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Abrasive Water Jet Machining- A Review

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Abstract: *As a manufacturing tool, the use of multi-axis machines is increasing rapidly. Nowadays, the Abrasive Water Jet Machining (AWJM) is a non-traditional method that offers a productive alternative to conventional techniques. Material removal occurs through erosion and results from the interaction between an abrasive material and given specimen. It is environment friendly and can machine any type of material almost up to depth over 100 mm. It is a non-conventional method used in industries, having wide range of applications from automotive and aerospace to medical and food industries. To vanish the tolerances, it is an attractive micro-machining method which uses different operations like cutting, polishing and deburring. In this present study, information of material, advantages, limitations, applications, characteristics and observations of AWJM are configured properly and equipped in definite manner.*
Keywords: *Abrasive, AWJM, Erosion, Manufacturing tool, Micro-machining.*

I. Introduction

Abrasive water jet machining technology is one of the most recent non-traditional methods used in the industry for material processing with the distinct advantages of small cutting forces, high flexibility, high machining versatility and no thermal distortion. It is the machine in which the water is an important accelerating medium where the material removal is done by using abrasive particles. This mechanism was first came in late 70's and developed by Franz to cut laminated paper tubes in 1968 and glasses in 1983. Actually, it is used for replacing coated wet saws which were responsible for stone cutting. The cutting of material with water is developed from river water. A stream of small abrasive particles is introduced in the water jet in such a manner that water jet's momentum is partly transferred to the abrasive particles. A high speed jet is achieved as the water accelerates in large quantities of abrasive particles to a greater velocity. To attain this high velocity, the particles are allowed to pass through a nozzle with compress carrier gas or air. So, this can be the advantage over conventional machining processes of enabling the accurate control of the removal of material rate. Due to less cost and more efficiency, cutting of stones and tiles usually done by abrasive water jet. Plane water jet cutting is useful on soft materials like "paper, food, textiles, paper and wood".

Generally, the abrasives used in AWJM are Garnet, Aluminium Oxide (Al2O3), Diamond and Silicon Carbide (SiC). The feed speed has been adjusted to enable full jet penetration for each type of abrasive while keeping some parameters like size of abrasive, pump pressure and stand-off distance [1]. Also, cutting, drilling, milling, surface preparation, cleaning, coating removal, water jet peening, water jet forming are various processes which can be performed with the help of water jet [2].

AWJM is complementary to Laser machining system. Operators of both type of system exploit the cutting speed of lasers on materials such as Steel and use abrasive water jets to cut materials that are difficult to cut with their laser systems. Lasers are rapidly evolving with exploitation of new beam generation modes, development of smaller beam diameters for micromachining, sustaining improvements in the efficiency of cutting generation of beam, power densities and higher cutting beam powers etc [3]. When the harden material to be cut, then the addition of a fine abrasive like Garnet allows to cut material, then it may be tool steel or marble up to 8 inches (203.2 mm) in thickness [4].

II. Study Of Experimental Procedure

Water is an accelerating medium which is compressed to very high pressures up to 1,00,000 PSI or more than that with the help of an Intensifier pump. On this, water will try to escape somewhere because of its incompressible property. This highly pressurized water is directed along high pressure piping through an orifice having very small diameter in between 0.0005 mm to 0.15 mm. The velocity of pressurized water is double the speed of sound. A mixing tube is employed after an orifice. The water create a vacuum that will pull the abrasives from a hopper. So, the jet is ready to cut any material. This prepared jet when comes along the material, it cuts some portion of the material having fine quality. This depends on thickness of material, speed of cut and type of garnet used. The difference between the size of kerf and width of tube orifice is 10 % and kerf is always greater than tube orifice [4].

III. Materials Used In AWJM

Table 1 summarizes various properties like components volume, average particle size, Vickers hardness number and Bond Work Index of Abrasive Water Jet Cutting (AWJC) materials. The most common abrasive used in water jet cutting is Garnet. Three sets of natural mineral abrasive types with varying concentrations of hessonite, grossularite and andradite (an iron rich grossular garnet occurring in this sample predominantly in a poly-crystalline form) were also prepared from crushed rock.

Study shows that, tensile stresses are introduced in the particles when brittle particles are loaded in compression or by impact. For splitting failure of brittle particles, these tensile stresses are responsible. Theoretical calculation of tensile strength of natural materials using the strengths of atomic bonds is ineffective as it is about 2 orders of magnitude lower than those predicted theoretically. Then strength is said to be structure sensitive property. Because, randomly oriented cracks or fractures are caused by the stress concentration around Griffith cracks. The energy required to fragment a material of one size to that of another is indicated by Bond Work Index (BWI). But, it is based on the assumption that the material is not ductile. BWI of abrasives was determined so as to evaluate its resistance to fragmentation during AWJC by impact with the machined material or within the mixing the tube. This method is widely used in designing full-scale grinding mills [5]. At low cutting depths, abrasives impinge on the target material at shallow angles [6].

Table 1: Summary Of Abrasives

Test abrasive	Components (% volume)	Average particle size (μm)	Vickers Hardness (kg/mm^2) and std. dev.	Bond Work Index
HDG (high density crushed glass)	100% Glass	715-152.5	1059 HV_{10} (201 HV_{10})	26.3
GMA 80 (almandine garnet)	84% garnet, 14% ilmenite, 2% carbonates	251	2711 HV_{10} (387 HV_{10})	37
TC-TU (grossular garnet and andradite)	43% hessonite garnet, 38% grossular garnet, 13% plagioclase (anorthite)	193	1799 HV_{10} (616 HV_{10})	32.6
TC-C1 (grossular garnet)	48% hessonite garnet, 38% grossular garnet, 13% plagioclase (anorthite)	193	2192 HV_{10} (535 HV_{10})	32.6
TC-K1 (grossular garnet)	63% hessonite garnet, 16% grossular garnet, 20% plagioclase (anorthite), 2% pyroxene	152	2130 HV_{10} (851 HV_{10})	34
PRC #3 (raw beach sand containing a high proportion of dense minerals)	26% garnet, 28% pyroxenes, 11% amphiboles, 10% serpentine, 9% carbonates, 6% staurolite, 5% ilmenite, 3% quartz, 2% magnetite	220	2090 HV_{10} (546 HV_{10})	27.7
Zircon	100% zircon	112	2823 HV_{10} (897 HV_{10})	39.5

3.1 Nozzle

Nozzle is an important part of AWJM through which the pressurized abrasive water jet comes outside the machine to cut the material as shown in Fig. 1.

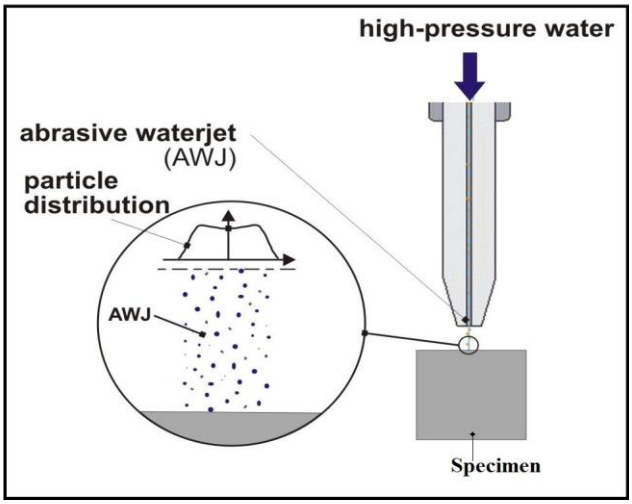


Fig. 1 Nozzle

It is made up of High carbon high chromium tool steel which contains 2.15% C; 12% Cr; 0.35% Mn; 0.2% Si; 0.8% Mo etc. It is having hardness nearly about 45 to 55 HRC. The length of the nozzle varies from 8.16 mm to 16.18 mm and diameter also lies between 0.8 mm to 1.62 mm. An entrance angle of AWJM can be 60^o, 90^o or may be 120^o as well as its inlet gauge pressure is 32.2780 N/m^2. It is having flow rate 3.5348 ltr/min. The mixture ratio flowing through nozzle can be defined as:-

$$\text{Mixture ratio} = \frac{\text{mass flow rate of abrasive particles}}{\text{mass flow rate of air and abrasive particles.}}$$

The distance between nozzle tip and workpiece surface is called "Stand-off distance" as shown in Fig. 2. Also, it is the most important parameter to be considered or controlled as well as feed rate and impingement angle are also important parameters as shown in Fig. 3. As length of the nozzle increases, nozzle's diameter and entrance angle decreases, so the wear also increases. The life period of nozzle can be 250 to 500 hours [7].

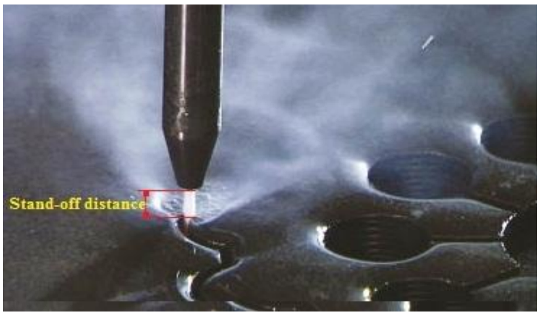


Fig. 2 Stand-off distance

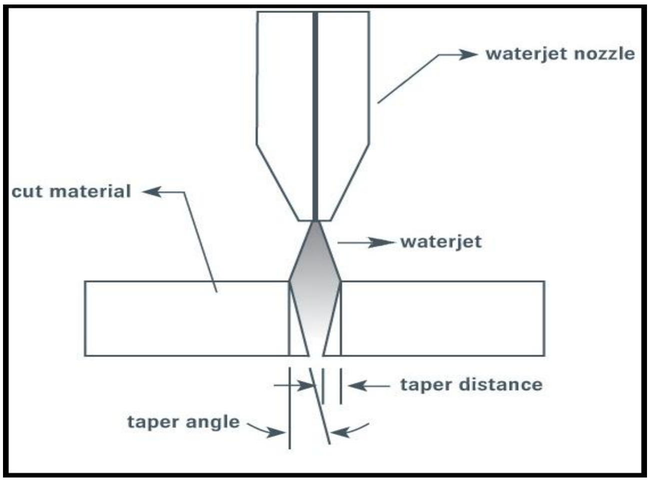


Fig. 3 Some important parameters of AWJM

IV. Review On Experimental Observations

4.1 Geometry of Kerf

Due to decrease in water pressure, the top kerf is always wider than bottom one as shown in Fig. 4. The kerf side view while entry in the workpiece and at the exit is as shown in Fig. 5 [8].

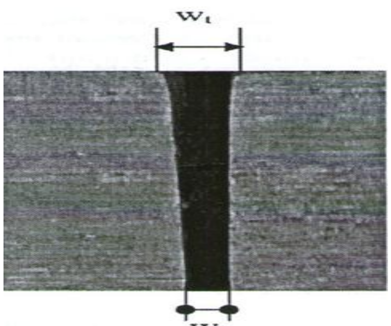


Fig. 4 A typical side view of the kerf

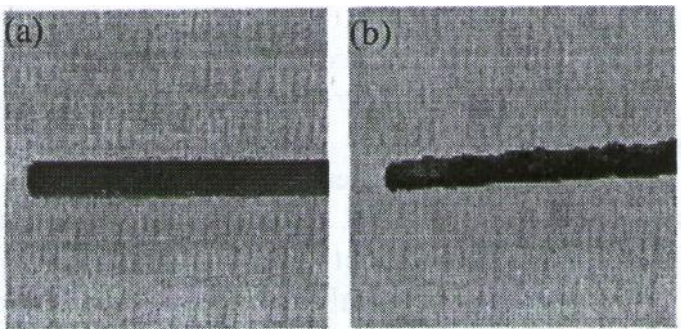
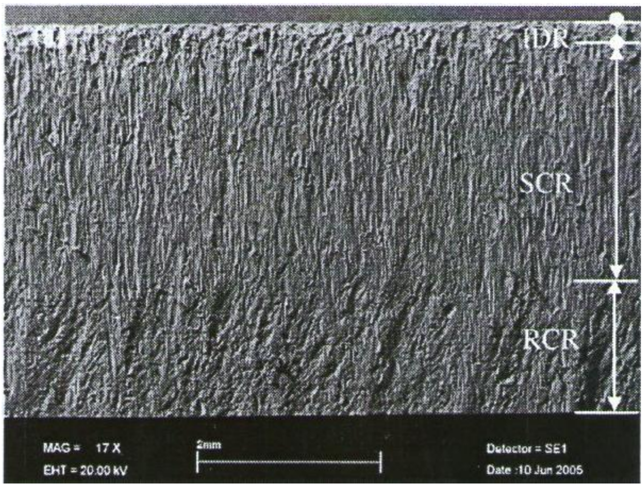


Fig. 5 A view of jet entry (a) and jet exit (b)

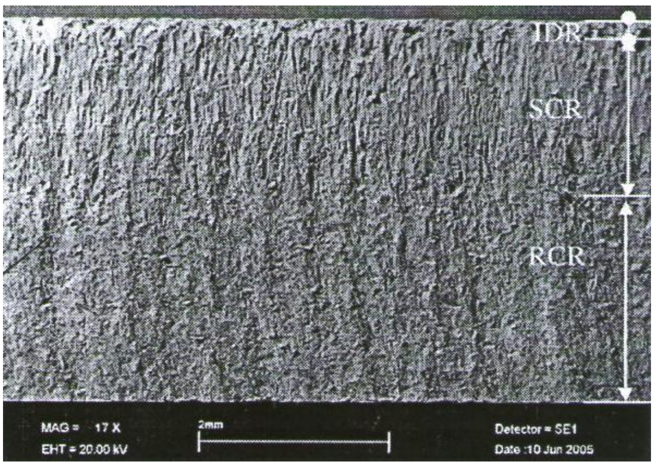
As traverse speed increases, top and bottom kerf widths decreases as well as kerf wall slope slightly increases. The kerf taper angle for each cut canbe given as:
θ = arc tan[(Wt – Wb)/(2xt)] …where, Wt ≡ top kerf width, t ≡ thickness of material, Wb ≡ bottom kerf width. [8]

4.2 Surface morphology

At 60 to 200 mm/min traverse speed, cutting surface view of sample is as shown in Fig. 6. Micro-structural evaluation of cutting surfaces of samples revealed three distinct zones named as: (1) an Initial Damage Region (IDR), it's a cutting zone at shallow angles of attack; (2) a Smooth Cutting Region (SCR), it's a cutting zone at large angles of attack; (3) a Rough Cutting Region (RCR), it's the jet upward deflection zone [8].



(a)



(b)

Fig. 6 AWJ machined surface for traverse speed of 60mm/min and (b) 200mm/min

From Fig. 6, as the traverse speed increases, the number of particles impinging on a given exposed target area decreases which reduces the IDR width slightly as well as SCR width also decreases, because the depth of penetration decreases. The mechanism of material removal is a combination of scooping induced ductile shear and ploughing actions of the abrasive particles. This one was revealed by Scanning Electron Microscopy analysis of the cutting surface texture [8].

4.3 SCR depth and surface roughness

Fig. 7 shows surface roughness versus depth of measurement with respect to traverse speed. The surface roughness is approximately constant as the depth of the cut gets deeper in SCR. After that, the surface quality deteriorates, because the jet loses its energy due to the jet material interaction and mutual particle impacts. So, it can be noticed that an increase in the traverse speed causes a constant increase in the surface roughness i.e. as increasing traverse speed allows less overlap machining action and some few abrasive particles to impinge the surface, increasing the surface roughness. In 60 to 200 mm/min, surface roughness values (Ra) measured as 2.3-3.57 μm at same measurement depth [8].

The two major characteristics of AWJ are the smooth cutting region and depth of cut. Smooth cutting regions is the average surface quality. For different traverse speeds, the depth of smooth cutting regions is as shown in Fig. 7.

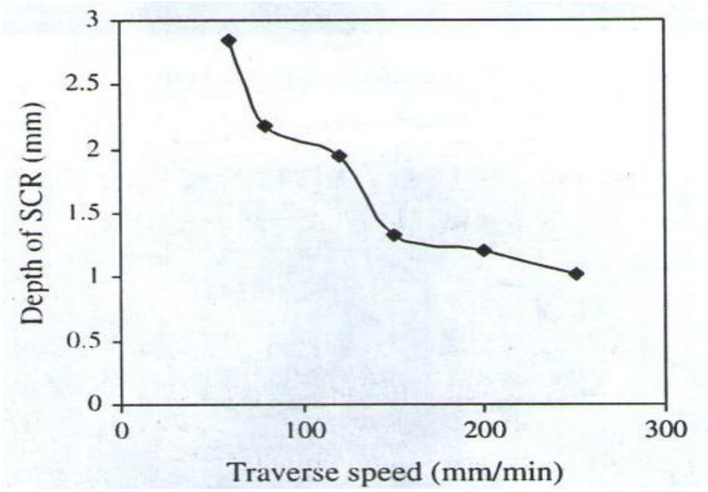


Fig. 7 The depth of smooth cutting regions for different traverse speeds

The depth of cut represents the capacity of jet to penetrate into the material. The traverse speed appears a significant parameter on a depth of SCR. Because, the SCR decreases nearly about to 25% of total cutting surface area at high traverse speed and 60% at low traverse speed [8].

V. Advantages

The biggest advantage of AWJM is that it can cut every type of material. Some more advantages are listed below:-

It is faster than EDM and can be cut much thicker materials than laser. Lasers and EDM cannot handle reflective materials and non-metals respectively. AWJM does not require start hole likewise EDM. So, it is clear that AWJM is better than EDM, laser, CNC etc. It can produces very little side force without warpage or deflector. For stamping and blanking operations, the advantage is that hard tooling for presses takes a long time to developed and also expensive. By using better programming, parts to be cut can be separated by .0.5" wall, so the scrap generation will be reduced one. Minimum stresses are induced and it has less cutting forces while operation [4].

VI. Limitations

There are some limitations also along with the advantages of AWJM like:-

- It requires a clean, filtered and soften water which is free from dust particles and minerals in large amount.
- After water requirement, huge quantity of sharp abrasive is required.
- Wastage of abrasives which can be used as landfill material.
- AWJM produces matte finish on the specimen while working.
- It produces noise having intensity more than 100 dB which is harmful to ears. So, protection is one of the main requirement. [4]

VII. Applications

In various processes where material removal is important, AWJM has an important role to play. The polishing of surfaces, deburring, and finishing operations can be carried out effectively using abrasive jet machining. Ordinary, optical and toughened glass are machined easily by this process. Brittle materials for which conventional machining processes may cause practical difficulties and vast changes in material properties, can be machined easily and successfully using abrasive jet machining.

7.1 Platinum cutting: The cutting of Platinum is very difficult to cut due to its gummy characteristics and high density. To cut it and obtaining good surface finish, a PCD tool is used which is very expensive. Bu, in some cases like cutting ring blanks from tubing, PCD will not survive. Even wide kerfs can be produced by using carbides or high speed steel tools which gives high scraps but takes a time.

So, tooling is the biggest obstacle, but AWJM do not have tooling to wear, re-sharpen and water jet and AWJM do not think about density and gummy characteristics of Platinum. Therefore the cutting of Platinum is better by using AWJM [4].

7.2 For Brittle materials: Brittle materials for which conventional machining processes may cause practical difficulties and vast changes in properties of material can be machined easily with AWJM [7].

7.3 For Automobile parts: The use of AWJM in Automobile industries is increasing day by day for preparing plates, gears etc.

Fig. 8 Automobile parts made by AWJM

VIII. Surface Characteristics

It is expressed as Roughness average (R_a), Root mean square (rms), Roughness (R_q), maximum peak to valley roughness (R_y or R_{max}). Surface roughness is responsible for technological quality of a product and a factor which greatly influences manufacturing cost. It is defined as the arithmetic value of the profile from centerline along the sampling path. The cut quality and abrasive embedment following water jet cutting of a commonly used titanium alloy, Ti6Al4V with 80 mesh garnet from five different sources (differing significantly in their hardness, crushing strength and morphology) were examined by Boud et. al (2010). The cut-face itself was examined to establish the presence or absence of sub-surface embedded abrasive; in addition, the top surface of the plateclose to the cut where particles outside the main core of the jet may have impinged was also examined. Embedment levels, surface waviness, roughness and the mechanisms of abrasive surface interactions were evaluated through a combination of scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX) and profilometry. It was found that despite the differences in abrasive characteristics, no significant differences in cut quality or abrasive embedment was seen. The effects of feed rate and thickness of workpiece on the roughness were explained as considering experimental data like effects of composition of the material on surface roughness were assessed. Al-6061 aluminium alloy, brass-353 ($\alpha + \beta$ brass), AISI 1030 and AISI 304 steel materials were cut with AWJM at various feed rates in pure aluminium. The effects of feed rate explained by Adnan Akkurt et al. (2004).

Gudimetla et al. (2002) found the machinability and kerf formation characteristics associated with the abrasive water jet cutting of industrial ceramics. It was found that at low cutting rates, the erosive process is associated with the initial surface fracture leading to a high degree of plastic flow and deformation of the subsurface, probably due to the incidence of high thermal stresses at the jet-target interaction zone. At higher speeds, surface fracture results in an intergranular network propagating downward, creating a critical shear plane that forms a kerf due to the hydrodynamic forces within the water jet. This study reveals that there exists a combination of process parameters for the effective machining of ceramics. A grooving wear effect exists for the uncut through kerf. Experimental study of the surface quality produced by abrasive water jet on metallic materials has been performed by Jack Valicek et al. (2007). The surface roughness/waviness was quantitatively evaluated by using the contactless optical measurement. In order to characterize the cut surface qualities, a single parameter criteria 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.

Arola and Ramulu (1997) determined the influence of material properties on the surface integrity and texture that results from abrasive water jet machining of metals. A microstructure analysis, microhardness measurements and profilometry were used in determining the depth of plastic deformation and surface texture that results from material removal. Models now available for dry abrasive erosion were adopted and found useful in understanding the influence of material properties on the hydrodynamic erosion process. The milling behavior of Ti6Al4V observed by Shipway et al. (2005). It is expressed in the terms of surface properties of the milled component like roughness, waviness and grit embedment level. The properties of the surface following milling depend strongly on the milling parameters such as jet-workpiece traverse speed, waterjet pressure, abrasive size and impingement angle.

Chetan et al. (2002) explained the microstructure by using scanning electron microscope (SEM) and advances surface analysis technique to quantitatively evaluate particle embedment at abrasive water jet generated mild steel surfaces. The pump pressure, traverse speed and cutting depth are the factors responsible for particle embedment. A new nozzle oscillation was applied to the AWJ cutting process in order to reduce contamination by embedded particles. The particle embedment at the surface could be reduced up to 200% by using the new nozzle application technique compared to the traditional AWJ technique under identical input cutting conditions. Orbanic and Junkar explained the macro-mechanism of AWJC from the point of cutting front and striation formation analysis. The striation on the surface cut with AWJ is a characteristic phenomena which is strongly present when cutting with high traverse velocities for particular material type and thickness of workpiece. The connection between the cutting front step formation was described through series of experiments which contains visual observations of cutting transparent material and through analogies, which deal with river meandering and wear of pneumatic conveyor bends.

Chen and Siores (2003) described the characterization of different materials cut surfaces by using a single electron microscope. The effect of abrasive particle distribution in the jet on striation formation was detailed. A non-invasive technique; laser Doppler anemometry was used to analyze the abrasive particle distribution in the jet. The mechanisms of striation formation were discussed in detail and an effective striation minimization technique applied to the cutting process was outlined. In 2009, Azmir and Ahsan explained kerf taper ratio (T_R) and surface roughness (R_a) of an abrasive water jet machined surfaces of glass/epoxy composite laminate. Taguchi's design of experiments and analysis of variance were used to determine the effect of machining parameters on T_R and R_a. The most significant control factor in influencing R_a and T_R considered were type of abrasive materials and Hydraulic pressure [1].

IX. KERF Characteristics

The "through" and "non-through" cuts are two types of kerfs produced in AWJM. A through cut is formed, when the jet is provided with sufficient energy. It has wider entry and gradual reduction towards exit afterwards, so a kerf taper is formed. When there is no penetration of the specimen by jet, a cut is formed which is known as non-through cut.

The study of metallic coated sheet steels presented by Wang and Wong in 1999 which is based on statistically designed experiment and it has proved that the cutting by using abrasive water jet machine is a long laster technology for processing metallic coated sheet steels with good kerf quality and productivity. The machinability experimental investigation showed that this technology is effective alternative for polymer matrix composite processing with good kerf quality and productivity. Also, by using a kerf-taper compensation technique, there is an elimination of kerf taper in alumina ceramics. Kerf-taper compensation angle have most significant effect on the kerf taper and its angle changes with compensation angle i.e. it is possible to achieve a zero kerf taper angle without compromising the nozzle traverse speed or cutting rate.

The kerf taper angle generated by abrasive water jet technique to machine the composites like glass epoxy and pre-impregnated graphite woven. In the change of the traverse speed, water pressure, stand-off distance and abrasive flow rate, comprehensive factorial design of experiments were conducted. The kerf taper angle relates to the operating parameters in a predictive model form by using the dimensional technique and adopting the energy conservation approach. Verification of the model for using it as a practical guideline has been found to agree with the experiments. There is an influence of key kinematic operating parameters like α-jet impingement angle and v-jet feed rate on the kerf geometry as well as its dimensional characteristics [1].

X. Effect On Surface Roughness

The surface roughness results of 5 mm thickness specimens cut with AWJC are higher than 20 mm thickness specimens [9].

10.1Effect of Water Jet pressure

The effect of water jet pressure on the surface roughness is analyzed in conjunction with the thickness of the cut. As water jet pressure increases, there is increase in surface quality. So, it results in decrease in surface roughness. Fig. 9. shows the effect of water jet pressure on the surface roughness. As the depth of cut increases, the effect of water jet pressure on surface roughness also increases [10].

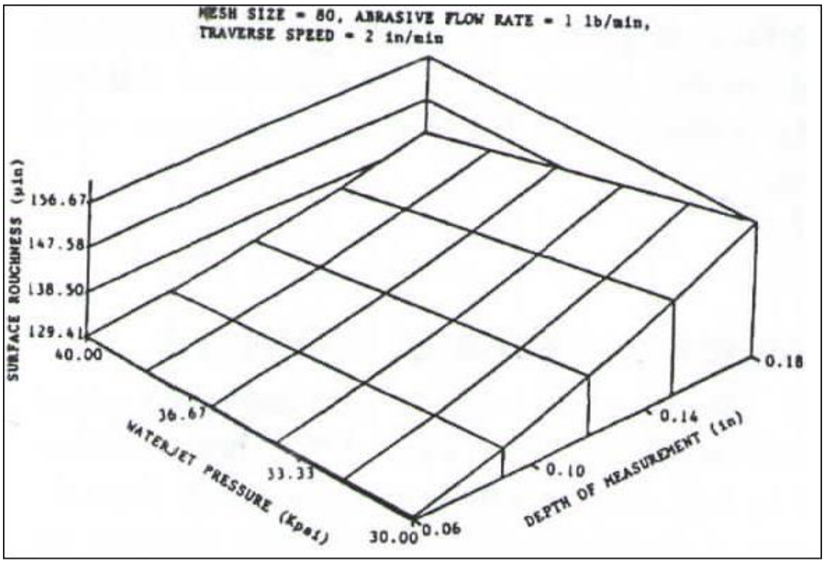
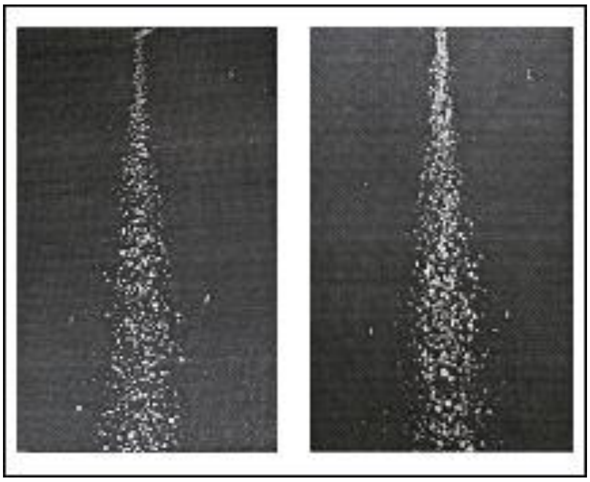


Fig. 9 Effect of water jet pressure on surface roughness

Following is the picture for the particle jet flow under different diameters of nozzle [11].



(a) **(b)**

Fig. 10 Particle Jet flow under 0.6 MPa for (a) 0.36 and (b) 0.46 mm nozzle

10.2Effect of abrasive flow rate

As the depth of cut increases, the effect of abrasive flow rate on surface roughness increases. But, there are some abrasives due to which with increase in their flow rate, the surface roughness decreases and Garnet of mesh No. 170 is one of them. Fig. 10. shows the effect of abrasive flow rate on the surface roughness [10].

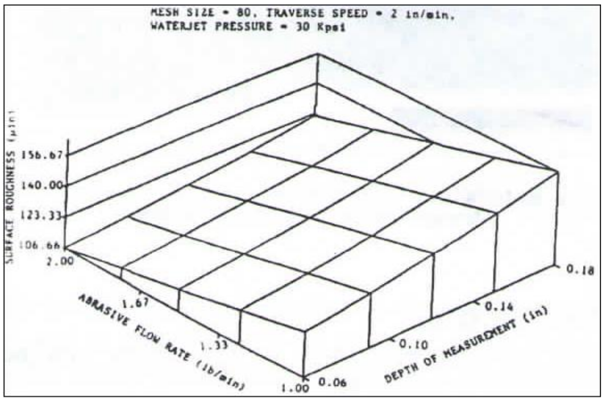


Fig. 10 Effect of Abrasive grain size on surface roughness

XI. Residual Stresses In Awjc

Sometimes, Residual stresses develop in the cutting material during operation. These stresses are compressive in nature. The stress magnitude in the cpTi ranged from 60 to 200 MPa and in Ti6Al4V, it ranges from 30 to 400 MPa. The largest compressive residual stress recorded in the cutting material is nearly about equal to 180 MPa [12].

XII. Safety

The most dangerous thing is the jet itself. It can easily cut any type of human body and second one is an exposed jet creates highest noise level which affects on human ears. These two factors are most difficult to deal with in fully three-dimensional cutting in applications like removing risers from castings with abrasive jets. The solution for these factors is sealing the entire apparatus in a cutting box or room completely. In cutting shapes from or slitting flat materials, the problem is much less severe. The nozzle is kept very close to the material for both safety and best cutting performance and the jet is received in a catcher immediately below the material. When cutting materials where wetting is not an issue, it's a good idea to cut half or more under water. This almost eliminates any noise of jet and makes a cleaner operation by suppressing splash back and mist that carries fine abrasive dust [13].

XIII. Conclusion

The Abrasive Water Jet Machine is a dynamic and versatile machine used in applications like forming, cutting, cleaning, milling and drilling. It can machine any type of material. Therefore, from above paper, the following conclusions can be drawn:-

1. AWJM is receiving more and more attention for machining hard materials for cutting purpose.
2. The process can be used with or without using abrasive materials and new applications are continuously being used.
3. AWJM is a damage-free and high potential method for hard and brittle materials i.e. Ceramics and High Carbon Steels.
4. It's an environment friendly method.

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