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Studies on machining characteristics of titanium alloy Ti-6Al-4V using abrasive water jet cutting

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ABSTRACT
Titanium alloy Ti-6Al-4V has achieved the significance in various applications because of its high modulus to density ratio, biocompatibility, high corrosion resistance, high temperature resistance etc. Therefore machining and machinability of which in different aspects is very important. In this research Titanium alloy Ti-6Al-4V is machined using advanced machining process viz., Abrasive water jet machine (AWJM) to study the effect of process parameters on machinability of Ti-6Al-4V alloy. In the study an attempt was made to study the effect of water pressure, volume fraction of abrasives and stand-off distance on the Volume removal rate, depth of cut. In the study it is observed that the 15g/sec mass flow rate of abrasives accompanied with pressure of 240MPa and SOD of 5mm results in peak Volume Removal Rate (VRR), beyond which it leads in declination of nozzle life. The results were incorporated and validated to simulate and mathematical model is generated using the multivariate regression analysis.

Keywords - Machinability of titanium alloys; Ti-6Al-4V; multivariate regression analysis; AWJM

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I. INTRODUCTION

Titanium has acquired the significant pace over other metals and alloys as it exhibits high strength to density ration which is of prime importance in various sectors of different industries. Over the various commercialized alloys of Titanium, Ti-6Al-4V alloy is significant on various mechanical and chemical properties as it exhibits high strength, high resistance on corrosion, light weight, bio compatible and fire retardant. Due to its eccentric properties it is widely known for bio medical implants, higher temperature withstanding capacity leads to widely being used in high performance automotive parts, marine, medical, aerospace industries [1]. Since the material is hard, it is very difficult to machine, especially intricate shapes by conventional processes, therefore it is highly recommended to make use of non-traditional machining processes such as Abrasive Waterjet Machining (AWJM), Abrasive Jet Machining (AJM), Electric Discharge Machining (EDM), Electro Chemical Machining (ECM) etc. So that the objective can be achieved with no direct involvement of physical tool and thus there is no much friction at the cutting zone [2]. The major difficulties in machining titanium and its alloys are high cutting temperatures and rapid tool wear. In the open literature, many authors have attempted to machine these materials with different cutting tools like straight grade cemented carbides WC, polycrystalline diamond (PCD), and cubic boron nitride (CBN) [2-3].

In AWJM process, since there is continuous impingement of water, the thermal stresses will be zero as water itself acts as a coolant, [4-5]. Waterjet machining has high machining versatility such as minimum stress on workpiece so cutting forces are low, high flexibility etc.[6-7]. So it has proven as effective technology for machining of various engineering materials [8]. It is an economical and environmental friendly process that can be adopted for machining the wide number of engineering materials notably difficult-to-cut materials such as hard materials, nickel, ceramics etc. [9-10].

In AWJM, the material removal mechanism is by the action of high velocity water mixed with abrasive particles as a result high velocity waterjet transfers kinetic energy to abrasive particles and the mixture impinges on the workpiece to remove the material as a result of abrasion and erosion [11-12]. The MRR is the function of abrasive strike and mechanical properties of the target material, which in turn governed by the process parameters [13-15]. The process parameters such as water pressure, flow rate of the abrasives, jet traverse rate, stand-off distance and diameter of nozzle have its direct effect on machinability of the materials such as machining accuracy, Volume removal rate (MRR/ VRR) and surface finish [16-18]. The surface finish and MRR is strongly influenced by the traverse speed of the jet. Low traverse speeds results in irregular surface morphology and significantly increased MRR. [19]. Besides, the other researcher has observed the high surface waviness [20].

The prime objective of this study is to experimentally investigate the machining characteristics such as depth of cut and VRR of titanium alloy Ti-6Al-4V using AWJM process by varying the process parameters such as water pressure, volume fraction of abrasives, SOD and Traverse speed.

II. EXPERIMENTAL WORK

The material used in the process is titanium alloy Ti-6Al-4V with the thickness of 6.25m. The chemical compositions of the material are as listed in Table-1. The specifications of the machine and abrasives used for the experimentations are listed in Table-2.

Table-1: Chemical Composition of Ti-6Al-4V Titanium Alloy (% Wt.)

Ti	Al	V	Fe	O	C	N	H
89.46	6.05	4.04	0.23	0.18	0.02	0.01	0.005

Table-2: Specifications of Equipment and Abrasives.

Maximum Working Pressure	350 MPa
Mixing Tube Length	101 mm
Mixing Tube Diameter	0.76 mm
Orifice Material	Sapphire
Orifice Diameter	0.35 mm
Carbide Nozzle Diameter	1.05 mm
Jet Impingement Angle	90^0
Abrasives used	Garnet particles
Average Diameter of abrasives	0.15-0.19 mm
Density of Abrasives	4120 Kg/m^3

In order to machine the material, following were the variables or parameters made for effective impingement of water jet with abrasives. Water pressure varied from 70MPa to 240MPa at a traverse speed varying from 0.5 mm/sec to 12 mm/sec and mass flow rate of abrasives 6 and 15 g/sec with particle sizing from 0.14mm to 0.19mm with two grades of mesh viz. 80 and 100 meshes. The trials were carried by varying the Stand-off Distance from 2 mm to 5 mm.

High pressure water is directed to the mixing chamber by passing through the small orifice made up of sapphire material to withstand the high pressure water and then it carries the abrasive particles with the constant mass flow rate of abrasives with known particles size which are then mixed by abrasive hopper in mixing chamber. Thus the mixture of abrasive particles and high pressure water in the form of abrasive water jet is impinged on the material through nozzle made up of hard material – sapphire. The nozzle wear rate was observed in regular intervals of time to make sure the proper machining outcomes. The mixing chamber and nozzle construction is as shown below:

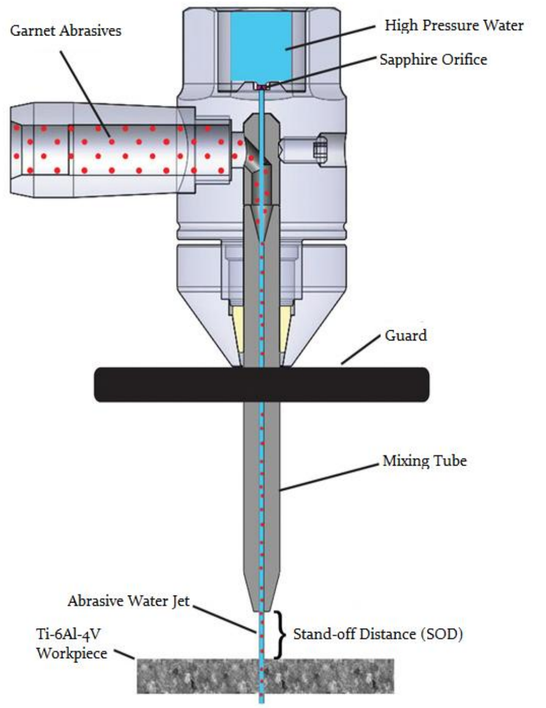


Fig-1: Mixing chamber of AWJ nozzle

III. EFFECT OF PROCESS PARAMETERS ON DEPTH OF CUT AND MRR

In the experimentations, the effect of process parameters such as Water pressure (P), stand –off distance (SOD), jet traverse speed (ν) and mass flow rate of the abrasives (Ma) on Material removal Rate (MRR) and Depth of cut was observed.

In the machining process, it is observed that the mass flow rate of the abrasives plays a vital role in MRR as it carries the kinetic energy of water and strikes with high impact, resulting in high rate of abrasion on material and simultaneously water jet also erodes the material, but since the density and strength of solid abrasive particle is higher, it hits the surface with impact and removes the material thus the depth of cut will also be more since material dugs out at faster rate. Similarly, as the water pressure increases, the energy of the particles increases and results in high MRR and DOC.

It is also seen that as the SOD increases, the MRR also increases but DOC is not linearly increases, as the distance from nozzle to surface increases, there causes the divergence of the jet, resulting in widening of cut and thus results in kerf width. Whereas MRR will be increased as the particle and jet constraints are less so high energy particles and low energy particles (abrasives) are involved in material removal mechanism, hence MRR will be increased with the increase in DOC. On the other hand, increase in size of the abrasive particles increases the MRR and DOC as the mass of each particle carrying the kinetic energy results in impact on surface.

Jet traverse speed provides the necessary time to dig and remove the material, as the number of particles strikes causes the removal of material, hence lower traverse speeds removes more material than the higher traverse speeds.

Figure 2 a & b shows the effect of stand-off distance and water pressure on material removal rate (MRR) of Ti-6Al-4V titanium alloy at constant mass flow rate of abrasives at 6g/sec and particle size of 0.18 i.e, 80 mesh garnet particles . The graph shows that MRR and DOC increases with the increase in SOD, but in case of MRR wide increment is observed than the increase in DOC, that's because of divergence of jet with increase in SOD. Simultaneously with the increase in water pressure the MRR and DOC has drastically increased.

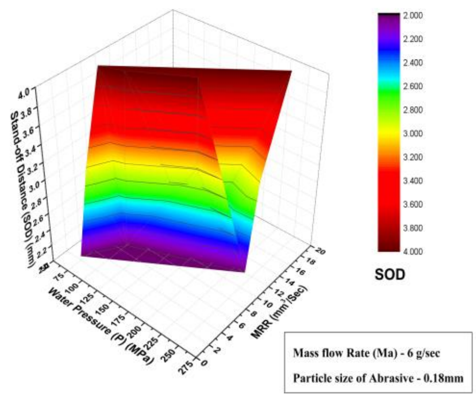
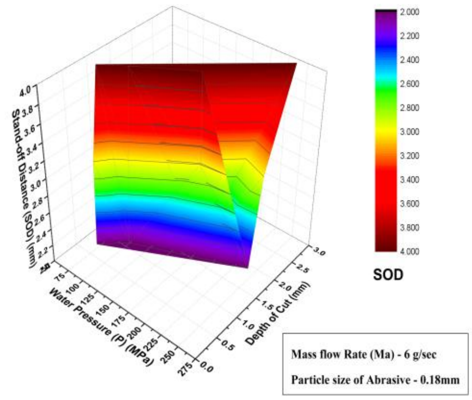


Fig-2 (a): Effect of SOD and Water Pressure on MRR at Average abrasive particle size of 0.18mm (80 Mesh)



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ig-2 (b): Effect of SOD and Water Pressure on Depth of Cut at Average abrasive particle size of 0.18mm (80 Mesh)

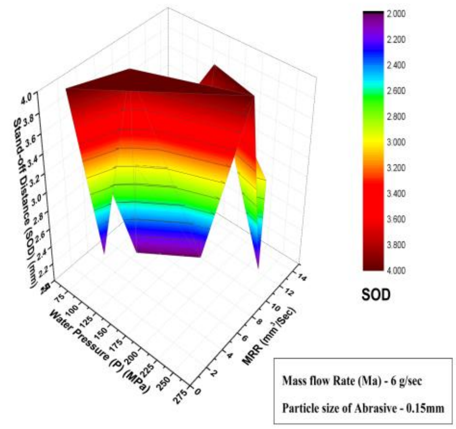
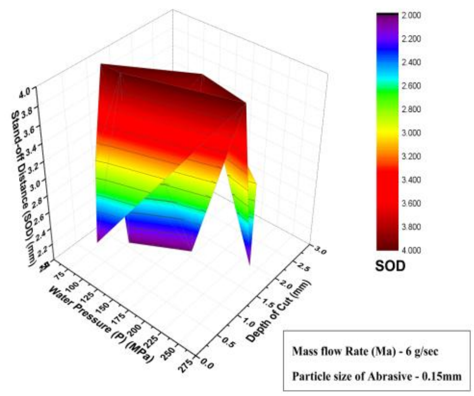


Fig-3 (a): Effect of SOD and Water Pressure on MRR at Average abrasive particle size of 0.15mm (100 Mesh)



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ig-3 (b): Effect of SOD and Water Pressure on Depth of Cut at Average abrasive particle size of 0.15mm (100 Mesh)

Figure 3 a & b shows the effect of stand-off distance and water pressure on material removal rate (MRR) of Ti-6Al-4V titanium alloy at constant mass flow rate of abrasives at 6g/sec and particle size of

0.15 i.e, 100 mesh garnet particles. The graph shows that MRR and DOC increases with the increase in SOD, but in case of MRR wide increment is observed than the increase in DOC, that's because of divergence of jet with increase in SOD. Simultaneously with the increase in water pressure the MRR and DOC has drastically increased. Also, it is observed that as the particle size is reduced the potential is also reduces and results in lower MRR and DOC.

Figure 4 a,b & c Exhibits the impact of varying nozzle jet traverse speed and stand-off distance on MRR and DOC of Ti-6Al-4V titanium alloy at constant mass flow rate of abrasives at 15g/sec, particle size of 0.18 i.e, 80 mesh garnet particles and at constant water pressure of 240MPa. The graph shows that MRR and DOC increases with the lower traverse speed of the jet for constant water pressure, as it allows the more abrasives to strike at same place and thus the material removal is effective as the rate of traverse is low.

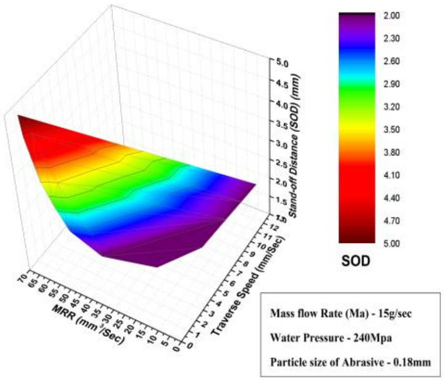

Fig-4 (a): Effect of SOD and Traverse Speed on MRR at Average abrasive particle size of 0.18mm (80 Mesh)

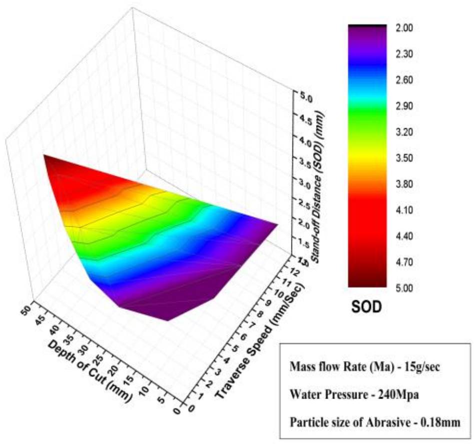

Fig- 4(b)

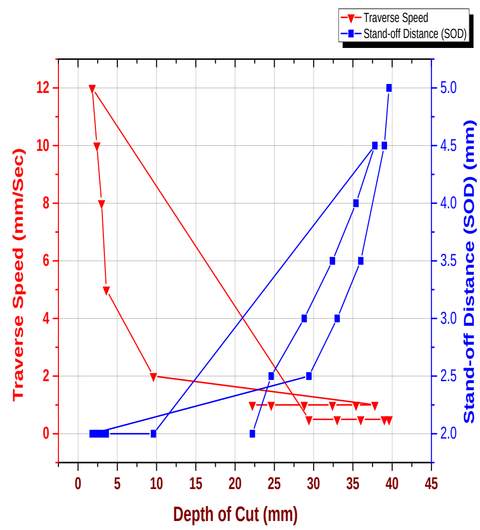

Fig- 4(c)

Fig- 4 (b & c): Effect of SOD and Traverse Speed on Depth of cut at Average abrasive particle size of 0.18mm (80 Mesh)

Figure 5 a,b & c Exhibits the impact of varying nozzle jet traverse speed and stand-off distance on MRR and DOC of Ti-6Al-4V titanium alloy at constant mass flow rate of abrasives at 15g/sec, particle size of 0.15 i.e, 100 mesh garnet particles and at constant water pressure of 240MPa. Here it is seen that the MRR and DOC is slightly decreased as the size of the particle is reduced.

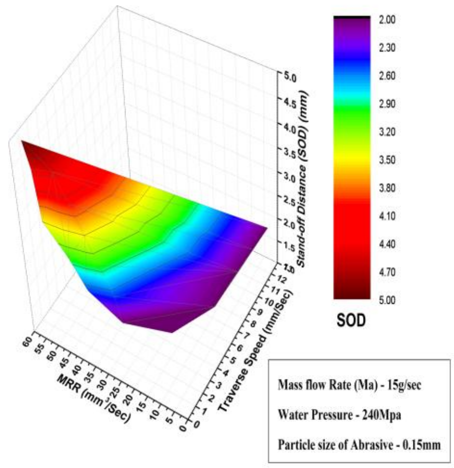

Fig-5 (a): Effect of SOD and Traverse Speed on MRR at Average abrasive particle size of 0.15mm (100 Mesh)

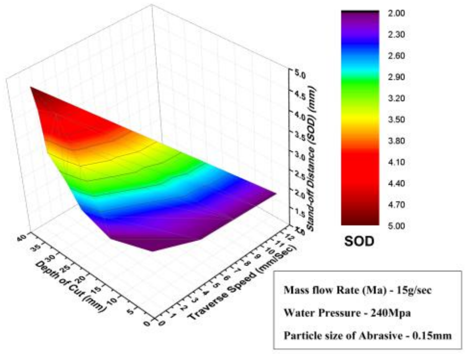

Fig- 5 (b)

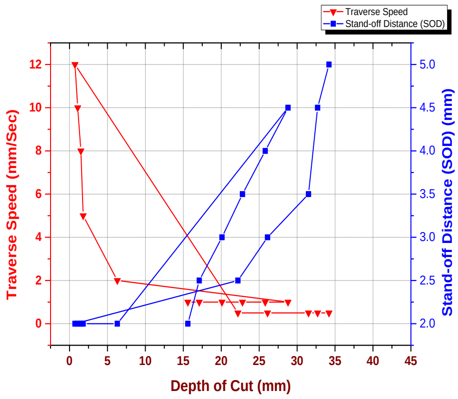

Fig- 5 (c)

Fig- 5 (b & c): Effect of SOD and Traverse Speed on Depth of cut at Average abrasive particle size of 0.15mm (100 Mesh)

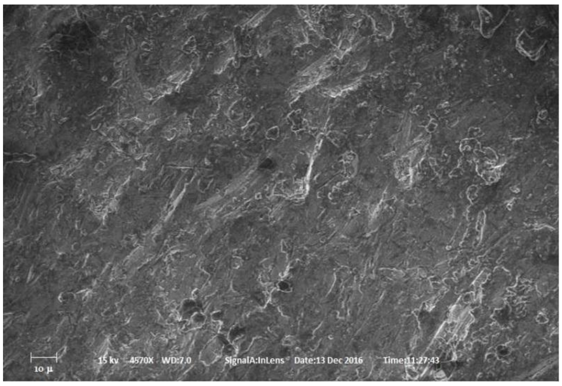

Fig-6 (a)

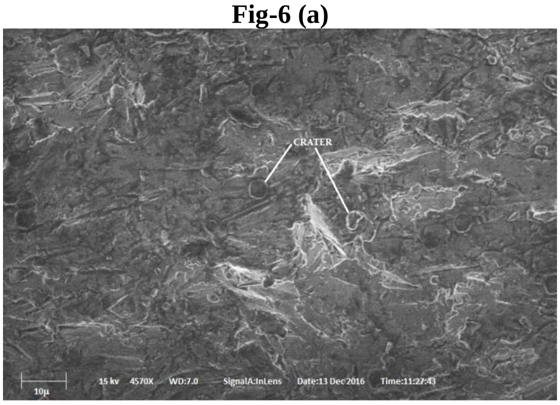

Fig-6 (b)

Fig- 6: Machined surface of Ti-6Al-4V alloy at SOD of 2mm, Water pressure of 100MPa and (a)grit size of 0.15mm (100 Mesh) (b)grit size of 0.18mm (800 Mesh)

IV. SURFACE MORPHOLOGY AND FRACTOGRAPHY ANALYSIS:

The surface of the machined material exhibits the machining characteristics in the form of finished and smoother surface with less peaks and valleys of machined surface at microscopic and nanoscopic scale. The surface quality of AWJ machining depends majorly on Stand-off distance, grit size of the particles and water pressure. As the water pressure carries the particles and results in abrasion of material with the particle impact, lower the pressure of water, lesser will be the crater size and hence surface will be smoother. Also, stand-off distance plays a key role in surface quality as the distance between nozzle edge and surface is larger, there exists the random distribution of energy associated with the particles, thus the impingement is uneven as the striking of particles randomly.

It is also observed from fig 6a & b that grit size of the particles creates larger craters by the impact and results in high peaks and valleys on the surface resulting in poor surface finish, smaller the particle size, higher will be the surface quality.

V. MULTI-VARIATE REGRESSION ANALYSIS:

Multivariate Regression model exhibits the impact of each parameter or input variable on dependent variables. Here MRR and DOC are taken as Dependent variables, whereas abrasive size (s), Stand-off distance (SOD), mass flow rate of the abrasives (Ma), water pressure (p) and jet traverse speed (ν) are taken as independent variables.

Therefore with the help of SPSS the multivariate regression models are developed for the two different dependent variables and are as mentioned in

Equation (1) model to predict the depth of cut with the variation of fore mentioned independent variables.

Equation (2) represents the prediction of MRR with the variation of independent variables.

DOC = 109.857(S) + 4.279(SOD) + 2.288(Ma) + 0.008P - 2.268ν - 39.801 ± e ---------(1)

MRR = 197.315(S) + 7.244(SOD) + 2.687(Ma) + 0.52P – 3.762ν - 61.685 ± e ---------(2)

VI. CONCLUSION

In the study, experimental investigations were carried on Ti-6AL-4V titanium alloy by varying the different process parameters of Abrasive water jet machine to study the machining characteristics of the alloy. In the investigation it was found that MRR and Depth of cut of Ti-6Al-4V has highly influenced by machining parameters such as water pressure, mass flow rate of abrasives, abrasive grit size (particle size), stand-off distance and traverse speed of the jet nozzle. From the results obtained by experimentation and trials, the following conclusions were drawn.

- Water pressure and mass flow rate of the abrasives has the significant effect on depth of cut.
- Material Removal rate is greatly influenced by water pressure, SOD, flow rate of abrasives and traverse speed.
- With the increase in SOD, depth of cut also slightly increases with the significant increase of kerf width, this is because of the flush of water from the cavity already made and low energy of water to be flushed making less constraints for high pressure water impinging from the jet to have greater impact on the material. On the other hand, it increases the kerf width and thus causing the tapering of the drill as a result of increase in divergence of the jet with increase in distance form nozzle to the surface (SOD).
- It is also seen that, high flow rate of abrasives and SOD and greater particle size results in low surface finish as the impingement of abrasives will not be constrained owing to the random distribution of energy.
- High surface finish was observed in smaller sized abrasive particles due to the small abrasive impression on surface, whereas larger crater size on bigger particles results in low surface finish.
- Based on the data obtained from several trials of experiments, the statistical models are prepared to predict the influence of process parameters on MRR and depth of cut, using Multivariate Regression Analysis. The Model is verified for further practice of machining by selecting the process parameters for the required MRR or DOC.

REFERENCES

[1]. Li H, Wang J. An experimental study of abrasive waterjet machining of Ti-6Al-4V. International Journal of Advanced Manufacturing Technology 2015; 81: 361-9.
[2]. Nabbani F. Machining of aerospace titanium alloys. Robot Com Int Manuf 2001;17:99–106.
[3]. Zoya ZA, Krishnamurthy R. The performance of CBN tools in the machining of titanium alloys. J Mater Process Technol 2000;100:80–6.
[4]. Maros Z. energy approach of the taper at abrasive waterjet cutting. Prod Process Sys 2013; 6: 89-96.
[5]. Hascalik A., Caydas U., Gurun H. (2007), "Effect of traverse speed on abrasive waterjet machining of Ti-6Al-4V alloy", Meter.Des.28: pp 1953-1957.
[6]. Akkurt A, Kulekci MK, Seker U, Ercan F. Effect of feed rate on surface roughness in abrasive waterjet applications. J Mater process Technol 2004;147:389–96.
[7]. Van Luttervelt CA. On the selection of manufacturing methods illustrated by an overview of separation techniques for sheet materials. Ann CIRP 1989;38(2):587–607.
[8]. Siores E., Wong W C K., Chen L., Wager J G. (1996), "Enhancing abrasive waterjet cutting of ceramics by head oscillation techniques", Ann CIRP, 45[1]: pp 215-218.
[9]. Wang J. (2003), "Abrasive Waterjet Machining of Engineering Materials", Uetikon-Zuerich [Swizerland]: Trans Tech Publications.
[10]. Shanmugam D. K., Wang J., Liu H. (2008), "Minimization of kerf tapers in abrasive waterjet machining of alumina ceramics using a compensation technique", International Journal of Machine Tools and Manufacture 48: pp 1527–1534.
[11]. John Rozario Jegaraj J., Ramesh Babu N. (2007), "A soft computing approach for controlling the quality of cut with abrasive waterjet cutting system experiencing orifice and focusing tube wear", Journal of Materials Processing Technology, vol.185, no.1–3: pp 217–227.
[12]. Shanmugam D. K., Masood S. H. (2009), "An investigation of kerf characteristics in abrasive waterjet cutting of layered composites", International Journal of Material Processing Technology 209: pp 3887–3893.
[13]. Hashish M. A modelling study of metal cutting with abrasive waterjets. J Eng Mater Technol 1984;106:88–100.
[14]. Arola D, Ramulu M. Mechanism of material removal in abrasive waterjet machining of common aerospace materials. In: Proceedings of the seventh American waterjet conference. Seattle (WA); 1993. p. 43–64.
[15]. Hashish M. Optimization factors in abrasive waterjet machining. ASME J Eng Ind 1991;113:9–37.
[16]. Blickwedel H, Guo NS, Haferkamp H, Louis H. Prediction of abrasive jet cutting

performance and quality. Jet Cutting Technol 1991:163–79.
[17]. E. Lemma, L. Chen, E. Siores, J. Wang. (2002), "Optimising the AWJ cutting process of ductile materials using nozzle oscillation technique", International Journal of Machine Tools and Manufacture 42: pp 781–789.
[18]. C. Ma, R.T. Deam (2006), "A correlation for predicting the kerf profile from abrasive waterjet cutting", Experimental Thermal and Fluid Science, vol.30, pp 337- 343.
[19]. Ojmertz KMC. Abrasive waterjet milling: an experimental investigation. In: Hashish M, editor. Proceedings of the seventh US water jet conference. St. Louis: Water Jet Technical Association; 1993. p. 777–91.
[20]. Fowler G, Shipway PH, Pashby IR. Abrasive water-jet controlled depth milling of Ti–6Al–4V alloy – an investigation of the role of jet workpiece traverse speed and abrasive grit size on the characteristics of the milled material. J Mater Process Technol 2005;161:407–24.

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