ABRASIVE WATER JET CUTTING OF STAINLESS STEEL

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CANDIDATE'S DECLARATION

I hereby declare that the work done in this project entitled "**Abrasive Water Jet Cutting of Stainless Steel**" in the partial fulfillment for the award of degree of "**MASTER OF ENGINEERING"** with specialization in "**PRODUCTION & INDUSTRIAL ENGINEERING"** submitted to **Delhi College of Engineering, University of Delhi,** is an authentic record of my own work carried out under the supervision of **Mr. Vipin**, Assistant Professor, Department of Mechanical Engineering, Delhi College of Engineering, University of Delhi. I have not submitted the matter in this dissertation for the award of any other Degree or Diploma or any other purpose whatsoever.

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The matter in this dissertation has not been submitted to any other university or institute for the award of any degree.

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(MUKESH KUMAR)

ABSTRACT

An abrasive water jet is a jet of water which contains abrasive material. Usually the water exits a nozzle at a high speed and the abrasive material is injected into the jet stream. The purpose of the abrasive water jet is to perform machining or finishing operation such as cutting etc. The use of the abrasive water jet for machining or finishing purposes is based on the principle of erosion of the material upon which the jet hits.

It is found from the study and analysis that to improve product quality to a greater extent by considering all factors (i.e. Thickness of Material, Pressure, Abrasive Flow rate, Orifice diameter and mixing tube diameter).

Linear Multiple Regression Software is used to solve the equations of the dependent and independent variables.

A C++ program is developed to solve the cutting speed of smooth, rough surface and Actual cutting power problem in a convenient way.

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CHAPTER 1

INTRODUCTION

An abrasive water jet is a jet of water which contains abrasive material. Usually the water exits a nozzle at a high speed and the abrasive material is injected into the jet stream. This process is sometimes known as entrainment in that the abrasive particles become part of the moving water much as passengers become part of a moving train. Hence as with a train the water jet becomes the moving mechanism for the particles. However a high speed jet of a pre mixture of the abrasive and the water would also be defined as an abrasive water jet. The purpose of the abrasive water jet is to perform some machining or finishing operation such as cutting, boring, turning, etc.

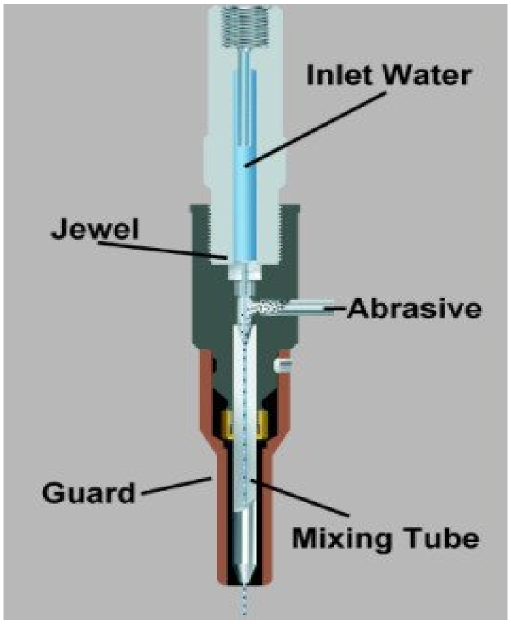


Figure 1.1: Abrasive Water Jet

The use of the abrasive water jet for machining or finishing purposes is based on the principle of erosion of the material upon which the jet hits. Each of the two components of the jet, i.e. the water and the abrasive material has both a separate purpose and a supportive purpose.

It is the primary purpose of the abrasive material within the jet stream to provide the erosive forces. It is the primary purpose of the jet to deliver the

Abrasive material to the work piece for the purpose of erosion. However the jet also accelerates the abrasive material to a speed such that the impact and change in momentum of the abrasive material can perform its function. In addition it is an additional purpose of the water to carry both the abrasive material and the eroded material clear of the work area so that additional processing can be performed. In one way or another in any machining process the spent material must be gotten out of the way and the water jet provides that mechanism.

1.1 HISTORICAL BACKGROUND

High-pressure water jets are in continuous development from 1900 onwards. In the USA these jets were introduced in mining applications to wash out valuable materials like gold by excavating the soft gold bearing rocks.

In the early 60's O. Imanaka, University of Tokyo applied pure water for industrial machining. The idea was based on the destruction of shell structures of air-planes by rain particle impact.

In the late 60's R. Franz of University of Michigan, examine the cutting of wood with high velocity jets. He got the idea from the way steam leaks were detected on invisible spots. A broom was moved through the locations where the leak was expected. By the damage to the broom the idea came up that a jet of high velocity water could also cut materials.

This led to the first industrial application manufactured by McCartney Manufacturing Company and installed in Alto Boxboard in 1972.

From that time high-pressure water jets were utilized in cutting soft materials like wood and leather. But also hard and brittle materials like granite and bricks and even some tough materials like titanium were cut with pure water.

Research led to the invention of the abrasive water jet in 1980 and in 1983 the first commercial system with abrasive entrainment in the jet became available. The added abrasives increased the range of materials, which can be cut with a Watergate drastically. Higher traverse speeds, thicker materials and better edge quality could be achieved.

1.2 USES OF ABRASIVE WATER JET MACHINING

Abrasive water jet machining if appropriate and cost effect for a number of procedures and materials. Several of these are listed below:

- ✓ Cutting of difficult-to-machine materials by abrasive water jets.
- ✓ Milling and 3-D-shaping by abrasive water jets.
- ✓ Turning by abrasive water jets.
- ✓ Piercing and drilling by abrasive water jets.
- ✓ Polishing by abrasive water jets.

These operations are similar to just plain water jet machining but because of special considerations such as the type of material or shape complexity require the addition of the abrasive phase. Operations where plain water jet machining would be sufficient include:

- ✓ Cutting of materials such as plastics, thin metal, textiles, or foam
- ✓ Deburring
- ✓ Surface Penning
- ✓ Conventional machining with water jet assists.

1.3 ABRASIVE WATER JET MACHINING VS OTHER METHODS

Abrasive water jet machining is a relatively new machining technique in that it makes use of the impact of abrasive material to erode the work piece material. It relies on the water to accelerate the abrasive material and deliver the abrasive to the work piece. In addition the water afterwards carries both the spent abrasive and the eroded material away from the working area. Conventional machining practices such as milling use a solid tool to cut the material usually by a shearing process. Conventional machining may also use a liquid medium in conjunction with the

cutting tool but its purpose is not to deliver but to carry away the material. In addition for both conventional and abrasive
Water jet machining the liquid medium will also act as a heat sink, taking heat away from the machining area.

1.4 When comparing with LASERS

- Abrasive water jets can machine many materials that lasers cannot. (Reflective materials in particular, such as Aluminum and Copper).
- Uniformity of material is not very important to an Abrasive jet.
- Abrasive jets do not heat your part. Thus there is no thermal distortion or hardening of the material.
- Precision abrasive jet machines can obtain about the same or higher tolerances than lasers (especially as thickness increases).
- Your capital equipment costs for water jet are generally much lower than that for a laser, i.e. for the price of a laser; you can purchase several abrasive jet-machining centers.
- Abrasive jets can machine thicker materials. How thick you can cut is a function of how long you are willing to wait. 2" (50mm) steel and 3" (76mm) aluminum is quite common. However, Lasers seem to have a maximum of 0.5" (12mm) - 0.75" (19mm).
- Abrasive jets are safer. No burnt fingers, no noxious fumes, and no fires. (You still have to keep those fingers out of the beam.)
- Abrasive jets are more environmentally friendly.
- Maintenance on the abrasive jet nozzle is simpler than that of a laser, though probably just as frequent.
- Abrasive jets are capable of similar tolerances on thin parts, and better on parts thicker than .5"
- Abrasive jets do not loose much "focus" when cutting over uneven surfaces.
- While lasers are often faster on thinner materials...

    - It may be cheaper and faster to simply buy two or three abrasive jet machining centers to do the same work

  - You can stack materials, so you are cutting multiple thin parts simultaneously.
  - You can run additional cutting heads in parallel on a single machine

- Modern Abrasive jets are typically much easier to operate and maintain than lasers, which means that every employee in your shop can be quickly trained to run one!
- Abrasive jets don't create "scaly" edges, which makes it easier to make a high quality weld
- Many shops that have lasers also have water jets, as they are complimentary tools. Where one leaves off, the other picks up.

1.5 When comparing with EDM

- Abrasive jets are much faster than EDM.
- Abrasive Jets machine a wider variety of materials (virtually any material).
- Uniformity of material is not very important to an Abrasive jet.
- Abrasive jets make their own pierce holes.
- Abrasive jets do not heat the surface of what they machine.
- Abrasive jets are capable of ignoring material aberrations that would cause wire EDM to lose flushing.
- Abrasive Jet machining is useful for creating start holes for wire insertion later on. (a mill could do the job, but only after spotting the hole, changing tools to drill a pilot, then changing tools again to drill out the hole).
- New technology allows Abrasive jets to obtain tolerances of up to +/-.003" (0.075mm) or better (I have personally done some +/-.001" (0.025mm) work, but that's the exception, not the norm, and only on certain shapes and materials.)
- No heat affected Zone with Abrasive jets.
- Abrasive jets require less setup.
- Make bigger parts.
- Many EDM shops are also buying water jets. Water jets can be considered to be like super-fast EDM machines with less precision. This means that many parts of the same

category that an EDM would do can be done faster and cheaper on an abrasive jet, if the tolerances are not extreme.

1.6 When comparing with PLASMA / FINE PLASMA

- Abrasive jets provide a nicer edge finish
- Abrasive jets don't heat the part
- Abrasive jets can cut virtually any material
- Abrasive jets are more precise
- Plasma is typically faster
- Water jets would make a great compliment to a plasma shop where more precision or higher quality is required or for parts where heating is not good, or where there is a need to cut a wider range of materials.

1.7 When comparing with FLAME CUTTING

- Abrasive jets provide a much nicer edge finish
- Abrasive jets don't heat the part
- Abrasive jets can cut virtually any material
- Abrasive jets are more precise
- Flame cutting is typically faster
- Flame cutting is typically cheaper, if you can use it.
- Water jets would make a great compliment to a flame cutting where more precision or higher quality is required or for parts where heating is not good, or where there is a need to cut a wider range of materials.

1.8 ADVANTAGES OF AWJ MACHINING

1.8.1 Extremely fast setup and programming

No tool changes required, so there is no need to program tool changes or physically qualify multiple tools. For some systems, programming simply involves drawing the part. If you customer gives you that drawing on disk, half the battle is won.

1.8.2 Very little fixturing for most parts

Flat material can be positioned by laying it on the table and putting a couple of 10 lb weights on it. Tiny parts might require tabs, or other fixturing. At any rate, fixturing is typically not any big deal.

1.8.3 Very low side forces during the machining

This means you can machine a part with walls as thin as .025" (0.5 mm) without them blowing out. This is one of the factors that make fixturing is so easy. Also, low side forces allow for close nesting of parts, and maximum material usage.

1.8.4 Almost No heat generated on your part

You can machine without hardening the material, generating poisonous fumes, recasting, or warping. You can machine parts that have already been heat treated with only a tiny, tiny decrease in speed. On piercing 2" (50mm) thick steel, temperatures may get as high as 120 degrees F (50 C), but otherwise machining is done at room temperature.

Aerospace companies (HAL, Nasik) use abrasive jets a lot because of this.

1.8.5 No start hole required

Wire EDM, eat your heart out. Start holes are only required for impossible to pierce materials. (Some poorly bonded laminates are about the only materials I can think of off hand)

1.8.6 Machine thick stuff

This is one huge advantage Abrasive jets have over lasers.

While most money will probably be made in thicknesses less than 1" (25mm) for steel, it is common to also machine up to 4" (100mm). The cutting speed is a function of thickness, and a part twice as thick will take more than twice as long. Typically, most money is made on parts 2" (50mm) thick or thinner.

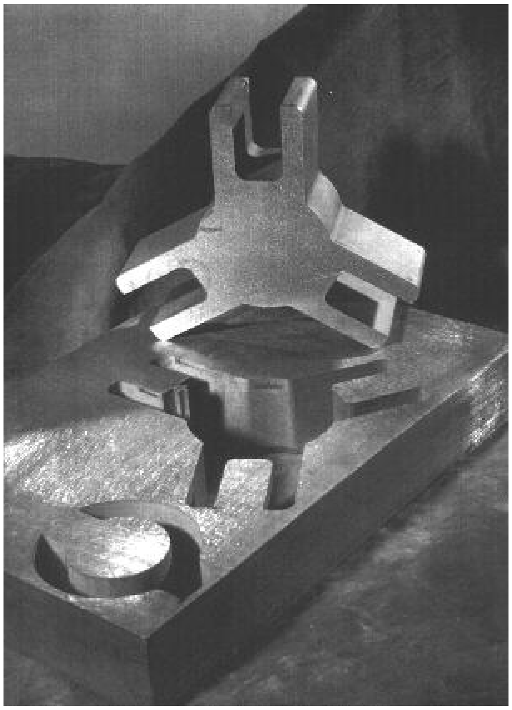


Figure 1.2: Thick Piece of 304 Stainless Steel

Pictured here is a 2" (50mm) thick piece of 304 stainless steel. In 1993 when this part is cut, it took just under 3 hours with a very small 10 horsepower pump and old control software to machine this to a tolerance of +/-.005" (0.125mm).   Today, using a 40 HP direct drive pump, and modern control software, this could be machined to the same tolerance in under an hour (including programming, setup, etc.)

1.8.7 Environmentally Friendly

Green Peace does not like some of those other tools in your shop. Not much of an issue now, but in the future I would expect the pressure will be on. There will be nothing to machine if our ecosystem collapses and all your customers die. Short of hand tools, abrasive jets provide the most environmentally friendly machining around. (Some of the pumps even use vegetable oil for assembly lube because water jets are used in the food industry).

As long as you are not machining a material that is hazardous, the spent abrasive and waste material become suitable for land fill. The red color of garnet abrasive also looks nice in your garden. If you are machining lots of lead or other hazardous materials, you will still need to dispose of your waste appropriately, and recycle your water. Keep in mind, however, that very little metal is actually removed in the cutting process. This keeps the environmental impact relatively low, even if you do machine the occasional hazardous material.

1.8.8 There is only 1 tool

There is no need to qualify multiple tools, or deal with programming tool changes. Programming, Setup and Clean up time is reduced significantly, meaning you make more money because you can turn more parts faster.

1.8.9 Here are some of the benefits to using a water jet

- Cheaper than other processes.
- Cut virtually any material:

  - Pre hardened steel
  - Mild steel
  - Exotics like Titanium, Inconel
  - 304 stainless
  - Brittle materials like glass, ceramic, quartz, stone.

- Cut thin stuff, or thick stuff
- Make all sorts of shapes with only one tool.
- Cut wide range of thickness' to reasonable tolerance up to 2" (50mm) thick
- Up to 5" (127mm) or thicker where tolerance not important, or in soft materials.
- No Heat Generated / No heat affected zones - this is cold cutting!

- No mechanical stresses
- Cut virtually any shape:
- Fast Setup:
- Only one tool to qualify / No tool changes required
- Fast turn around on the machine. Make a part, then 2 minutes be making a completely different part from a completely different material.
- Leaves a satin smooth finish, thus reducing secondary operations
- Clean cutting process without gasses or oils
- Makes its own start holes
- Narrow kerf removes only a small amount of material.
- Your "scrap" metal is easier to recycle or re-use (no oily chips!)
- Modern systems are now very easy to learn.
- You can trade off tolerance vs speed from feature to feature on your part.

1.9 Limitations

- Noise Levels.
- Hazards due to rebounding of the abrasives.
- Pollution with abrasives.
- Problems with the Abrasive Jet Nozzles.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Abrasive water jets have been used for many years for the cutting of materials. Abrasive particles are entrained into a rapidly moving jet of water which impinges onto a substrate. Material is removed by erosion processes and the jet fully penetrates the material being cut in a single pass. More recently, abrasive water jets have been employed for the machining of materials where the abrasive water jet does not penetrate the sample as is the case in abrasive water jet cutting. Such a technology may be employed to mill components in materials that are difficult to machine by conventional methods. Due to the differences in flow patterns, the erosion conditions are very different to those occurring in conventional cutting. This work examines the abrasive water jet surface finish behavior of Stainless Steel 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 [1].

While Stainless Steel has found extensive applications, the processing of such materials has primarily relied on conventional punching and blanking. These methods may be claimed to be justified and effective in mass production, however, manufacturing industry is getting more time conscious and the requirement for prototype samples and small production batch is increasing. To cope with this trend, laser cutting technology has been employed. Unfortunately, Stainless Steel Sheets exhibit an anomalous behavior when subjected to the laser light due to the high reflectivity and thermal conductivity of the coatings [2]. As a consequence, both productivity and work piece quality are affected.

By contrast, Abrasive Water jet (AWJ) cutting technology, which is claimed to have the distinct advantages of no thermal distortion, high machining Versatility, high flexibility and small cutting forces [3], offer, potential for the processing of metallic coated sheet steels. A considerable amount of work has been conducted in recent years to study the mechanism of AWJ cutting and to develop kerf geometry and surface roughness models for process control and optimization [4-16]. These have involved the processing, of ductile [5-9] and brittle materials [10-12], leathers, woods and rubbers [13], as well as, composites and plastics [17, 18]. It is interesting to note, however, that very little has been reported on the AWJ cutting of thin sheet steels [19] and there is a little knowledge of the cutting performance in AWJ machining of metallic coated sheet metals.

In this, a study of abrasive water jet surface finishing/cutting of Stainless Steel sheets is presented which examines the cutting performance as assessed by the various kerf Characteristic measures (i.e. kerf shape and quality) and the effect of process parameters on the kerf characteristics using a statistically designed experiment. Visual examination and scanning electron microscopy (SEM) analysis is employed to study the topography of the cut surfaces and to develop a further Under standing of the mechanism of sheet metal processing under, abrasive water jets. Statistical analysis of the trends and relationships between the kerf characteristics and the process parameters, as well as the selection of the process parameters for cutting the Material under investigation, are also discussed together with the established empirical equations.

AWJ cutting technology uses a jet of high pressure and velocity water and abrasive slurry to cut the target by means of erosion. In early investigations, it has been found [5-10] that three cutting zones exist in the processing of ductile and brittle materials under abrasive water jets namely, the primary cutting zone at shallow angles of attack, the secondary cutting zone at large angles of attack and the jet upward defection zone. The attack angle is defined as the angle between the initial jet direction and the particle Cutting direction. Based on the proposal by Bitter [20] and finnie [21] for particle erosion of materials, Hashish [4] claimed that the cutting mechanism in the first two zones Could be considered as cutting wear and deformation wear, respectively. It is proposed that the cutting wear Mode is characterized by ploughing and cutting deformation, Where ploughing occurs at large negative rake angle by the abrasives while cutting deformation Occurs when the particles cut the material at positive rake angles. The wear process is similar to that in conventional grinding process, however, it is very difficult to describe since the particles may have linear velocity as well as angular velocity. The surface generated by the cutting wear is generally of good finish and can he assessed by a surface roughness measure, such as centre-line average.

In the steady cyclic cutting stage, the particles will change the attack angle between the initial jet and Cutting directions from shallow to large and have reduced kinetic energy due to such phenomena as particle deflection, reduction in impact velocity and particle fragmentation. Under this condition, material is removed by cutting as well as deformation (or the so-called deformation wear) processes where the particles push the material into a plastic state until it is removed. Chen et al. [10] show that as the jet further penetrates into the work piece, deformation is the dominant mechanism. This is associated with striations formed at the lower portion of the cut surface, although the response mechanism has not been fully investigated.

In the jet upward deflection zone, the cutting process is considered as being controlled by erosive wear at large particle attack angles. This process is associated with jet upward deflection which increases the local rate of change of momentum. This zone is responsible for the raggedness of the cut at the bottom of the kerf and occurs only when the material is thick enough to prevent complete penetration.

The kerf geometry of a through cut generated by abrasive water jet is characterized by small rounded corner at the top edge due to the plastic deformation of material caused by jet bombardment. As the kerf is wider at the top than at the bottom due to the decrease in water pressure, a taper is produced. In addition, the plastically deformed material rolls over at the bottom of the kerf forming burrs at the jet exit when cutting ductile materials.

Hashish and du Plassis [22] have proposed a model for jet spreading profile and strength zones, in a study of the effect of standoff distance between the nozzle and work piece. Hashish [19] later used this model to explain the kerf characteristics in abrasive water jet cutting. These authors as well as Chen et al. [23] believed that the particle velocity at any cross-section of the jet should vary from zero at the nozzle wall to a maximum at the jet Centre. This velocity distribution corresponds to an energy or strength distribution in the jet. Which have higher velocities and are convergent, can result in tapered cuts on the material. The kerf width is dependent on the effective width (or diameter) of the jet, which in turn depends on the jet strength in that zone and the target material.

2.2 KERF CHARACTERISTICS

2.2.1 Effect of Process Parameters on Kerf Geometry

Kerf geometry is a characteristic of major interest in abrasive water jet cutting. Abrasive water jets generally open a tapered slot with the top being wider than the bottom. Kerf taper is defined as a half of the kerf width variation per millimeter of depth of cut (or penetration).

Show some typical and representative trends and relationships between kerf geometry (top and bottom kerf widths and kerf taper) and the process parameters. This May be expected as higher water pressure should result in greater jet kinetic energy and open a wider slot on the work piece. It is interesting, to note that water pressure exhibits a reduced effect on the top kerf width. This is consistent with earlier findings [24, 25], i.e. abrasive water jets become less effective at pressures above a threshold value depending on the other process parameters.

The effect of standoff distance on top kerf width, bottom kerf width and kerf taper can be seen that the top and bottom kerf widths increase with an increase in the standoff distance although the rate of increase for the bottom kerf width is smaller. This may be a result of jet divergence. Since the jet is losing its kinetic energy as it penetrates into the work material, the outer rim of the diverged jet does not take effect as it approaches the lower part of the kerf. As such, the standoff distance has a lesser effect on the bottom kerf width than the top. As a consequence of this effect, kerf taper is increasing with the standoff distance.

2.2.2 Effect of Process Parameters on Surface Roughness

Surface roughness and striation are the major factors in assessing kerf quality in AWJ cutting. While surface finish is a common phenomenon in all machining, striation or waviness is a special feature of cuts with beam cutting technology, such as AWJ cutting. It is formed when the ratio between the available energy of the beam and the required energy of the destruction becomes comparatively small [23]. In AWJ cutting, the cutting power of the jet decreases as it penetrates into the work piece and striations are formed at the lower portion of the cut surface. As striation does not appear to be a common feature of the cut surface for thin sheet steels under abrasive water jets, as noticed in the present study, only surface roughness as assessed. From the experimental results, an increase in traverse speed causes a constant increase in the surface roughness.

2.2.3 Effect of Process Parameters on Burr Formation

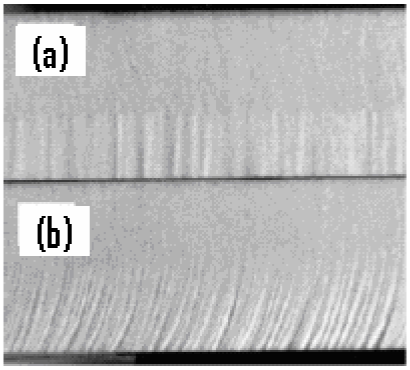
Due to the irregularity of the burrs and the difficulty in measurement, the measured burr heights were grouped as categorical (or qualitative) in table

Table 2.1: Category of Burr Height [42]

Burr Category	**Burr height (mm)**
Burr less	0-0.02
Low burr	0.02-0.05
Medium burr	0.05-0.08
Height burr	0.08-0.12
Very high burr	>0.12

2.3 STRIATION FORMATION MECHANISMS ON THE JET CUTTING SURFACE

Hashish [26] conducted a visualization investigation of the AWJ cutting process. He found that the material removal process was a cyclic penetration process that consists of two cutting regimes which he termed as cutting wear zone and deformation wear zone. Based on these visualization experiments, it was derived that the cause of striation was the change to the mode of material destruction. The author divided the total depth of cut into two distinct zones which is shown in Figure 2.1. In the upper zone, which was called ‘‘cutting wear zone’’; material was removed by the impacting of abrasive particles at shallow angles. In the lower zone which was called ‘‘deformation wear zone’’, the material removal process was unsteady and sequential steps were formed, leading to large particle impact angles and the formation of striations or waviness on the wall of the cut surface. However, the idea of two different material removal modes has been rejected by other researchers [27] who found that the material removal mechanism is independent of the depth of cut for a given material. In contradiction to these findings, it was believed that the striation formation was a result of external disturbances, such as machine vibration [28].



(a) Oscillation Cutting: Traverse Speed = 0.33 mm/sec.

(b) Cutting without Oscillation: Traverse Speed = 0.25 mm/sec.

Figure 2.1: The two cutting zones proposed by Hashish [4].

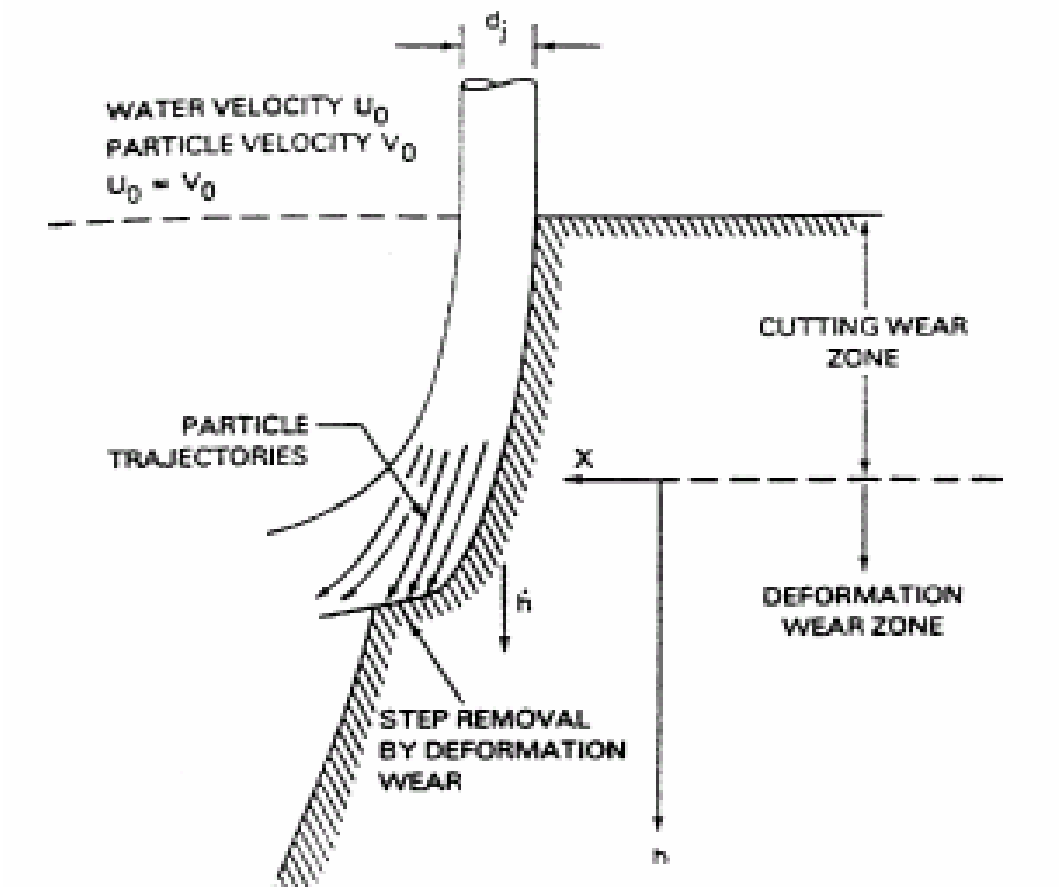


Figure 2.2: The two cutting zones proposed by Hashish [4].

2.3.1 Striation Formation Due to Machine System Vibration

Chao and Geskin [28] have experimentally studied the cutting head control and robot dynamic behavior under various operation conditions and their effect on the striation formation. Using a spectral analysis, they found that the structure dynamics of the traverse system correlated with the cut surface striation, and that the machine vibration was the main cause of striation in AWJ cutting. The motor drive system and rack and pinion transmissions were identified as the main sources of machine vibration in this study. In addition, the study found that the profiles of the surfaces had the usual appearance of an upper smooth zone and a lower striated or wavy zone. The amplitude of striations on these surfaces was found to increase as the depth of cut increased. A second-order polynomial function in terms of the depth of jet penetration was found to fit the increase in the amplitude of striations from the upper smooth zone to the lower striated zone. The authors explained that the amplitude of vibration in the direction normal to the plane of cut progressively increases as the depth of cut increases, which results in an increased jet side oscillation and increased amplitude of cut surface striation. It was thus deduced that a reduction in the vibration associated with the machine tool system could result in a corresponding decrease in the striations on the cut surface.

2.4 Characteristics of the Surface of a Titanium Alloy Following Milling with Abrasive Water Jets

For successful industrial implementation of Abrasive Water Jet controlled-depth milling (AWJ-CDM), there is a desire to minimize the surface waviness in order that tight tolerances may be achieved without the requirement of further finishing operations. Whilst specifications on roughness depend upon specific applications, minimization of the embedment of abrasive grit in the work piece surface is normally sought since such grit can cause reduction in the fatigue life of a component [29, 30]. Indeed, other characteristics of an AWJ cut surface such as roughness [31] and morphology [29, 32] have been shown to influence fatigue failure. However, whilst certain characteristics of the surface are desirable, they must be considered alongside material removal rate in order that an efficient process can be developed.

One of the key requirements is a low waviness which can be achieved by employing a high jet traverse speed, a small grit size, a low water jet pressure and a low jet impingement angle. However, such process parameter selection also minimizes the rate of material removal, thus making the process less efficient.

2.5 Comparative Study of Jet Machining Technologies over Laser Machining Technology for Cutting Composite Materials

2.5.1 Techniques Used for Cutting Composites Materials

2.5.1.1 Water Jet

In water jet machining, materials are removed by the impingement of a continuous stream of high-energy water beads. The machined chips are flushed away by the water. As in conventional machining tools, the water jet exerts machining force on the work piece during the cutting process. This force is transmitted by the water beads causing the cut. The direction of the force is given predominantly by the attack angle of the water jet and is insignificantly affected by the tail flow beyond the cut.

2.5.1.2 Abrasive Water Jet

Abrasive water jet cutting technology uses a jet of high pressure and velocity water and abrasive slurry to cut the target material by means of erosion. The impact of single solid particles is the basic event in the material removal by abrasive water jets (Figure 2.3).

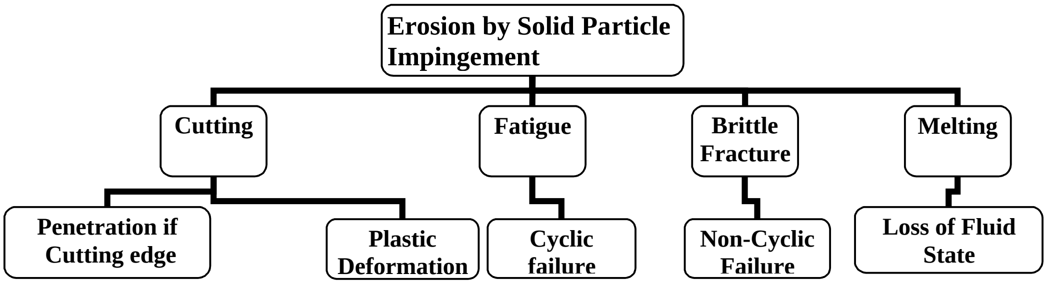


Figure 2.3: Mechanisms of material removal by solid-particle erosion [1].

In previous investigations, it has been found [33] that three cutting zones exist in the processing of ductile and brittle materials under abrasive water jets, that is the primary cutting zone at shallow angles of attack, the primary cutting zone at large angles of attack, and the jet upward defection zone. The attack angle is defined as the angle between the initial jet direction and the particle cutting direction at the point of attack.

2.5.1.3. Laser Cutting

The three essential components of a laser-cutting machine are laser medium, excitation source and the optical resonator. The excitation source drives the atom, ions or molecules of the laser medium to a situation where there is an excess of those at high energy level over those at a low level. This inversion of the normal thermodynamic population distribution leads to laser action: an excited member of the medium undergoing a transition from high to low energy will emit a photon, which in turn stimulates further emission, perfectly in phase, and at the same wavelength, from the other excited members of the medium. The radiation is thus rapidly amplified the role of the optical resonator is to direct and control the radiation by allowing an appropriate fraction to be bled off as a near-parallel beam while the remainder is circulated within the cavity to maintain laser action.

2.5.1.4 Review of Previous Work

Machining of composite materials often poses a tremendous challenge, particularly in machining fine profiles and contours and for hybrid laminates consisting of two or more vastly dissimilar materials. Experiments in the field of composite machining like drilling, grinding, turning and screw thread machining were carried out using conventional and jetting techniques [34–40]. Limited research has been carried out in the field of machining composites using jetting techniques. Wang and Wong [41] conducted studies for machining polymer matrix composites using abrasive water jet. Bear brand phenolic fabric matrix composites, which were non-metallic, laminated sheets made by impregnated layers of fibre reinforcement with resin matrix of 300 x 300 mm and 16 mm thick was used. Four different pressures were used by them, and for each level of water pressure four levels of transverse speed (400, 1000, 1600 and 2000 mm/min) were tested at four levels of abrasive flow rate (0.1, 0.2, 0.3 and 0.4 kg/min) and a single level of jet impact angle of 90. 64 tests were conducted by them for straight cuts of 60 mm long with a standoff distance between the nozzle and the work piece set at 4 mm. For all tests, the other parameters were kept constant using the system standard configuration, i.e., the orifice diameter was 0.33 mm, the mixing tube diameter was 1.27 mm, and the length of mixing tube was 88.9 mm. The abrasives used were almandite garnet sand with a mesh number of 80. Observation by them showed that jets with sufficient energy provided a through cut whereas jets with low pressure causes a non-through cut and at the point where there was a non-through cut a pocket was formed with an irregular shape. Delamination was also observed by them on some specimens which were not cut through by the jet and remarks by him says that there was no obvious reason established between the cutting parameters and delamination, the results again showed that delamination can be avoided if clear through cuts can be achieved by correctly selecting the cutting parameters.

Hamatani and Ramulu [42] work concerned with the machining of high temperature composites by abrasive water jet. Two types of composite were chosen in that study, one was a silicon carbide/titanium di-boride and another one was a metal matrix composite (MMC). It was observed by them that the top of the abrasive water jet cut was damaged and rounded, not knife-edge sharp, since the response of a material to erosion by solid-particle impact depends on the angle of impact governing the material removal mechanisms, namely cutting wear and deformation wear. At the upper section the material was removed due to impact at shallow angles and the deformation wear at the lower part due to impact at large angles. It was also noted that burrs were observed on the bottom surface of the abrasive water jet cuts on the MMC, which implied that plastic deformation might be dominant in the cutting of that type of ductile composite. The performance characteristics of abrasives water jet machining showed by them are widely dependent not only on the work piece material, but also on the abrasive water jet system process parameters. For piercing of the ceramic particulate composite, results similar to those of the MMC were observed by them. The taper of the hole produced increased with increasing standoff distance. The one notable exception between the two materials was that while the metal matrix material exhibited a nearly linear increase in hole taper with standoff distance, the variation for the ceramic matrix was clearly non-linear. Based on the preliminary investigation of the machinability of two classes of high temperature composites, they concluded that silicon carbide/titanium di-boride composite was easily machinable by abrasive water jet and could able to produce good surface finish. The degree of orthogonal accuracy in the cut surface seems to be better under slow cutting conditions. Abrasive water jet machining of the ceramic matrix composite also seemed possible for them and they could able to produce better holes with minimal damage.

Caprino and Tagliaferri [43] did experiments to determine the maximum cutting speed for cutting fibre reinforced plastics using laser cutting. Glass fibre reinforced plastic (GFRP), carbon fibre reinforced plastics (CFRP) and aramide fibre reinforced plastics (AFRP) panels were hand laid and press moulded. Different thicknesses, ranging from 2 to 3.5 mm for GFRP, 1.5 to 3.5 mm for CFRP, 2.0 to 4.5 mm for AFRP, were examined by them. In all cases fibre volume content of approximately 50% was achieved. An inert gas jet, coaxial with the laser beam impinged orthogonally on the sample through a nozzle 2 mm in diameter. The gas flow rate was 80 l/min. It has been shown that the proposed model closely agrees with experimental results obtained by laser machining of polymer matrix composites reinforced with aramide glass and carbon fabric. According to them the model was expected to work well for high power density and feed rates, under these conditions low interaction times are necessary for obtaining through cuts, heat conduction losses was neglected and the cut process was considered quasi-adiabatic. A criterion relying on kerf morphology was applied, a close dependence of the cut quality on the cutting parameters was found by them showing the results in correspondence to maximum cutting speed. They concluded that high power laser system plus high speed feed rates would give best performances; this would permit high quality together with high productivity. However in this case they prohibited the cost of the laser system compared to other cutting systems.

EXPERIMENTAL SET-UP

Abrasive Water Jet is one of the most recently developed non-traditional manufacturing processes. Abrasive water jet offers the potential for the development of a tool which is less sensitive to material properties, has virtually no thermal effects, and imposes minimal stresses.

3.1 Abrasive Water Jet Machine

Perfect Technology manufactures the premier performance Abrasive Jet and Water Jet Machine.

Figure 3.1: Abrasive Water Jet Machine

Both the Abrasive Jet and Water Jet Machines are driven with a linear servo motor package. Cutting Head movement is achieved by magnetic coupling between the flat motor coils and rare earth magnet sets; therefore a linear drive requires no power transmission components such as belts, ball screws, chains or rack/pinions to operate. Elimination of these components improves machine reliability and reduces maintenance costs.

Linear drives operate with zero backlashes so that the cutting head is positioned with superior accuracy compared to belt, screw or rack/pinion driven machines. Linear servo drives position faster than rotary servo drive systems.

Machine is constructed with 100% stainless steel structural frames and water catch tanks. The cutting bridge is fabricated from aluminum and the machine linear ways are stainless steel. This premium construction is the ultimate in both corrosion resistance and durability. Steel frames that rely on paint or epoxy coating to attempt to inhibit corrosion.

Motion control of the machine is achieved using PTC propriety configured Mach 3 software. Cut files are generated using Lantek Expert Cut Cam post processing software that comes standard with a PTC machine. Lantek software is recognized as one of the premium water jet cut file control packages.

The PTC water jet machines operate at rates from 1/2 inch per minute to a maximum cutting speed of 4200 inches per minute based on media.

3.2 VARIOUS COMPONENTS

3.2.1 Water Preparation System

In concept the equipment required for abrasive water jet machining is quite straightforward. A head mechanism is needed to form the jet of water and a delivery and injection system must act to entrain the abrasive particles into the jet stream. Since the jet is a high-speed stream of water there must be a pump to increase the pressure on the water. Usually a table is necessary for placement of the material to be machined.

However to this basic conceptual equipment must be factored in the realities of the operating environment and materials. First the water supply must conform to certain standards so that the water jet head does not become clogged. This then necessitates a water preparation system. The pump must provide a high pressure that will not vary over time. This requirement demands a special class of pump. And lastly much research has gone into the head design for the generation of the high-speed jet and introduction of the abrasive material to the work piece. Figure 3.2: gives a basic schematic of the equipment

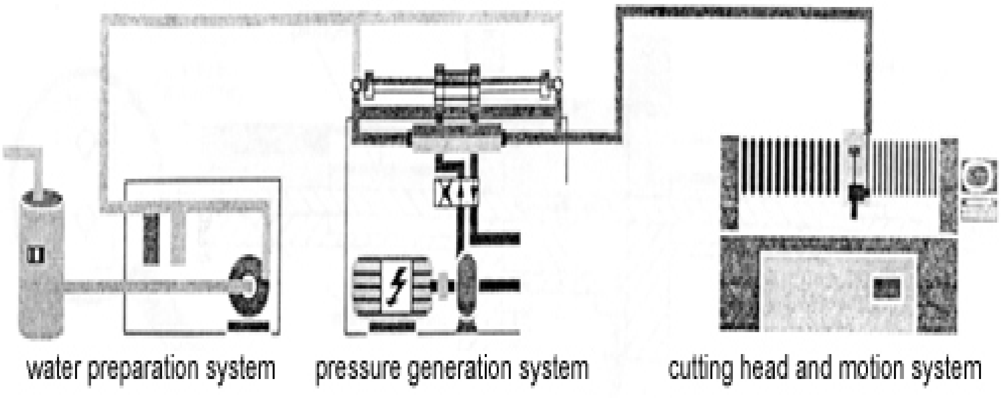


Figure 3.2: Basic Abrasive Water Jet Cutting Set -up

As can be seen included in the setup is the water preparation system, the pressure generation system and the cutting head and motion system.

3.2.2 PRESSURE GENERATION SYSTEM

The pressure generation system must deliver a constant and continuous flow of high pressure water at a prescribed pressure. This means that both the volume and the pressure of the water must be controlled.

For low to intermediate pressures up to 280 MPa direct pressurization the use of triplex positive displacement pumps is adequate. These deliver water by the action of oscillating pistons, which are directly coupled to a crankshaft rotating at a constant speed. Thus the delivered flow of water is constant in time. Fig. 3.3 is a schematic of a pump system.

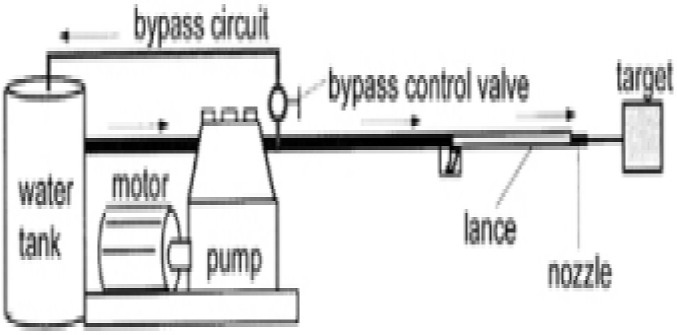


Figure 3.3: Schematic of Pump and Water Supply Setup

However, with high pressures, this type pump is less reliable and additional components must be incorporated to maintain a constant volume at a constant high pressure. One such method is the use of an intensifier. An intensifier usually consists of two cylinders with different inner diameters. The piston with the largest diameter is driven by a low-pressure hydraulic system (normally 5 to 35 Mpa). The pressure in the other cylinder is higher due to the difference in diameter and the ratio of the pressures varies directly as the ratios of cross sectional areas of the two cylinders making up the intensifier. These ratios are typically of the order of 1:10 to 1:25. The resulting magnification in pressure results in values up to 400 Mpa. To operate in a quasi-continuous mode, two or more intensifiers are used together.

In a double acting intensifier design the units are directly connected and work alternately; while one intensifier unit delivers pressurized water to the system; the other unit is refilled. Because of the compressibility of water the first 15% of the piston stroke is used to pressurize and compress the water without any volume delivery. This results in pressure fluctuations and this in turn causes inaccuracies in the water jet/abrasive water jet machining operation.

3.2.3 JET FORMER

The purpose of the Jet Former is take the high pressure water and by Bernoulli’s Principle change the pressure differential into a kinetic energy differential. In other words as the stream of water exits the jet former the pressure drops to atmospheric and consequently the kinetic energy of the stream increases which means that the velocity of the fluid increases. This is critical because the abrasive particles will hence be picked up by the jet and accelerated to speed. Because of the added mass of the particles however they cannot reach the speed of the jet but will obtain some portion of it. The faster the jet the faster the abrasive particles will travel. As would be expected a tapered nozzle is the best design when the fluid mechanics, economics and operating realities are all taken into account. One such profile is shown in Fig.3.4.

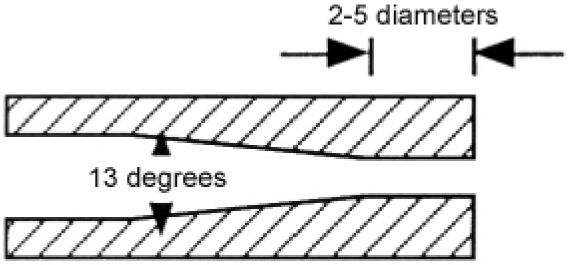


Figure 3.4: Jet Former.

Upon exiting, the jet stream then entrains the abrasive particles for delivery to the work piece.

There are at least two requirements in forming the jet. The first is to increase the velocity and pressure of the fluid with the intent to speed up the abrasive particles and the second is to have the jet as long and as straight as possible after exiting from the jet former.

It is assumed that the water enters from the left and exits from the right, thus resulting in an increase in fluid velocity. A conical section in a typical nozzle has an inclination of thirteen degrees (the included angle) that reduces the cross sectional area of the flow. Afterwards the fluid enters a straight section of pipe, which is 2 to 5 cross sectional diameters in length.

As can be seen at greater distances (referred to as the standoff distance) from the jet orifice the use of rounded corners results in greater retention of the nozzle (stagnation) pressure. This determines how far away the material to be machined can be from the nozzle. Not discussed here but of equal importance in the operation of any abrasive jet machining operation is the consideration of the nozzle material and its alignment in the system. As the nozzle wears the reliability decreases. Machining reliability is also decreased by nozzle misalignment. In addition having good alignment between the water supply and the jet nozzle can increase the effective jet length. In the area of the nozzle material, work has been done on using ceramics and various carbide materials.

3.2.4 ABRASIVE PARTICLES AND WATER MIXING

This part of the abrasive water jet machining is certainly the most crucial. Ordinarily the abrasive particles are fed into the side of the jet, speed up by the jet and delivered to the work piece. Conceptually the following system, Fig. 3.5, would work.

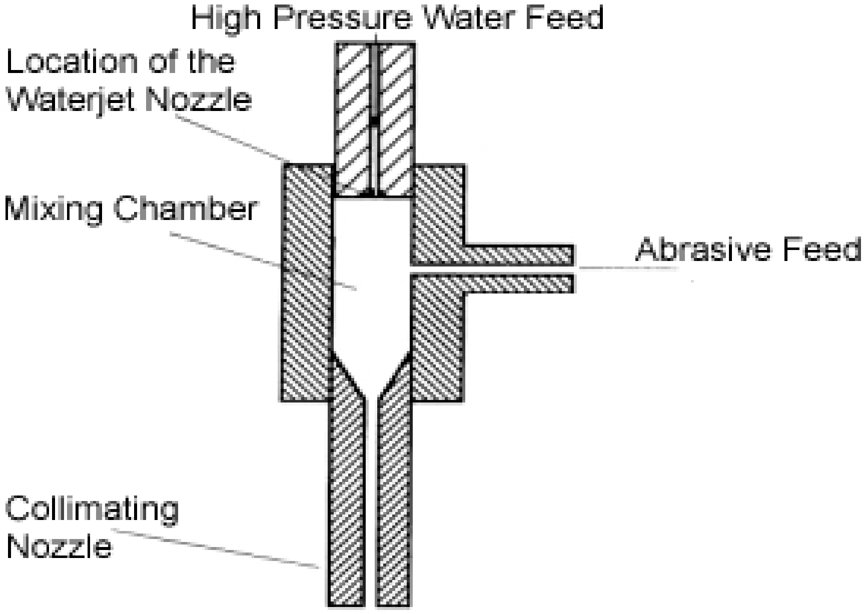


Figure 3.5: Abrasive Particle Water Jet Mixing Design

However there are several considerations. First the velocity profile across the jet is not uniform and hence the particles would tend to enter the side of the jet where the velocity is slowest. If the abrasive particles are not moving to begin with they will act as drag on the jet. As they enter into the jet they tend to increase the turbulence of the jet. Therefore much effort has gone into the Abrasive Particle Delivery System

Here are several other potential designs, two of which try to give the particles speed either due to gravitational force or air pressure, and the other being a design using a premix of the water and particles before jet formation.

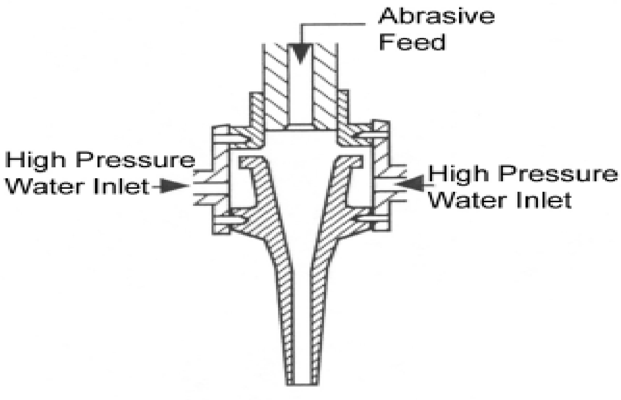


Figure 3.6: Particle Water Premix

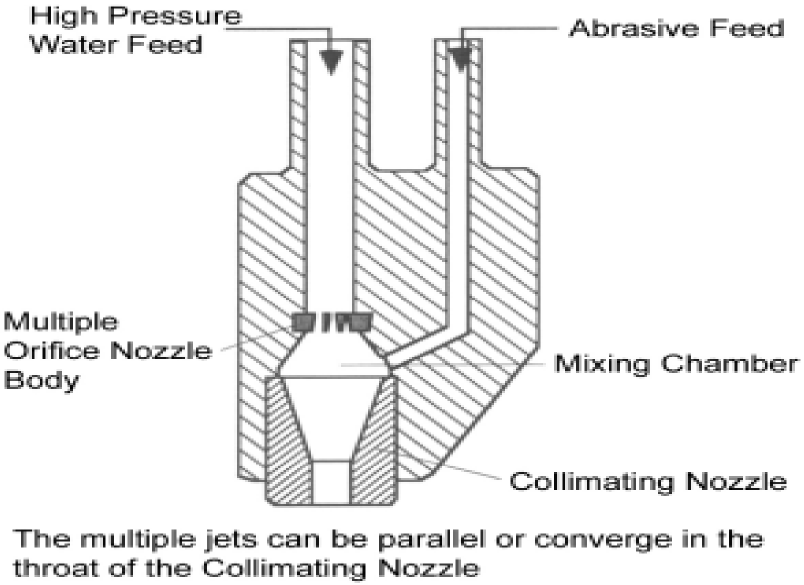


Figure 3.7: Abrasive Particle Gravity Feed

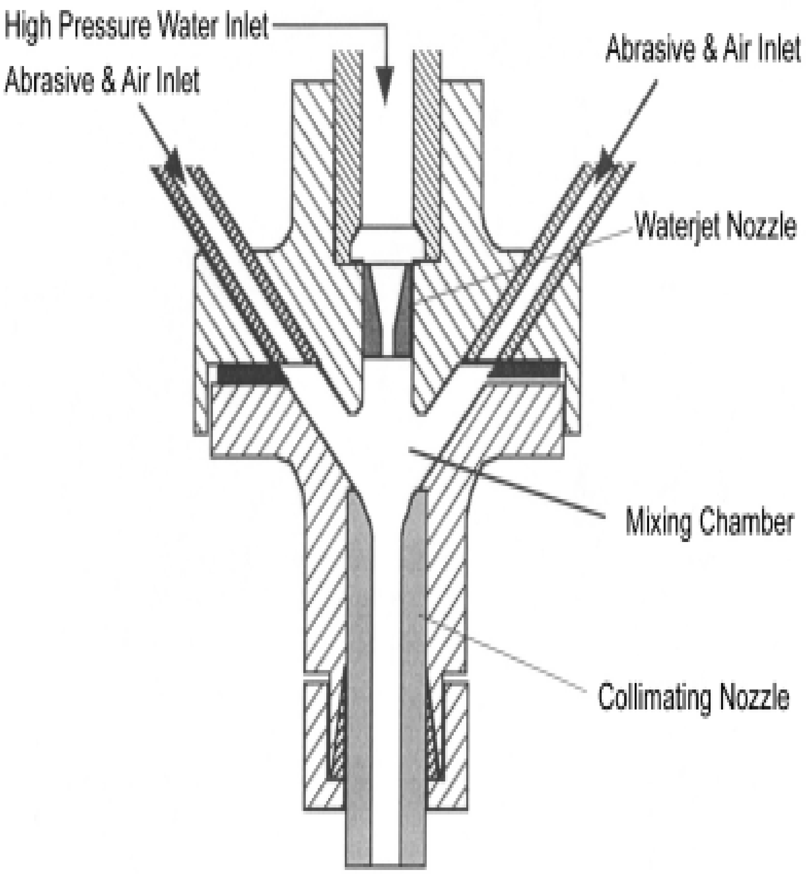


Figure 3.8: Forced Air Particle Feed

For illustrative purposes Fig. will be used since it is a basic model that combines the jet former, the mixing chamber and the collimator (which is also known as the focus tube). The top section is the exiting straight portion of the jet former. Here the jet exits the nozzle and enters into the mixing chamber.

Here it is assumed that the pressure in the jet former is significantly greater than in the mixing chamber and the velocity of the exiting jet into the mixing chamber is much greater than the fluid velocity in the jet former. With these assumptions then the formula above is a good approximation to the jet speed as it enters the mixing chamber.

The abrasive particles are supplied from the right inlet tube and are pulled in by a pressure differential created by the moving fluid past the inlet port (similar to the lift developed on an aircraft wing as the air above the wing moves faster than the air under the wing bottom thus creating an upward pressure potential or lift.)

The purpose of the final reduced cross-sectioned nozzle is to collimate or focus the abrasive laden water jet before it exits just above the material to be machined. This is to insure that all the abrasive particle velocities are directed toward the work piece. Some energy however is lost because some of the abrasive particles do collide with the focusing tube wall. Hence there is some overall velocity reduction as the jet exits the focusing tube (from 3000ft/s to 1000ft/s).

Several problems occur in the abrasive water jet-mixing chamber. First upon impact of the abrasive particles by the high speed jet there is the potential that the particles will be fractured and hence reduced in size. Secondly the entrainment of the particles in the jet stream is by no means uniform. In fact most of the abrasive is in the peripheral section of the jet with very little in the center of the jet. The center of the jet is of course the area of highest speed, so the particles are in the slower boundary region of the jet. This entrainment of the particles within the jet periphery is not bad since as will be seen later on, the actual cutting by the jet results from the interaction of the jet surface with the material.

3.2.5 STAND OFF

Stand off is defined as the distance between the face of the nozzle and the working surface of the work. SOD has been found to have considerable effect on the rate of metal removal as well as the accuracy. A large SOD results in the flaring up of the jet which leads to poor accuracy.

Small metal removal rates at a low SOD is due to a reduction in nozzle pressure with decreasing distance, whereas a drop in material removal rate at large SOD is due to a reduction in the jet velocity increasing distance.

3.3 ABRASIVE PARTICLES

Classification and Properties of Abrasive Materials:-

A large number of different types of abrasive materials are used in the abrasive water-jet technique. The evaluation of an abrasive material for abrasive water-jet processes includes the following important parameters:

- ✓ Material structure
- ✓ Material hardness
- ✓ Mechanical behavior
- ✓ Grain shape
- ✓ Grain-size distribution
- ✓ Average grain size

Structural aspects of abrasive materials include the following features :

- ✓ Lattice parameters
- ✓ chemical composition
- ✓ Crystalloid chemical formula
- ✓ inclusions (water-gas inclusion, mineral inclusion)
- ✓ cleavage
- ✓ Crystallographic group

Since the abrasive particles erode the material and this is a mechanical operation, which is a cross between the shearing and compressing the material by the particle, it can be seen that the above characterization of the particles is crucial. The particles must be hard so that they are the eroders as opposed to being the eroded. The shape is important. Particles with sharp edges can be envisioned to be good cutters and upon impacting the material at one of their sharp edges can cause high stress concentrations. Figure 3.9, gives a few examples of shapes that would be good for such purposes

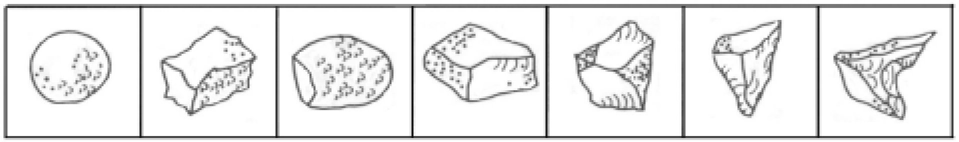


Fig. 3.9: Typical shapes of garnet abrasive used for abrasive water-jet machining

3.4 VELOCITY OF THE ABRASIVE JET

The kinetic energy of the abrasive jet is utilized for metal removal by erosion. Erosion to occur, the jet must impinge the work surface with a certain minimum velocity.

The jet velocity is a function of the nozzle pressure, nozzle design, abrasive grain size and the mean number of abrasives per unit volume of the carrier gas.

3.5 SIZE OF THE ABRASIVE GRAINS

The rate of metal removal depends on the size of the abrasive grain. Finer grains are less irregular in shape, and hence, possess lesser cutting ability. Moreover, a finer grain tends to stick together and choke the nozzle. The most favorable grain sizes range from 10 to 50 μ. Coarse grains are recommended for cutting, where finer grains are useful in polishing, deburring, etc.

3.6 WORK MATERIAL

AWJM is recommended for the processing of brittle materials, such as glass, ceramics, refractory, etc. most of the ductile materials are practically unmachinable by AWJM.

CHAPTER 4

DATA COLLECTION

4.1 Abrasive Water Jet Machining of Stainless Steel

Stainless steels are characterized primarily by their corrosion resistance, high strength and ductility, and high chromium content. They are called stainless because in the presence of oxygen (air) they develop a thin, hard adherent film of chromium oxide that protects the metal from corrosion (Pssivation). This protective film builds up again in the event that the surface is scratched. For Pssivation to occur, the minimum chromium content should be 10% to 12% by weight.

The higher the carbon content is, the lower is the corrosion resistance of stainless steels. The reason is that the carbon combines with the chromium in the steel and forms chromium carbide; the reduced availability of chromium lowers the passivity of the steel. Still worse, the chromium carbide introduces a second phase and, thereby, promotes galvanic corrosion.

4.2 Stainless steel generally divided into five types

4.2.1 Austenitic (200 and 300 series)

These steels are generally composed of chromium, nickel, and manganese in iron. They are non-magnetic and have excellent corrosion resistance, but they are susceptible to stress-corrosion cracking: austenitic stainless steels are hardened by cold-working. They are more ductile of all stainless steels and so they can easily be formed, although, with increasing cold work, their formability reduced. These steels are used in a wide variety of applications.

4.2.2 Ferritic (400 series)

These steels have a high chromium content-up to 27%. They are magnetic and have good corrosion resistance, but they have lower ductility than austenitic stainless steels. Ferritic stainless steel are hardened by cold working and are not heat-treatable.

4.2.3 Martensitic (400 and 500 series)

Most martensitic stainless steels do not contain nickel and are harden able by heat treatment. Their chromium content may be as much as 18%. These steels are magnetic, and they have high strength, hardness, and fatigue resistance, good ductility, and moderates corrosion resistance.

4.2.4 Precipitation-hardening (PH)

These steels content chromium and nickel, along with copper, aluminum, titanium, or molybdenum. They have good corrosion resistance and ductility, and they have high strength at elevated temperatures.

4.2.5 Duplex Structure

These steels have a mixture of austenite and ferrite. They have good strength, and they have higher resistance to both corrosion and stress- corrosion cracking than do the 300 series of austenitic steels. Typical applications are in water-treatment plants and in heat-exchanger components.

Table 4.1: Stainless Steel, Thickness 1mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel

Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
1	1500	0.125	0.15	0.254	176	467	1
	2000				298	791	1.5
	2500				449	1191	2
	2750				534	1418	2.5
	3000				627	1664	3
	4000				1062	2819	4.5
1	1500	0.3	0.15	0.254	248	660	1
	2000				421	1118	1.5
	2500				634	1682	2
	2750				755	2004	2.5
	3000				886	2350	3
	4000				1500	3981	4.5
1	1500	0.5	0.15	0.254	304	807	1
	2000				515	1367	1.5
	2500				776	2058	2
	2750				924	2451	2.5
	3000				1083	2875	3
	4000				1835	4870	4.5
1	1500	1	0.15	0.254	400	1061	1
	2000				677	1797	1.5
	2500				1019	2705	2
	2750				1214	3222	2.5
	3000				1424	3779	3
	4000				2413	6402	4.5

Table 4.2: Stainless Steel, Thickness 1mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel

Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
1	1500	0.125	0.15	0.254	176	467	1
	2000				298	791	1.5
	2500				449	1191	2
	2750				534	1418	2.5
	3000				627	1664	3
	4000				1062	2819	4.5
1	1500	0.125	0.2	0.254	277	736	2
	2000				470	1247	3
	2500				707	1877	4
	2750				842	2235	4.5
	3000				988	2621	5
	4000				1674	4441	8
1	1500	0.125	0.3	0.254	526	1397	4
	2000				892	2366	6
	2500				1342	3562	9
	2750				1599	4241	10
	3000				1875	4975	11.5
	4000				3177	8428	17.5
1	1500	0.125	0.4	0.254	829	2200	7
	2000				1405	3728	11
	2500				2115	5612	15.5
	2750				2519	6683	18
	3000				2954	7838	20
	4000				5005	13279	31

Table 4.3: Stainless Steel, Thickness 1mm, (Abrasive Flow Rate and Orifice Diameter constant, and at Varying Mixing tube Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
1	1500	0.125	0.15	0.254	176	467	1
	2000				298	791	1.5
	2500				449	1191	2
	2750				534	1418	2.5
	3000				627	1664	3
	4000				1062	2819	4.5
1	1500	0.125	0.15	0.762	80	214	1
	2000				136	362	1.5
	2500				205	545	2
	2750				245	650	2.5
	3000				287	762	3
	4000				486	1291	4.5
1	1500	0.125	0.15	1.143	60	160	1
	2000				102	271	1.5
	2500				154	409	2
	2750				183	487	2.5
	3000				215	571	3
	4000				365	968	4.5
1	1500	0.125	0.15	1.524	49	130	1
	2000				83	221	1.5
	2500				125	333	2
	2750				149	397	2.5
	3000				175	466	3
	4000				297	789	4.5

Table 4.4: Stainless Steel, Thickness 2mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness	Pressure	Abrasive flow	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth	Linear cutting speed for rough	Cutting
(mm)	(bar)	rate (kg/min.)	(mm)	(mm)	Surface finish(mm/min.)	Surface finish(mm/min.)	power(kW)
2	1500	0.125	0.15	0.254	79	210	1
	2000				134	357	1.5
	2500				202	537	2
	2750				241	639	2.5
	3000				282	750	3
	4000				479	1270	4.5
2	1500	0.3	0.15	0.254	112	297	1
	2000				190	504	1.5
	2500				286	758	2
	2750				340	903	2.5
	3000				399	1059	3
	4000				676	1794	4.5
2	1500	0.5	0.15	0.254	137	364	1
	2000				232	616	1.5
	2500				349	927	2
	2750				416	1104	2.5
	3000				488	1295	3
	4000				827	2195	4.5
2	1500	1	0.15	0.254	180	478	1
	2000				305	810	1.5
	2500				459	1219	2
	2750				547	1452	2.5
	3000				642	1703	3
	4000				1087	2885	4.5

Table 4.5: Stainless Steel, Thickness 2mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel

Thickness	Pressure	Abrasive flow	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth	Linear cutting speed for rough	Cutting
(mm)	(bar)	rate(kg/min.)	(mm)	(mm)	Surface finish(mm/min.)	Surface finish(mm/min.)	power(kW)
2	1500	0.125	0.15	0.254	79	210	1
	2000				134	357	1.5
	2500				202	537	2
	2750				241	639	2.5
	3000				282	750	3
	4000				479	1270	4.5
2	1500	0.125	0.2	0.254	125	332	2
	2000				212	562	3
	2500				319	846	4
	2750				380	1007	4.5
	3000				445	1181	5
	4000				754	2001	8
2	1500	0.125	0.3	0.254	237	629	4
	2000				402	1066	6
	2500				605	1605	8.5
	2750				720	1911	10
	3000				845	2242	11.5
	4000				1431	3798	17.5
2	1500	0.125	0.4	0.254	374	992	7
	2000				633	1680	11
	2500				953	2528	15.5
	2750				1135	3011	18
	3000				1331	3532	20.5
	4000				2255	5984	31

Table 4.6: Stainless Steel, Thickness 2mm, (Abrasive Flow Rate and Orifice Diameter, and at Varying Mixing tube diameter constant)

Stainless Steel							
Thickness	Pressure	Abrasive flow	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth	Linear cutting speed for rough	Cutting
(mm)	(bar)	rate(kg/min.)	(mm)	(mm)	Surface finish(mm/min.)	Surface finish(mm/min.)	power(kW)
2	1500	0.125	0.15	0.254	79	210	1
	2000				134	357	1.5
	2500				202	537	2
	2750				241	639	2.5
	3000				282	750	3
	4000				479	1270	4.5
2	1500	0.125	0.15	0.762	36	96	1
	2000				61	163	1.5
	2500				92	246	2
	2750				110	293	2.5
	3000				129	343	3
	4000				219	582	4.5
2	1500	0.125	0.15	1.143	27	72	1
	2000				46	122	1.5
	2500				69	184	2
	2750				83	219	2.5
	3000				97	257	3
	4000				164	436	4.5
2	1500	0.125	0.15	1.524	22	59	1
	2000				37	100	1.5
	2500				56	150	2
	2750				67	179	2.5
	3000				79	210	3
	4000				134	355	4.5

Table 4.7: Stainless Steel, Thickness 5mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
5	1500	0.125	0.15	0.254	28	73	1
	2000				47	124	1.2
	2500				70	187	2
	2750				84	222	2.5
	3000				98	261	3
	4000				167	443	4.5
5	1500	0.3	0.15	0.254	39	104	1
	2000				66	176	1.5
	2500				100	264	2
	2750				118	315	2.5
	3000				139	369	3
	4000				235	625	4.5
5	1500	0.5	0.15	0.254	48	127	1
	2000				81	215	1.5
	2500				122	323	2
	2750				145	385	2.5
	3000				170	451	3
	4000				288	765	4.5
5	1500	1	0.15	0.254	63	167	1
	2000				106	282	1.5
	2500				160	425	2
	2750				191	506	2.5
	3000				233	594	3
	4000				379	1005	4.5

Table 4.8: Stainless Steel, Thickness 5mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
5	1500	0.125	0.15	0.254	28	73	1
	2000				47	124	1.2
	2500				70	187	2
	2750				84	222	2.5
	3000				98	261	3
	4000				167	443	4.5
5	1500	0.125	0.2	0.254	44	115	2
	2000				74	196	3
	2500				111	295	4
	2750				132	351	4.5
	3000				155	412	5
	4000				263	698	8
5	1500	0.125	0.3	0.254	83	219	4
	2000				140	372	6
	2500				211	559	8.5
	2750				251	666	10
	3000				294	781	11.5
	4000				499	1324	17.5
5	1500	0.125	0.4	0.254	130	345	7
	2000				221	586	11
	2500				332	881	15.5
	2750				396	1050	18
	3000				464	1231	20
	4000				786	2086	31

Table 4.9: Stainless Steel, Thickness 5mm, (Abrasive Flow Rate and Orifice Diameter constant, and at Varying Mixing tube Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
5	1500	0.125	0.15	0.254	28	73	1
	2000				47	124	1.2
	2500				70	187	2
	2750				84	222	2.5
	3000				98	261	3
	4000				167	443	4.5
5	1500	0.125	0.15	0.762	13	33	1
	2000				21	57	1.5
	2500				32	86	2
	2750				38	102	2.5
	3000				45	120	3
	4000				76	203	4.5
5	1500	0.125	0.15	1.143	9	25	1
	2000				16	43	1.5
	2500				24	64	2
	2750				29	76	2.5
	3000				34	90	3
	4000				57	152	4.5
5	1500	0.125	0.15	1.524	8	20	1
	2000				13	35	1.5
	2500				20	52	2
	2750				23	62	2.5
	3000				27	73	3
	4000				47	124	4.5

Table 4.10: Stainless Steel, Thickness 20mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
20	1500	0.125	0.15	0.254	5	15	1
	2000				9	25	1.5
	2500				14	38	2
	2750				17	45	2.5
	3000				20	53	3
	4000				34	90	4.5
20	1500	0.3	0.15	0.254	8	21	1
	2000				13	35	1.5
	2500				20	53	2
	2750				24	64	2.5
	3000				28	75	3
	4000				48	127	4.5
20	1500	0.5	0.15	0.254	9	25	1
	2000				16	43	1.5
	2500				24	65	2
	2750				29	78	2.5
	3000				34	91	3
	4000				58	155	4.5
20	1500	1	0.15	0.254	12	34	1
	2000				21	57	1.5
	2500				32	86	2
	2750				38	103	2.5
	3000				45	120	3
	4000				77	204	4.5

Table 4.11: Stainless Steel, Thickness 20mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
20	1500	0.125	0.15	0.254	5	15	1
	2000				9	25	1.5
	2500				14	38	2
	2750				17	45	2.5
	3000				20	53	3
	4000				34	90	4.5
20	1500	0.125	0.2	0.254	9	23	2
	2000				15	40	2.5
	2500				22	60	4
	2750				27	71	4.5
	3000				31	83	5
	4000				53	141	8
20	1500	0.125	0.3	0.254	17	44	4
	2000				28	75	6
	2500				43	113	8
	2750				51	135	10
	3000				60	158	11.5
	4000				101	269	17.5
20	1500	0.125	0.4	0.254	26	70	7
	2000				45	119	11
	2500				67	179	15.5
	2750				80	213	18
	3000				94	250	20
	4000				159	423	31

Table 4.12: Stainless Steel, Thickness 20mm, (Abrasive Flow Rate and Orifice Diameter constant, and at Varying Mixing tube Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
20	1500	0.125	0.15	0.254	5	15	1
	2000				9	25	1.5
	2500				14	38	2
	2750				17	45	2.5
	3000				20	53	3
	4000				34	90	4.5
20	1500	0.125	0.15	0.762	2	7	1
	2000				4	11	1.5
	2500				6	17	2
	2750				8	20	2.5
	3000				9	24	3
	4000				15	41	4.5
20	1500	0.125	0.15	1.143	2	5	1
	2000				3	8	1.5
	2500				5	13	2
	2750				6	15	2.5
	3000				7	18	3
	4000				11	31	4.5
20	1500	0.125	0.15	1.524	1	4	1
	2000				2	7	1.56
	2500				4	10	2
	2750				4	12	2.5
	3000				5	15	3
	4000				9	25	4.5

Table 4.13: Stainless Steel, Thickness 45mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
45	1500	0.125	0.15	0.254	2	6	1
	2000				3	10	1.5
	2500				5	15	2
	2750				6	18	2.5
	3000				8	21	3
	4000				13	35	4.5
45	1500	0.3	0.15	0.254	3	8	1
	2000				5	14	1.5
	2500				8	21	2
	2750				9	25	2.5
	3000				11	29	3
	4000				19	50	4.5
45	1500	0.5	0.15	0.254	4	10	1
	2000				6	17	1.5
	2500				9	26	2
	2750				11	31	2.5
	3000				13	36	3
	4000				23	61	4.5
45	1500	1	0.15	0.254	5	13	1
	2000				8	22	1.5
	2500				13	34	2
	2750				15	40	2.5
	3000				18	47	3
	4000				30	80	4.5

Table 4.14: Stainless Steel, Thickness 45mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
45	1500	0.125	0.15	0.254	2	6	1
	2000				3	10	1.5
	2500				5	15	2
	2750				6	18	2.5
	3000				8	21	3
	4000				13	35	4.5
45	1500	0.125	0.2	0.254	3	9	2
	2000				6	15	2.5
	2500				9	23	4
	2750				10	28	4.5
	3000				12	33	5
	4000				21	55	8
45	1500	0.125	0.3	0.254	6	17	4
	2000				11	29	6
	2500				17	44	8.5
	2750				20	53	10
	3000				23	62	11.5
	4000				40	106	17.5
45	1500	0.125	0.4	0.254	10	27	7
	2000				17	47	11
	2500				26	70	15.5
	2750				31	84	18
	3000				37	98	20
	4000				63	166	31

Table 4.15: Stainless Steel, Thickness 45mm, (Orifice Diameter and Abrasive Flow Rate constant, and at Varying Mixing tube Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
45	1500	0.125	0.15	0.254	2	6	1
	2000				3	10	1.5
	2500				5	15	2
	2750				6	18	2.5
	3000				8	21	3
	4000				13	35	4.5
45	1500	0.125	0.15	0.762	1	2	1
	2000				1	5	1.5
	2500				2	7	2
	2750				3	8	2.5
	3000				3	9	3
	4000				6	16	4.5
45	1500	0.125	0.15	1.143	1	2	1
	2000				1	3	1.5
	2500				2	5	2
	2750				2	6	2.5
	3000				3	7	3
	4000				4	12	4.5
45	1500	0.125	0.15	1.524	1	1	1
	2000				1	2	1.5
	2500				1	4	2
	2750				2	5	2.5
	3000				2	6	3
	4000				3	10	4.5

Table 4.16: Stainless Steel, Thickness 75mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
75	1500	0.125	0.15	0.254	1	3	1
	2000				2	5	1.5
	2500				3	8	2
	2750				3	10	2.5
	3000				4	11	3
	4000				7	19	4.5
75	1500	0.3	0.15	0.254	1	4	1
	2000				3	8	1.5
	2500				4	11	2
	2750				5	14	2.5
	3000				6	16	3
	4000				10	27	4.5
75	1500	0.5	0.15	0.254	2	5	1
	2000				3	9	1.5
	2500				5	14	2
	2750				6	17	2.5
	3000				7	20	3
	4000				13	34	4.5
75	1500	1	0.15	0.254	3	7	1
	2000				4	12	1.5
	2500				7	19	2
	2750				8	22	2.5
	3000				10	26	3
	4000				17	44	4.5

Table 4.17: Stainless Steel, Thickness 75mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
75	1500	0.125	0.15	0.254	1	3	1
	2000				2	5	1.5
	2500				3	8	2
	2750				3	10	2.5
	3000				4	11	3
	4000				7	19	4.5
75	1500	0.125	0.2	0.254	2	5	2
	2000				3	8	2.5
	2500				5	13	4
	2750				6	15	4.5
	3000				7	18	5
	4000				11	31	8
75	1500	0.125	0.3	0.254	3	9	4
	2000				6	16	6
	2500				9	25	8.5
	2750				11	29	10
	3000				13	34	11.5
	4000				22	59	17
75	1500	0.125	0.4	0.254	5	15	7
	2000				10	26	11
	2500				14	39	15.5
	2750				17	46	17.5
	3000				20	54	20
	4000				35	92	31

Table 4.18: Stainless Steel, Thickness 75mm, (Abrasive Flow Rate and Orifice Diameter constant, and at Varying Mixing tube Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
75	1500	0.125	0.15	0.254	1	3	1
	2000				2	5	1.5
	2500				3	8	2
	2750				3	10	2.5
	3000				4	11	3
	4000				7	19	4.5
75	1500	0.125	0.15	0.762	0.5	1	1
	2000				1	2	1.5
	2500				1	4	2
	2750				2	4	2.5
	3000				2	5	3
	4000				3	9	4.5
75	1500	0.125	0.15	1.143	0.5	1	1
	2000				1	2	1.5
	2500				1	3	2
	2750				1	3	2.5
	3000				1.5	4	3
	4000				2	6	4.5
75	1500	0.125	0.15	1.524	0.5	1	1
	2000				0.5	1	1.5
	2500				1	2	2
	2750				1	3	2.5
	3000				1	3	3
	4000				2	5	4.5

Table 4.19: Stainless Steel, Thickness 100mm, (Orifice Diameter and Mixing tube diameter constant, and at Varying Abrasive Flow Rate)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
100	1500	0.125	0.15	0.254	1	2	1
	2000				1	4	1.5
	2500				2	6	2
	2750				2	7	2.5
	3000				3	8	3
	4000				5	14	4.5
100	1500	0.3	0.15	0.254	1	3	1
	2000				2	5	1.5
	2500				3	8	2
	2750				3	10	2.5
	3000				4	11	3
	4000				7	20	4.5
100	1500	0.5	0.15	0.254	1	4	1
	2000				2	7	1.5
	2500				4	10	2
	2750				4	12	2.5
	3000				5	14	3
	4000				9	24	4.5
100	1500	1	0.15	0.254	2	5	1
	2000				3	9	1.5
	2500				5	13	2
	2750				6	16	2.5
	3000				7	19	3
	4000				12	32	4.5

Table 4.20: Stainless Steel, Thickness 100mm, (Abrasive Flow Rate and Mixing tube diameter constant, and at Varying Orifice Diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
100	1500	0.125	0.15	0.254	1	2	1
	2000				1	4	1.5
	2500				2	6	2
	2750				2	7	2.5
	3000				3	8	3
	4000				5	14	4.5
100	1500	0.125	0.2	0.254	1	3	2
	2000				2	6	3
	2500				3	9	4
	2750				4	11	4.5
	3000				5	13	5
	4000				8	22	8
100	1500	0.125	0.3	0.254	2	7	4
	2000				4	12	6
	2500				6	18	8
	2750				8	21	10
	3000				9	25	11.5
	4000				16	42	17.5
100	1500	0.125	0.4	0.254	4	11	7
	2000				7	18	11
	2500				10	28	15.5
	2750				12	33	18
	3000				15	39	20
	4000				25	65	31

Table 4.21: Stainless Steel, Thickness 100mm, (Abrasive Flow Rate and Orifice Diameter constant, and at Varying Mixing tube diameter)

Stainless Steel							
Thickness (mm)	Pressure (bar)	Abrasive flow rate (kg/min.)	Orifice dia. (mm)	Mixing tube dia. (mm)	Linear cutting speed for smooth Surface finish (mm/min.)	Linear cutting speed for rough Surface finish (mm/min.)	Cutting power(kW)
100	1500	0.125	0.15	0.254	1	2	1
	2000				1	4	1.5
	2500				2	6	2
	2750				2	7	2.5
	3000				3	8	3
	4000				5	14	4.5
100	1500	0.125	0.15	0.762	0.5	1	1
	2000				0.5	2	1.5
	2500				1	2	2
	2750				1	3	2.5
	3000				1	4	3
	4000				2	6	4.5
100	1500	0.125	0.15	1.143	0.5	1	1
	2000				0.5	1	1.5
	2500				1	2	2
	2750				1	2	2.5
	3000				1	3	3
	4000				2	5	4.5
100	1500	0.125	0.15	1.524	0.5	0.5	1
	2000				0.5	1	1.5
	2500				1	1	2
	2750				1	2	2.5
	3000				1	2	3
	4000				1	4	4.5

CHAPTER 5

DEVELOPMENT OF EQUATIONS

5.1 Linear Multiple Regression Analysis

The literal meaning of regression is ‘moving backward’ or the return to the mean value’ or ‘stepping back towards the average’. Sir Francis Galton used this term in the study of heredity. According to him with a correlation coefficient of 0.8 between heights of fathers and children if the average height of a certain set of fathers is x cm. above the general average, average height of children shall be 0.8x cm. above the general average. Thus, there is a tendency to move towards the average. The term ‘regression; in statistics is used without making any reference to biometry.

Regression analysis is ‘mathematical’ measure of the average relationship between two or more variables, in terms of the original units of the data.

The regression equation takes the form $Y = k*T^{n}*P^{n1}*AF^{n2}*OD^{n3}*MT^{n4}$, where Y is the true dependent, the b's are the regression coefficients for the corresponding x (independent) terms, c is the constant or intercept, and e is the error term reflected in the residuals. The logarithmic of regression equation

$$\log Y = \log k + n * \log T + n1 * \log P + n2 * \log AF + n3 * \log OD + n4 * \log MT$$

where Y is the estimated dependent and c is the constant (which includes the error term). Equations such as that above, with no interaction effects (see below), are called main effects models.

- Predicted values, also called fitted values, are the values of each case based on using the regression equation for all cases in the analysis.
- Adjusted predicted values are the values of each case based on using the regression equation for all cases in the analysis except the given case.

R^2, also called multiple correlation or the coefficient of multiple determination, is the percent of the variance in the dependent explained uniquely or jointly by the independents. R-squared can also be interpreted as the proportionate reduction in error in estimating the dependent when knowing the independents. That is, R^2 reflects the number of errors made when using the regression model to guess the value of the dependent, in ratio to the total errors made when using only the dependent's mean as the basis for estimating all cases. Mathematically, R^2 = (1 - (SSE/SST)), where SSE = error sum of squares = SUM((Yi - EstYi)squared), where Yi is the actual value of Y for the ith case and EstYi is the regression prediction for the ith case; and where SST = total sum of squares = SUM((Yi - MeanY)squared). The "residual sum of squares" in SPSS output is SSE and reflects regression error. Thus R-square is 1 minus regression error as a percent of total error and will be 0 when regression error is as large as it would be if you simply guessed the mean for all cases of Y. Put another way, the regression sum of squares/total sum of squares = R-square, where the regression sum of squares = total sum of squares - residual sum of squares.

5.1.1 Assumptions

Proper specification of the model, If relevant variables are omitted from the model, the common variance they share with included variables may be wrongly attributed to those variables, and the error term is inflated. If causally irrelevant variables are included in the model, the common variance they share with included variables may be wrongly attributed to the irrelevant variables. The more the correlation of the irrelevant variable(s) with other independents, the greater the standard errors of the regression coefficients for these independents. Omission and irrelevancy can both affect substantially the size of the b and beta coefficients. This is one reason why it is better to use regression to compare the relative fit of two models rather than to seek to establish the validity of a single model.

Linearity. Regression analysis is a linear procedure. To the extent nonlinear relationships are present, conventional regression analysis will underestimate the relationship. That is, R-square will underestimate the variance explained overall and the betas will underestimate the importance of the variables involved in the non-linear relationship. Substantial violation of linearity thus means regression results may be more or less unusable. Checking that the linearity assumption is met is an essential research task when use of regression models is contemplated.

- Non-recursivity. The dependent cannot also be a cause of one or more of the independents. This is also called the assumption of non-simultaneity or absence of joint dependence. Violation of this assumption causes regression estimates to be biased and means significance tests will be unreliable.
- No over fitting. The researcher adds variables to the equation while hoping that adding each significantly increases R-squared. However, there is a temptation to add too many variables just to increase R-squared by trivial amounts. Such over fitting trains the model to fit noise in the data rather than true underlying relationships. Subsequent application of the model to other data may well see substantial drops in R-squared.

5.2 Curvilinear regression, Linear Regression

In case there exists association or relationship between two variables X and Y, the dots of the scatter diagram will be more or less concentrated round a curve, which may be called the curve of regression and the relationship is said to be expressed by means of curvilinear regression. More precisely, the line of regression is the straight line, which gives the ‘best’ fit in the least square sense to the given frequency or probability distribution.

5.3 Linear Multiple Regression Software

Multiple regressions is R^2, multiple correlation, which is the percent of variance in the dependent variable explained collectively by all of the independent variables.

Multiple regression shares all the assumptions of correlation, linearity of relationships, the same level of relationship throughout the range of the independent variable ("homoscedasticity"), interval or near-interval data, absence of outliers, and data whose range is not truncated.

Linear multiple regression software is used to solve the data of different variables such as Thickness, Pressure, Abrasive flow rate, Orifice Diameter, Mixing tube diameter. This gives the values of linear cutting speed for smooth surface, rough surface and required cutting power.

The Equations are developed by taking 95% Confidence level of Coefficient, with 504 observations at different variables.

5.4 Equations with the help of Linear Multiple Regression Software

5.4.1 Linear Cutting Speed for Smooth Surface VS Thickness, Pressure, Abrasive Flow, Orifice Diameter, Mixing tube diameter.

Test: Linear Regression

n	504
R^2	1.00
Adjusted R^2	1.00
SE	0.0464

Term	**Coefficient**	**SE**	**p**	**95% CI of Coefficient**
Intercept	-2.2986	0.0556	<0.0001	-2.4078 to -2.1894
log T	-1.1652	0.0028	<0.0001	-1.1708 to -1.1597
log p	1.8392	0.0154	<0.0001	1.8090 to 1.8695
log AF	0.4115	0.0081	<0.0001	0.3956 to 0.4274
log OD	1.6270	0.0171	<0.0001	1.5933 to 1.6607
log MT	-0.6832	0.0084	<0.0001	-0.6997 to -0.6666

Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Due to regression	462.236	5	92.447	42923.83	<0.0001
About regression	1.073	498	0.002		
Total	463.308	503			

$$\log Y = \log k + n * \log T + n1 * \log P + n2 * \log AF + n3 * \log OD + n4 * \log MT$$

$$Y = k * T^{n} * P^{n1} * AF^{n2} * OD^{n3} * MT^{n4}$$

Where

K = 0.0050280, n = -1.1652, n1 = 1.8392, n2 = 0.4115, n3 = 1.627, n4 = -0.6832

Y = Linear Cutting Speed for Smooth Surface, T = Thickness, P = Pressure, AF = Abrasive flow rate, OD = Orifice diameter, MT = Mixing tube diameter

5.4.2 Linear Cutting Speed for Rough Surface VS Thickness, Pressure, Abrasive Flow, Orifice Diameter, Mixing tube diameter.

Test: Linear Regression

n	504
R^2	1.00
Adjusted R^2	1.00
SE	0.0244

Term	Coefficient	SE	p	95% CI of Coefficient	
Intercept	-2.0280	0.0292	<0.0001	-2.0853	to -1.9706
log T	-1.1602	0.0015	<0.0001	-1.1631	to -1.1573
log p	1.8663	0.0081	<0.0001	1.8504	to 1.8822
log AF	0.3963	0.0043	<0.0001	0.3879	to 0.4046
log OD	1.5881	0.0090	<0.0001	1.5704	to 1.6058
log MT	-0.7301	0.0044	<0.0001	-0.7388	to -0.7214

Source of variation	SSq	DF	MSq	F	p
Due to regression	462.112	5	92.422	155585.38	<0.0001
About regression	0.296	498	0.001		
Total	462.408	503			

$$\log Y = \log k + n * \log T + n1 * \log P + n2 * \log AF + n3 * \log OD + n4 * \log MT$$

$$Y = k * T^{n} * P^{n1} * AF^{n2} * OD^{n3} * MT^{n4}$$

Where

K = 0.0093756, n = -1.1602, n1 = 1.8663, n2 = 0.3963, n3 = 1.5881, n4 = -0.7301

Y = Linear Cutting Speed for Rough Surface.

5.4.3 Cutting Power VS Thickness, Pressure, Abrasive Flow, Orifice Diameter, Mixing tube diameter.

Test: Linear Regression

n	504
R^2	1.00
Adjusted R^2	1.00
SE	0.0192

Term	**Coefficient**	**SE**	**p**	**95% CI of Coefficient**	
Intercept	-3.2533	0.0230	<0.0001	-3.2985	to -3.2081
log T	-0.0003	0.0012	0.8126	-0.0026	to 0.0020
log p	1.5414	0.0064	<0.0001	1.5289	to 1.5539
log AF	-0.0010	0.0033	0.7700	-0.0076	to 0.0056
log OD	2.0050	0.0071	<0.0001	1.9911	to 2.0189
log MT	-0.0008	0.0035	0.8206	-0.0076	to 0.0061

Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Due to regression	60.004	5	12.001	32557.39	<0.0001
About regression	0.184	498	0.000		
Total	60.188	503			

$$\log Y = \log k + n * \log T + n1 * \log P + n2 * \log AF + n3 * \log OD + n4 * \log MT$$

$$Y = k * T^{n} * P^{n1} * AF^{n2} * OD^{n3} * MT^{n4}$$

Where

K = 0.00055808, n = -0.0003, n1 = 1.5414, n2 = -0.0010, n3 = 2.0050, n4 = -0.0008

Y = Required Cutting Power.

CHAPTER 6

RESULT AND CONCLUSIONS

When the pressure is varied with abrasive flow rate keeping orifice diameter and mixing tube diameter constant, it is noticed that the linear cutting speed for the smooth finish increases but the rate of increase in the cutting speed for rough cutting/ machining is rapid (As can be seen from the graph). Also, the power does not change for the different values of the pressure, since the power changes for change in the orifice diameter.

Next, the abrasive flow rate and mixing tube diameter are kept constant and orifice diameter is varied with respect to pressure. It is found that the linear speed for rough cutting increases at a higher rate than that of for the smooth cutting. Here, in this case, the power does not remain same because it depends upon the orifice diameter (which is variable in this case), with an increase in orifice diameter there is also increase in the actual cutting power.

When the pressure is varied with mixing tube diameter keeping abrasive flow rate and orifice diameter as constant, it is noticed that the linear cutting speed for the smooth finish increases but the rate of increase in the cutting speed for rough cutting/ machining is rapid (As can be seen from the graph). Also, the power does not change for the different values of the pressure, since the power is directly proportional to the variation in the orifice diameter.

Hence, Linear Cutting speed for Smooth surface finish increases linearly but in case rough surface finish increases rapidly (due to the variation of Abrasive flow rate with respect to the pressure). Actual cutting power depends on orifice diameter (due to the variation of pressure with respect to the orifice diameter)

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APPENDIX - I

```
/* This is a program To Calculate Linear Cutting Speed for Smooth and Rough Surface
Finish and for Required Cutting Power*/
#include<iostream.h>
#include<conio.h>

main()
{
        int i,j;
        float k,l,m;
        clrscr();
        printf("\n\n\n\n\n\n SOFTWARE DEVELOPEMENT AS A PART OF M.E.
                PROJECT\n
                TO OBTAIN LINEAR CUTTING SPEED FOR SMOOTH AND
                ROUGH SURFACE FINISH\n AND REQUIRED CUTTING
                POWER \n\n (MECH.DEPTT.) DELHI COLLEGE OF
                ENGINEERING DELHI YEAR 2006");

        printf("Enter the values of \nThickness,\nPressure"
        "\nAbrasive flow rate,\nOrifice dia,\nMixing tube dia");
        scanf("%d%d%f%f%f",&i,&j,&k,&l,&m);

        printf("\n%d\n%d\n %f\n %f\n %f",i,j,k,l,m);
        if(((i>=1)&&(i<=100))&&((j>=1500)&&(j<=4000))&&((k>=0.125f)&&(k<=1
        ))&&((l>0.15f)&&(l<=0.4f))&&((m>0.254f)&&(m<=1.524f)))

        {
                float y,x,p;

        printf("\nThe linear cutting speed for smooth surface is Finish = %f",y);
```

```
Y = 0.0050280 * power(T,-1.1652) * power(P,1.8392) * power(AF,0.4115) *
        power(OD,1.627) *  power(MT,-0.6832)

        printf("\nThe linear cutting speed for Rough Surface Finish =%f",x);

Y = 0.0093756 * power(T,-1.1602) * power(P,1.8663) * power(AF,0.3963) *
        power(OD,1.5881) * power(MT,-0.7301)

        printf("\nThe Required cutting Poweris =%f",p);

Y = 0.00055808 * power(T,-0.0003) * power(P,1.5414) * power(AF,-0.001) *
        power(OD,2.005) * power(MT,-0.0008)

        }
else
printf("YOU ENTER WRONG NO.");
getch();

}
```

APPENDIX - II

Abrasive Waterjet Glossary

Abrasive

The cutting medium of an abrasivejet. Usually garnet or similar "sand like" substance.

Abrasive Flow Rate

The rate at which abrasive flows into the cutting head. Typically, abrasive is added to the nozzle from 0 - 1 lb/minute.

Abrasivejet

A **waterjet** with the addition of **abrasive** . Used to cut or machine nearly any hard material such as metal, stone, glass, etc. Other terms loosely used to mean 'abrasivejet'

- waterjet
- water jet
- water-jet
- water cutter
- water jetting
- h20 jet
- abrasive water jet
- Aquajet
- hydrojet
- JetMachining
- water knife
- AWJ (Abrasive water jet)
- UHP (Ultra high pressure) abrasive water jet.
- Amazing water cutter thingy that cuts steel and stuff (or "AWCTTCSAS")

Attenuator

An attenuator is a pressure vessel that maintains output pressure for a constant water flow, compensating for uneven pressure generated by some pumps. (Also called accumulator).

AWJ

Acronym for "Abrasive Water Jet" (or **abrasivejet**)

Bit Stream

A stream of "bits" used to control machine movements on OMAX controllers. Effectively allowing the machine to set independent feed rates at over 2000 points per inch.

Bridge / Bridging

When cutting multiple parts that might tip and fall into the tank, it is sometimes useful to "bridge" the parts with a thin piece of metal that connects them

together. Then, once the cutting is finished, the parts are removed from the machine, and the bridges are cut off. (This is similar to the way parts are held together in plastic for plastic hobby models).
See also: **Tabbing**

C-Axis
Sometimes used to refer to a 3rd axis on the machine, such as a rotary lathe axis.

CAD (and CAD / CAM)
Computer **A**ided **D**esign. CAD software is the software that you use to make drawings of parts. **CAM** is **C**omputer **A**ided **M**anufacturing. CAM software is used to make tool paths.

Catch Tank
A tank of water underneath the cutting head to allow the cutting beam to disperse, and prevent holes in your floor. Often catch tanks are filled with other material to slow the jet down, such as ceramic balls. The catch tank is also used to accumulate spent abrasive, and drop outs from your parts.

CNC
Acronym for "Computer Numerical Control". In basic terms a CNC machine has a computer that is controlling the motion. **See G-Code** .

Common Line Cutting
Common line cutting is used when making multiple parts, so that when one part is cut, a portion of the second part is cut as well. The advantage is that much time is saved, because one cut can make two parts. The disadvantage is that it is sometimes difficult to program (depending on the geometry), and generally produces lower precision cuts than cutting the parts separately.

Crankshaft Pump
A type of pump where the pressure is generated by plungers that are driven by a crankshaft.
See also **Triplex Pump or Intensifier pump** .Also often called "direct drive pump"

Cutting index
See **Machineability**

Cutting Quality
1. Simply the "quality" of cut. 2. A term used on OMAX, and sometimes other controllers to indicate how the machine should cut a given surface of the part. A quality of "1" being a very rough, high

speed cut, and a quality of "5" being a very smooth, highly precise operation. "Quality" was coined by OMAX Corporation, and is becoming the standard for describing surface finish for abrasivejet machined parts. **Note, however, that different manufacturers of equipment use "Quality" to mean different things**

Cutting Model
A model of how the abrasivejet or waterjet will behave when cutting. Cutting models are used to predict how to slow down and compensate for the effects of cutting with a "floppy tool".

Draft Angle
The angle caused by Taper.
See Also: **Taper**

Dynamic Pierce
A method of piercing a material by allowing the jet to start moving along the part path.
See **Pierce** for other popular methods of piercing.

DXF File
Drawing **E**xchange **F**ormat. This is a kind of graphical file format, defined by AutoDesk, inc., that is designed to be a common platform to exchange CAD drawing files between various CAD software packages.

DWG File
An Autocad Drawing file. The official specification for this file format is proprietary to AutoDesk corporation, which makes it difficult for third party vendors to be compatible with it.

EDM
Acronym for "Electrical Discharge Machining". A slow, but extremely precise method of machining using electrical sparks to remove material in very small increments.

E-Stop
Emergency Stop. Typically a button that you press to stop the machine in the event of an emergency.

Etch
To mark the material without cutting all the way through. This is typically accomplished by reducing pressure, reducing abrasive flow rate or increasing feed rate.
See also: **Scribe**

Feed Rate

The speed at which the cutting head moves. See also **Cutting Model.**

Focusing tube

See **Mixing Tube** .

Frosting

An effect of stray abrasive particles "frosting" the material you are cutting. It typically occurs right at the edge of where you have cut, or in a circular pattern around where you pierced the material.

Garnet

The most popular abrasive used in abrasivejet machining. It is capable of cutting an extremely wide range of materials, yet is soft enough to give you long life of your mixing tube.

G-Code

Although not particularly well suited for precision abrasivejet machining, G-Code is the most popular programming language used for programming CNC machinery.

Hard Limit

A hard limit is a stop on the machine that prevents the machine from moving further in a given direction. Typically these are used to prevent the machine from moving beyond its physical limits. See **Soft Limit**

Hard Water

"Hard" water is water with a lot of dissolved minerals in it, typically calcium and magnesium. Because water is an excellent solvent, it dissolves small amounts of minerals as it percolates through rocks and soil. As the mineral content increases, so does the "hardness" of the water. Hard water will tend to leave behind mineral deposits, which require frequent cleaning or replacement of pipes, filters, and jewels. (I suppose that Ice is also hard water, but that's typically not what we are talking about when used in then context of waterjetting.)

Hazing

See **Frosting**

Home

A spot on the machine that is defined either in software or hardware as a reference point.

IGES File

A CAD file format for exchanging CAD Drawing data between different CAD software systems.

Intensifier

A type of high pressure pump that uses hydraulics to make very high pressures.

Jewel

The orifice in which water exits to form the cutting stream. Typically jewels are made from sapphire, ruby, or diamond (thus, the name "jewel".)

Jet Lag

As the cutting head moves across the material that it is cutting, the spot where the jet exits the material will lag behind the spot where it entered the material. This lag is "jet lag".

Kerf

The width of the cutting beam. Typically the kerf width for an abrasivejet ranges from 0.020" to 0.060", depending on the nozzle. A waterjet has a narrower kerf, with 0.005" to 0.014" being typical. See also **tool offset** .

Kick back

As the machine accelerates out of a corner that it has just cut, the jet will "kick back"

.

KSI

Thousands of pounds per square inch. 1 KSI = 1000 Pounds Per Square Inch (PSI)

Lag

See **Jet Lag**

Machineability

A number used to represent how easy it is for the abrasivejet or waterjet to machine a given material. Sometimes referred to as "Cutting Index"

Mesh

The coarseness of abrasive used. For example, 80 mesh abrasive is typical of most abrasivejet applications, but 120 mesh, which is a finer abrasive, might be used for special applications.

Mixing Tube

Sometimes referred to as "nozzle" or Focusing tube. This is a tube, made from extremely hard material, that focuses the abrasive and water into a coherent beam for cutting.

Muff

A sponge or brush around the tip of the nozzle to prevent splash

Nesting software:

Nesting software is used to optimally fit many different parts to a single sheet of material.

Newtonian Accelerations

Term used to describe accelerations having to do with the physical limits of the machine, due to Newton's Laws. (As opposed to acceleration limits due to the cutting effects of the jet, and cutting model.).

Nozzle

Usually, when someone says "nozzle" they are either referring to the complete nozzle assembly (mixing tube + Jewel + nozzle body and perhaps some plumbing.) Other times, "nozzle" is used as a synonym for Mixing tube.

ORD File

OMAX **R**outed **D**ata File. A file format containing routed tool path information. (I.e. it's a tool path, and not a CAD drawing.). This is the information that the controller needs in order to machine a part.

Orifice

See **Jewel**

Offset

See **Tool Offset**

Pierce

A "Pierce" is the process of drilling through the material to be machined. Abrasivejets make their own start holes by "piercing" the material.

-There are various methods for piercing:

Stationary Piercing (very slow on thick materials, but good for small hole drilling or piercing thin materials.)
Dynamic Piercing (usually faster than stationary, but requires a lot of room on thick materials)
Wiggle Piercing (usually the fastest method of piercing where there is not enough room for dynamic)

PWJ (Pure Water Jet)
See **Waterjet**

Quality
See **Cutting Quality**

Reverse Osmosis
A method for filtering water.

Scribe
This is a word that is sometimes use to distinguish between etching with abrasive, and scribing with water only. Similar processes, except etch uses abrasive and scribe does not. See also **Etch**

Silicosis
"Silicosis is a disabling and sometimes fatal lung disease which can afflict workers who are overexposed to fine airborne particles of crystalline silica. Since crystalline silica is the second most common mineral in the earth's crust a basic component of sand, quartz and granite rock more than 1 million workers in many different types of jobs are at-risk of developing silicosis, including highway construction workers, miners, sand-blasters, and foundry workers. When workers breathe in dust containing silica, scar tissue can form in their lungs and reduce their ability to extract oxygen from the air.

Slat
One of the supports used to support the material you are machining. They are typically disposable.
See also: **Waterjet Brick**

Soft Limit
Software limit. A means of defining an area or boundary of motion for which the machine cannot exceed. Typically these are used to define the cutting envelope in which the head can move without crashing into something. This is done in software, instead of hardware, so that it can be changed when you change your fixturing or setup, and so that the machine can warn you ahead of time before you attempt to do an impossible move.
See **hard limit**

Splash back
The mess that is made when you don't cut all the way through, or the jet ricochets off of a slat. Very common during piercing, or when nozzles fail.

This is the reason you often see sponges or other guards wrapped around nozzles.

Stationary Pierce

A method of piercing the material where the jet turns on, then stays stationary until the material is pierced. This is typically a very slow method of piercing, but is fine for thin materials that pierce quickly no matter what. It also allows you to pierce the material in the minimal amount of space, and is the only option for piercing very small holes. See **Pierce** for other options.

SUPER-WATER®

SUPER-WATER® is a chemical that is added to the water of an abrasivejet or waterjet in order to focus the cutting stream, increase cutting speed, and reduce wear of high pressure components.

Striation marks

The marks left by the jet as it wiggles around. The faster you cut, the more striation marks form.

Tab / Tabbing:

Tabbing is a method for holding parts in place, by leaving a small piece of material that is connected to the original plate from which it is being cut, so that they don't fall into the tank or tip and collide with the nozzle after they are done being cut out.

See also **Bridging**

Tail

See **Jet Lag**

Taper

Taper is the difference between the top profile of the cut verses the bottom profile.

It is also possible to find "combination taper

The biggest causes of taper are:

- Distance of nozzle from material. The closer you can get the nozzle to the material, the less the taper.
- Hardness of material (usually harder materials exhibit the least taper)
- Speed of cut. Machine too fast and get taper in one direction; machine

    too slow and get taper in the other direction.
  - Quality of jet exiting the nozzle. The more focused the nozzle, the less taper exhibited.
  - Quality of abrasive used.
  - Thickness of material (thinner materials tend to exhibit more taper than thicker materials)

Tool Offset

Because the cutting beam of an Abrasivejet or a waterjet is not infinitely thin, it is necessary to offset the tool slightly from the geometry of the part. For example, a typical **kerf** width of a nozzle is about 0.030". If you were to trace the exact outline of the part you want to cut, the part would be undersized by 0.015", which is half of the kerf width. Therefore, it is necessary to follow a path that is "offset" by this amount.

So how do you measure the width of the jet?

Obviously, you can't use a ruler! What you do, is you cut a part of known dimensions, then measure the error. For low precision work, you can just guess that it's 1/2 the width of the mixing tube's inside diameter. For high precision work, it is necessary to measure the error on a previously machined part.

Traverse

Normal machine movement without cutting, for example to move the cutting head into position to cut.

Triplex pump

A type of pump that uses 3 plungers driven by a crankshaft to make pressure. See **Crankshaft pump .**

Ultra High Pressure:

A term to describe the extreme pressures that are used in waterjet and abrasivejet machining. Typically pressures range from 20,000 PSI to 100,000 PSI. Most pumps are limited to pressures below 60,000 KSI due to metal fatigue limitations in all areas of high pressure plumbing.

UHP

Acronym for "**Ultra High Pressure** ".

Waterjet:

A pressurized jet of water exiting a small orifice at extreme velocity. Used to cut soft materials such as foam, rubber, cloth, paper, etc.

Waterjet Brick

An surface made from corrugated plastic as an alternative to slats. It is very useful when machining tiny parts that would fall between the slats and get lost. It is also useful when cutting scratch-prone materials where splash back from the slats might frost the underside of the material. The primary disadvantage is that waterjet brick wears very quickly, and as it wears, it fills the catch tank with gooey plastic powder. See also: **Slats**

Weep hole

A small hole drilled into high pressure fittings to allow the water to escape in a safe manner should a leak occur.

Wiggle pierce

A method of piercing where the jet "wiggles" back and forth to "dig" it's way down. This is much faster than "stationary" and sometimes faster than "dynamic" piercing because it allows the jet to escape and clear out removed material. See **Pierce**

WJTA

WaterJet Technology Association. A good source for *hard core* information on waterjet and abrasivejet related technology.