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A Review: Challenges Associated with advance material machinability using AWJM

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Abstract: Machinability is a critical engineering aspect, evolving from basic techniques to advanced computational methods for precision machining, thereby enhancing material performance and productivity. Titanium and steel, vital to military, biomedical, and aerospace industries, require effective shaping techniques that preserve their properties. Titanium's high strength-to-weight ratio and resistance to heat and corrosion, along with stainless steel ease of welding and machining, make them essential materials. Abrasive Water Jet Machining (AWJM) stands out for its superior deformation and fabrication capabilities across materials like plastics, ceramics, polymers, and metals. This study focuses on key output factors such as flatness, straightness, depth of cut, Material Removal Rate (MRR), surface roughness, kerf width, and kerf taper. Optimal results depend on precise control of parameters like water jet pressure, stand-off distance, traverse speed, abrasive flow rate, abrasive material, abrasive size, orifice diameter, nozzle diameter, nozzle length, and nozzle angle. Despite extensive research and simulations, further refinement is needed to minimize metal stress and improve cutting quality. This paper examines the machinability of titanium, stainless steel, Inconel, and their alloys, highlighting the challenges and limitations in optimizing AWJM parameters for these materials.

***Keywords**: Abrasive Water jet Machining, Machinability, Nozzle wear, Inconel*

Introduction

Machinability is an important aspect of engineering, which has evolved from coarse attachment and edge works to the employment of computing and machines to boost precision machining which can keep the performance of the material at constant to produce exceptional machining potency and productivity. Machinability is a complex work material property that is a result of properties of the machining system which is principally governed by the materials that they are used to machine. Among the properties, the cutting properties, the geometry of the tool, type of machining operation and cutting conditions also influence the machinability of the tool. Machining tools are a vital aspect in terms of progressive material machining and are thus an essential aspect that affect the machinability and selection of tool chosen for machining as they provide a platform for assisting the method kinematics, dynamics and thermal management of cutting processes. Thus such combination machining platforms for a majority of machining processes that enable improvements in productive work by decreasing the time for manual interventions are essential for improving the machinability of modern machine tools [1]. Metal alloys are machined using an ISO grade K tungsten carbide which is generally linear and uncoated. The exception to this broaching where steels tools are still utilized. For machinability to produce required machined component, the grain size/binder content must be chosen appropriately and depend on the conditions and process required for cutting [2][18].

1.1 Metal Machining usingAWJM

Abrasive water jet machining (AWJM) is classified as a non-traditional machining process as it uses abrasive particles fused in a jet of water, pushed to high speeds due to pressure variances to erode materials without the production of shock and heat. The speed of the water jet is enhanced by allowing it to pass through a fine nozzle/orifice. The surface of the material is acted upon by particles dispersed in the water which causes abrasive loss of particles at the point of contact. There are numerous variables that affect the erosion process which is also depends on the type of material that has to be machined. Two major processes govern the erosion process. Ploughing and micro cutting action removes the ductile particles while crack formation and propagation action is responsible for crack formation in brittle material [2].

In the AWJM process water is pumped at a high pressures of about 200 to 400 MPa (2000- 4000 bar) by means of the intensifier technology. The intensifier builds up pressure by means of a hydraulic cylinders of different cross-

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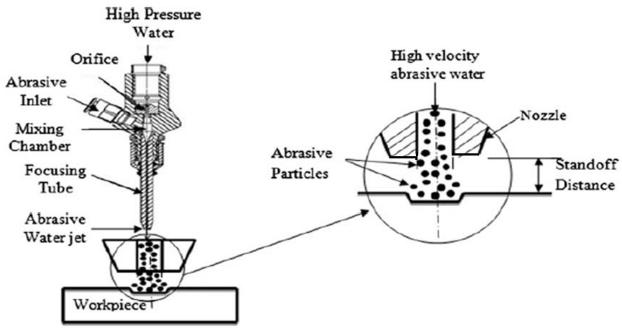


Fig.1 Diagram of Water jet Machining

sections according to the principles of pressure amplification and converts the potential energy of water tokinetic energy by allowing it to pass through an arrow opening (0.2- 0.4 mm in diameter). The high velocity water jet (1000 m/s) is ideal for cutting thin sheets/foils of aluminium, leather, textile, frozen food etc. [1] [3]

Chen et al. In the water jet, an abrasive with suitable characteristics is introduced. This broadens the cutting tool's application range, allowing it to be used on tougher materials. As a result, the water jet, in conjunction with the abrasive, cuts the metal. The craters created on the surface of the manufactured material define the average surface roughness of the metal. The amount of energy thrust on the metal's surface has a significant impact on the creation of craters and the surface property. The impact energy is proportional to the nozzle's distance from the metal surface. This understanding has made a significant contribution to the machinability of a number of commercially important metals [4].

K. Gupta et al. AWJM has a number of advantages over other conventional traditional machining, including the potential to manufacture machined parts without generating heat. It is especially beneficial in terms of environmental effect because it is clean and does not produce dust. The comparatively high cutting cost of Material removal is one of its main drawbacks. Currently, reducing machining costs and increasing profit margins are major problems in AWJM technology. [2] [3] [4]

1.2 Research Constraint

Many modern engineering technologies, such as aerospace, biomedical equipment, and other advanced engineering projects that demand materials with great tensile strength and low weight, rely on titanium and their alloy, Inconel, steel and their alloy. Titanium, Inconel, and stainless steel and their alloys are among the greatest metals to work with since they offer a high strength-to-weight ratio, as well as resistance to temperature, pH, and corrosion.[3] with upcoming simulation tests that have backed the investigation, AWJM has theoretically demonstrated its effectiveness in processing such metals (particularly titanium alloys). At the moment, the concentrate is on industrialising the processes. Furthermore, the research is primarily focused on a few process characteristics that are isolated from the others.

1. Literature Review

In research of abrasive water jet machining (AWJM) of metals, with an emphasis on titanium, stainless steel and Nical based alloy, has been examined for this study. The milled surface's essential input process characteristics, such as nozzle size, abrasive size, nozzle movement control over the material surface, standoff distance, abrasive flow rate, and abrasive types, will receive special attention. The output factors of the machined metal, such as flatness, straightness, depth of cut, Material Removal Rate (MRR), surface roughness, kerf width, and kerf taper, will be given specific consideration in studies. So it is very important to set all parameter related to machining different material to get the desire output like law surface roughness, minimum kerf width, minimum taper angle, higher material removal rate, higher depth off cut, low nozzle wear rate. So it is very challenging task to set machining parameter to achieve precision in machining.[1][4][50]

2.1 Challenges associated with machining metal Alloys and non-metal

Traditional machining of metals has become difficult because of the differences in material removal mechanisms demonstrated by various hard metals such as Titanium and Stainless Steel, Nical base alloy as well as the present demand for precision machining. Delamination, debonding, matrix cracking, fibre pull-out, spalling, and surface cavities are all linked with traditional metal machining, while burr development, discoloration, and feed markings are also related with specific procedures. Plastic strain occurs at the site of contact for materials such as Stainless Steel and Titanium alloys. The material is removed when the value of this strain exceeds the capacity of the material to resist strain. There is a reduction in overall energy usage, cost, and waste produced by using non-traditional machining methods. The current research will look at AWJM, its process parameters, and the problems of metal machining (Ni based alloy, Titanium and Stainless Steel) [3]. Despite multiple research aimed at optimising the AWJM process parameters, there appear to be some persistent issues. Because surface quality is a key aspect controlled by AWJM, we will observe various process parameters that affect on it, such as nozzle speed, water pressure, abrasive flow rate, and how they affect AWJM performance. There may also be issues with the machined parts that are traditionally referred to as flaws, such as striation markings, abrasive particle trapping, and delamination.

2.2 Machining of Titanium and its alloys with AWJM.

Various studies have described the process variables that affect the machining of Nical alloy, titanium and its alloys using AWJM. Among the various parameters, water jet pressure, orifice diameter, nozzle size, abrasive size, standoff distance, abrasive flow rate, Traverse speed etc. are the common optimization parameters that drew the majority of attention. [20]

Sharma et al. Research studies have been also showed the effects of these parameters on depth of cut, Material Removal Rate (MRR), the surface roughness and the width of the kerf**.**. Observed that stand off distance had the greatest impact on volume removal rate, MRPI and surface roughness. [5]

Wang et al. have observed that reverse speed and standoff distance were linked to the volume removal rate and the depth of cut in a study by**.** They studied the effects of water pressure, volume fraction of abrasives and nozzle distance on MRR and the cut depth. The study concluded that when the mass flow rate of abrasives and pressure of water were 15g/sec and 240MPa respectively, it resulted in peak Material removal rate (MRR). Any further increase beyond these parameters led to declination in nozzle life. [6] [7]

The machining of an alloy of titanium (Ti-6AL-4V) was studied by varying the different process parameters of the abrasive water jet. The investigation showed that MRR and the cut depth of Ti-6Al-4V were predominantly influenced by machining variables like water pressure, mass flow rate of abrasives, particles size of the abrasive, stand-off distance and speed of the nozzle movement over the surface of the material of the jet nozzle.[8][9]

Sharma et al. Investigated time required to drill and the effect of pressure on an alloy of titanium (Ti-6Al-4V). From their research it was observed that the diameter and the depth of the cut increased with rise in water pressure and drilling time. Traverse speed had a negative impact cut depth. Lower traverse speed showed deeper cut and increasing the speed of the nozzle over the material was found to have insignificant influence on the material depth of cut.[5] [6][16][30]

2.3 Machining of non-metal

Vishal Gupta et al. have faced problem during traditionally cutting of marble a number problems was observed such as time consuming process, dust and noise nuisance, material wastage while cutting of slots, not suitable in loose and crack strata and jamming of hammer and bit. by the literature survey it has been found that standoff distance, transverse speed and a water pressure have the more effect on the kerf taper angle than the abrasive flow rate. A combination of high water pressure, low transverse speed and a small standoff distance generate more parallel kerf. in this research researcher have investigated effect of AWJM process parameters on top kerf width and kerf taper angle. Further, optimization of process parameters is also performed for minimum values of top kerf width and kerf taper angle. For top kerf width, nozzle transverse speed has emerged as most significant parameter with a percent contribution of 84.004% followed by water pressure (13.619%). It was found that abrasive flow rate failed the test of significant at 95% confidence level therefore it was pooled out. Optimal settings of process parameters for minimum top kerf width are water pressure and nozzle transfer speed at highest levels of 340 M Pa and 100 mm/min respectively. For minimum kerf taper angle lowest levels of water pressure and nozzle transfer speed at 200 M Pa and 50 mm/min emerged as optimal settings. [30][17]

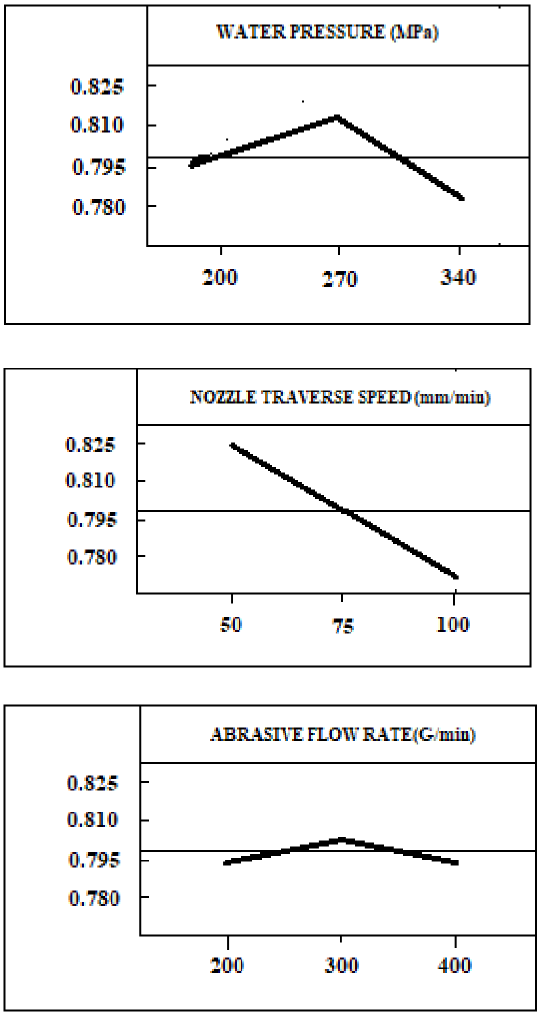
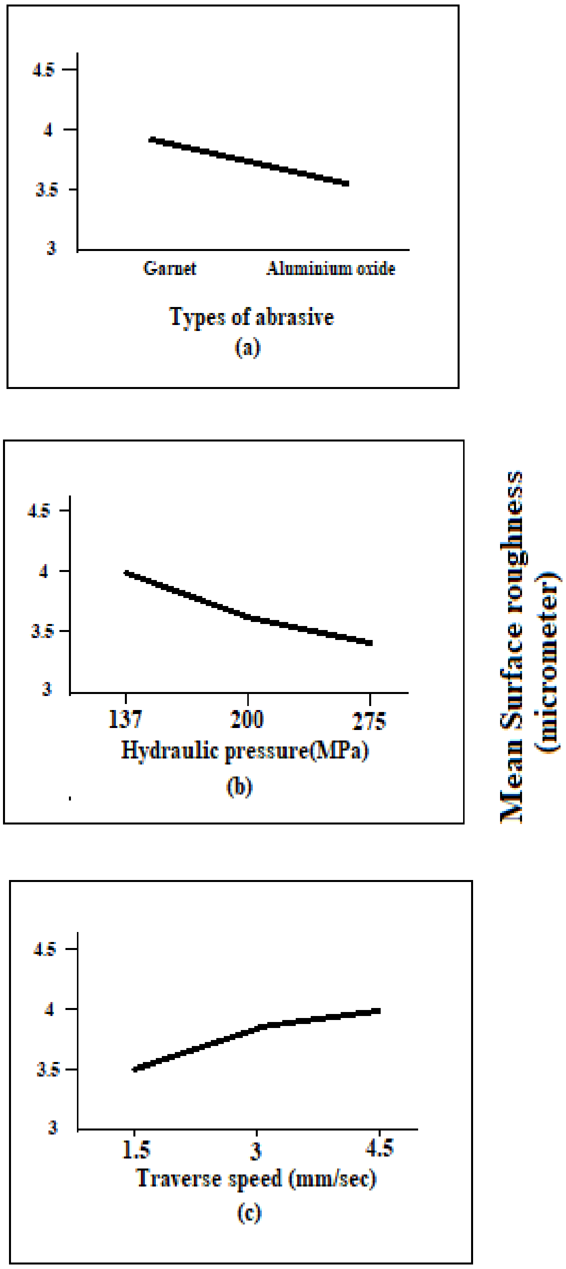


Fig.2 Effect of Input parameter on Kerf width [21]

M. A. Amir et al. have studied that effect of abrasive water jet machining (AWJM) process parameters on surface roughness (Ra) and kerf taper ratio (TR) of aramid fibre reinforced plastics (AFRP) composite. With help of ANOVA they found that traverse speed is significant factor for surface roughness and kerf taper quality. Surface roughness and kerf taper reduce by increasing jet pressure and reducing the stand of distance and traverse rate. other hand they could not found clear pattern for surface roughness and taper angle. a Mathematical models were also developed using multiple linear regression analysis to predict the performance of surface roughness and taper angle in terms of AWJM process parameters. because of variable force require to machine composite material there will be the possibilities to damage machining area of work material such as delamination, fibre pull out and poor hole quality when drilling operation carried out. Multiple linear regression analysis was used in developing mathematical models to predict the performance Ra and TR in AWJM of AFRP laminate. [22][49][13]



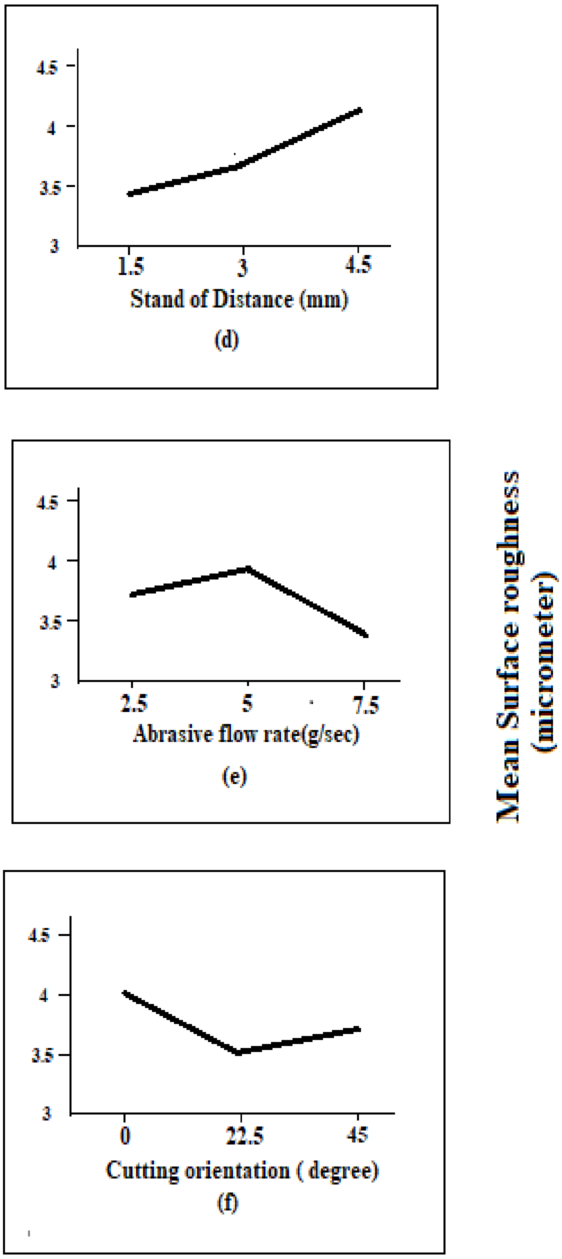


Fig.3 Effect of (a) types of abrasives, (b) hydraulic pressure, (c) traverse rate (d) standoff distance, (e) abrasive mass flow rate, and (f) cutting orientation on surface roughness. [37]

2.4 Machining of ductile material

When machining of ductile material like aluminium and its alloy with AWJM, a abrasive particle are impinge into base material and retain the defect in machined parts so it is crucial work to identify parameters which are affect to machine the ductile material other many difficulty arise while machining the ductile material by AWJM. M. Takaffoli et al. been used numerical model to understand the complexities of solid particle erosion phenomenon of material removal mechanism. Such models allow the tracking of individual particle impact, and can be beneficial in analysing the cooperative effect of multiple impact on the resulting region in addition to allowing the study of individual process parameters separately. In contrast of an analytical model which suffer from simplified assumptions and require turning certain parameter computer model can developed based on more sophisticated and realistic modelling of the target and particles. the average difference between the predicted and measured erosion rate was 7%, with maximum difference of 13% occurring at an angle of incidence of 15^0.[22][11][15]

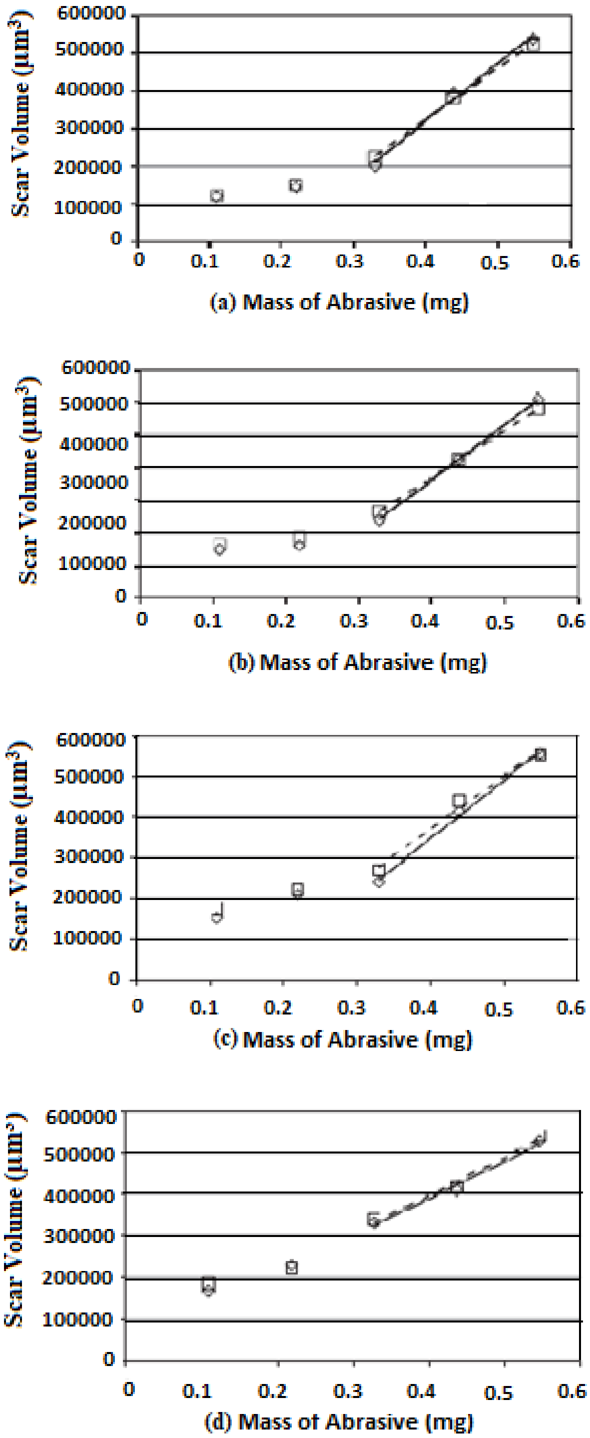


Fig. 4 Variation of remove volumes at impact angle of (a) 15^0 (b) 30^0 (c) 45^0 (d) 60^0 [29]

2.5 Stainless Steel and it's Alloys

Numerous studies in the past have ascertained the process parameters for AWJM in terms of stainless steel machining, the important among which are discussed here. In machinability studies, the volume removal rate (also used as material removal rate) was investigated. In a study conducted by Ramprasad and colleagues, they examined the variables that could increase the material removal rate (MRR) of Stainless steel according to AWJM. They checked for three parameters; water pressure, abrasive flow rate and stand-off distance. The study was conclusive in identifying water pressure (WP) as the most important variable to work with stainless steel, with standoff distance and the rate of flow of the abrasive, which follow respectively. [10]

When considering Hardox steel and its machinability through AWJM in which factorial design model was used to assess process parameters. The study aimed at assessing variables such as the speed of the nozzle over the material and the standoff distance. The measurements of dimensions and roughness of parts, the influence of parameters showed that parameters had significant influence on the roughness of the parts and the dimensions of the material [11].

When considering the common variables of the AWJM process such as rate of abrasive flow, pressure of the water and the distance between the nozzle and the Stainless Steel material were analyzed using TGRA (Taguchi grey relational analysis) by Satyanarayana et al. From statistical analysis (ANOVA) it was observed that there was a detectable influence of the pressure of the water on the width of the kerf and Material Removal Rate (MRR) than on the flow rate of the abrasive and standoff distance. [12]

Deepak Doreswamy et al. assessed the impact of standoff distance and rate of abrasive flow on the width of the kerf and surface roughness for machining of steel using AWJM and suggested that in single pass machining, when there was unchanged in the distance between the material and the nozzle, the width of the kerf at the top was also increased by approximately 18% while the bottom showed decrease in width of the kerf by about 25%. Also, the positive change in stand-off distance and feed rate has a positive influence the surface roughness. [13]

Process parameters that can be changed such as pressure of the water, speed of the nozzle movement over the surface of the material and abrasive flow rate were studied with the depth of cut being the focal output parameter. The results showed that that the pressure and speed of the nozzle movement over the surface of the material had a greater contribution towards cut depth than flow rate of the abrasive. [11]

T. V. K. Gupta et al. have studied the process variables of AWJM and their influences on Stainless steel where the variables such as Abrasive size, rate of flow, distance between the nozzle and the material, and speed of the nozzle movement over the surface of the material were altered. It indicated that greater traverse speeds improved the depth of cut which may be due to a decrease the energy density of the particle and lower depth. They noted that an increase in the distance between the nozzle and the material and the rate of the abrasive flow showed a drastic reduction in the material removal rate. This was attributed to the jet loses and due to collisions within the particles. [14] [33][42]

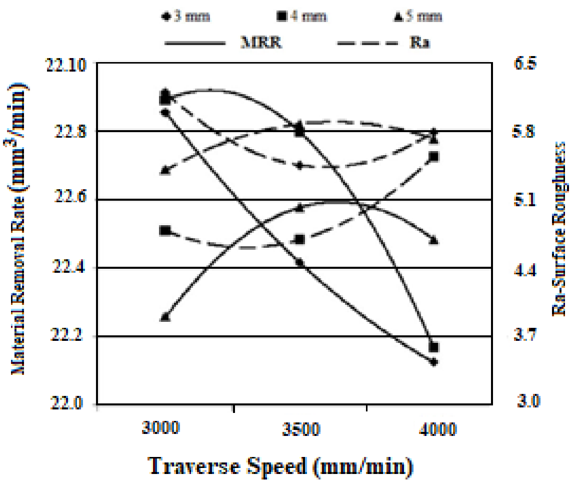


Fig.5 Effect of standoff distance with traverse speed on MRR and Ra

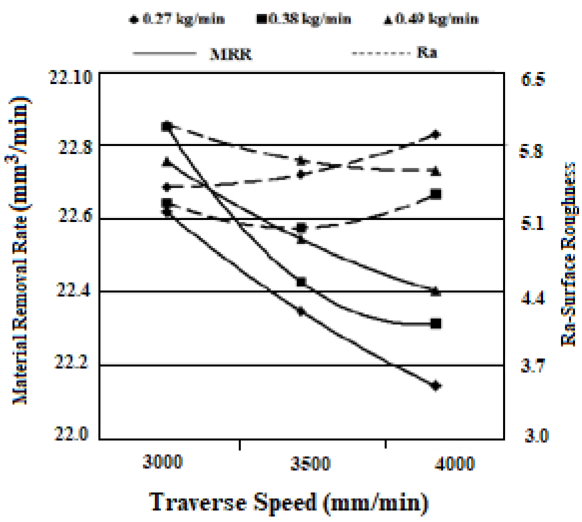


Fig.6 Effect of AFR with traverse speed on MRR and Ra

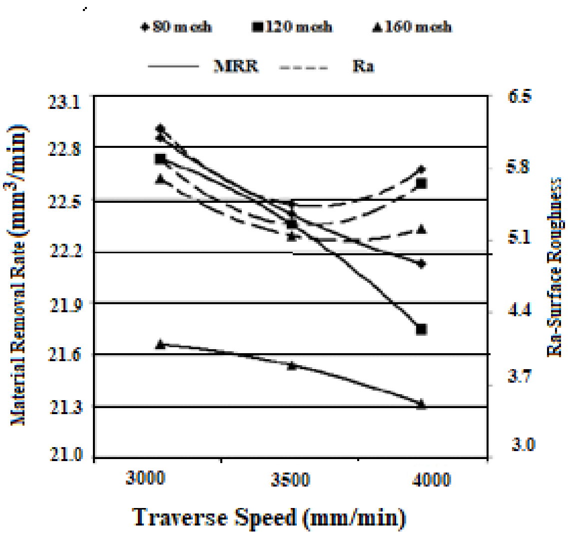


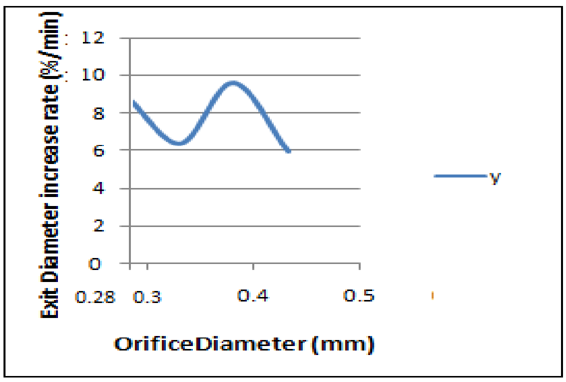
Fig.7 Effect of abrasive size with Traverse Speed on MRR and Ra

This method of machining is more powerful than the other machining process. it is able to machine any kind of material whether hard or soft instead of other machining of process. No tool change required during AWJM whereas in other machining process it is require. Easy to programming the machining process .thicker material can be machined by this AWJM. By this machining process we can machine intricate shape of component.

2.6 Nozzle Wear in AWJM

Nozzle is most countable part in Abrasive Water jet Machining, so its design and condition under which it work is very important. Many researchers have worked on impact of abrasive particle on erosion effect but a few researchers have worked on nozzle wear and FEA analysis of nozzle wear.

Syazwani et al. have observed that Regular and rapid wear measurements can be used to assess nozzle wear. The nozzle bore profile method, nozzle weight loss method, and pinning profile can all be used it to determine the wear profile. [33]



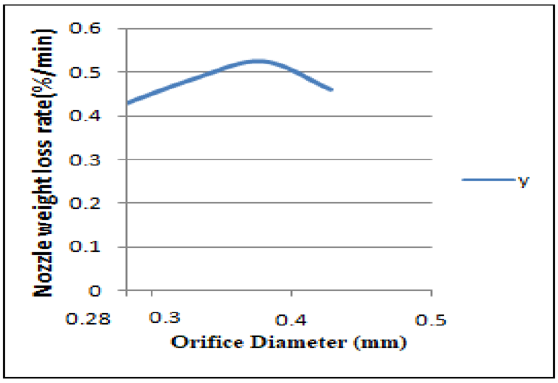


Fig.8 Effect od orifice diameter on exit diameter and Nozzle weight loss rate

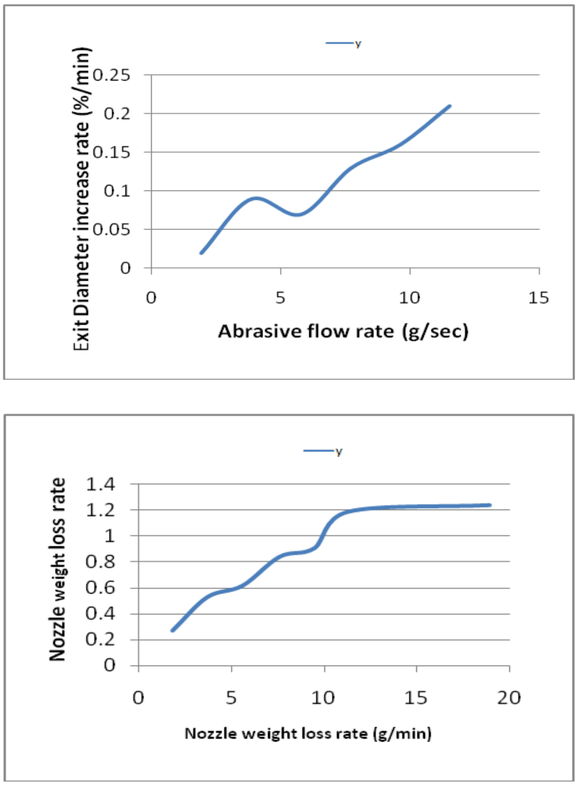
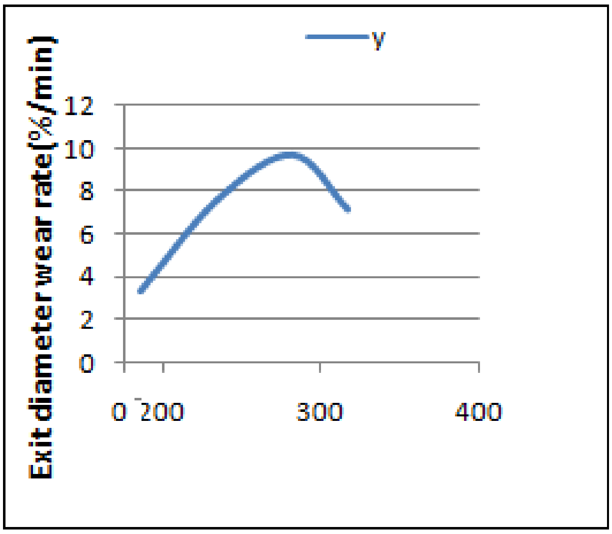


Fig.9 Effect of Abrasive flow rate on Exit diameter and Nozzle weight loss rate



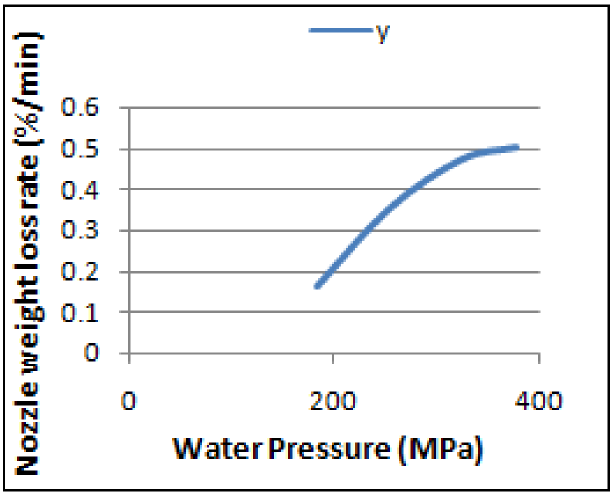


Fig.10 Effect of water pressure on Exit diameter and Nozzle weight loss rate [37]

Mehdi et al. In their research the configuration tool algorithm was suggested in this work to adjust for the influence of nozzle diameter increase on cut surface quality and kerf width. This is done in order to generate items with dimensions that are within acceptable limits. [23][26]

Verma et al., In their research they observed that Traverse speed is most significant factor for MRR. Also abrasive flow rate has also affected the MRR. But beyond some limit increase traverse speed and abrasive flow rate higher the surface roughness. [28]

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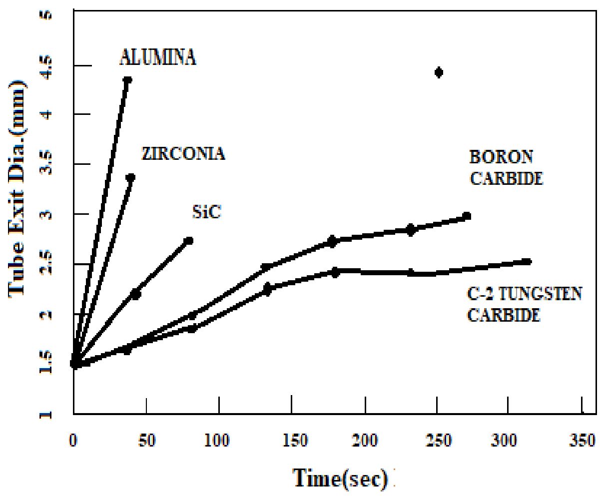
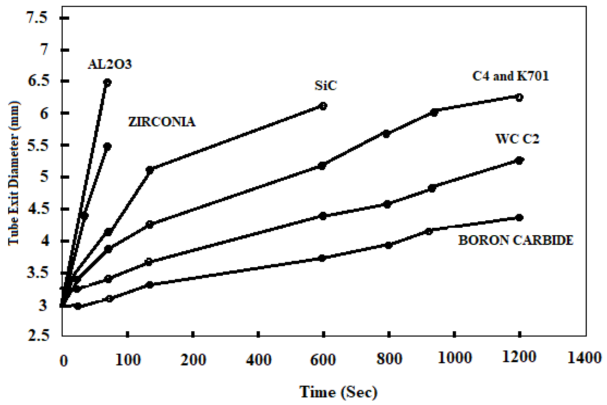


(a)



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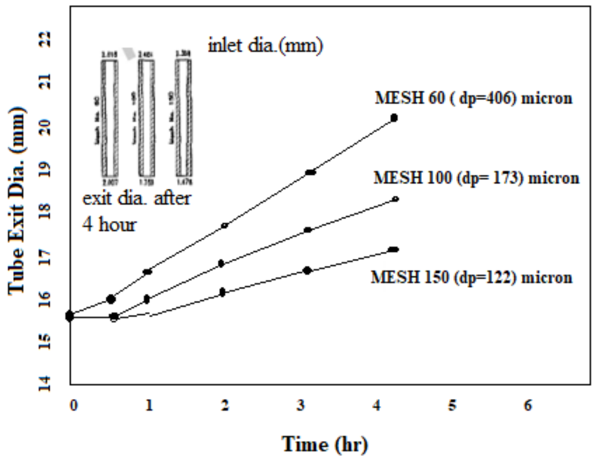

(c)

Fig.11 Effect of different parameter on tube exit diameter (a) different abrasive Particles (b) focusing tube length (c) size of abrasive Particles [2].

2. Summary

The analysis of various AWJM process parameters shows that MRR increases as water pressure rises, but the significant disadvantage is that surface roughness and sub-surface damage rises as well. The various quality criteria of the work component are also affected by the types of abrasives used and the traverse speed. A comparative analysis and a summary of the results were shown at the table.

Effect of process parameters on Response parameters in AWJM							
Process parameters	Quality parameters	material removal rate	Surface roughness	Kerf taper angle	Top width of cut	Bottom kerf width	nozzle Wear
Water jet pressure	increase	↑	↑	↓	↓	↓	↓
	decrease	↓	↓	↑	↑	↑	↑
Abrasive flow rate	increase	↓	↑	↑	↑	↓	↑
	decrease	↑	↓	↓	↓	↑	↓
Traverse speed	increase	↑	↑	↑	↑	↑	↓
	decrease	↓	↓	↓	↓	↓	↑
stand of Distance	increase	↑	↓	↑	↑	↑	↓
	decrease	↑	↑	↓	↓	↓	↑

3. Conclusion

1. In AWJM, the quality of the cutting surface is determined by a variety of operating parameters. Hydraulic pressure, standoff distance, abrasive kinds, size of abrasives, abrasive flow rate, nozzle diameter, orifice size, and traverse speed are all process parameters that have an impact on cutting quality in the AWJM. Material removal rate, surface quality, kerf breadth, and kerf taper ratio are all indicators of cutting surface quality. According to the literature review,

All these parameters effected individually in different way for machining of different material. So it is very difficult to choose machining parameter to get batter machining quality and material removal rate.

2. Efficiency of AWJM process is depending on nozzle wear and nozzle wear is depending on so many process parameter and geometrical parameters.

3. Nozzle wear is measured by % change in exit bore diameter rate and % volume loss rate of nozzle.

4. The abrasive flow rate is an important factor in improving MRR. The surface roughness decreases when the abrasive flow rate and traverse speed increase beyond a particular point. The kerf geometry increases when the traverse speed is raised. It is vital to set the ideal conditions for process parameters in order to increase the quality of the cutting surface. Traverse speed is proportional to productivity and should be adjusted as high as feasible while maintaining kerf quality and surface roughness.

5. Water jets have been proved to be a versatile, unconventional machining method that is now used in various industrial processes. AWJM has been used in a wide range of applications, including rock, wood, composites, and glass.

6. The majority of optimization research has focused on process parameters to improve a specific quality attribute, such as depth of cut, surface roughness, and material removal rate. There are just a few research papers on the optimization of the AWJM process for power consumption, dimension accuracy, and multi-objective optimization.

7. Various optimization techniques are used to optimize operating parameters to impart quality attribute in product i.e. Weighted principle components analysis (WPCA), Response surface method and Box–Behnken methodology (RSM),(BBD),grey wolf optimizer (GWO) , Artificial Neural Network(ANN), Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, VIKOR method, Jaya Algorithm etc.

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