Abrasive Water Jet Machining
On
Aluminium and Copper

A dissertation submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF ENGINEERING
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Submitted by

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DECLARATION

I hereby, declare that the work which is being presented in this report entitled, **"Abrasive Water Jet Machining on Aluminium and Copper",** submitted as dissertation towards the partial fulfillment of the requirements for the award of the degree of **Master of Engineering** with specialization in **Production and Industrial Engineering (Mechanical Engineering),** Delhi College of Engineering, Delhi, is an authentic record of my own work carried out under the supervision of **Sh. Vipin,** Asst. Professor, Department of Mechanical Engineering, Delhi College of Engineering, Delhi.

I have not submitted the matter embodied in this dissertation report for the award of any other degree.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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CONTENTS

ABSTRACT

An Abrasive Water Jet is one of the most recently developed non-traditional manufacturing processes. This technique uses jet of water which contains abrasive material. Usually, the water exits a nozzle at a very high speed and the abrasive material is injected into the jet stream. The stream along with abrasive particles impinges onto the material and does the required action of machining and cutting.

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. This process was first introduced as a commercial system in 1983 for cutting of glass. Now a days, this process is being widely used for machining of hard to machine materials like ceramics, ceramic composites, fiber-reinforced composites, and titanium alloys where conventional machining is often not technically or economically feasible. The fact that it is a cold process has also important applications where heat-affected zones are to be avoided.

In this work, a deep study of this newer non-conventional technique of machining i.e., abrasive water jet machining is done and finally it has been applied on two popular non-ferrous materials viz., Aluminium and Copper. The two materials, in the work, are the basic alloys of the above mentioned non-ferrous materials. The alloys of Aluminium and Copper are Al-2024 and Red Brass respectively. Eventually, the effects of various parameters namely Pressure, Abrasive flow rate, Orifice diameter and Mixing tube diameter on the Linear cutting speed for a smooth surface finish and Linear cutting speed to just barely cut through the material is investigated for the two alloys. After the investigation, a few graphs are plotted to have a clear idea of the variation of cutting speed (for smooth finish and to just barely cut through the material) with pressure when the various parameters (abrasive flow rate, orifice diameter and mixing tube diameter) are kept constant.

This study can be of great assistance to understand the abrasive water jet process and also the behavior of Aluminium and Copper in the perspective of this technique.

CHAPTER 1

INTRODUCTION

1.1 ABRASIVE WATER JET MACHINING

An abrasive water jet is one of the most recently developed non-traditional manufacturing processes. This technique uses jet of water which contains abrasive material. Usually, the water exits a nozzle at a very high speed and the abrasive material is injected into the jet stream. This process is sometimes known as entrainment in which the abrasive particles become part of the moving water like the passengers become part of a moving train. Hence, as with a train the water jet becomes the moving mechanism for the particles. The purpose of the abrasive water jet is to perform some machining or finishing operations. 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. Abrasive water jet machining 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. This process was first introduced as a commercial system in 1983 for cutting of glass. Nowadays, this process is being widely used for machining of hard to machine materials like ceramics, ceramic composites, fiber-reinforced composites, and titanium alloys where conventional machining is often not technically or economically feasible. The fact that it is a cold process has important implications where heat-affected zones are to be avoided.

A typical abrasive jet machining is made up of the following components:

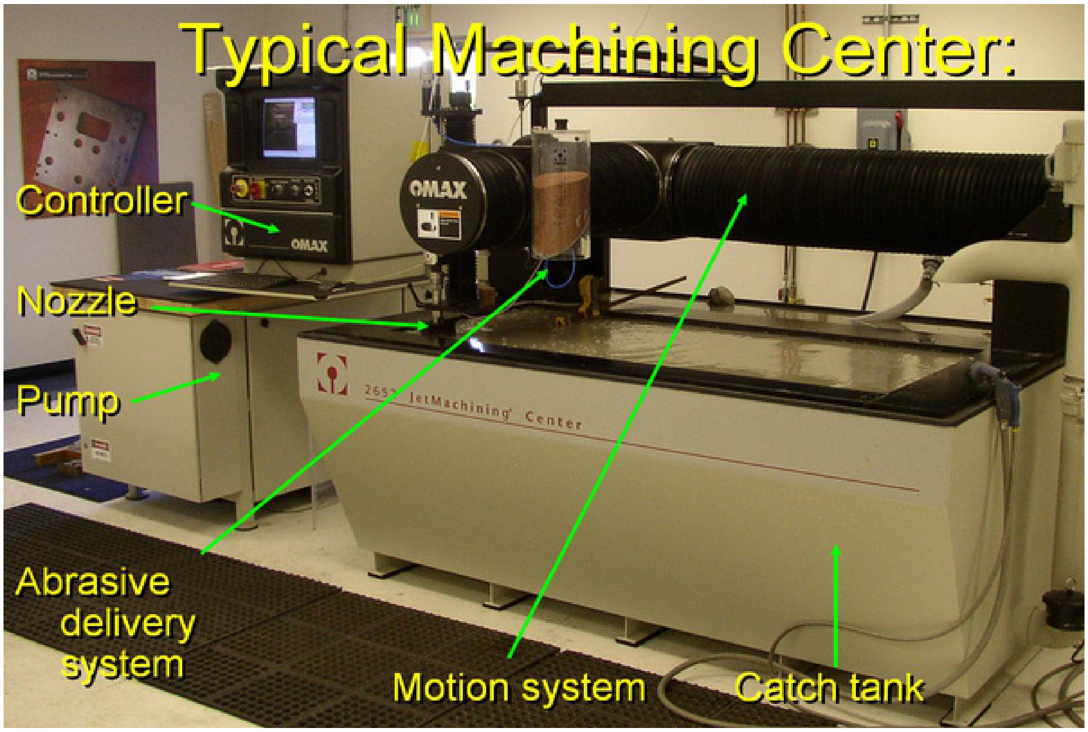


Fig.1.1: A typical Abrasive water jet machining centre.

High-pressure water starts at the pump, and is delivered through special high-pressure plumbing to the nozzle. At the nozzle, abrasive is (typically) introduced, and as the abrasive/water mixture exits, cutting is performed. Once the jet has exited the nozzle, the energy is dissipated into the catch tank, which is usually full of water and debris from previous cuts. The motion of the cutting head is typically handled by an X / Y axis structure. Control of the motion is typically done via a computer following the lines and arcs from a CAD drawing.

Advantages of the process include: easier to operate and maintain, less thermal or deformation stresses since the work piece is cold cut, decreased power consumption, high accuracy due to little work piece deformation, no fire hazards because water is inflammable, ability to cut almost any material, deep kerfing capability, high edge surface quality and no heavy clamping of work piece is needed. The following limitations are relevant to abrasive water jet machining: high capital investments are required, high cutting power is required, the jet has only a limited stability perpendicular to its own axis, and the process is noisy and produces a great deal of spray. The process is being extensively used in diverse fields of applications.

1.2 HISTORICAL BACKGROUND

High-pressure water jets are in continuous development from 1900 onwards. In 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 airplanes by rain particle impact. In the late 60's, R. Franz of University of Michigan examined 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 this technique drastically. Higher traverse speeds, thicker materials and better edge quality could be achieved.

1.3 PRINCIPLE OF WORKING

The abrasive water jet machining system is composed of the following components: high pressure intensifier, water jet, abrasive feed system, abrasive-jet nozzle, abrasive and water catcher, and supporting accessories such as hoses and control valves. The heart of the abrasive water jet system is the abrasive jet nozzle. Water is pressurized up to 400 MPa or more in the intensifier and expelled through a sapphire nozzle to form a coherent high-velocity jet. Abrasives are added into a specially shaped abrasive jet nozzle from separate feed ports. A part of the water jet's momentum is transferred to the abrasives, whose velocities rapidly increase; as a result, a focused, high-velocity stream of abrasives exits the nozzle and performs the cutting action of the work piece surface. After cutting, a water-filled catcher tank collects the abrasive water mixture. The tank also acts to support the material and reduce noise.

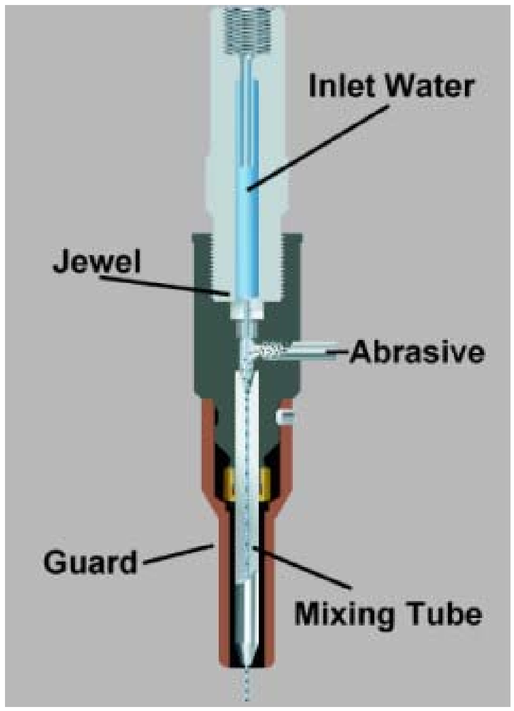


Fig.1.2: A typical Abrasive Water Jet.

High pressure abrasive water jet cutting is essentially an erosion process which involves two distinct mechanisms depending upon whether the eroded material is brittle or ductile in nature. The ductile erosion is defined as a cutting process in which the abrasive particles progressively cut the eroded material, eventually causing volume removal. The brittle erosion is described as a cracking process in which material is removed by the propagation and intersection of cracks ahead of and around the abrasive particles. In fact, abrasive water jet cutting of any material takes place as a combination of ductile and brittle erosion wear mechanisms, but one or the other may dominate the cutting process.

There are several parameters that affect the cutting performance of the abrasive water jet: **Hydraulic parameters**; water jet nozzle diameter and supply pressure, **Abrasive parameters**; abrasive material, abrasive size and abrasive flow rate, **Mixing parameters**; mixing tube dimensions and nozzle material, **Cutting parameters**; traverse rate, stand off distance, impingement angle and depth of cut and material to be cut.

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. The conventional machining practices such as milling use a solid tool to cut the material usually by a shearing process. The 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.

1.4 USES OF ABRASIVE WATER JET MACHINING

Abrasive water jet machining, if appropriate and cost effective for a number of procedures and materials has several uses as listed below:

- Cutting of difficult to machine materials.
- Milling and 3-D shaping.
- 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/ particles. The operations where plain water jet machining would be sufficient include cutting of materials such as plastics, thin metal, textiles, or foam.

CHAPTER 2

LITERATURE REVIEW

Abrasive water jets have been used for many years for the cutting of materials. 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. 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 [45].

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 [34], offers 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 [4-6]. These have involved the processing, of ductile [8] and brittle materials [5-7], leathers, woods and rubbers, as well as, composites and plastics [19-22]. It is interesting to note, however, that very little has been reported on the AWJ cutting of thin sheet steels [20] 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 Aluminium and Copper 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. 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.

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 [7-10] 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 [7] and Finnie [2] 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. Also, as the jet further penetrates into the work piece, deformation is the dominant mechanism [10]. 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 [20] has 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 [20] later used this model to explain the kerf characteristics in abrasive water jet cutting. These authors 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.

2.1 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).
It is interesting, to note that water pressure exhibits a reduced effect on the top kerf width. This is consistent with earlier findings [25, 26], 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 observed when 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.

2.1.2 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 [26]. 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 only surface roughness as assessed. From the experimental results, an increase in traverse speed causes a constant increase in the surface roughness.

2.1.3 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

Category of Burr height:

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

2.2 Striation formation mechanisms on the jet cutting surface

Hashish [32] 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 Fig. 2. 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.

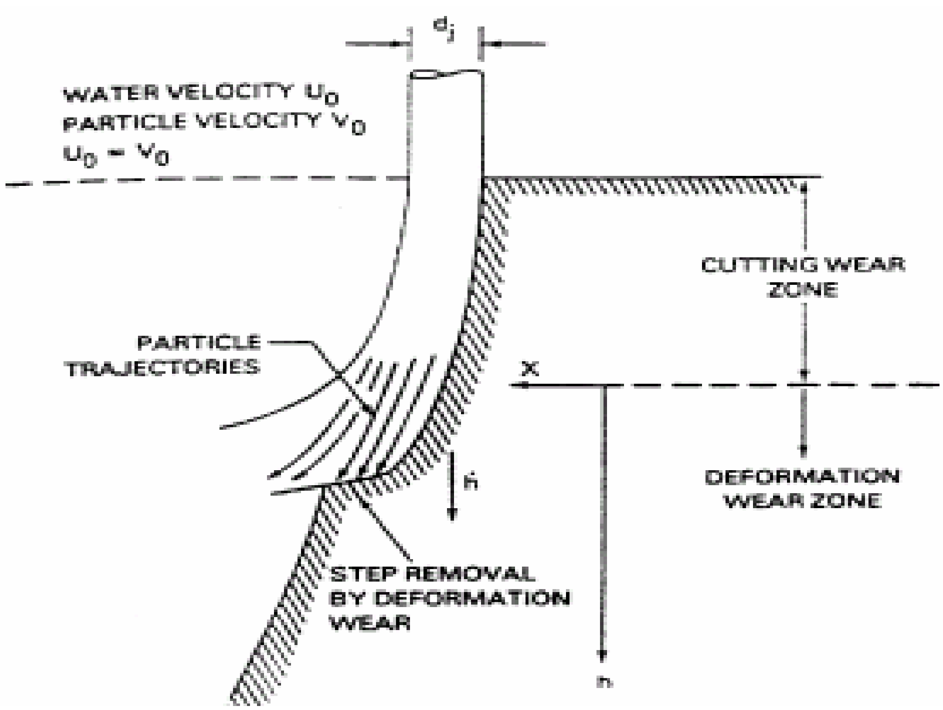


Fig. 2.1: The two cutting zones proposed by Hashish [4].

2.2.1 Striation formation due to machine system vibration

Chao and Geskin [43] 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.

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.

2.4.1 Techniques used for cutting composites materials

2.4.1.1 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.

2.4.1.2 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.

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.

2.4.1.4 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 degrees. 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.

CHAPTER 3

EXPERIMENTAL SET-UP

3.1 INTRODUCTION

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 of the water. Usually a table is necessary for placement of the material to be cut/ machined. **Fig. 3.1** gives a basic schematic of the equipment:

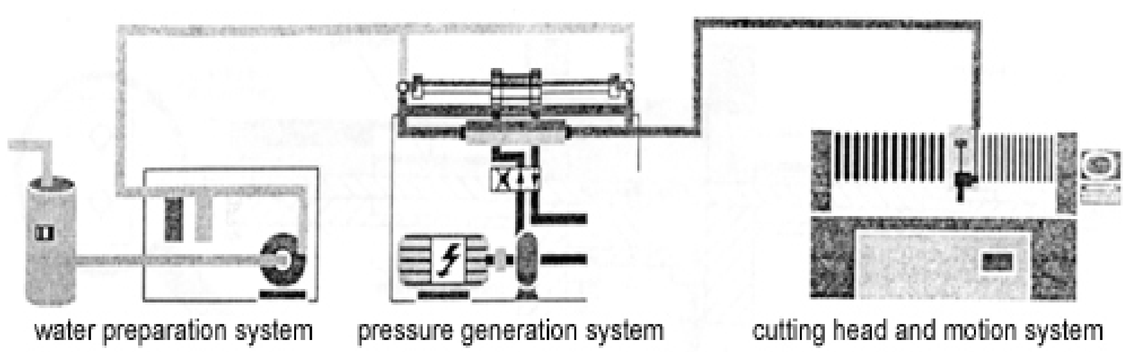


Fig.3.1: Basic Abrasive Water Jet Cutting Set-up

As can be seen included in the setup are the three systems, which are discussed as following:

- Water preparation system.
- Pressure generation system, and

- Cutting head and Motion system.

3.2 WATER PREPARATION SYSTEM

However, to this basic conceptual equipment must be factored in the realities of the operating environment and materials. First, the water supply must confirm 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 [1-4].

The more horsepower at the nozzle(which actually makes it to the nozzle), faster the jet cuts. The horsepower at the nozzle is a function of the pressure and the orifice diameter through which water at high pressure and velocity is coming out. Simply put, the higher the pressure, the faster the cut. The more water flows, the faster is the cut. Unfortunately, as the pressure increases, so does the cost and maintenance, so this is not as simple as it seems.

3.3 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.

The positive displacement pump is adequate for low to intermediate pressures i.e., up to 280 MPa. These deliver water by the action of reciprocating pistons, which are directly coupled to a crankshaft rotating at a constant speed. Thus the delivered flow of water is constant in time. **Fig. 3.2** is a schematic of a pump system.

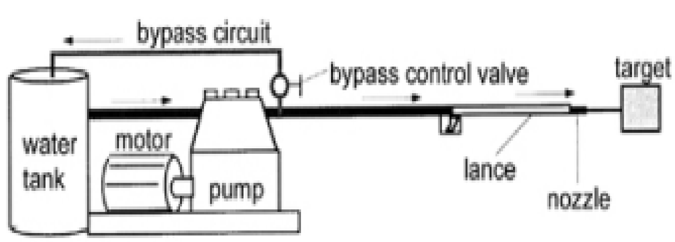


Fig.3.2: Schematic of Pump and Water Supply Setup

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 or more. To operate in a quasi-continuous mode, two or more intensifiers are used together. **Fig. 3.3** gives an example of an intensifier.

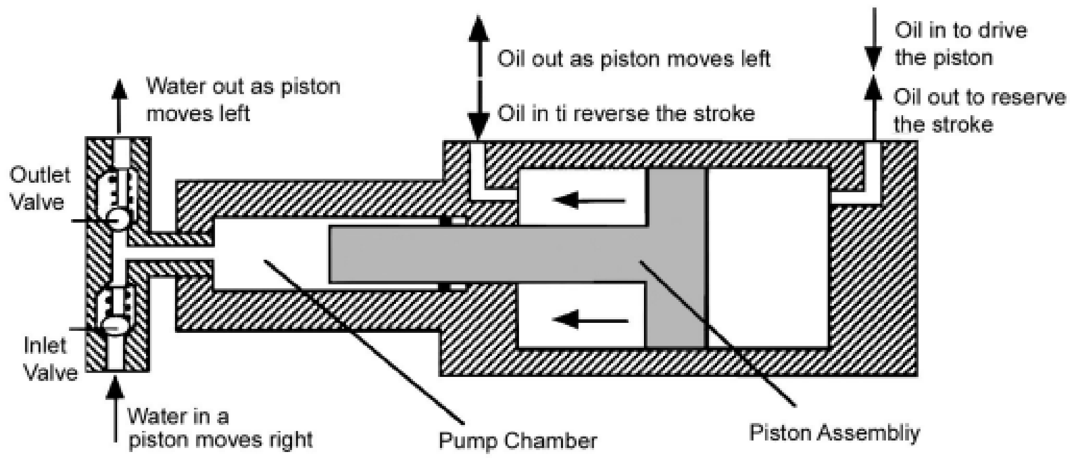


Fig.3.3: An Intensifier [10].

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% [9] 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.

One method to address this problem of pressure fluctuation is to include an accumulator, which is shown in **Fig. 3.4**. (This is also known as an attenuator since its purpose is to reduce or attenuate the variation in maximum to minimum pressure values. This is akin to the attenuation of a waveform as the energy is dissipated over time and hence the amplitude of the vibration decreases).

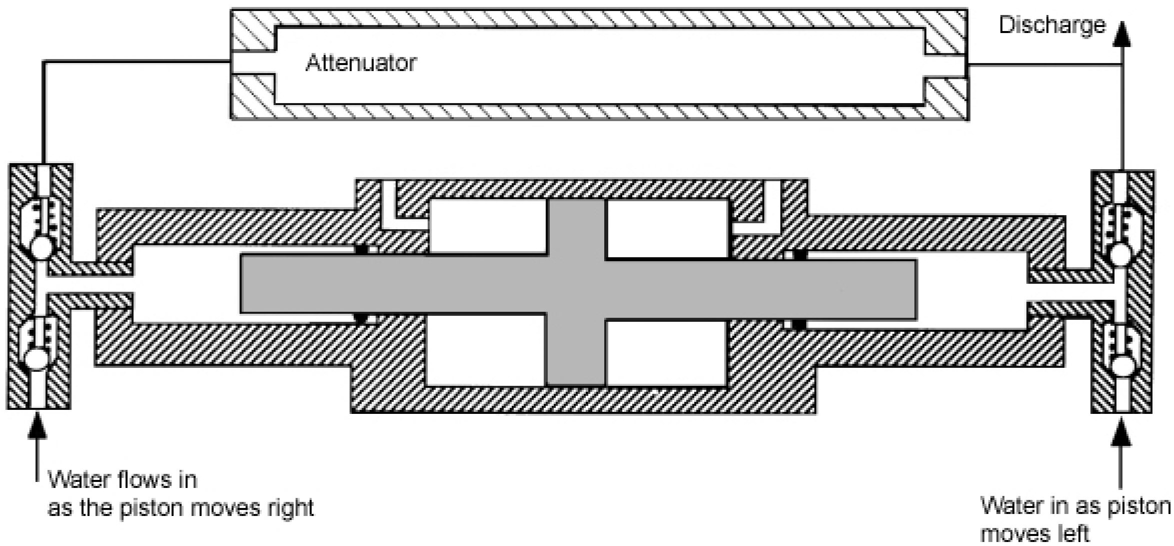


Fig.3.4: Accumulator with a Double Acting Intensifier [10]

The attenuator stores a volume of water at an elevated pressure which it will release into the system as a decrease in pump pressure is sensed. This then reduces the variations in system pressure. The size of the attenuator tank must be correlated to the pump to insure successful operation.

An alternate method to reduce variation in pressure is to use two single intensifier pistons together so that one has started its compression stroke, before the second has completed its delivery. Thus as one piston stops, the other is already at pressure and continues the delivery.

It has been found that higher water jet pressure results in better surface quality of the cut. However, too high a jet pressure can result in fragmentation of the abrasive particles leading to poorer cutting operations [11]. Water jet pressure depends on the material and the abrasives being used.

3.4 CUTTING HEAD AND MOTION SYSTEM

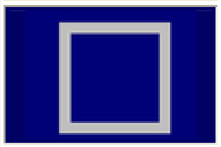
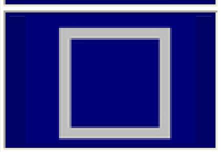
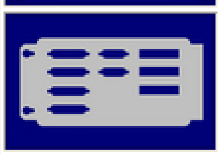
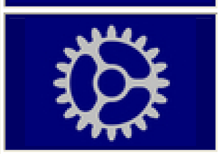
In order for the abrasive water jet to perform a machining operation there must be a relative motion between the part being machined and the jet. The one exception to this is drilling in which the part and the jet are stationary relative to each other. For all other operations there are two logical possibilities. One the jet can be moved over the material by means of a moving gantry in which the piece is held stationary. The other possibility is that the jet head can be stationary and the piece can be moved underneath it. Both systems are plausible.

Fig. 3.5: Abrasive water jet in action

3.4.1 Cutting speeds:

Ideally, it is required to make the most precise part in the least possible amount of time, and for the least amount of cost. The cutting speed is a function of the material to cut, the geometry of the part, the power and efficiency of the pump pressurizing the pressure, and a few other factors such as the abrasive used etc.

The chart below should gives some idea of what a few typical water jet parts might take to machine:

Picture	Description	Approximate Cutting time
	2.5" x 2.5" Box cut from 0.5" thick mild steel(63 x 63mm from 12mm steel)	5 minutes
	the same part as above, only in 3"(76 mm) mild steel	2.25 hours
	8" wide Electrical Panel cut from 0.06" mild steel(200 mm from 1.5mm steel)	1-3 minutes
	3" wide gear cut from 0.25" thick nylon (75mm from 6mm nylon)	1.25 minutes
	10" wide thingy cut from 1" thick titanium (254 mm wide from 25 mm thick titanium)	22 minutes
	7" tall horse cut from 0.25" thick aluminum (178 mm cut from 6 mm thick aluminum)	4.8 minutes

3.4.2 Factors affecting Cutting speed:

The primary factors that determine cutting speed are as follows:

(A) Material being cut:

- **Hardness:** Generally, harder materials cut slower than soft materials. However, there are a lot of exceptions to this. For example, granite, which is quite hard, cuts copper significantly faster, which is quite soft. This is because the granite easily breaks up because it is brittle in nature. It is also interesting to note that hardened tool steel cuts almost as quickly as mild steel.

- **Thickness:** The thicker the material, slower is the cut. For example, a part that might take 1 minute in 1/8" (3mm) steel, might take a half hour in 2" (50mm) thick steel, and maybe 20 hours in 10 inch (250mm) thick steel.

(B) Geometry of the part

It is necessary to slow the cutting speed in order to navigate sharp corners and curves. It also takes additional time to pierce the material. Therefore, parts with lots of holes and sharp corners will cut much slower than simpler shapes.

(C) Desired Result

If a smooth surface finish is required, then the part will take longer time to make. Some areas of the part with high tolerance must be taken with slower cutting speeds and other areas with high cutting speed, so that to get the optimal balance between cutting speed and final part quality.

2.5 JET FORMER

The purpose of the Jet Former is to 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.3.6**:

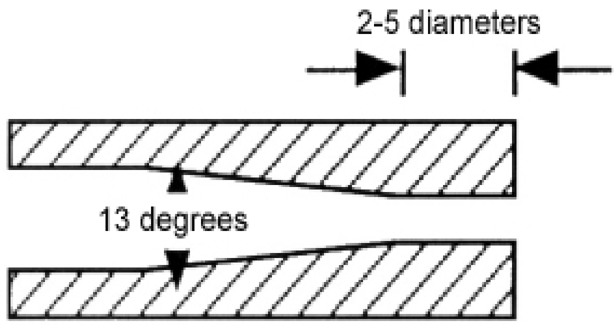


Fig.3.6: Jet Former Design [12].

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.

Fig. 3.7: Abrasive Water jet Nozzles.

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.

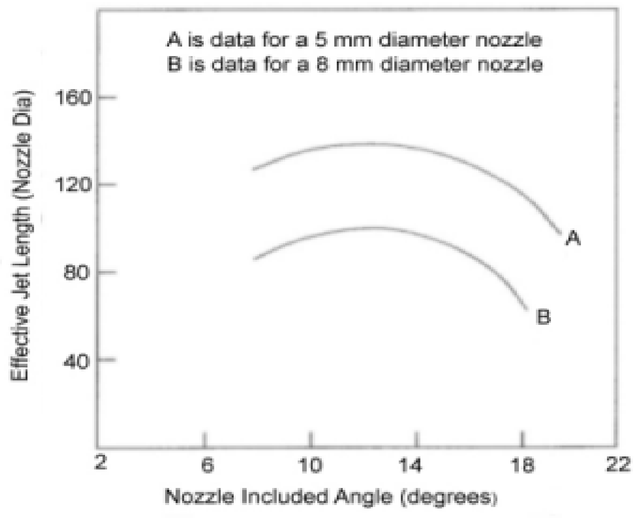


Fig.3.8: Effective Jet Length vs. Nozzle Included Angle [13]

As can be seen the best jet length results from an angle of inclination of about 12 to 13 degrees. The length of the straight section, the throat length also has an effect on the effective jet length as shown in **Fig. 3.9**:

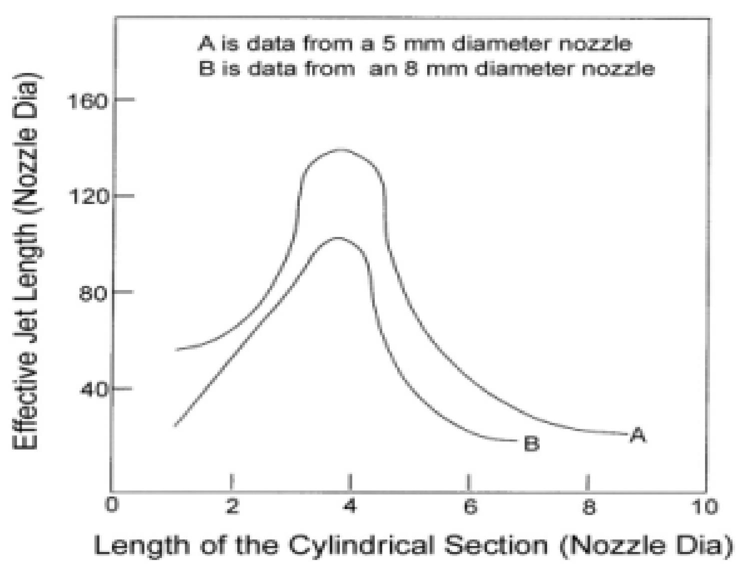


Fig.3.9: Effective Jet Length vs. Jet Former Throat Length [13]

Here it is seen that a throat length of about 4 nozzle diameters gives the best effective jet length.

In addition, it has been found that rounded corners at the inlet aid in the jet performance as shown in **Fig. 3.10**:

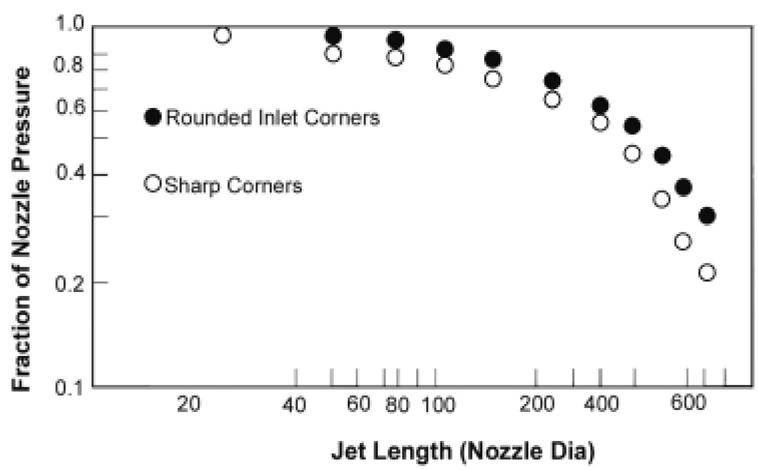


Fig.3.10: Effect of Nozzle Inlet Corner Shape on the Nozzle

3.5.1 Pressure at various Jet Lengths

As can be seen at greater distances (referred to as the standoff distance, explained below) from the jet orifice the use of rounded corners results in greater retention of the nozzle (stagnation) pressure[13]. This determines how far away the material to be machined can be from the nozzle. As the nozzle wears, the reliability decreases [14]. 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 [15]. In the area of the nozzle material, work has been done on using ceramics and various carbide materials [16].

3.5.2 STAND OFF DISTANCE

Stand off distance is defined as the distance between the face of the nozzle and the working surface of the work. The stand off distance has been found to have considerable effect on the rate of metal removal as well as the accuracy.

A large stand off distance results in the flaring up of the jet which leads to poor accuracy. A drop in material removal rate at large stand off distance is due to a reduction in the jet velocity with increasing distance.

CHAPTER 4

ABRASIVE PARTICLES

4.1 Introduction

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 [17]:

- Lattice parameters.
- Chemical composition.
- Crystallographic group and symmetry.
- Crystallochemical formula.
- Inclusions (water-gas inclusion, mineral inclusion).

4.2 ABRASIVES: SHAPE AND SIZE

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. **Fig. 4.1** gives a few examples of shapes that would be good for such purposes

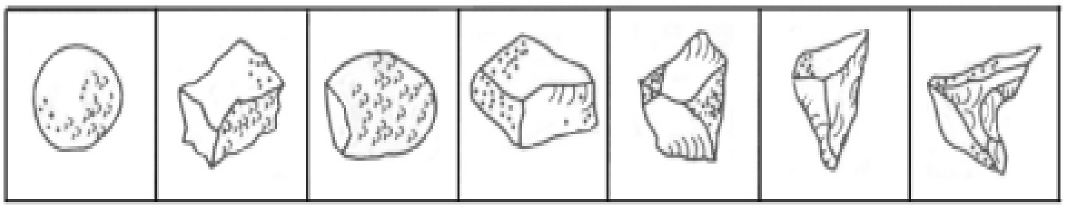


Fig. 4.1: Typical shapes of garnet abrasives [18].

As used in manufacturing processes, abrasive particles are generally very small compared to the size of cutting tools and inserts. Also, abrasives particles/grains have sharp edges, allowing the removal of very small quantities of material from the work piece surface. Consequently, very fine surface finish and dimensional accuracy can be obtained.

The size of an abrasive grain is identified by **grit number**, which is a function of sieve size; the smaller the grain size, the larger the grit number. For example, number 10 is regarded as very coarse, 100 as fine, and 500 as very fine. 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. The coarse grains are recommended for cutting, where finer grains are useful in polishing etc.

4.3 Quantity and Quality of abrasive used

4.3.1 Type of abrasive: In the manufacturing industries, the 80 mesh garnets are extensively used as abrasive grains. However, it is possible to cut slightly faster with harder abrasives but the harder abrasives also cause the mixing tube on the nozzle to wear rapidly. So, garnet is the popular choice in the industries. It is worth mentioning that not all garnet is the same. There are big variations between purity, hardness, sharpness, etc, that can also affect the cutting speed and operating costs.

4.3.2 Quantity of abrasive: Typically, abrasive jets consume between 0.5 and 1 Lb (0.25 and 0.5Kg) of abrasive per minute. There is a particular amount of abrasive flow rate for every nozzle size and pressure as to what will cut the fastest, and what amount will cut the cheapest.

4.4 ABRASIVE RECYCLING

The Abrasive water jet machining, an emerging technology is experiencing continuous growth. Its industrial usage depends on cost effectiveness. In general, the overall cost of Abrasive water jet machining systems remains quite high compared to traditional machining techniques, despite the thrust by the industry to reduce the equipment cost and increase the system reliability. The largest component of operating cost is that of abrasive, constituting nearly 75% of the total operating expenses. When abrasive disposal is included, this percentage can be even higher. The cost of abrasives has restricted many opportunities and usage of this technology. This cost, however must be considered along with abrasive performance. Good abrasive performance is more important than the cost of abrasives, since any disadvantage in higher abrasive purchase cost can be outweighed by the higher cutting speed achieved with a better performing abrasive. Therefore, cost of abrasive should be weighed against its performance and the most cost effective abrasive should be selected. The cutting efficiency is influenced by the particle size, particle size distribution, and shape of the abrasive particles.

Natural abrasives are often mined from riverbeds or sand deposits. These natural abrasives generally contain unknown amounts of impurities and possess non-uniform properties; consequently, their performance is inconsistent and unreliable. As a result, abrasives are now made synthetically. The impurities are removed to improve the performance of cutting. The abrasives are subsequently sized. This multi step process uses metal screen sieves to remove very fine and oversized particles. Among the abrasives, the industries frequently use garnet, as it demonstrated effectiveness of it’s:

- Hardness,
- Sharp edges,
- Flowability,
- Availability, and
- Reasonable cost.

The comparison of garnet, silica and steel grit indicated improved performance of garnet. However, different types of garnet, even when chemically and physically similar, perform quite differently.

Abrasive particles disintegrate during the acceleration and focusing processes and also after cutting. During the cutting process, the breakdown of abrasive particles occurs in two stages:

(1) Particle/particle, particle/water jet and particle/wall collisions in the mixing chamber/focusing tube assembly.
(2) Particle/particle and particle target collisions.

With proper cleaning and sorting, an important portion of sludge may be recycled and fed back to the cutting process. Only the remaining portion, the microchips of the work piece material and the used abrasive material of finer size particles usually less than 90 μm are disposed. The recycling of the abrasives makes the process more economical, effective and environmentally friendly.

4.5 ABRASIVE PARTICLES AND WATER MIXING

The mixing of abrasive particles and water is certainly the most crucial section of the abrasive water jet machining. 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. 4.2**, would work.

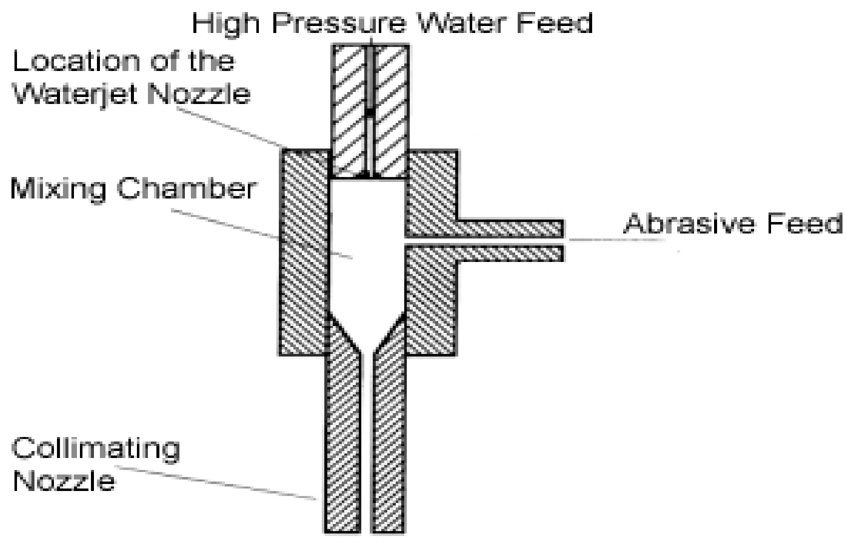


Fig. 4.2: Abrasive Particle Water Jet Mixing Design

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, which try to give the particles speed either due to gravitational force or air pressure as shown in **Fig. 4.3**:

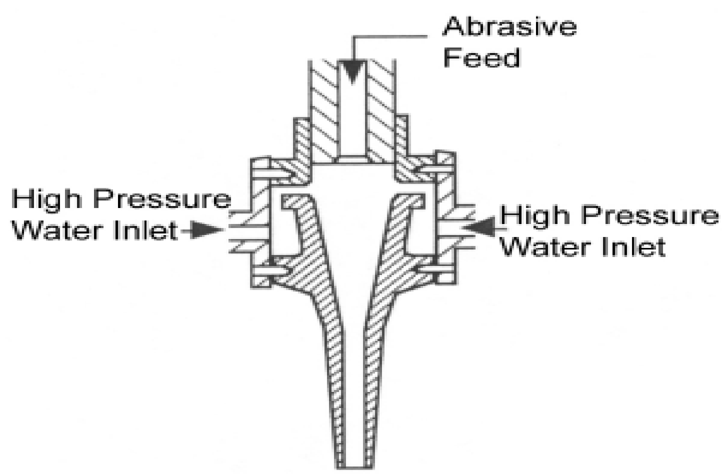


Fig. 4.3: Particle Water Premix

The top section is the exiting straight portion of the jet former. Here the jet exits the nozzle and enters into the mixing chamber. From Bernoulli's equation one can approximate the jet speed into the chamber as:

$$\mathbf{V=\sqrt{(2p/\rho w)}}$$

where P is the pressure developed in the straight portion of the jet former and ρw is the density of the water. 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.

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 ensure 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.

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.

CHAPTER 5

STRIATION AND METAL REMOVAL RATE IN AWJM

5.1 STRIATION FORMATION PHENOMENON

The striation phenomenon is a common feature of cuts made with beam-cutting techniques such as jets, lasers or plasmas. The general cut surface produced by abrasive water jet cutting consists of an upper smooth zone which is free of any striations where the primary surface irregularity is roughness, and a lower rough zone where the wavy striations are the dominant characteristic features.

The geometry of the cut surface is shown in **Fig 5.1**. As can be seen this surface shows curved striation marks/lines. At the top of the figure they are vertical, but at a quarter of the way down they take on a parabolic shape. The striations are indicative of the lag of the jet as it traverses through the material and can be related to the jet loss of energy during the cutting process.

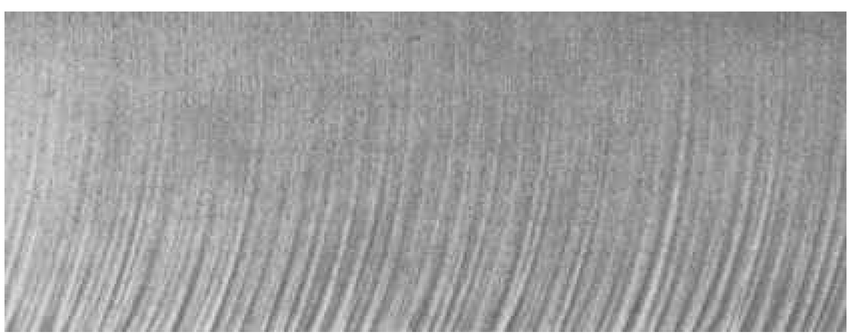


Fig.5.1: Geometry of the cutting front generated.

A desirable surface finish can be obtained only when the thickness of the work piece is less than the depth of the smooth zone. Despite the importance of elimination or minimization of this striation formation phenomenon, so far the striation formation mechanism is still not very well understood.

5.1.1 Causes of Striation Phenomenon

The striation formation is believed to be caused by the wavy abrasive particle kinetic energy distribution related to the cut surface. All factors which have an effect on this kinetic energy magnitude and its distribution related to the cut surface must affect the striation patterns and result in striation irregularities. Therefore, the causes of striation formation have been reasonably described in terms of the internal effect, which is wavy abrasive particle kinetic energy distribution, and external effects such as

- Fluctuations or unsteadiness of the abrasive water jet process parameters such as traverse speed, pressure and abrasive flow rate;
- Vibration of the work piece and nozzle while cutting;
- Vibration due to the nozzle traverse system.

This can also be the source of error in the following places:

- **Around curves:**

  As the jet makes its way around a radius, the jet lag causes a tapering effect. Therefore it is necessary to slow the jet down, so that the tail may catch up with the head (And / or tilt the cutting head to compensate).

- **Inside corners:**

  As the jet enters the corner, the traverse speed must slow down to allow the jets tail to catch up. As the jet exits the corner, the feed rate must not be increased too quickly, to avoid the lagging effect of the jet.

- **Acceleration:**

Any sudden movement (like a change in feed rate) will cause a slight blemish as well. Thus, for highest precision it is necessary to control the acceleration as well as feed rate.

- **Nozzle Focus:**

Some nozzles produce more taper than others. Holding the nozzle close to the work piece produces less taper or lagging effect of the jet.

- **Speed of Cutting:**

The slower is the cutting, the higher is the tolerance. This is because as the cutting is slowed down, the surface finish improves, and the taper begins to disappear.

- **Active Taper Compensation:**

Some newer machines now have the option of tilting the cutting head against the taper. This can be used to virtually eliminate the taper. The big advantage to active taper compensation is that taper can be reduced without to slowing down the cutting.

- **Consistency of Pump Pressure**:

Variations in water jet pump pressure can cause marks on the final part. It is important that the pump pressure vary as little as possible while machining is in progress to prevent the striation effects.

5.2 Metal Removal Rate

Material removal is mainly the result of particle impacts as the jet delivers abrasive particles at high velocities to the target surface. **Fig.5.2** shows the hierarchy of this process.

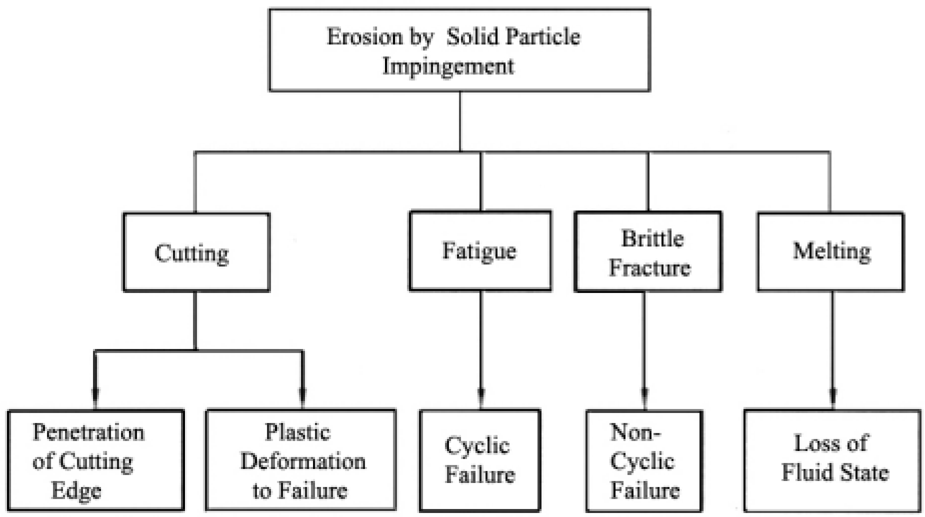


Fig.5.2: Mechanisms of material-removal [1]

These mechanisms are cutting, fatigue, melting, and brittle fracture. Clearly, these mechanisms generally do not act separately, but in combination. Their importance for the particular erosion process depends on several factors, such as the impact angle, the particle kinetic energy, the particle shape, target-material properties, and environmental conditions. Nevertheless, all four mechanisms are observed during the abrasive water jet cutting and at least three of them are applied for the material removal modeling of the abrasive water-jet machining process.

In addition the materials being machined by the abrasive water jet differ in character. Some materials are brittle and some are ductile. The type of erosion detailed in the figure will be influenced by the nature of the material.

5.2.1 ENERGY BALANCE FOR MATERIAL REMOVAL

An energy balance is one way to evaluate the cutting process of the abrasive water jet. The appeal of this method of evaluation is that it is based on conservation of work and energy. Since, work and energy both are scalar quantities so in using the method we concern ourselves with only magnitudes. The abrasive water jet hits the material with a kinetic energy, E_A. The jet then exits the material with energy of E_{ex}, which cannot be greater than E_A. The difference between these two is the energy that has been dissipated in the impact, friction, cutting, etc. and can be written as

$$E_{diss} = E_A - E_{ex} \qquad \ldots (5.1)$$

The kinetic energy of the abrasive water jet is

$$E_A = \frac{1}{2} m_A v_A^2 \qquad \ldots (5.2)$$

The mass is calculated from the mass flow rates of the two major components (Particle and water) of the abrasive water jet such that $m_A = (\dot{m}_P + \dot{m}_W)t$ where t is the time required for the jet to traverse one nozzle diameter and is equal to d_F/v. The equation then becomes

$$E_A = \frac{d_F}{2v}\left(\dot{m}_P + \dot{m}_W\right) v_A^2 \qquad \ldots (5.3)$$

With the conservation of momentum for an inelastic collision the velocity of the abrasive water jet is

$$v_A = \alpha \frac{v_W}{1 + \dot{m}_P / \dot{m}_W} \qquad \ldots (5.4)$$

Where α is the mixing efficiency coefficient. The speed of the water jet V_W can be calculated from the pump pressure by using Bernoulli's Equation as

$$v_W = \varphi\sqrt{\frac{2P}{\rho_W}}$$ ... (5.5)

and here φ characterized the energy transfer in the orifice.

The depth of the cut can characterize the amount of cutting by the abrasive water jet. If the material is not cut then the depth of the cut is h = 0. If the material is cut to the maximum depth possible for the parameters of the jet then the depth of the cut is $h = h_{max}$. Experimentally h_{max} can be determined by looking at the striations of the cut surface and if at the bottom of the cut the striations are tangent then it is assumed the maximum cut depth has been reached. The amount of the cutting thus, can be defined by a dimensionless parameter which is just the ratio of the actual depth of the cut to the maximum possible depth of cutting or

$$\Phi = \frac{h}{h_{max}}$$ ... (5.6)

Thus the amount of energy that is dissipated in cutting is

$$E_{diss}(\Phi) = \chi(\Phi)(E_A - E_{ex})$$ ... (5.7)

Where $\chi(\Phi) = 0$ for $\Phi = 0$ and $\chi(\Phi) = 1$ for $\Phi = 1$. This equation can then be seen to depend not only on the initial kinetic energy of the abrasive jet and the energy with which it exits the material but also on whether or not the material is cut and if cut what is the efficiency of that cutting. In other words if the material is not cut then the above equation says that none of the energy lost was due to energy dissipated resulting from cutting. $\chi(\Phi)$ is an efficiency factor indicating the portions of the available energy that was used for cutting purposes. When the material is cut to the maximum possible depth than all of the energy lost by the jet was used in making the cut. If the depth of the cut is less than h_{max} but greater than zero then some of the energy lost by the jet was used in making the cut and some was dissipated due to friction, impact, etc.

5.2.2 Threshold Pressure

The ability of the jet to cut depends upon the pump pressure. If the pressure is greater than a certain amount then the material can be cut. If it is less than that amount the material will not be cut. In other words there is a threshold for the pump pressure that must be met in order for the material to be cut. For this reason, this pressure is known as the threshold pressure and designated P_{thr}. If the pressure is less than the threshold pressure then there is no debris sample surface which means that the sample was not cut. Looking at this effect on the energy gives the following results:

If $P \leq P_{thr}$ then $E_{diss} = 0$ ... (5.8)

If $P > P_{thr}$ then $E_{diss} > 0$ ... (5.9)

Thus, it can be concluded that the threshold pressure is a boundary between cutting and not cutting process.

CHAPTER 6

COMPARISON WITH OTHER PROCESSES

6.1 INTRODUCTION

The Abrasive Water Jet Machining is a newer technique in the field of manufacturing processing. Here, this process is compared with some famous techniques like Laser, EDM, Milling, Punch Press,

6.1.1 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 the 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).
- The capital equipment costs for water jet are generally much lower than that for a laser.
- Abrasive jets can machine thicker materials.
- Abrasive jets are safer. No noxious fumes and no fires.
- 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 0.5".
- Abrasive jets do not loose much "focus" when cutting over uneven surfaces.
- Modern Abrasive jets are typically much easier to operate and maintain than lasers.
- Abrasive jets don't create "scaley" edges, which makes it a high quality technique.

6.1.2 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.
- New technology allows Abrasive jets to obtain tolerances of up to +/-0.003" (0.075mm) or better
- No heat affected Zone with Abrasive jets.
- Abrasive jets require less setup.
- Abrasive jets can make bigger parts.

6.1.3 When comparing with Milling:

- There is only one tool to qualify on an abrasive jet.
- Setup and fixturing typically involves placing the material on the table with an abrasive jet.
- Cleanup is much faster with an abrasive jet.
- Machine virtually any material, including:
  - Brittle materials.
  - Pre hardened materials.
  - Otherwise difficult materials such as Titanium, Hastalloy, Inconel, SS 304, hardened tool steels.
- Water jets are used a lot for complimenting or replacing milling operations. They are used for roughing out parts prior to milling, for replacing milling entirely, or for providing secondary machining on parts that just came off the mill. For this reason, many traditional machine shops are adding water jet capability to provide a competitive edge.

6.1.4 When comparing with Punch Press:

- Lower cost per piece for short runs.
- Place holes closer to the materials edge.
- Fast turn-around.
- Minimal setup and fixturing.
- Thick materials are fine.
- Brittle materials are no problem for abrasive jet.
- Hard materials are easy to machine/cut.

- Some stamping houses are using water jets for fast turn-around, or for low quantity / prototyping work.

- Water jets make a great complimentary tool for punch presses and the like because they offer a wider range of capability for similar parts. For high production of thin sheet-metal, the stamp will be more profitable in many cases, but for short runs, difficult material, thick material, and many other similar but different applications, water jets have their place.

6.1.5 When comparing with PLASMA CUTTING:

- 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 than Abrasive Jet.

- Water jets would make a great compliment to a plasma shop where more precision or higher quality is required or for parts where there is a need to cut a wider range of materials.

6.1.6 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.

- Water jets would make a great compliment to a flame cutting where more precision or higher quality is required, or for parts where there is a need to cut a wider range of materials.

6.2 ADVANTAGES OF ABRASIVE WATER JET MACHINING

- **Extremely fast setup**

No tool changes required, so there is no need to program tool changes or physically qualify multiple tools.

- **Machine virtually any shape**

Including tight inside radii, make a carburetor flange with holes drilled. Some machines are capable of 3D machining, (robot arms, (x,y) machines with lathe axis. In other words, abrasive jets are exceptional at 2D machining, but limited in 3D capability.

- **Very low side forces during the machining**

It can machine a part with walls as thin as 0.025" (0.5 mm) without them blowing out. This is one of the factors that make fixturing it so easy. Also, low side forces allow for close nesting of parts, and maximum material usage.

- **Almost No heat generation**

It can machine without hardening the material, generating poisonous fumes, or warping. It can machine parts that have already been heat treated. On piercing 2" (50mm) thick steel, temperatures may get as high as 50 degrees centigrade, but otherwise machining is done at room temperature. Aerospace companies use abrasive jets a lot because of this.

- **Machine thicker cross sections**

This technique can be successfully used for the thicker cross sections. This is one huge advantage Abrasive jets have over lasers.

Eco friendly

Abrasive jets provide the most environmentally friendly machining. (Some of the pumps even use vegetable oil for assembly lube).

There is only one tool

There is no need to qualify multiple tools, or deal with programming tool changes. Programming, Setup and Clean up time is reduced significantly.

Here are some of the benefits of using abrasive water jet:

- Cheaper than other processes.
- Cut virtually any material:
    - Pre hardened steel.
    - Mild steel.
    - Exotics like Titanium, Inconel, Hastalloy.
    - Stainless steel, SS-304.
    - Copper, Brass, Aluminum.
    - Brittle materials like glass, ceramic, quartz, stone.
    - Laminates.
    - Flammable materials.
- Cut thin and thick stuff with great ease.
- Make all sorts of shapes with only one tool.
- Cut wide range of thickness to reasonable tolerance up to 2” (50mm) thickness.
- Up to 5” (127mm) or thicker where tolerance is not important or in soft materials.
- No Heat Generated / No heat affected zones so called cold cutting.
- No mechanical stresses developed.

- Cut virtually any shape.
- The minimum hole size that can be produced satisfactorily to date is about 0.12” (3mm); maximum hole depth is on the order of 1” (25mm).
- Only one tool to qualify/ No tool changes required.
- Fast turn around on the machine thus saving tool set up and tool changing time.
- Leaves a smooth finish, thus reducing secondary operations.
- Clean cutting process without gasses or oils.
- The "scrap" metal or used abrasive grains are easier to recycle or re-use (no oily chips).
- Can easily switch between high production, and single piece production, on the same machine, with no extra effort.
- Are very safe to operate. (They don't explode, because of the incompressible property of water).
- Machine composite materials or materials where dissimilar materials are combined together.

6.3 Limitations:

- High noise levels.

- Short life of an expensive wear part like Mixing Tube.

- Occasional plugging of the Mixing Tube caused by dirt or large particles of abrasive.

- Wear, misalignment, and damage to the jewel. Jewels can crack, plug, or form deposits on them. Cracking and plugging happens as a result of dirty inlet water, and is easily avoided with proper filtration. Deposits accumulate gradually as a result of minerals in the water.

- Hazards due to rebounding of the abrasives.

- Problems with the Abrasive Jet Nozzles.

CHAPTER 7

AWJM on Aluminium and Copper Alloy

7.1 Aluminium

Aluminium occupies third place among commercially used engineering materials after Iron and Copper. The normal purity of Aluminium from its ore i.e. bauxite ranges from 99.0 to 99.5%. The main impurities are Iron and Silica. The important factor in selecting Aluminum and its alloys are their high strength to weight ratio, their resistance to corrosion by many chemicals, their high thermal and electrical conductivity, non toxicity, reflectivity, and appearance, and their ease of formability and machinability and non magnetic properties.

The important uses of Aluminium and its alloys are in container and packaging (cans and foils), in building in other type of constructions, in transportation (aircraft and aero-space applications, buses, automobile, railway, and marine craft), in electrical applications (economical and non-magnetic electrical conductor), in consumer durables (appliances, cooking utensils and furniture), and in portable tools. Nearly all high voltage transmission line is made of Aluminium. Aluminium alloys are available as mill products, which are, as wrought products made in to various shapes by rolling, extrusion, drawing and forging. Aluminium ingots are available for casting as is Aluminium in powder form for powder metallurgy applications.

7.1.1 Properties of Aluminium:

- The most important characteristic of Al is light weight, with density of 2.70 gm/cc , which is about 1/3rd that of steel or copper alloys.
- Aluminium has high electrical and thermal conductivity. Its electrical conductivity is about 62% that of copper.

- Aluminium has high corrosion resistance in water, industrial and marine atmosphere. Anodizing can further increase corrosion resistance of aluminum.
- Aluminium has good machinability, formability, Workability and castability.
- Aluminium has high light reflectivity and non tarnish ion characteristic.
- Aluminium is non toxic non magnetic, and non-sparking.
- It is readily available and less expensive as compared to other metals.

The main drawback of Aluminium is its low hardness and poor strength.

7.1.2 Aluminium Alloy (Al-2024):

Al-2024 is an Aluminium alloy that contains 99.90% of Aluminium and the rest is copper. So, it attains a high strength to weight ratio, low resistance to corrosion and heat treatable nature. The properties of Al-2024 are:

Ultimate Tensile Strength---------------470MPa
Yield Strength--------------------------325 MPa
Elongation in 50 mm---------------------19-20%

7.1.3 Applications of Al-2024:

The Alloy is extensively used in

- Aircraft structures
- Screw machine products
- Truck wheels
- Sheet metal work

7.2 COPPER

7.2.1 Introduction

First produced in about 4000 B.C., copper(Cu) and its alloys have properties somewhat similar to those of aluminium and its alloys. It is one of the most used non-ferrous metals in industry. It is a soft, malleable ductile material with a reddish-brown appearance. Its specific gravity is 8.9 and Melting Point is 1083 degrees centigrade. It is largely used in making electrical cables & wires for electrical machinery & appliances, in electroplating, making coins and household utensils. It may be casted, forged, rolled and drawn into wires. It is non- corrosive under ordinary conditions and resists weather very effectively. Copper in the form of tubes is widely used in industries. Also, it is used for making useful alloys with Tin, Zinc, Nickel and Aluminium.

Copper alloys often are attractive for applications in which a combination of electrical, mechanical, non-magnetic, corrosion resistant, thermally conductive, and wear-resistant qualities is required. Applications include electrical and electronic components; springs; cartridges for small arms; plumbing; heat exchangers; marine hardware, and consumer goods, such as cooking utensils, jewelry, and other decorative objects. The pure copper can also be used as a solid lubricant an hot metal forming operations.

Copper alloys can acquire a wide variety of properties by the addition of alloying elements and by heat treatment, to improve their manufacturing characteristics.

7.2.2 Copper Alloy (Red Brass, 85%):

Red Brass, 85% is a Copper alloy that contains 85.0% of Copper and the rest 15.0% is Zinc. It has good resistance to corrosion and excellent electric and heat conductor.

7.2.3 The properties of Red Brass are:

Ultimate Tensile Strength---------------270-725MPa

Yield Strength--------------------------70-435MPa

Elongation in 50 mm---------------------55%

7.2.4 Applications of Red Brass, 85%:

The Alloy is extensively used in

- Conduits.
- Sockets.
- Fasteners.
- Condensers and Heat Exchangers.

CHAPTER 8

DATA COLLECTION

8.1 Data collection for the Al-2024 and Red Brass, 85%

In order to study the behavior of the two alloys towards Abrasive Water Jet Machining, for a particular thickness of the material (in mm), pressure (in bar), abrasive flow rate (in kg/min), orifice/ jewel diameter (in mm) and mixing tube diameter (in mm), the following data is collected in terms of:

- Linear cutting speed for smooth finish (mm/min).
- Linear cutting speed to barely cut through the material (mm/min).
- Actual Cutting Power(kW).

The data is obtained and tabulated as following:

8.1.1 For thickness 1 mm, three different sets of five values (on varying abrasive flow rate as 0.125kg/min, 0.25 kg/min and 0.5 kg/min) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the orifice diameter (0.3 mm)and mixing tube diameter (1.016 mm).

8.1.2 For thickness 1 mm, three different sets of five values (on varying orifice diameter as 0.20 mm, 0.32 mm and 0.4 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.3 kg/min) and mixing tube diameter (0.508 mm).

8.1.3 For thickness 1 mm, three different sets of five values (on varying mixing tube diameter as 0.254 mm, 0.762 mm and 1.524 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.75 kg/min) and orifice diameter (0.25 mm).

8.2.1 For thickness 2 mm, three different sets of five values (on varying abrasive flow rate as 0.125kg/min, 0.25 kg/min and 0.5 kg/min) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the orifice diameter (0.3 mm)and mixing tube diameter (1.016 mm).

8.2.2 For thickness 2 mm, three different sets of five values (on varying orifice diameter as 0.20 mm, 0.32 mm and 0.4 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.3 kg/min) and mixing tube diameter (0.508 mm).

8.2.3 For thickness 2 mm, three different sets of five values (on varying mixing tube diameter as 0.254 mm, 0.762 mm and 1.524 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.75 kg/min) and orifice diameter (0.25 mm).

8.3.1 For thickness 5 mm, three different sets of five values (on varying abrasive flow rate as 0.125kg/min, 0.25 kg/min and 0.5 kg/min) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the orifice diameter (0.3 mm)and mixing tube diameter (1.016 mm).

8.3.2 For thickness 5 mm, three different sets of five values (on varying orifice diameter as 0.20 mm, 0.32 mm and 0.4 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.3 kg/min) and mixing tube diameter (0.508 mm).

8.3.3 For thickness 5 mm, three different sets of five values (on varying mixing tube diameter as 0.254 mm, 0.762 mm and 1.524 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.75 kg/min) and orifice diameter (0.25 mm).

8.4.1 For thickness 10 mm, three different sets of five values (on varying abrasive flow rate as 0.125kg/min, 0.25 kg/min and 0.5 kg/min) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the orifice diameter (0.3 mm)and mixing tube diameter (1.016 mm).

8.4.2 For thickness 10 mm, three different sets of five values (on varying orifice diameter as 0.20 mm, 0.32 mm and 0.4 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.3 kg/min) and mixing tube diameter (0.508 mm).

8.4.3 For thickness 10 mm, three different sets of five values (on varying mixing tube diameter as 0.254 mm, 0.762 mm and 1.524 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.75 kg/min) and orifice diameter (0.25 mm).

8.5.1 For thickness 20 mm, three different sets of five values (on varying abrasive flow rate as 0.125kg/min, 0.25 kg/min and 0.5 kg/min) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the orifice diameter (0.3 mm)and mixing tube diameter (1.016 mm).

8.5.2 For thickness 20 mm, three different sets of five values (on varying orifice diameter as 0.20 mm, 0.32 mm and 0.4 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.3 kg/min) and mixing tube diameter (0.508 mm).

8.5.3 For thickness 20 mm, three different sets of five values (on varying mixing tube diameter as 0.254 mm, 0.762 mm and 1.524 mm) are taken on varying Pressure (2500 bar, 2750 bar, 3000 bar, 3500 bar and 4000 bar) but keeping constant the abrasive flow rate (0.75 kg/min) and orifice diameter (0.25 mm).

(A) At thickness = 1mm (With variable Abrasive Rate)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish(mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.125	0.3	1.016	1545.74	722.94	4100.97	1918.01	8.71	8.71
2750	0.125	0.3	1.016	1840.72	860.9	4883.59	2284.04	10.05	10.05
3000	0.125	0.3	1.016	2158.92	1009.72	5727.8	2678.88	11.45	11.45
3500	0.125	0.3	1.016	2863.64	1339.32	7597.48	3553.32	14.42	14.42
4000	0.125	0.3	1.016	3657.55	1710.63	9703.78	4538.44	17.62	17.62
2500	0.25	0.3	1.016	2031.78	950.26	5390.48	2521.11	8.71	8.71
2750	0.25	0.3	1.016	2419.52	1121.61	6419.19	3002.24	10.05	10.05
3000	0.25	0.3	1.016	2837.78	1327.22	7528.86	3521.23	11.45	11.45
3500	0.25	0.3	1.016	3764.09	1760.46	9986.44	4670.63	14.42	14.42
4000	0.25	0.3	1.016	4807.64	2248.52	12755.06	5965.51	17.62	17.62
2500	0.5	0.3	1.016	2676.66	1249.06	7085.47	3313.86	8.71	8.71
2750	0.5	0.3	1.016	3180.32	1487.43	8437.66	3946.27	10.05	10.05
3000	0.5	0.3	1.016	3730.09	1744.56	9896.24	4628.45	11.45	11.45
3500	0.5	0.3	1.016	4947.68	2314.02	13126.59	6139.27	14.42	14.42
4000	0.5	0.3	1.016	6319.36	2955.55	16765.78	7841.31	17.62	17.62

(B) At thickness = 1mm (With variable Orifice Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.3	0.2	0.508	1882.83	880.59	4595.29	2336.28	3.87	3.87
2750	0.3	0.2	0.508	2242.14	1048.64	5948.59	2782.14	4.46	4.46
3000	0.3	0.2	0.508	2629.73	1229.92	6976.9	3263.08	5.09	5.09
3500	0.3	0.2	0.508	3488.13	1631.39	9254.31	4328.22	6.41	6.41
4000	0.3	0.2	0.508	4455.18	2083.67	11819.95	5528.16	7.83	7.83
2500	0.3	0.32	0.508	3956.76	1850.57	10497.62	4909.71	9.91	9.91
2750	0.3	0.32	0.508	4711.87	2203.73	12500.97	5846.67	11.43	11.43
3000	0.3	0.32	0.508	5526.39	2584.68	14661.97	6857.37	13.02	13.02
3500	0.3	0.32	0.508	7330.32	3428.37	19447.95	9095.76	16.41	16.41
4000	0.3	0.32	0.508	9362.57	4378.85	24839.66	11617.4	20.05	20.05
2500	0.3	0.4	0.508	5629.47	2632.89	14935.45	6985.27	15.48	15.48
2750	0.3	0.4	0.508	6703.79	3135.35	17785.71	8318.33	17.86	17.86
3000	0.3	0.4	0.508	7862.65	3677.34	20860.27	9756.29	20.35	20.35
3500	0.3	0.4	0.508	10429.19	4877.71	27669.5	12941	25.64	25.64
4000	0.3	0.4	0.508	13320.56	6229.99	35340.54	16528.7	31.33	31.33

(C) At thickness = 1mm (With variable Mixing Tube Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.75	0.25	0.254	6292.84	2943.15	16695.43	7808.41	6.05	6.05
2750	0.75	0.25	0.254	7493.76	3504.81	19881.57	9298.56	6.98	6.98
3000	0.75	0.25	0.254	8789.18	4110.68	23318.42	10906	7.95	7.95
3500	0.75	0.25	0.254	11658.16	5452.49	30930.06	14465.9	10.02	10.02
4000	0.75	0.25	0.254	14890.24	6964.13	39505.04	18476.4	12.24	12.24
2500	0.75	0.25	0.762	2882.42	1348.1	7647.29	3576.62	6.05	6.05
2750	0.75	0.25	0.762	3432.5	1605.37	9106.69	4259.18	6.98	6.98
3000	0.75	0.25	0.762	4025.86	1882.88	10680.93	4995.45	7.95	7.95
3500	0.75	0.25	0.762	5339.99	2497.5	14167.42	6626.07	10.02	10.02
4000	0.75	0.25	0.762	6820.43	3189.9	18095.16	8463.06	12.24	12.24
2500	0.75	0.25	1.524	1761.23	823.72	4672.67	2185.4	6.05	6.05
2750	0.75	0.25	1.524	2097.34	980.92	5564.4	2602.46	6.98	6.98
3000	0.75	0.25	1.524	2459.89	1150.49	6526.3	3052.33	7.95	7.95
3500	0.75	0.25	1.524	3262.86	1526.03	8656.63	4048.68	10.02	10.02
4000	0.75	0.25	1.524	4167.44	1949.1	11056.57	5171.13	12.24	12.24

(A) At thickness = 2mm (With variable Abrasive Rate)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.125	0.3	1.016	696.55	325.77	1848	864.3	8.71	8.71
2750	0.125	0.3	1.016	829.48	387.94	2200.67	1029.25	10.05	10.05
3000	0.125	0.3	1.016	972.87	455.01	2581.09	1207.17	11.45	11.45
3500	0.125	0.3	1.016	1290.43	603.53	3423.61	1601.22	14.42	14.42
4000	0.125	0.3	1.016	1648.18	770.85	4372.77	2045.13	17.62	17.62
2500	0.25	0.3	1.016	915.57	428.21	2429.09	1136.08	8.71	8.71
2750	0.25	0.3	1.016	1090.3	509.93	2892.65	1352.89	10.05	10.05
3000	0.25	0.3	1.016	1278.77	598.08	3392.69	1586.75	11.45	11.45
3500	0.25	0.3	1.016	1696.19	793.31	4500.14	2104.7	14.42	14.42
4000	0.25	0.3	1.016	2166.44	1013.24	5747.75	2688.21	17.62	17.62
2500	0.5	0.3	1.016	1203.47	562.86	3192.89	1493.31	8.71	8.71
2750	0.5	0.3	1.016	1433.13	670.27	3802.22	1778.29	10.05	10.05
3000	0.5	0.3	1.016	1680.87	786.14	4459.5	2085.7	11.45	11.45
3500	0.5	0.3	1.016	2229.55	1042.75	5915.17	2766.51	14.42	14.42
4000	0.5	0.3	1.016	2847.66	1331.84	7555.08	3533.49	17.62	17.62

(B) At thickness = 2mm (With variable Orifice Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.3	0.2	0.508	848.45	396.82	2251	1052.79	3.87	3.87
2750	0.3	0.2	0.508	1010.377	472.55	2680.58	1253.7	4.46	4.46
3000	0.3	0.2	0.508	1185.02	554.23	3143.97	1470.42	5.09	5.09
3500	0.3	0.2	0.508	1571.84	735.15	4170.22	1950.4	6.41	6.41
4000	0.3	0.2	0.508	2007.61	938.96	5326.37	2491.13	7.83	7.83
2500	0.3	0.32	0.508	1783.02	833.91	4730.49	2212.44	9.91	9.91
2750	0.3	0.32	0.508	2123.29	993.06	5633.25	2634.66	11.43	11.43
3000	0.3	0.32	0.508	2490.33	1164.72	6607.05	3090.1	13.02	13.02
3500	0.3	0.32	0.508	3303.23	1544.91	8763.74	4098.78	16.41	16.41
4000	0.3	0.32	0.508	4219.01	1973.22	11193.38	5235.11	20.05	20.05
2500	0.3	0.4	0.508	2636.78	1186.45	6730.29	3147.74	15.48	15.48
2750	0.3	0.4	0.508	3020.9	1412.87	8014.69	3748.45	17.86	17.86
3000	0.3	0.4	0.508	3543.11	1657.1	9400.16	4396.43	20.35	20.35
3500	0.3	0.4	0.508	4699.66	2198.02	12468.58	5831.52	25.64	25.64
4000	0.3	0.4	0.508	6002.58	2807.39	15925.34	7448.24	31.33	31.33

(C) At thickness = 2mm (With variable Mixing Tube Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.75	0.25	0.254	2835.71	1326.26	7523.38	3518.67	6.05	6.05
2750	0.75	0.25	0.254	3376.88	1579.36	8959.14	4190.17	6.98	6.98
3000	0.75	0.25	0.254	3960.63	1852.38	10507.87	4914.51	7.95	7.95
3500	0.75	0.25	0.254	5253.86	2457.03	13937.87	6518.71	10.02	10.02
4000	0.75	0.25	0.254	6709.92	3138.21	17801.97	8325.93	12.24	12.24
2500	0.75	0.25	0.762	1298.89	607.49	3446.06	1611.71	6.05	6.05
2750	0.75	0.25	0.762	1546.77	723.42	4103.71	1919.29	6.98	6.98
3000	0.75	0.25	0.762	1814.15	848.87	4813.1	2251.07	7.95	7.95
3500	0.75	0.25	0.762	2406.33	1125.44	6384.2	2985.87	10.02	10.02
4000	0.75	0.25	0.762	3073.46	1437.45	8154.14	3813.67	12.24	12.24
2500	0.75	0.25	1.524	793.65	371.19	2105.63	984.8	6.05	6.05
2750	0.75	0.25	1.524	945.11	442.03	2507.46	1172.73	6.98	6.98
3000	0.75	0.25	1.524	1108.49	518.44	2940.92	1375.46	7.95	7.95
3500	0.75	0.25	1.524	1470.33	687.67	3900.9	1824.44	10.02	10.02
4000	0.75	0.25	1.524	1877.96	878.32	4982.37	2330.24	12.24	12.24

(A) At thickness = 5mm (With variable Abrasive Rate)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.125	0.3	1.016	242.84	113.58	644.27	301.33	8.71	8.71
2750	0.125	0.3	1.016	289.18	135.25	767.23	358.83	10.05	10.05
3000	0.125	0.3	1.016	339.17	158.63	899.85	420.86	11.45	11.45
3500	0.125	0.3	1.016	449.89	210.41	1193.59	558.24	14.42	14.42
4000	0.125	0.3	1.016	574.61	268.74	1524.49	713	17.62	17.62
2500	0.25	0.3	1.016	319.2	149.29	846.86	396.07	8.71	8.71
2750	0.25	0.3	1.016	380.11	177.78	1008.47	471.66	10.05	10.05
3000	0.25	0.3	1.016	445.82	208.51	1182.81	553.2	11.45	11.45
3500	0.25	0.3	1.016	591.35	276.57	1568.9	733.77	14.42	14.42
4000	0.25	0.3	1.016	755.29	353.25	2003.86	937.2	17.62	17.62
2500	0.5	0.3	1.016	419.57	196.23	1113.15	520.62	8.71	8.71
2750	0.5	0.3	1.016	499.64	233.68	1325.58	619.97	10.05	10.05
3000	0.5	0.3	1.016	586.01	274.07	1554.73	727.14	11.45	11.45
3500	0.5	0.3	1.016	777.29	363.54	2062.23	964.5	14.42	14.42
4000	0.5	0.3	1.016	992.79	464.33	2633.95	1231.89	17.62	17.62

(B) At thickness = 5mm (With variable Orifice Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.3	0.2	0.508	295.8	138.34	784.78	367.04	3.87	3.87
2750	0.3	0.2	0.508	352.25	164.75	934.54	437.08	4.46	4.46
3000	0.3	0.2	0.508	413.14	193.22	1096.09	512.64	5.09	5.09
3500	0.3	0.2	0.508	548	256.3	1453.88	679.98	6.41	6.41
4000	0.3	0.2	0.508	699.92	327.35	1856.95	868.49	7.83	7.83
2500	0.3	0.32	0.508	621.62	290.73	1649.21	771.33	9.91	9.91
2750	0.3	0.32	0.508	740.25	346.21	1963.94	918.53	11.43	11.43
3000	0.3	0.32	0.508	868.21	406.06	2303.44	1077.31	13.02	13.02
3500	0.3	0.32	0.508	1151.62	538.61	3055.33	1428.97	16.41	16.41
4000	0.3	0.32	0.508	1470.89	687.93	3902.38	1825.14	20.05	20.05
2500	0.3	0.4	0.508	884.41	413.63	2346.4	1097.41	15.48	15.48
2750	0.3	0.4	0.508	1053.19	492.57	2794.19	1306.84	17.86	17.86
3000	0.3	0.4	0.508	1235.25	577.72	3277.21	1532.74	20.35	20.35
3500	0.3	0.4	0.508	1638.46	766.3	4346.96	2033.06	25.64	25.64
4000	0.3	0.4	0.508	2092.7	978.75	5552.1	2596.71	31.33	31.33

(C) At thickness = 5mm (With variable Mixing Tube Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.75	0.25	0.254	988.62	462.38	2622.9	1226.72	6.05	6.05
2750	0.75	0.25	0.254	1177.29	550.62	3123.45	1460.83	6.98	6.98
3000	0.75	0.25	0.254	1380.81	645.8	3663.39	1713.36	7.95	7.95
3500	0.75	0.25	0.254	1831.53	856.6	4859.21	2272.64	10.02	10.02
4000	0.75	0.25	0.254	2339.3	1094.09	6206.36	2902.7	12.24	12.24
2500	0.75	0.25	0.762	452.84	211.79	1201.41	561.9	6.05	6.05
2750	0.75	0.25	0.762	539.26	252.21	1430.69	669.13	6.98	6.98
3000	0.75	0.25	0.762	632.47	295.81	1678.01	784.8	7.95	7.95
3500	0.75	0.25	0.762	838.93	392.36	2225.74	1040.57	10.02	10.02
4000	0.75	0.25	0.762	1071.51	501.14	2842.8	1329.57	12.24	12.24
2500	0.75	0.25	1.524	276.69	129.41	734.09	343.33	6.05	6.05
2750	0.75	0.25	1.524	329.5	154.11	874.18	408.85	6.98	6.98
3000	0.75	0.25	1.524	386.46	180.74	1025.3	479.53	7.95	7.95
3500	0.75	0.25	1.524	512.6	239.74	1359.98	636.06	10.02	10.02
4000	0.75	0.25	1.524	654.72	306.21	1737.02	812.4	12.24	12.24

(A) At thickness = 10mm (With variable Abrasive Rate)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.125	0.3	1.016	109.43	51.18	290.33	135.78	8.71	8.71
2750	0.125	0.3	1.016	130.31	60.95	345.73	161.7	10.05	10.05
3000	0.125	0.3	1.016	152.84	71.48	405.5	189.65	11.45	11.45
3500	0.125	0.3	1.016	202.73	94.82	537.86	251.56	14.42	14.42
4000	0.125	0.3	1.016	253.93	121.1	686.98	321.3	17.62	17.62
2500	0.25	0.3	1.016	143.84	67.27	381.62	178.48	8.71	8.71
2750	0.25	0.3	1.016	171.29	80.11	454.44	212.54	10.05	10.05
3000	0.25	0.3	1.016	200.9	93.96	533	249.28	11.45	11.45
3500	0.25	0.3	1.016	266.48	124.63	706.99	330.66	14.42	14.42
4000	0.25	0.3	1.016	340.35	159.18	902.99	422.33	17.62	17.62
2500	0.5	0.3	1.016	189.07	88.43	501.61	234.6	8.71	8.71
2750	0.5	0.3	1.016	225.15	105.3	597.34	279.37	10.05	10.05
3000	0.5	0.3	1.016	264.07	123.51	700.6	327.67	11.45	11.45
3500	0.5	0.3	1.016	350.27	163.82	929.29	434.63	14.42	14.42
4000	0.5	0.3	1.016	447.38	209.24	1186.93	555.12	17.62	17.62

(B) At thickness = 10mm (With variable Orifice Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.3	0.2	0.508	133.29	62.34	353.64	165.4	3.87	3.87
2750	0.3	0.2	0.508	158.73	74.24	421.13	196.96	4.46	4.46
3000	0.3	0.2	0.508	186.17	87.07	493.93	231.01	5.09	5.09
3500	0.3	0.2	0.508	246.94	115.49	655.15	306.41	6.41	6.41
4000	0.3	0.2	0.508	315.4	147.51	836.79	391.36	7.83	7.83
2500	0.3	0.32	0.508	280.12	131.01	743.17	347.58	9.91	9.91
2750	0.3	0.32	0.508	333.57	156.01	885	413.91	11.43	11.43
3000	0.3	0.32	0.508	391.24	182.98	1037.99	485.46	13.02	13.02
3500	0.3	0.32	0.508	518.95	242.71	1376.81	643.93	16.41	16.41
4000	0.3	0.32	0.508	662.82	310	1751.58	822.45	20.05	20.05
2500	0.3	0.4	0.508	398.54	186.39	1057.35	494.52	15.48	15.48
2750	0.3	0.4	0.508	474.59	221.97	1259.13	588.89	17.86	17.86
3000	0.3	0.4	0.508	556.63	260.34	1476.79	690.69	20.35	20.35
3500	0.3	0.4	0.508	738.33	345.32	1958.85	916.15	25.64	25.64
4000	0.3	0.4	0.508	943.02	441.05	2501.92	1170.14	31.33	31.33

(C) At thickness = 10mm (With variable Mixing Tube Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.75	0.25	0.254	445.5	208.36	1181.95	552.79	6.05	6.05
2750	0.75	0.25	0.254	530.52	248.12	1407.51	658.29	6.98	6.98
3000	0.75	0.25	0.254	622.23	291.01	1650.82	772.08	7.95	7.95
3500	0.75	0.25	0.254	825.33	386.01	2189.68	1024.11	10.02	10.02
4000	0.75	0.25	0.254	1054.15	493.02	2796.74	1308.03	12.24	12.24
2500	0.75	0.25	0.762	204.06	95.44	541.39	253.21	6.05	6.05
2750	0.75	0.25	0.762	243	113.65	644.7	301.53	6.98	6.98
3000	0.75	0.25	0.762	285.01	133.3	756.15	353.65	7.95	7.95
3500	0.75	0.25	0.762	378.04	176.81	1002.98	469.09	10.02	10.02
4000	0.75	0.25	0.762	482.85	225.83	1281.04	599.14	12.24	12.24
2500	0.75	0.25	1.524	124.69	58.31	330.8	154.71	6.05	6.05
2750	0.75	0.25	1.524	148.48	69.44	393.93	184.24	6.98	6.98
3000	0.75	0.25	1.524	174.15	81.45	462.03	216.09	7.95	7.95
3500	0.75	0.25	1.524	230.99	108.03	612.84	286.62	10.02	10.02
4000	0.75	0.25	1.524	295.03	137.99	782.75	366.09	12.24	12.24

(A) At thickness =20mm (With variable Abrasive Rate)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.125	0.3	1.016	49.31	23.06	130.83	61.19	8.71	8.71
2750	0.125	0.3	1.016	58.72	27.46	155.8	72.87	10.05	10.05
3000	0.125	0.3	1.016	68.87	32.21	182.73	85.46	11.45	11.45
3500	0.125	0.3	1.016	91.36	42.73	242.37	113.36	14.42	14.42
4000	0.125	0.3	1.016	116.68	54.57	309.57	144.78	17.62	17.62
2500	0.25	0.3	1.016	64.82	30.31	171.97	80.43	8.71	8.71
2750	0.25	0.3	1.016	77.19	36.1	204.78	95.78	10.05	10.05
3000	0.25	0.3	1.016	90.53	42.34	240.18	112.33	11.45	11.45
3500	0.25	0.3	1.016	120.08	56.16	318.59	149	14.42	14.42
4000	0.25	0.3	1.016	153.37	71.73	406.91	190.31	17.62	17.62
2500	0.5	0.3	1.016	85.2	39.85	226.04	105.72	8.71	8.71
2750	0.5	0.3	1.016	101.46	47.45	269.18	125.89	10.05	10.05
3000	0.5	0.3	1.016	119	55.65	315.71	147.66	11.45	11.45
3500	0.5	0.3	1.016	157.84	73.82	418.76	195.85	14.42	14.42
4000	0.5	0.3	1.016	201.6	94.29	534.86	250.15	17.62	17.62

(B) At thickness = 20mm (With variable Orifice Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.3	0.2	0.508	60.07	28.09	159.36	74.53	3.87	3.87
2750	0.3	0.2	0.508	71.53	33.45	189.77	88.76	4.46	4.46
3000	0.3	0.2	0.508	83.89	39.24	222.58	104.1	5.09	5.09
3500	0.3	0.2	0.508	111.28	52.04	295.23	138.08	6.41	6.41
4000	0.3	0.2	0.508	142.13	66.47	377.08	176.36	7.83	7.83
2500	0.3	0.32	0.508	126.23	59.04	334.89	156.63	9.91	9.91
2750	0.3	0.32	0.508	150.32	70.3	398.8	186.52	11.43	11.43
3000	0.3	0.32	0.508	176.3	82.46	467.74	218.76	13.02	13.02
3500	0.3	0.32	0.508	233.85	109.37	620.43	290.17	16.41	16.41
4000	0.3	0.32	0.508	298.88	139.69	792.43	370.62	20.05	20.05
2500	0.3	0.4	0.508	179.59	83.99	476.47	222.84	15.48	15.48
2750	0.3	0.4	0.508	213.86	100.02	567.4	265.37	17.86	17.86
3000	0.3	0.4	0.508	250.83	117.31	665.48	311.24	20.35	20.35
3500	0.3	0.4	0.508	332.71	155.61	882.71	412.84	25.64	25.64
4000	0.3	0.4	0.508	424.95	198.75	1127.43	527.29	31.33	31.33

(C)At thickness = 20mm (With variable Mixing Tube Dia.)

Pressure	Abrasive rate	Orifice dia.	Mixing tube dia.	Linear cutting speed for smooth finish (mm/min.)		Linear cutting speed to barely cut through (mm/min.)		Cutting Power(kW)	
(bar)	(kg/min.)	(mm)	(mm)	Al	Cu	Al	Cu	Al	Cu
2500	0.75	0.25	0.254	200.75	93.89	532.61	249.1	6.05	6.05
2750	0.75	0.25	0.254	239.06	111.81	634.26	296.64	6.98	6.98
3000	0.75	0.25	0.254	280.39	131.14	743.9	347.92	7.95	7.95
3500	0.75	0.25	0.254	371.92	173.94	986.73	461.49	10.02	10.02
4000	0.75	0.25	0.254	475.03	222.17	1260.28	589.43	12.24	12.24
2500	0.75	0.25	0.762	91.95	43.01	243.96	114.1	6.05	6.05
2750	0.75	0.25	0.762	109.5	51.21	290.52	135.88	6.98	6.98
3000	0.75	0.25	0.762	128.43	60.07	340.74	159.36	7.95	7.95
3500	0.75	0.25	0.762	170.36	79.67	451.97	211.38	10.02	10.02
4000	0.75	0.25	0.762	217.58	101.76	577.27	269.99	12.24	12.24
2500	0.75	0.25	1.524	56.19	26.28	149.07	69.72	6.05	6.05
2750	0.75	0.25	1.524	66.91	31.29	177.51	83.02	6.98	6.98
3000	0.75	0.25	1.524	78.48	36.7	208.2	97.38	7.95	7.95
3500	0.75	0.25	1.524	104.09	48.68	276.16	129.16	10.02	10.02
4000	0.75	0.25	1.524	132.95	62.18	352.72	164.97	12.24	12.24

CHAPTER 9

RESULTS AND DISCUSSION

The effect of the process parameters on Aluminium and Copper are investigated and presented graphically:

a) For a particular thickness of the Al and Cu alloys (1 mm, 2 mm, 5 mm, 10 mm and 20 mm) graphs are plotted between Linear cutting speed for smooth finish (mm/min.) vs. Pressure (bar), linear cutting speed to barely cut through the material (mm/min) vs. pressure (bar) and actual cutting power (kW) vs. pressure (bar) for a varying abrasive flow rate of 0.125 kg/min., 0.25 kg/min. and 0.5 kg/min.

b) For a particular thickness of the Al and Cu alloys (1 mm, 2 mm, 5 mm, 10 mm and 20 mm) graphs are plotted between Linear cutting speed for smooth finish (mm/min.) vs. Pressure (bar), linear cutting speed to barely cut through the material (mm/min) vs. pressure (bar) and actual cutting power (kW) vs. pressure (bar) for a varying orifice diameter of 0.20 mm, 0.32 mm and 0.40 mm.

c) For a particular thickness of the Al and Cu alloys (1 mm, 2 mm, 5 mm, 10 mm and 20 mm) graphs are plotted between Linear cutting speed for smooth finish (mm/min.) vs. Pressure (bar), linear cutting speed to barely cut through the material (mm/min) vs. pressure (bar) and actual cutting power (kW) vs. pressure (bar) for a varying mixing tube diameter of 0.254 mm, 0.762 mm and 1.524 mm.

The plotted graphs, corresponding to the data tabulated in the previous chapter are as follows:

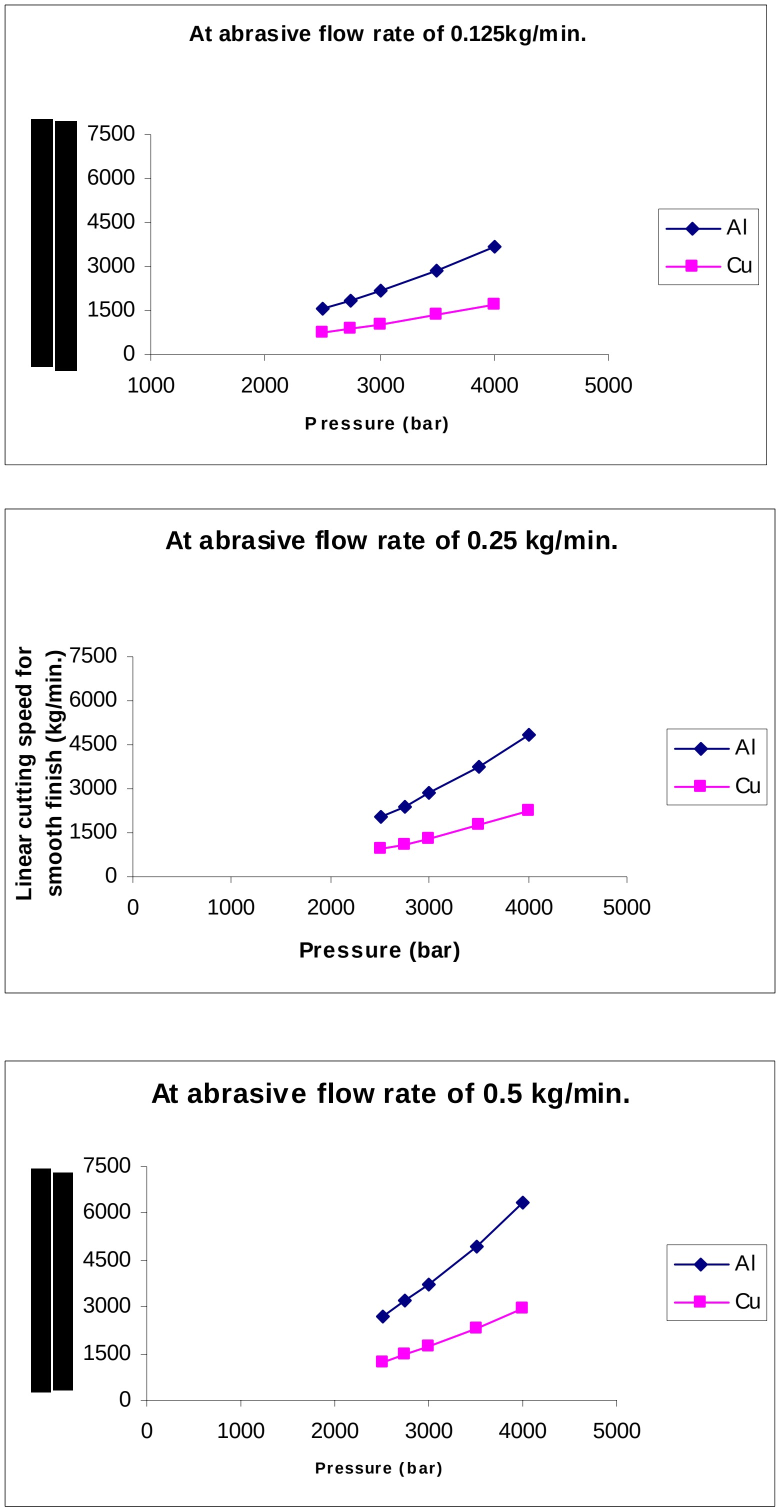
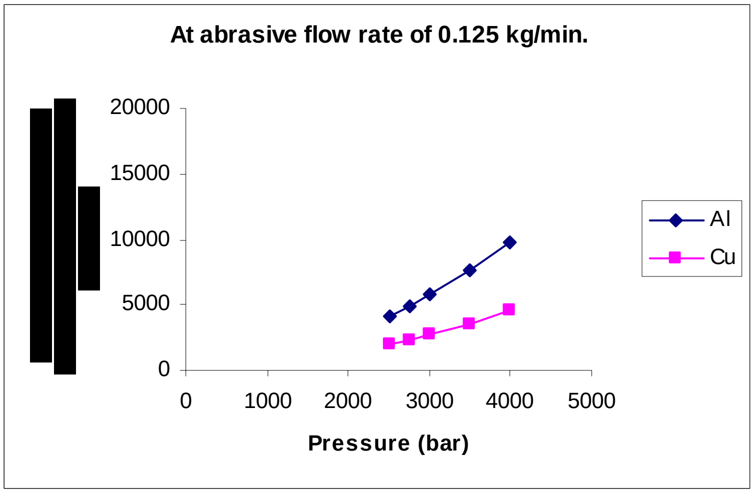
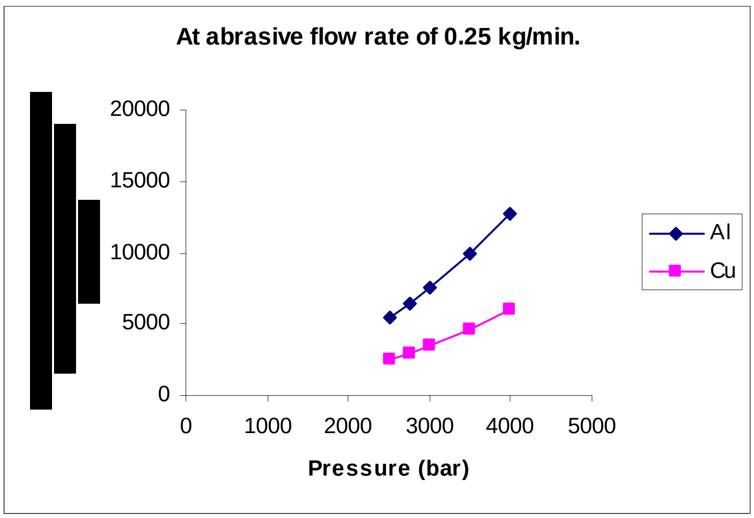


Fig. 9.1: At thickness 1mm and varying abrasive flow rate.


At abrasive flow rate of 0.125 kg/min.
[redacted]
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
Pressure (bar)
Al
Cu


At abrasive flow rate of 0.25 kg/min.
[redacted]
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
Pressure (bar)
Al
Cu

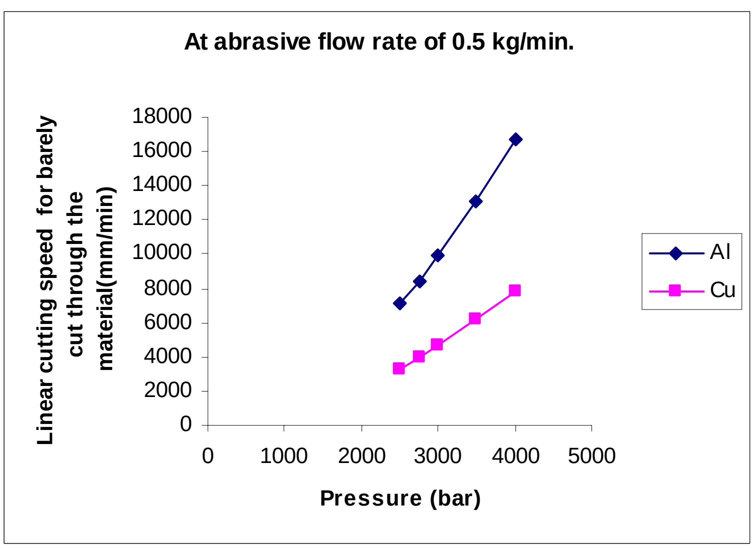
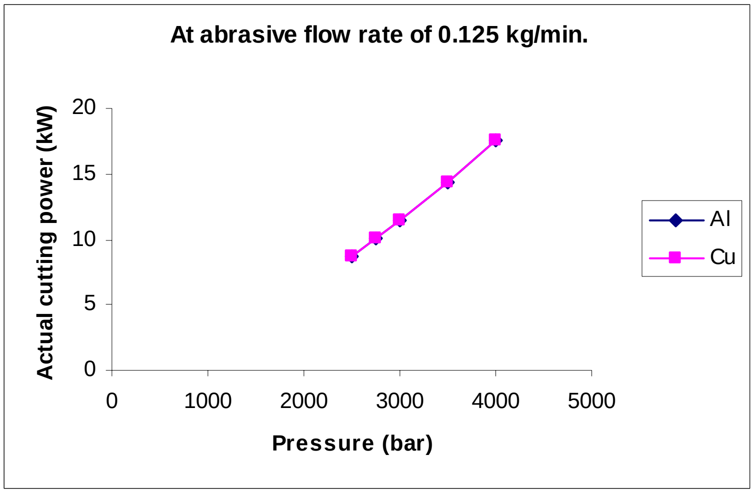
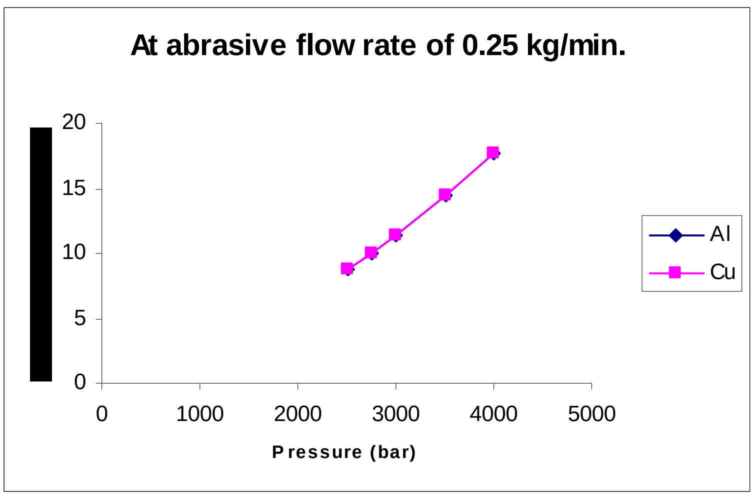

At abrasive flow rate of 0.5 kg/min.
Linear cutting speed for barely cut through the material(mm/min)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
1000
2000
3000
4000
5000
Pressure (bar)
Al
Cu

Fig. 9.2: At thickness 1mm and varying abrasive flow rate.





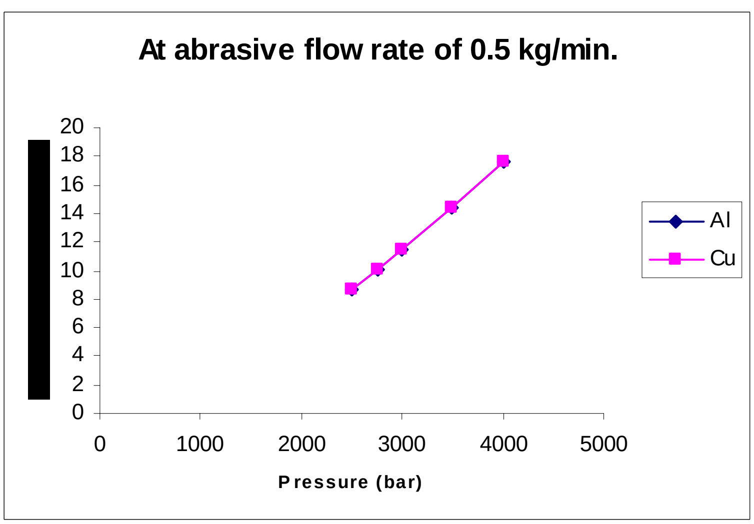
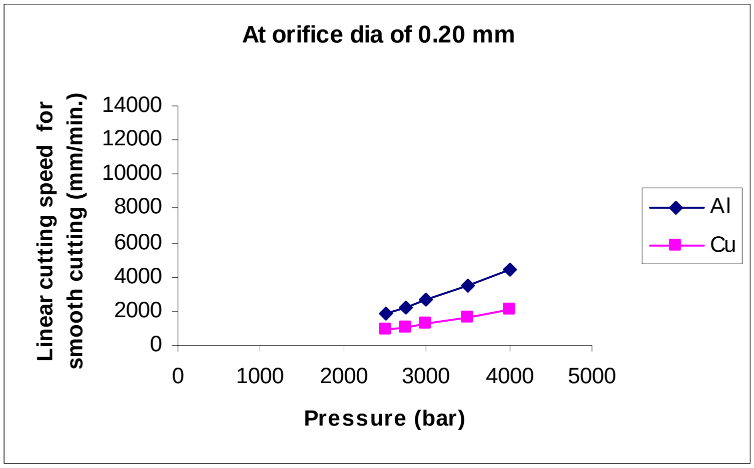
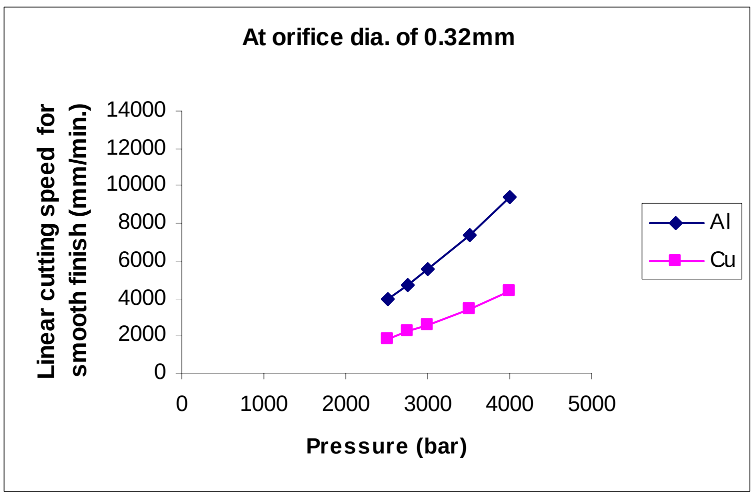


Fig. 9.3: At thickness 1mm and varying abrasive flow rate





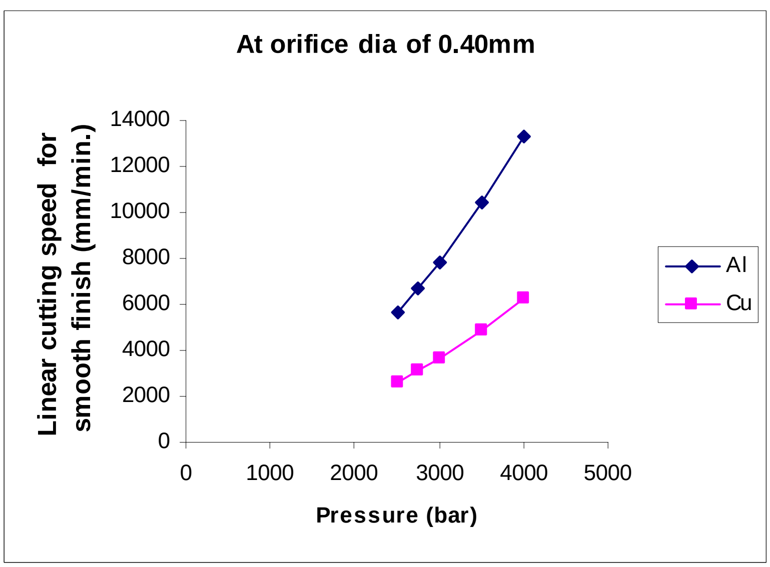


Fig. 9.4: At thickness 1mm and varying orifice diameter.

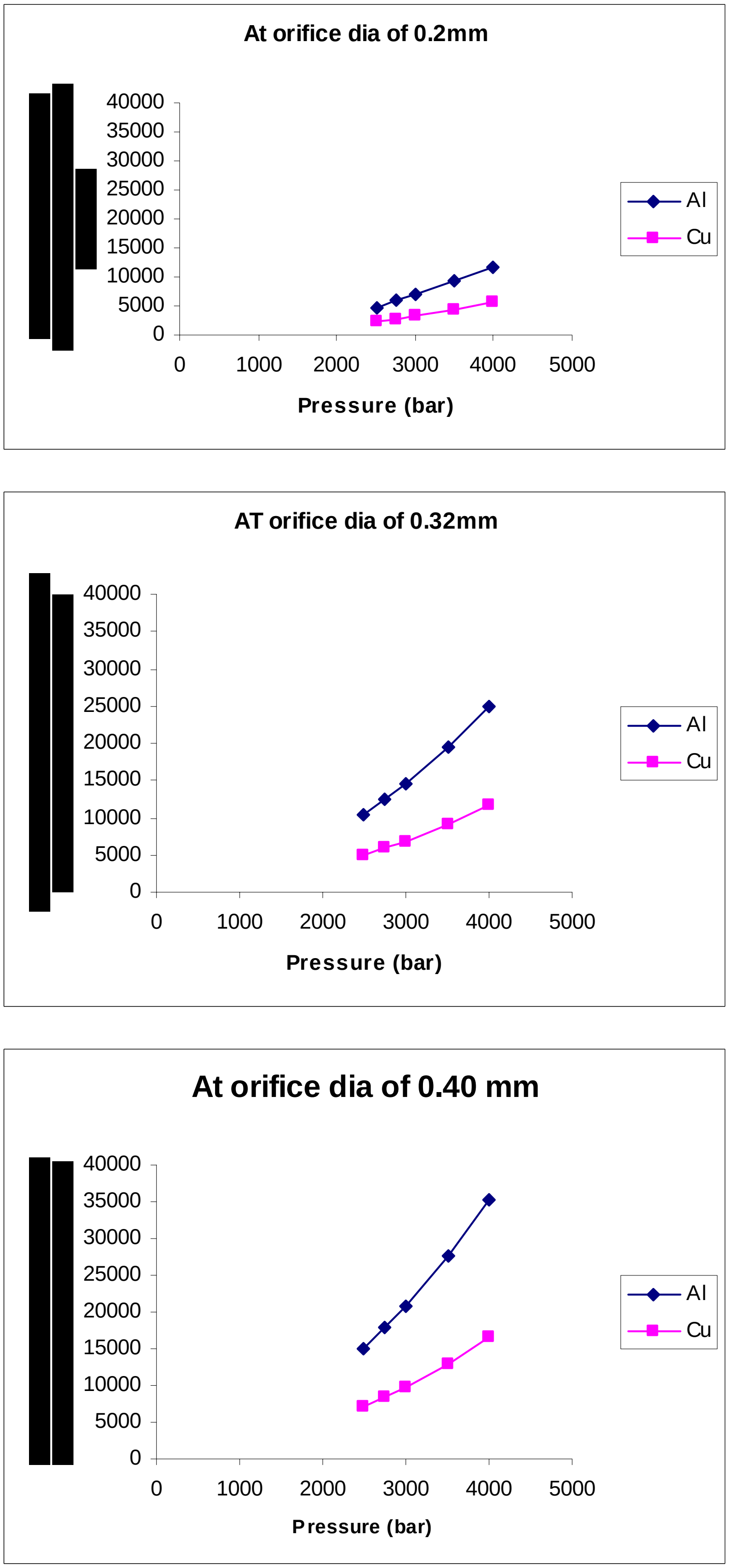
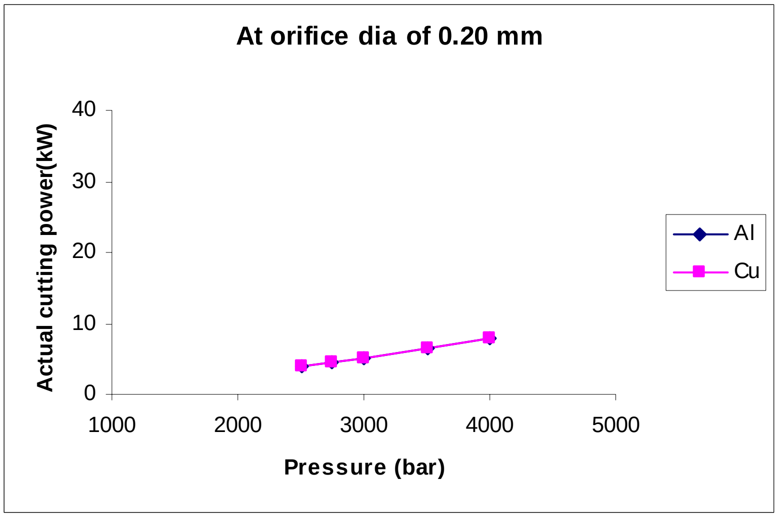
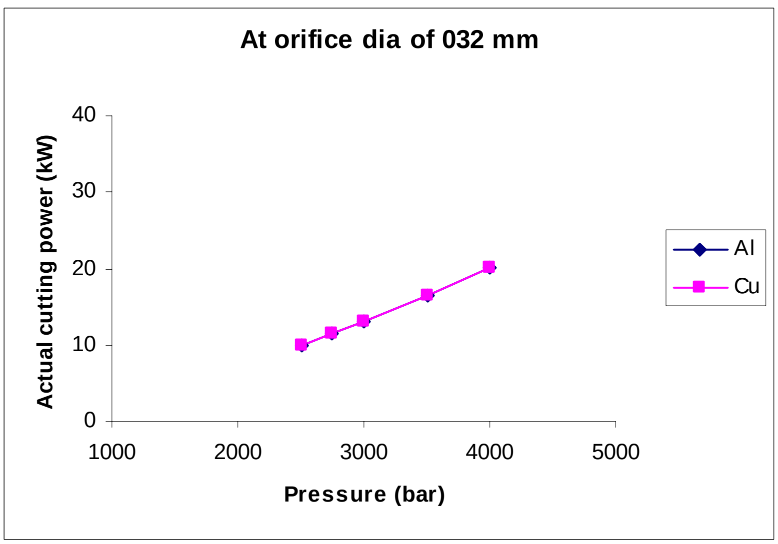


Fig. 9.5: At thickness 1mm and varying orifice diameter





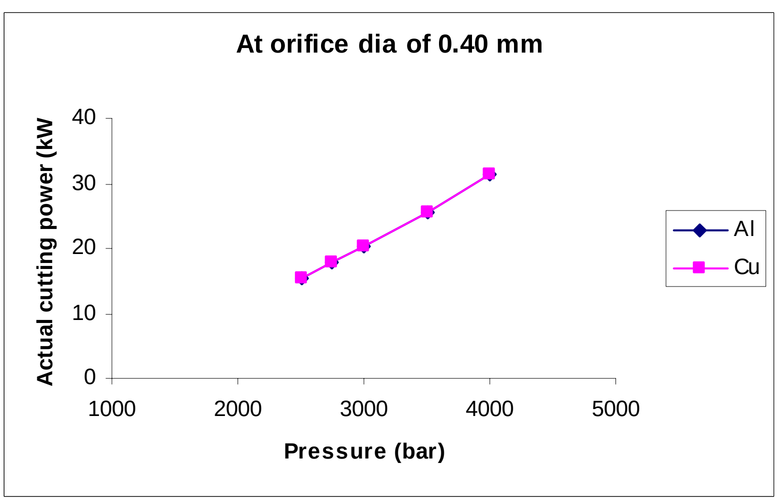


Fig. 9.6: At thickness 1mm and varying orifice diameter

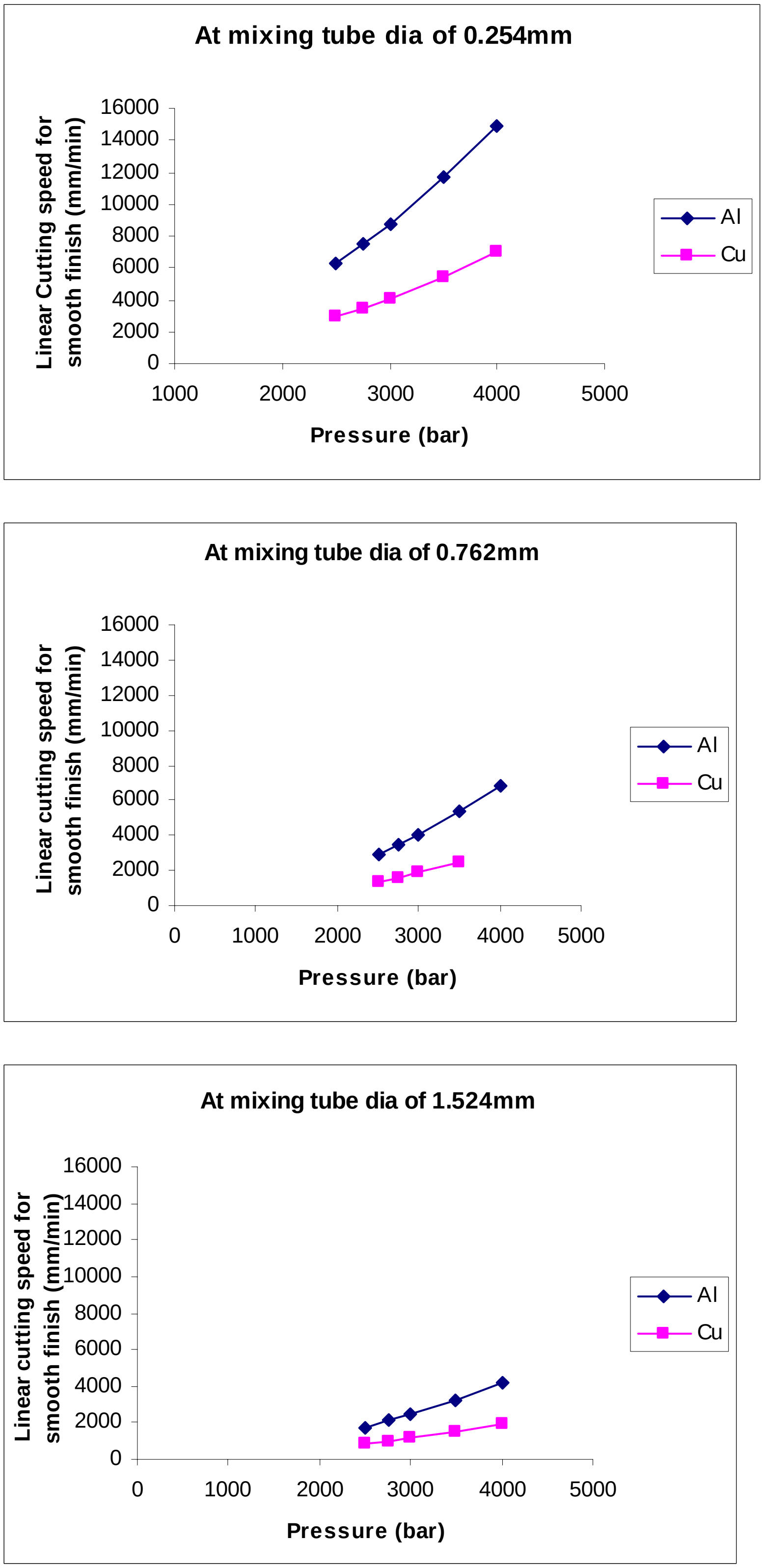


Fig. 9.7: At thickness 1mm and varying mixing tube diameter.

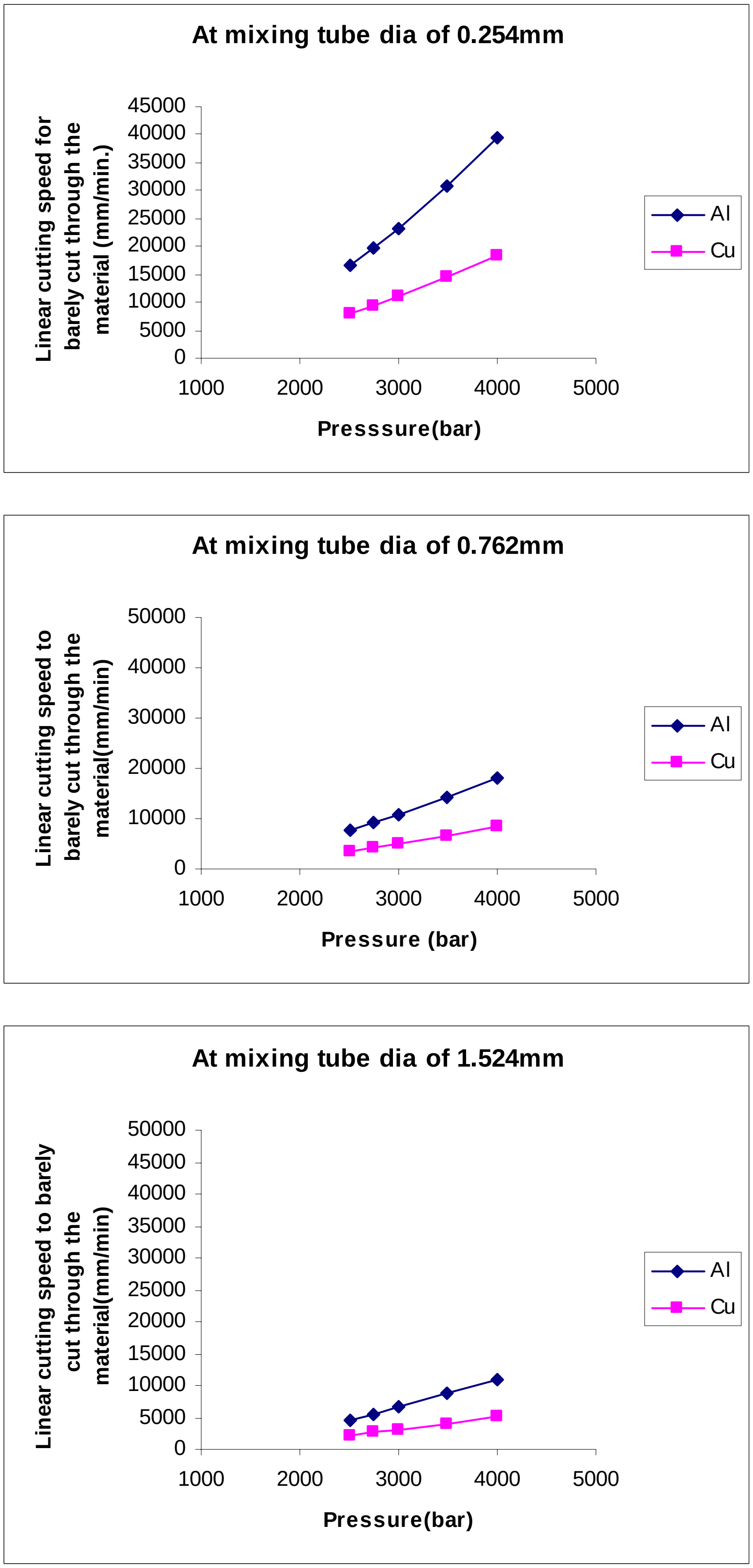


Fig. 9.8: At thickness 1mm and varying mixing tube diameter.

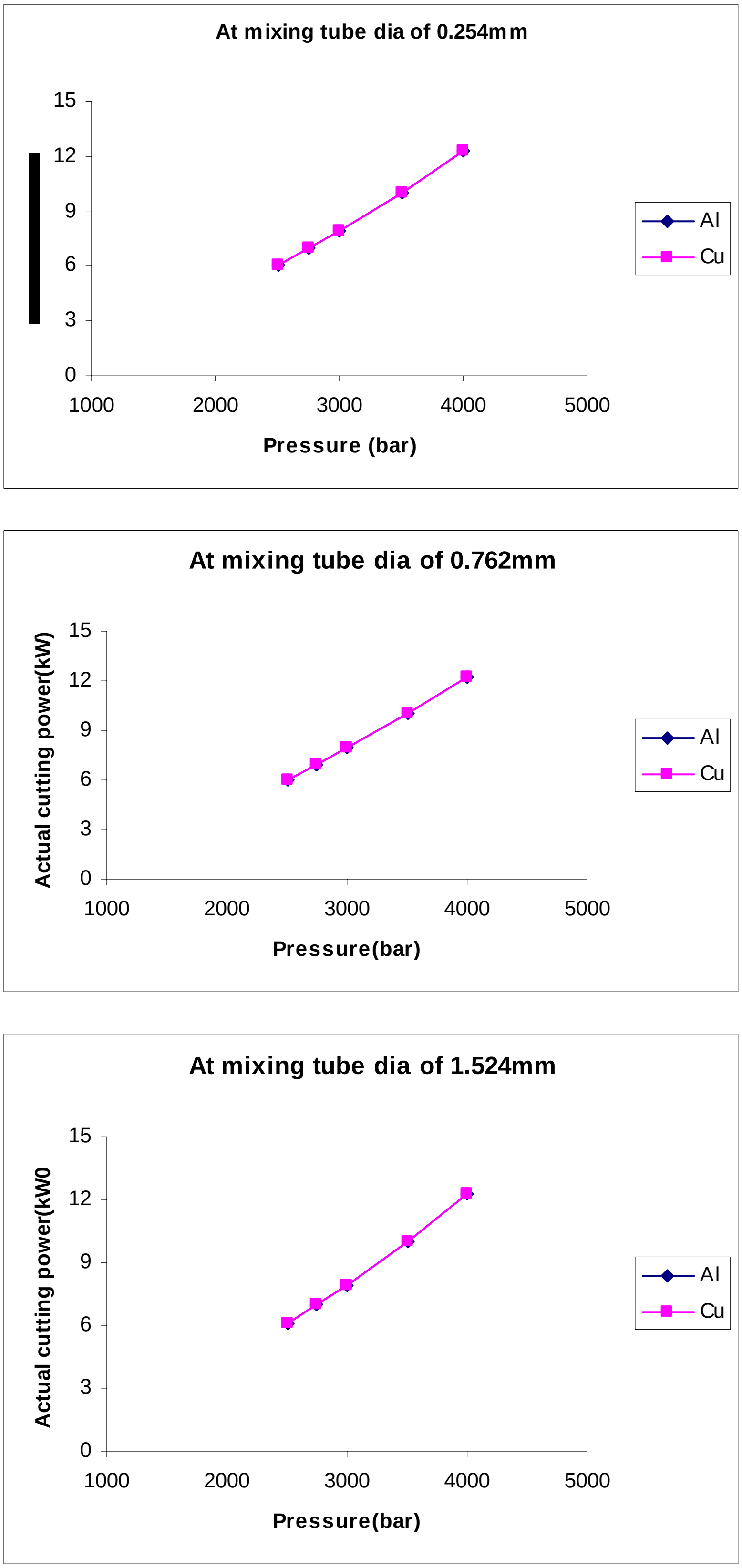
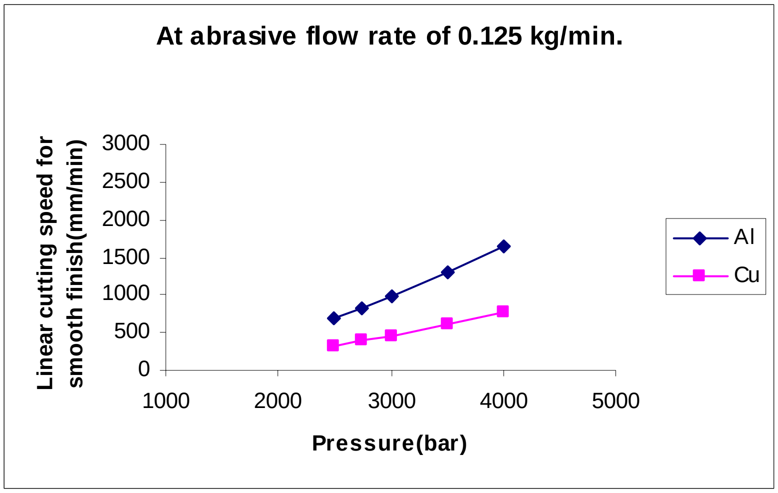
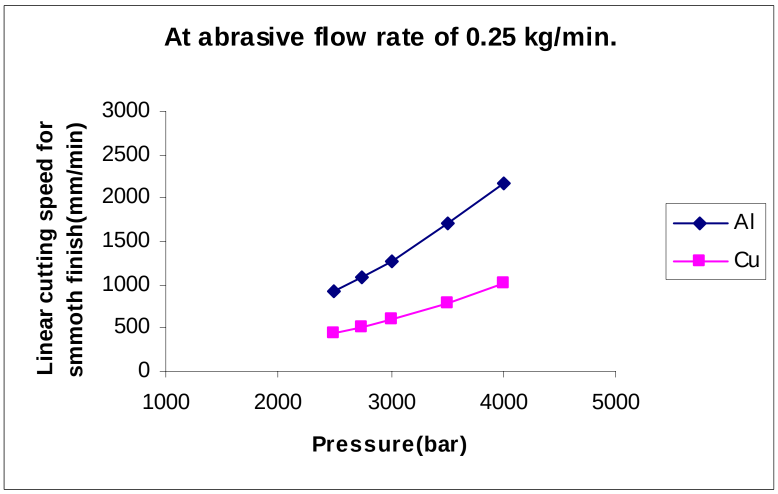


Fig. 9.9: At thickness 1mm and varying mixing tube diameter.





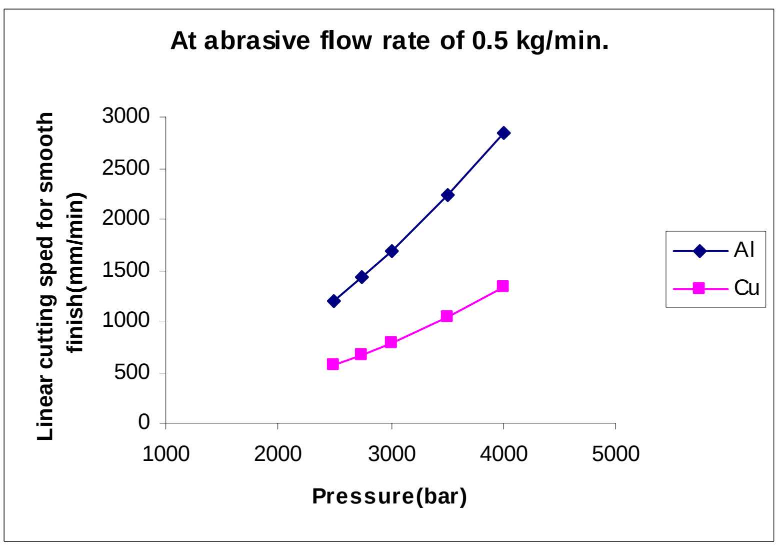
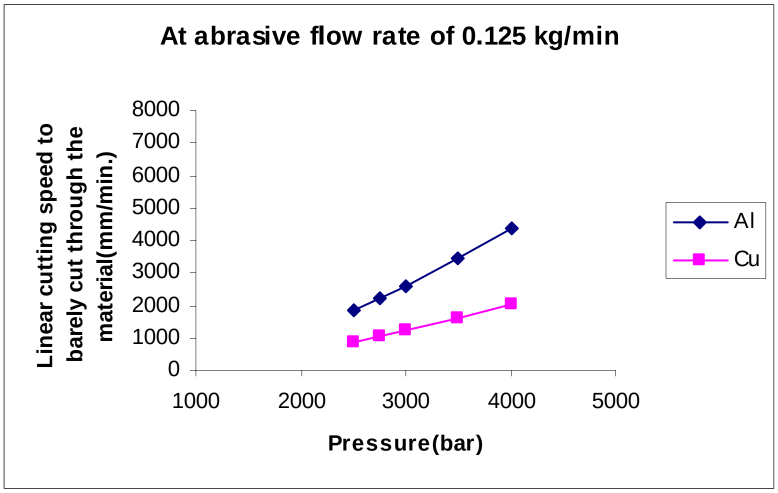
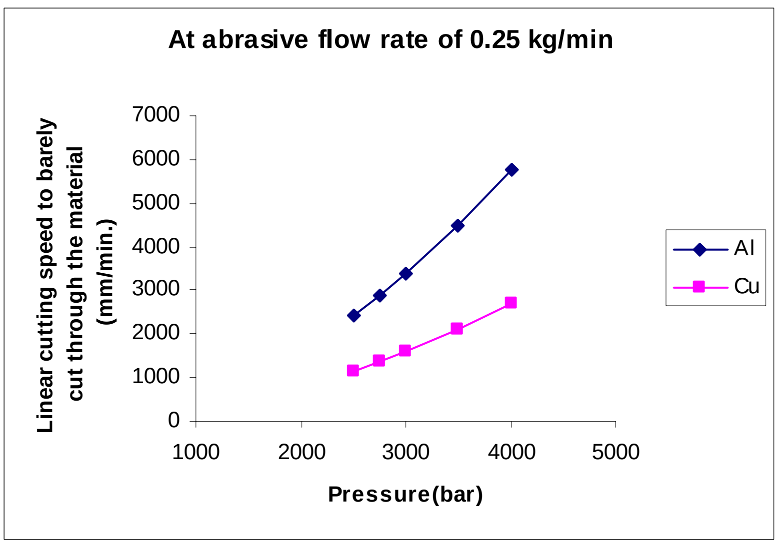


Fig. 9.10: At thickness 2mm and varying abrasive flow rate.





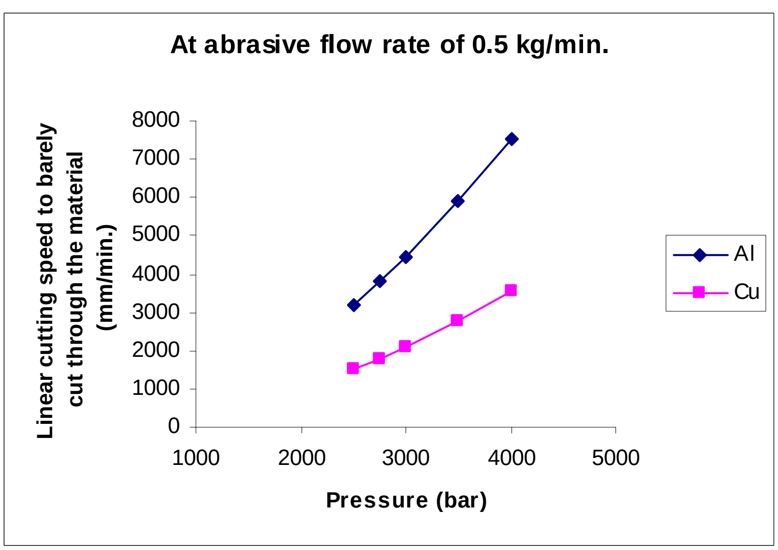
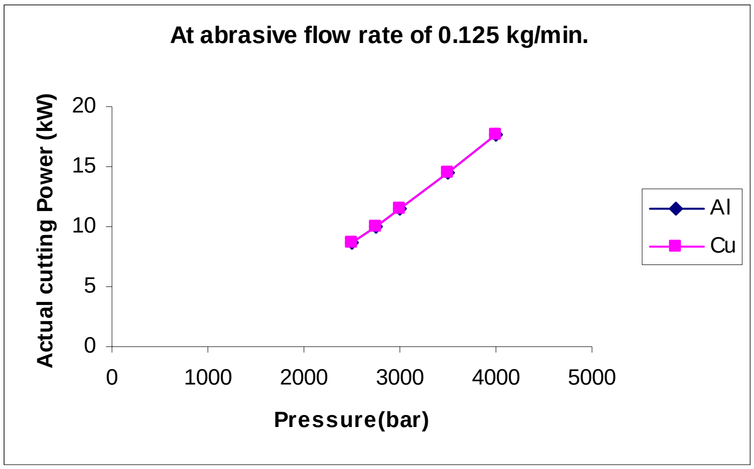
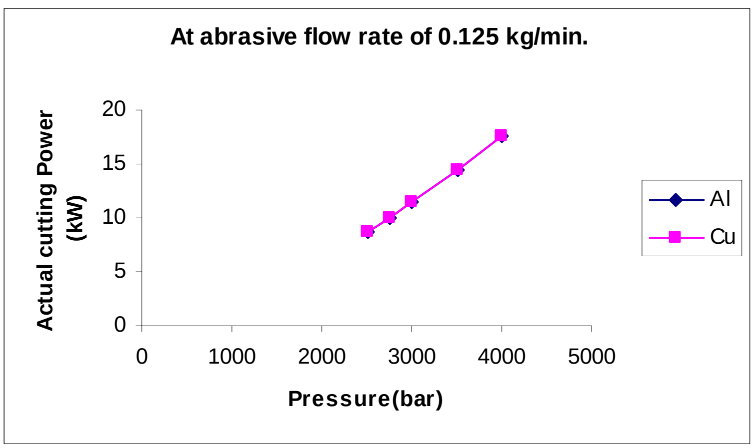


Fig. 9.11: At thickness 2mm and varying abrasive flow rate.





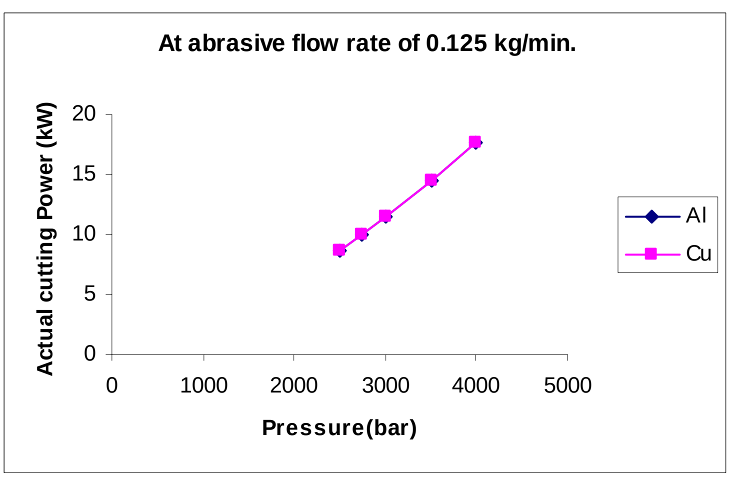
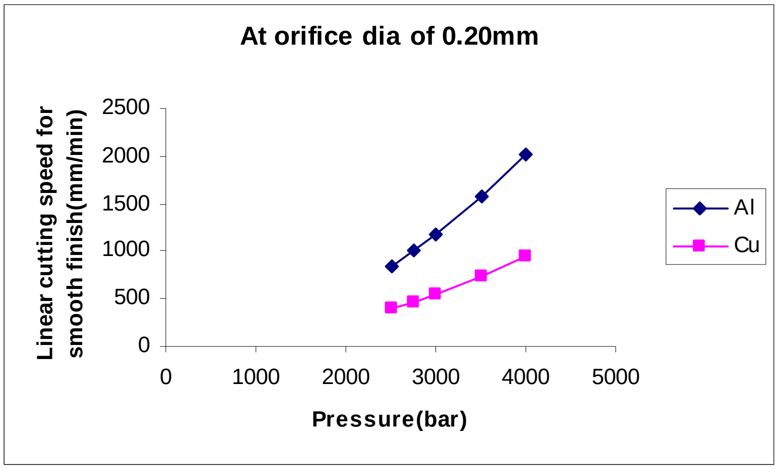
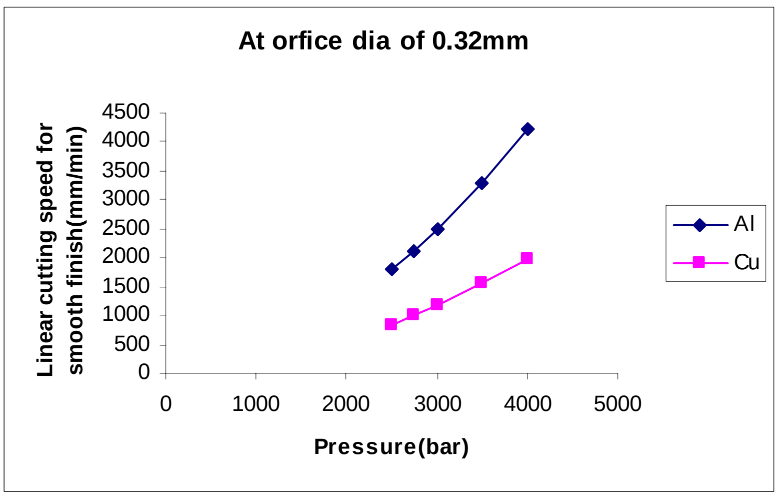


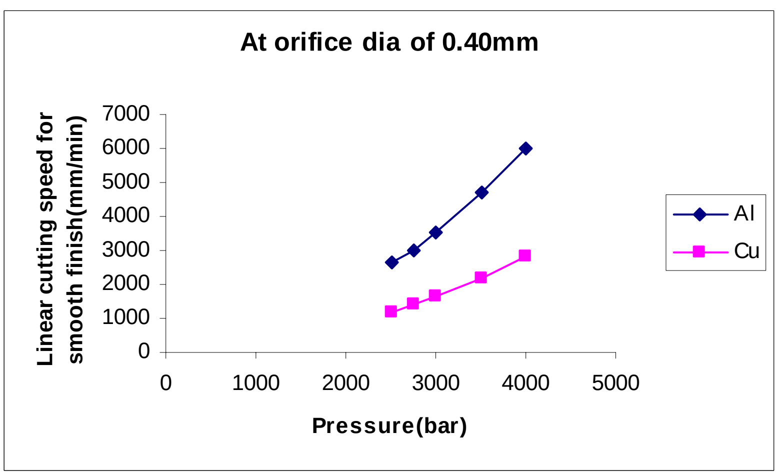
Fig. 9.12: At thickness 2mm and varying abrasive flow rate



At orifice dia of 0.20mm
Linear cutting speed for smooth finish(mm/min)
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu



At orfice dia of 0.32mm
Linear cutting speed for smooth finish(mm/min)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu



At orifice dia of 0.40mm
Linear cutting speed for smooth finish(mm/min)
7000
6000
5000
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu

Fig. 9.13: At thickness 2mm and varying orifice diameter

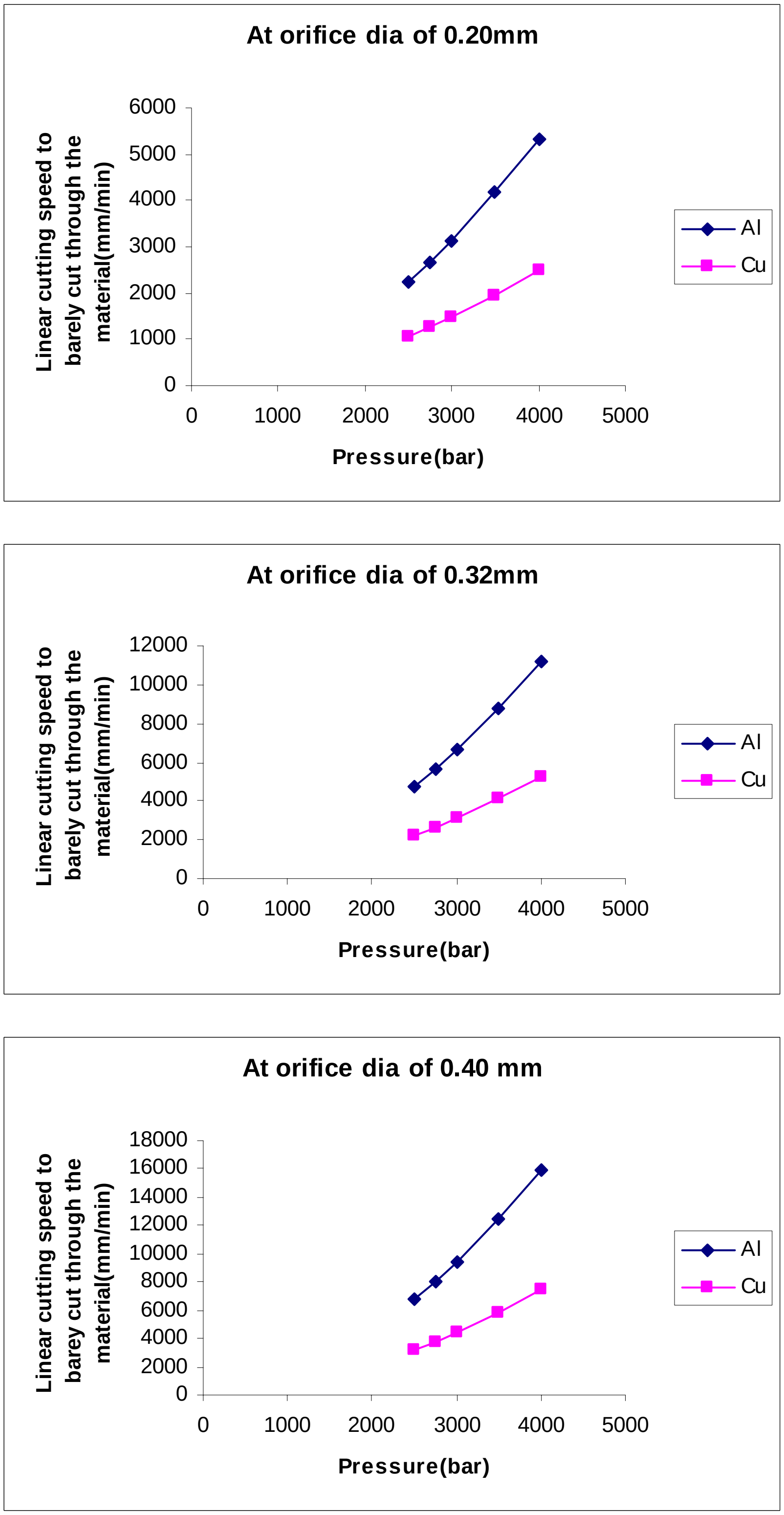
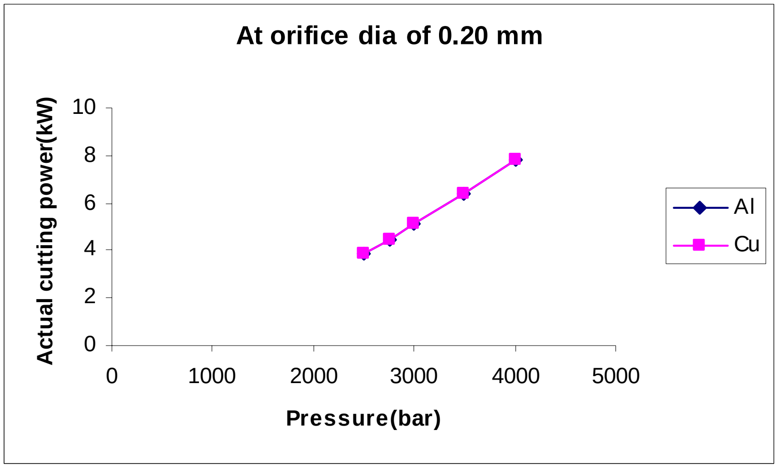
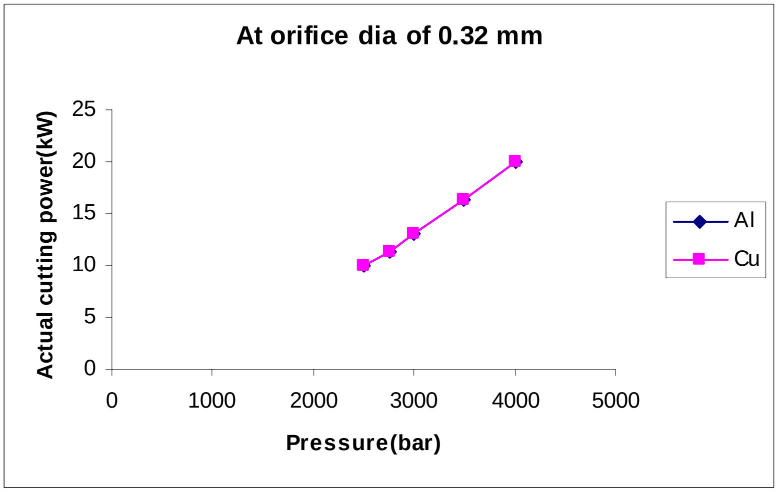


Fig. 9.14: At thickness 2mm and varying orifice diameter


At orifice dia of 0.20 mm
Actual cutting power(kW)
10
8
6
4
2
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu


At orifice dia of 0.32 mm
Actual cutting power(kW)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu

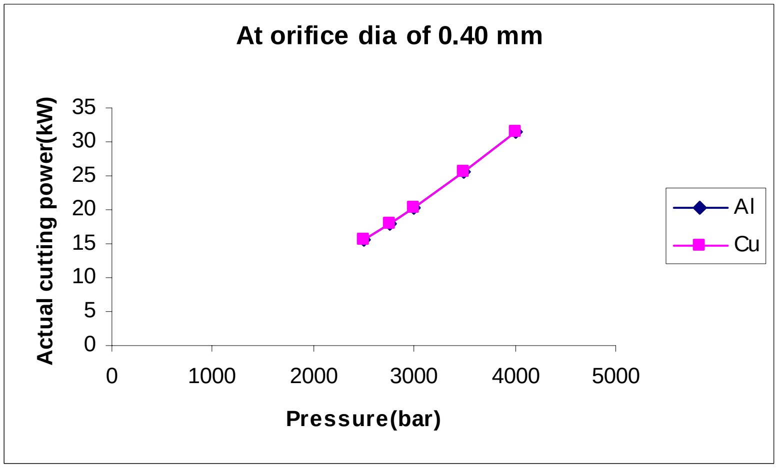
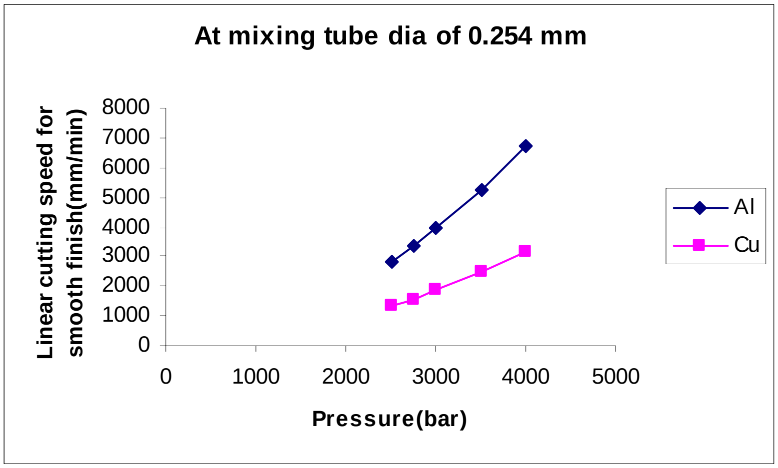
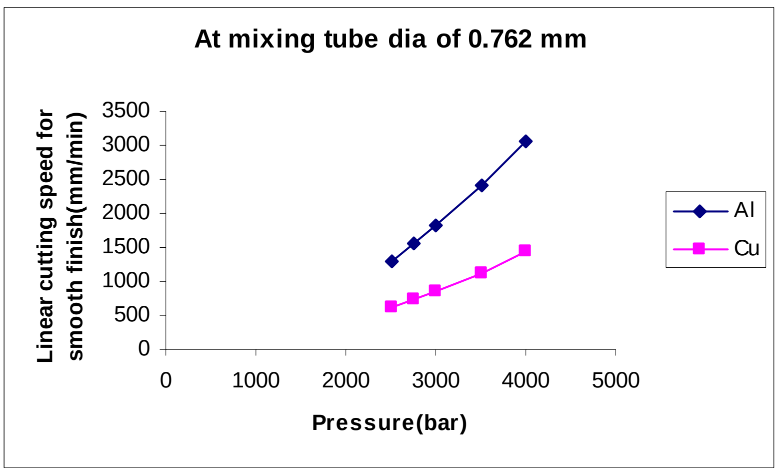

At orifice dia of 0.40 mm
Actual cutting power(kW)
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Pressure(bar)
Al
Cu

Fig. 9.15: At thickness 2mm and varying orifice diameter





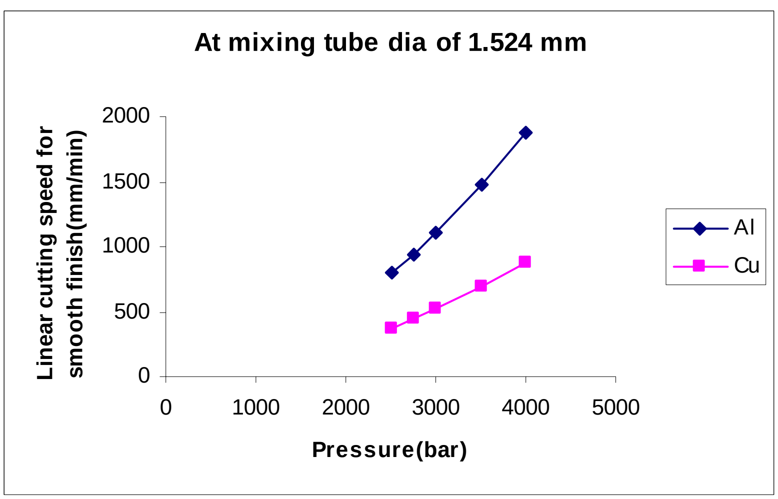
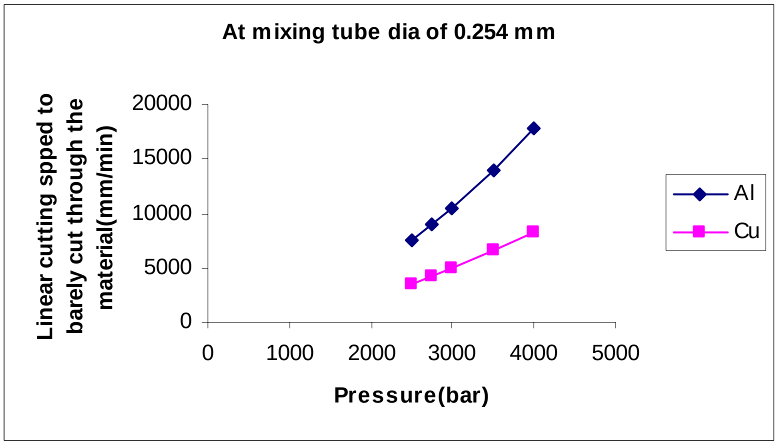
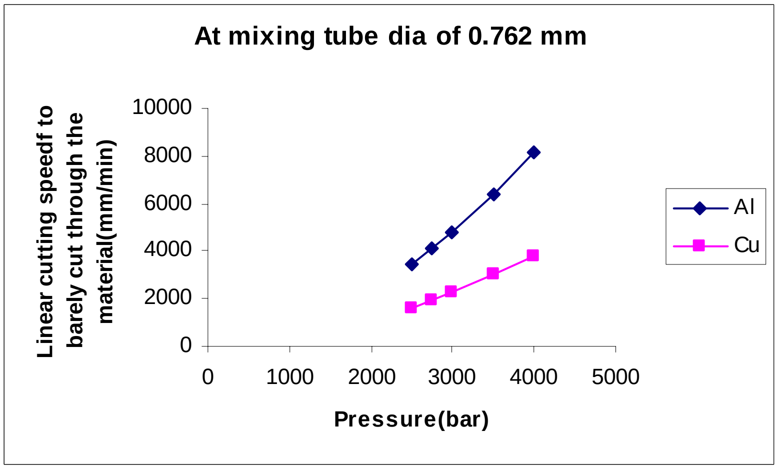


Fig. 9.16: At thickness 2mm and varying mixing tube diameter





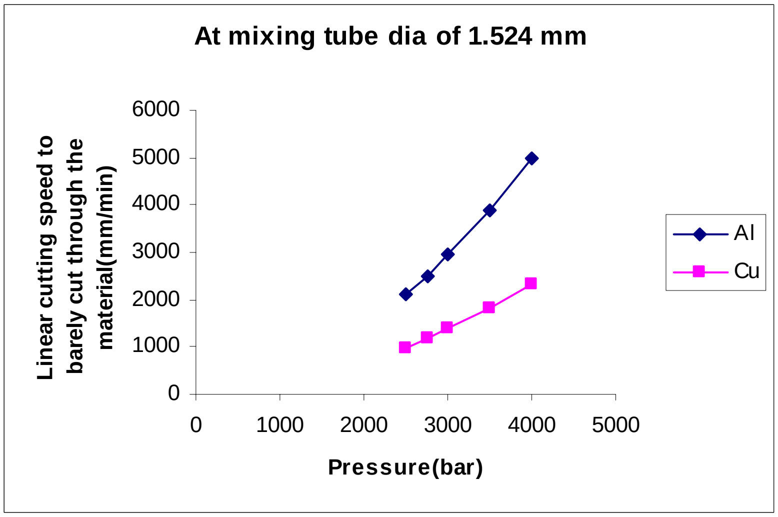
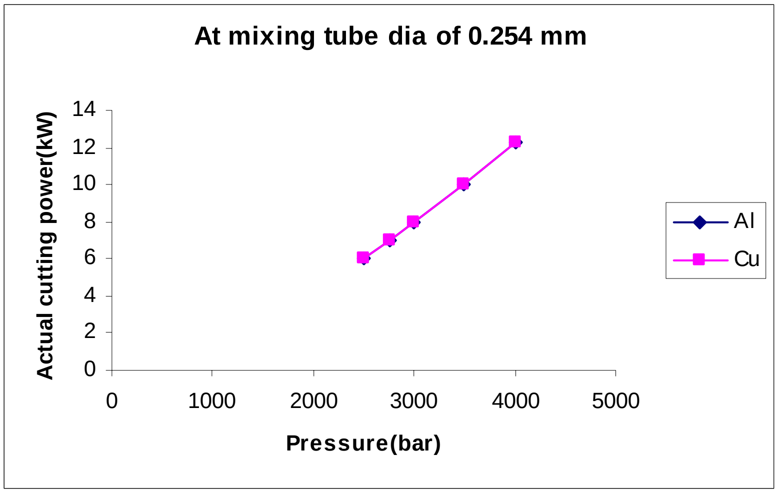
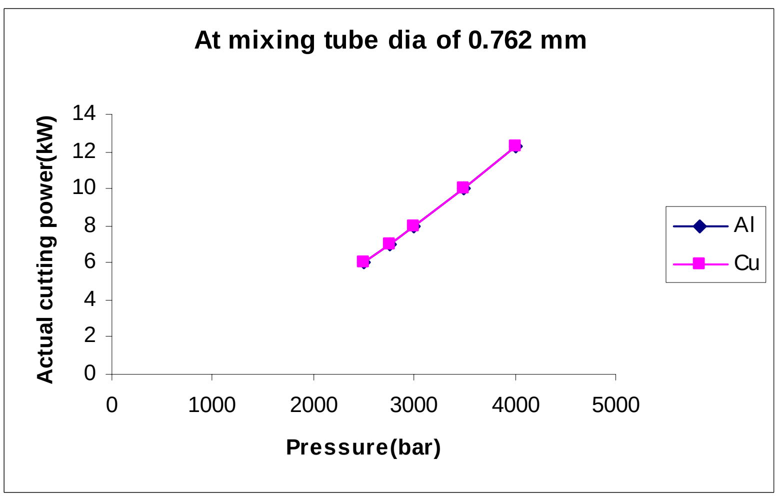


Fig. 9.17: At thickness 2mm and varying mixing tube diameter





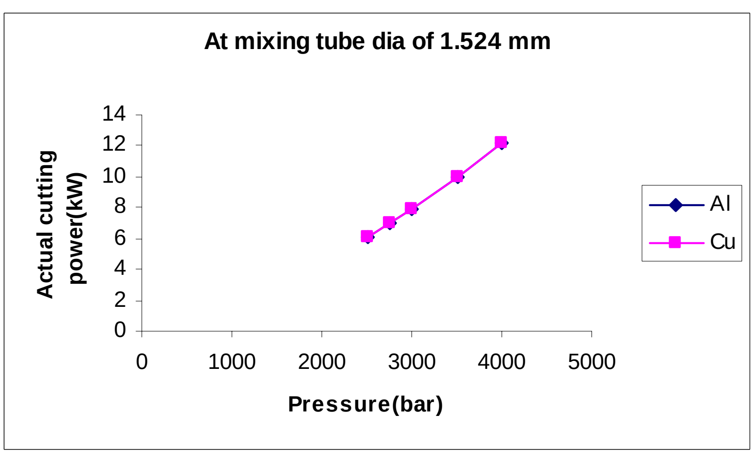
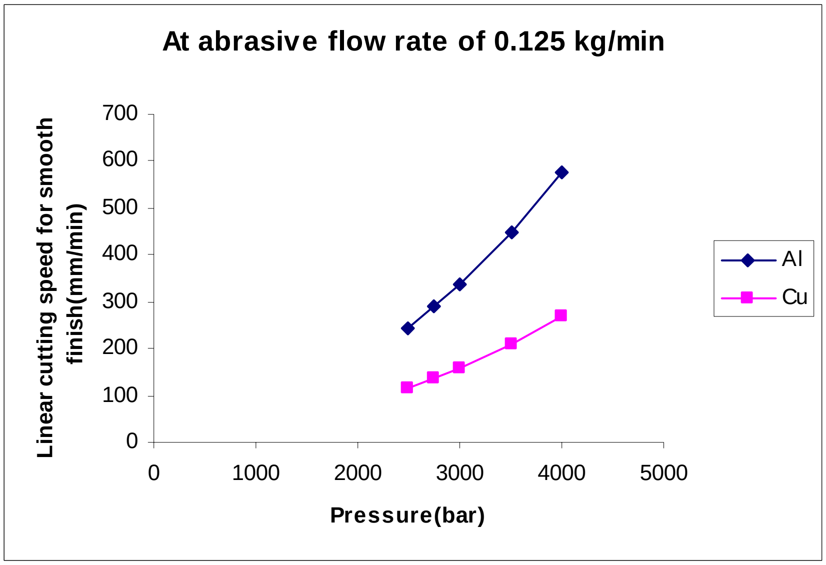
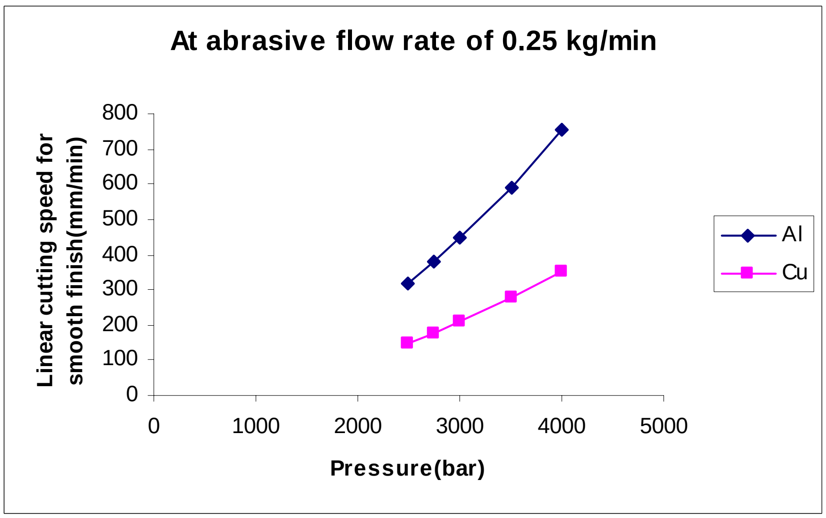


Fig. 9.18: At thickness 2mm and varying mixing tube diameter





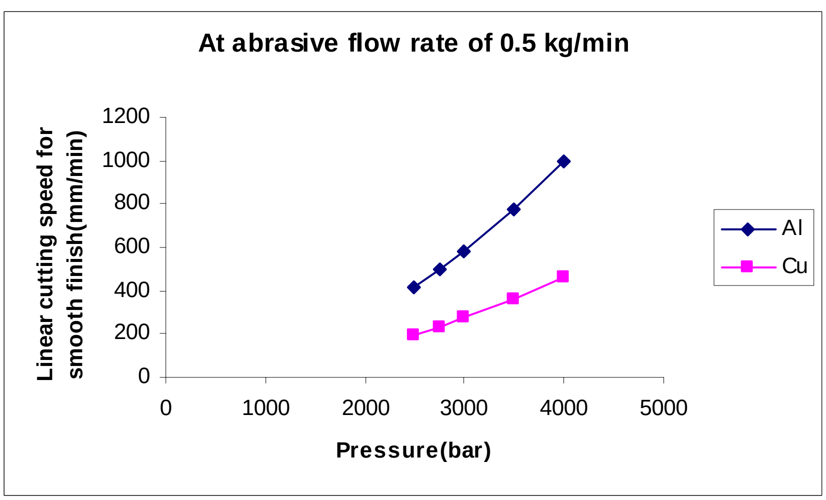
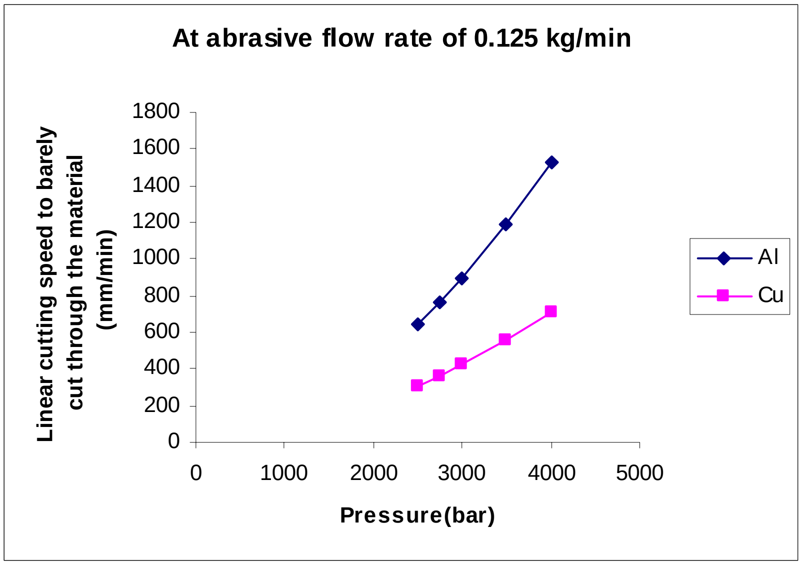
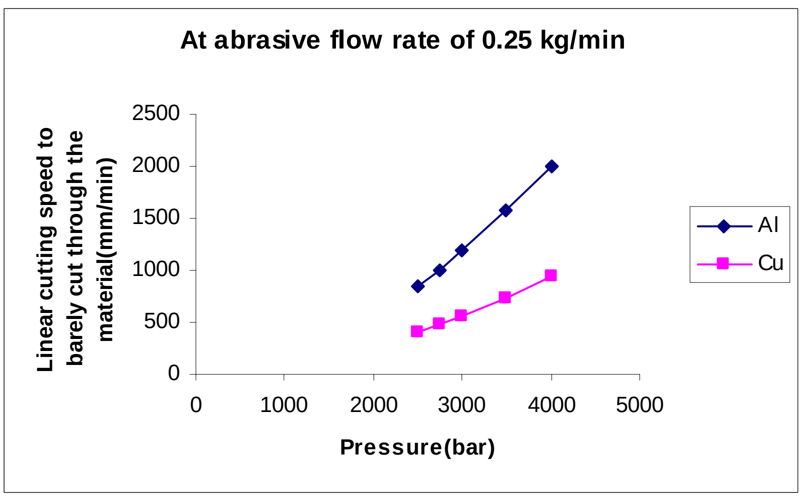


Fig. 9.19: At thickness 5mm and varying abrasive flow rate





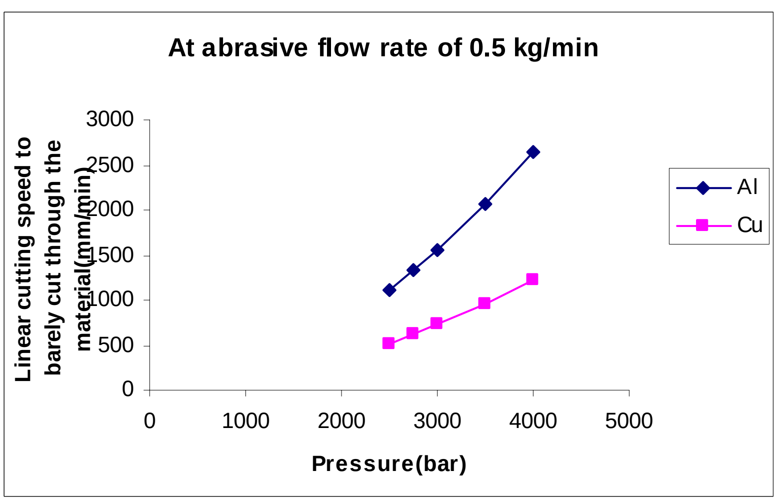
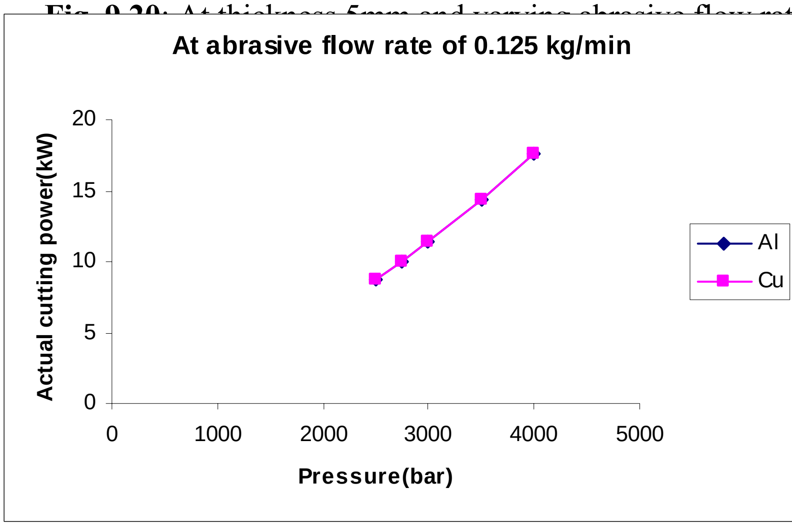
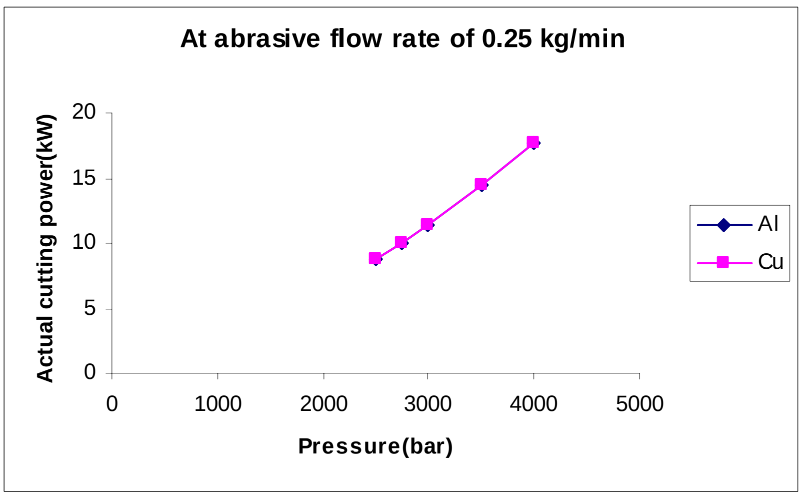


Fig. 9.20: At thickness 5mm and varying abrasive flow rate





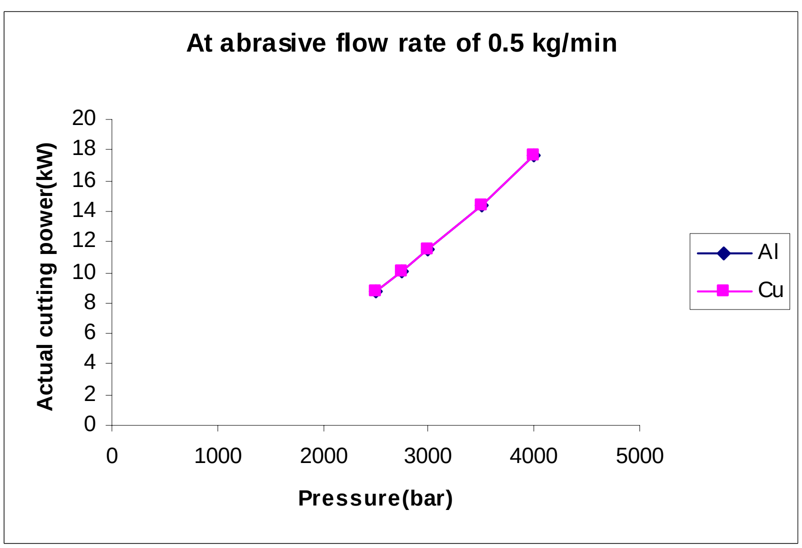
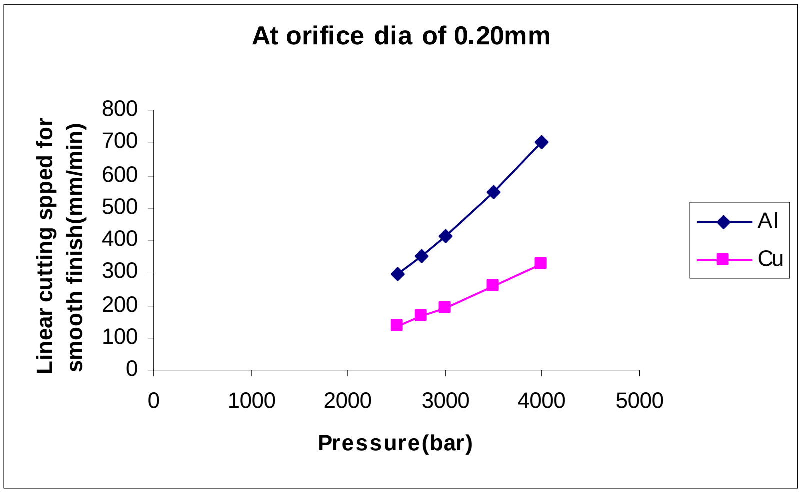
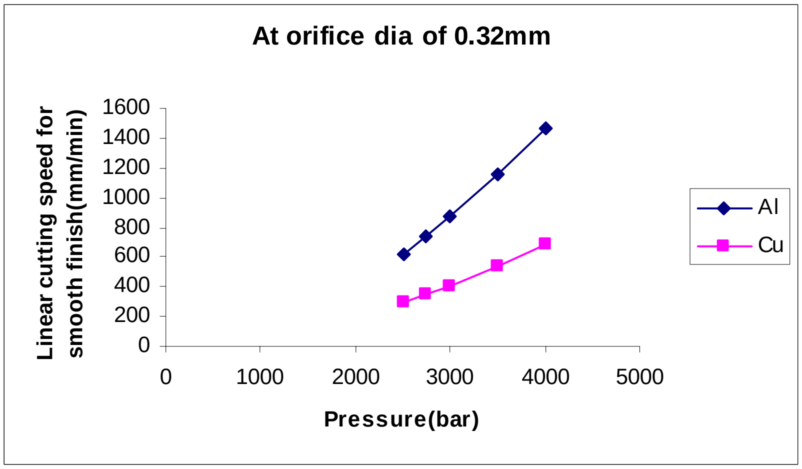


Fig. 9.21: At thickness 5mm and varying abrasive flow rate





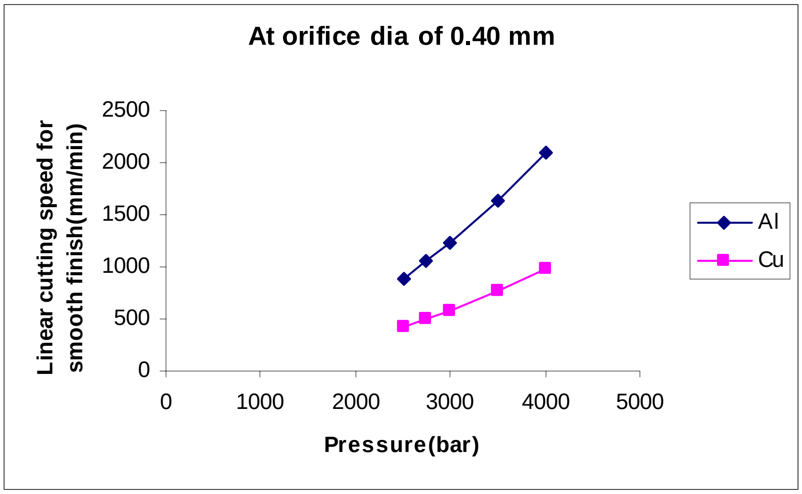
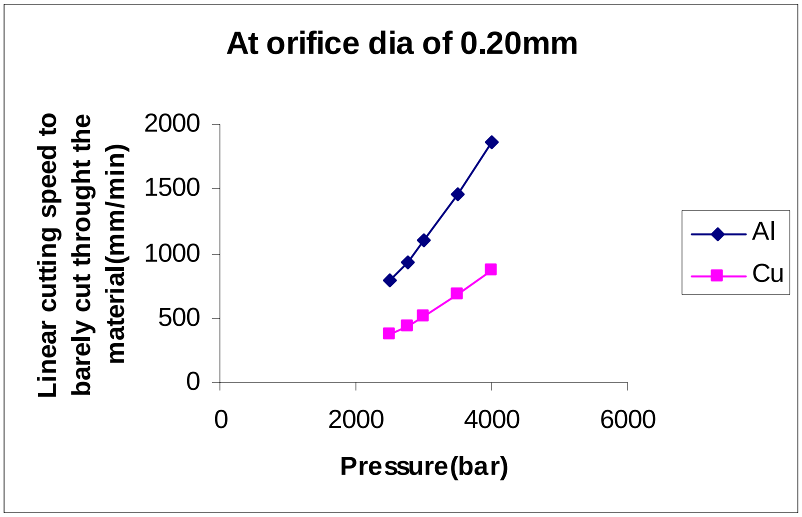
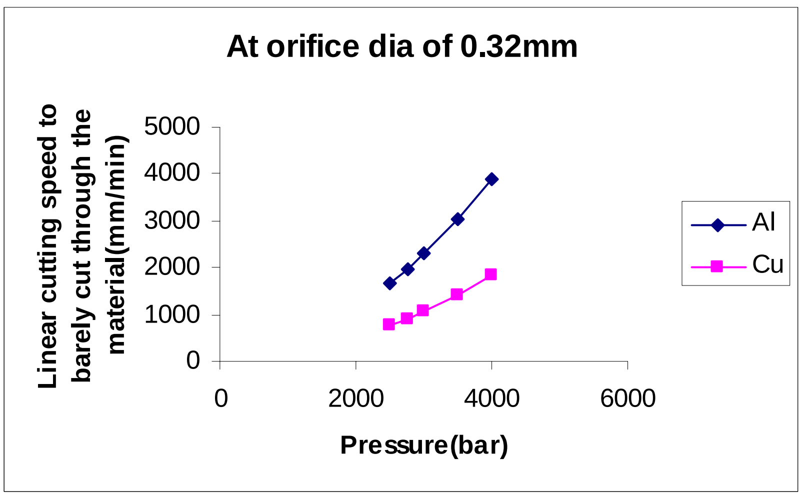


Fig. 9.22: At thickness 5mm and varying orifice diameter





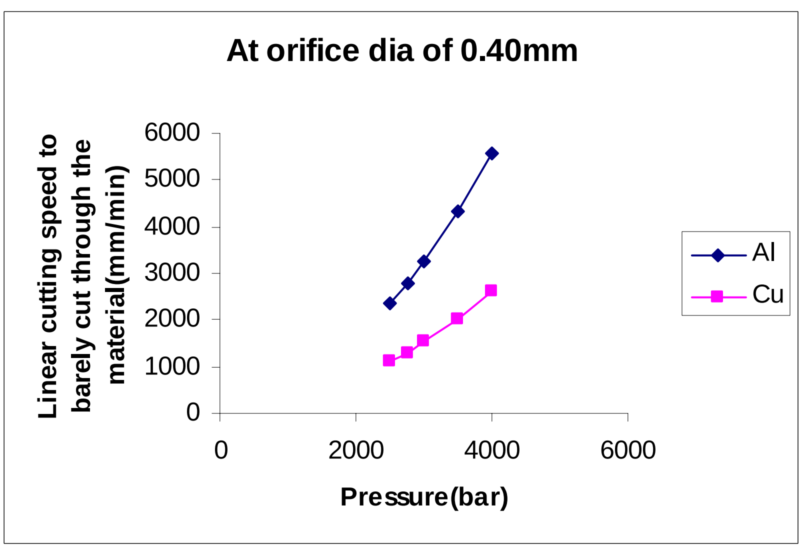
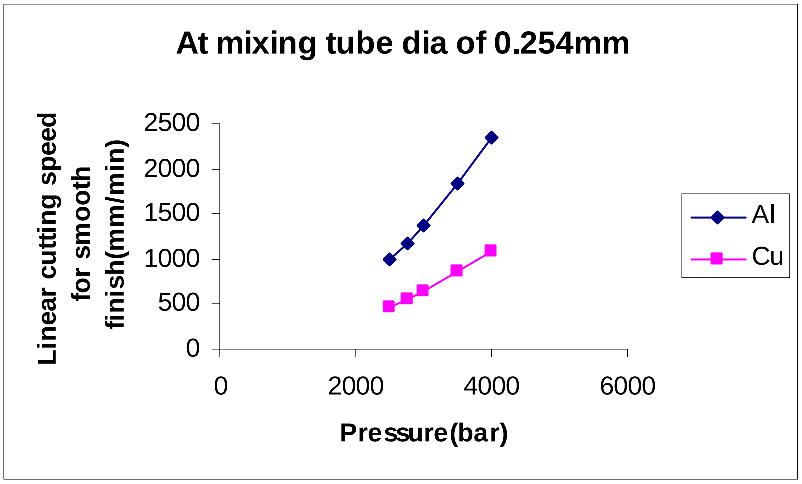
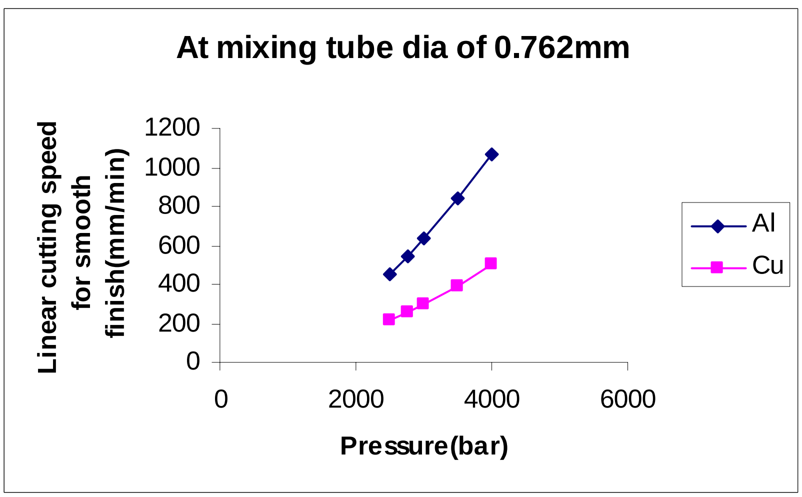


Fig. 9.23: At thickness 5mm and varying orifice diameter





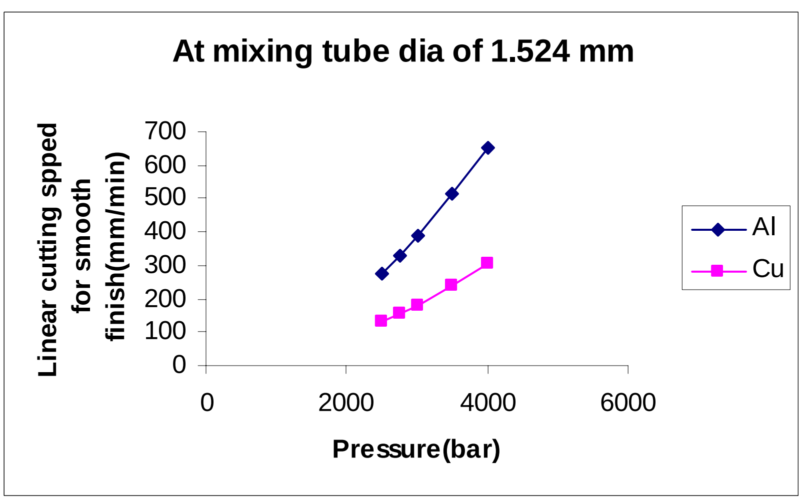
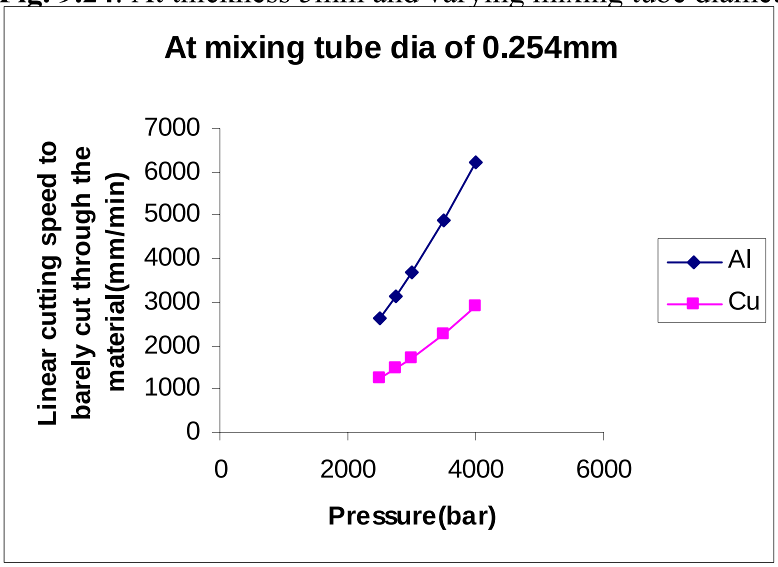
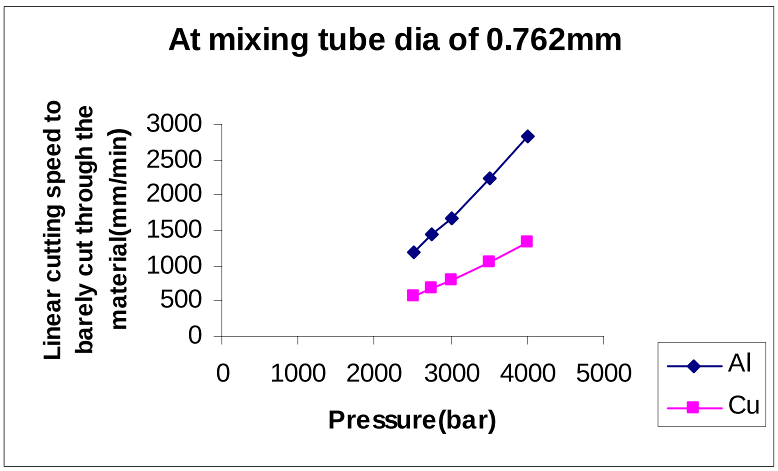


Fig. 9.24: At thickness 5mm and varying mixing tube diameter





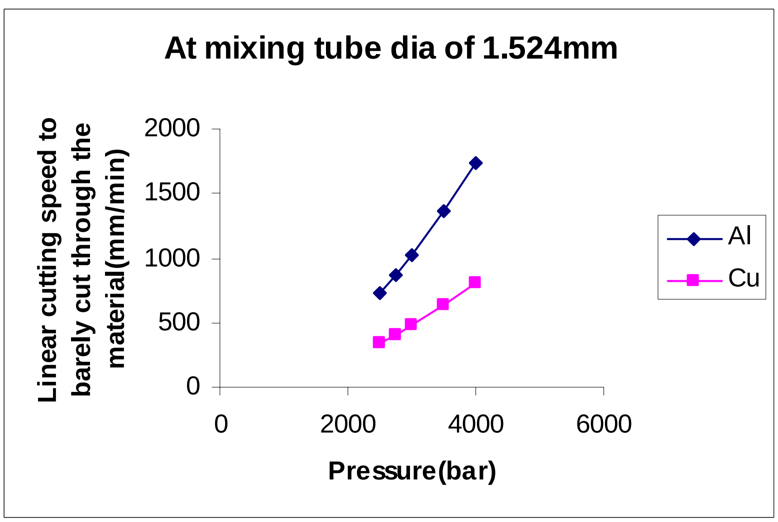


Fig. 9.25: At thickness 5mm and varying mixing tube diameter

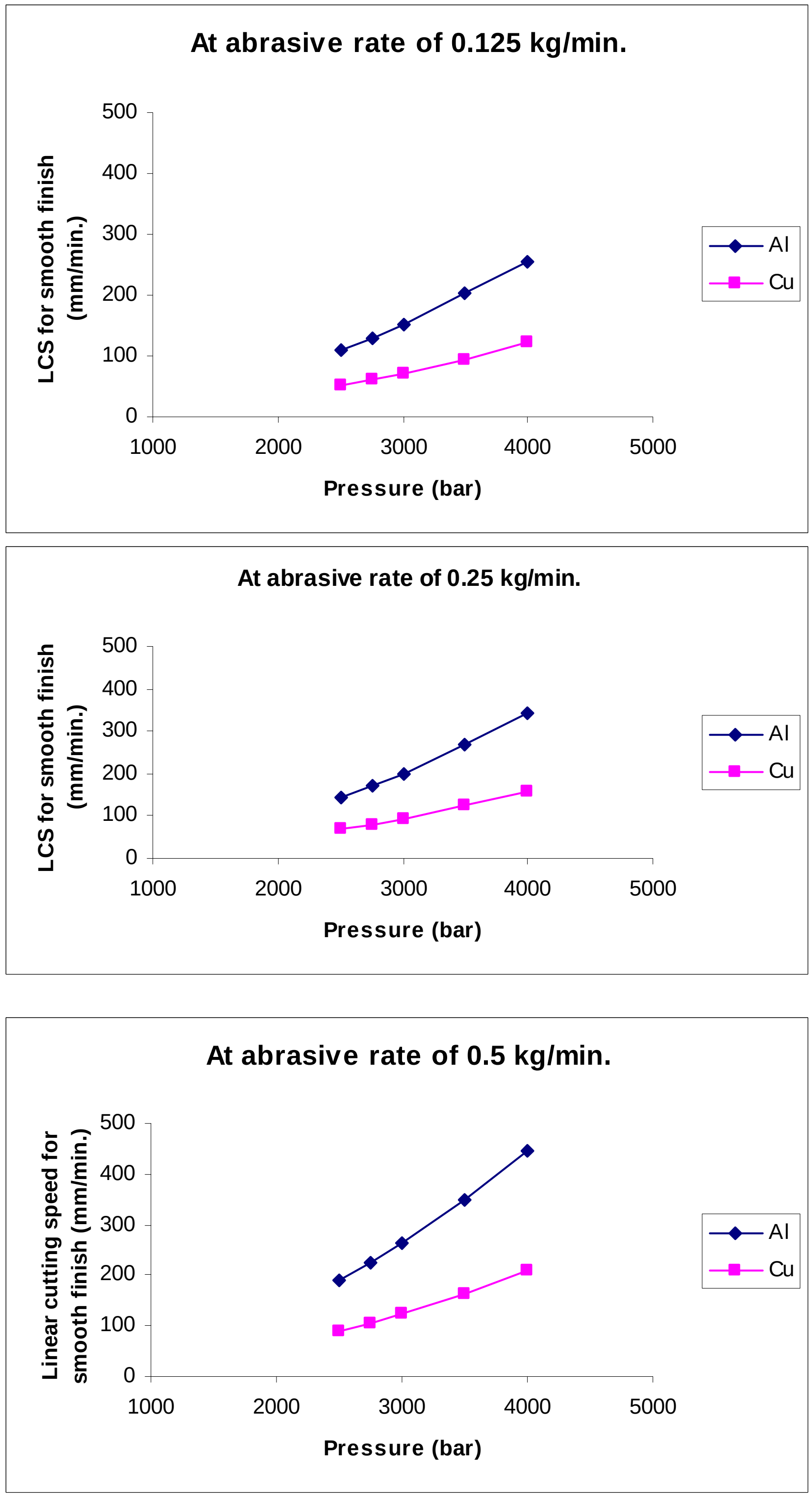
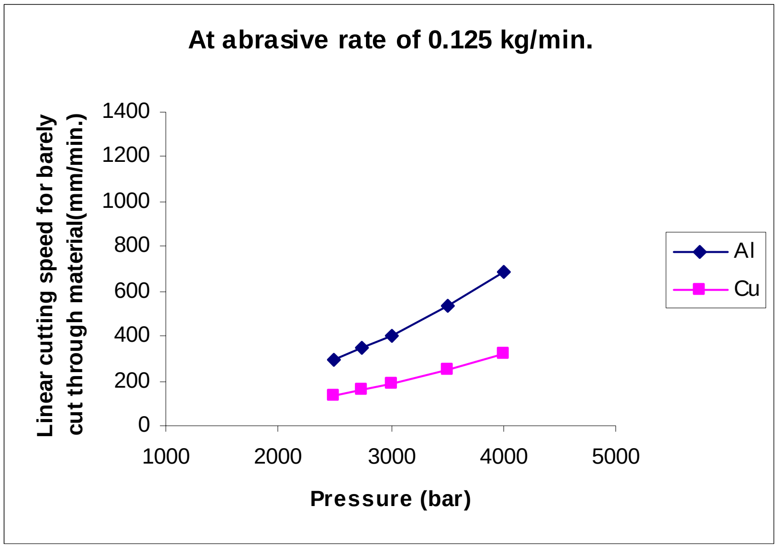
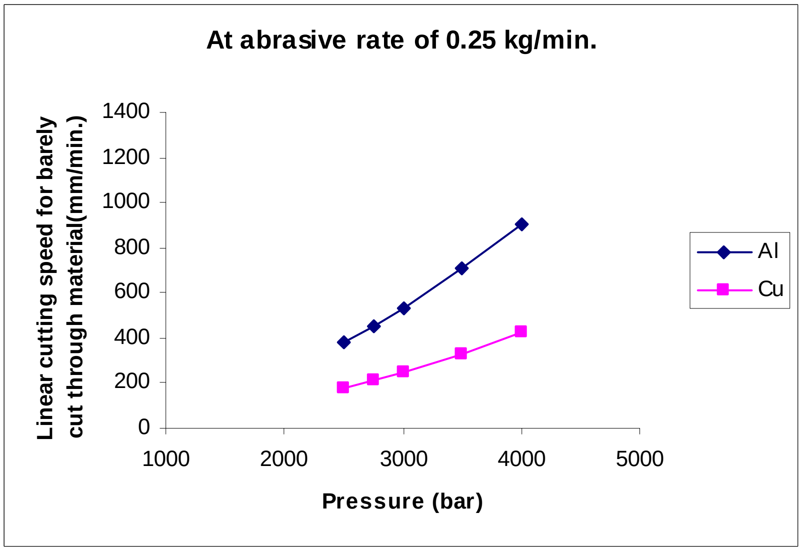


Fig. 9.26: At thickness 10mm and varying abrasive flow rate





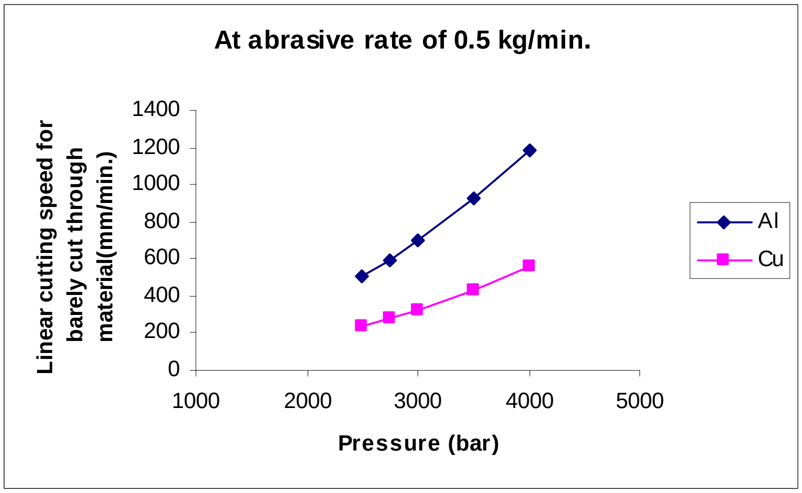
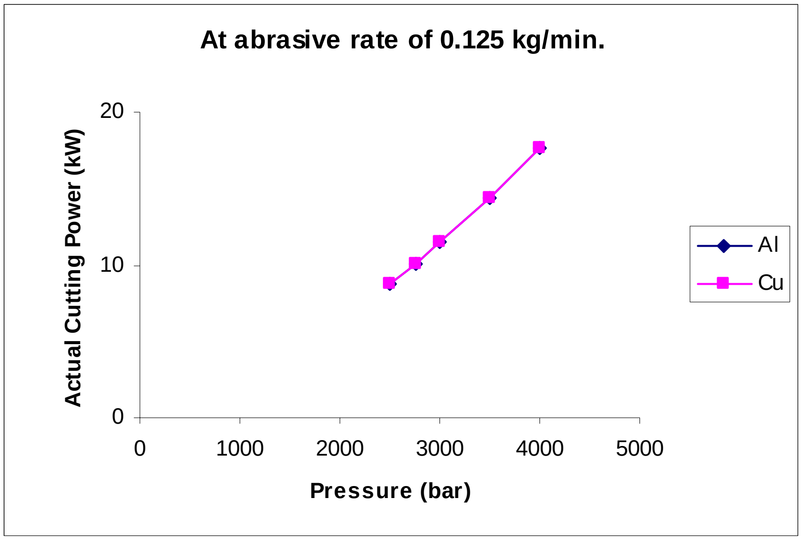
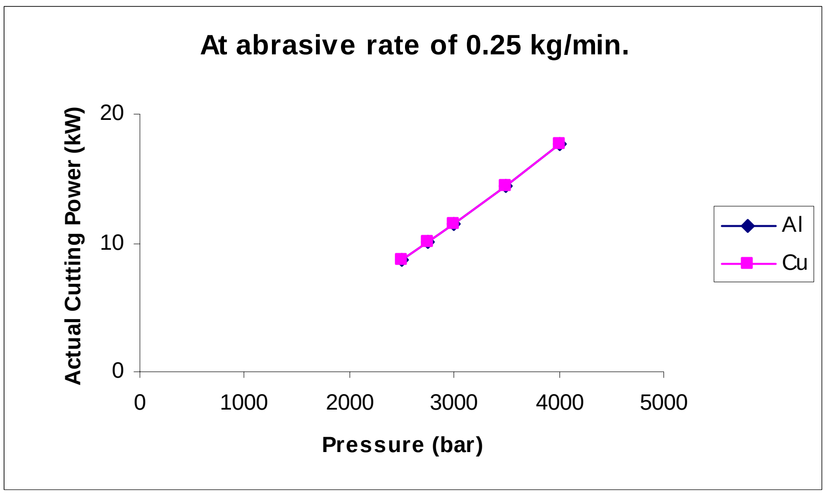


Fig. 9.27: At thickness 10mm and varying abrasive flow rate





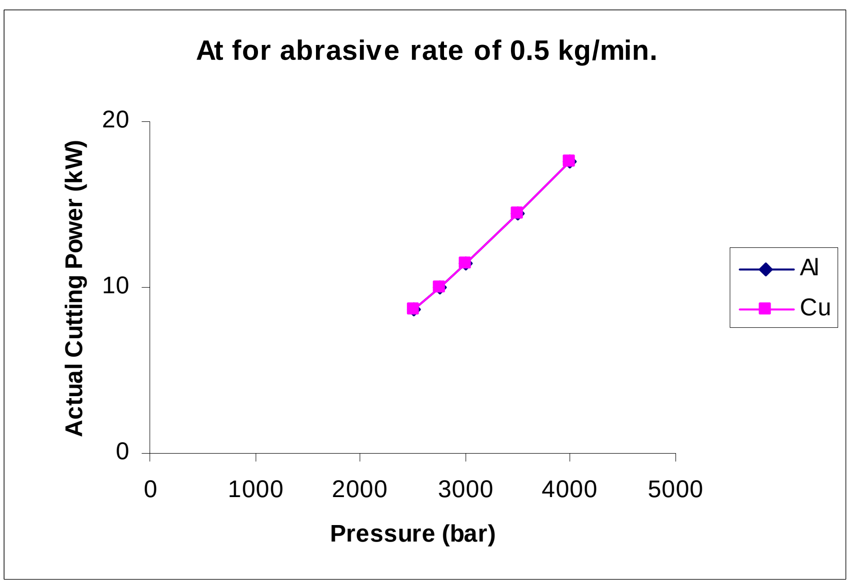


Fig. 9.28: At thickness 10mm and varying abrasive flow rate

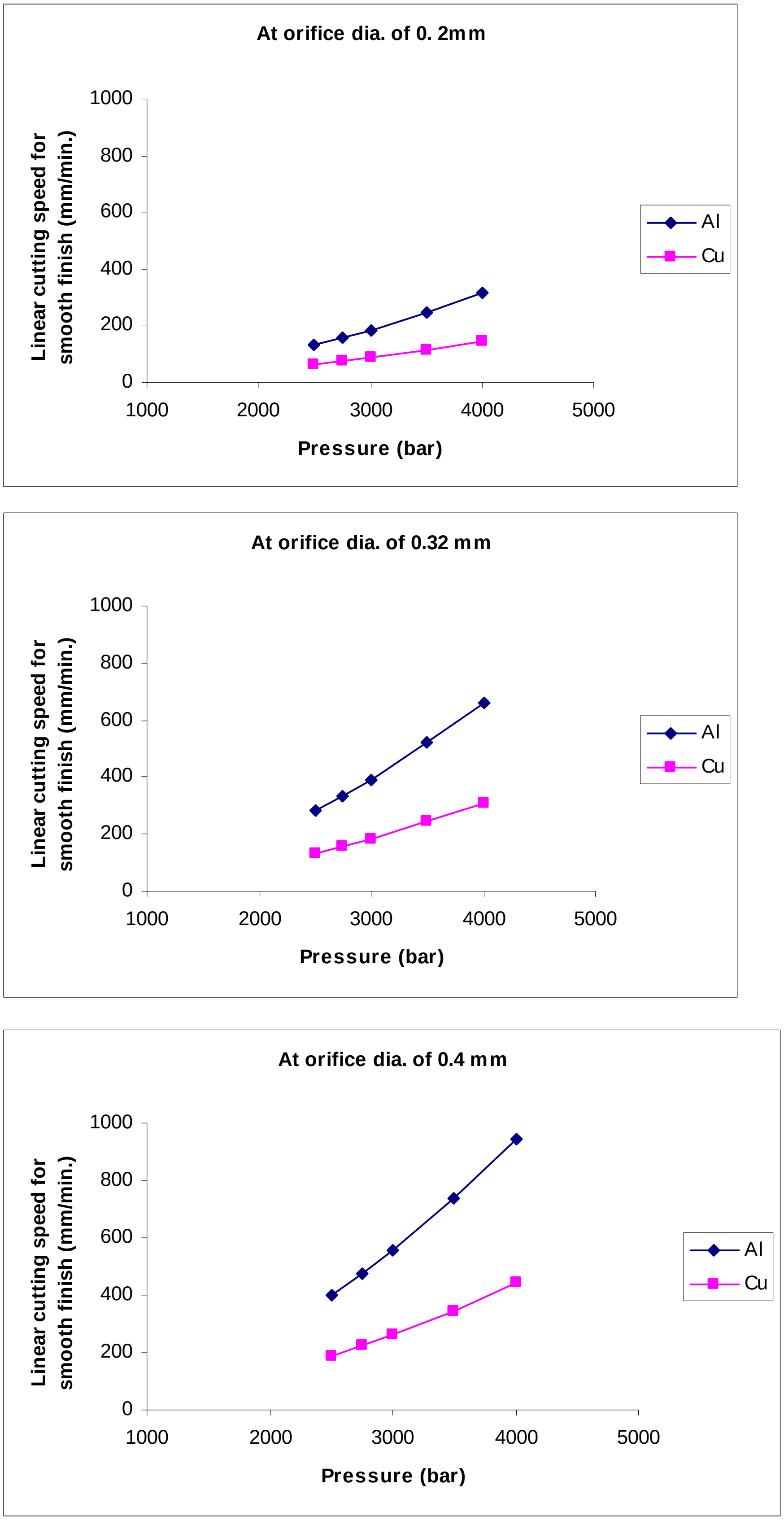
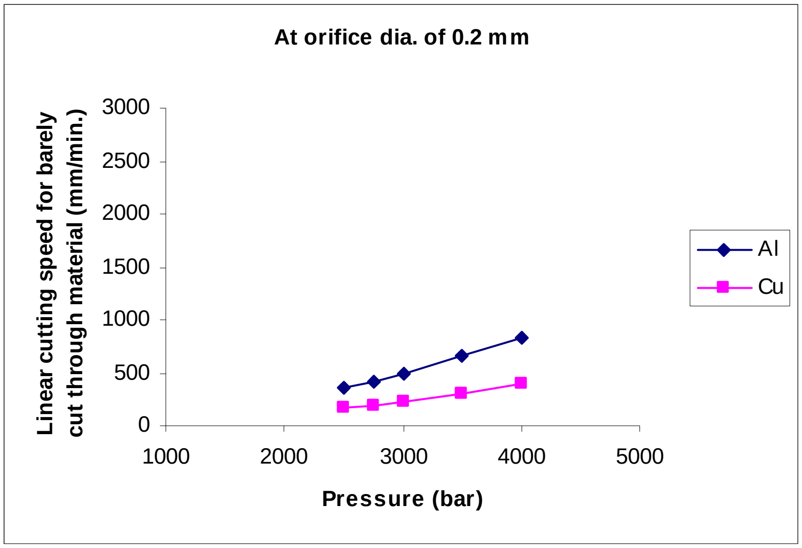
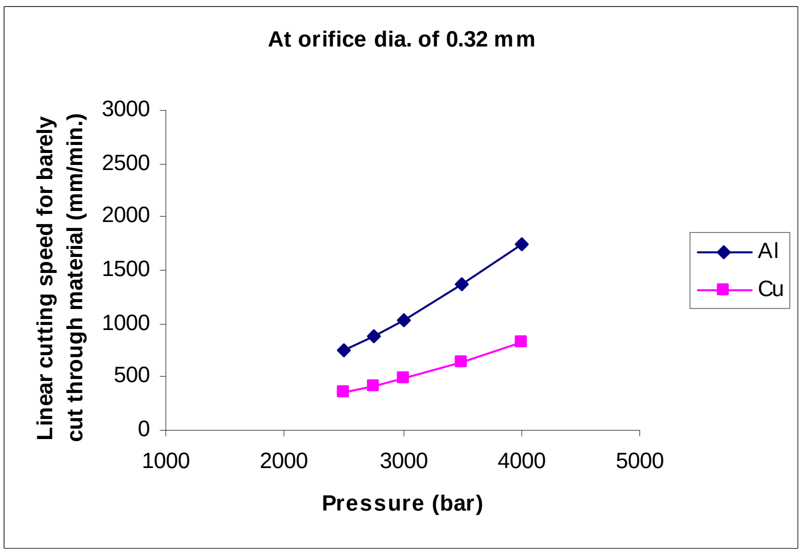


Fig. 9.29: At thickness 10mm and varying orifice diameter





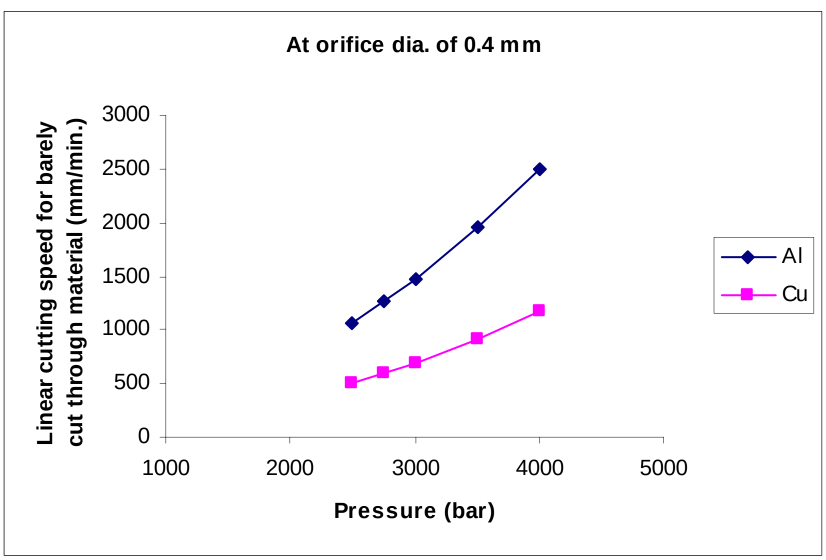
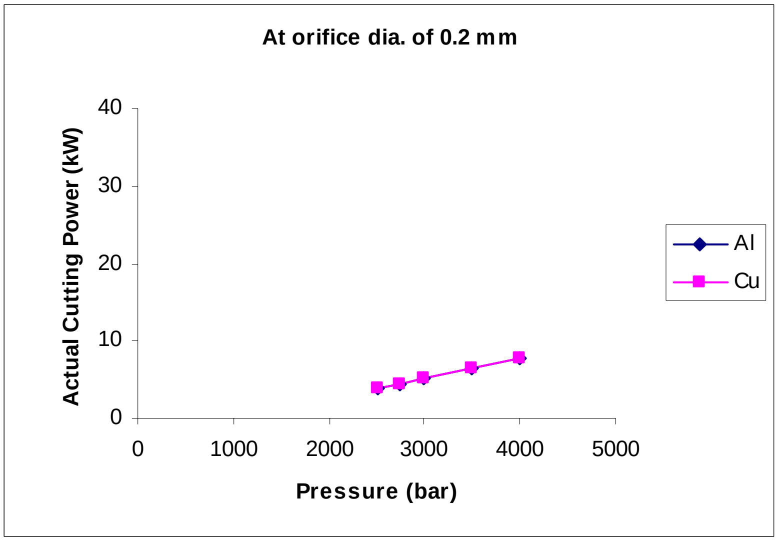
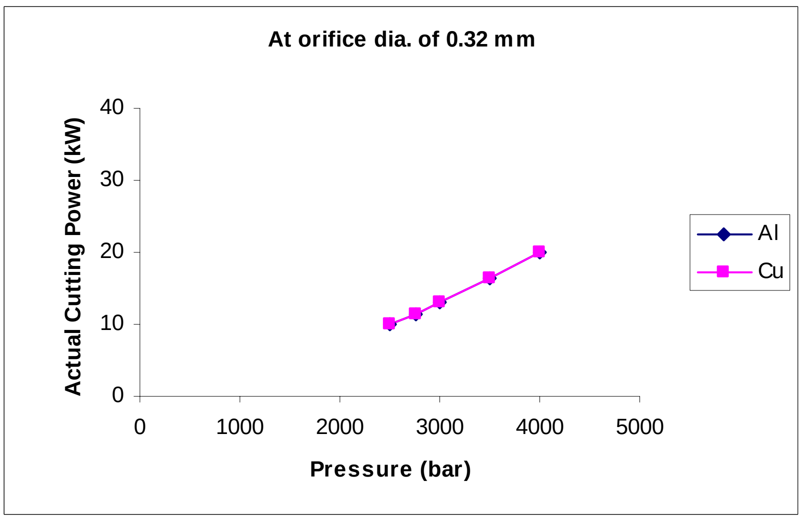


Fig. 9.30: At thickness 10mm and varying orifice diameter





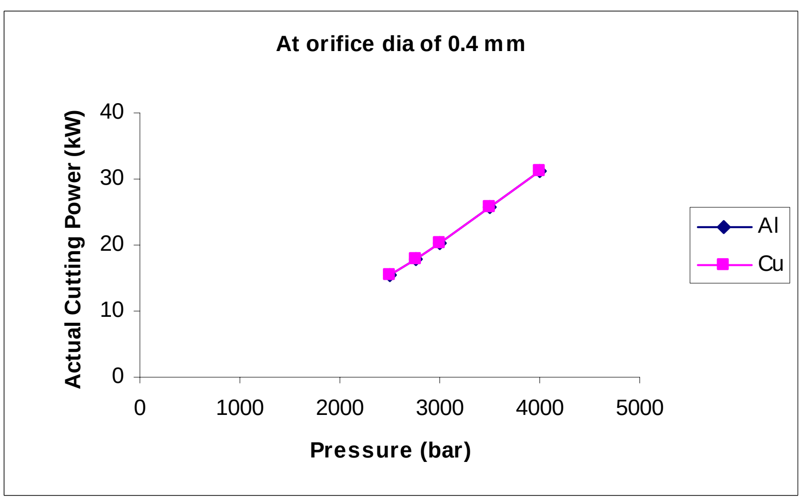


Fig. 9.31: At thickness 10mm and varying orifice diameter

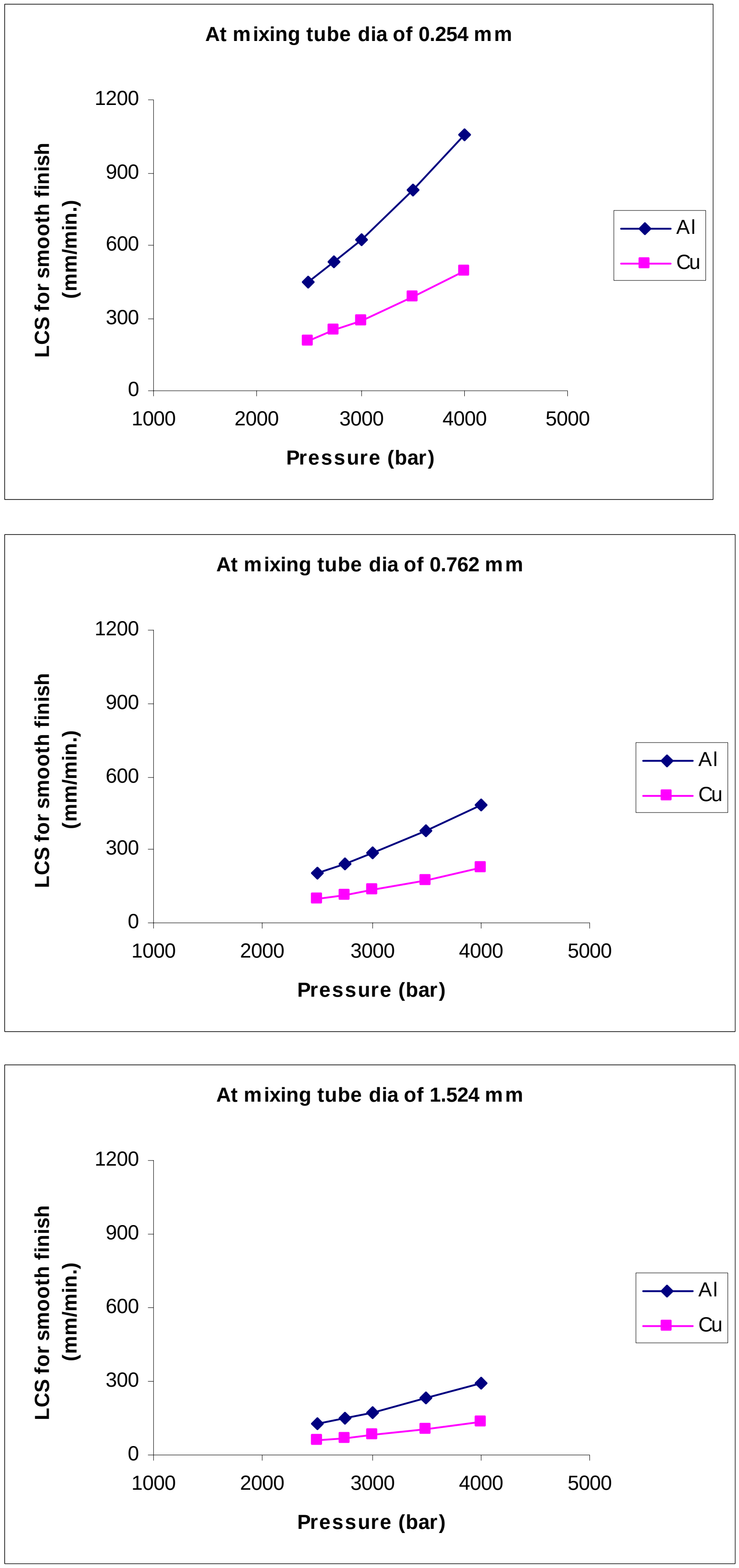


Fig. 9.32: At thickness 10mm and varying mixing tube diameter

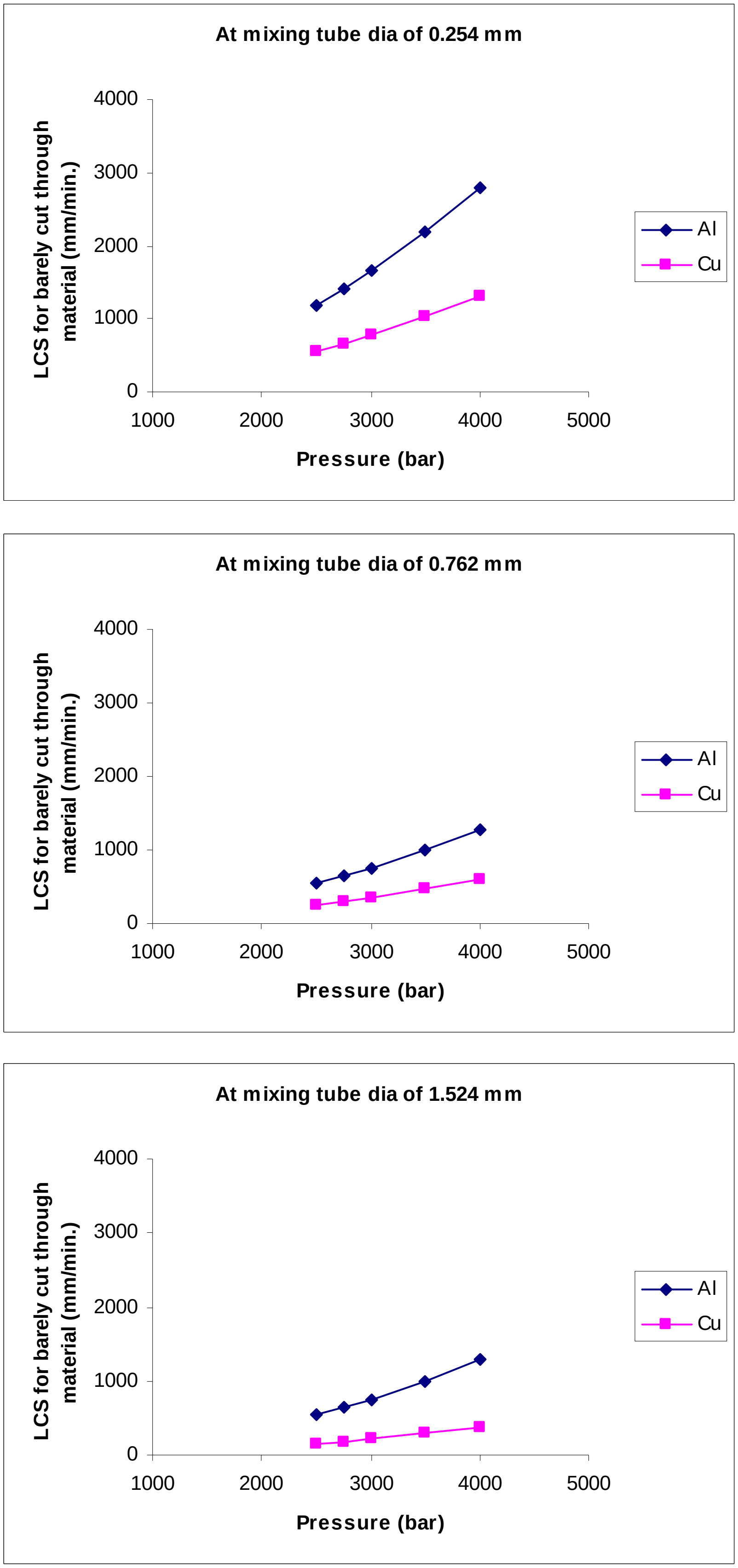


Fig. 9.33: At thickness 10mm and varying mixing tube diameter

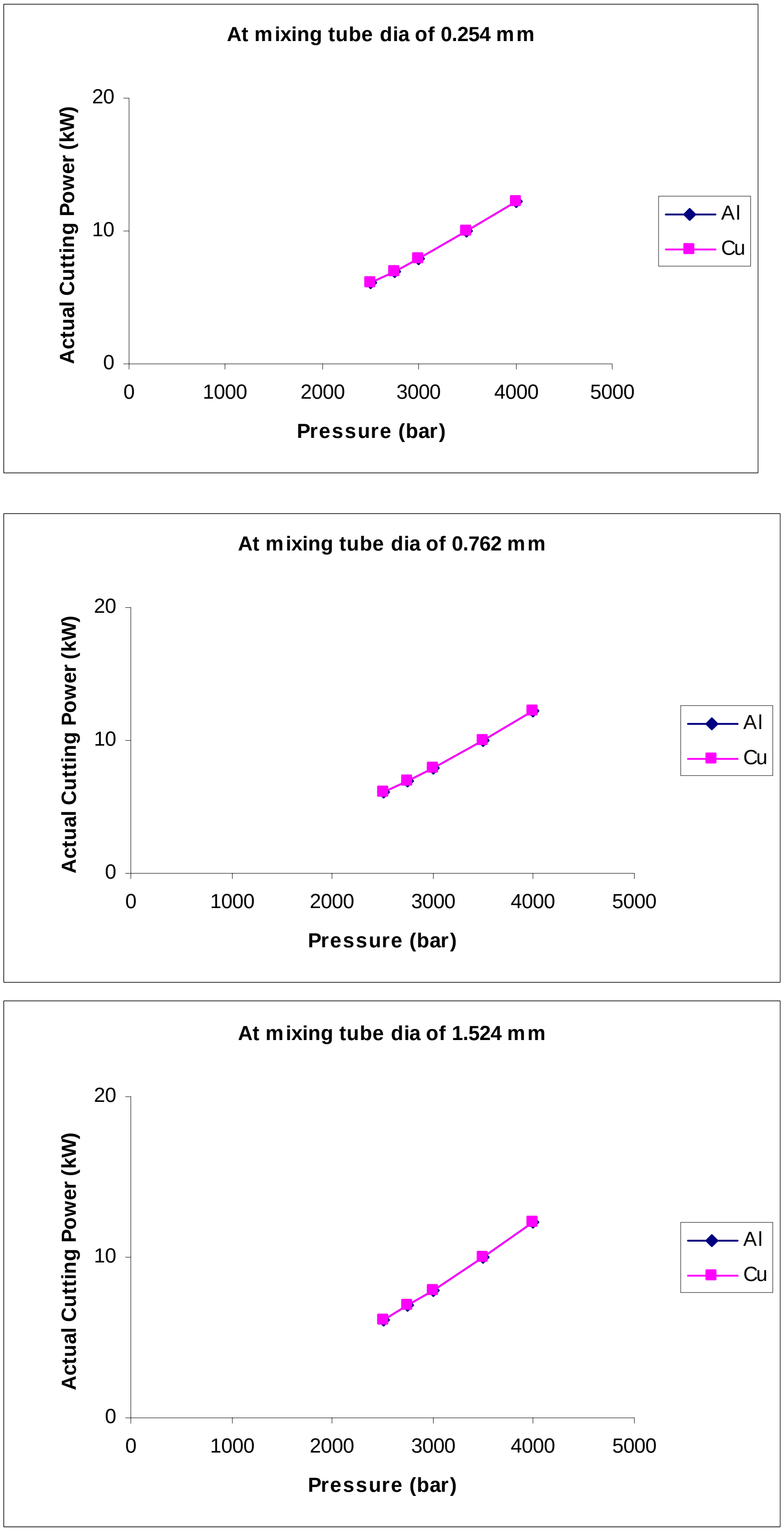
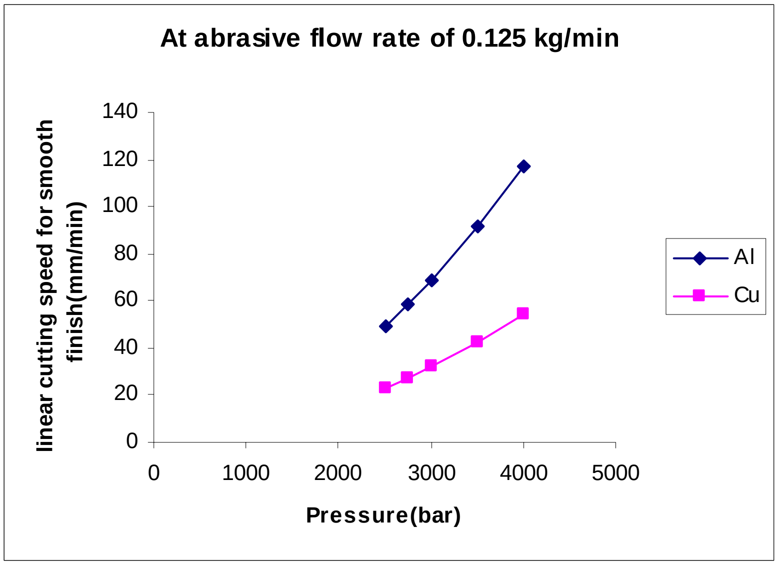
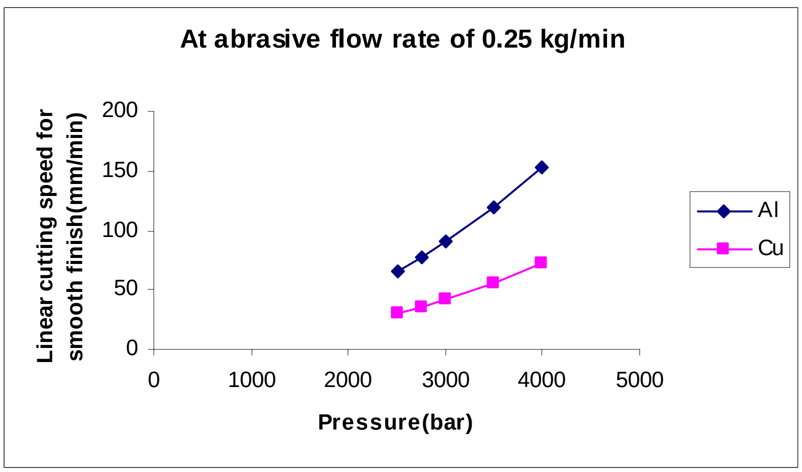


Fig. 9.34: At thickness 10mm and varying mixing tube diameter





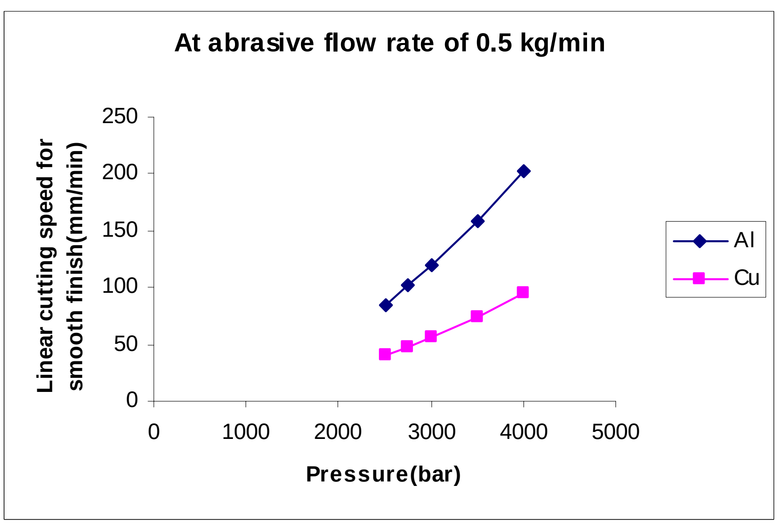


Fig. 9.35: At thickness 20mm and varying abrasive flow rate

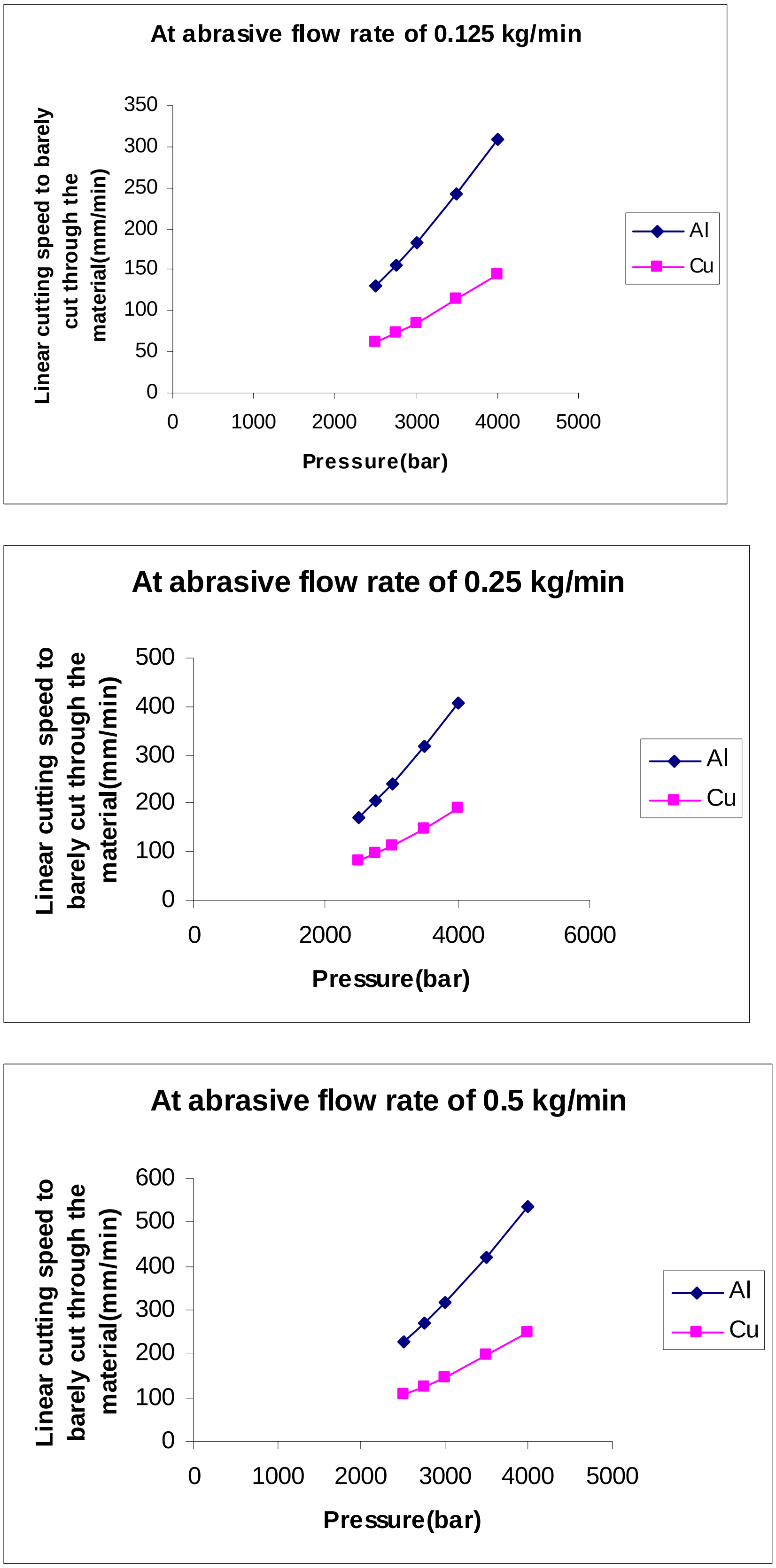
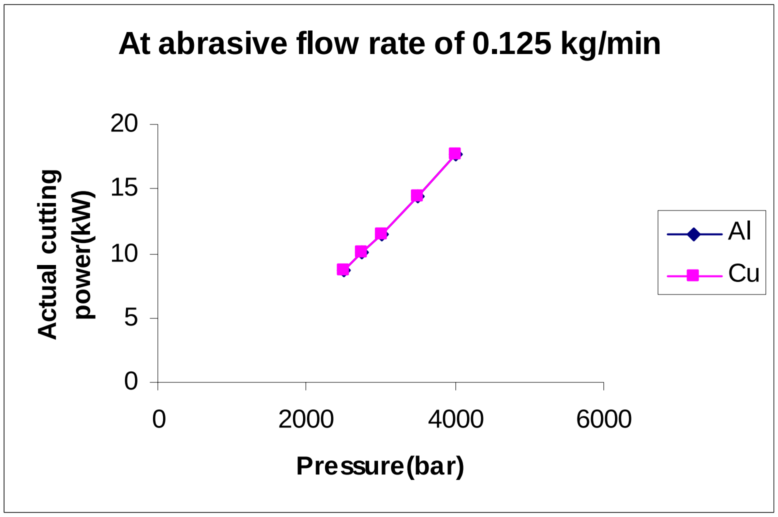
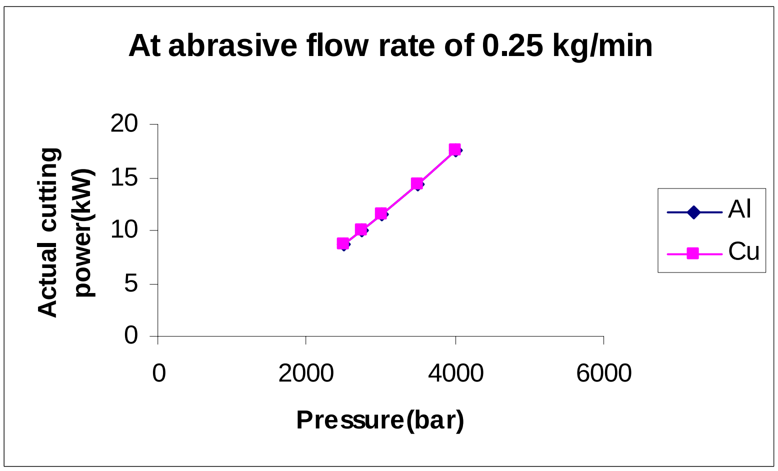


Fig. 9.36: At thickness 20mm and varying abrasive flow rate





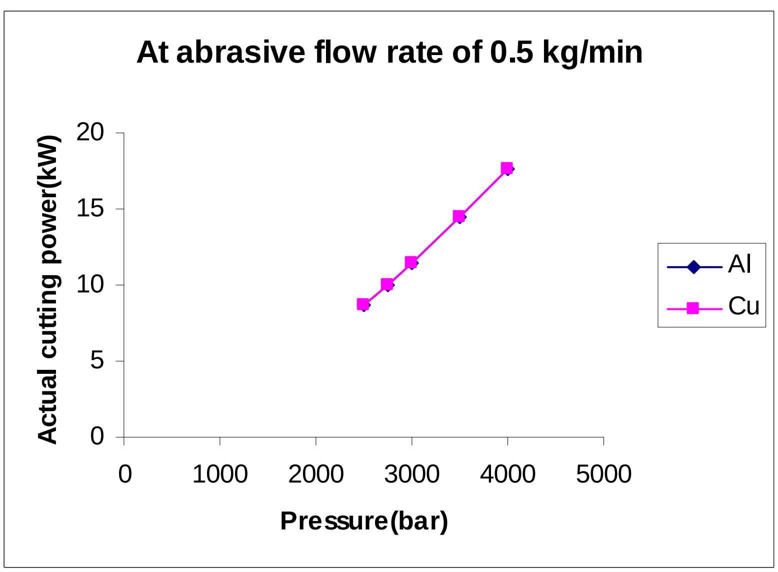


Fig. 9.37: At thickness 20mm and varying abrasive flow rate

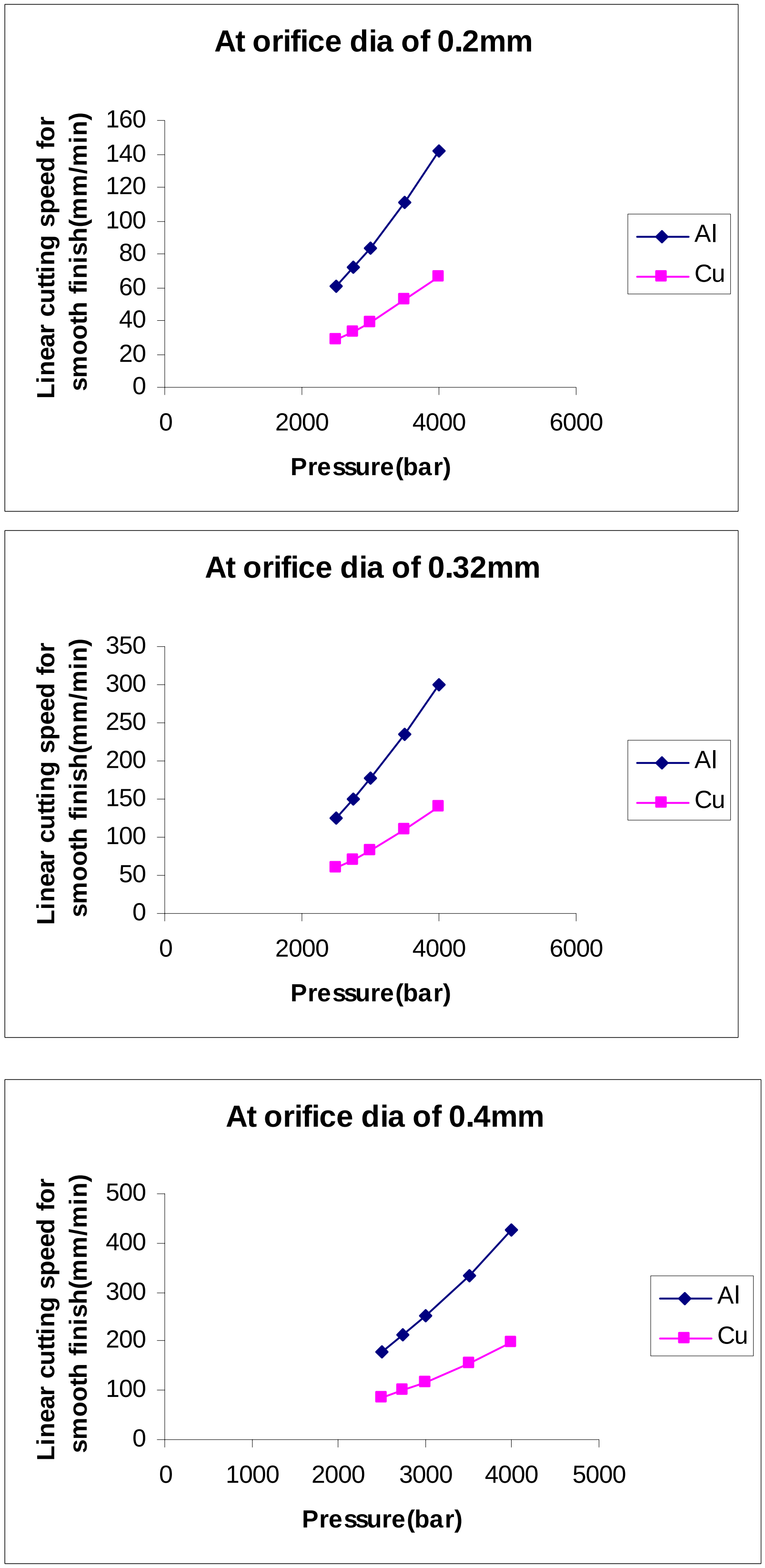


Fig. 9.38: At thickness 20mm and varying orifice diameter

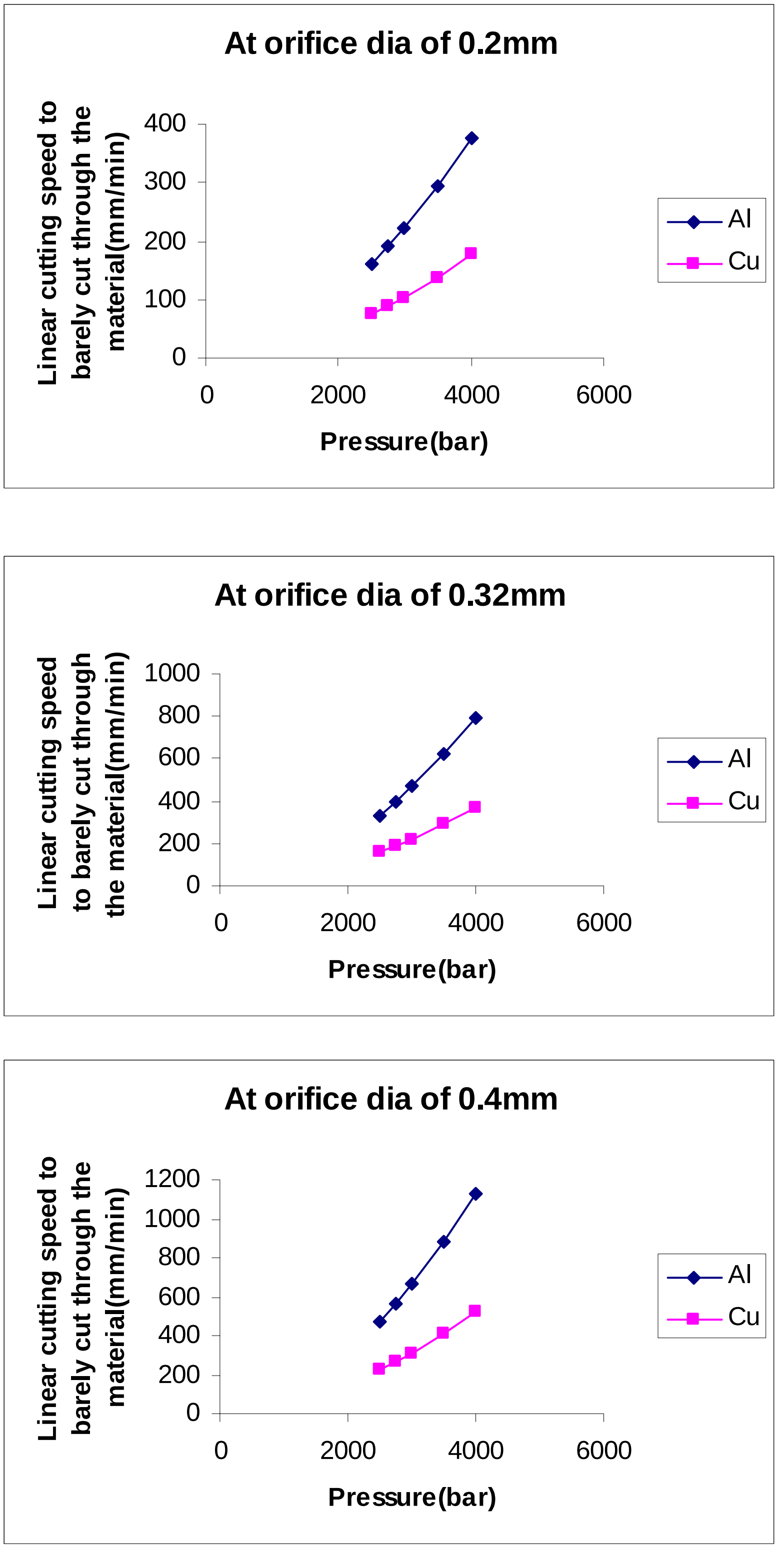
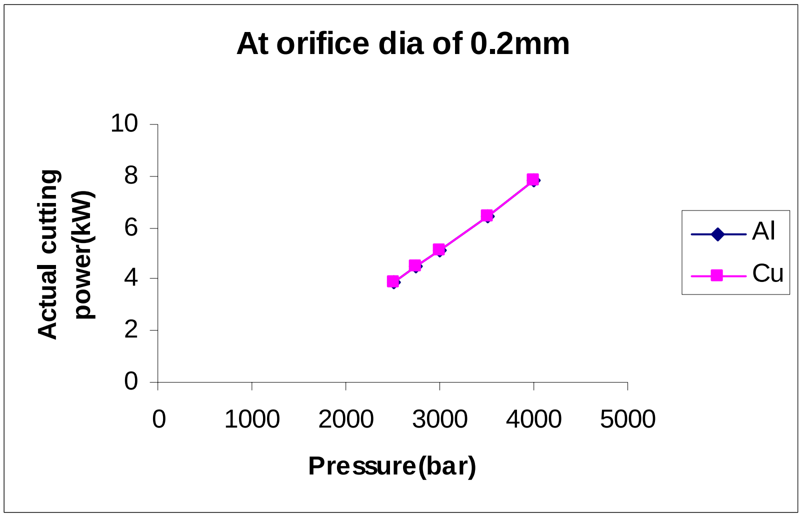
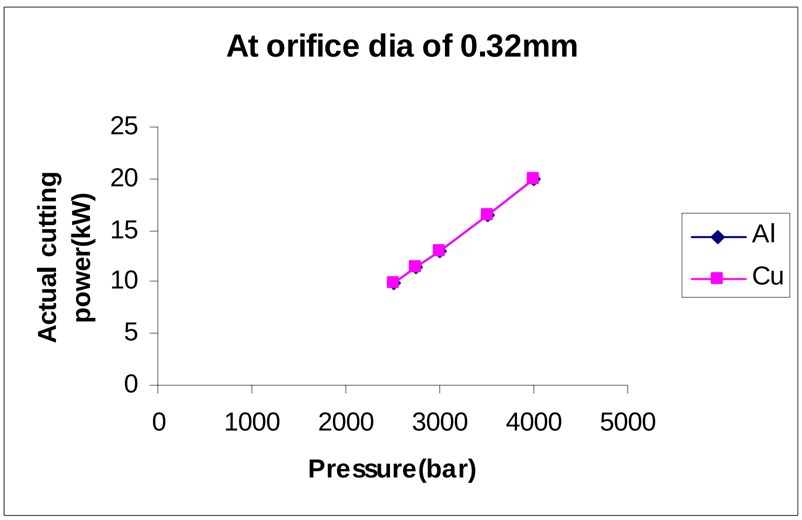


Fig. 9.39: At thickness 20mm and varying orifice diameter





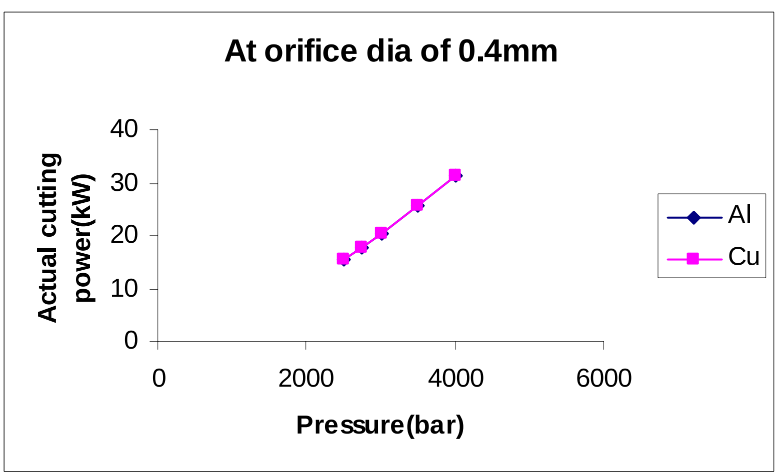


Fig. 9.40: At thickness 20mm and varying orifice diameter

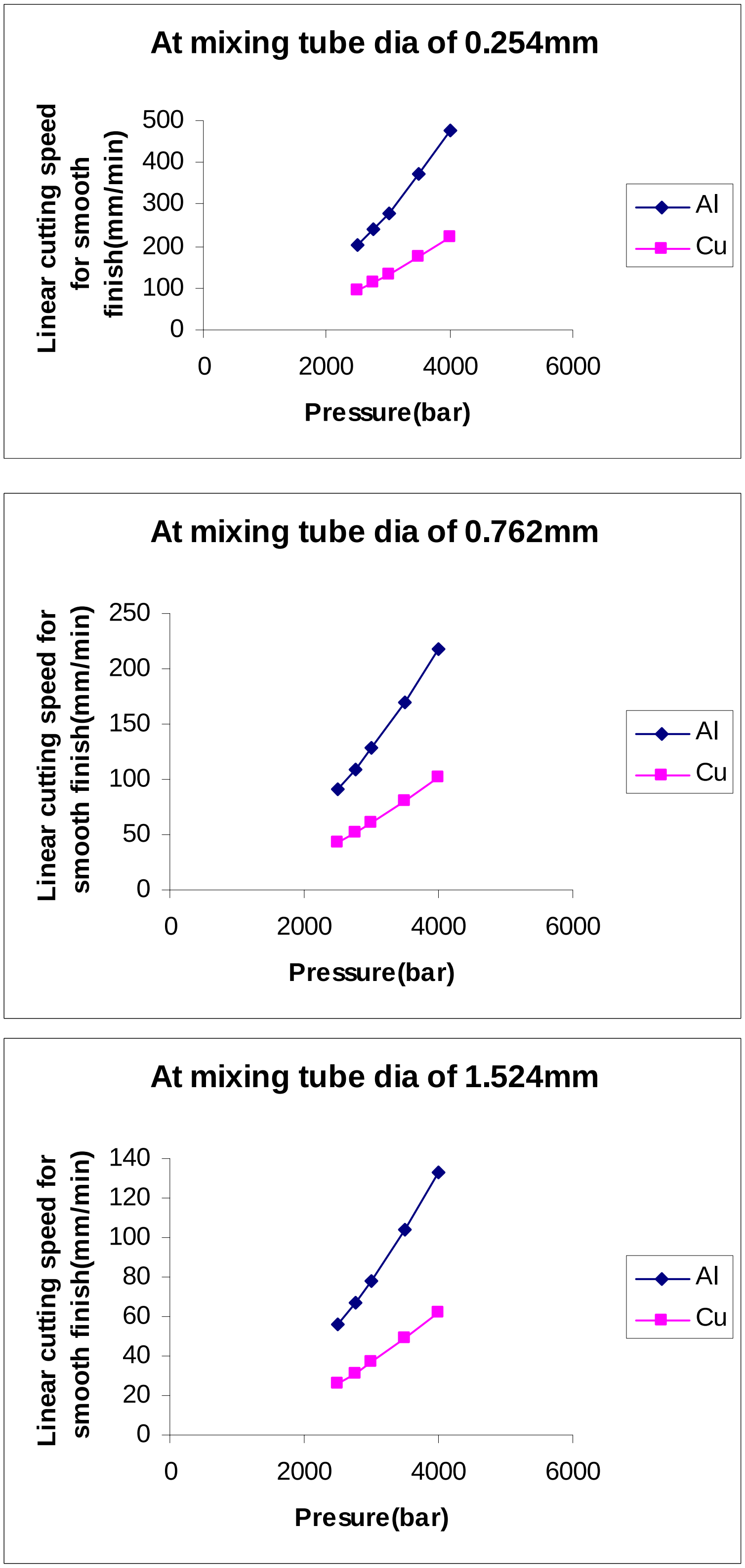


Fig. 9.41: At thickness 20mm and varying mixing tube diameter

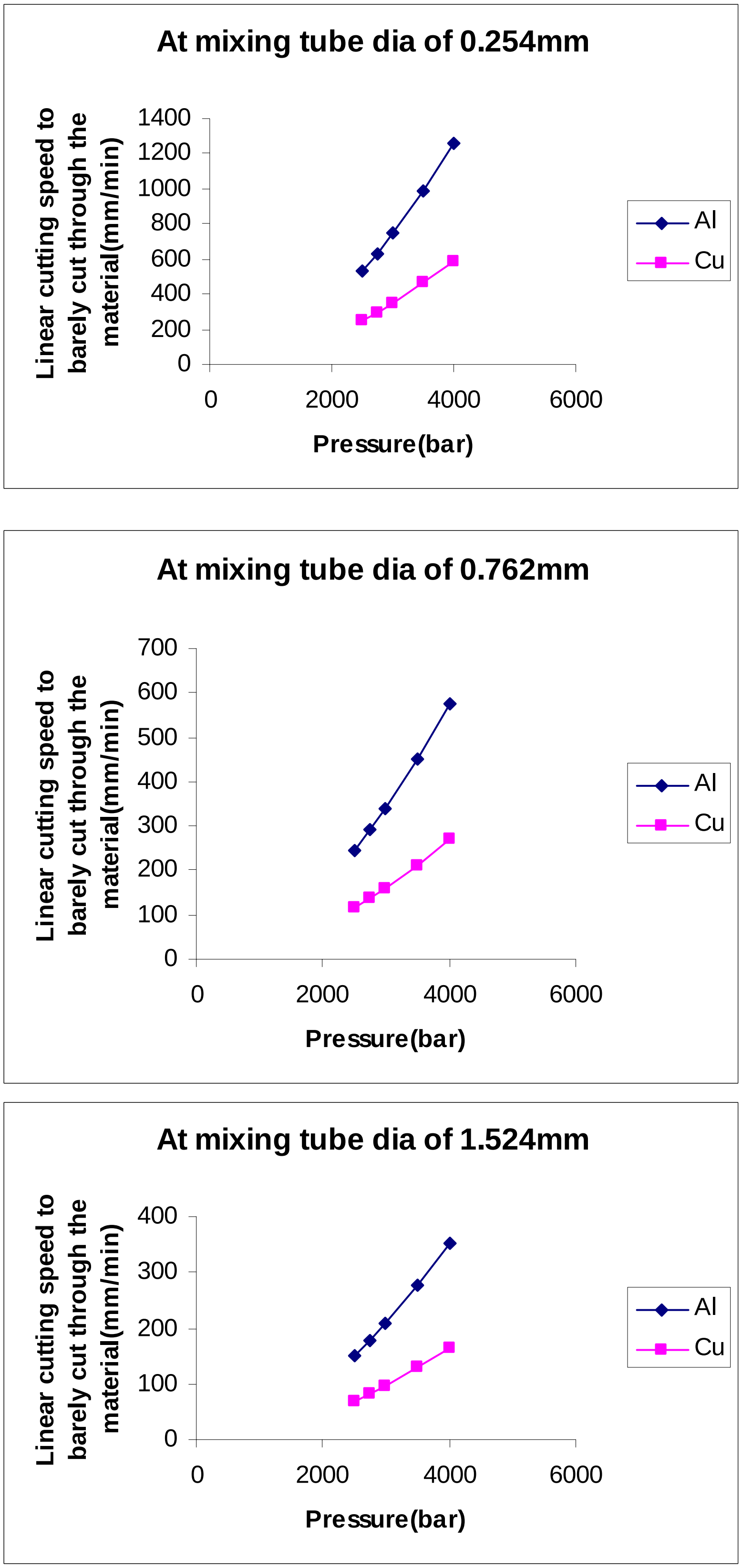
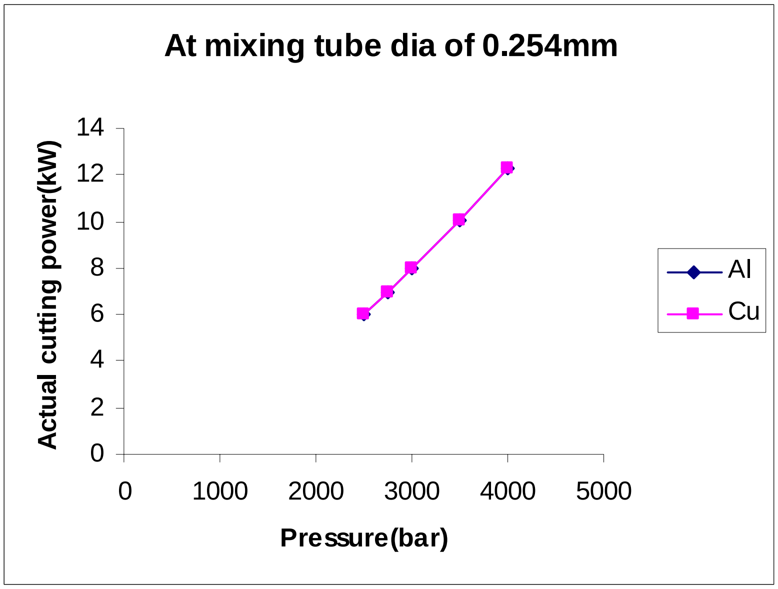
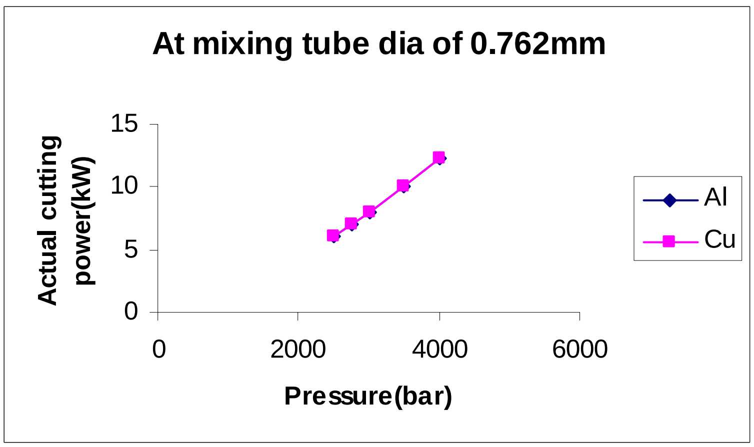


Fig. 9.42: At thickness 20mm and varying mixing tube diameter





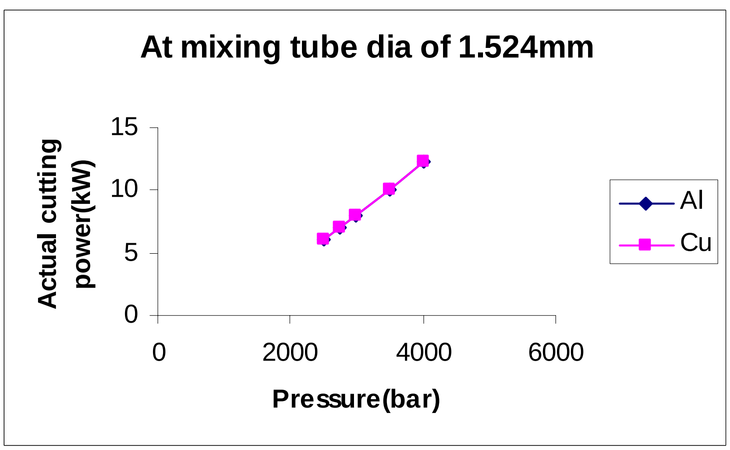


Fig. 9.43: At thickness 20mm and varying mixing tube diameter

CHAPTER 10

CONCLUSIONS

1) **With abrasive flow rate as a variable**:

a) As the abrasive flow rate is increased, a rise in the graphical representation of cutting speed for smooth finish is noticed. Al curve rises more sharply than Cu curve.

b) There is also a sharp rise noticed in the graphical representation of cutting speed barely cut through the material, but this rise is sharper than that of linear cutting speed for smooth finish. The speed required for cutting Al is always greater than Cu.

c) The actual cutting power remains same on increasing the abrasive flow rate. This rise is equal and similar to both the materials. This shows that the actual cutting power is insignificant of the material.

2) **With Orifice diameter as a variable**:

a) With an increase in the orifice diameter, it is noticed that at smaller orifice diameters, cutting speed for smooth finishing is very less. But as the orifice diameter is increased, the speed rises almost linearly. Al requires higher cutting speeds than Cu at all orifice diameters.

b) The cutting speed to barely cut through the material increases sharply with increase in orifice diameter. Al requires higher cutting speeds than Cu at all orifice diameters.

c) The actual cutting power increases with increase in orifice diameter. The graphical representation is similar for Al and Cu. This shows that the actual cutting power is insignificant of the material to be cut.

3) **With mixing tube diameter as a variable**:

a) The plot between linear cutting speed for the smooth finish and pressure for increasing mixing tube diameter clearly shows that increasing the mixing tube diameter, results in decreasing the linear cutting speed for smooth finish. This occurs due to the better entrainment of the abrasive particles into the water jet.

b) The same pattern is observed for linear cutting speed to barely cut through the material. With an increase in the mixing tube diameter, keeping all other parameters constant, the speed required decreases. This is again due to the better entrainment of the abrasive particles into the high pressure and velocity water jet.

c) The actual cutting power again shows that it is insignificant of the material to be cut. The plot for Al and Cu coincides with each other.

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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.

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"

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.

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

CAD (and CAD / CAM)
Computer Aided Design. CAD software is the software that you use to make drawings of parts. CAM is Computer Aided Manufacturing. 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.

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.

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.

Dynamic Pierce

A method of piercing a material by allowing the jet to start moving along the part path.

DXF File

Drawing Exchange Format. 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.

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.

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.

Hazing

See Frosting

Home

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

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".

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 Routed Data 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.

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)

Reverse Osmosis

A method for filtering water.

Scribe

This is a word that is sometimes used to distinguish between etching with abrasive, and scribing with water only. Similar processes, except etch uses abrasive and scribe does not.

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. There is no cure for silicosis -- prevention is the only answer."

Slat

One of the supports used to support the material you are machining. They are typically disposable.

Soft 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.

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.

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

Taper

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

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.

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 ".

Water jet

A pressurized jet of water exiting a small orifice at extreme velocity. Used to cut soft materials such as foam, rubber, cloth, paper, etc. Sometimes people use the word "waterjet" when they really mean "abrasivejet".

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.

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.

WJTA

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