopting the energy conservation approach, the kerf taper angle had been related to the operating parameters in a form of a predictive model. Verification of the model for using it as a practical guideline has been found to agree with the experiments.

Shanmugam et al [4] in their study presents a minimize or eliminate the kerf taper in AWJC of alumina ceramics by using a kerf-taper compensation technique. Among the cutting parameters studied, kerf-taper compensation angle is found to have the most significant effect of the kerf taper and the kerf taper angle varies almost linearly with this compensation angle. they showed that with this technique, it is possible to achieve a zero kerf taper angle without compromising the nozzle traverse speed or cutting rate.

Jun Wang [5]in his experimental investigation of the machinability and kerfs characteristics of polymer matrix composite sheets by abrasive water jets reported that this unique cold cutting technology is an effective alternative for polymer matrix composite processing, resulted a good product and kerfs quality. Plausible trends of kerf quality with respect to the input parameters were discussed.

Bitter [6] study the effects of collision of the elastic sphere with a plain that deform both elastically and plastically. He divided the process of material removal into two forms, the first one is cutting wear which happens at a low impact angle, and the second is the deformation wear that occurs at high impact angle. Cutting wear is caused by the cutting action of the free movement of particles while deformation wear is a result of repeated deformation of particles during collisions. Two wear formulas resulted depending on the angle of incidence. In the first one the particle exits the material with a velocity component tangential to the surface, and in the second, all the tangential kinetic energy will dissipate.

2.3 Erosion and Material Removal

There are many studies describing the material removal mechanism for brittle materials.Most of them agree that the erosion of brittle material starts with a cracking process, and material is removed by the propagation and intersection of cracks around of the abrasive particles.

Choi et al [7]conducted their studies on the erosion of brittle material from the point of a view of acting force. They noted that there are two different modesof material removal depending on the force that the abrasive particles exert on the surface. Their experimental results indicate that for crack initiation, there exists a threshold force. In cases where there is a force larger than the required threshold, material removal is mainly due to the micro crack propagation.

JiyueZeng and Thomas J. Kim [8] investigated the erosion phenomenon associated with abrasive water-jet cutting of polycrystalline ceramics. The erosion mechanisms observed in their study include intergranular network, cracking and plastic flow. Material removal due to network, cracking was calculated with a crack network model which relates the fracture surface energy in forming the crack network to the energy of the impact induced stress waves. The contribution of plastic flow was evaluated with Finnie's model. The derived erosion model was verified by abrasive water-jet erosion experiments.

Zeng and Kim [9**]** stated that removal of material is processed through the formation, propagation and interaction of micro cracks which are produced by particles impacts. Based on this observation, classified the brittle material erosion mechanism into three levels; conical crack model, lateral crack model, and inter granular crack model. In the Conical crack model they assumed that the erosion occurs entirely by crack propagation and chipping as a result of contact stress during impact, and these stresses cause cracks grow from pre-existing cracks in the work piece surface. Lateral cracks mechanism considered that the lateral crack formation during a single particle impact as the major reason in establishing the material volume removal model. The intergranular crack model directly assumes that the damage produced by an impacting particle is in the form of grain boundary cracking.

Paul et al [10] based on their experimental studies that the mechanism at or near the top of the kerfs is predominantly micro cuts at shallow angles, followed by plastic deformation at near- orthogonal angles of impact. Such deformation occurs to remove the step formation.They summarized that all of the mechanism, (inter granular cracking or micro cutting of material) is a mixed modeof predominantly inter-granular cracking and micro cutting by free flowing abrasive particles and plastic deformation along with plumbing.

2.4 Modeling of AWJ Process

Mingbo Wang and Ruihe Wang [11] conducted a theoretical analysis in order to develop a flow model for the abrasive water jet technique. The main concern is whether the abrasive particles can be treated as a pseudo-fluid phase. A two-fluid model is developed based on the fundamental laws of conservation. A control volume method is used to discredit the equations, and a phase-coupled simple algorithm was adopted to solve the pressure–velocity coupling equations. The quasi two-dimensional flow field outside a conventional nozzle used in abrasive water jet was analyzed and computed to validate the model. Good agreement was observed comparing the numerical results with the experimental measurements.

Liu et al. [12] in their studies of computational fluid dynamics (CFD) models for ultra high velocity water jets and abrasive water jets using the Fluent6 flow solver. Jet dynamic characteristics of the flow downstream from a very fine nozzle were then simulated under steady state, turbulent, two-phase and three-phase flow conditions. Water and particle velocities in a jet were obtained under different input and boundary conditions to provide an insight into the jet characteristics and a fundamental understanding of the kerf formation process in AWJ cutting. For the range of downstream distances considered, the results indicated that a jet is characterized by an initial rapid decay of the axial velocity at the jet center while the cross-sectional flow evolves towards a top-hat profile downstream.

Deam et al [13] searched on model for predicting the shape of the cut profile in industrial cutting processes. He reported that the physics of abrasive wear was used in the process model, which is cast in intrinsic coordinates. This choice of coordinates enables a formulation of the problem that leads to simple solutions and also a good understanding of the process.The model predicts that fluctuations in the local curvature of the cutting face are an inherent property of the cutting process and that no matter how precise the control over the cutting parameters, the fluctuations cannot be eliminated.

Vikram and N. Ramesh Babu [14] proposed a new approach for modeling the three-dimensional topography produced on abrasive water jet cut surface. It makes use of the trajectory of jet, predicted from the theory of ballistics and Bitter‘s theory of erosion for material removal, for numerically simulating the cutting front. The two dimensional topography at different depths of the cut surface was generated by considering the trajectories on the cutting front and the abrasive particles impacting the walls of cut surface randomly. For a realistic generation of topography on the cut surfaces, several instantaneous profiles generated in each region of cut are superimposed to obtain an effective profile. The nature of effecting profiles, thus predicted was analyzed and validated using power spectral density analysis. The effective profiles predicted at different depths are in turn used to generate the three dimensions' topography of abrasive water jet cut surface. Results obtained with the proposed model are validated with the experimental results.

Wang [15] in his study of particle velocity variations across and along an abrasive water jet based on, in-depth understanding of the jet dynamic characteristics from a computational fluid dynamics (CFD) simulation study. The models were then assessed qualitatively and quantitatively. It was found that the model predictions are reasonable and consistent with the data from a verified CFD model with an average percentage error of less than 1%.

2.5 The Effects of Abrasive Water Jet Parameters

2.5.1 Surface Quality

Azmir [16],in his study of surface roughness (Ra) and a kerf taper ratio (TR) characteristic of an abrasive water jet machined surfaces of glass/epoxy composite laminate. Taguchi's design of experiments and analysis of variance was used to determine the effect of machining parameters on Raand TR. Water jet pressure and type of abrasive materials were considered as the most significant control factor in influencing Raand TR, respectively.

Adnan Akkurt et al[17]explained the effects of feed rate and thickness of the work piece on thesurface roughness. Considering experimental data, the effects of the composition of material on the surface roughness were assessed. The study also evaluated the deformation effect of AWJ on work pieces that have the same composition but different thickness.

Shipway et al [18] examined the abrasive water jet milling behavior of Ti6Al4V in terms of the surface properties of the milled component, such as roughness, waviness and level of grit embedment. The properties of the surface following milling depend strongly on the milling parameters, such as jet-work piece traverse speed, impingement angle, water jet pressure and abrasive size.

Jan Valicek et al [19], in their experimental study of the surface quality produced by abrasive water jet (AWJ) on metallic materials. They found that the surface roughness/waviness was quantitatively evaluated by using the contactless optical measurement. In order to characterize the cut surface qualities, a single-parameter criterion has been proposed. Based on root mean square (RMS) roughness evaluation of the worst cut surface zone, the dimensionless statistical parameter C can be calculated as a basic quantity for AWJ surface cut characterization.

Kovacevic [20] showed in his study that at the upper portion of the kerfs, the effect of water pressure on surface roughness is insignificant. An increase of the value of water pressure due to decrease in work piece surface roughness. This result is normal that because of the increasing of water jet pressure causesan increase of particle velocity and the fragmentation of particles inside the abrasive nozzle, which causes positive result on surface quality. But too high value of water jet pressure, it will generate a negative result of surface roughness, because it makes the abrasive particles lose the cutting ability with too fragmented value.

Ramulu and Arola[21] in their study of abrasive water jet cutting for graphite epoxy/ laminate, they had found similar results and they explained the phenomenon from the point of view of the value of kinetic energy. The higher value of water jet pressure increases the kinetic energy of abrasive particles and prolongs their capacity for material removal during the depth of cut. However the surface roughness decreases when increase on water pressure.

Çaydaş and Hasçalık [22] have studied the effect of abrasive water jet parameters on surface roughness for AA 7075 Aluminum alloy. Taguchi's method of experiment is used for the purpose of reducing the number of experiments. Based on the analysis of variance (ANOVA) and F-tests, they found that the water pressure is the most effective parameter, then followed by traverse speed, abrasive flow rate and the last is a standoff distance. A constant increase of surface roughness is a result of an increase of nozzle traverse speed, the reason of this increasing is that the increase in traverse speed causes less overlap cutting action and fewer abrasive particles to impinge the surface, which increase the surface roughness .But if the nozzle traverse speed is too low, the change in the surface roughness is indiscernible; also the traverse speed has little influence on the surface roughness at the top of the cut.

Karakurt et al. [23] have investigated the relationship of abrasive water jet parameters on granite finishing surface. Experimental studies have been conducted by applying Taguchi's experimental method. For surface roughness parameter, the average value of surface roughness (Ra) is used and it is concluded that the value of surface roughness of the specimens increases when the increase of traverse speed.

Candar and Filiz [24] have investigated the effects of abrasive water jet cutting parameters on the surface quality of Al 7075 alloy. From their experiments, it is noted that the traverse speed and stand off distance are the most effective parameters on surface quality. Surface roughness increase with an increase in any of these two parameters. On the other hand, increase in the water jet pressure result in a decrease in surface roughness while the thickness of the material has the least effect on the surface quality.

2.5.2 Material Removal Rate in AWJ Cutting

Wang and Xu [25] performed an experiment of the AWJ multi pass cutting of 87% alumina ceramic with nozzle oscillation. The cutting capacity in terms of depth of cut and the major kerf geometrical features as represented by the top kerf width, bottom kerf width and kerf taper was analyzed with respect to the major process variables including the number of passes, the nozzle traverse speed, water pressure and oscillation parameters. Optimum combinations of the major process parameters were recommended to maximize the depth of cut, taking intoaccount the economic or productivity aspects. The general guidelines and suggestions were given for the selection of the number of passes and the other major cutting variables.

Hashish [26] in his experimental investigation of the cutting process of ductile materials and gray cast iron, he noticed that there exists a critical threshold pressure below which no cutting occurs. Beyond the critical pressure the depth of cut increases linearly with an increase in the water pressure in a certain range.

Momber [27] designed a system to monitor the depth of abrasive water jet cutting. In his point of view, increasing the water pressure is a most effective method of increasing the cutting ability. The main reason of this effecting is that the transfer rate of momentum and the velocity of the jet of the particles at the nozzle exit is increased in accordance with the water jet pressure, thus resulting in increased impact energy and accordingly the depth of cut.

Chen et al [28] conducteda researchof abrasive water jet cutting of aluminum-based ceramics to investigate the effect of water pressure on both depth of cut and smooth depth of cut. They reported that the effect of varying water pressure on the smooth depth of cut is similar to that on the depth of cut. Anyway, it was found that the ratio of smooth depth of cut to the depth of cut decreases as the water pressure increases.

Momber and Kovaeivic [29] on their study of abrasive water jet cutting of rocklike material indicates that the relationship between the water jet pressure and the depth of cut is nonlinear with a decreasing progress at high values of water pressure, indicating that the material removal process is less efficient at higher pressure levels. They reported that a critical pressure exists which is corresponding to the minimum pressure to cut the material. There are a lot of explorations of the effect of nozzle traverse speed on the depth of cut. It was found that the typical relationship is a non-linear curve, it has been reported that the depth of cut decrease with an increase of the value of nozzle traverse speed.

Axinte et.al [30] reported a preliminary study of the capability of AWJ cutting of polycrystalline diamond (PCD) using abrasive media with different hardness, i.e. aluminum oxide (Al2O3), silicon carbide (Sic) and diamond. While keeping some operating parameters constant (pump pressure, stand-off distance and size of abrasives) the feed speed had been adjusted to enable full jet penetration for each type of abrasives. It was found that not only the material removal rates vary significantly with the employment of different types of abrasive, but also the nozzle wear ratios, with further implications on the kerf quality (width, taper angle) of diamond cut surfaces.

Gi Sang Choi and Gi Heung Choi [31] attempted to develop an analytical model for material removal in abrasive water jet machining (AWJM) of brittle material. The size of the fracture that takes place on the backside of the work piece as the jet passes through the work piece was then predicted. The proposed model was experimentally evaluated. In addition, acoustic emission (AE) generated from AWJM of alumina ceramics was evaluated in view of establishing an experimental relationship with the parameters of material removal process. The experimental results indicated that a strong correlation between the RMS AE signal and the characteristics of AWJM exists and, therefore, suggest that AE can be implemented in practice for monitoring purpose.

Hashish and Due [32] studied the optimum of the stand off distance for maximum depth of cut. After consideration of each of cutting performance and cutting efficiency, they suggest an optimum standoff distance which is equal to 2.0mm. They noted that it should be compared to other cutting parameters; the influence of standoff distance is not significant in many cases when the standoff distance varies with a small range.

2.6 AWJ Turning Process

In turning process, the work piece is rotated while the nozzle of abrasive water jet is traversed in radial and axial directions to get the result and produce the required geometry. There are a lot of researchers reported about the materials properties, volume removal rate, surface finish control, flow visualization, and modeling of the turning process, using AWJ technique.

Zhong and Han [33] studied the influence of variation in process parameters on turning of the glass with abrasive water jet. They reported that the lower value of traverse speed of the water jet with higher rotational speed of work piece resulted in lower waviness with surface roughness for turning specimen.

Hening, A [34] presented semi-empirical analysis to predict radius reduction in turning. He considered that the material removal in abrasive water jet turning process is assumed to be the superposition of volume removed by single particle which impacts on the surface of the material work piece. From a visualization study Hashish reported that the material removal takes place on the circumference of the work piece.

Ansari and Hashish [35] suggested an analytical model; that relates the volume sweep rate to the material removal rate. This model could predict the final diameter of rotating work piece in various sets of abrasive water jet turning process parameters. Hashish modified his linear AWJ cutting model for AWJ turning,he considered that material is removed from the face of the rotating work piece and assumed that the total depth of cut consists of cutting-wear depth and deformation-wear depth in turning.

Uhlmann et al. [36] investigated the performance of machining titanium, aluminum alloys by conventional turning with different cutting part inserts. For the investigations a near-gamma structured Ti44.5Al5Nb extruded alloy was used as work piece material and cemented carbide was chosen as the tool material. A cutting speed of 30 m/min, a feed of 0.1 mm at a depth of cut of 1 mm as well as a cooling lubricant at a jet pressure of 0.5 MPa was used for the investigation of the tool life time. Another characteristic to qualify cutting tools is the volume of removing material during the tool life (tool life volume).

Hashish [37] investigated the AWJT parameters jet pressure, the abrasive flow rate, the abrasive particle size, the orifice size and the feed rate. Most of the experiments were performed with a standard aluminum work piece material (AlMg1SiCu). It was noted that the maximized MRR correlates with coarse-grained surface conditions.

Manu and Babu [38]in their study, they applied the Finnie's theory of erosion model for abrasive water jet turning of ductile materials. Their model is not able to predict accurate final diameter in various traverse rates. Moreover, at angles near to zero (when the impact angle is very low) it predicts higher Volume of removing material.

Zahoor and Zohourkari [39] developed and experimentally validate a comprehensive process model for AWJ turning of cylindrical specimens subjected to various traverse rates. They noted that the flow stress may even beconsidered as an empirical constant which accounts for the material property and all other effects which are not accounted in the erosion models. Since the proposed model does not consider the jet divergence, so further attempts should be done to model abrasive water jet turning more precisely.

2.7 The Place of This Workin AWJ Turning

In this study a serious of experiments of turning process ofAl-7075 have been performed to investigate the effects of cutting parameters on the material removal rate and surface quality. There are few studies which are related to AWJ turning process. In each study differentparameters are considered.The place of this research is to make contribution on the determination of the effects of process parameterson the surface quality, material removal rate, and final diameter of the work piece.

The effects of rotational speed and direction of rotation of the work piece on the target parameters are demonstrated. The mechanism of the AWJ turning process, the calculation ofmaterial removal rate, and measurement of surface roughness are also presented in this study. The comprehensive view of the final results of the effect of all AWJ parameters on the surface roughness,material removal rate and final diameter are investigated, by using MINITAB program-ANOVA method analyzing the effect of process parameters, then determining the most effective and least effective turning parameters which give the best surface quality with highest amount of material removal rate in turning process.

CHAPTER 3

A REVIEW ON ABRASIVE WATERJET CUTTING MACHINE

3.1 Introduction

This Chapter presents a review on abrasive water jet cutting and abrasive water jet machine. Basic principles of water jet cutting and jet forming are given in section 3.2. The history and stages of abrasive water jet development are given in section 3.3. The sections 3.4 and 3.5 include the characteristics,comparison of abrasive water jet cutting with another method, and parameters involved in abrasive water jet machining respectively. The general descriptions and operation components of AWJ machine,pumping types, jet power with plumping,and a brief explanation of AWJ parts and componentsare given in section 3.6.In section 3.7 the types of abrasive materials, the properties, and the technical data of abrasive material are described.

3.2 Principle of Water Jet Cutting

Water jet machining is a technology which has been used for decades and is considered as one of new developments and fastest growing machining processes. The water jet technique is based on a rather simple idea. Using a strong (high pressure) pump, water is pressurized to very high values (typically about 4000 bar), and forced into a small circular orifice of about 0.25 mm in diameter to form a thin height speed stream of water. Figure 3.1 shows the abrasive water jet stream forming.

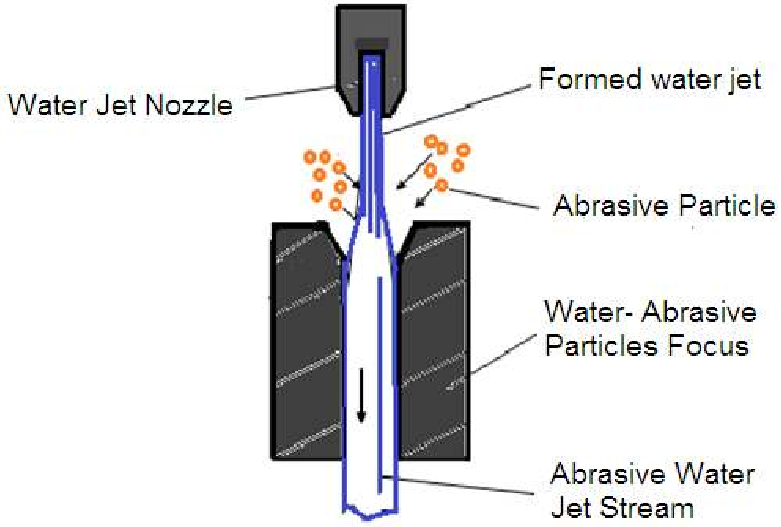


Figure 3.1 Abrasive water jetforming

The majority of water jet types is able to cut hard materials like stone, metals, etc.A granular abrasive material (typically garnet) is added to the water, increasing the cutting energy of the water jet before exits the nozzle, asshown in Figure 3.2. This flexibility greatly enhances the versatility of a water jet machine, as it can easily change over from cutting thickness of 12.7 mm for foam gaskets to 101.6 mmfor titanium brackets.

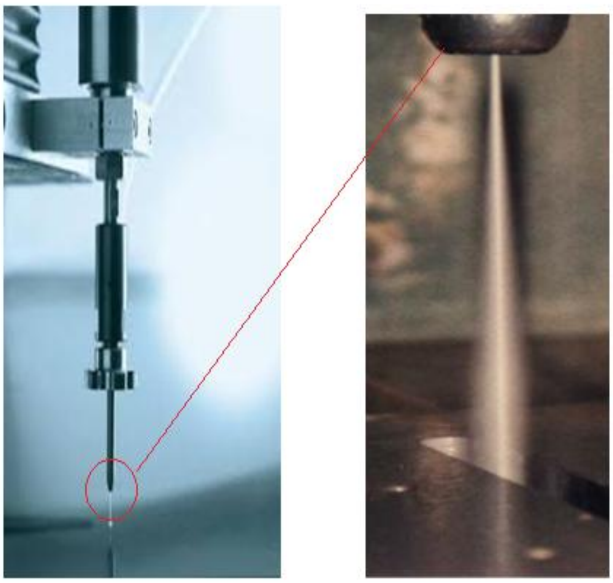


Figure 3.2View of outlets high pressure water jet

Abrasive water jet machine technology has extra advantages over other manufacturing properties. Because of the water jet machining is essentially controlled erosion; this technique is able to deal with almost any material [40]. Additionally, water jet processes do not generate heat when machining, leaving the target undamaged. Other processing technologies induce a heat affected zone that often needs for additional processes to be treated after the initial cutting. Besides limiting the need for extra operations, the fact that the water jet technique creates no heat affected zone increases the range of materials which need to be cut. By using a thin and small stream of water to cut rather than a solid tool, water jets able to create complex geometries with minimal particle material loss.

3.3 Historyof AWJ Machine

Using the stream of water as a cutting method for light and soft materials has been around for many decades, one of the first operations was seen in the 1930s in the company for paper metering system. Low pressure water was used. Early figures such as a form of paper metering system by the Paper Patents Company in the 1930s used relatively a system of low-pressure water. High pressure water jet technique took form in the post-war era, resulting with faster cutting and greater accuracy and precision. Reliability remained a challenge, though, until the early 1970s, when Mr. John Olsen, of Operations at the Omax Corporation in United State, developed and apply the first reliable ultra-high pressure system [40].

While the early water jet system could easily cut the light and soft materials, they were not effective in cutting thicker and harder materials such as metals. This capability was achieved by adding an extra kind of material with some controlling to be able to penetrate the harder materials.Therefore, adding an abrasive to the water jet in some place into the cutting nozzle after the jet stream was formed. With the combination of a durable abrasive water jet nozzle material with a dependable, high pressure water pump, an abrasive water jet system could immediately practice to cut a wide range of materials, including a type of hardened tool steel, titanium, glass, and rock. In 1930, low-pressure water jet machine was used to cut light and soft materials, like wood, paper, and leather. The Abrasive water jet nozzle system concept is patented.In 1940, the technique of high pressure water jet system is developed and utilized in air power and automotive hydraulics systems.

In 1950, technology of ultra high-pressure about (6900 bar) liquid jet system is developed and applied for cutting many kinds of textiles in the aerospace manufactures. Also numerical control (NC) systems were developed, at this time.In 1960, Pulsing Water jet pressure created at Union Carbide was employed to cut a stone and metals applying pressure water up to (3450 bar). At 1970, Bendix Corporation started to acquire the concept of using the corundum crystal as a water jet orifice, also using high pressure fluid intensifier. In 1980, Boride searches and scope in roctec ceramic tungsten carbide composite in mixing tubes making. Evaluation of 1930, abrasive nozzle design brings abrasive nozzle jet machining to work and reality.In 1990, Mr. John Olsen searched and developed and patenteda new technique and design of motion control system to precisely locate and exact position of the water jet stream.In 2000, cutting model development and improvement significantly increase in value of cutting speed in some kinds of water jet systems, high precision with zero taper water jet is introduced.In 2010, anindustrial Company produced many types of rotary axis machining and new design such as A-jet brings 6 Axis technology machining, also the water pump technology significantly increases reliability, adding an advanced system monitoring and advanced 3D Tools.

3.4 Characteristicsof AWJ Machining

Abrasive water jet machining technique has been increasingly used and practiced since it has various distinguished advantages over other processes;

- No thermal effect due to damage or distortion. Any heat process may be generated is instantaneously carried away by the flow water. As a consequence, on that point is, no temperature rise occurs at the working space or work piece. This is especially useful for processing (cutting, turning, milling, drilling, etc.) thermal sensitive materials and other type of metals where excessive heat will certainly change the properties of the material.
- Abrasive water jets have the ability to produce contours. They are exceptionally good at two-dimensional machining. It is possible to trace with very complicated shapes.
- It has high machining versatility. An abrasive water jet machine can cut virtually any materials, particularly for machining a variation difficult-to-machine materials such as titanium alloys, pre-hardened steels, brass, copper, aluminum, and brittle materials like ceramics, glasses, and quartz. Some examples are shown in Figure 3.3.

The applications and benefits of AWJ technology are limitless and really expanding. The following below are several advantages of AWJ in addition to versatility and no heat affected zone;

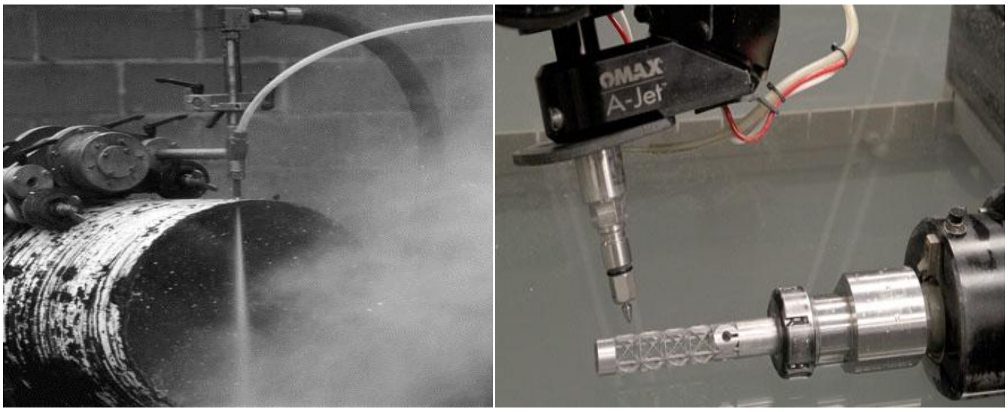
- Unlike other machining process (turning, grinding), AWJ cutting does not produce any dust or particles which are harmful if inhaled.
- With setting for any geometry on a drawing programed can be easily transformed CNC codes.
- The extremely detailed geometries can be easy to cut because the kerf widthof AWJ cutting is about (0.5 to 1.27 mm).
- AWJ cutting provides a little amount of material loss due to cutting, this takes place for increasing production efficiency.
- No extra operations or no burr formation after cutting process and it eliminates the other types of machining operations such as finish sanding and grinding.
- No extra preparing before processing or start hole required. It can start directly.

In Table 3.1somecomparison of abrasive water jet process to other unconventional machining processes, including plasma, laser, and EDM is provided. Most advantageous, abrasive water jet machine has the ability to machine any material, with little variance in setup for different materials. In Figure 3.3some examples of abrasive water jet Machining on different Materials.

Table 3.1 Comparison of water jet, with respect to Plasma, Laser and EDM [42]

	WATERJET	PLASMA	LASER	EDM
Process	Erosion process: high speed liquid sandpaper.	Burning/melting process using high temperature ionized gas arc.	Melting process using concentrated laser light beam.	Erosion process using electrical discharge.
Materials	Any material	Primarily steel, stainless and aluminum.	Primarily steel, stainless and aluminum. Can also cut a variety of other materials	Conductive materials only.
Thickness	Up to 24 inches, virtually any material. Z constraint is only limit to thickness	Up to 2-3 inches, depending on material.	Generally 1 inch or less, depending on materials.	Generally 12 inch or less.
Part Accuracy	Up to .001"	Up to .010"	Up to .001"	Up to .0001"
Machine Setup	Same setup for all materials	Different setup for different jobs	Different gases and parameters for different jobs	Different wire types for different jobs

(a)Stainlesssteel cut by AWJ (b)Carbon steel cut by AWJ



(c) Cristal milling by AWJ **(d) Barrel turned by AWJ**

Figure 3.3. Some examples on Machining of different materials.

3.5Parameters Involved in AWJ

3.5.1 Input Parameters:

- Hydraulic parameters: Water jet pressure, Water jet diameter.
- Target material parameters: Fracture strength, Hardness, Ductility.
- Mixing parameters: Mixing tube diameter, Mixing tube length.
- Cutting parameters: Traverse speed, Standoff distance, and impact angle.
- Abrasive parameters: Abrasive particle size, Abrasive material, Abrasive flow rate.

3.5.2 Output Parameters:

The main output parameters of abrasive water jet are; Surface waviness, kerfs width and taper,burr formation,surface finish, depth of cut.Geometrical and dimensional accuracy, material removal rate.

3.6 General Descriptionsof AWJ Machine Components

The water jet machine includes three main systems: water filtration, pressure generation, and cutting unit, these systems are schematically shown in Figure3.4it is also consist of several subunits, these are; 1- high pressure pump, 2- plumbing, 3- catcher tank, 4- abrasive hopper, 5- cutting head, 6-XY Traverse system, 7-PC controller. The details of the subunits of abrasive water jet machine are shown in Figure 3.5

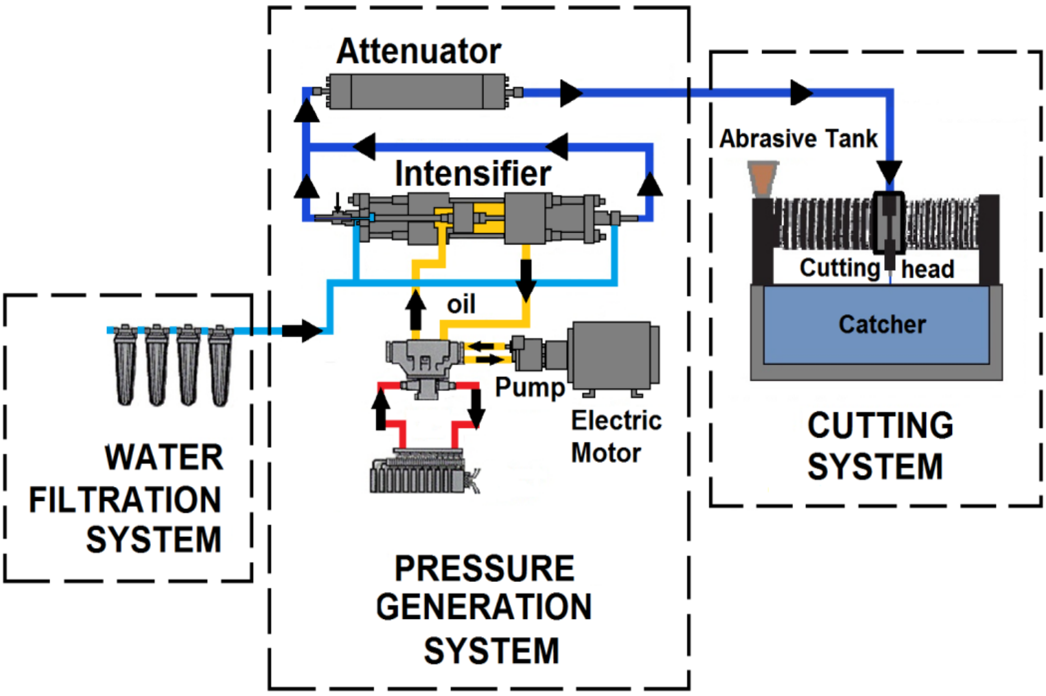


Figure 3.4Schematic representation of abrasive water jet systems[50]

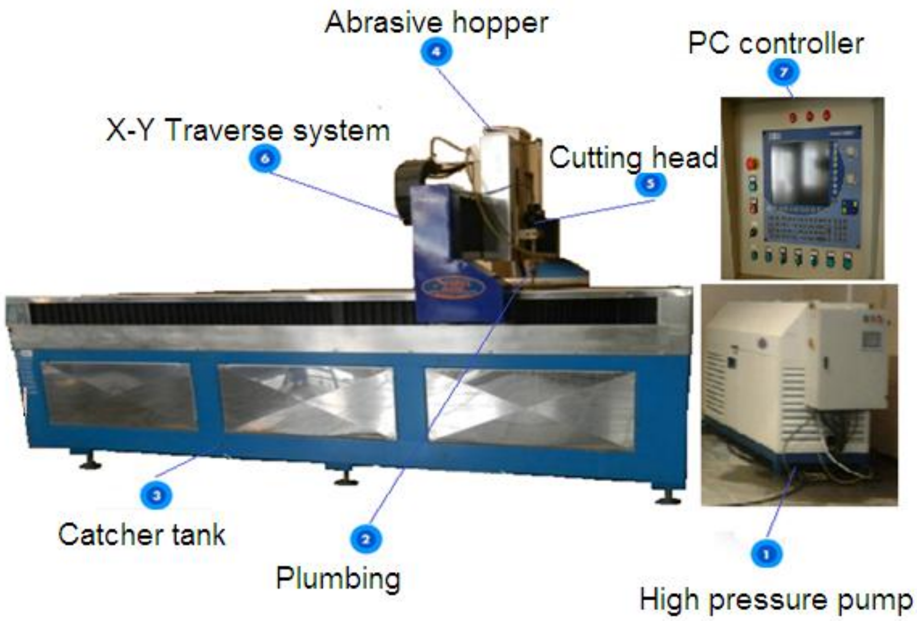


Figure 3.5Subunits in AWJ machine.

3.6.1 Water Treatment and Filtration Unit

Most water supply systems deliver small particles along with the water, and inlet filtration is necessary to protect the pump and the nozzle from particles.

Often water contains dissolved calcium and magnesium at levels that can precipitate within the pump and on nozzle surfaces. A water softener removes these elements economically.

Iron and silica are other water impurities that can precipitate and cause the same problems as calcium and magnesium. However, softeners cannot remove these impurities; a reverse-osmosis system usually is needed.The final impurity to watch for is acid. Acidic water can cause early fatigue failure of high-pressure components. Accessories are available to neutralize acid water. Finally, water inlet temperature is a concern because it has a dramatic effect on the life of the polymer seals used in the pump. Raising the water temperature from 50 degrees F to 100 degrees F can reduce seal life by a factor of 25[42]. Inlet water chillers are available as an accessory for areas in which water is supplied as warm water, Figure 3.6 shows a part of a water filtration unit without softener.

Figure 3.6 Filtration unit with cartridge filters

3.6.2 Pressure Generation Unit

3.6.2.1 High Pressure Pumping System

High pressure needed to drive an abrasive jet, the water compresses up to 11 percent [40]. Figure 3.7 shows the percentage compression of water at pressure up to 690 MPa

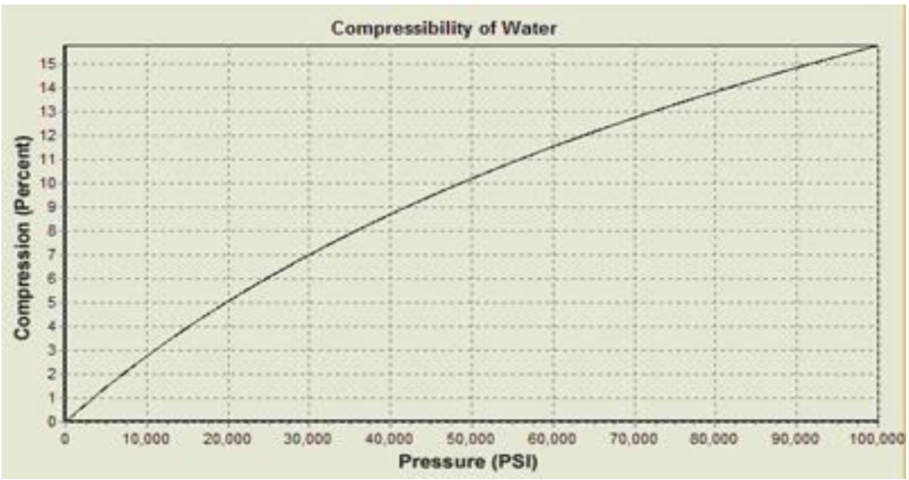


Figure 3.7 Compressibility of water [40]

This compressibility has a safety implication. A pump that is shut off and not vented may be suddenly surprised the mechanic who opens a fitting. one should be sure that the pressure is drained away before opening the high-pressure fittings; Figure 3.8 shows a picture of abrasive water jet pumping system.

Figure 3.8Abrasive water jet machine pumping system

3.6.2.2 Heat and Energy Conversion

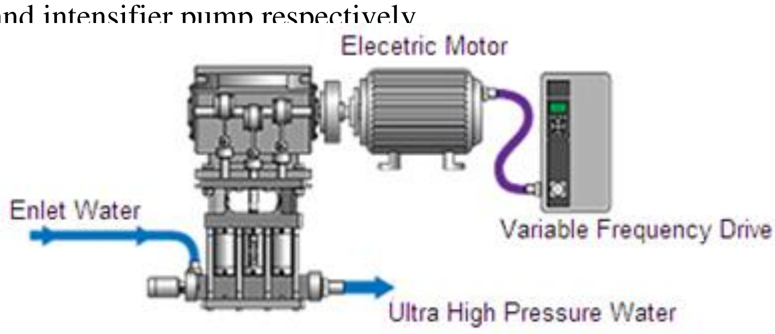
The process of pumping water up to (400MPa) requires a huge amount of energy. In fact, it may be about the same energy as it's enough to heat the water to 166 degrees [40]. So to pumping one gallon per minute (GPM) of water takes approximately the same amount of energy as it needed to heat 1 GPM from an icy 46 degrees to the boiling point. If the water is shot out of a nozzle, the energy will be the kinetic energy of the high-speed jet. A part of the jet energy then is used for cutting process, and the other part will change to become a hit when the jet is stopped by the catcher. This resulting of why the catcher tank becomes warm during working.

3.6.2.3The Pumping

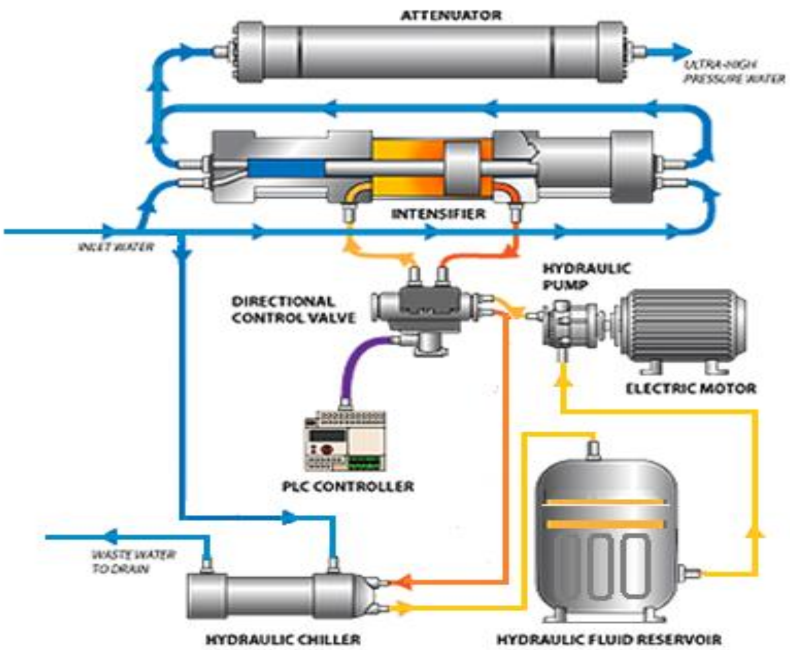
The higher pressure water system is one of the most critical and expensive components of a water jet system. In order to generate the high kinetic energy with a high velocity stream of water that need to cut through hard materials quickly, industrial water jets employ kind of pumps that generate a water pressure about (400MPa).

Water jet systems utilize a complex hydraulic intensifier pump, simpler system crankshaft-driven triplex plunger pump. Crankshaft pump systems are inherently more efficient than that one with intensifier pumps because they do not need a power-robbing hydraulic system. The crankshaft system work is a purely mechanical direct-drive system and has minimal friction losses with efficiencies between 85%

and 90% are typical. This means that more than 85% of the electric power supplied to the starter motor can actually be delivered to the cutting head, compared to the typical 65% of an intensifier [42]. Historically intensifier pumps had an advantage of longer seal and check-valve life, on the other hand ongoing improvements in seal designs and types of materials also the wide availability and reduced cost of ceramic material valve components now make it possible to work and operate a crankshaft pump in pressure about (400MPa) range with long practically maintenance intervals and very good reliability. Figure 3.9 show a schematic views of two systems; direct drive pump and intensifier pump respectively.



(a) Direct drive pump



(b)Intensifier pump

Figure 3.9 Pumping systems in AWJ machines

3.6.2.4 The Jet Power Depends on Pressure Pump

The power and energy required to run a jet stream are the pressure value behind the jet times the value of the jet flow rate. This is may easily illustrate in the basic form of a simple pump mechanic. In Figure 3.10 piston of area with value of A is starting to push at a speed of V, then the orifice forming the jet develops a pressure P as a result of this process, in the cylinder. Actually the power being input to the pump is simply the force on the piston times the speed of this piston. The value of the force on the piston is the pressure, P, times the piston area, A. So the power value calculated by;

$$H = PAV \tag{3.1}$$

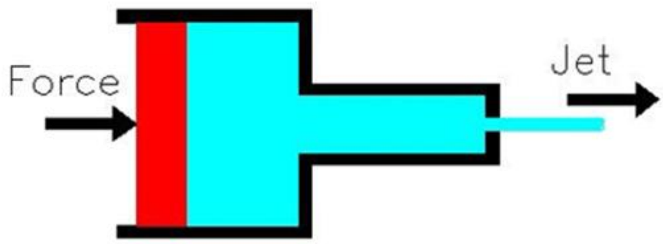


Figure3.10Relation between power input and jet power output

But the area times the velocity value of the piston is equal to the flow rate of the water, Q. So,

$$H = PQ \quad (3.2)$$

Now if a force push on the piston harder, that may raise the pressure and, at the same time, force more quantity of water through the nozzle. In this case, both P and Q will increase, so that the power of the jet will increase. The value of jet power for a 0.015-inch of Orifice as a function of pressure is shown in Figure 3.11. And the velocity profile AWJ nozzle is shown in Figure 3.12.

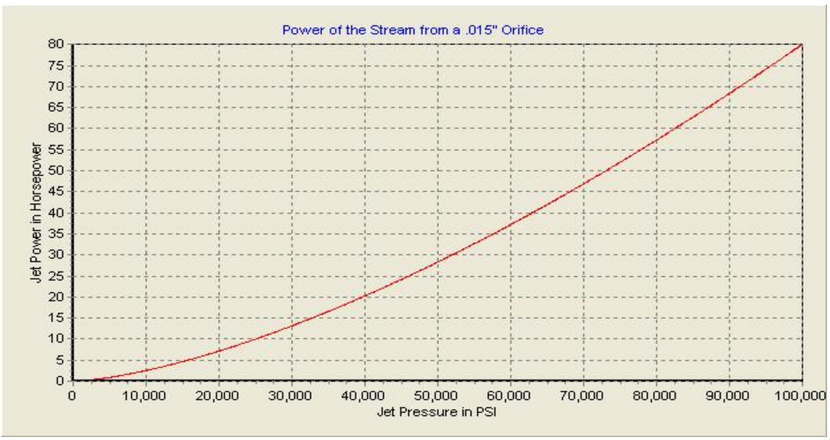


Figure 3.11Increasing operating pressure requires increasing pumping power [40]

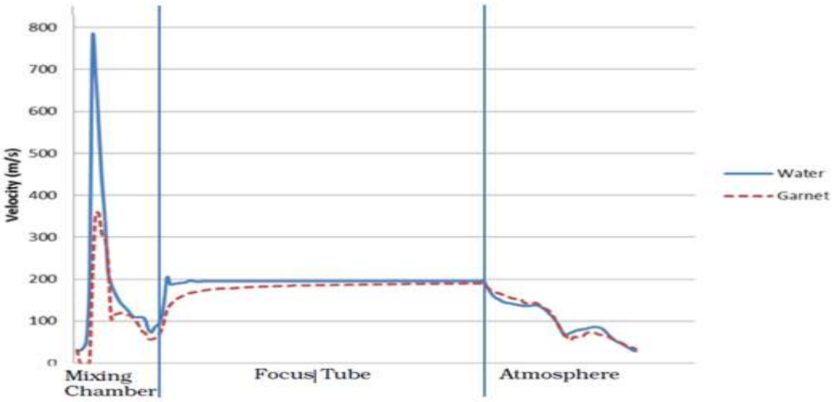


Figure 3.12Velocity profile AWJ nozzle [40]

Now if a force can push on the piston with a constant value, keeping the pressure value constant, and increase the diameter of orifice to let the more quantity of water flow through. The increased flow rate is also increasing the jet power.The variation of jet power at (366.6MP) for various jet diameters is shown in Figure 3.13.

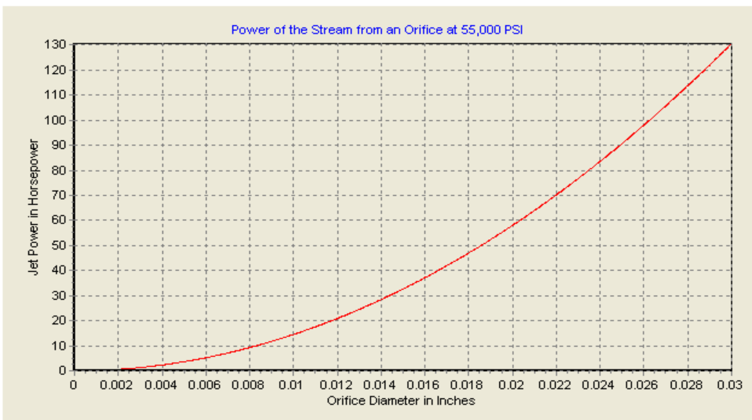
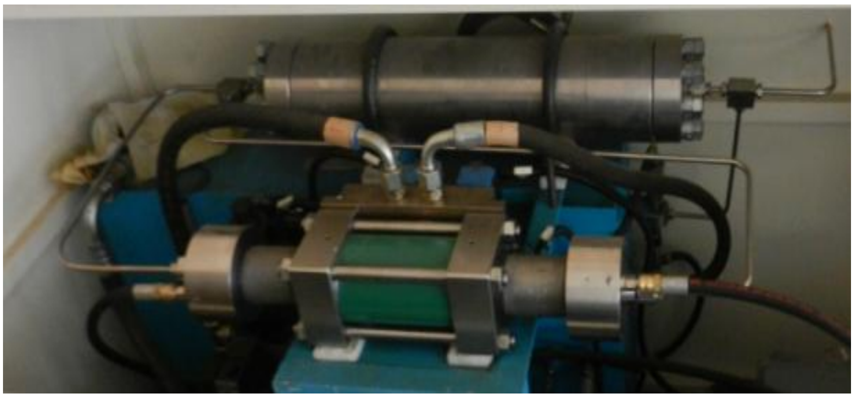


Figure 3.13 Larger-diameter jets operating require increased pumping power[40]

3.6.3 Intensifier

The intensifier is important equipment inpressure unit that used to increase the pressure of water around 6000 bars. The hydraulic pressure is applied to the first step that is low-cylinder of the intensifier, and then the pressure is developed into the high pressure cylinder.Figure3.14 illustrates the main parts of the intensifier. It consists of two units, the first one is the small cylinders for water and the other one is the large central cylinder which dealing with oil.



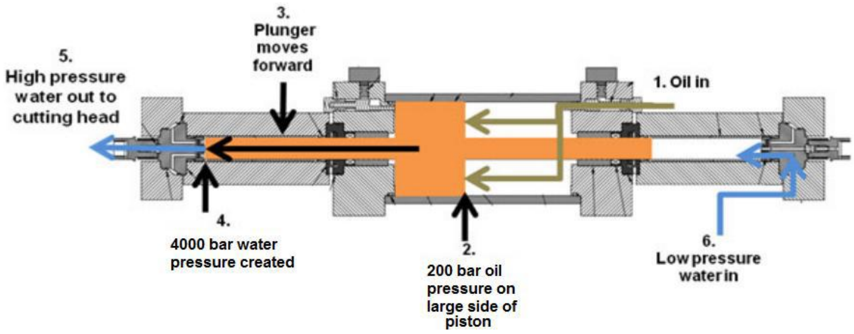


Figure 3.14High pressure processing into the intensifier[47]

Determination of the pressure increasing in intensifier is dependent on the ratio of the working pressure areas for two cylinders. The following equations explain the relationships between pressure and area [19].

$P_h . A_p = P_w . A_w$ (3.3)

$P_w = (A_p / A_w) .P_h$ (3.4)

$P_w = P_h . A_{ratio}$ (3.5)

whereP_hA nd$P_w$are the pressures of hydraulic and the water pressure, A_p; is the cross sectional area of the piston and Aw; is the cross sectional area of the plunger respectively. For example; If the area ratio is 30, and hydraulic pressure is set to 200 bar, water pressure is found at P_w = 30 x 200 = 6000 bar.

3.6.4 The Plumbing

In abrasive water jet system there are two liquid plumbing units: one connects the water flow from a sink to the water inlet of the pressure pump, and the other one connects the flow of high pressure water from the outlet water to the pressure pump to the cutting head. The first plumbing, process from the sink to the water inlet on the pressure pump consists of piping (pipe fittings), water tubing, and a single 5-micron water filter. Generally, a filter used to ensure that the quantity of water has to be particular-free before entering the pumping unit to protect the pump seals from any damage or abrasion. The second plumping travel from the water oulet of the pressure pump to the cutting head consist of several fittings, a pressure transducer, an analog pressure gage, a pneumatically-actuated ball valve, a arupture disc assembly, and high-pressure flexible housing.

3.6.4.1 High-pressure Plumbing

High-pressure parts always are connected together with tubing. Properly preparing and connecting ultra high pressure tubing is critical in maintaining a safer and leak-free high-pressure system. High pressure tubing is shown in Figure 3.15

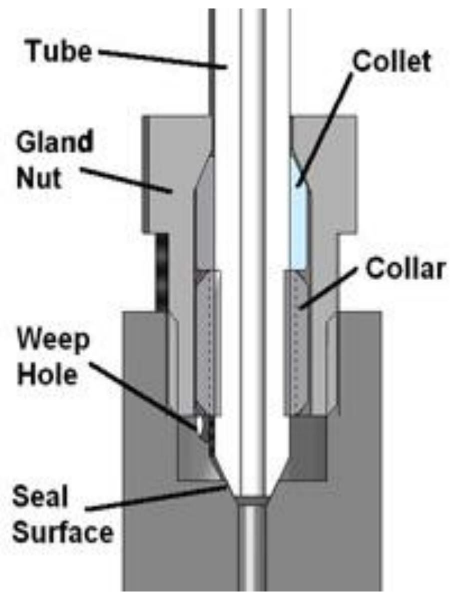


Figure 3.15High pressure tubing fitting [40].

3.6.5 Cutting Head Assembly

Cutting head, it is the last equipment of the water jet system which the high pressure water stream passes through it before impacting the work piece. It includes five sections these are; Water inlet section, orifice, abrasive inlet section, mixing chamber, and nozzle. Generally inside the cutting head the pressurized water flow passes through a small-diameter circular orifice due to coherent jet of water. And then the jet passes through a venture section, at the same time of a metered amount of abrasive material particles is drawn into the water stream. The mixture of water with abrasive particles passes through a special material (ceramic) mixing tube to result a mixture of abrasive/water slurry exits the nozzle as a coherent cutting tool stream of abrasive particles travelling with very high speed. Figure 3.16 shows the mixing process into the cutting head.

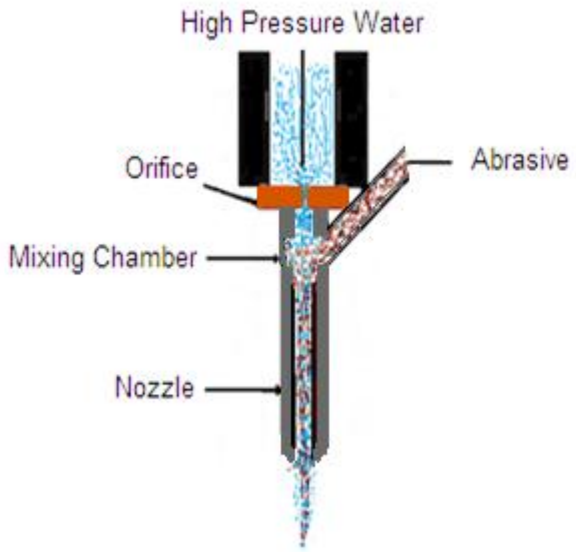


Figure 3.16cuttinghead assembly

3.6.5.1 Water Inlet

In cutting head design the water inlet is the section that delivers the high pressure water from the pumping unit. The critical aspect of the water inlet section is assuring that there is a completely tight, secure connection between the cutting head and the housing. Once the water stream flow passed through this point, it is fully within the self-contained unit of the body of cutting head, where bursts leaks are a thin and lesser concern.Figure 3.17 shows the section of water inlet.

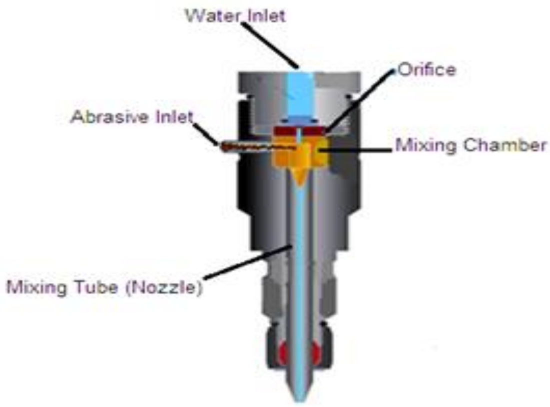


Figure 3.17Sections of cutting head

3.6.5.2 Abrasive Inlet

The section of abrasive inlet accepts a (19.05mm) or 3/8”outside-diameter hose tubing from the abrasive material hopper. This hose is pressed-fitted into the abrasive inlet asshown in figure 3.17

3.6.5.3 The Orifice

Orifice, the part which is a component essentially just an extremely special hard material with a small diameter hole through it, in fact the orifice is the most important part of the cutting head. It is the part which responsible for converting a high pressure water into high velocity water. Typically, industrial water jet system operators for different hard material like a diamond orifice, which has a resistance and life working of around 1000 hours. A kind of orifice, Ruby orifices are considerably cheaper cost, but are rated may be only for 40 working hours. Since this water jet system operates at only for lower pressures than those found in design, the cutting head uses a ruby orifice kind. Figure 3.18 shows different forms of orifice.

Figure 3.18Different kinds of orifices

3.6.5.4 The Mixing Chamber

The mixing chamber section is admitted water from the outlet of the small orifice hole and garnet particles from the abrasive inlet, allowing the garnet particles to be thoroughly mixed (with water particles) before exiting to the next position of the cutting head. Since the abrasive particles inlet is downstream of the orifice, the garnet does not effect or damage the orifice upon as shown in Figure 3.17.

3.6.5.5 The Nozzle

Nozzle is the last component of the cutting head, it is generally made of steel, composite carbide with special tungsten carbide. The nozzle serves to focus the water abrasive particle mixture that leaves the mixing chamber. Typically, nozzle diameters are selected with a ratio of 3:1 to the orifice diameter. Figure 3.19 shows the focusing tube (nozzle)

Figure 3.19Focusing tube (Nozzle)

3.6.6. X-Y Traverse System (Gantry)

The cutting head in the water jet system is attached to a custom designed and manufactured two-axis CNC gantry as shown in Figure 3.20 This design allows the water jet to cut out any arbitrary planar geometry within its work area.

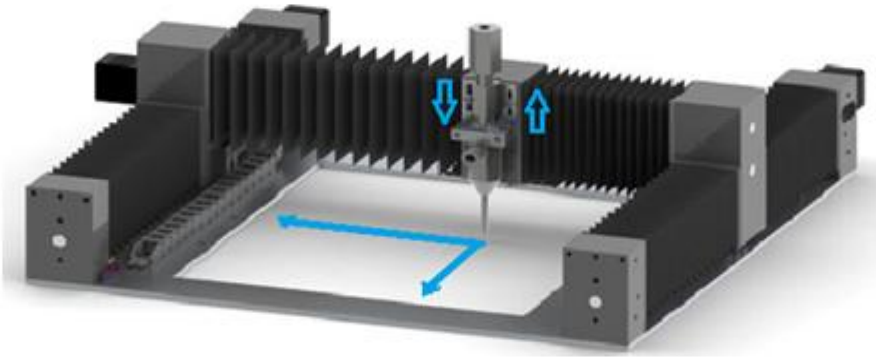


Figure 3.20The X-Y traverse system (Gantry)

3.6.7 Catcher Tank

The water-filled catcher tank serves to dissipate the high energy of the abrasive jet after the cutting process through the material being machined. It is also useful to reduce the noise which associated the process of the jet after it passes through the target material. The catcher tank has deep enough for water jet to break up and dissipate its energy before reaching the bottom to cause any damage. Figure 3.21 shows the structure of catcher tank.

Figure 3.21The structure of catcher tank

3.6.8 Abrasive Hopper

The abrasive hopper and associated abrasive flow control system provide a metered flow of granular abrasive to the nozzle. Figure 3.22shows a structure of the abrasive material hopper.

Figure 3.22Structure of abrasive material hopper

3.6.9 PC-Based Controller

In abrasive water jet machine the advanced motion controllers for this technique is PC-based and permit the production of completely accurate parts with minimal operator experience. It is shown in Figure 3.23

Figure 3.23Abrasive water jet PC controller

3.7 The Abrasive Material

Abrasives material which is used in abrasive water jet systems are generally made of natural crashed rocks or sands like garnet, olivine, and aluminum oxides, etc. The garnet material is the most widely used natural sand inthe abrasive water jet system.The water jet system industry standard is 80 mesh grain size garnets, denoting abrasive particles sized between 150 and 300 microns, which is more appropriate for 0.010 to 0.014 mm orifice. Another option of grain size is a finer 120 mesh garnet, consisting of100-200 micron particles and used for 0.007-0.10 orifice etc.the abrasive material is stored in the hopper, it is a large funnel above the water jet machine, the important is to be above of the cutting head, and flows into its head under gravity. There is a kind of brass valve between the end of the hopper and abrasive inlet in the cutting head to control the abrasive flow.

The abrasive material need for grinding operation to take a form of sharp edged, irregularly shaped. This geometry results better performance with high penetration effect. Some typical abrasive materials are shown in Figure 3.24

Figure 3.24different types ofabrasive materialparticles

The benefits of garnets can be summarized as follows;

- High hardness. Garnet abrasive material will last a long time, making it a very good cost effective abrasive.
- The garnet material can be recycled a number of times; depending on the grit size (generally it can obtain recycle garnet two times, perhaps more when starting use with a coarse grade).
- The garnet abrasive material is safe and non toxic with very low free silica levels (generally it is less than 1%).
- Low Dusting. Garnet considers as a fast and clean blast media.

Technical data and physical characteristics for garnet abrasive are given in Table 3.2, Table 3.3, Table 3.4, and table 3.5 respectively.

Table 3.2 Average chemical composition (wt %)of garnet

SiO2	38%
Al2O3	22%
Fe2O3	30%
TiO2	1%
MnO	1%
CaO	1%
MgO	7%

Table 3.3 The physical characteristics of garnet

Bulk density	131-137 lbs/ft³
Specific Gravity	4.1
Hardness (Mohs)	7.50
Melting Point	1,250°C
Particle Shape	Sub-rounded to sub-angular
Reactivity	Inert

Table 3.4 Mineral composition (Typical) of garnet

Garnet (Almandite)	+98-99%
Limonite	<0.8%
Zircon	<0.2%
Quartz	<0.5%
Others	<0.2%

Table 3.5 Other characteristics of garnet

Conductivity	0-15ms/m (max 25 ms/m)
Radioactivity	Not detectable above background
Moisture Absorption	Non-hydroscopic
Total Chlorides	10-15 ppm (max 25 ppm)
Free Iron	Less than 0.01%
Copper	Less than 0.01%
Other Heavy Metals	Less than 0.01%

CHAPTER 4

TURNING PROCESS WITH AWJ MACHINE

4.1 Introduction

In this chapter, turning operation with abrasive water jet machine is discussed. General considerations of abrasive water jet turning process are presented in section 4.2. The theory of abrasive water jet turning processes is given in section 4.3. Kerf geometry in abrasive water jet turning and themechanism of material removal in abrasive water jet turning are given in section 4.4 and 4.5 respectively. The section 4.6 includes the design andconstructing of abrasive water jet construction of the turning system.

4.2 General considerations

Abrasive water jet turning is a new machining method that holds promise for efficient processing of difficult to machine materials. In abrasive water jet turning process the configuration of turning is similar to the conventional lathe, except that an abrasive water jet is used as a cutting tool. The impact of high velocity abrasive particles with a rotating surface of work pieces causes material removal, which generally be classified as erosive wear. Abrasives strike this surface at approximately one million collisions per second on limited area of the rotating work piece, thus transferring a huge amount of kinetic energy to that limit work material [37].

As mentioned above, in the abrasive water jet process use the stream jet as a cutting tool that deflects from its path progress upon interaction with the work piece. Therefore, the value of the final work piece diameter, in addition to depth of cut, is considered a function of abrasive water jet, work piece and turning parameters.

4.3 Theoryof AWJ Turning Erosion

The abrasivewater jet technique works by forcing a large volume of water with abrasive particles through a small orifice in the nozzle. The first purpose of the abrasive material within the water jet stream is to develop enough force to erode particles of the rotating work piece material. That does when the jet of water accelerates the abrasive material to a high speed so that the kinetic energy of the abrasive water is high enough to perform an erosion process to the work piece material. The secondary purpose of the water jet is to carry away both the abrasive particle's material and the eroded particles of work piece material from the machining zone then to clear the work area. Abrasive water jet machining gives a clean cut without any damage of the cut surface [51].

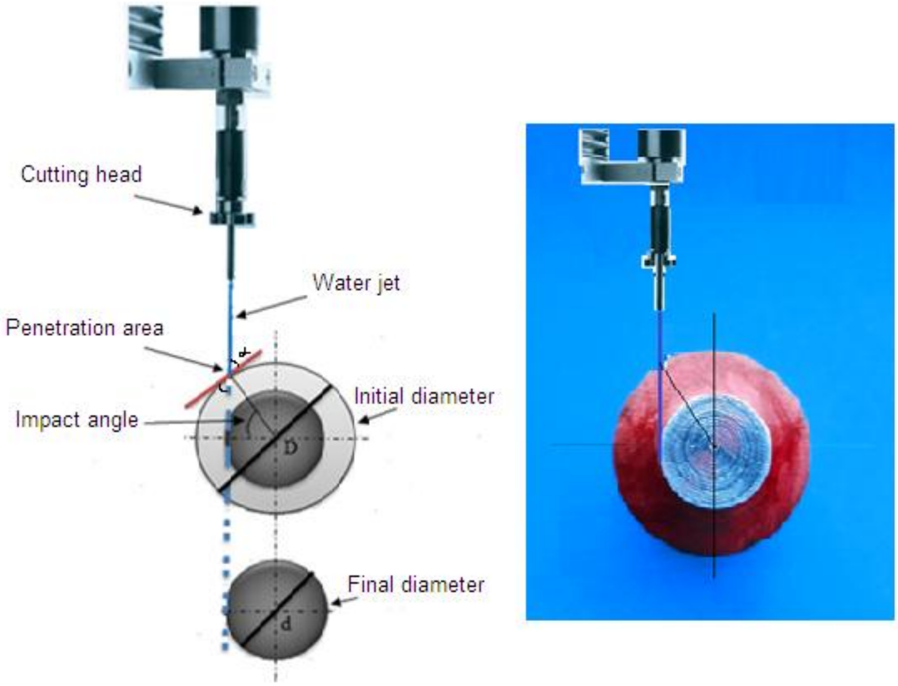


Figure 4.1impact angle and penetration area in AWJ turning

In abrasive water jet turning process the extreme high pressure of the accelerated abrasive water particle contacts a small area of the rotating work piece with a specific value of impacting angle results a penetration process as shown inFigure 4.1. In this penetration area small cracks are developed of the work piece due to stream impacts. The material is removed from the surface of the rotating work piece and assumed that the total depth of cut consists of cutting-wear depth and deformation-wear depth. [37].

The model assumes a hard particle with high velocity Va impacting a surface of work piece at an angle α. The material of the surface is assumed to be a rigid plastic one. The final expression and boundary conditions for the volume of material removed from the work piece due to the impact of a single particle can be obtained from;[49]

$$Q = \frac{m\,v^2}{\psi p k}[\mathrm{Sin}(2\alpha) - \frac{6}{k}6\,sin^2(\alpha)], \qquad \tan\alpha \leq \frac{k}{6} \tag{4.1}$$

Where α is the impact angle, k is the ratio of vertical to horizontal force components, and ψ is the ratio of the depth of contact l to the depth of the cut y_t as shown in Figure 4.2 , p is the flow stress of the eroded work piece material and Q is the total volume of target material removed.

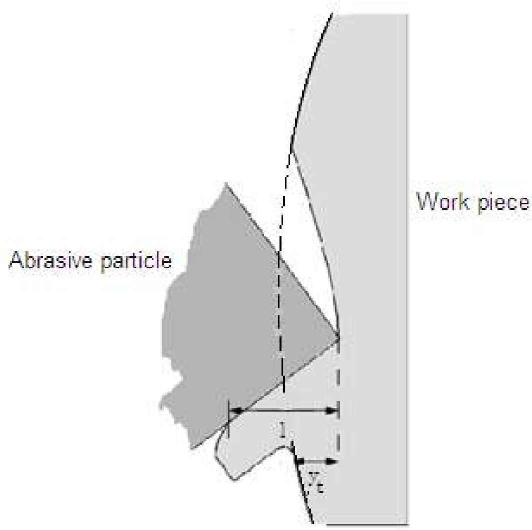


Figure 4.2 Depth of cut and depth of contact

4.4 Kerf Geometryin AWJ Turning

With AWJ turningin order to estimate the amount of material removed, Manu and Babu [38] assumed the kerf geometry to be rectangular. Analysis of the kerf profile showed that this is not completely true. Since the geometry of kerf in abrasive water jet turning depends on the main turning process parameters such as jet traverse rate, water pressure, abrasive mass flow rate, for right profile kerf it is essential to consider all these turning parameters for developing logical relations for predicting the AWJ turning kerf geometry.

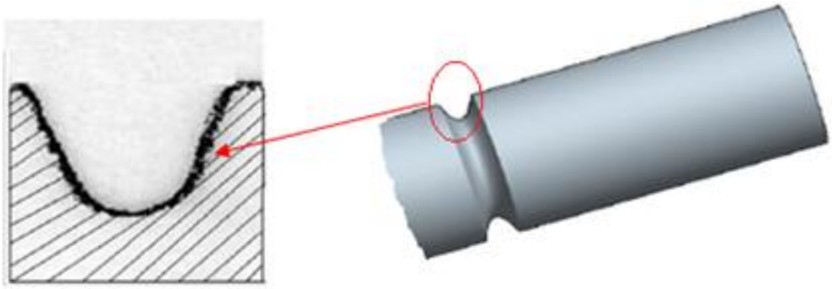


Figure 4.3 Schematicdiagram ofkerfformation in AWJ turning

4.5 Mechanismof Material Removalin AWJ Turning

In abrasive water jet turning,the water jet with a velocity of vstrikes the surface of the rotating work piecewith an initial diameter of diat a speed of N revolutions per minute.The erosion is started and the material removal takes place on the circumference of the rotating work piece [1]. The materialremoval is extended by axial travelling of the jet. The distance between the jet centerline and the specimen centerline is termed as the radial position of jet and is denoted by x. The angle α is the local impact angle that the jet makes with the tangent of the surface at the point of impact, as shown in Figure 4.4 where, α can be computed as:

$$\alpha = \cos^{-1} = \left(\frac{2x}{di}\right) \qquad (4.2)$$

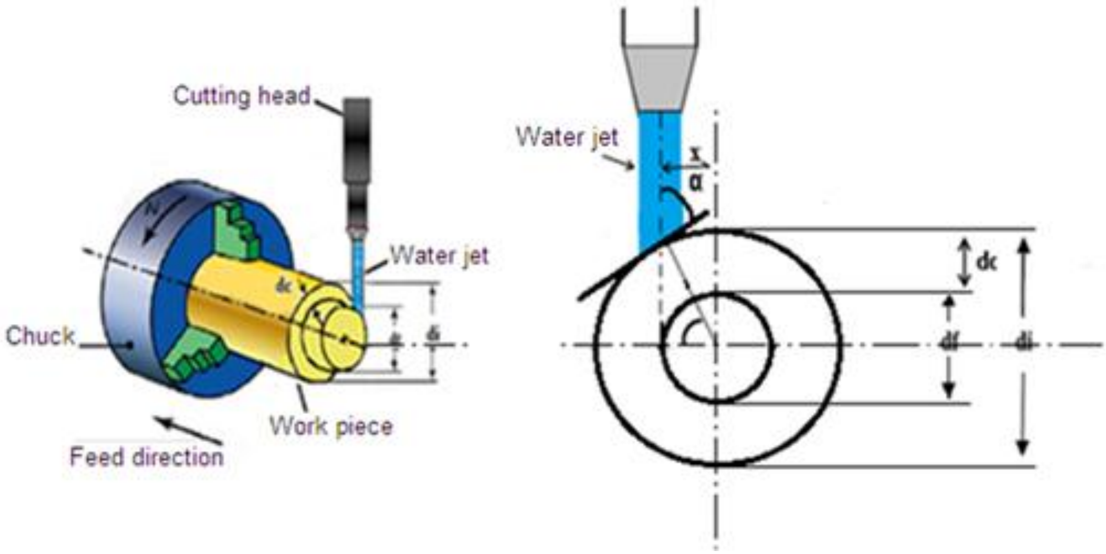


Figure 4.4Mechanism of material removal in AWJ turning

Local impact angle is continuously changing due to change in work piece diameter; on the other hand the final diameter depends on the value of impact angle. However, in abrasive water jet turning there is a range and limitation of the impact angle values and then the penetration point. Figure 4.5 explains the working area of turning process.The change of the work piece diameter depends on the impact angle (α) and the distance between the center line of jet and the center line of rotating work piece (x).

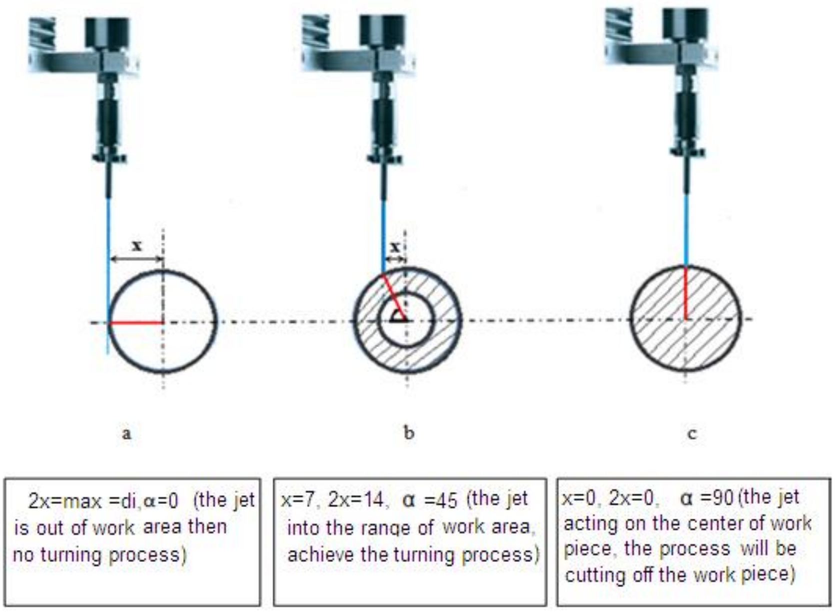


Figure 4.5

In abrasive water jet turning an important expression is to estimate the primary and most crucial output process parameters applying the input parameters. One of the critical input parameters related to the material removal rate is the depth of cut (dc), which reflects the diameter of the work-piece material to be removed. There are many complex mechanisms of material removal and a large quantity of particles involved in the machining produce a strongly stochastic and nonlinear behavior of the system [1]. The generated fine and high quality surface depends on work piece properties and various machining parameters. Because the abrasive water jet turning process is a dynamic system, the interactions of this system inputs (work piece properties and machining parameters) play an important role in machining. From the technical point of view, the most important machining parameters are the water jet pressure, jet feed rate, and the standoff. All these parameters and others like work piece rotating speed and the direction of rotating can be controlled during abrasive water jet turning machining. Other parameters, like work piece material properties, cutting head components, abrasive properties, geometry, are unchanged during the experimental work.

4.6 Turning System Coupled to AWJ Machine

The purpose here is to present the design and construction of turning system for turning process to be coupled with abrasive water jet machine available in the innovation center of the Mechanical Engineering Department.

4.6.1 Design and Constructionthe Turning System

Turning system is actually a simple lathe which consists of main drive unit and the frame which carries the main drive unit. Its schematicall view is shown in Figure 6.4.Design of this unit is governed by dimensional requirement and strength and deflection requirements. Since it is to be coupled to the available AWJ machine its height is determined from the height of the machine. The elements must have adequate strength, and deflection at the tip point of the chuck must be considerably small since it will adversely affect the surface quality of the work piece. The first step of turning unit design is to study and examine the dimensions of the abrasive water jet cutting machine in order to have an idea about the overall size of this unit. Figure 4.6 shows the dimensions of the abrasive water jet cutting machine.

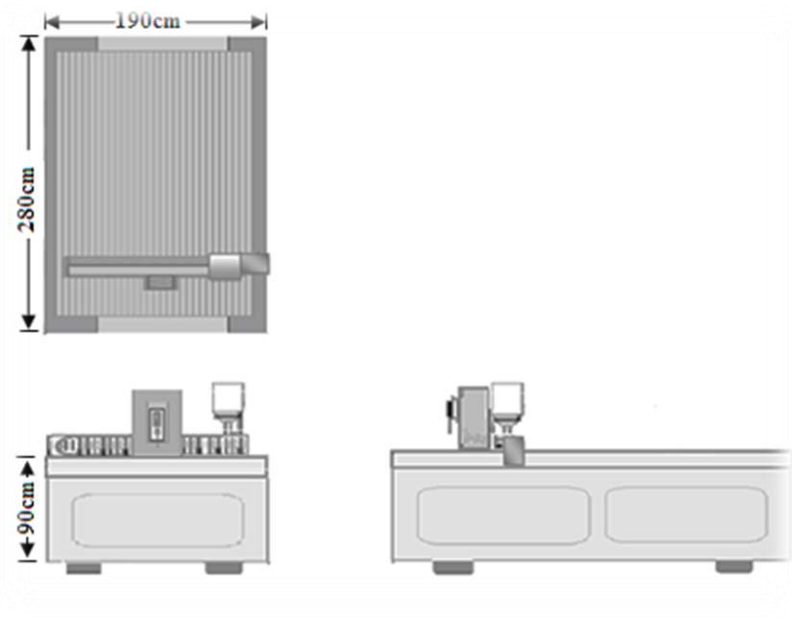


Figure 4.6 Maindimensions of AWJ cutting machine

Turning system is considered to consist of a spindle unit, a transmission unit and speed control unit. Spindle unit consist a chuck, a spindle shaft, and two bearings. The power transmission unit consists of pulleys, v- belts and an electric motor. Control unit includes of main power switch, and speed control (inverter). And the last unit is the supporting unit, it is a frame made from steel profile with rectangular cross section. It is designed to carry spindle unit,transmission unit and speedcontrol unit. Figure 4.7 shows the overall dimensions of the turning system.

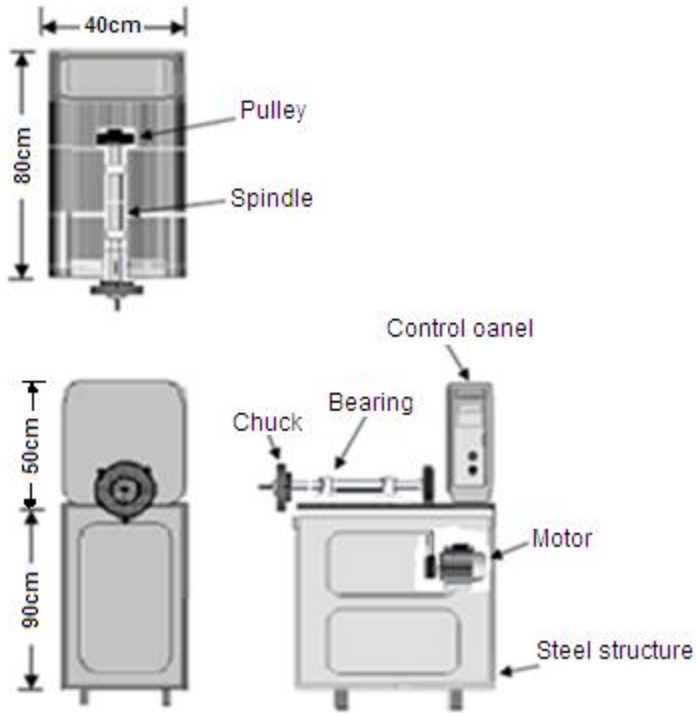


Figure 4.7 Turning system dimensions

All mechanical components (shafts, bearings, belts and pulleys) are designed based on the strength and stiffness considerations[43] Work piece is mounted on the chuck and is rotated at a specified speed. This speed can be adjusted by using the control unit. This setup is coupled with water jet cutting machine (NSJ-2040 (Nevtaşmaking), equipped with a dual intensifier system, with a maximum of 410 MPa output pressure made in Turkey for performing cylindrical turning operations. All AWJ turning experiments and measurements are conducted in Innovation Center in the Mechanical Engineering Department.

4.6.2 Design and /or Selection of Components in Spindle Unit

4.6.2.1 Spindle Shaft

Considering that the cutting force is negligibly small compared to the force developed from the weight of the chuck and from the pulley forces fitted over the stepped shaft may be schematically shown in Figure 4.8. The shaft rotates at 1000 rpm. Pulley at D has a diameter of 110 mm and 95 mm for the pulley of the motor. The chuck has outer diameter of 120 mm and 40 mm for inner diameter. The bearings are carrying the radial loads. The distance between the chuck at A and the bearing at B is 140 mm and the distance between the two bearings at B and C is 260 mm, and also the distance between the bearing at C and the pulley at D is 140 mm.

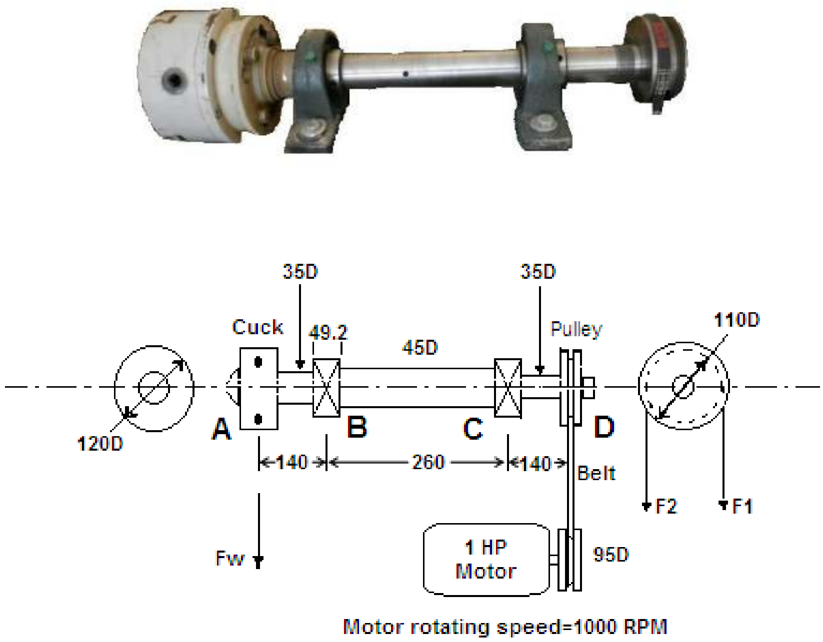


Figure 4.8Turning shaft with pulley and the chuck base

4.6.2.2 Bearings

Selection is to be based on the diameter of the spindle at the supporting point and life requirement. In the configuration given, only radial force exist at the supporting points of the spindle shafts. Therefore a single deep groove ball bearing designated as SKF UC 209 has been selected among other types.

Selected diameter of the shaft is 45mm therefore deep groove ball bearings with a bore diameter of 45mm will be suitable for the given application. As shown in Figure 4.9

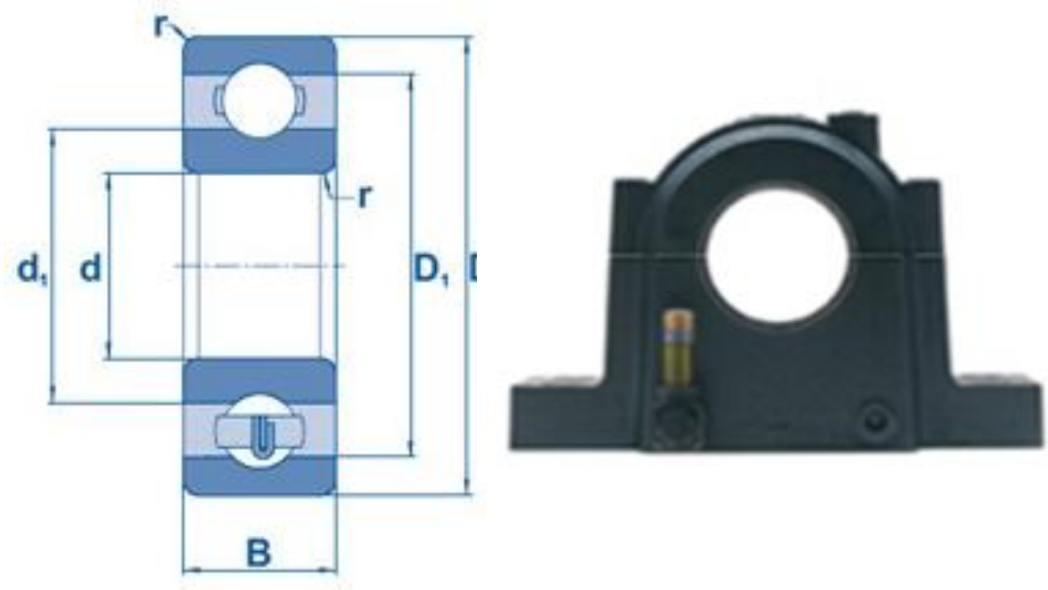


Figure 4.9deep groovebearing and its dimensions

4.6.2.3 Chuck

This part is a specialized type of clamp in which use to hold an object. It fixes the part to the spindle axis of the machine it has a diameter of 120 mm with a length of 90mm and 45 mm of bore diameter, three- jaw chuckwith jaws that are all driven by the same chuck key. The chuck is shown in Figure 4.10

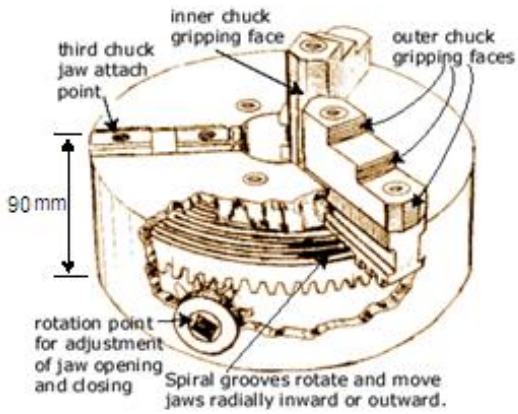


Figure 4.10turning chuck

4.6.3 Power Transmission Unit

4.6.3.1 Pulleys and belts

Pulleys and belts have two uses; to increase or reduce speed or torque, or to transfer power from one shaft to another. For the pulley,double groove V belt with diameter of110mm for the pulley of shaft and diameter of 95 mm for the pulley of motor has been selected as shown in Figure 4.11

Figure 4.11 Pulley selection

For the belt selection, V- Belts considered solved the slippage and alignment problem. It is now the basic belt for power transmission. In Figure 4.12 section of V beltexplains the design and main dimensions of the cross section, V belts has been selected because it provide the best combination of traction, speed of movement, load on the bearings, and long service life. Section 3L is selected for this application .

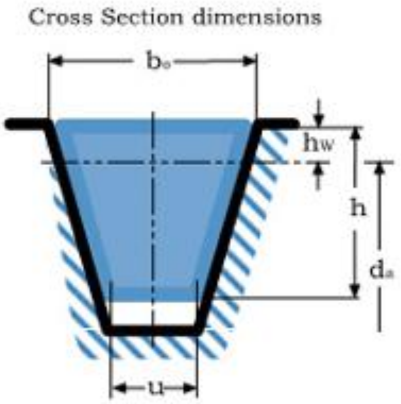


Figure 4.12 V- belts selection

4.6.4AC Electric Motor and speedcontrol unit

Thealternating current (AC) motors can be classified into two main groups namely: single phase and three phase.Single phase motors are used in most of theapplications.Cutting force is small therefore a single phase with power of 1 Hp and 1500 rpm AC motor has been selected and shown in Figure 4.13.

Figure 4.13AC electricmotor

The control unit consists of an inverter (speed controller) with a power of 0.75 KW, input of 200-230 V, 9.2 Asingle phase, and anoutput of 0.1 input V, 5 Athree phase. Also, it includes a main power switch, selector switch and an alarm light as shown in Figure 4.14.

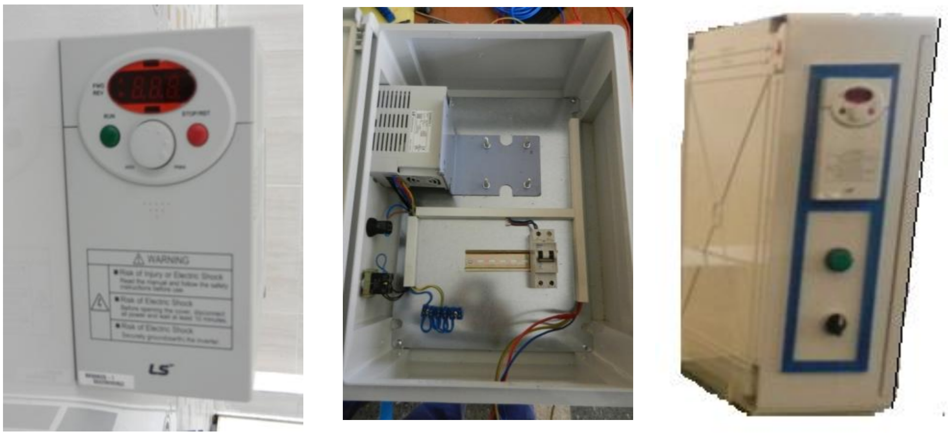


Figure 4.14 Control panel

4.6.5 Supporting Unit

Supporting unit is the frame made from rectangular tube of structural carbon steel. Rectangular carbon steel tube has good properties such as easy to cut, bend, weld, and drill, paint or powder coat, therefore a hollow section of D=80 mm, B=40, and thickness of 3.2 mm has been selected to carry both spindle unit and control unit as shown in Figure 4.15.Table 4.3 shows the dimensions and main mechanical properties of rectangular hollow section, the main stages of frame construction including the steel cutting, welding, combining, painting, coupling, and the finished form are illustrated in Figure 4.16. Operation of turning system and the products obtained are illustrated in Figure 4.17.

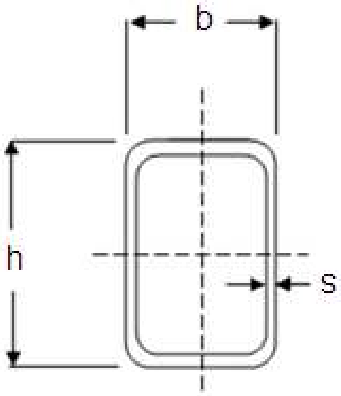


Figure 4.15 Rectangular carbon steel tube section

Table 4.3 Rectangular hollow section carbon steel properties

Outside dimensions b x h mm	W.T. s mm	Linear mass Kg/m	Moment of inertia of bending Ix cm^4	Moment of inertia of bending Iy cm^4	Radius of inertia ix cm	Radius of inertia iy cm	Section modulus Wx cm^3	Section modulus Wy cm^3	Modulu of torsion C cm^3
80 x 40	**3,2**	5,62	7,16	18,90	2,830	1,630	14,30	9,46	16,10
	4,0	6,90	8,79	22,20	2,790	1,590	17,10	11,10	18,90
	5,0	8,42	10,70	25,70	2,740	1,550	20,10	12,90	21,90
	6,3	10,30	13,10	29,20	2,670	1,490	23,30	14,60	24,80
	7,1	11,40	14,50	30,70	2,630	1,460	25,00	15,40	26,20
	8,0	12,50	16,00	32,10	2,580	1,420	26,50	16,10	27,40
	8,8	13,50	17,20	33,00	2,530	1,380	27,60	16,50	28,20
	10,0	14,90	18,90	33,70	2,470	1,330	28,80	16,90	28,90
	12,5	17,30	22,10	33,60	2,320	1,230	29,80	16,80	28,70

Figure 4.16Stages of construction of turning system

Figure 4.17Operation of the turning system and products obtained

CHAPTER 5

EXPERIMENTAL WORK

5.1 Introduction

In this chapter the experimental work has been presented and the effects of process parameters on surface roughness, material removal rate and final workpiece diameter are investigated. The material selected for work piece and properties of (Al 7075-T6) are given in section 5.2. Technical specification of abrasive water jet machine which coupled with turning system is included in section 5.3. Section 5.4 consists of the design of experiments including the tables of turning parameters setting and the layout of experimental design respectively. The surface roughness measurement with the profile roughness parameters are given in section 5.5. Section 5.6 includes the material removal measurement and the calculation of material removal rate. The design of the experimental procedure is given in section 5.7. The section 5.8 is devoted to the experimental results and discussion, including the experimental results of process parameters on material removal rate and surface roughness respectively.

5.2 Material Selection

The aluminum alloy (Al 7075-T6) is selected as the work piece material, it has low density, high strength to weight ratio, toughness, ductility, resistance to fatigue, and offers improved stress-corrosion cracking resistance [44].

This material used in a wide range of applications such as; Aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defense applications; bike frames, all terrain vehicle. Material is provided by ALTEK METAL inTurkey, three different diameters of 20mm, 25mm, and 30mm.The chemical properties and mechanical composition of Al(7075-T6) are given in Table5.1 and Table 5.2 respectively.

Table 5.1 ChemicalProperties of Aluminum Alloy 7075-T6 [50]

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
89.57	0.07	0.16	1.60	0.06	2.50	0.20	5.80	0.04

Table 5.2Mechanical Properties of Aluminum Alloy 7075-T6 [50]

Material	Temper	UTS (MPa)	Elongation%	0.2 %proof
Al 7075	T651	593	13	521

5.3 AWJ Cutting Machine Coupled with Turning Sys

The cutting process of specimens and all the turning experiments were conducted in the Innovation Centre of the Mechanical Engineering Department. As an abrasive water jet cutting machine, NSJ-2040 (NevtaşMakine – Figure 5.1), equipped with a dual intensifier with 410 MPa of maximum output pressure, made in Turkey has been used. The specifications of this machine are given in Table 5.3.

Figure 5.1 NSJ-2040 (NevtaşMakine)

Table 5.3 Technical properties of AWJ machine [45]

Technical Properties of AWJ model; NSJ-2040 (NevtaşMakine)	
Machine Dimensions	2000x4000x1650 mm
Cutting Area	1600x3000 mm
Z stroke	180 mm
Axis Speeds	15 m/min
Mini Abrasive Tank	50 kg
Weight (without water)	4000 kg
Pump Power	50 HP
Maximum Pressure	4100 bars
Noise Level	<85 db
Weight	750 kg
CNC control unit	ECS
Motion controller	PMAC2 104
Software	NC 400 G-Code
Operating system	MS Windows CE.net

As abrasive material, type of garnet sand, it is provided from Supreme Garnet (the Indian brand) with One mesh size stocks, 80 mesh (grain size is 150-200 µm) has been used. The Physical characteristics and mineralogical composition of the garnet are given in Table 5.4

Table 5.4 Physical characteristics and mineralogical composition of garnet [50]

Specific Weight	**4.1 g/cm3**
Average Bulk	2.4 g/cm3
Hardness	8 (Mohs Scale)
Garnet (Almandite)	97-98%
Ilmenite	1-2%
Quartz	½%
Others	½%

The turning system which was explained in Chapter 4 is coupled to the abrasive water machine as shown in Figure 5.2.The Specificationsof the turningunit which designed and constructed aregiven in Table 5.5

Table 5.5 Technical properties of turning system

Machine Dimensions /cm	**80*40*142**
Motor Power	**1 HP/ 870kw/1480 rpm**
Max. Rotation speed	**2000rpm**
Chuck Diameter	**120mm**
Spindle diameter	**45mm**
Operation system	**Control panel with two direction inventor**
Weight/kg	**230**

Figure 5.2 AWJ machine coupled with the turning system

5.4 Design of Experiments

As mentioned in previous chapters, abrasive water jet turning process involves a large number of variables. Traverse speed, water pressure and the standoff distance are the three factors considered in most of previous studies. In this study, the standoff distance is kept constant and the water jet impact distance is added as another factor to the turning process parameters. During the experiments machine parameters were kept at their standard values: the diameter of the nozzle is 1.02mm, the orifice diameter is 0.33mm, the length of the mixing chamber is 76mm, the level of abrasive flow rate is approximately (0.3kg/min),and the standoff distance is adjusted to 5 mm in all experiments.

Prior to perform the experiments, we had to decide on the direction of rotating (c.w or c.c.w) of the work piece. For this purpose, two trials are made under the same cutting condition and surface quality is observed for both clockwise and counter clockwise rotations. As shown in Figure 5.3 rotation against the flow direction (c.c.w) results better surface finish than rotation is in CW direction.

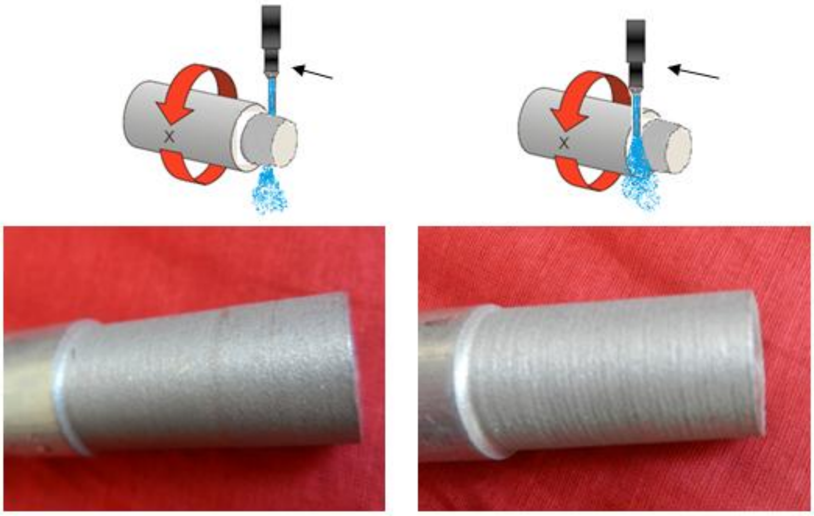


Figure 5.3 opposite and direct direction cutting

The work piece rotational speed to be applied in all experiments is another factor to be determined. A series of experiments were performed. The levels of selected turning process parameters were identified with respect tothe AWJ turning machine specification.The levels of water jet pressure have been determined according to specifications and the capacity of the pumping and hydraulic unit in the system. Therefore, water jet pressure values were decided as 2000, 2500 and 3000 bar. The impact distance levels are determined after going through a series of experiments. It is found that large values of impact distance have the worst effects impact on the surface quality. Then, 1mm, 2mm, and 3mm are the three values of impact distance selected. For nozzle feed rate the values of 2mm, 6mm, and 10 mm per minute has been selected, and the diameter of workpiecewas selected as 20mm, 25mm, and 30mm.The three levels with the four settings of turning process parameters are given in Table 5.6.

Table 5.6 AWJ turning parameters setting in experiments

AWJ turning parameters	Level1	Level 2	Level 3
Waterjet pressure, p (Kbar)	2	2.5	3.0
Waterjet impact distance, e (mm)	1	2	3
Feed rate, f (mm/min)	2	6	10
Work piece diameter, di (mm)	20	25	30

Full set of experiments designed using the full factorial method and totally$(3)^4$, number of 81 experiments were conducted to study the relation between the turning process parameters and their effects on surface quality material removal rate and final diameter. Layout of the experiments is given in Table 5.7

Table5.7Layout of experimental design

No	di	F	p	e	No	di	F	p	e	No	di	f	p	e
1	20	2	2000	1	**28**	25	2	2000	1	**55**	30	2	2000	1
2	20	6	2000	1	**29**	25	6	2000	1	**56**	30	6	2000	1
3	20	10	2000	1	**30**	25	10	2000	1	**57**	30	10	2000	1
4	20	2	2500	1	**31**	25	2	2500	1	**58**	30	2	2500	1
5	20	6	2500	1	**32**	25	6	2500	1	**59**	30	6	2500	1
6	20	10	2500	1	**33**	25	10	2500	1	**60**	30	10	2500	1
7	20	2	3000	1	**34**	25	2	3000	1	**61**	30	2	3000	1
8	20	6	3000	1	**35**	25	6	3000	1	**62**	30	6	3000	1
9	20	10	3000	1	**36**	25	10	3000	1	**63**	30	10	3000	1
10	20	2	2000	2	**37**	25	2	2000	2	**64**	30	2	2000	2
11	20	6	2000	2	**38**	25	6	2000	2	**65**	30	6	2000	2
12	20	10	2000	2	**39**	25	10	2000	2	**66**	30	10	2000	2
13	20	2	2500	2	**40**	25	2	2500	2	**67**	30	2	2500	2
14	20	6	2500	2	**41**	25	6	2500	2	**68**	30	6	2500	2
15	20	10	2500	2	**42**	25	10	2500	2	**69**	30	10	2500	2
16	20	2	3000	2	**43**	25	2	3000	2	**70**	30	2	3000	2
17	20	6	3000	2	**44**	25	6	3000	2	**71**	30	6	3000	2
18	20	10	3000	2	**45**	25	10	3000	2	**72**	30	10	3000	2
19	20	2	2000	3	**46**	25	2	2000	3	**73**	30	2	2000	3
20	20	6	2000	3	**47**	25	6	2000	3	**74**	30	6	2000	3
21	20	10	2000	3	**48**	25	10	2000	3	**75**	30	10	2000	3
22	20	2	2500	3	**49**	25	2	2500	3	**76**	30	2	2500	3
23	20	6	2500	3	**50**	25	6	2500	3	**77**	30	6	2500	3
24	20	10	2500	3	**51**	25	10	2500	3	**78**	30	10	2500	3
25	20	2	3000	3	**52**	25	2	3000	3	**79**	30	2	3000	3
26	20	6	3000	3	**53**	25	6	3000	3	**80**	30	6	3000	3
27	20	10	3000	3	**54**	25	10	3000	3	**81**	30	10	3000	3

5.5 Surface Roughness Measurement

Surface roughness is quantified and measured by the vertical deviations of a real surface of its ideal form. If these values of deviations are large, the surface is rough; but if they are small that means the surface is placed.

5.5.1 Profile roughness parameters

A roughness value can be calculated on a profile (line), and on a surface (area). Both of two profile roughness parameter (Ra, Rq.) are more common. Also the area roughness parameters (Sa, Sq,) give more significant values. Each of the surface roughness parameters is calculated using a formula for describing the surface quality [54].In following a brief of some main surface roughness parameters;

- Roughness average (Ra):It is an arithmetic average of the absolute measurements of the surface roughness profile ordinates.

$$Ra = \frac{1}{l}\int_0^l z(x)dx \quad (5.1)$$

where

l Is the measuring length

- Root mean square roughness (Rq): it is defined as the root mean square average of the surface roughness profile. Figure 5.4.

$$Rq= \sqrt{\frac{1}{l}\int_0^l z^2(x)dx}(5.2)$$

z (x) = profiles ordinates of the roughness profile.

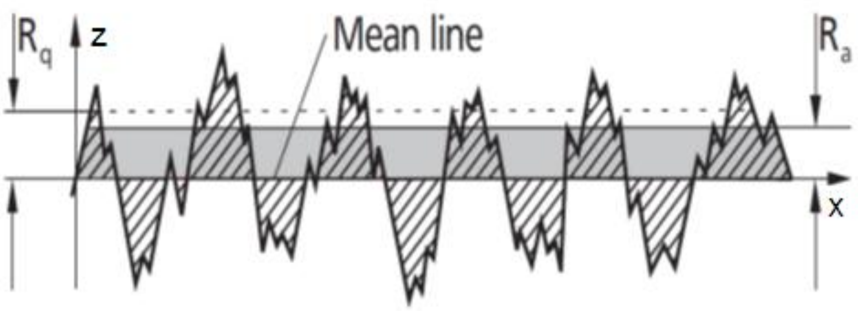


Figure 5.4 Representations of Ra and Rq [58]

- Single roughness depth (Rzi):It means the value of the vertical distance between the highest peak and the deepest valley within a sampling length.

- Mean roughness depth (R_z):It represents the arithmetic mean value of the single roughness depths (Rz_i) of consecutive sampling lengths.

$$R_z = \frac{1}{n} \left(R_{z1} + R_{z2} + \ldots\ldots\ldots.. R_{zn}\right) \qquad (5.3)$$

- Peak depth and peak height (R_v,R_p): $R_V$is the deepest profile and$R_{\boldsymbol{p}}$is the highest peak of the roughness profile within one sampling length. The sum of R_v and R_P is equal the single roughness depth (R_{zi}), as shown in Figure 5.5.werel_r is the sampling length.

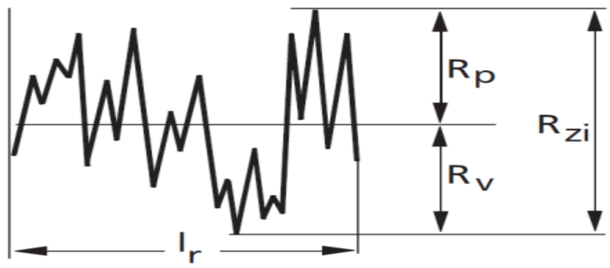


Figure 5.5Representations of R_p, R_vAndR_{zi} [58]

- Maximum roughness depth (Rmax):It represents the largest value of single roughness depth within the evolution length.

- Maximum height of the profile (Rt):It is the sum of the deepest RP and the highest Rv along the total length. Figure 5.6.

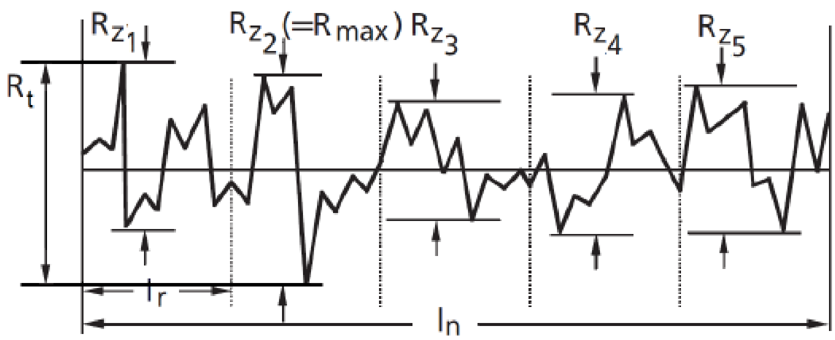


Figure 5.6Representations of Rz and Rmax [58]

The most common parameter used is the average roughness, Ra. It provides a simple value for accept or reject decisions. Add to that, there are many methods using for measuring surface roughness parameters such as profile tracing instruments, stylus type instruments, image processing, etc. In this research stylus type measuring method has been applied and Mahr stylus instrument (MarSurf XR 20 with GD 25) which is available in the department's laboratory was used.The main specifications of this instrument are listed in Table 5.8 below.

Table 5.8 Properties of instrument measuring and parameters

Software	**MarTalk®**
Drive Unit	GD 25
Probe	MFW-250: 1 (#6851855) -1.0%
Traversing Speed [Vt] (mm/sec)	0.5
Traversing Length [Lt] (mm)	17.5
Cut off length [λc] (mm)	2.5x5

Mahr stylus instrument (MarSurf XR 20 with GD 25) and the details of measuring are illustrated in Figure 5.7. The result of measurement is given in Figure 5.8.

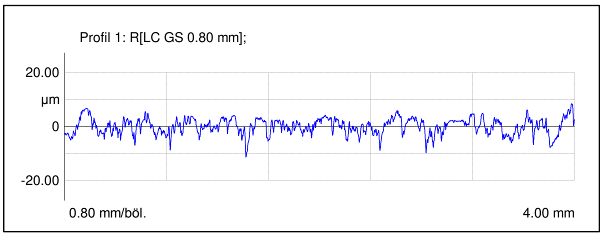
Figure 5.7 Mahr stylus instrument

Mahr	**MarWin** 3.06-07 SP 5	**Gaziantep Universitesi** **Makine Muhendisligi** Gaziantep / Turkiye	**21.12.2013 7** 05:17:01 İnceleyen:
Parça: **TEST 20.1**	Çizim n°: **1**	Çalıştırma işlemi:	İmza:

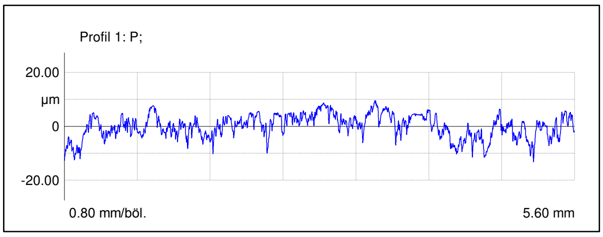
Yorum:

Ölçüm donanımıi:	MarTalk
Sürücü ünitesi:	DriveUnit.GD 25
Prob:	MFW-250:1 (#6851855) -1.0 %

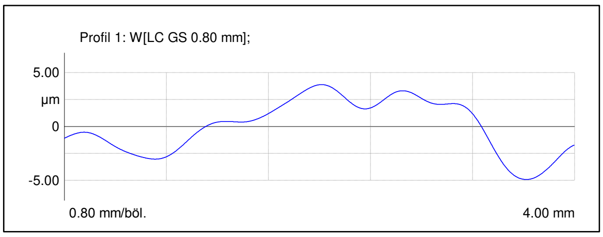
Lt:	5.599 mm
Ls:	2.50 µm
VB:	+/-250.0 µm
Vt:	0.500 mm/s
Noktalar:	11200



Ra	2,3686	µm
Rq	2,9409	µm
Rz	14,2661	µm
Rmax	16,1282	µm
Rt	19,7794	µm
Rp	5,8837	µm
Rpm	5,8837	µm
Rp(ASME)	8,3625	µm
Rv	8,3824	µm
R3z	10,3486	µm
R Sm	121,9355	µm
R S	53,5208	µm
R Sk	-0,315	
R Ku	3,188	
Rdq	0,364	
Rdc (10.00, 5.00)	-0,9652	µm



Pa	3,4459	µm
Pq	4,2734	µm
Pt	22,7450	µm
Pp	6,9964	µm
Pv	9,5294	µm



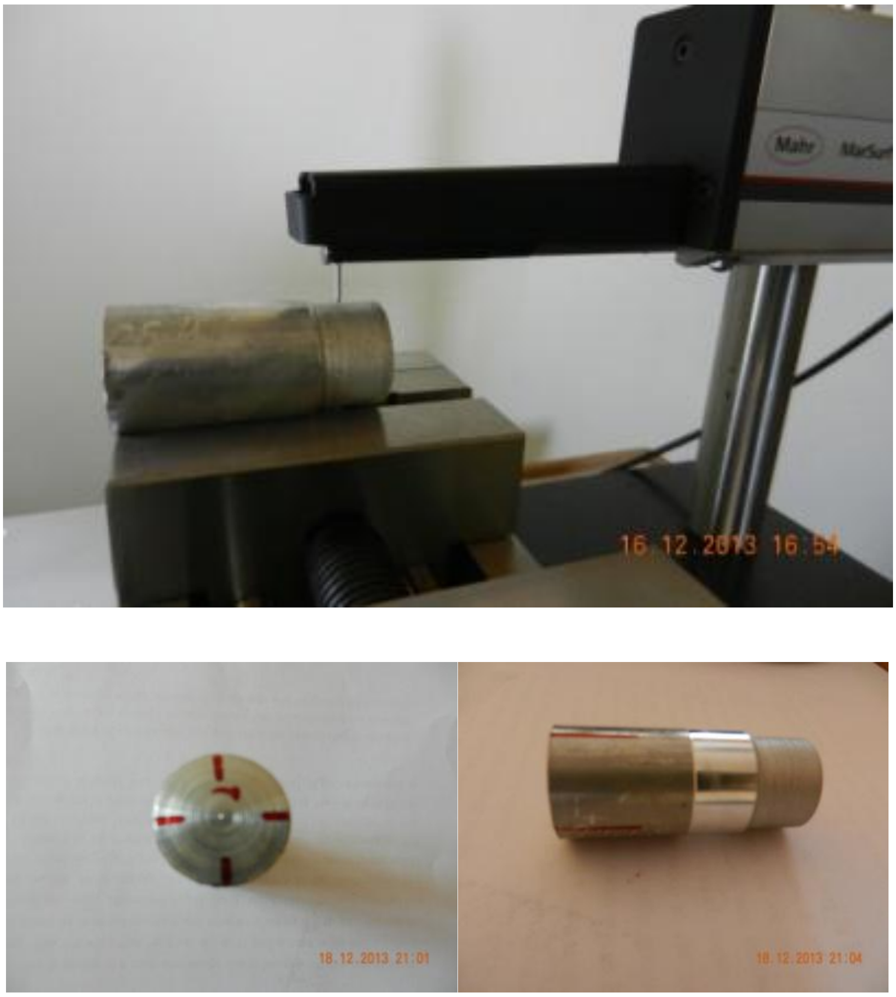
Wa	2,1748	µm
Wq	2,5036	µm
Wt	8,8103	µm
Wp	2,0208	µm
Wv	2,6347	µm
W Sm	-,----	
W Sk	-0,279	
W Ku	1,915	
Wdq	0,008	
Wdc (10.00, 5.00)	-0,3285	µm

C:\Mahr\Users\MDERE\QE\Cut off 5,6.qe *

Figure 5.8 Sample of surface roughness reading

Surface roughness (Ra) measurement has been designed for distance to cut with (5.6 mm) for each specimen. The average of four readings of each specimen considered as the final value of roughness for each specimen.By dividing the surface into four sections, surface roughness are measured at each section and their average is taken as the surface roughness at the specimen.

Figures (5.9) explain the determination of surface roughness of the specimen.Minitab Software - full factorial design of experiments was carried out in order to the final results of surface roughness values.



.Figures 5.9Experimental of 4 sections surface roughness measurement

5.6 Material RemovalMeasurement

There are three main important key mechanical inputs in material removal operations; feed rate, work piece rotational speed and depth of cut. Feed rate: is the rate at which the cutting head is moved along the length of the work piece. Feed can be measured in inches or millimeters per time period.Rotational speed; is the rate of rotation of the work piece. It is measured in revolutions per minute, rpm. Depth of Cut (dc): difference between the initial and final radii. It is usually measured in millimeters. Material removal rate (MRR).Andit is expressedin terms of feed rate, rotational speed and depth of cut.

MRR = Feed Rate * Width of Cut *Depth of Cut.

5.6.1 Material Removal Rate calculation

In turning operation there are many parameters to be calculated to determine the material removal rate (MRR). The relationship between cutting speed and rotational speed can be written as;

$N = \frac{v}{\pi * di}$(5.1)

where

v is the cutting speed (mm/min),and di, is the initial diameter (mm).

Cutting timetc is defined as the measure of actual time that nozzle is engaged in the cut.

$tc = \frac{L}{f}$(5.2)

where

tcis the cutting time / min. L is the length of cut (mm) and f is the machine feed rate (mm/min)

The Material removal rate is calculated as;

$MRR = \rho * \pi * \; dc = \left(\frac{di - df}{2}\right) * \; d_{avg} = \left(\frac{di + df}{2}\right) \; * f$ (5.3) where

ρ is the density,

di and df ; are the initial and final diameter respectively

And $dc = \left(\frac{di - df}{2}\right), d_{avg} = \left(\frac{di + df}{2}\right)$ (5.4)

dc is the depth of cut, d_{avg} is the average diameter and f is the nozzle feed rate,

MRR therefore can be expressed as

MRR = $\rho * \pi * \; dc \; * \; d_{avg}$ (5.5)

5.7 Designof experimental procedure

5.7.1 The specimen preparation

The specimens are made from the rod of aluminum alloy (7075-T6), a total number of 81 specimens for all three different diameters, a total length of (50mm) each has been cut. A number of 27 specimens from each of 20mm, 25mm, and 30mm diameter, are made. Material removal is performed for a distance of 15 mm from the tip point of the work piece. as shown in Figure 5.10.

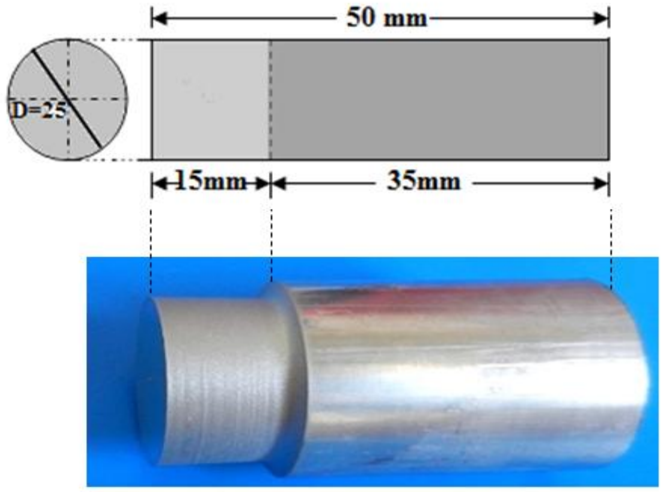


Figure 5.10Work piece and turning distance in experiments

5. 7. 2 AWJ Tuning System

According to the AWJ machine specification and the operating conditions, the water filtration unit was renewed, cooling system and oil level was checked, new nozzle and orifice were mounted, and at last, a mesh of 80 grade abrasive material has been added.

In this work the stand off distance is adjusted to 5 mm in all experiments, and the impact distance e is considered as an effective parameter. In order to determine this distance a series of CNC machine turning experiments were performed to produce a number of 18 dummy as shown in Figure 5.11. For differentvalueof e there are sixdifferent diameters of dummies are produced. Figure 5.12 shows the procedure of determining dummies,the values of dummy diameters are listed in Table 5.9

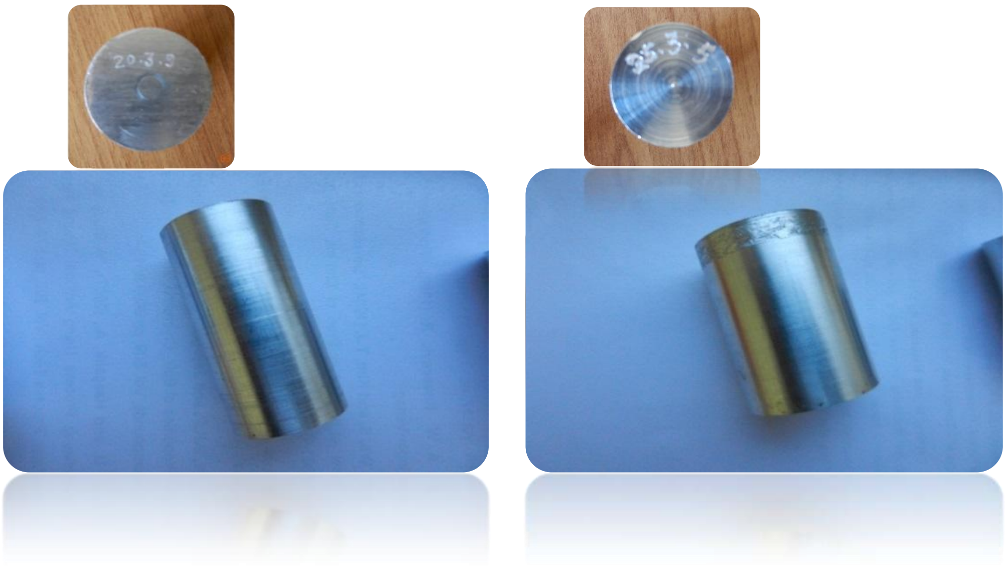


Figure 5.11 Samples of two different dummy diameters dummy

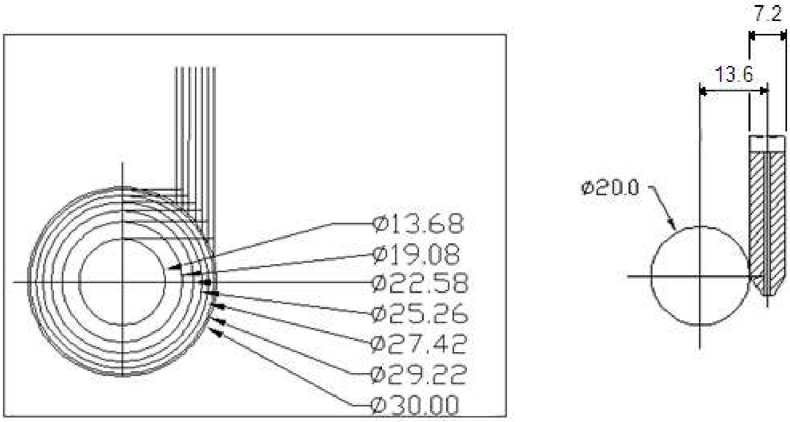


Figure 5.12 Dummy diameters for d_i=30 mm

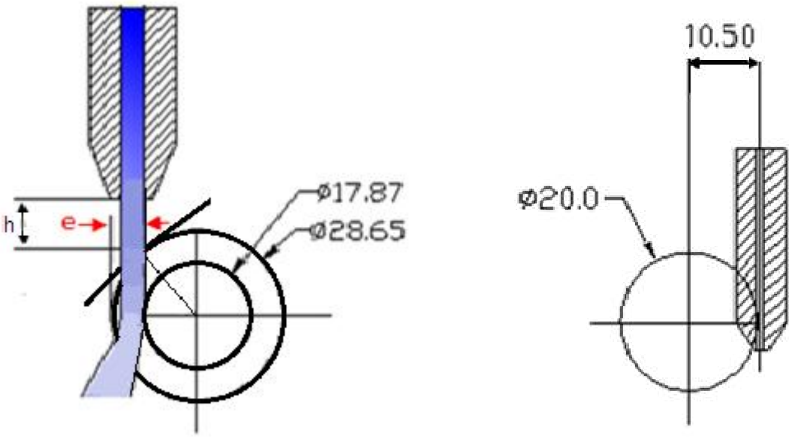


Figure 5.13An example of 20mm specimen adjusting

Table 5.9The Dummy diameters for different e and H

		H							
d	**e**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
20	1	12.24	14.24	16.24					
	2	19.23	18.58	20.54					
	3	19.23	21.23	23.23	25.23	27.23	29.23	31.23	33.23
	4			25.20					
	5			26.70					
	6			27.86					
		H							
d	**e**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
25	1	13.0	15.0	17.00					
	2	17.87	19.87	21.87					
	3	21.00	23.00	25.00	27.00	29.00	31.00	33.00	35.00
	4			27.35					
	5			29.21					
	6			30.71					
		H							
d	**e**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
30	1	13.68	15.68	17.68					
	2	19.08	21.08	23.08					
	3	22.58	24.58	26.58	28.58	30.58	32.58	34.58	36.58
	4			29.26					
	5			31.42					
	6			33.22					

5. 7. 3 Work Piece Adjusting Procedure

The first step of the work piece adjusting is to hold the workpiece into the turning chuck then give an order to the machine control to keep the nozzle in touch with the workpiece side across the nozzle to determine the distance between the center lines of water jet and the workpiece as shown in Figure 5.14.

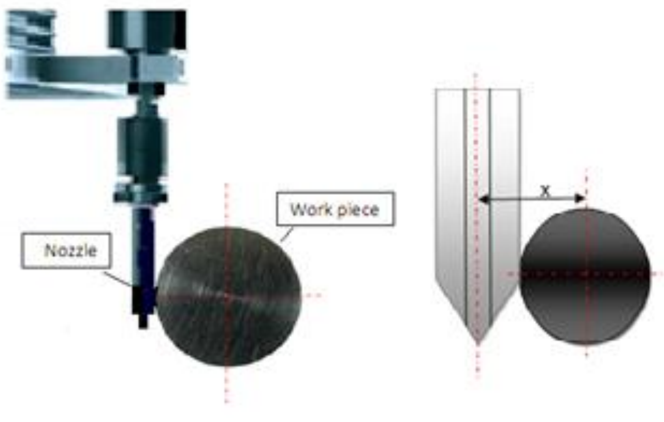


Figure 5.14 First step of adjusting

remove away the nozzle, then replace the work piece by a specimen of dummy depend on the first turning operation require, The end of the nozzle touch the specimen at top side to determine the distance of erosion or assuming the value of depth of cut as shown in Figure 5.15.

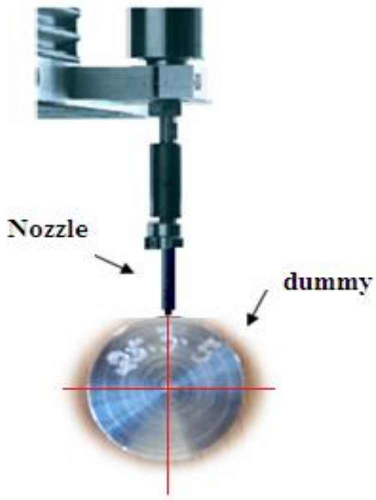


Figure 5.15Dummyadjusting

Move away the nozzle again, then replace the dummy with the specimen, move the nozzle to take place as a working position depending on the data's in steps 1, and 2, to be ready for starting the penetration as shown in Figure 5.16.

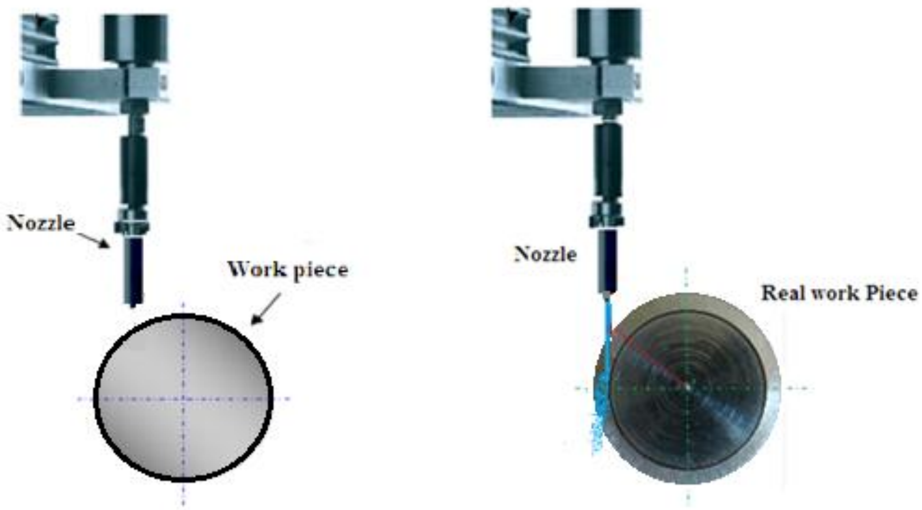


Figure 5.16Working position of cutting head

5.8 Experimental Resultsand Discussion

In this section the experimental results of the surface roughness quality (Ra), material removal rate (MRR), andfinal diameter (df) for different process parameters (f, p, e) are givenin a table. The effects of the turning process parameters on Ra, MRR, anddfand also the relationship between these parameters have been investigated. By using Minitab software – full factorial method, the main effect and interaction effect plots are obtained and compared in order to observe the effect of each factor and their interaction which factor is the most effective one.

5.8.1 Experimental results of rotational speed

The first experiment was to investigate the effect of work piece rotational speed on final diameter. A number of experiments with three different levelsrotational speed of (200, 500, 1200 rpm)were performed, and final diameter obtained are listed in Table 5.10

Table 5.10 Experiments ofrotational speed on final diameter

Exp	N	E	P	f	df
20.1	200	2	2000	5	**16.5**
20.2	200	2	2000	10	**17.4**
20.3	200	2	2000	15	**17.8**
20.4	500	2	2000	5	**16.4**
20.5	500	2	2000	10	**17.3**
20.6	500	2	2000	15	**17.7**
20.7	1200	2	2000	5	**16.55**
20.8	1200	2	2000	10	**17.3**
20.9	1200	2	2000	15	**17.75**

As shown in Table 5.10 it is clearthat the work piece rotational speed has no significant effect on final diameter; therefore the rotational speed of all experiments in this study is taken as constant speed of 1000 rpm.

5.8.2 .Experimental results on surface roughness

The effect of the turning process parameters on surface quality has been studied graphically as illustrated in main and interaction effect plot in Figure 5.17, and Figure 5.18 respectively, and the results of these parameter effects are listed in Table 5.11.

Table 5.11 Experimental results of (Ra)

Exp	di	e	P	f	Df	Ra	Exp	di	e	p	f	df	Ra
1	20	1	2.0	2	19.1	2.56	43	25	2	3.0	2	20.2	4.57
2	20	1	2.0	6	19.6	2.85	44	25	2	3.0	6	20.8	4.21
3	20	1	2.0	10	19.7	2.96	45	25	2	3.0	10	21.2	4.93
4	20	1	2.5	2	19.7	2.82	46	25	3	2.0	2	19.0	4.39
5	20	1	2.5	6	19.7	2.86	47	25	3	2.0	6	20.4	4.52
6	20	1	2.5	10	19.8	2.95	48	25	3	2.0	10	21.5	4.85
7	20	1	3.0	2	19.8	2.75	49	25	3	2.5	2	19.3	4.31
8	20	1	3.0	6	19.8	3.05	50	25	3	2.5	6	20.1	5.75
9	20	1	3.0	10	19.9	3.11	51	25	3	2.5	10	21.0	5.95
10	20	2	2.0	2	15.9	3.82	52	25	3	3.0	2	19.0	3.92
11	20	2	2.0	6	17.0	3.97	53	25	3	3.0	6	20.0	4.58
12	20	2	2.0	10	17.5	4.12	54	25	3	3.0	10	20.7	5.60
13	20	2	2.5	2	16.6	2.72	55	30	1	2.0	2	28.2	3.71
14	20	2	2.5	6	17.1	2.80	56	30	1	2.0	6	28.8	3.83
15	20	2	2.5	10	17.5	2.86	57	30	1	2.0	10	29.0	3.94
16	20	2	3.0	2	16.7	2.85	58	30	1	2.5	2	28.4	2.85
17	20	2	3.0	6	17.3	3.27	59	30	1	2.5	6	28.7	3.27
18	20	2	3.0	10	17.5	3.19	60	30	1	2.5	10	29.0	3.93
19	20	3	2.0	2	14.3	2.57	61	30	1	3.0	2	28.4	2.57
20	20	3	2.0	6	14.6	3.53	62	30	1	3.0	6	28.8	3.53
21	20	3	2.0	10	16.2	3.24	63	30	1	3.0	10	29.0	3.24
22	20	3	2.5	2	13.8	2.78	64	30	2	2.0	2	27.5	3.78
23	20	3	2.5	6	14.9	3.11	65	30	2	2.0	6	28.0	4.11
24	20	3	2.5	10	15.9	3.20	66	30	2	2.0	10	28.3	4.28
25	20	3	3.0	2	13.6	3.04	67	30	2	2.5	2	27.2	3.04
26	20	3	3.0	6	15.3	4.15	68	30	2	2.5	6	28.0	4.15
27	20	3	3.0	10	15.9	4.76	69	30	2	2.5	10	28.3	4.76
28	25	1	2.0	2	22.5	3.75	70	30	2	3.0	2	26.5	3.10
29	25	1	2.0	6	22.7	3.97	71	30	2	3.0	6	25.8	5.11
30	25	1	2.0	10	22.8	4.33	72	30	2	3.0	10	27.0	4.80
31	25	1	2.5	2	23.2	3.59	73	30	3	2.0	2	23.8	5.41
32	25	1	2.5	6	24.1	5.41	74	30	3	2.0	6	25.9	8.41
33	25	1	2.5	10	23.7	5.53	75	30	3	2.0	10	27.3	8.55
34	25	1	3.0	2	23.3	3.22	76	30	3	2.5	2	22.7	6.06
35	25	1	3.0	6	23.5	3.53	77	30	3	2.5	6	24.3	8.15
36	25	1	3.0	10	23.7	3.82	78	30	3	2.5	10	25.8	6.80
37	25	2	2.0	2	19.6	3.99	79	30	3	3.0	2	22.5	5.06
38	25	2	2.0	6	20.5	5.88	80	30	3	3.0	6	24.1	6.83
39	25	2	2.0	10	21.4	6.79	81	30	3	3.0	10	25.8	6.66
40	25	2	2.5	2	19.7	5.82	*di, df, e [mm]*						
41	25	2	2.5	6	20.5	5.83	*P [kbar]*					*Ra [μm]*	
42	25	2	2.5	10	21.2	5.96	*f [mm/min]*						

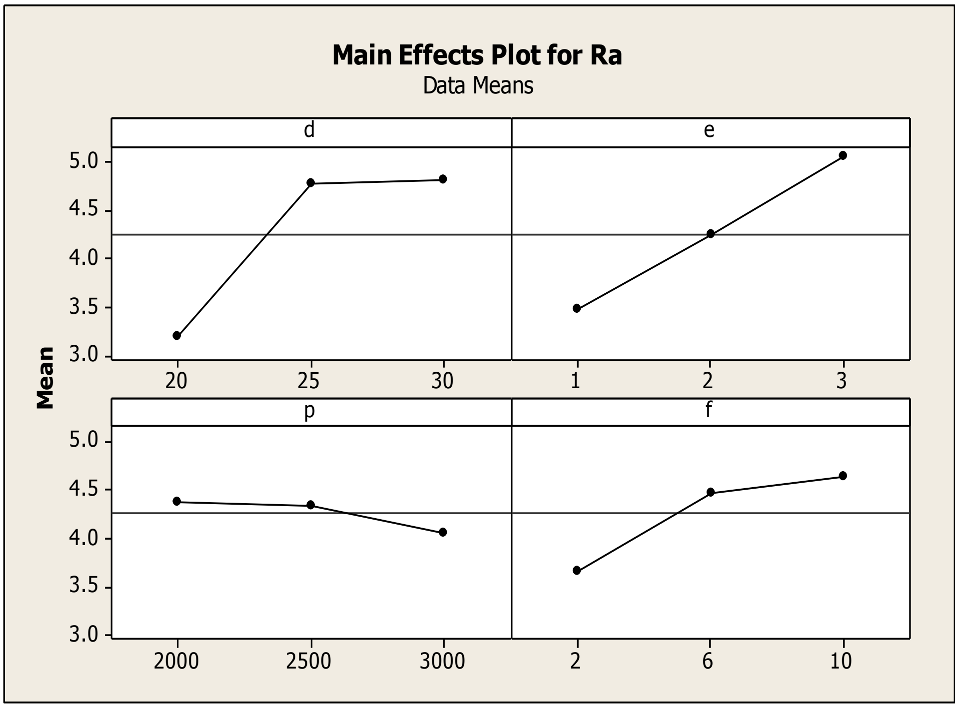


Figure 5.17Main effect plots for surface roughness Ra

From the Figure5.17 it is apparent that an increase in impact distance causes a steep rise in the surface roughness monotonically. However, the impact distance and traverse speed appear a linear relationship effecting on surface quality. Indicating that increasing in impact distance and traverse speed aggravate the effect on surface quality. For the traverse speed this may be because the high speed of traverse generates a kind of particles flow, overlapping and this action causes a turbulence impacting on the workpiece surface due to rise the roughness. An increase in the impact distance it can be a reason to reduce the abrasive material particles in the outer perimeter of the expanding of the jet and the energy of particles at the attack points will increase the roughness.

For the effect of work piece diameter on surface quality it can be found from the Figure that there are two sections, the first one between 20 to 25mm, in this section the effect of work piece diameter is similar to the each impact distance and traverse speed effect which has a steep rising in roughness, it can be seen the linearly increases with an increase in work piece diameter, and then the trend of the effect changes to be less steep, this transmission in theeffecting between 25 to 30 mm diameter it may be respectto the particles impacting on a rotating section area depend on the velocity of the rotating area.

The effects of water jet pressure have a different trend, an increase in water jet pressure results to decrease in surface roughness, that may be the increasing in jet pressure due to increase the velocity of the jet, then to generate a higher energy, this energy due to reduce the impacting process on the workpiece surface.

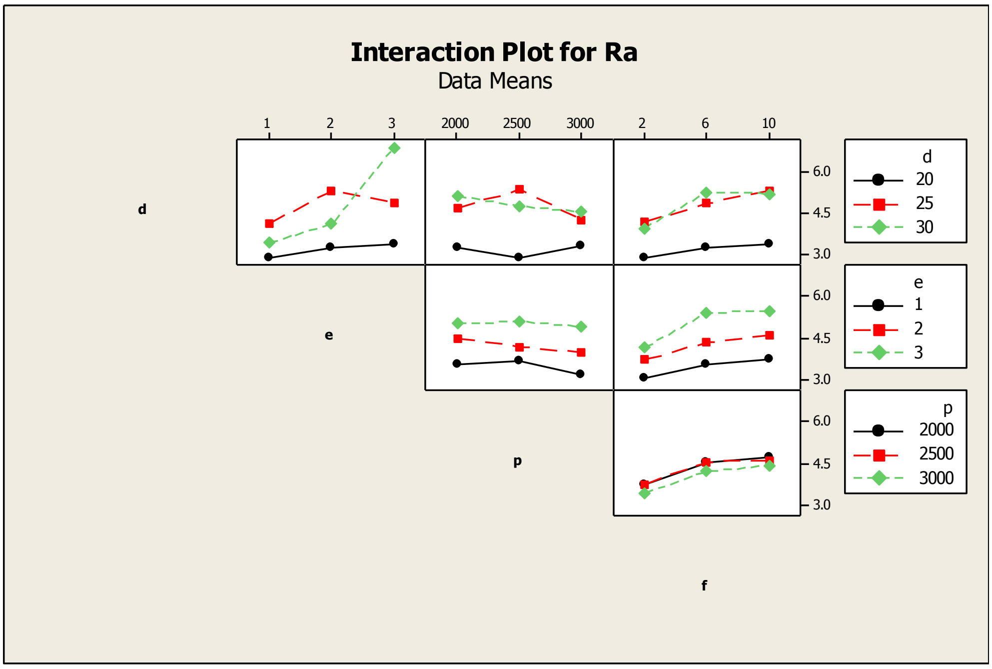


Figure 5.18Interaction effect plot for surface roughness Ra

In the Figure 5.18 the interaction effect of the AWJ turning process parameters for surface roughness are given. This figure shows the effect of these parameters in more detail. Also the effects of AWJ turning process parameters are confirmed by ANOVA tests at the confidence level of 95% ($\alpha = 0.05$) and it is given in Table 5.12 From probability values (P),the statistical analysis revealed that the effect of pressure (p) and jet pressure- feed rate (p*f) interaction effects of surface roughness Ra may be neglected. It is also seen from F values in the table that the most effect parameter is the jet impact distance (e), (F=78.51) for average surface roughness Ra.

The analysis of the surface roughness demonstrate that the effect of water pressure on surface roughness is minimal and positive. This indicates that the lag of the jet pressure in the AWJ turning process has a negative effect on the surface quality, and the increase in water jet pressure value makes the quality of surface better.

Table 5.12 Analysis of variance for Ra, using adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
di	2	46.8995	46.8995	23.4497	78.51	0.000
e	2	33.0597	33.0597	16.5298	55.34	0.000
p	2	1.6878	1.6878	0.8439	2.83	0.069
f	2	14.3941	14.3941	7.1970	24.09	0.000
di*e	4	34.8106	34.8106	8.7026	29.13	0.000
di*p	4	6.2169	6.2169	1.5542	5.20	0.001
di*f	4	2.7007	2.7007	0.6752	2.26	0.076
e*p	4	0.8156	0.8156	0.2039	0.68	0.607
e*f	4	1.8153	1.8153	0.4538	1.52	0.212
p*f	4	0.0741	0.0741	0.0185	0.06	0.993
Error	48	14.3377	14.3377	0.2987		
Total	80	156.8119				

In Figure 5.19, and Figure 5.20 a schematic explain the effects of water jet pressure on the surface quality of 25mmdiameter and the effect of impact distance on surface quality of 20 mm diameter respectively.

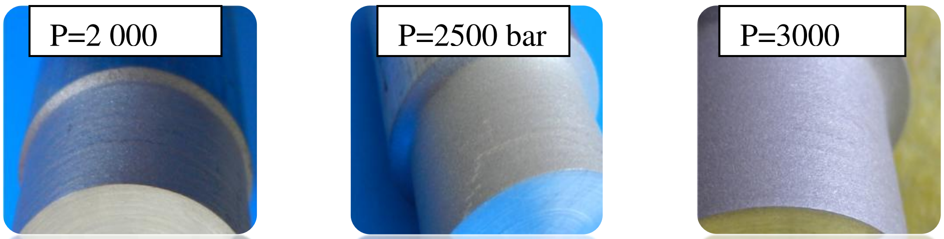


Figure 5.19 Surface qualities on 25 mm diameter specimens with different p values

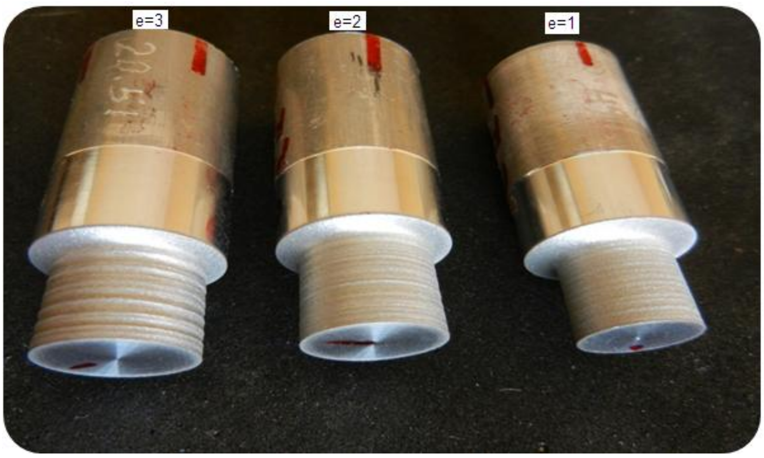


Figure 5.20 Surface qualities on 20mm diameter specimens with different values of impact distance

5. 8.3 Experimental results of material removal rate

The material removal rate for the work piece under specified cutting conditions are calculated and listed in Table 5.13

Table 5.13 Experimental results of (MRR)

Ex	di	e	p	f	Df	MRR
1	20	1	2.0	2	19.1	2.59
2	20	1	2.0	6	19.6	3.48
3	20	1	2.0	10	19.7	3.65
4	20	1	2.5	2	19.7	0.36
5	20	1	2.5	6	19.7	2.19
6	20	1	2.5	10	19.8	2.92
7	20	1	3.0	2	19.8	0.59
8	20	1	3.0	6	19.8	1.32
9	20	1	3.0	10	19.9	1.46
10	20	2	2.0	2	15.9	10.81
11	20	2	2.0	6	17.0	24.47
12	20	2	2.0	10	17.5	33.83
13	20	2	2.5	2	16.6	9.16
14	20	2	2.5	6	17.1	23.74
15	20	2	2.5	10	17.5	34.47
16	20	2	3.0	2	16.7	8.79
17	20	2	3.0	6	17.3	22.22
18	20	2	3.0	10	17.5	34.47
19	20	3	2.0	2	14.3	14.38
20	20	3	2.0	6	14.6	40.88
21	20	3	2.0	10	16.2	50.58
22	20	3	2.5	2	13.8	15.39
23	20	3	2.5	6	14.9	38.74
24	20	3	2.5	10	15.9	54.12
25	20	3	3.0	2	13.6	15.06
26	20	3	3.0	6	15.3	36.58
27	20	3	3.0	10	15.9	54.12
28	25	1	2.0	2	22.5	8.73
29	25	1	2.0	6	22.7	24.19
30	25	1	2.0	10	22.8	38.66
31	25	1	2.5	2	23.2	6.38
32	25	1	2.5	6	24.1	9.75
33	25	1	2.5	10	23.7	23.28
34	25	1	3.0	2	23.3	6.04
35	25	1	3.0	6	23.5	16.05
36	25	1	3.0	10	23.7	23.28
37	25	2	2.0	2	19.6	17.71
38	25	2	2.0	6	20.5	45.16
39	25	2	2.0	10	21.4	61.41
40	25	2	2.5	2	19.7	17.42
41	25	2	2.5	6	20.5	45.16
42	25	2	2.5	10	21.2	64.54

Ex	di	e	P	df	df	MRR
43	25	2	3.0	2	20.2	15.95
44	25	2	3.0	6	20.8	42.43
45	25	2	3.0	10	21.2	64.54
46	25	3	2.0	2	19.0	19.41
47	25	3	2.0	6	20.4	46.07
48	25	3	2.0	10	21.5	59.83
49	25	3	2.5	2	19.3	18.57
50	25	3	2.5	6	20.1	48.75
51	25	3	2.5	10	21.0	67.65
52	25	3	3.0	2	19.0	19.41
53	25	3	3.0	6	20.0	49.63
54	25	3	3.0	10	20.7	72.25
55	30	1	2.0	2	28.2	7.69
56	30	1	2.0	6	28.8	15.56
57	30	1	2.0	10	29.0	21.69
58	30	1	2.5	2	28.4	6.87
59	30	1	2.5	6	28.7	16.83
60	30	1	2.5	10	29.0	21.69
61	30	1	3.0	2	28.4	6.87
62	30	1	3.0	6	28.8	15.56
63	30	1	3.0	10	29.0	21.69
64	30	2	2.0	2	27.5	10.57
65	30	2	2.0	6	28.0	25.59
66	30	2	2.0	10	28.3	36.44
67	30	2	2.5	2	27.2	11.78
68	30	2	2.5	6	28.0	25.59
69	30	2	2.5	10	28.3	36.44
70	30	2	3.0	2	26.5	14.54
71	30	2	3.0	6	25.8	39.39
72	30	2	3.0	10	27.0	62.87
73	30	3	2.0	2	23.8	24.53
74	30	3	2.0	6	25.9	50.56
75	30	3	2.0	10	27.3	56.88
76	30	3	2.5	2	22.7	28.29
77	30	3	2.5	6	24.3	68.27
78	30	3	2.5	10	25.8	86.16
79	30	3	3.0	2	22.5	28.95
80	30	3	3.0	6	24.1	69.76
81	30	3	3.0	10	25.8	86.16

di, df, e [mm] *MRR [mg/sec]*
P [kbar]
f [mm/min]

The effect of abrasive water jet turning process parameters on the material removal rate has been illustrated in main and interaction effect plot in Figure 5.21, and Figure 5.22 respectively

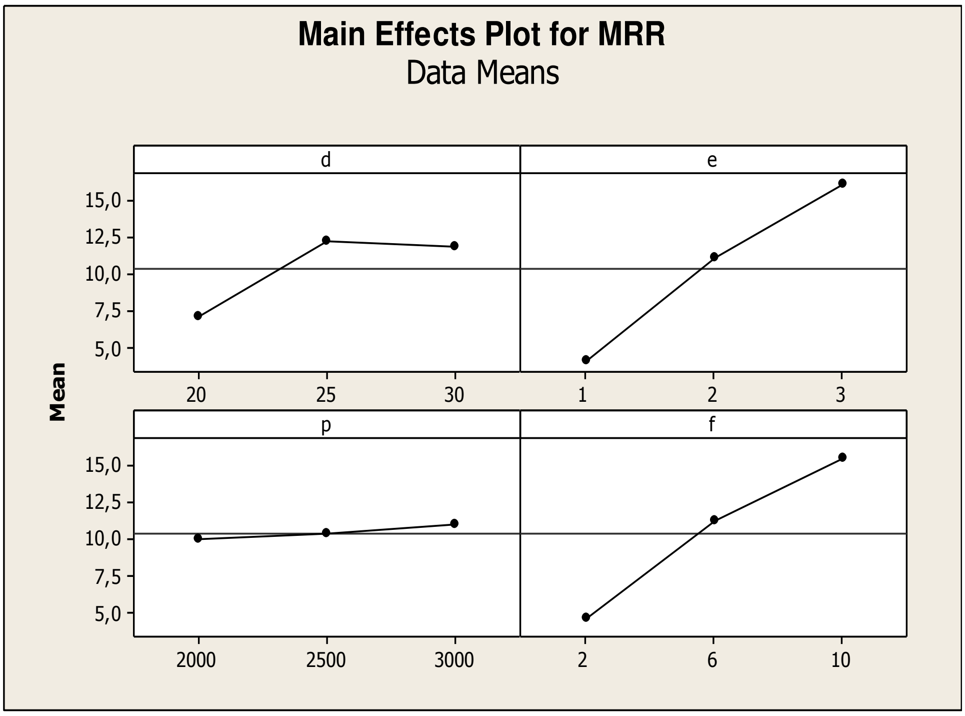


Figure 5.21Main effect plot for material removal rate

It is seen from the Figure 5.21that the trend of work piece diameter has a steep variable.A linear steep rise in increasing between 20 to 25mm diameters, which is the material removal increase with an increase in work piece diameter, for further increase in diameter between 25 to 30 mm there is almost no change in material removal rate, that the effect of diameter start to take a kind of stability when the diameter be a large.This may be due to interaction effects of impact distance (e) and surface speed ($V=\pi dN$). Figure 5.22 shows the material removal on different diameters. For other parameter effects, it can be noted from the figure that the traverse speed and impact distance, are the most effective parameters of material removal rate while the pressure jet is not influenced.Increase in traverse speed effect on material removal a similar activity is observed in an increasing in impact distance. The water jet pressure has the least effect on the material removal rate, an increase in water jet pressure results a small rate in increasing of MRR,that can be attributed to the fact that abrasive material particles gain high energy because of its high velocity when water jet pressure is high.However the positive effect of water jet pressure on the material removal rate is reduced as a result of the increased material particle fragmentation and interference when water pressure levels are high which reduce the material removing efficiency.An increase in traverse speed due to a larger amount of abrasive particles attacking on the target surface and hence large material removed so that the material removal rate will be large.

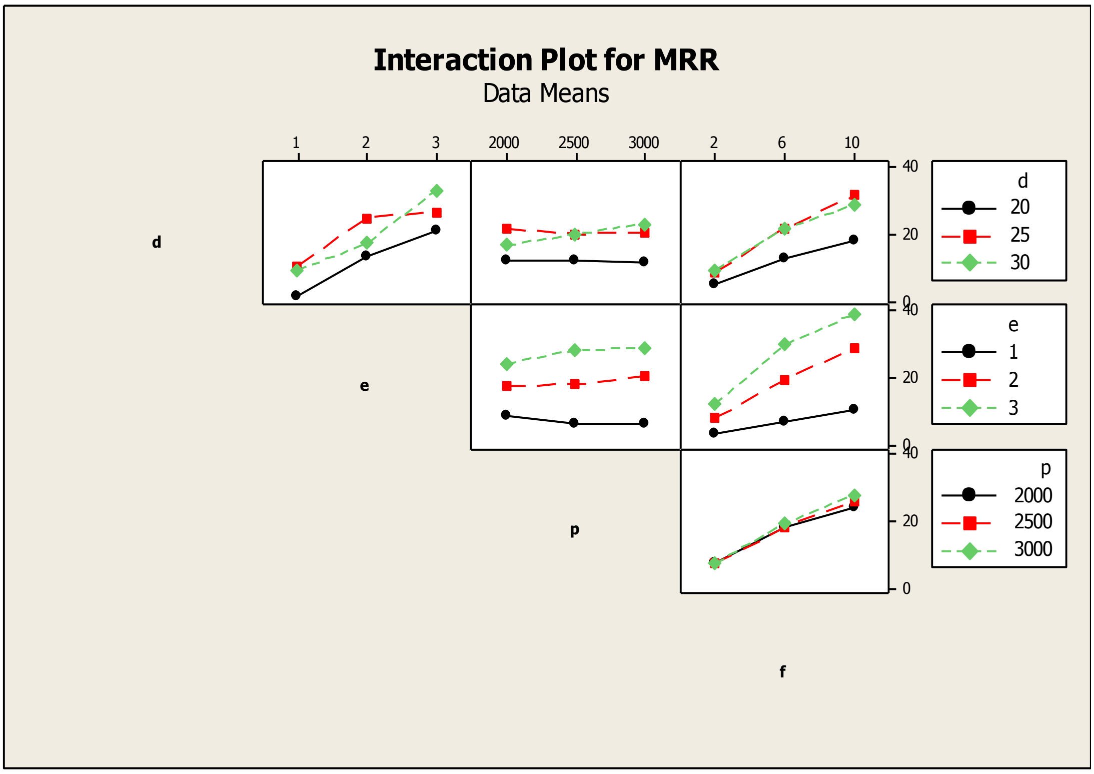


Figure5.22Interaction effect plot for material removal rate

In Figure 5.22 an interaction effect of AWJ turning process parameters of material removal rate MRR is presented. And the analysis of these process parameters effecting are listed in Table 5.14 by using ANOVA tests at the confidence level of 95% (α=0.05). As the statistical analysis in the section (P), the effect of pressure (p) and the jet pressure- feed rate interaction (p*f) effect on material removal rate MRR, and from the section F in the analysis table it is seen that the jet impact distance (e) is the most effective factor for material removal rate MRR F value of 412.15.

Table5.14 Analysis of Variance for MRR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
di	2	3483.2	3483.2	1741.6	92.46	0.000
e	2	15525.9	15525.9	7762.9	412.15	0.000
p	2	104.8	104.8	52.4	2.78	0.072
F	2	12890.1	12890.1	6445.0	342.	0.000
di*e	4	1230.9	1230.9	307.7	16.34	0.000
di*p	4	439.1	439.1	109.	5.83	0.001
di*f	4	688.7	688.7	172.2	9.14	0.000
e*p	4	415.0	415.0	103.8	5.51	0.001
e*f	4	2614.1	2614.1	653.5	34.70	0.000
p*f	4	99.8	99.8	25.0	1.32	0.274
Error	48	904.1	904.1	18.8		
Total	80	38395.6				

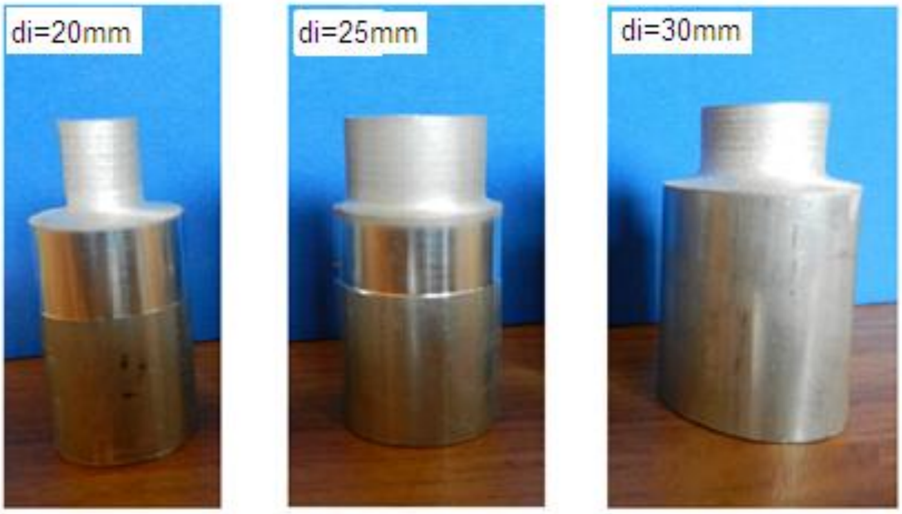


Figure 5.23The variation of material removal rate for specimens with different diameter

5.8.4Experimental Results on Final Diameter

The results of AWJ turning process parameters (di, e, p, f) on final diameter are listed in Table 5.15 The effects and the relationship between these parameters has been investigated by using Minitab® software. The main and interaction effect plots are drawn by the ANOVA method to compare the relative strength of the effects of the factors.

Table 5.15 Experimental results of (df)

Exp	di	e	P	f	df
1	20	1	2.0	2	19.1
2	20	1	2.0	6	19.6
3	20	1	2.0	10	19.7
4	20	1	2.5	2	19.7
5	20	1	2.5	6	19.7
6	20	1	2.5	10	19.8
7	20	1	3.0	2	19.8
8	20	1	3.0	6	19.8
9	20	1	3.0	10	19.9
10	20	2	2.0	2	15.9
11	20	2	2.0	6	17.0
12	20	2	2.0	10	17.5
13	20	2	2.5	2	16.6
14	20	2	2.5	6	17.1
15	20	2	2.5	10	17.5
16	20	2	3.0	2	16.7
17	20	2	3.0	6	17.3
18	20	2	3.0	10	17.5
19	20	3	2.0	2	14.3
20	20	3	2.0	6	14.6
21	20	3	2.0	10	16.2
22	20	3	2.5	2	13.8
23	20	3	2.5	6	14.9
24	20	3	2.5	10	15.9
25	20	3	3.0	2	13.6
26	20	3	3.0	6	15.3
27	20	3	3.0	10	15.9
28	25	1	2.0	2	22.5
29	25	1	2.0	6	22.7
30	25	1	2.0	10	22.8
31	25	1	2.5	2	23.2
32	25	1	2.5	6	24.1
33	25	1	2.5	10	23.7
34	25	1	3.0	2	23.3
35	25	1	3.0	6	23.5
36	25	1	3.0	10	23.7
37	25	2	2.0	2	19.6
38	25	2	2.0	6	20.5
39	25	2	2.0	10	21.4
40	25	2	2.5	2	19.7
	25	2	2.5	6	20.5
42	25	2	2.5	10	21.2

Exp	di	e	p	f	df
43	25	2	3.0	2	20.2
44	25	2	3.0	6	20.8
45	25	2	3.0	10	21.2
46	25	3	2.0	2	19.0
47	25	3	2.0	6	20.4
48	25	3	2.0	10	21.5
49	25	3	2.5	2	19.3
50	25	3	2.5	6	20.1
51	25	3	2.5	10	21.0
52	25	3	3.0	2	19.0
53	25	3	3.0	6	20.0
54	25	3	3.0	10	20.7
55	30	1	2.0	2	28.2
56	30	1	2.0	6	28.8
57	30	1	2.0	10	29.0
58	30	1	2.5	2	28.4
59	30	1	2.5	6	28.7
60	30	1	2.5	10	29.0
61	30	1	3.0	2	28.4
62	30	1	3.0	6	28.8
63	30	1	3.0	10	29.0
64	30	2	2.0	2	27.5
65	30	2	2.0	6	28.0
66	30	2	2.0	10	28.3
67	30	2	2.5	2	27.2
68	30	2	2.5	6	28.0
69	30	2	2.5	10	28.3
70	30	2	3.0	2	26.5
71	30	2	3.0	6	25.8
72	30	2	3.0	10	27.0
73	30	3	2.0	2	23.8
74	30	3	2.0	6	25.9
75	30	3	2.0	10	27.3
76	30	3	2.5	2	22.7
77	30	3	2.5	6	24.3
78	30	3	2.5	10	25.8
79	30	3	3.0	2	22.5
80	30	3	3.0	6	24.1
81	30	3	3.0	10	25.8

di, df, e [mm],
f [mm/min]

Figure 5.24 shows the final diameter of samples with 20, 25 and 30 mm after turning with e = 20 and p = 2500 bar and different feed rate.

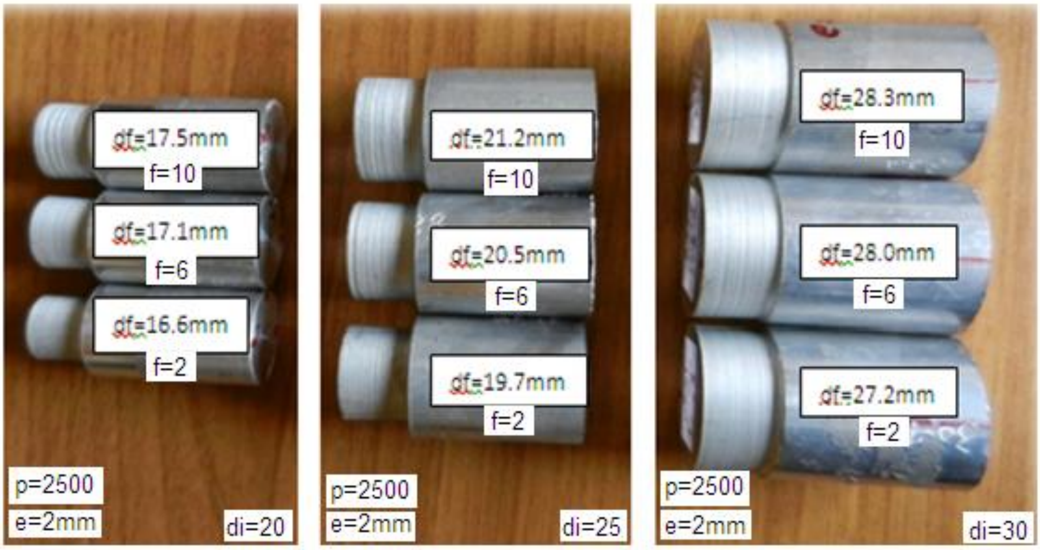


Figure 5.24Final diameter values for the specimens after AWJ turning

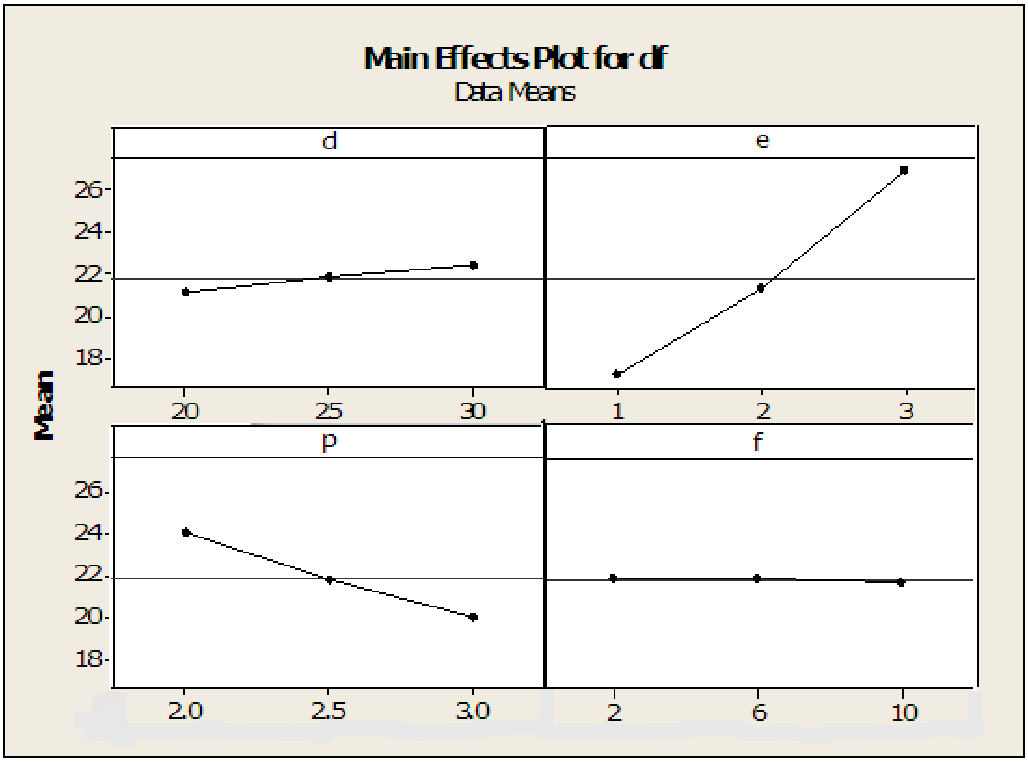


Figure 5.25 Main effect plot for final diameter df

It is well-defined from the Figure 5.25 that the impact distance, water jet pressure, nozzle traverse speed, and the work piece diameter are effective parameters on final diameter dissimilarity. Anincrease in theimpact distance(e) results a steepincrease in the final diameter values, that means the depth of cut decrease with an increase of the impact distance, it is explained that this increasing in impact distanceresulted a decrease in the jet energy which generated a higher penetration on the surface of work piece.

An increase in water jet pressure result in decrease in final diameter, higher jet pressure due to increase the velocity of jet particles and that generate higher energy to achieve a high rate of penetration and higher erosion processat the impacting points on the surface of the rotating work piece, while an increase in value of traverse speed has the less effect, an increase of traverse speed almost doesn't have a discernible effect on the final diameter. Also, it is noted from the figure that the variety of work piece diameter has a significant effect, the increase in work piece diameter result an increase in final diameter, that may be respect in the mechanism ofparticles impactingon section area under the same conditions, an increase in the section area causes to decrease of amount of particles that erode the surface comparing with smaller area.

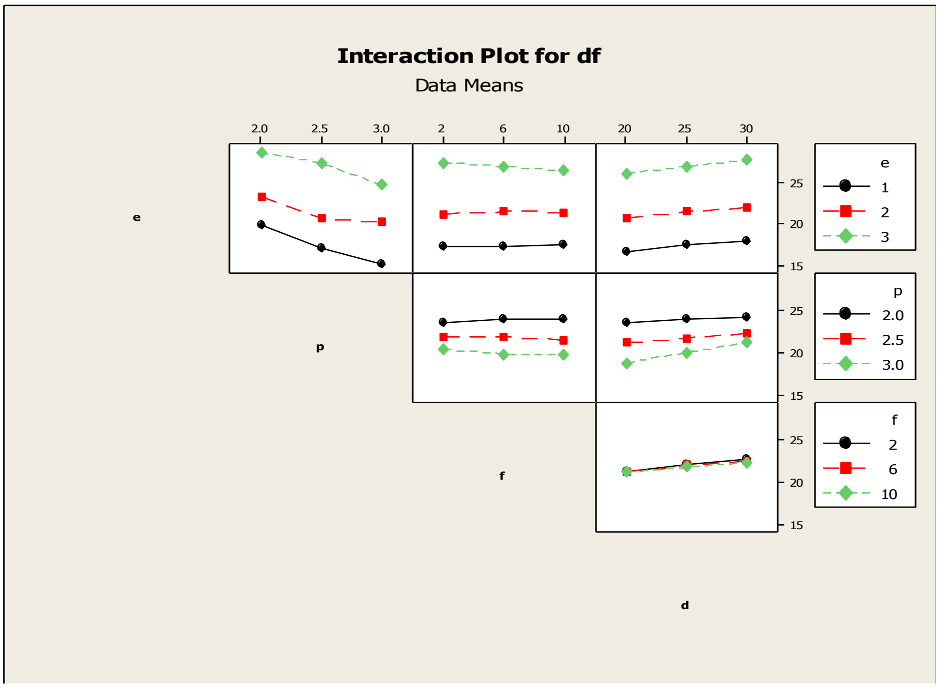


Figure 5.26Interaction effect plot for final diameter df

In Figure 5.26 of interaction plots shows the overall relation between process parameters. It is noted that the impact distance is the most effective parameter on the final diameter has a tendency to increase with an increase in impact distance. This may be because the section of jet has a different form when be far from the penetration point on the workpiece surface, small impact distance means less diameter of jet and more concentrate than large distance.The analysis of this effecting are listed in Table 5.16.And from the section F in the analysis table it is seen that the jet impact distance (e) is the most effective factor for final diameter with a value of (501.11). The difference of work piece diameter has a similar effect of the impact distance, but with lesser value. An increase in work piece diameter due to increase in the trend of the final diameter changing.The water jet pressure has an opposite effect on the final diameter, an increase in water jet pressure results decreases in the final diameter that may be the increasing in water jet pressure due to concentrate the energy of particles.

Table5.16 Analysis of Variance for df, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
di	2	3856.1	3856.1	1823.4	97.65	0.000
e	2	16235.2	16235.2	7925.7	501.11	0.000
P	2	162.5	162.5	63.6	2.69	0.076
F	2	13311.4	13311.4	7276.0	426.	0.000
di*e	4	1345.6	1345.6	318.5	18.90	0.000
di*p	4	469.5	469.5	116.	6.40	0.001
di*f	4	723.6	723.6	168.3	8.30	0.000
e*p	4	485.7	485.7	122.4	6.72	0.001
e*f	4	3116.5	3116.5	587.6	53.60	0.000
p*f	4	88.7	88.7	25.0	1.94	0.358
Error	48	869.2	869.2	21.9		
Total	80	42327.1				

CHAPTER 6

CONCLUSIONS

6.1 Introduction

In this chapter the conclusion which related to the results obtained from these experiments is presented, also feature works of the turning abrasive water jet process with different types of materials to investigate the effects of AWJ turning process parameters in these materials has been discussed.

6.2 Conclusion

During these experiments, it was found that the effects of turning parameters have varying results (increasing and decreasing) on the surface quality and material removal rate, and these results are totally respected on values of input turning process parameters.Four process parameters (traverse speed, water jet pressure, impact distance, and work piece diameter) are considered as the main input turning parameters in this study. A total number of 81 turning process by using abrasive water jet machine have been undertaken based on design of full factorial of experimental method in order to study the interactions between these parameters also the effects of each process parameteron turning quality for acircumference section of Al 7075 alloy.

Based on the AWJ turning parameters, the main plots and surface plot effects have been obtained by Minitab Software®. It is demonstrated thatthe diameter of the work piece in the range of 20 to 25 mm has a significant effect on material removal rates, and surface quality. The most effective factors are determined are feed rate and jet impact distance, and water pressure has the least effect among these parameters. In order to remove high amounts of material, the feed rate should be high. Also, in order to get fine surface quality, the water jet pressure should be high and feed rate and jet impact distance values should be lower.In abrasive water jet technique when turning aluminum alloy 7075-T6 the maximum value of material removal rate was (54.12) mg/sec for 20 mm diameter, (72.25) mg/sec for 25 mm diameter, and(86.16) mg/sec for 30 mm diameter, under the same conditions of process parameters. Besidesthe mean surface quality part range from (2.56) to (6.66) µn. The following important notes would be extracted from the experimental results;

1-The main and interaction plotted help in establishing a fine equation for the given turning conditions, and the AWJ turning for any depth of turn can be found out.

2-From the results it is noted that during AWJ turning experiments, some parameters may take unexpected trend with sudden changing, this kind of actions is logical in practical experimentation, but need for deep analysis with other type of material to compare the results.

3-In abrasive water jet process the jet considering as the main cutting tool for all process performing, so the variation of jet energy well predicting factor on surface roughness and material removal rate, in fact the jet drive all the parameters and it is the main effective factor in AWJ (jet stand off distance, jet pressure, jet impact distance, jet travers speed, jet diameter and jet velocity, etc.), in nature of interaction of abrasive water jet turning process parameters with this jetshould take more investigation that the jetenergy concentrate should have a special attention in AWJ turning processes.

6.3 Future Investigationof the AWJ Turning Process

In manufacturing industries which use the abrasive water jet turning process technique, the effects of input process parameters play the main roles on surface quality and material removal rate also on the final diameter. So the analysis of effects the process parameters during production is very important.

As a supplementary investigation for future work in turning with abrasive water jet processes, it is suggested to extend the experimental study on other types of materials with other variable's properties and then compare the results. Stand off distance may be included an another factor whose effect on thesurfaceroughnesswould be evaluated.

REFERENCES

[1] Ramu G.,BapirajuB., KumariM.Leela,(2013).Theoretical and graphical analysis of abrasive water jet turning, *International Journal of Modern Engineering Research* (IJMER),**3**, 3207-3215

[2] Chen L., Siores, E. and Wong, W.C.K. (1696). Kerf Characteristic in abrasive jet cutting of ceramic materials, *International Journal of Machine Tools and Manufacture*, **11**, 1201-1206.

[3] Shanmugam D. K., Masood S. H.(2009). Investigation of kerf characteristics in Abrasive Water jet Cutting of Layered Composites, *International Journal of Material Processing Technology*, 3887–3893.

[4] Shanmugam D. K., Wang J., Liu H. (2008) Minimization of kerf tapers in Abrasive Water jet machining of Alumina Ceramics using a compensation technique, *International Journal of Machine Tools and Manufacture,*1527–1534.

[5] Wang, J. and Wong, W.C.K., (1999). A Study of Abrasive Water jet Cutting of Metallic Coated Sheet Steels, *International Journal of Machine Tools Manufacturing*,**39**, 855-870.

[6] Bitter J.G.A., (1963) A study of Erosion Phenomena—part II,*Wear*, **6**, 169-190.

[7] Choi, G. S. and Choi, G.H., (1997) Process analysis and monitoring in abrasive water jet machining of aluminum ceramics, *International Journal of Machine Tools and Manufacture*, **37**, 295-307.

[8] ZengJiyue, Kim Thomas J., (1996). An Erosion Model of Polycrystalline Ceramics in Abrasive Waterjet Cutting. *Wear*, **193**, Issue 2, 207-217.

[9] Zeng J., Wu S., and Kim T.J., (1994). Development of a Parameter Prediction Model for AbrasiveWater jetTurning, in: Proc. of12th *International Conference on Jet Cutting Technology*, Rouen, France, 601–617.

[10] Paul, et Al., (1998). Analytical Modeling of the total Depth of Cut in the AWJ machining of polycrystalline brittle material, *Journal of Material Processing Technology,***73**, 206-212.

[11] Wang Ruihe, Wang Mingbo, (2010). Two-Fluid Model of Abrasive Water jet. *Journal of Materials Processing Technology*, **210**, Issue 1, 190-196.

[12] Liu H., Wang J., Kelson N., Brown R.J., (2004). A study of abrasive water jet characteristics by CFD simulation*, Journal of Materials Processing Technology*, **153-154**, Issue 10, 488-493.

[13] Deam R. T., Lemma E., Ahmed D. H., (2004) Modeling of the Abrasive Water jet Cutting process, *Wear*, **257**, Issues 9-10, 877-891.

[14] Vikram G., Babu N., (2002)Modeling and analysis of Abrasive Water jet cut Surface Topography*, International Journal of Machine Tools and Manufacture*, **42,** Issue 12, 1345-1354.

[15] Wang J. (2009). A new Model for the Prediction Depth of Cut in Abrasive Water jet contouring of Alumina Ceramics. *Journal of material processing technology*, **209**, 2314-2320.

[16] Azmir M.A., Ahsan A.K., (2009) High A study of Abrasive Water jet machining process on Glasspoxy composite laminate, *Journal of Materials Processing Technology*,**209**, Issue 20, 6168-6173.

[17] Akkurt Adnan, Kulekci Mustafa Kemal, SekerUlvi, ErcanFevzi, (2004). Effect of feed rate on Surface Roughness in Abrasive Water jet Cutting applications. *Journal of Materials Processing Technology*, **147**, Issue 3, 389-396.

[18] Shipway P.H., Fowler G., Pashby I.R., (2005). Characteristics of the Surface of a Titanium alloy following milling with Abrasive Water jet Wear, **258**, Issues 1-4, 123-132.

[19] Valicek Jan, Drzik Milan, HlochSergej , OhlidalMiloslav, MiloslavLupták, GombarMiroslav, RadvanskaAgata, HlavacekPetr, PalenikovaKaterina, (2007) Experimental analysis of Irregularities of Metallic Surfaces Generated by Abrasive Water jet. *International Journal of Machine Tools and Manufacture*, **47**, Issues 11, 1786-1790.

[20] Kovacevic R., (1991). Surface Texture in Abrasive Water jet Cutting. *Journal of Manufacturing Systems*, **10**, Issue 1, 32-40.

[21] Ramulu, M. and Arola, D., (1994).Influence of Abrasive Water jet Cutting condition on the Surface quality of Graphite/ epoxy laminate, *International Journal of Machine Tools and Manufacture*, **34**, 295-313.

[22] Çaydaş, U. and Hasçalık, A., (2007) A Study on Surface Roughness in Abrasive Water jet Machining Process Using Artificial Neural Networks and Regression Analysis Method, J. Mater. *Process Tech*., **202**, 574–582.

[23] Karakurt, İ., Aydın, G., Aydıner, K., (2010). Effect of Cutting Parameters on the Surface Roughness of Granite in Abrasive Water jet Cutting, J. Earth Sci. App. Res. Centre of Hacettepe U., **32**, 99-110.

[24] Candar,H., Filiz,I., (2012). Effects of Abrasive Water Jet Cutting Parameters on Surface Roughness Quality of Al 7075.

[25] Wang J, Xu S. (2005). Enhancing the AWJ cutting performance by multi pass machining with controlled oscillation. *Key Engineering Materials,***291-292**, 453-458.

[26] Hashish M. (1987). Turning with Abrasive Water jets - a first investigation. ASME *Journal of Engineering for Industry*,**109(4),** 281-290.

[27]Momber, A.W, and Kovacevic, R., (1997) Test parameter Analysis in Abrasive Water jet Cutting of Rocklike materials*, International Journal of Rock Mechanics and Mining Sciences,***34(1)**, 17-25.

[28] Chen, L., Siores, E. and Wong, (1998) W.C.K., Optimizing Abrasive Water jet Cutting of ceramic materials, *Journal of Materials Processing Technology,***74(1-3)**, 251- 254.

[29]Momber, A.W, and Kovacevic, R. (1998) Principle of Abrasive Water jet machining, *New York, Springer.*

[30] Axinte D.A., Srinivasu D.S., Kong M.C., Butler-Smith P.W., (2009) Abrasive Water jetcutting of polycrystalline diamond, A preliminary investigation. *International Journal of Machine Tools and Manufacture*, **49**, Issue 10, 797-803.

[31] Gi Sang Choi, Gi Heung Choi, (1997). Process analysis and monitoring in abrasive water jet machining of alumina ceramics*, International Journal of Machine Tools and Manufacture,***37**, Issue 3, 295-307.

[32] Hashish, M. and Due Plessis, M.P., (1979). Prediction equation relating high velocity jet cutting performance to stand off distance and multipasses, *Journal of engineering of Industry,***101**, 311-318.

[33] Zhong Z. W. and Han Z.Z., (2002). Turning of glass with abrasive water jet," Mat. andManuf. Process., **17**, no. 3, 330–349.

[34] Henning A., (1999) Modeling of turning operation for abrasive water jets, *Proc. of 10th American Water jet Conf.,* Houston, Texas, 795– 810.

[35] Ansari A.I. and Hashish M., (1995) Effect of Abrasive Water jet parameters on volume removal trends in turning,*ASME J. of Eng. for Indus*., **117**, no. 4,475–484.

[36] Uhlmann E, Herter S, Roeder M, and Gerstenberger R. (2009). Quasi-static chip formation of intermetallic titanium aluminizes Production engineering – *research and development,**3**, 261-270.*

[37] Hashish M. (1987) Turning with abrasive waterjets - a first investigation. *ASME Journal of Engineering for Industry*,**109**(4):281-290

[38] Manu R. and Babu N.R., (2009) An Erosion-based model for abrasive water jet turning of ductile materials,*Wear,***266**, 1091–1097.

[39] Zohoor Mehdi, ZohourkariIman,(1991) Modeling of Abrasive Water jet Turning,*Australian Journal of Basic and Applied Sciences*, **5(8),** 70-79, 2011
ISSN -8178.

[40] Olson H. John (2007). A Publication of the Fabricator and Manufacturers Association, *www. The fabricator .com.*

[41] Patrick, Hale, (2012). Multi-Modeling of Abrasive Water jet Machining.*Open Access Dissertations and Theses*.

[42] Ward jet. http://www.wardjet.com/02-waterjet-relationship-parameters.html, 26.05.2012.

[43] Filiz, I.Huseyin, (2012). Machine Design-Lecture Notes, Gaziantep

[44] Metals-Properties and Selection,(1990), Nonferrous Alloys and Special-Purpose Materials*, ASM International 10th Ed.*

[45] NevtaşMakine. *http://www.nevtasmakine.com/* , 26.05.2012

[46] Filiz, I.Huseyin, (2009) Machine Elements, solved problems-volume 1 and 2 GaziantepUneversity.

[47] Youssef, H.A., El-Hofy, H. (2008). Machining Technology. Machine Tools and Operations. **13**,978-1-4200-4339-6. U.S.A, CRC Press.

[48] KhanAhsan Ali and Ali Mohammad Yeakub(2011). Application of Silicon Carbide in Abrasive Water Jet Machining, - *ISBN,* 978-953-307-968-4,

[49] Flow. http://www.flowwaterjet.com/en/ask-dr-hashish.aspx, 2012

[50] Folkes, J., (2009). Water jet-An innovative tool for manufacturing, *J. Mater. Process Tech.,***209**, 6181–6189.

[51] Finnie I., (1960) Erosion of surfaces by solid particles,**3,** 2, 87–103,