Design and Manufacturing Optimization of Abrasive Water Jet Machining using Expert System

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Abstract: This paper addresses the concept of the expert system for abrasive waterjet machining. For optimization of abrasive waterjet machining, computer based concurrent engineering environment is used. The design specification is acquired through a feature based approach. The expert system links with feature base library. The expert system links with material database which holds attributes of more than 20 type of materials. It also links with abrasive data base which hold attributes of 8 types of abrasive, and also 4 type and size of machine. expert system also links with machine database which hold machine parameters. For each design feature, the expert system provides information needed for optimization of design and manufacturing. The expert system can be used as an advisory system for optimization of design and manufacturing. It can be used as a teaching program for new abrasive waterjet machining operators. For each design feature, the expert system provides information such as machining cycle time and cost and cutting rate. By changing machine parameters, we can optimize machining cycle time and cost and cutting rate. Comparison results of the expert system and experimental CNC Abrasive waterjet results for different design feature shows that machining time and cost of expert system is 10% less than experimental.

Keywords: Waterjet Machining, Abrasive, Expert System, Optimization

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1 INTRODUCTION

Abrasive Water Jet Machining (AWJM) is defined as a non-traditional machining methods which offers wide range of advantages and considered as promising method for machining difficult-to-machine materials. AWJ is non-thermal process, which does not rely on a conductive work piece material. It does not result in heat affected zone and involves minimum reactive forces. In AWJM, the material is removed by erosion process by the action of high-speed water jet mixed with abrasive particles. The high-speed water jet transfers the kinetic energy to the abrasive particles (typically garnet) and both impinge on to the workpiece.

Garnet is frequently used as an abrasive, since it is relatively hard, sharp edged, it has flow ability, availability and reasonable cost. Commercially, garnet is available in three grades namely mesh # 80, mesh # 100 and mesh # 120. Researches and manufacturers used AWJM process for machining different materials for various applications. Literature review related to machining of brittle materials using AWJM, the effect of different size of abrasives and optimization of machining process parameters are briefly presented here. In recent days, Nano material such as graphite particles are impregnated with glass fiber reinforced polymer (GFRP) to enhance specific properties.

Shivamurthy et al. [1], found that mechanical properties of glass/epoxy composite, namely, Young's modulus, tensile strength, impact strength, and wear resistance, show improvement with addition of graphite flakes. Such composites are highly suitable for manufacturing of bearing liners, gears, seals, cams, wheels, brakes, rollers, clutches, bushings, and so forth. Studies on electrical properties of graphite filled composites by Goyal and Kadam [2] and Bhattacharya et al. [3] revealed that these composites are also suitable to shield electromagnetic interference in electronic devices. Traditional machining of GFRP composites for secondary operations (trimming and drilling) is more difficult than machining of metals.

A review on traditional machining of composites by Teti [4] and Abrao et al. [5] highlights the problems such as exposure of fibers to environmental attack, material degradation due to localized heating, poor dimensional accuracy, shorter tool life, delimitation, and fiber pullout due to anisotropic, no homogeneous, and abrasive nature of such composite materials. To address these challenges, advanced machining methods have been explored. Study of machining of carbon fiber reinforced polymer (FRP) composite by electrical discharge machining [6] and laser beam machining [7] reported the formation of recast layer on cut surface due to relatively higher localized temperature. AWJ machining is a relatively new manufacturing tool which has been realized to address limitations mentioned earlier. The importance of AWJM machining is that, the machined surface does not damage from low heat that is generated during machining and also due to water that acts as coolant. The impacting abrasives exert smaller cutting force on the localized spots of the work piece. Machining requires simple fixtures to support the workpiece, and the process does not produce mechanical distortion on the cut surface. One of the major problems encountered while machining of FRP composite by traditional methods is formation of the fine dust which leads to air pollution that causes serious lung related health problems to the machine operators.

In AWJ machining, the dust generated is carried away by the water jet and also no hazardous chemical is used in the process. Hence, AWJ is considered as environmentally friendly machining process. This machine tool can be electively used for machining of FRP composites [8]. In AWJ machining, the mixture of abrasive and water is directed on the target material. The nozzle is attached to CNC control to produce required profiles on workpiece. Material removal rate (MRR) in AWJ machining depends on operating parameters and properties of target material. In addition, other parameters such as hardness, shape, size, and quantity of abrasives laced in the water jet play a vital role in MRR [9].

Huttunen-Saarivirta et al. [10] studied the effect of particle shape on AWJ erosion process using silica sand abrasive. It was observed that spherical shaped or blunt edged abrasives tend to create ductile fracture with low MRR and angular shaped abrasive with sharp edges resulting in brittle fracture contributing to higher MRR.

In 1958, Billie Schwacha of North American Aviation developed a system using ultra-high-pressure liquid to cut hard materials. This system used a 100,000 psi (690 MPa) pump to deliver a hypersonic liquid jet that could cut high strength alloys such as PH15-7-MO stainless steel [11].

Waterjet technology is one of the fastest growing machining processes. It is environmentally friendly, can machine almost any material [12], [13] and can cut metal to depths of over 100 mm [12], [14] It is used in a wide range of industries from automotive and aerospace to medical and the food industries [14], [16]. Current applications include stripping and cutting of fish [14], [15], [16], cutting of car carpets [17], removal of coatings from engine components [18], [19], [20]. The eject of particle size on erosion of titanium workpiece was studied by Yerramareddy and Bahadur [21] and ElTobgy et al. [22], using experimental and finite element analysis, respectively. The erosion rate was found to increase considerably for particle size up to 200 micrometers and remained constant for further increase in the particle size. Machining performance of various abrasives on glass workpiece was investigated by Khan and Haque [23]. Taper of the machined surface was found to increase with decrease in hardness of abrasive. Abrasive particles with higher hardness have better machining capability, but they have limitations like accelerating the wear of machine components and abrasive embedment on cut surface.

Hence, AWJ machining industry uses garnet abrasive due to its specific advantages like low nozzle wear rate, good machinability, and economical availability [24–27]. In addition to abrasive properties, machining performance is also influenced by operating parameters such as jet angle, SOD, feed rate, number of cutting passes, jet pressure, abrasive flow rate, and nozzle geometry. The effect of abrasive impact angle on machining of ceramic material was investigated by Srinivasu et al. [28], using silicon carbide as abrasive. The effect of particle impact angle was also studied by Junkar et al. [29], using finite element analysis. Authors found that maximum material removal occurs at jet impact angle of 90∘.

Studies on the effect of jet pressure on cotton FRP composite by Wang and Guo [30] reported that the delamination occurs due to incapability of jet penetration into composite at lower operating pressures. There are also recognized authorities in various aspects of waterjet technology, for instance, for machining, materials behavior during machining, characteristics and quality of surface after waterjet treatment [31], Professor Louis investigates WJM for cleaning, machining, precise cutting, abrasives, surface quality and medical applications [32] and Dr Momber investigates WJM for wear of materials and erosion of ductile materials [32], [33].

Recent developments have seen that the components of the waterjet system become more reliable and robust. Pump technology is such that pressures of over 4.14×10^8 Pa (4140 bar or 60,000 psi) are commonly used and pumps producing 6×10^8 Pa (6000 bar or 87,000 psi) have just recently been introduced to the market [34], [35], [36], [37], [38], [39]. Such pressures are capable of reliably machining a whole range of materials. These high pressures also allow the use of multi-heads which can enhance the process viability due to the increased throughput [40]. Head and nozzle design has led to excellent systems being available with minimal maintenance and accurate performance.

Study of kerfs taper angle produced on glass and graphite reinforced epoxy composite was made by Shanmugam etal. [41] and also developed a model to predict delamination length. Authors observed that, at higher operating pressures, considerable surface taper and elimination are found on the cut surface due to higher feed rates, flow turbulence, and brittle nature of composite material. Investigations on the effect of process parameters by Azmir and Ahsan [42] on glass fiber reinforced epoxy composites infer that abrasive hardness, operating pressure, SOD, and jet traverse rate were significant control factors which affect surface roughness (R_a) and a mathematical model was developed by authors to predict(R_a). Further analysis of machined surface by Azmir and Ahsan [43] shows that at a jet angle of 90∘, glass fibers were found to be perfectly chopped.

Alberdi et al. [44] studied the suitability of machinability model developed for metals to use it in composite materials. The machinability index was found to vary with thickness and composition of the composite. A comparative analysis of AWJ machining of metals in air and in submerged conditions is made by Haghbin et al. [45]. The study shows that machining under submerged conditions produced narrower kerf than the free jet machining. In AWJ machining, the kerf profile produced depends on jet energy, jet exposure time on the workpiece, jet orientation, and material properties. Axinte et al. [46] developed a geometrical model to predict jet footprint (kerf) in maskless controlled milling applications.

AWJ milling experiments were conducted on silicon carbide ceramic material at 90∘ jet impingement angle at various jet feed rates to validate the model. Kong et al. [47] developed a mathematical model to predict the jet foot prints for arbitrarily moving jets in single straight paths. Vundavilli et al. [48] used fuzzy logic based expert system such as simulated annealing and genetic algorithm to optimize process parameters and develop a mathematical model to predict depth of cut. Zain et al. [49] also used computing techniques to optimize the process parameters that produced low surface roughness.

Billingham et al. [50] developed model that predicts jet foot prints of the overlapped single and multiple straight paths. Narayanan et al. [51] developed model to predict the jet energy distribution by considering parameters such as abrasive particle size distribution and the effect of particle fracture. Nouraei et al. [52] developed surface evolution model that can predict the shape features in micromachining of brittle material such as borosilicate glass. These models were found to be powerful tools to develop advanced jet path strategies on complex geometries using CAD/CAM by considering various process parameters including jet exposure time and orientation.

2 HIGH PRESSURE ABRASIVE WATERJET MACHINING

Waterjet Pumps: Pure water jets for cutting applications are used in a range between 10 to 400 MPa (1450 to 58013 psi) and created by pumps with intensifiers (high pressure and low volume flow). Pure water jets with high discharges are used for cleaning and milling applications. These jets are created by plunger pumps. Waterjet Nozzles: The water with a maximal pressure up to 400 MPa (58013 psi) is led by tubes made out of metal to nozzle. The high pressure causes a compression of the water, so that water can no longer be considered as a fluid with a constant density. The compression of water forced with 400 MPa is up to 13 %. The water jet with a very high velocity (theoretically up to 900 m/s) is created by the change of potential energy (pressure) into kinetic energy in the nozzle.

Velocity of the Waterjet: The nozzle changes the potential energy of the water which is forced with a pressure into kinetic energy of the jet. The velocity of the jet can be calculated very simple with the equation of Bernoulli (Eq. (1)):

$$v_{th} = \sqrt{\frac{2p}{\rho}} \tag{1}$$

The change of energy shows losses. The used nozzles show a sharp-edged flow channel which causes a contraction of the diameter of the water jet. The ratio of diameter of the jet and the diameter of the nozzle orifice is called contraction number α. The contraction causes friction which reduces the average velocity in comparison to the theoretical possible velocity of the jet. The reduction of velocity can be taken into account by the velocity number which is defined by the ratio between velocity of the jet and the theoretical velocity of the jet. The velocity number can have values between 0.97 and 0.99. The described effects reduce the theoretical possible velocity of the jet. The real velocity of the jet can be calculated by Eq. (2).

$$\begin{aligned} v_s &= \alpha\varphi v_{th} \\ &= \mu v_{th} \end{aligned} \tag{2}$$

The number μ is the so called discharged coefficient μ and can have values between 0.65 and 0.7. This number can be practically evaluated by measurements of the volume flow, because it is very difficult to measure the contraction number and the velocity number. Up to now the compressibility of water was not considered in these contemplations. The higher density and higher inertia of the water cause a reduction of the velocity of the jet. On the other hand, the expansion causes an increase of the velocity in the direction of the jet and an increase of the cross section of the jet. The real situation caused by all effects is very complex and depends on the design/shape of the nozzle.

Spreading of the Waterjet: The water jet leaves the nozzle spreads more and more with increasing the stand-off distance of the nozzle. This is caused by turbulences in the jet and by friction between the jet and the air and that results in a reduction of the velocity of the jet. One possibility to influence the structure of the jet, that means to improve the length of the parallel and compact zone of the jet can be done by adding long chain polymers to the water. The polymers decrease the losses by friction in the nozzle and increase the average velocity of the jet. The improved coherence of the jet improves the quality of the edges of the cut if greater nozzle stand-off distances are used.

Mechanism of Material Removal: The removal of material by high pressure water jets is caused by a fluid dynamic erosion process. This process can be characterised by the following mechanisms:

- The friction between jet and work piece causes shear forces, which causes a plastic flow of the material out of the cutting die clearance**.**
- The high frequent-dynamic stresses of the material by the fluid particles of the jet cause a destruction of the material which can be described by the following mechanisms: hardening of the material, cracking, crack growth, agglomeration of cracks and breaking out of material particles.
- The local dynamic pressure which interacts with the surface of the work piece gets into existing gaps like cracks and pores and causes an increase of these faults of the material in space to removal of the material.
- A local induced stress field by the local acting dynamic pressure causes cracks by passing a critical stress.

The described mechanisms exist alone or in combination depending on the properties of the material. The application for high pressure water jets in practise is only useful for the treatment of non-metal and non-ceramic materials. One possibility to influence the structure of the jet, that means to improve the length of the parallel and compact zone of the jet can be done by adding long chain polymers to the water. The polymers decrease the losses by friction in the nozzle and increase the average velocity of the jet. The improved coherence of the jet improves the quality of the edges of the cut if greater nozzle stand-off distances are used.

Nozzles and cutting heads: The pure water jet cannot cut hard materials like metal and ceramics. That's the reason of adding abrasive particles to the pure water jet. An additional mixing head (cutting head) is necessary to feed the abrasive to the water jet and to mix both to a jet. The abrasive water jet (AWJ) can be created by using the injection principle. The feeding of the high pressure water is done by a special high pressure tube. This high pressure tube carries the cutting head. The water jet nozzle creates the pure water jet. The diameters of these pure water jet nozzles used for the abrasive water jet applications are between 0,15 - 0,4 mm. The quality of water influences the lifetime (up to 200 hours) of the nozzles. The abrasive particles are fed by pneumatic hose into the cutting head. The abrasive particles are carried by air which is sucked in by the water jet. The particles are accelerated up to 500 m/s by the water jet in the focus tube. The length and the diameter of the focus tube depends on the diameter of the water jet nozzle. The diameter of the focus tube can be between 0,8 - 1,5 mm. The length of the focus tube must be between 40 to 100 mm to obtain an optimal acceleration of the abrasive particles.

The cutting head consists of an upper and a lower part. By using the alignment screws, it is possible to align the centre line of the focus with the centre line of the water jet nozzle. This is very important, because the water jet must be able to pass the focus tube without any obstacles. If the water jet contacts the focus tube, the wear of the focus tube will increase. The focus tube consists of special hard metal. It was possible to improve the wear resistance of focus tube materials during the last years. This was very important to improve the quality and the reliability of the cuts. The lifetime of commercial focus tubes is between 50 and 100 hours. The pure water jet causes a low pressure in the cutting head by passing the mixing chamber and the focus tube. The low pressure sucks in a mixture of air and abrasive particles. Water, air and abrasive particles are mixed during passing the focus tube and leave the cutting head as an abrasive water jet.

Cutting results: The top of the kerf, the parallelism of the edges, the topography of the edge cut and the burr are decisive for cutting results. Effects of turbulences are the reason that some abrasive particles leave the abrasive water jet after the focus tube. These particles have less energy but cause a slight curving of the cutting edge**.** The radius is influenced by the stand-off distance of the cutting head. By increasing the stand-off distance, the radius increases as well. This effect can be observed only by cutting in air, not by cutting under water.

The cut kerf has a smooth surface up to the half of the depth of the kerf and a high parallelism of the edges. The width decreases in this region of the kerf between 0,1 - 9,2 mm. In the lower part of the kerf there is an increasing roughness and the surface shows a lot of striation marks. The kerf is no longer a line. This effect becomes more and more visible by a bad alignment of the nozzles. The cutting speed has a great influence on the quality of the edge of cut. There are similar rules for the quality of the edge of cut as for the application of pure water jets.

The edge of cut shows very deep striations for separation cuts (maximum cutting speed). The lower part of the edge of cut shows a high roughness and a high waviness. Generally, a quality of cut can be obtained by half of the maximum cutting speed. The cut edge shows less striations and only a slight waviness that increases to the bottom of the kerf. This effect can be observed by all materials in a similar way. The distinction between separation cut and quality cut is decisive on the roughness on the cut edge. Furthermore, it is important to distinguish between the roughness at the top and at the bottom of the edge cut. Up to now there were no thermal stresses observed. There were no internal stresses found that may be caused by small deformations (hardening) of the micro cutting process. This is the great difference between abrasive water jet cutting and all the other thermal and mechanical cutting technologies.

This advantage enables to cut materials and work pieces that need a finishing process (annealing treatment or burr removing) if they were cut by other cutting technologies. The design of the nozzle is very easy. There is an orifice jewel, which is fixed by an orifice mount. Nozzles produced by different companies have different geometries of the Sapphire plate and a different design of the fixing. The life time of nozzles depends on the quality of water (erosion) and the amount of switch on and off with pneumatically or with electrical valves. In Fig. 1 typical example of cutting head is demonstrated.

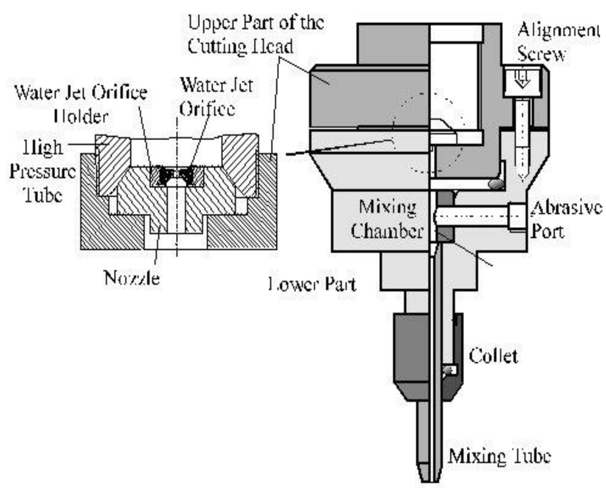


Fig. 1 Cutting Head (Injection principle)

Abrasive: The most common abrasive used in waterjet cutting is garnet. It is supplied from various sources. GMA 80 which is 150–300 µm mesh is from Australia – Garnet Mines [57]. GMA 80 cuts most materials with a good surface finish and processing time. Other mesh sizes and suppliers can be used. A finer mesh size such as 120 mesh (100–200 µm) produces a smoother cut surface [58] but the cutting time is increased than if a coarser grade is used [58]. If a coarser grade such as 60 mesh (200–400 µm) is used, a rougher cut surface finish is achieved but the cutting speed is increased, decreasing the cutting time [58]. The choice of mesh size is also dependant on the orifice and nozzle used. The abrasive flow rate is dependent on how the abrasive mixes with the water and how the abrasive is drawn into the mixing chamber. Nozzle blockages can result if the abrasive flow rate is too high, the particle size too large or large particles in the distribution or in some cases if the abrasive is too fine and it does not flow properly [59]. Vacuum assist can be added to help the abrasive flow too. For each setting there is an optimum abrasive flow rate above which increasing or decreasing the prices for abrasive varies from 15 cents per pound to 40 cents per pound, depending on the quality of the abrasive, and where you buy it. Abrasive is one of the biggest operating costs associated with running the machine. If you want maximum cutting speed, then you can choose a coarser abrasive, such as 60 mesh or 80 mesh. If you want smoother surface finish, then choose a finer abrasive such as 100, 120, or 150 mesh. The 80 mesh abrasive is very popular, and in high demand. A waterjet will use from about 0.25 pound (0.1 kg) per minute to 2.0 pounds (1 kg) per minute depending on the pump and nozzle you are using. The typical usage is about one pound (0.45 kg) per minute. The flow rate of abrasive will generally be constant for a given setup. The overwhelming choice for most waterjets is garnet abrasive.

3 ADVANTAGES AND APPLICATION OF AWJM

One of the biggest advantages is water jet's inherent cold cutting quality. This allows materials to be cut that would be burned, melted, or cracked by other cutting methods. Some thermal processes cause surface hardening, warping and emission of hazardous gasses. In contrast, materials cut with water jet machines undergo no thermal stress, eliminating such undesirable results. Some advantages of water jet machining are:

- Cold cutting – no heat affected zones, no hardening
- Omni-directional cutting – ability to cut in any direction
- Perforates most materials without starting holes
- Cuts virtually any material
- Net-shape or near-net-shape parts (no secondary processing required in many applications)
- Minimal fixture required
- Environmentally friendly
- Reduces dust and hazardous gases
- Does not workload material – stress-free cutting
- Flexible machine integration
- Saves raw materials (small cutting kerf width, nesting capabilities)
- Faster than many conventional cutting tools
- There is non-thermal removal of the material
- The use of high pressure water jets avoids the creation of chemical or toxic products.
- The narrow cutting curves enables an optimal use of material utilization by using CNC-controlled flexible production systems.
- High pressure water jets can generally be used for cutting several materials with different physical and chemical properties.
- High pressure water jets can cut in all directions and are especially useful for cutting designs with small radius with a minimum between 0,05 - 0,1 mm.
- During the cutting process the removed material is carried out of the cutting curve by the water jet. Therefore, the cutting process produces no dust and no fumes, which is very important for cutting unhealthy materials.
- It is possible to cut with other fluids like oil or liquid chocolate.

This opens the door to a variety of waterjet applications across different industries including Glass, Stone, Metals to Aerospace and Textiles. Another major advantage of water jet cutting is waterjet's ability to cut fiber-reinforced materials, reflective materials, uneven surfaces and stacked layers of different materials. Since the mechanical processes take place on a microscopic level, the contents and surface finish of the material are not critical factors. Despite the high kinetic energy in water jet cutting during the working of a high pressure waterjet cutting machine, part deformation is avoided and high cutting accuracy is achieved without leaving any frayed edges or burrs.

This produces excellent edge quality, which in many cases eliminates the need for secondary finishing processes. Waterjet cutting is especially advantageous in cutting complex shapes. Materials can be cut into almost any shape. Sharp corners, bevels, pierce holes, and shapes with minimal inner radii are all possible. Stacking, nesting and tabbing optimizes material and can significantly reduce cutting times. Waterjet cutting is particularly "friendly" in regard to the environment. Normally, the process is clean and does not create grindings, chips, or hazardous gases. Cutting oils or emulsions are not needed. In today's world of high-priced raw material and limited resources, waterjet's small kerf, or cut width, and part-on-part nesting capabilities optimizes material use, increasing cost-effectiveness. Using pure water, it is possible to cut textiles, elastomers, thin plastics, food products and many other products. These materials can be cut at speeds of several hundred feet per minute.

The most common application of the abrasive waterjet is cutting. There are numerous publications and investigations in this field covering all areas of the technology. A whole range of materials and thicknesses can be cut with good cut quality and little taper. Cutting speeds typically well in excess of 2 mm/s (120 mm/min or 7.2 m/hr) are commonly used in industry, however, for thicker and harder material this will drop to 0.1 mm/s (6 mm/min or 0.36 m/hr) or less. The process at this speed has to be carefully assessed as to whether it is economically viable. The cutting speed also depends on the surface finish required (rough cut or good quality cut), the pump pressure and nozzle set up (size of nozzle and size of orifice used) as well as the abrasive flow rate. Other factors such as the angle of jet attack, the standoff distance between the material surface and the nozzle and the actual material properties will also influence the cut and cut quality achieved [57].

There are optimum cutting speeds for each material. As a rough guide, glass cuts twice as fast as aluminum and titanium cuts at half the speed as it would take to cut aluminum. Nickel and stainless steel tend to cut a bit slower than titanium, about 60% slower than aluminum [58]. For example, if the glass was cut at 2 mm/s, aluminum would be in the order of 1 mm/s, titanium 0.5 mm/s and nickel and stainless steel 0.4 mm/s [59]. The effect of thickness on cutting speed is that increasing the thickness decreases the cutting speed. This is not quite a linear decrease. A material with a thickness of 12.7 mm would cut at a cutting speed half that required to cut a thickness 6.35 mm (half the thickness). However, the cutting speed of a material with a thickness of approximately 25.4 mm would be expected to be cut at a speed of 1/5 of the cutting speed that would be required to cut it if the material has a thickness of 6.35 mm (1/4 of the thickness [59].

Recently, the waterjet has found significant demand in the composite industry where it is used to cut components for the aircraft fuselage [58]. In some cases, where the fuselage itself is made from composite material, the waterjet can be used to cut out the windows. Another example of the use of waterjet technology is in the cutting of car carpets. The application of abrasive waterjets in drilling is increasing and waterjets are commonly used to drill a wide range of components with varying sizes of holes. Holes in difficult to machine materials such as ceramics and metal matrix composite materials are of particular interest since these are difficult to machine with other methods. Another application of waterjet technology is surface preparation, cleaning, coating removal. Waterjet forming is in its infancy and results from placing the waterjet over a surface in a specific pattern to generate the form required. The waterjet process can machine almost any material. The nozzle size used in normal waterjet applications is typically 1 mm, so, hole sizes greater than this can be achieved. Smaller hole sizes require a smaller nozzle diameter (and orifice). Nozzles of 0.5 mm diameter are commonly available but smaller than that they have to be specially ordered. Also, finer abrasive sizes (120 mesh) are commonly used to avoid any blockage of the nozzle. No matter what the material, metal, stone, glass, plastic, composite, wood, textile, and all others such as fish and beef cutting. The waterjet cutting heads work with all flow. In Fig. 2 typical examples parts machined by AWJM is shown.

Fig. 2 Examples parts machined by AWJM

Sadegh amalnik and Mcguegh [60] develop an expert system for manufacturability evaluation of electrochemical machining. Sadegh amalnik et al also developed and intelligent system for manufacturability evaluation for electrochemical spark machining [61]. In this research an Expert System Approach is used for manufacturability evaluation of abrasive waterjet machining. This paper addresses the concept of optimization of abrasive waterjet machining process by developing an expert system in computer based concurrent engineering environment. The expert system links with feature library.

The design specification is acquired through a feature based approach. The exert system links with material data base which holds attributes of materials. It also links with abrasive waterjet machining data base which hold attributes of 5 types of abrasive waterjet machining, expert system also links with abrasive waterjet machine data base which hold abrasive waterjet machine parameters. For each design feature, expert system provides information needed for design and manufacturing optimization. The expert system can be used as an advisory system for designers and manufacturing engineers. It can be used as a teaching program for new abrasive waterjet operators in computer based concurrent engineering environment by stimulated emission due to the incident photons of high energy. figure1 shows schematic of abrasive waterjet machining system. Schematic diagram of abrasive waterjet machining is demonstrated in Fig. 3.

4 EXPERT SYSTEM FOR ABRASIVE WATERJET MACHINING

An expert system is an interactive intelligent program with an expert-like performance for solving a particular type of problem using knowledge base, inference engine and user interface. In this paper the following step has been used:

1. An expert system for abrasive waterjet machining has been developed in a computer based concurrent engineering environment. The third version of an expert system shell (NEXPERT), based on object-oriented techniques (OOT) is used. A Hewlett

Packard (HP) workstation was used in development of the expert system. A geometric specification of design feature, and material type of the workpiece and its thickness and hardness is sent for manufacturability evaluation at the various stages of design. Within the manufacturability procedure, the machining time and cost of producing part, is estimated. The labour and depreciation cost of abrasive waterjet machining for each selected design feature specification, is estimated. Also various machining parameters are estimated.

2. The material specification is described in terms of its thickness, width and its hardness etc. The attributes of different material types for abrasive waterjet machining, and different type of abrasive waterjet machine are stored in working memory or data-bases.
3. The system expert can retrieve information from working memory and advise the designer on the appropriate choice of material, for workpiece, and type of machine.
4. The expert system also contains information related to good practice rules for abrasive waterjet machining process capabilities, and constraints.
5. For the present expert system, knowledge has been gathered from literature and talking with expert and experimental results on abrasive waterjet machining.
6. For each selected design feature undergoing evaluation for its manufacturability by abrasive waterjet machining, the cost of the machine cycle is estimated from those costs for abrasive waterjet machine depreciation, labour, and machining cost.
7. Machine cycle time is also a key factor, which depends for example on setting-up of abrasive waterjet machining loading and unloading of work-piece, inspection of component, and general maintenance.
8. Assessment of the manufacturability of a workpiece material, usually from machining cycle time and cost, is established automatically by the expert system.
9. This expert system can advise on the manufacturing of each work piece material. From this information, the process variables can be selected that best balances between the required quality against efficiency of manufacturing are achieved.

5 ARCHITECTURE OF EXPERT SYSTEM FOR AWJM

The expert system contains expertise gathered from both experiment and general knowledge about abrasive waterjet machining that can be provided to designers and manufacturing engineers. A flow chart of the expert system contains the following modules:

1. Material (workpiece) database: The material (workpiece) database contains 10 different material types for work-piece which interactively are acquired by the expert system. Each of which can be produced by abrasive waterjet machine. Material selection is an important stage and a complicated one that is made early in the design process. The direct material cost frequently forms more than 50 per cent of the total product cost [20]. In order to select a material, the system prompts the user to choose between two options for the material selection. The first option is that the user selects to specify the material based on his own criteria. The second one is that the system executes Cambridge Material Selection (CMS) software [55]. CMS is a computer package consisting of a database, a management system and a graphical user interface. The database contains quantitative and qualitative data for a wide range of engineering material: metals, polymers, ceramics, composites and natural materials. With CMS, the most appropriate material will be determined on the basis of previous input of product concepts and requirements. The properties of the candidate material are stored as a data file. Architecture of material selection/costing module is demonstrated in figure 4. A database is a group of cross-referenced data files. These contain all the necessary information for an application. There are four approaches to construct a database, namely the hierarchical, the network, the object-oriented and the relational approaches. Material selection/costing module proposed system was developed using the relational database approach which in turn comprised permanent (static) and temporary (dynamic) databases. The permanent database, includes laser beam machine tools and a feature specification database. The databases in the system consist of four separate groups of databases: feature database, material database, machine database, machine parameters databases.

2. Abrasive waterjet machine database: Information is contained on five different machine type of abrasive waterjet machines and their capital cost and machine parameters.

3. Machining cycle time and cost module: The knowledge base provides estimates of cycle time based on the selected material type, and selected design feature and waterjet process conditions such as on-time, off-time, current. In figure 3 Schematic diagram of abrasive waterjet machining is demonstrated.

4. Manufacturability evaluation: The manufacturability is assessed by consideration of the work piece specification, the abrasive waterjet production rate, efficiency and its effectiveness of the machine used in their production.

5. Production rules knowledge based representation

Knowledge and facts about a problem domain can be represented as a rule in the form *If* Premises *Then* conclusion.

In Fig. 5 Architecture of expert system for abrasive waterjet machining is demonstrated.

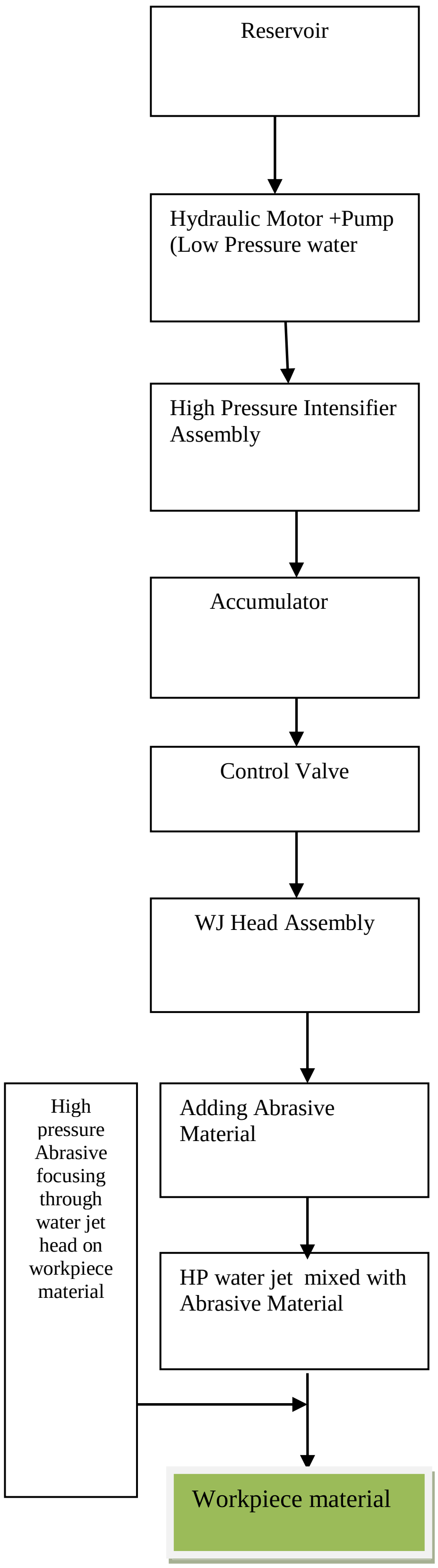


Fig. 3 Schematic diagram of abrasive waterjet machining

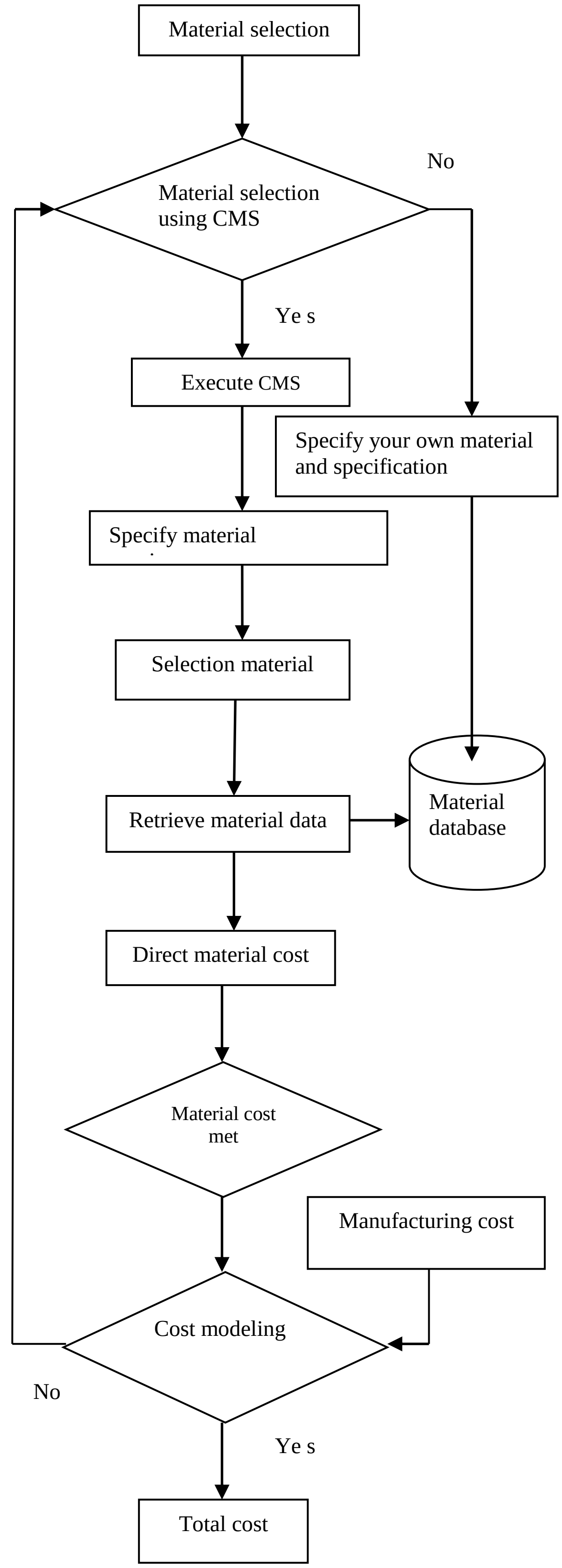


Fig. 4 The material selection/costing module

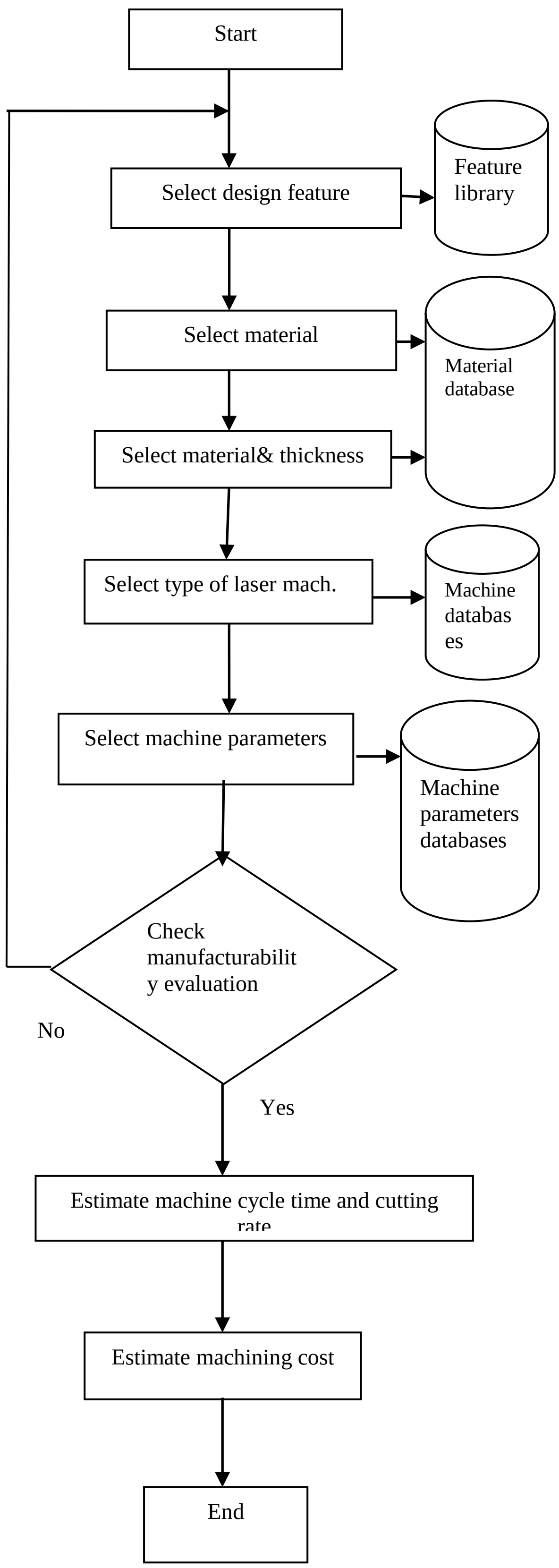


Fig. 5 Architecture of expert system for AWJM

6 EXPERIMENTAL VERIFICATION AND VALIDITY OF EXPERT SYSTEM FOR AWJM

The expert system for abrasive waterjet machining described above was compared with experimental one. Results are presented in Table 1. Table 2 Shows expert system results for different design feature and different material. These experiments have been carried out on abrasive waterjet machining. Table 1 demonstrated results of abrasive waterjet machining of cubic hole making and cutting slab with 200 mm width & 6.35 mm thickness for different material.

7 CONCLUSION

Abrasive waterjet machining (AWJM) is a nontraditional machining. Some advantages of AWJM are lack of thermal damage, low tool wear, small cutting forces and high productivity as compare to other conventional and non-conventional process. The most significant process parameters are transverse speed, standoff distance, abrasive water pressure and mass flow rate. The waterjet is a tool and can be used in many applications such as cutting, drilling, milling, cleaning, forming and coating removal.

The process can be used with or without the addition of abrasive media and new applications are being continuously found. In this research an expert system was developed for abrasive waterjet machining. The expert system was used to optimize AWJM. The design specification was acquired through a feature-based approach. The expert system links with feature base library. The expert system is linked with material database which holds attributes of more than 20 type of materials. It is also linked with abrasive data base which hold attributes of 8 types of abrasive, and also 4 type and size of machine. Expert system was also linked with machine database which hold machine parameters.

For each design feature, the expert system provided information needed for optimization of design and manufacturing. The expert system was used as an advisory system for optimization of design and manufacturing, because in expert system, optimum parameters were selected. For each design feature, the expert system provided information such as machining cycle time and cost and cutting rate in less than 30 seconds for different design hole and cutting of different materials such as Glass, Composite, Aluminum, Titanium, Nickel and Stainless Steel. By changing machine parameters, one could optimize machining cycle time and cost and cutting rate. Comparison results of the expert system and experimental CNC Abrasive waterjet results for different design feature showed in table 1 that machining time and cost of expert system is 10% less than experimental.

8 APPENDIX

Table 1 Comparison of expert system results with CNC Abrasive waterjet results for different material and for cubic hole making and slab cutting, nuzzle is diamond with diameter of 0.5mm and brasive mesh of 100. Machining parameters are: Operating pressure 120 MPa, Abrasive concentration 10 (wt.%), Standoff distance 3mm for all workpiece materials

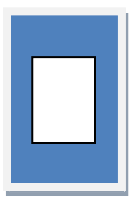
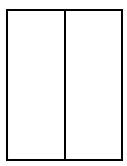
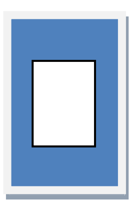
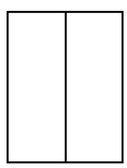
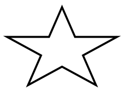
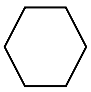
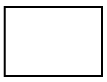
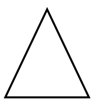
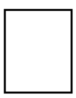
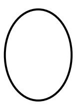
Procedure	Design Feature Type	Work piece material for cutting slab with 125.6 mm width	Work piece material type	Type of abrasive & Size of mesh	Cutting rate mm/s	Machining time (min)	Machining cost ($US)
Experimental results AWJM (Abrasive waterjet machining)	Cubic hole with 50 mm edge & 6.35 mm thickness 	slab with 200 mm width &6.35 mm thickness 	Glass	100	122.4	1.63	0.085
			Composite	100	102.6	1.95	0.097
			Aluminium	100	60.0	3.33	0.166
			Titanium	100	30.0	6.66	0.333
			Nickel	100	26.4	7.57	0.378
			Stainless steel	100	26.4	7.57	0.378
Expert System results for (AWJM) (Abrasive waterjet machining)	Cubic hole with 50mm edge & 6.35 mm Thickness 	slab with200 mm width &6.35 mm thickness 	Glass	100	132	1.51	0.075
			Composite	100	109.8	1.82	0.091
			Aluminium	100	66	3.03	0.152
			Titanium	100	33	6.06	0.303
			Nickel	100	28.8	6.95	0.347
			Stainless steel	100	28.8	6.95	0.347
			Stainless steel	100	28.8	6.95	0.347

Table 2 Expert system results for different design feature and different material for abrasive waterjet machining. Machining parameters are: Operating pressure 120 MPa, Abrasive concentration 10 (wt.%), Standoff distance 3mm for all work piece materials. Material thickness is 12.7 mm for all material

{PRIVATE} Design feature shape	Design feature type	Feature description (mm)	Material type	abrasive type & Size of mesh	Cutting rate (mm/min)	AWJ machining time (min)	AWJ Machining cost US $
	Star hole with 10 edge	edge size 100 mm	Nickel	100	12	83.4	4.2
	Hexagonal hole	edge 100 mm	Stainless Steel	100	12	50	2.5
	Rectangular hole	width 100, length 150	Aluminum	100	30	16.7	0. 8
	Triangular hole	Edge 100 mm	Composite	100	50	11.25	0. 56
	Cubic hole	edge 100mm	Titanium	100	15	26.7	1.3
	Circular hole	diameter 100 mm	Glass	100	60	13	0. 6

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