EXPLORING ABRASIVE WATER JET CUTTING FOR NEAR NET SHAPE PROCESSING OF TITANIUM AEROSPACE COMPONENTS

R. de Bruyn[1] and N.F. Treurnicht[2]
[1]Department of Industrial Engineering
University of Stellenbosch, South Africa
15319180@sun.ac.za

[2]Department of Industrial Engineering
University of Stellenbosch, South Africa
nicotr@sun.ac.za

ABSTRACT

Establishment of a local titanium industry is the focal point of a broad South African initiative to exploit the country's reserves of this sought after material. In parallel to the process development, manufacturing technologies is being developed for competitive component manufacture. The high cost of both the titanium alloy and the machining of the material constrain the use and the market size for the material. Currently the use is limited to aerospace, medical implant and high value sporting equipment applications. The classic manufacturing method is to machine from a solid billet. In the light of titanium alloys being classified as difficult to machine materials, this is a high cost approach. Several initiatives are in development to address this challenge. Significant development is being devoted to technologies such as press and sinter powder metallurgy, metal additive manufacturing, investment casting as well as isothermal forging. In this study the possibility of abrasive water jet cutting is investigated as a near net shaping process. The capabilities and limitations of the process are presented. A case study of a typical aerospace part where the conventional method of machining is compared to a near net shape process utilising abrasive water jet cutting and final machining is discussed.

1 INTRODUCTION

The use of titanium in the aerospace industry has received attention from the 1950's, due to the material's high strength-to-weight ratio. As titanium has such favourable physical properties, it is also difficult to machine and process. It is also very reactive at elevated temperature, and readily reacts with oxygen in the atmosphere during machining; forming what is known as alpha-case on the surface of a part. This is a concern for the aerospace industry, as this reduces the metallurgical integrity of the part, serving as the source for crack propagation that can ultimately cause unexpected failure of a part. Additionally, aerospace parts typically require extensive machining, as the parts tend to have complex geometries and the need to be as light as possible. With the cost of machining titanium being especially high and hard to justify, near-net shape processing is becoming particularly attractive.

Near-net shape processing is currently receiving global attention, especially in the aerospace industries. These processes convert the raw material into a near-net shape of the final part. Secondary processing, such as milling, is then used to convert the near-net shape to the final functional part. It results in shorter lead times, improved quality and reduced costs to manufacture a part. Various established manufacturing techniques can be used to realise near-net shape processing, such as certain metal forming and material removal processes. As metal forming techniques generally require either large forces or elevated temperatures, the focus of this study is placed on material removal processes. More particular, the focus is placed on Abrasive Water Jet Cutting (AWJC), as this process is considered a cold process, with parts machined using this process typically having no heat-affected zone. This is particularly attractive to the aerospace industry, as it entirely eliminates the possibility of alpha-case forming, but many aspects about this cutting technology is still under development.

The goal of this study is to investigate AWJC for the purpose of near-net shape processing of titanium aerospace parts. This is done by means of an explorative case study of a typical aerospace component. A candidate aerospace part used by a major aircraft manufacturer is used as concept demonstrator. The argument is presented that AWJC is a suitable technology to reduce manufacturing cost and lead time for Ti-6Al-4V aerospace parts. This is achieved by reducing the amount of machining required by implementing AWJC as a near-net shape processing technique. This enables a more cost effective manufacturing technology that could improve the competitiveness of South African aerospace part manufacturers in global aerospace supply chains.

2 CHALLENGES OF TITANIUM MACHINING

Ti-6Al-4V is the most commonly used titanium alloy in aerospace applications. This is an alpha + beta alloy. The alpha-phase is stable below the transition temperature of 882˚C. Above this transition temperature the crystal structure changes from hexagonal close packed to a body centred cubic structure [1]. If the alloy is heated to beyond the transition temperature during manufacturing, oxygen is absorbed into the crystal structure causing severe microstructural change. The most important effect of this microstructural change is the severe degradation of fatigue properties. The failure mechanism is the formation of an oxygen enriched outer layer referred to as alpha-case. This alpha-case layer is hard and brittle and serves as crack initiation sites for fatigue cracking. It is therefore of critical importance to limit temperatures during manufacturing process to below the transition temperature [2] [3].

Titanium is regarded among machinists and researchers as a difficult-to-machine material. Its thermal properties contribute largely to this phenomenon. Table 1 illustrates that Ti-6Al-4V has a lower thermal conductivity than the referenced materials, namely 11% of that of

AISI 1018 steel and 1/25th of 6061 aluminium. In titanium machining the low thermal conductivity tends to accumulate heat in the cutting zone that leads to high local temperatures. This leads to a high risk for alpha-case to develop [4].

From Table 1 it can be seen that the specific heat (c), or heat storage capacity, of Ti-6Al-4V is relatively large, being 27% higher than for the referenced steels. The thermal diffusivity ($\alpha = \lambda/\rho c$) is the ability of the metal to adapt its temperature to that of its surroundings. Again it can be seen from Table 1 that the thermal diffusivity of Ti-6Al-4V is only 1/8th of that of AISI 1018 steel. This causes the alloy to accumulate heat locally, increasing tool wear and the risk of microstructural degradation. Titanium is an exceptionally reactive material at elevated temperatures. This reactivity with tool materials, such as Tungsten Carbide, is responsible for accelerated tool wear [5].

Table 1: Thermal properties of Ti-6Al-4V and comparative materials [6]

Material	Thermal conductivity	Density	Specific heat	Thermal diffusivity
	λ (W/m°C)	ρ (kg/m^3)	c (J/kg°C)	α (m^2/s)
Ti-6Al-4V	6.7	4430	586	0.0258
Inconel 718	12.1	8190	435	0.0340
AISI 4340 Steel	33.4	7830	460	0.0925
AISI 1018 Steel	59	7850	460	0.165
Al 2024	164	2780	883	0.666
Al 6061-T6	177	2710	892	0.733

Considering the challenges of titanium machining, especially the high strength alloys, the value of avoidance of machining by near-net shaping is considerably larger than in the case of other, less difficult to machine, alloys. In South Africa, techniques that are researched in Europe for near-net shaping application, such as rotary forging, have limited value, due to high capital costs and lack of subsequent support infrastructure. On the other hand, AWJC is well established in South Africa. Therefore this explorative study is considered to be valuable specifically in South Africa.

3 BACKGROUND OF ABRASIVE WATERJET CUTTING

AWJC is a non-traditional method of machining that offers a productive alternative to conventional machining techniques. AWJC uses a fine, high-pressure, high-velocity stream of water directed at the work surface to cause cutting of the work piece, with abrasive particles added to the stream to facilitate cutting. The cutting power is obtained by means of a transformation of a hydrostatic energy into a jet of sufficient kinetic energy to disintegrate the material [7].

Various variables have to be considered during machining, the most dominant being the waterjet pressure, the traverse speed of the nozzle and stand-off distance [8]. These variables are illustrated in Figure 1.

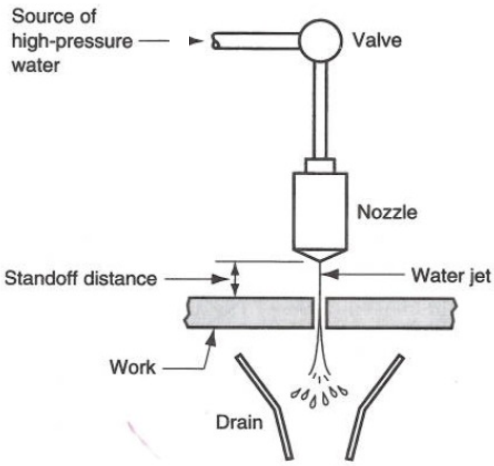

Figure 1: Waterjet cutting process [7]

3.1 Advantages

- No heat effected zones [9]
- Low machining forces [10]
- Current AWJC technology is a full-scale production process with precise, consistent results [11]
- Technology widely available [7]

3.2 Disadvantages

- Issues with dimensional accuracy due to cutting jet variation and striation, which is visualised in Figure 2 [12].
- Limited depth of cut, can cut material ranging from 1.6 to 300mm in thickness with a tolerance of ±0.05mm [11].
- Abrasive particle embedment in surface [13].
- Secondary processing usually needed to remove abrasive particles embedded in work piece surface [13].
- Disposal of the sludge of metal and abrasive particles after processing [11].

3.3 Profile of cut

There are three stages during the AWJC process, with each having different characteristics that have to be considered during the process design.

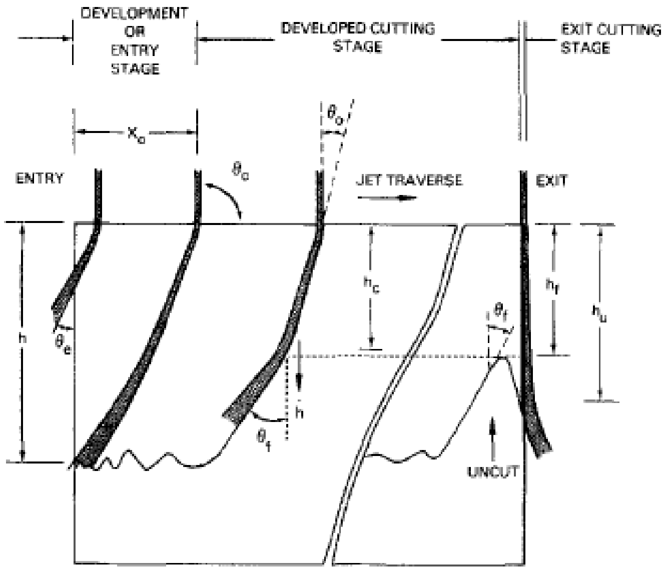

Figure 2: Profile of a cut using AWJC [14]

3.3.1 Profile of cut

3.3.1.1 Development of entry stage and penetration

The first step in the AWJC process is the entry, or penetration stage. The jet stream has to penetrate the material surface before linear cuts can be made. For material with a hard hardness, the penetration can be difficult. The upper hardness limit for material to be machined using AWJC is typically around 55-60 Hardness measured on the Rockwell C scale (HRC). The nozzle traverse speed has to be reduced to almost stationary, until the jet stream penetrates the entire required depth or thickness of the workpiece. After penetration, the jet stream will be deflected on the uncut material in the cut plane [14]. The entry stage lasts until the jet stream reaches the desired depth of cut.

3.3.1.2 Developed cutting stage

After the development stage, the nozzle traverse speed is kept constant and the jet stream is entirely contained in the cutting plane in the material. This results in a constant depth of cut and consistent surface quality.

3.3.1.3 Exit cutting stage

When the jet stream reaches the proximity of the exit face of the material, the jet stream will tend to exit the material before the full depth of cut is realised. This results in an uncut triangular shape on the material, where the jet traverse speed has to be reduced to remove the excess material to ensure consistent surface quality.

3.3.2 Different depth zones in the kerf

The kerf can further be described in 3 distinct zones, when viewed perpendicular to the cutting plane.

$$D = C\left(\frac{qP}{Va}\right) \quad \textbf{(1)}$$

Equation 1 describes the full depth of cut for a single pass of the water jet. From literature it is seen that the depth of cut is primarily dependent on the waterjet pressure (P), nozzle traverse speed (V) and abrasive flow rate (q). Coefficient C and exponent a are a function of the abrasive and workpiece materials and the nozzle geometry. These constants can be determined through experimentation [15].

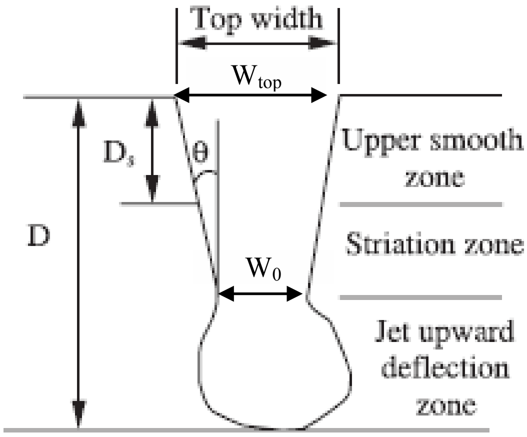

Figure 3: Schematic drawing of kerf geometry [16]

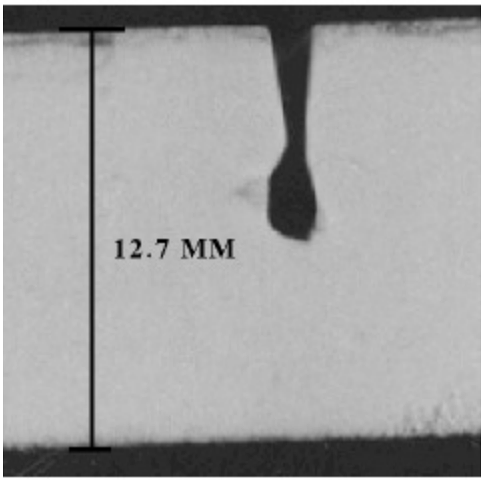

Figure 4: Kerf profile after single pass of AWJ at V = 200 mm/min and P = 345 MPa [16]

3.3.2.1 Upper smooth zone

The upper zone is characterised by a tapered zone from the surface of the part. The depth of the upper zone can be calculated using equation 2. The taper angle can be calculated using equation 3. W_{top} and W_0 can be taken as a constant, and vary little as water pressure, traverse speed and abrasive flow rate change.

$$D_S = C\left(\frac{qP^b}{V^a}\right) \quad \textbf{(2)}$$

$$\cot(\theta) = \frac{2D_S}{W_{top} - W_0}$$

(3)

3.3.2.2 Middle striation zone

The middle zone is characterised by perpendicular cuts, with visible striations originating here. W_0 remains virtually constant and surface roughness tends to be good [17]. As stated W_0 appears to remain constant as water pressure, traverse speed and abrasive flow are changed.

3.3.2.3 Jet upward deflection zone

The lower zone is characterised by a rough and fairly unpredictable surface finish. The lower zone tends to have visible jet striations and variation, which tend to increase as depth is increased. As traverse speed is decreased, the surface quality is increased, as seen in Figure 6. It is possible to eliminate this zone entirely, if the upper and middle zone is extended to the bottom of the cut, when making a through cut, as illustrated in Figure 1.

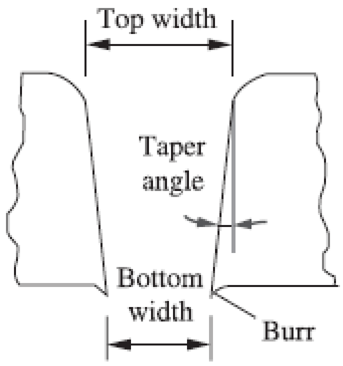

Figure 5: Through cut using AWJC [16]

4 MAIN FACTORS TO CONSIDER DURING AWJC

4.1.1 Traverse speed

The traverse speed is the speed of the nozzle of the waterjet cutter relative to the work piece. The choice of traverse speed is paramount, as it is the operative mechanism of material removal and thus influences the material removal rate. The traverse speed also has a strong influence on surface finish. The surface waviness can be reduced if the traverse speed is decreased and the surface roughness is not strongly dependent on traverse speed [18].

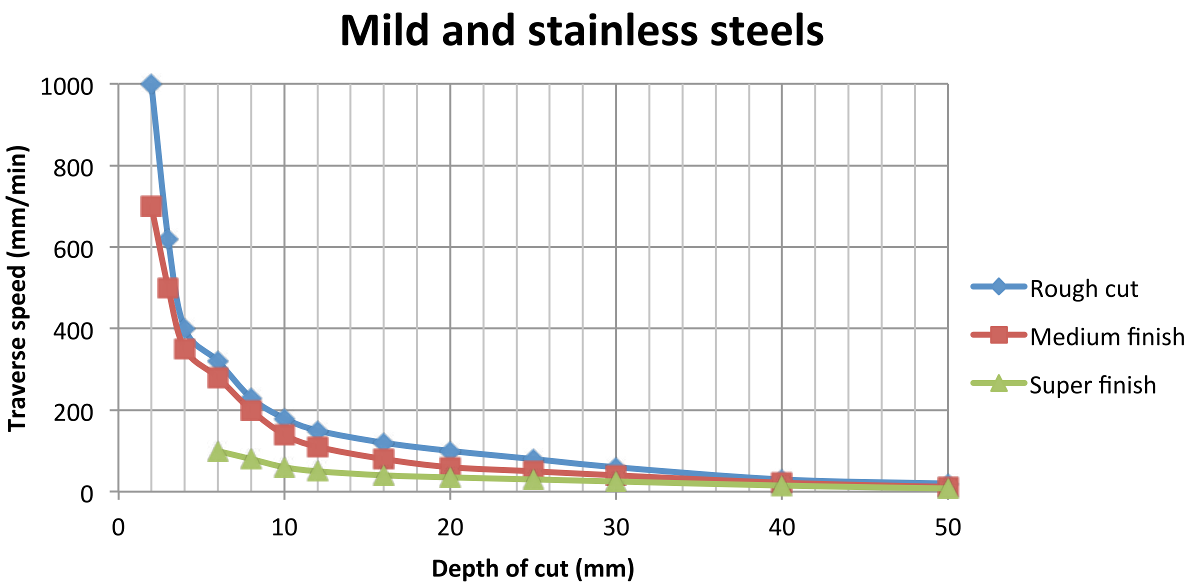

Figure 6: The traverse speed with different surface finishing and depth of cuts

4.1.2 Stand-off distance

The stand-off distance is the distance the waterjet has to travel from the nozzle to the workpiece. From work done by Fowler, et al [19], the material removal rate is insensitive to a stand-off distance between 2 mm and 5 mm and is at a maximum in this region. It should be noted that a decrease in stand-off distance results in an increase in the depth of cut with a smoother surface finish, and a decrease in kerf taper and surface roughness [16].

4.1.3 Abrasive particles and flow rate

There is a wide variety of abrasive particles available for AWJC, and the selection of particles is often based on economics rather than performance. The two parameters of abrasive particles that have the biggest influence on the process are grit size and hardness. Harder particles tend to have a larger material removal rate, but tend to embed into the surface of the work piece [13]. Examples of abrasive particles that can be used for AWJC include garnet, glass beads, AlO_3 (white), AlO_3 (brown) and steel shot.

4.1.4 Secondary processing

Secondary processing has a significant role in near-net shape processing. In most cases near-net shape processing is only used as a roughing operation, to eliminate the use of expensive roughing tools and extensive machining times on milling machines. A study done at an industry partner shows that approximately 73% of the time to machine the test part (Figure 7, left) on the CNC milling machine is spent on a single roughing operation. As the AWJC operation has certain quality concerns with respect to dimensional accuracy as depth is increased, material compensation has to be done that the part can still be machined to specification. The AWJC process also requires secondary processing to remove the embedded abrasive particles in the surface of part and localised surface hardening [20]. Figure 7 shows the difference between the finished test part, and the near-net shape part with material compensation.

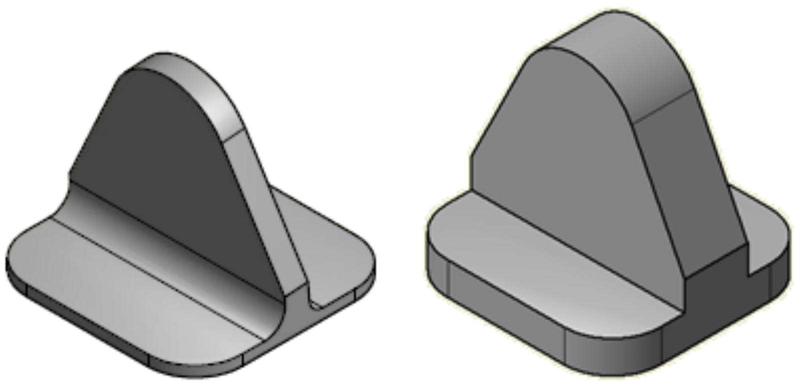

Figure 7: Finished test part (left) and near-net shape part (right)

The current process to create the test part requires 156 minutes machining time, of which 113 minutes is spent on the roughing process. When using AWJC it requires an estimated 23 minutes to produce the near-net shape part, with secondary processing taking an estimated 42 minutes. The result is an expected 42% reduction in lead time to produce a test part.

5 RESULTS

AWJC is a suitable candidate for the near-net shape processing of Ti-6Al-4V aerospace parts, provided that the geometric features of the parts do not require a depth of cut larger than 300mm [11]. The process has some tolerance issues when making deep cuts in some material, as well as impingement of abrasive particles in the surface of the workpiece. As the AWJC technology is intended as a near-net shape technology in this study, secondary processing is used to machine the part into its final shape. This processing also removes the impinged particles on the surface of the material, removes any localised surface hardening and removes all the geometrical issues with jet striation, provided adequate material compensation is provided [21]. AWJC results in a more energy efficient production method than conventional milling, as bulk sections of the material can be removed, whereas with milling the bulk sections of the material is simply converted to chips.

6 CONCLUSION

In the goal of this study and the introduction, the challenges of titanium alloy machining in aerospace applications have been discussed. A prominent challenge is to prevent heat degradation and related risk of fatigue failure of the final part. AWJC supports this objective by being a low temperature process with no risk of adverse microstructural change.

Replacing machining with AWJC results in inherent cost savings due to bulk section removal rather than reducing the workpiece section to chips. These inherent savings include the absence of cutting tool wear, with slag removal being similar to cutting fluid disposal. As energy is only applied to cut along specific lines and not to convert the entire material section to chips, energy is applied more effectively. For similar reasons the lead time for primary material removal is reduced.

As discussed in the paper the AWJC process also exhibits some disadvantages. The primary disadvantage is the limited depth of cut. At larger depths, the dimensional accuracy is adversely affected due to jet striation. Slag removal is a necessary disadvantage due to silicates as well as metallic compounds present in the slag. Another constraint to be considered is the impingement and embedment of silicate particles in the workpiece surface. This process requires secondary processing, namely machining, to create the final form of the part. Ultimately disadvantages such as dimensional accuracy and particle embedment become process constraints that are negated by secondary processing.

The conclusion can be reached that where part geometry enables AWJC as a near net shaping process for titanium aerospace parts, it is a suitable and more favourable alternative than machining processes.

7 RECOMMENDATIONS

It is recommended that the use of multiple passes of the jet stream be investigated, which has the possibility to improve surface quality and dimensional accuracy. This could reduce the amount of material compensation needed, resulting in less material being removed through secondary processing. Further experimentation is needed to investigate and validate the expected lead times and costs, to be able to study the economic feasibility of implementing this method in the industry.

8 REFERENCES

[1] **M. Donarchie,** Titanium: A Technical Guide, ASM International, 2000.

[2] **A. McEvily**, "Failures in inspection procedures: case studies," *Engineering Failure Analysis,* vol. 11, no. 1, pp. 167-176, 2004.

[3] **G. Luthering and J. Williams**, Titanium, New York: Springer-Verlag, 2003.

[4] **S.-Y. Sung and Y.-J. Kim**, "Alpha case formation mechanism on titanium investment castings," *Material Science and Engineering A,* vol. 405, pp. 173-177, 2005.

[5] **I. Gurappa**, "An oxidation model for predicting the life of titanium components in gas-turbine engines," *Journal of Alloys and Compounds,* vol. 389, pp. 190-197, 2005.

[6] **W. Skliniarz and G. Smolka**, "Analysis of volume effects of phase transformation in titanium alloys," *Journal of Materials Processing Technology,* vol. 53, pp. 413-422, 1995.

[7] **M. P. Groover**, Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 3rd ed., Hoboken: John Wiley & Sons, 2007.

[8] **A. W. Momber and R. Kovacevic**, Principles of Abrasive Water Jet Machining, London: Springer-Verlag London Limited, 1998.

[9] **J. Singh and S. Jain**, "Mechanical Issues in Laser and Abrasive Water Jet Cutting," *JOM,* pp. 28-30, 1995.

[10] **G. Fowler, I. Pashby and P. Shipway**, "The effect of particle hardness and shape when abrasive water jet milling titanium alloy Ti6Al4V," *Wear,* no. 266, pp. 613-620, 2009.

[11] **A. Akkurt, M. Kulekci, U. Seker and F. Ercan**, "Effect of feed rate on surface roughness in abrasive waterjet cutting applications," *Journal of Materials Processing Technology,* no. 147, pp. 389-396, 2004.

[12] **F. Chen and E. Siores**, "The effect of cutting jet variation on striation formation in abrasive water jet cutting," *International Journal of Machine Tools & Manufacture,* no. 41, pp. 1479-1486, 2001.

[13] **G. Fowler, P. Shipway and I. Pashby**, "A technical note on grit embedment following abrasive water-jet milling of a titanium alloy," *Journal of Materials Processing Technology,* no. 159, pp. 356-368, 2005.

[14] **M. Hashish**, "Visualisation of the Abrasive-Waterjet Cutting Process," *Experimental Mechanics,* pp. 159-169, 1988.

[15] **L. Chen, E. Siores and W. Wong**, "Kerf characteristics in abrasive waterjet cutting of ceramic materials," *International Journal of Machine Tools for Manufacturing,* vol. 36, no. 11, pp. 1201-1206, 1996.

[16] **J. Wang, T. Kuriyagawa and C. Huang**, "An experimental study to enhance the cutting performance in abrasive waterjet machining," *Machining Science and Technology,* vol. 7, no. 2, pp. 191-207, 2003.

[17] **D. Arola and M. Ramulu**, "Material removal in abrasive waterjet machining of metals: Surface integrity and texture," *Wear,* no. 210, pp. 50-58, 1997.

[18] **A. Hascalik, U. Caydas and H. Gurun**, "Effect of traverse speed on abrasive waterjet machining of Ti-6Al-4V alloy," *Materials and Design,* no. 28, pp. 1953-1957, 2007.

[19] **G. Fowler, P. Shipway and I. Pashby,** "Abrasive water-jet controlled depth milling of Ti6Al4V alloy - an investigation of the role of jet-workpiece traverse speed and abrasive grit size on the characteristics of the milled material," *Journal of Materials Processing Technology,* no. 161, pp. 407-414, 2005.

[20] **D. Arola, M. McCain, S. Kunaporn and M. Ramulu**, "Waterjet and abrasive waterjet surface treatment of titanium: a comparison of surface texture and residual stress," *Wear,* no. 249, pp. 943-950, 2002.

[21] **P. Shipway, G. Fowler and I. Pashby**, "Characteristics of the surface of a titanium alloy following milling with abrasive waterjets," *Wear,* no. 258, pp. 123-132, 2005.