Intelligent Knowledge Based System Approach for Optimization of Design and Manufacturing for Abrasive Water Jet Machining

Morteza Sadegh Amalnik[1*]
[1]Department of Mechanical Engineering, University of Qom, I. R. Iran
[*]Email of Corresponding Author: sadeghamalnik@yahoo.com
Received: August 19, 2015; Accepted: October 27, 2015

Abstract
A water jet machining is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. This paper addresses the concept of the Intelligent knowledge base system (IKBS) for optimization of product design and manufacturing process for water jet machining in computer based concurrent engineering environment. The I KBS links with feature library. The design specification is acquired through a feature based approach. The IKBS links with material data base 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. IKBS is also links with machine data base which hold machine parameters. For each design feature, IKBS provides information needed for design and manufacturing optimization. The IKBS can be used as an advisory system for designers and manufacturing engineers. It can be used as a teaching program for new water jet operators in computer based concurrent engineering environment.

Keywords
Water jet machining, Abrasive, Intelligent Knowledge Base System

1. Introduction

A water jet machining is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The term abrasive jet refers specifically to the use of a mixture of water and abrasive to cut hard materials such as metal or granite, while the terms pure water jet and water-only cutting refer to water jet cutting without the use of added abrasives, often used for softer materials such as wood or rubber[1]. While using high-pressure water for erosion dates back as far as the mid-1800s with hydraulic mining, it was not until the 1930s that narrow jets of water started to appear as an industrial cutting device. Water jet technology evolved in the post-war era as researchers around the world searched for new methods of efficient cutting systems. In 1956, Carl Johnson of Durox International in Luxembourg developed a method for cutting plastic shapes using a thin stream high-pressure water jet, but those materials, like paper, were soft materials. 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 [1]. Water jet technology is one of the fastest growing machining processes. It is environmentally friendly, can machine almost any material [2, 3] and can cut metal to depths of over 100 mm [2, 4] It is used in a wide range of industries from automotive and aerospace to medical and the food industries [4, 6]. Current applications include stripping and cutting of fish [4-6], cutting of car carpets [7], removal of coatings from engine components[8-11]to cutting of composite fuselages for aircraft construction [12] The impact of the water alone is enough to machine a material, however, with the addition of abrasive, the material removal rate in the process is several orders of magnitude higher [5]. The technology and applications of water jet machining has been investigated since the early 1960s. There are established reference sources such as [2, 5] which are essential reading and give a deep insight into this technology. There are also recognized authorities in various aspects of water jet technology, for instance, [12-14], for machining, materials behavior during machining, characteristics and quality of surface after water jet treatment [3], Louis for cleaning, machining, precise cutting, abrasives, surface quality, medical applications [15] and Momber for wear of materials treated by water jets, erosion of ductile materials[15, 16]. Recent developments have seen the components of the water jet 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 [17-22]. 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 [23, 24]. Head and nozzle design has led to excellent systems being available with minimal maintenance and accurate performance. Figure 1 shows the detail of a typical water jet head in this case used for cutting.

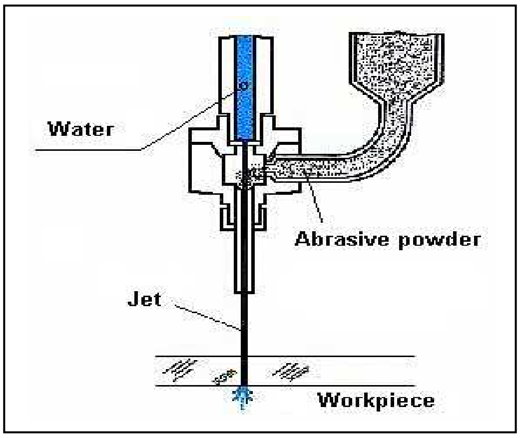


Figure1. A typical water jet head

The water is accelerated through an orifice. This can be ruby, sapphire (usually for water only applications) or diamond with a hole that is, for abrasive water jet machining typically between 0.2 and 0.4 mm in diameter. The water then passes into a chamber where the abrasive (if it is being used) is introduced. Finally, the water then passes into a nozzle which is made of hard tungsten carbide or boron carbide material and usually has a diameter of between 0.5 and 2 mm. For water only applications the chamber and the nozzle need not necessarily be used. The nozzle life is dependent on its design and the material it is made from. A normal nozzle (equivalent to a Roctec 100 from Boride Products) generally needs changing after around 100 h of processing time when used in typical applications, such as cutting with 80 mesh (150–300 μm) garnet [25]. A ruby orifice is commonly used in abrasive water jet machining and tends to last longer than the nozzle. Diamond orifices have the longest life time (3 times longer) but are significantly more expensive (5–10 times). More recently, for ease of use, the water jet manufacturers have introduced an integral diamond orifice and mixing chamber unit [20, 21]. This is more expensive but saves issues with alignment and is suitable for applications where repetitive work is being undertaken. Figure2 demonstrates components of a typical water jet machining. Figure 3 shows function of components of a typical water jet machining.

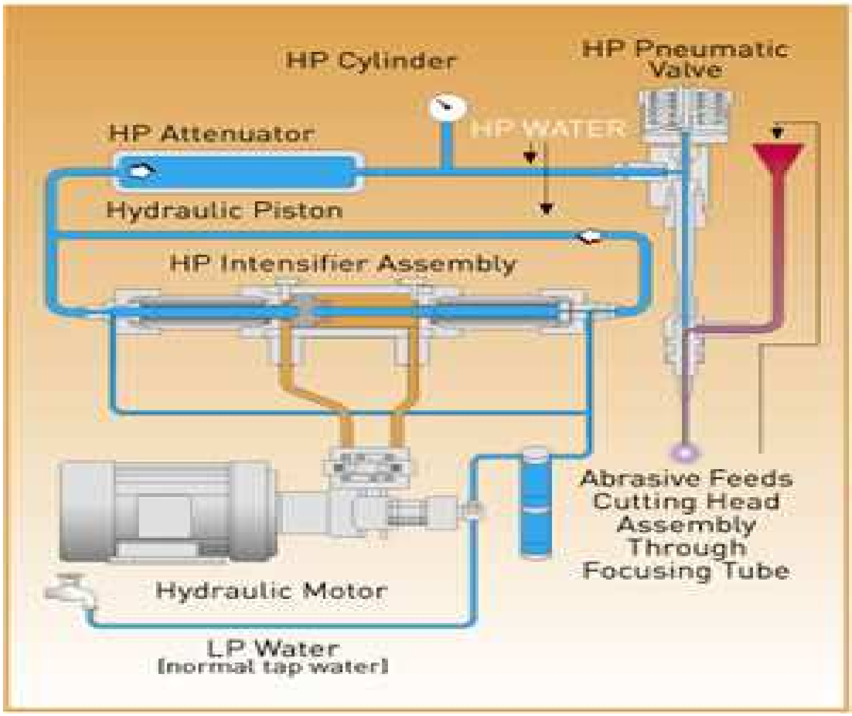


Figure2. Components of a typical water jet machining

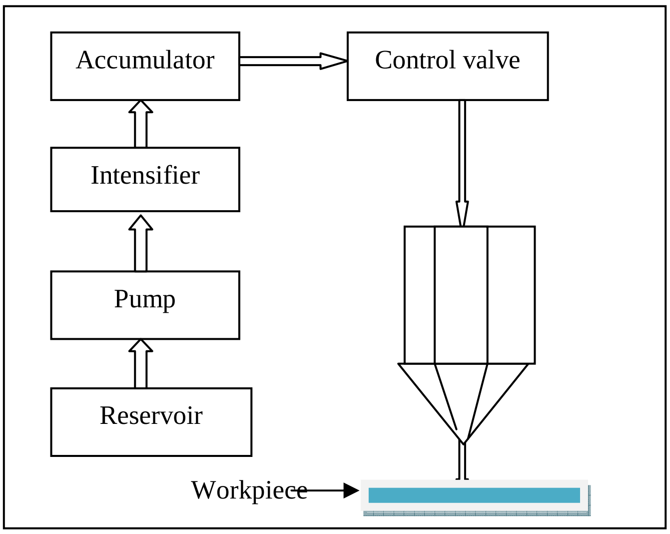


Figure3. Function of components of a typical water jet machining.

The most common abrasive used in water jet cutting is garnet. It is supplied from various sources and the work horse in the United Kingdom is GMA 80 which is 80 (150–300 μm) mesh (garnet from a source in Australia – Garnet Mines Australia, [25]. 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 [3, 24, 26] but the cutting time is increased than if a coarser grade is used [1, 26]. 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 [26, 3, 24]. Also, thicker materials can be cut. 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 [1, 5, 24]. Vacuum assist can be added to help the abrasive flow too [17, 18, 19]. Also, it does not necessarily follow that the higher the flow rate the better the cut. For each setting there is an optimum abrasive flow rate above which increasing or decreasing the abrasive flow only serves to roughen the cut rather than enhance it [3, 24]. Also, other garnet suppliers or materials can be used. The other garnet suppliers perform just as favorably as GMA. For some specific applications other sources may be preferable [25]. Issues to be borne in mind, aside from the physical characteristics of the garnet, are the quality and consistency of the garnet supply and the presence of contaminants, such as chlorine, or excessive iron content which could be an issue in some applications. There is currently no standard specification for industrial garnet used in water jet machining so specifications and conformities from the manufacturer or standards relating to blast process abrasive are applied. 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. One should pay the extra money for good abrasive, especially if you are new to this technology, as quality abrasive will result in quality products. 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. Consult the manufacturer of your nozzle for recommendations. The 80 mesh abrasive is very popular, and in high demand. Therefore, it is also the most expensive. If you go with a coarser or finer abrasive, then you can save some money. The trade-off is that you may not cut as well. One should look for an abrasive that is pure. An abrasive with impurities will affect your cutting performance. Softer impurities will lengthen your cutting time, while garnet with unusually hard bits in it, such as aluminum oxide, may cut marginally faster with a severe drop in nozzle life. Sharp abrasive particles cut better. Mined garnet is sharper than garnet from a beach, or alluvial garnet, that has been worn into round beads. A water jet 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 flow rate does not vary depending on what you are making (unless you turn abrasive flow off and use water-only cutting). An abrasive jet uses a mixture of water and abrasive to more effectively cut through materials. A pure water jet (one without abrasives) is effectively only for very soft materials, such as rubber or food products. Adding abrasive, however, greatly enhances the cutting capability and the abrasive water jet can cut through steel. The *type* of abrasive is important. The overwhelming choice for most water jets is garnet abrasive. Figure 4 shows different types of abrasive used in industries.

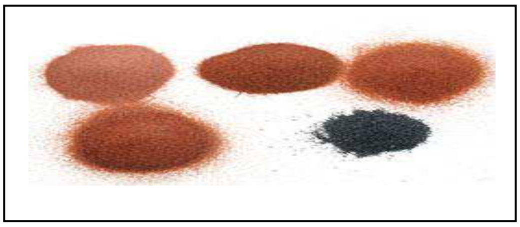


Figure4. Different types of garnet abrasive used in water jet cutting

Other abrasives ranging from broken glass (or glass beads for coating removal) to olivine and alumina have also been studied for abrasive water jet machining but garnet is still the most widely accepted [3, 26] used liquid nitrogen, instead of water, in a system that was similar to a water jet for cutting contaminated material in the nuclear industry. The system cuts with minimal contaminated waste producing only a dry dust as the bi-product. In the medical industry water soluble, pharmalogically safe, biocompatible abrasives such as disaccharides, sugar, alcohols, amino acids and salt have been used for cutting, for example α lactose monohydrate was used to cut chancellors bone [27].

2. The Application of Abresive Waterjet

The most common application of the abrasive water jet is cutting. There are numerous publications and investigations in this field covering all areas of the technology [3, 14, 28, 29, 30, 31]. A whole range of materials and thicknesses can be cut with good cut quality and little taper. Cutting speeds typically well in excess of 2mm/s (120mm/min or 7.2m/hr) are commonly used in industry, however, for thicker and harder material this will drop to 0.1mm/s (6mm/min or 0.36m/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 stand off distance between the material surface and the nozzle and the actual material properties will also influence the cut and cut quality achieved [3]. 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 [3]. Nickel and stainless steel tend to cut a bit slower than titanium, about 60% slower than aluminum [18]. For example, if the glass was cut at 2mm/s, aluminum would be in the order of 1mm/s, titanium 0.5mm/s and nickel and stainless steel 0.4mm/s [32, 33, 34, 35].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 12.7mm would cut at a cutting speed half that required to cut a thickness 6.35mm (half the thickness). However, the cutting speed of a material with a thickness of approximately 25.4mm 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 6.35mm (1/4 of the thickness [34]. When cutting thicker materials striations on the surface become particularly noticeable. The average roughness (R_a) of the areas without striations is around 3.2μm which is typical for a high quality metal surface cut using the water jet. Significant research has been conducted into the exact mechanisms behind this and the process has been modeled and studied using high speed cameras to understand it more fully. Various overviews of this are available but the recent publication by [5] presents a good comprehensive review of this area. What is of concern is that when this occurs, the cut surface quality decreases and striations start to form on the lower part of the cut. At some point this process becomes totally unstable with such a large lag that the surface quality is very poor and unacceptable for most applications so the cutting speed is too fast. Several studies have been conducted in and established a relationship between the kerf width and the gap size [36, 37] and high speed. There is almost no material that cannot be cut using the water jet, though care has to be taken with some materials to avoid shattering or delaminating [12]. Recently, the water jet has found significant demand in the composite industry where it is used to cut components for the aircraft fuselage [17, 18, 19] In some cases, where the fuselage itself is made from composite material, the water jet can be used to cut out the windows. Another example of the use of water jet technology is in the cutting of car carpets [7]. Water jets have also been used to cut tissues and fish so their versatility in modern day industry is expanding. Industry has found benefits from this technology to include increased productivity, faster cutting and high quality parts, flexibility to adapt designs and material changes, minimal kerf, raw material savings and reduced scrap, low operating costs, minimal force on the component, no thermal damage, net or near-net cutting with little or no hand finishing, reduced tooling costs, lighter, flexible tooling [17]. Comparisons of this technology with others such as Electro Discharge Machining (EDM) and Laser cutting have been made elsewhere [38, 39] however, these technologies tend to be complimentary rather than competitive.

The application of abrasive water jets in drilling is increasing and water jets 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. The requirement is similar to cutting in that the initial piercing operation has to be done with care on some materials. Trepanning of holes is common and the process is faster if the water jet is moving rather than stationary when initiating the hole. As with water jet and abrasive water jet cutting the depth and quality of hole required depends on the application and is process dependant. Holes can be drilled through multi-layered or coated materials without any problems. The hole can be tapered or not as required as well as angled. The water jet process can machine almost any material.. The nozzle size used in normal water jet 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 is available.

Water jet milling with or without abrasive is another application where over the next few years will see significant development. The depth of removal of a material can be controlled by the traverse speed (slower speeds give more depth of penetration), the water pressure (higher pressures result in higher penetration depths) and various other factors [13, 33, 40-43]. Material can be removed with or without abrasive and a sacrificial mask laid over the surface can be used if desired. Abrasive embedment can be an issue for some applications of this type of processing; however, there are ways to minimize it by using novel abrasives (e.g. liquid nitrogen) or water only systems. Various configurations for milling have been reported including water jet milled ribbed silicon carbide mirrors [44]. Figure5 Shows examples of parts machined by water jet.

Figure5. Examples parts machined by water jet

Another application of water jet technology is Surface preparation, cleaning, coating removal. Over the last decade turn-key systems have become readily available for stripping and cleaning of engine components or other materials [45-46]. Again, these can be water only or can involve some media such as glass beads. Applications include a water jet system to removes thermal protective coatings from the space shuttle's solid rocket boosters and stripping of paint and coatings from helicopter blades and ship hulls as well as water jet cleaning of engine seals at KLM in Holland [47].

3.Intelligent Knowledge Based System for Abrasive Water jet Machining (AWJM)

At present most procedures for estimation of machining time and cost and cutting rate and manufacturability evaluation are based on personal knowledge and judgment. The complexity of the process and interrelationship between its process variables means that designer and process planners have limited knowledge of Water jet machining. In planning they have to turn to the literature or experts. The information required by the former is often difficult to obtain. Moreover, the training of both designers and process planners is time-consuming and expensive. Consequently if the knowledge is not available from a reliable source, the water jet product development cycle time and cost increases, and both quality and productivity is likely to decrease. Intelligent Knowledge-based system (IKBS) provides a route to overcoming these problems. In this paper an intelligent knowledge-based system (IKBS) is developed to integrate design and manufacturing in computer based concurrent engineering environment for water jet machining. The knowledge-based is expressed in computer codes in the form of If-Then rules and can generate a series of questions. A mechanism is employed for using these rules to solve problems is called an inference engine. The IKBS can communicate with CAD data base and other computer software packages. The latest version of an expert system shell (NEXPERT) based on object oriented techniques is used. The output of the IKBS can be used by designers and manufacturing engineers, and new operator of water jet user. IKBS estimates machining time and cost. It retrieves all necessary information from databases and working memory for different design feature and different type of material in this paper. In this paper an IKBS for water jet machining has been developed in computer based concurrent engineering environment. The developed program is based on object oriented technique (OOT). The latest model Hewlett Packard (HP) workstation was used in development of IKBS. The system links with feature based design database. For each design feature, the system evaluates its manufacturability, machining cycle time and cost, and gives useful advice to designer for improving design in term of manufacturability and machining time and cost**,** cutting rate and etc. The system also gives some advice to manufacturing engineers for selection of optimum machining parameters. Inanition the system works as a teaching system for new manufacturing operators to train them how to work with water jet machine.

4. Architecture of IKBS for AWJM

The IKBS contains expertise gathered from both experiment and general knowledge about AWJM that can be provided to designers and manufacturing engineers. A flow chart of IKBS is presented in figure.6 from which the following modules are noted:

4.1 Design feature library

Number of type of parametric features are stored in feature library. Features such as circular hole, cubic hole, rectangular hole, fraction disc, star hole, etc. are stored in feature library.

4.2 Nozzle library

Attributes of five different nozzle with different size of diameter are stored in Nozzle library. Nozzle diameters such as 1mm, 0.75mm, 0.5mm, 0.4mm and 0.2mm are stored.

4.3 Material (work piece) database

The material (work piece) database contains different material types for work-piece which interactively acquired by the IKBS. Each of which can be cut and manufactured by AWJM machine.

4.4 Abrasive type and size

Properties of four different types and size of abrasive for water jet are stored in database, from which the expert system can deliver information on abrasive type and size.

4.5 WJM machine database

Characteristics of four different type of WJ machine and their capital cost.

4.6 Machining cycle time and cost module

The knowledge base provides estimates of cycle time and costs for each selected design feature based on the selected material type for wire tool, dielectric, and WEDM process conditions such as on-time, off-time, and current.

4.7 Manufacturability

The manufacturability is assessed by consideration of the work piece specification, the AWJM production rate, efficiency and its effectiveness of the machine used in their production.
Architecture of IKBS for water jet machining is shown in figure 6. Flow chart of IKBS is presented in Figure7.

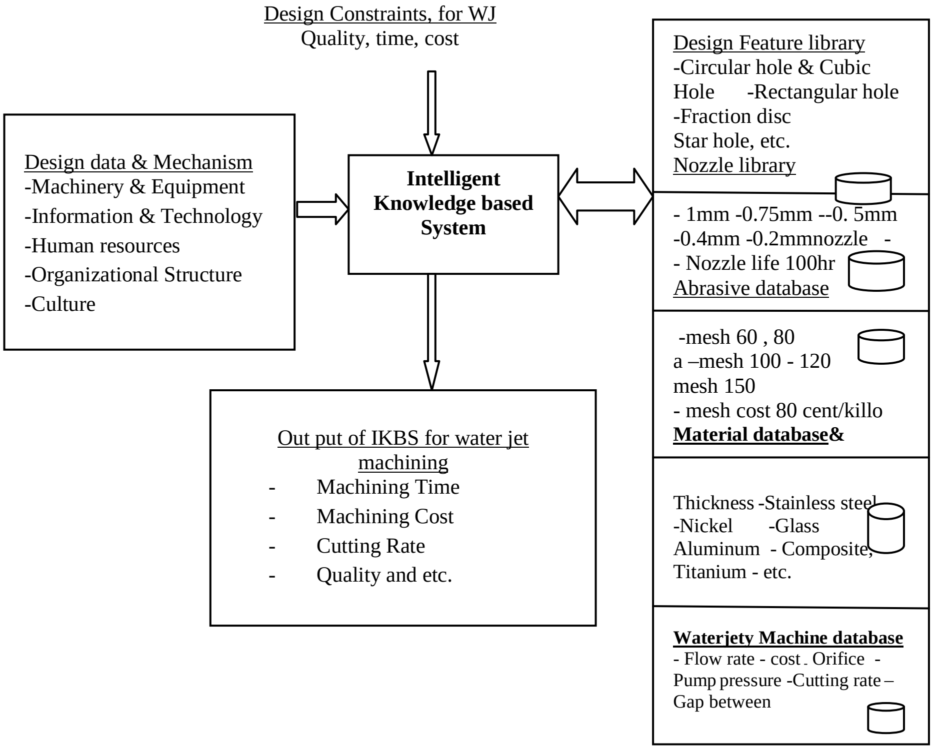


Figure6. Architecture of IKBS for water jet machining

5. Experimental verification

A schematic diagram of water jet machining (WJM) is used is presented in figure 1 and water jet apparatus is shown in figure.2. Function of components of the abrasive water jet machining is shown in Figure3. Different types of abrasive used in water jet cutting is shown in Figure4. In this experiment different material types and different feature type machined by abrasive water jet including ceramic, papers, carpets, glass, composite, nickel, titanium, aluminum, stainless steel. The results are presented in table1. Table1 shows machining time and machining cost and cutting rate for different design features with different type of material by CNC abrasive water jet. It also compares the results of machining time and cost and cutting rate for various type of design feature and cutting slap between IKBS and experimental one. The results show that by increasing material thickness or increasing material hardness, cutting rate decrease. It also shows that machining time and cost and cutting rate of IKBS is 10 present less than experimental, because optimum selecting machining parameters. The results of comparison between IKBS and experimental are presented in Figure 1, 8, 9 and 10. We compare CNC Abrasive water jet machining results for different material type and different design feature with the result of intelligent knowledgebase system and for hole making of and slab cutting, nuzzle is diamond with diameter of 0.5mm and abrasive mesh of 120. The work piece was fixed to minimize the over-cut. The abrasive water jets are used to drilling various holes according to design feature. The water is accelerated through an orifice. This can be ruby, sapphire (usually for water only) or diamond with a hole that is, for abrasive water jet machining typically between 0.2 mm and 0.5 mm in diameter. The water then passes into a chamber where the abrasive (if it is being used) is introduced.

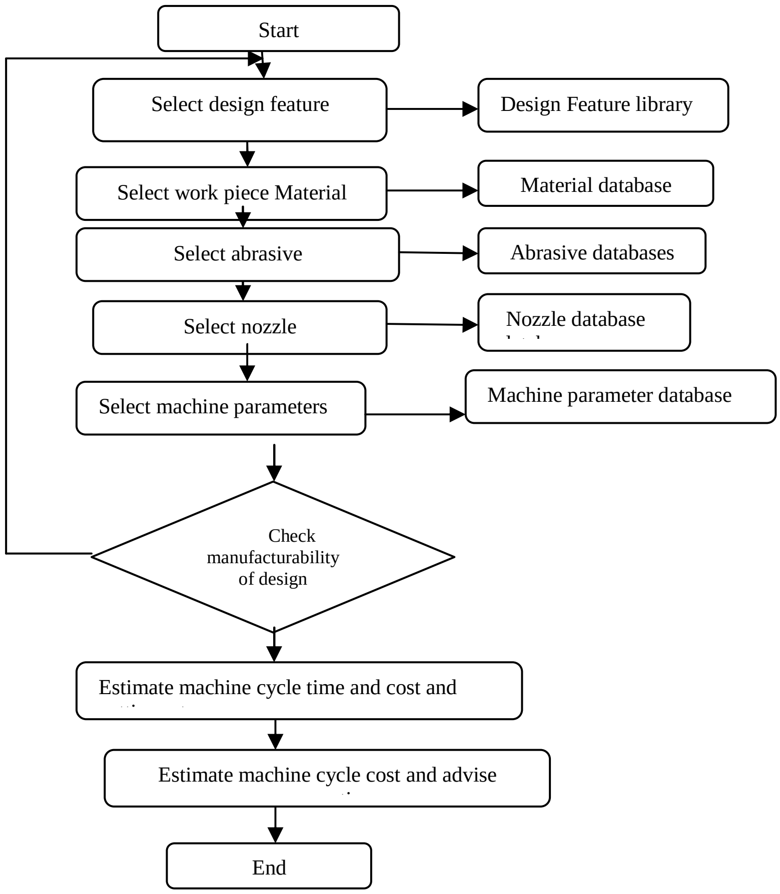


Figure7. Flowchart of IKBS is presented

6. Validation Results of the IKBS

As a result, from table 1 shows that estimation of expert system for machining time and cost for abrasive water jet hole making is 10 percent less and better than experimental.

Table1. Comparison of CNC abrasive water jet results for different material for hole and making and slab cutting, nuzzle is diamond with diameter of 0.5mm, abrasive mesh 120.

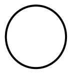
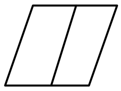
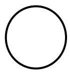
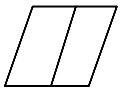
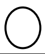
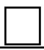
Procedure	**Design Feature Type**	**Work piece material for cutting slab with 125.6 mm width**	**Work piece material type**	**Type of abrasive & Size of mesh**	**Cutting rate mm/s**	**Machining time (min)**	**Machining cost ($US)**
Experimental Abrasive water jet machining	Circular hole with 40 mm diameter & 6.35 mm thickness 	slab with 125.6 mm width & 6.35 mm thickness 	Glass	120	1.83	1.14	0.057
			Composite	120	1.55	1.35	0.0675
			aluminium	120	0.91	2.3	0.115
			Titanium	120	0.455	4.60	0.138
			Nickel	120	0.4	5.75	0.288
			Stainless steel	120	0.4	5.75	0.288
Intelligent Knowledge based system for abrasive water jet machining (IKBSAWJ)	Circular hole with 40mm diameter & 6.35 mm Thickness 	slab with 125.6 mm width & 6.35 mm thickness 	Glass	120	2	1.05	0.052
			Composite	120	1.66	1.26	0.063
			aluminium	120	1	2.1	0.105
			Titanium	120	0.5	4.186	0.126
			Nickel	120	0.4	5.23	0.261
			Stainless steel	120	0.4	5.23	0.261

Table2. IKBS result of different design feature for different material for AWJ

Design feature shape	**Design feature type**	**Feature description (mm)**	**Material type**	**Material thickness (mm)**	**Cutting rate (mm/s)**	**AWJ machining time (min)**	**AWJ Machining cost US $**
	Circular hole	diameter 10 mm	Glass	12.7	1	0.5	0.025
	Triangular hole	Edge 10 mm	Composite	12.7	0.83	0.6	0.03
	Rectangular hole	width 10, length 15	Aluminum	12.7	0.5	1.6	0.08
	Cubic hole	width 10mm	Titanium	12.7	0.25	2.6	0.13
	Star hole with 10 edge	edge size 10 mm	Nickel	12.7	0.2	8.3	0.41
	Hexagonal hole	edge 10 mm	Stainless Steel	12.7	0.2	5	0.22

Also shows that estimation of IKBS for machining time and cost for cutting slap with wide 125.6 mm and depth of 6.35mm is equal with hole making with 40mm diameter and 6.35mm depth for experimental computer numerical control abrasive water jet. As a result, table 1 shows machining time and cost for hole making or cutting slap for different material for IKBS is 10 percent less than experimental. Table 1 also shows, for experimental or IKBS, machining time and cost for cutting slap of hole making for Glass material<Graphite < Aluminum < Titanium <Nickel < Stainless Steel Glass is less than other material in the table1 respectively. Figure 8. Shows comparison between IKBS cutting rate and experimental; Figure9. Shows comparison between IKBS machining time and experimental.

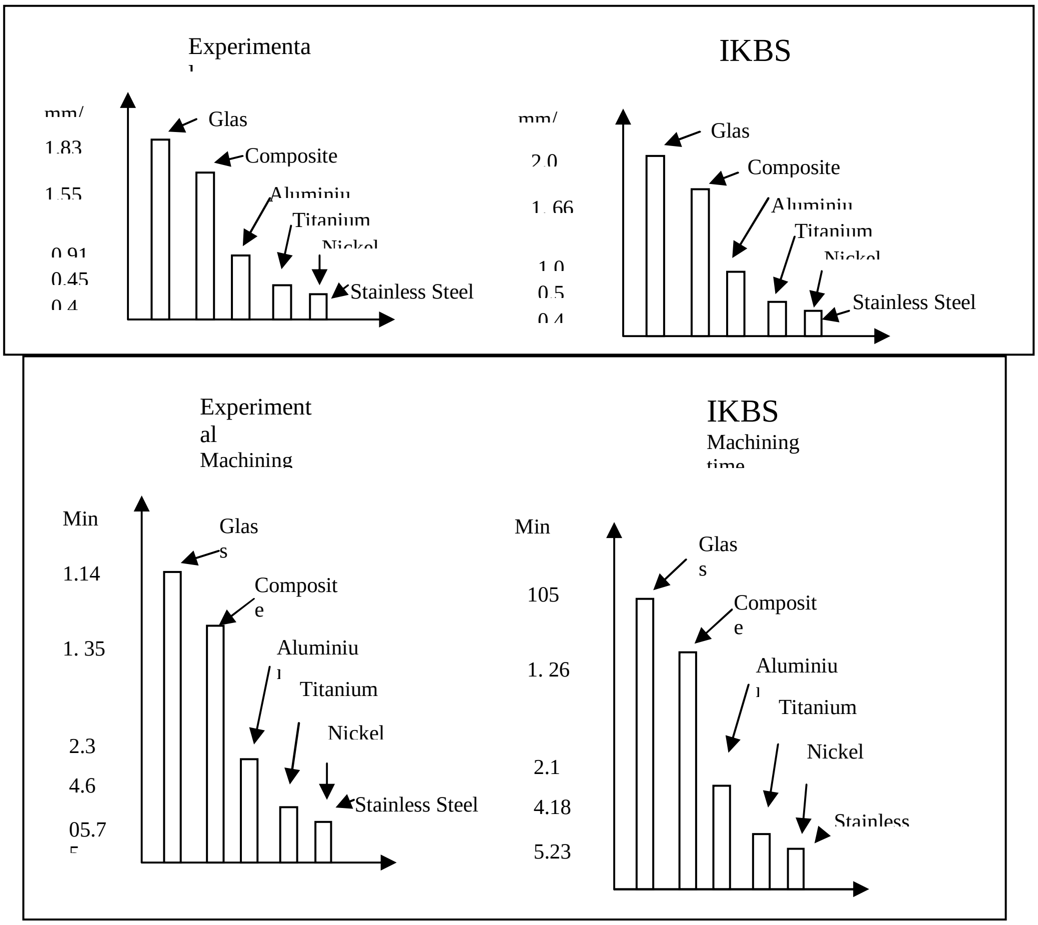


Figure 8. Comparison between IKBS cutting rate and experimental

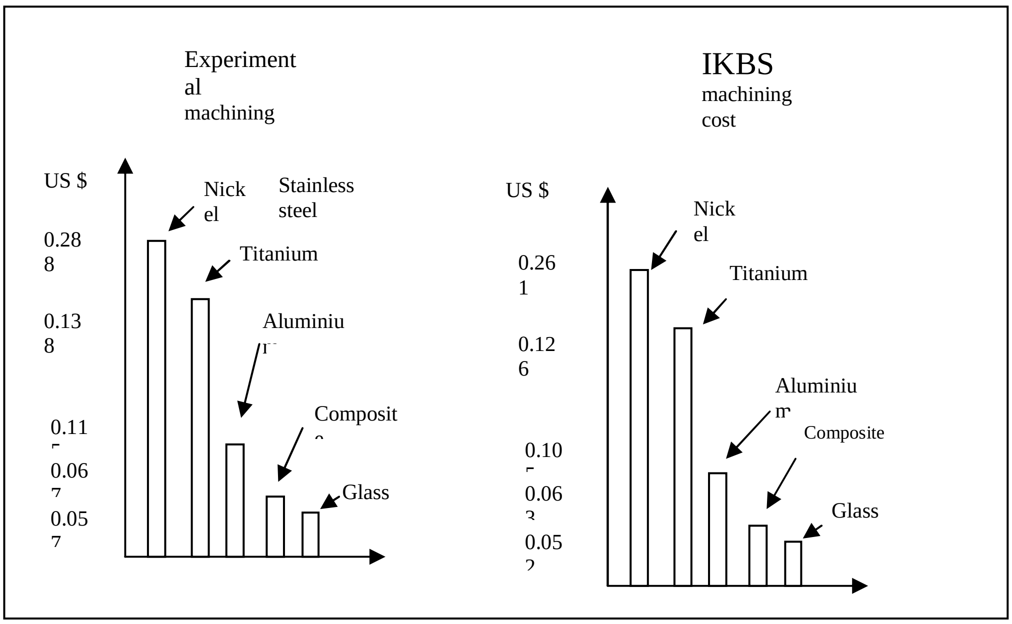


Figure 9. Comparison between IKBS machining time and experimental

After that, Composite has less machining time and cost. Cutting rate of hole making or cutting slab for IKBS is approximately 10 percent faster and better than experimental one. But cutting rate of hole making or slab cutting for Glass material>graphite> Aluminum> Titanium> Nickel > Stainless Steel material. IKBS for AWJ can be used by product designer to improve part or product. It also can be used by manufacturing engineers to select optimum machine parameters in concurrent engineering environment.

7. Conclusions

The water jet machining is a machining tool and can be used in applications such as cutting, drilling, milling, cleaning, forming and coating removal. It can machine almost any material and competes with other technologies since there is minimal force, no heat damage and it is an environmentally friendly process. The drive for flexibility, speed and harder to process materials has meant that the uptake of water jet technology in recent years has risen significantly. The process can be used with or without the addition of abrasive media and new applications are being continuously found. concept of abrasive water jet machining and its parameters were described. Architecture of intelligent knowledge base system (IKBS) for AWJM was demonstrated. The IKBS system described above was compared with experimental AWJM machine**.** Results were presented. Estimate machining time and cost, and cutting rate for different design hole or cutting work piece of different materials such as Glass, Composite, Aluminum, Titanium, Nickel and Stainless Steel in less than 30 seconds. Estimation of IKBS for machining time and cost for hole making or cutting work piece is 10 percent less than experimental one. Because in expert system, optimum parameters are selected. Estimation of IKBS for machining time and cost and cutting rate for different type of material were estimated.

8. References

[1] Anderson, J. 2006. Hypersonic and High-Temperature Gas Dynamics Second Edition. AIAA Education Series.

[2] Summers, D.A. 1995. Waterjetting Technology, E & FN Spon, London, England.

[3] Kovacevic, R., et al. 1997. State of the art of research and development in abrasive waterjet machining, J. Manuf. Sci. Eng., 119 , 776–785.

[4] Mines Barton, Barton high performance waterjet abrasives, 2008, http://barton.com/waterjet_abrassive.cfm

[5] Wang, J. 2003. Abrasive Waterjet Machining of Engineering Materials, Trans Tech Publications Ltd., Switzerland.

[6] Lyons loyd, F. L., Morrison, C.H. and Rustad, S.C. 1991. Apparatus and Method utilizing a waterjet for cutting frozen fish slabs into a plurality of individual portions. US Patent5, 031, 496.

[7] Assarsson, B. 1994. Robotized Waterjet Cutting, Industrial Robot, 21, 12–17.

[8] Blades, B. and Sohr, J. 1993. Water jet coating removal applications aircraft engines and beyond, 6th National Thermal Spray Conference Anaheim, CA, USA.

[9] Scrivani, A., Bardi, U., Ballerini, G., Bonacchi, D., Fantini, M., Groppetti, R., Ianelli, S. and Rizzi, G. 2000. Removal of Zirconia thermal barrier coatings and MCrAlY bond coatings from turbine blades: a comparison of methods on chemical strippi ng, waterjet and salt bath, Proc. of AMPET2000 Huntsville, AL, USA.

[10] Engine Year Book, 2002. Working under pressure, 108–111.

[11] Engine Year Book, 2002. Independent specialist engine repair survey, 140–147.

[12] Hashish, M. 2008. Abrasive-Waterjet Machining of Composites, WJTA Jet News, Saint Louis, MO, USA, 1–18.

[13] Hashish, M. 1994. Controlled-depth milling techniques using abrasive-waterjets. In: N.G. Allen, Editor, Jet Cutting Technology, Mechanical Engineering Publications Ltd., London, 449–461.

[14] Hashish, M. 1993. Comparative evaluation of abrasive liquid jet machining system, J. Eng. Ind., 115(1), 44–50.

[15] Momber, A.W. 2003. Hydroblasting and Coating of Steel Structures, Elsevier.

[16] Momber, A.W. and. Kovacevic, R. 1999. An engineering balance of high-speed abrasive water jet erosion, Proc. Inst. Mech. Eng. 213, 463–471.

[17] Flow, 2008a. (HyperJet Pump) http://www.flowcorp.com/waterjet-products.cfm?id=574.

[18] Flow, 2008b. (Vacuum assist) http://www.flowcorp.com/waterjet-products.cfm?id=137.

[19] Flow, 2008c. (Boeing) http://www.flowcorp.com/waterjet-resources.cfm?id=251

[20]KMT, 2008a.http://www.kmtgroup.com/opencms/en_UK/waterjet_systems/products/pro_serie/.

[21] KMT, 2008b. (Integrated Diamond Head) http://www.kmtwaterjet.com/ide.aspx

[22] World Pumps, 2009. High psi waterjet pump increases productivity. World Pumps, 508, 9.

[23] Manufacturing Talk, 2005. 10 head waterjet machine ups productivity by 50%. April, http://www.manufacturingtalk.com/news/waj/waj101.html.

[24] Chalmers, E. 2006. Achieve peak waterjet performance by optimising components.

[25] GMA, 2007. http://www.garnetsales.com/default.asp?id=s&custID=

[26] R.W. Agnew. 2001. Investigating the Effects of Abrasive Particle Size Using an Abrasive Waterjet. B.Eng. dissertation. School of Mechanical, Materials and Manufacturing, University of Nottingham, England.

[26] Schneider, R. and Kloster, S. 1996. Liquid nitrogen and water jet milling of energetic material production wastes, Proceedings of the Tri-Services Environmental Technology Workshop, Enhanced readiness Through Environmental Quality Technology Hershey, PA, USA.

[27] Schwieger, K., et al. 2004. Abrasive waterjet cutting as a new procedure for cutting cancellous bone—in vitro testing in comparison with the oscillating saw, J. Biomed. Mater. Res., 71B(2), 223–228.

[28] Arola, D. and Ramulu, M. 1993, Mechanism of material removal in abrasive waterjet machining of common aerospace materials, Proc. 7th American Water Jet Conference Seattle, USA, 43–64.

[29] Hashish, M. 1988. Visualization of the abrasive-waterjet cutting process, Eng. Mech., 159–169.

[30] Chen, F.L., Wang, J., Lemma, E. and Siores, E. 2003. Striation formation mechanisms on the jet cutting surface, J. Mater. Process. Technol., 141, 213–218.

[31] Henning, A., Westkamper, E. 2007. Dynamic analysis of the spatial-temporal behaviour of the cutting f ront in abrasive waterjet cutting. American WJTA Conference and Expo., Houston, Texas, 5-B.

[32] Hascalik, A., Caydas, U. and Gurun, H. 2007. Effect of traverse speed on abrasive waterjet machining of Ti–6Al–4V alloy, Mater. Design, 28 ,1953–1957.

[33] Fowler, G. 2003. Abrasive Water-jet: Controlled Depth Milling of Titanium Alloys. PhD Thesis. School of Mechanical, Manufacturing, Engineering and Management, University of Nottingham, UK.
[33] Accustream, Abrasive Waterjet Cutting. Applications and Capability, 2007. http://www.accustream.com/pdf /waterjet-cutting-white-papers.pdf
[34] Flow, 2002b. http://www.flowcorp.com/waterjet-applications.cfm?id=108.
[35] Orbanic, H. and Junkar, M. 2008. Analysis of striation formation mechanism in abrasive water jet cutting, 265, 821–830.
[36] Quality Waterjet Newsletter, 2008. http://www.qualjet.com/Newsletter/Newsletter-20081007.htm
[37] Louis, H. and Von, C.H. 2000. Cutting of hollow structures with abrasive water suspension jets, Proc. 15th International Conference on Jetting Technology Ronneby, Sweden, 59–67.
[38] Fedtech, 2008. http://www.fedtech.com/compare.html.
[39] Hann, J., Julian, A., Maier, C., Neff, R., Schneider, R., 2008. Making sense of metal cutting technologies.
[40] Etchells, P. 1997. Cutting head design lowers abrasive waterjet cutting costs, Aircraft Eng. Aerospace Technol., 69(2), 147–150.
[41] Fowler, G., Pashby, I.R. and Shipway, P.H. 2009. The effect of particle hardness and shape when abrasive water jet milling titanium alloy Ti6Al4V, 266 ,613–620.
[42] Ojmertz, K.M.C. 1993. Abrasive water jet milling: an experimental investigation. In: M. Hashish, Editor, Proc. 7th US Water Jet Conference, Water Jet Technology Association, St. Louis, USA, 777–791.
[43] Ojmertz, K.M.C. 1997. A study on Abrasive Water Jet Milling. Ph.D. Thesis. Chalmers University of Technology, Gotenborg, Sweden.
[44] K.R. Webb, Water jet milled ribbed silicon carbide mirrors. US Patent 20,070,161,340., 2007
[45] Progressive Technologies, 2008.
[46] Roesler, 2008. http://typo3.rosler.com/aerospace-english/water-jet-cleaning.html.P.H. Shipway and J.A Folkes,. Mechanisms of coating removal with waterjets, 19th International Conference on Water Jetting, BHR Group, Nottingham, England.
[47] Shotpeener, 2006. Sure waterjet can clean, but can it peen, 4–10, http://www.shotpeener.com/library/pdf/2006001.pdf.