INVESTIGATION OF SURFACE MOPHOLOGY AND INTEGRITY IN MULTI AXIS ABRASIVE WATERJET MACHINING (AWJM)

Conference Paper · November 2018

2 authors:

Yigit Ozcan
Sabanci University

Taner Tunc
Sabanci University

INVESTIGATION OF SURFACE MOPHOLOGY AND INTEGRITY IN MULTI AXIS ABRASIVE WATERJET MACHINING (AWJM)

Yigit Ozcan[a], **Lutfi Taner Tunc**[a]

a, Integrated Manufacturing Technologies Research and Application Center, Faculty of Engineering and Natural Sciences, Sabanci University, yigitozcan@sabanciuniv.edu
b, Integrated Manufacturing Technologies Research and Application Center, Faculty of Engineering and Natural Sciences, Sabanci University, ttunc@sabanciuniv.edu

Abstract

Abrasive particle embedment leads to surface issues in AWJM, which may require further surface treatment, delamination in composites and decrease in fatigue life of metals are major consequences. In this paper, abrasive particle embedment and morphological effects after AWJM of Al6061-T6 are investigated experimentally. It is observed that increase in feed rate, lead and tilt angles reduces waviness. It is also seen that distance between two valleys in cross feed direction is equal to two times step length if step length is given lower than nozzle diameter. It is found that embedded grits are much lower than the average abrasive sizes. Exothermic reaction was seen in some experiments, resulting in melt pools as observed in SEM and EDX.

Keywords: Abrasive water jet machining (AWJM), Surface morphology

1 Introduction

AWJM enables machining of difficult-to-cut materials such as Ni and Ti alloys, Ceramics, etc. It exerts relatively low machining forces compared to conventional machining with a very small heat affected zone. Main parameters governing the cut are jet feed rate, standoff distance, pressure, abrasive flow rate, nozzle and orifice diameter, and abrasive mesh size. AWJM is prone to demonstrate several problems in surface quality and cutting efficiency such as tapered kerf, roughness and waviness on the kerf profile and grit embedment.

Surface morphology is an issue in AWJM, especially for controlled depth milling because jet is not rigid like in conventional mills. According to Ramulu et al.[1] , surface hardness is a one of the main parameters effecting erosion rate and hence the surface morphology. Fowler and Shipway [2], investigated the effects of abrasive size, feed and number of passes on surface morphology in controlled depth AWJM. Increased abrasive size increased roughness and waviness, while increased number of passes decreased waviness. Wang et al. [3] suggested that kerf profile can be modelled in the form of parabola. Due to the nature of abrasive water jet machining process, both erosion and deformation occur on the workpiece, which may result in undesired surface defects such as cracks, domes, ribs etc. When employing abrasive particles on the cut surface, containment may also occur through the depth, which is "grit embedment". It is a serious drawback of AWJM because it may lead to reduced fatigue life, residual stress on the surface, delamination on composite materials [4]. In previous studies on grit embedment, there are important results providing insight about mechanism and specific parameters leading to particle contamination.

In an experimental investigation done by G.B. Stachowiak and G.W. [5], it was found that type of the particle affects cut surface smoothness significantly due to particle morphology and structure. According to these different particles, while more rounded shape particle has less tendency to embed on the surface, harder particles produces more embedding. Shipway et al. [6] observed embedment with respect to different number of passes, grit size and impingement angle. They found out that number of passes does not affect embedment, and grit size has a small effect on ratio of embedment, but it is not the case for the depth of embedded particle. It was mentioned that embedment of particle size is directly related with the momentum of the particle.

Additionally, in this study, it was shown that reducing angle of attack of the particle can decrease the ratio of embedment from 36% to 5%. However, it is also mentioned that even the small amount of embedment may be the source of fatigue failure. Kong and Axinte [7] studied AWJM on Ti-Al alloy. They realized that there are also grit embedment on the kerf side planes. Another study by Boud et al. [8] done on Ti alloy supports such result. Additionally, in their study, they showed that embedding is highly correlated with angularity of the particle. It was thought because of the effect of ploughing for intricate shape particle is relatively higher than rounded ones. They observed most of the embedded particles at the bottom of the kerf. According to Getu et al. [9], lead angle is another parameter affecting embedment. They obtained better surface smoothness for the case of cutting in forward direction because of less embedding particle compared to backward direction. Their hypothesis relies on the fact that forward cutting leads to lower material removal rates, which needs quantitative result. They mentioned that embedded particles create resistance for drilling deep holes. According to Maruyama et al. [10], momentum of the abrasive particle, contacted number of particles with the surface in a specific time, elastic, yield and plastic behavior of particle and workpiece are the key parameters. According to their study, the velocity change of the particle with respect to its size is negligible. Therefore, the main reason in embedding in the context of momentum is due to size, and hence the mass of the particle.

Analysis of surface morphology is one of the important topics for AWJM. Kong et al. [11] investigated the erosion and wear mechanism in metals. It was stated that plastic side flows or ‘micro swelling’ occurs around embedded grits. In the case of low angles on jet axis, the abrasive particle generates microchips and stick on the surface. At high feed rates, due to short exposure time, the abrasive particle is not able to generate ‘deformation wear’, there is not much contamination at the bottom sections of the kerf. However, embedment can be observed in rough cutting region at lower feed rates. The cut region on the workpiece is critical. If edge or corner region of the workpiece is to be cut, it should be noted that particles may not escape, resulting in embedment. However, it is not the case for middle portion of the workpiece due to same reason [12]. Henceforth, the paper is organized as follows; In Section 2 experimental procedure is presented, which is followed by results and discussion in Section 3. Then, conclusions of the study are given in Section 4.

2 Experimental Procedure and Materials

In the experiments Al6061 T6 is used. Though it is an easy-to-cut material and there are no challenges in high-speed milling, the aim of the experiments was to observe the effect of AWJ milling on the surface integrity and morphology. Further phase of the experiments needs to be performed on Ni alloys to demonstrate industrial validity.

Parameter	Level 1	Level 2	Level 3
Feed rate (mm/min)	1000	2000	3000
Lead Angle (deg)	0	10	-
Tilt Angle (deg)	0	10	-

Table 1: Levels and values of process parameters for Aluminum 6061 T6.

In AWJ machining, controlled depth milling is an important approach to generate surface features. Therefore, grit embedment needs to be investigated to get insight into preferable parameters for different materials. In this early phase of experiments, the parameters were kept limited to feed and impingement angle as listed in Table 1. However, pump pressure, abrasive flow rate and stand-off distance are the other important parameters. As full factorial experimental design is costly, a level is changed at a time to build the experiment matrix (see Table 2). There are 5 cutting experiments, where at each experiment the part is water jet milled by 20 consecutive cutting passes to generate a surface for investigations.

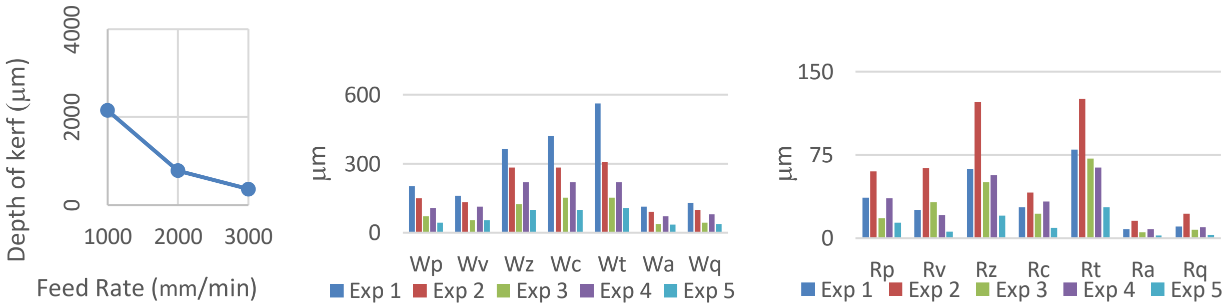
Experiment Number	Feed Rate (mm/min)	Lead (deg)	Tilt (deg)	Rz in Feed direction (µm)	Wz in Cross feed direction (µm)	Max Depth of cut (µm)
1	1000	0	0	62	362	2151
2	2000	0	0	123	283	786
3	3000	0	0	50	125	366
4	1000	0	10	57	220	625
5	1000	10	0	20	98	1089

Table 2: Experimental Conditions.

In cutting tests, KMT 3800 bar Double Intensifier Pump on KUKA KR16-F robot is used. Abrasives were Si based garnet, used at a rate of 2.4 g/s. Sample size is 35x19x6 mm^3. Surface morphology is measured by Nano Focus µsurf Non-Contact 3D Profilometer. Surface integrity is analyzed by Leo Supra 35VP Field Emission Scanning Electron Microscope (SEM) and elemental analysis of abrasives is done by using Energy-Dispersive X-ray (EDX). Zig-zag tool path pattern is selected to distinguish the tool passing points in SEM observations. The step over among the cutting steps was 0.5 mm. For analysis, the specimens are sectioned after cuts.

3 Results and Discussion

In surface morphology analysis, the geometry of the resulting surface is investigated in terms of kerf profile. Roughness along feed direction and waviness along cross feed direction are measured. Surface integrity analysis were performed to investigate the grit embedment and cracking issues.



(a) Feed rate versus kerf depth. (b) Variation of waviness. (c) Variation of roughness.

Figure 1. Variation of surface morphology among experiments.

3.1 Surface Morphology

At each cutting pass, the jet produces a kerf profile, which is over machined at the consecutive step, leading to a new kerf profile. The nozzle diameter is 0.75 mm, where the jet was observed to scatter by 5 degrees of angle, α, after focusing nozzle. 2500 MPa of pump pressure was used. Standoff distance, h_{st}, was set at 3mm as literature. By known process parameters, the kerf width, w, can be approximated as follows;

$$w = d + 2 * h_{st} * \tan\left(\frac{\alpha}{2}\right) \tag{1}$$

In Equation (1), approximately 1 mm of kerf width was expected in the experiments. However, the obtained surface can be different in multiple pass AWJ milling due to overlapping. As the cuts are performed done with same step length, the profile in cross feed direction is expected to demonstrate a periodic trend. Assuming a sinusoidal shape for the kerf with amplitude of depth *a*, successive surface profile, y(x), is obtained as follows;

$$y(x) = \sum_{i=0}^{n-1} -a \left| \sin\left(\frac{\pi}{w} * (x - i * s) \right) \right| \tag{2}$$

where a is kerf depth, i is the step number, s is the step length. For the cases, where s<w period of kerf depth is equal to two times step length, $2s$. It is also verified by experiments. The measured kerf profiles are shown in Figure 2, where the distance between each cut step is measured as 1 mm.

A clear relation between jet feed rate and waviness in cross feed direction was observed. Since exposure time at a specific point is high at low feed rate, depth of cut is higher, which increases waviness on the surface (see Table 2). The comparison is provided in Figure 1 and Figure 2. It was observed that feed rate does not affect roughness significantly, but kerf depth as seen in Figure 1a, b, and c. The variation of kerf depth with feed rate, for Experiment #1, #2 and #3 is plotted Figure 1a, where a nonlinear variation is seen.

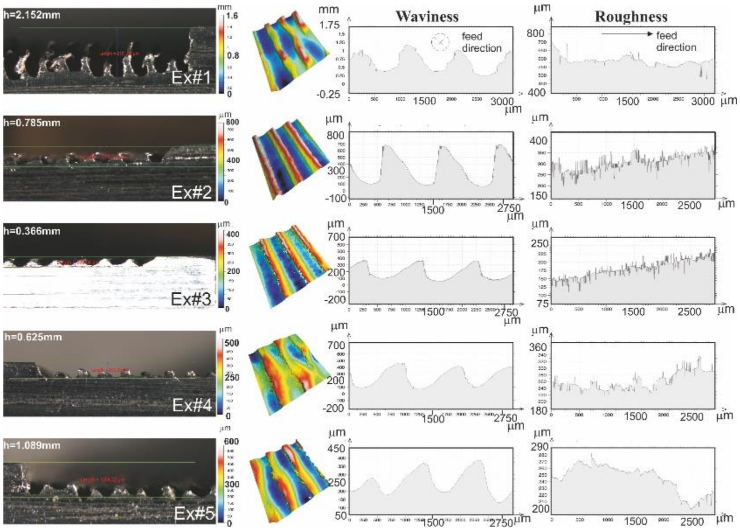
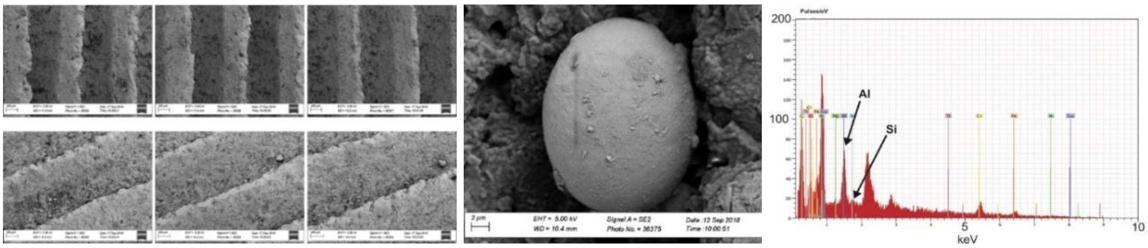


Figure 2. Measured kerf profiles in cross feed and feed direction.

The effect of jet axis can be clearly observed by comparing Experiment #1 and #4 (lead angle), and Experiment #3 and #5 (tilt angle). It was observed that increasing lead and tilt angle affects the kerf width and depth. When the jet axis is tilted, as the exposure area and effective standoff distance increases, erosion rate in z- direction decreases. However, a positive effect on waviness was observed. Tilting results in erosion at the kerf sides, leading to decreased waviness. When the jet axis led, it has a positive effect on the surface roughness in feed direction and demonstrates a better erosion rate compared to the tilted case, i.e. comparison of Experiment #4 and Experiment #5. Leading the jet reduced the surface roughness.

3.2 Surface Integrity

In analysis SEM and EDS images are taken from top of the surface. In SEM screening, small intricate shapes are considered as Silicon and these can be classified to be garnet as most of the weight percentage of a garnet is Silicon. Such small shapes can be observed in Figure 3a, showing a wide view from top surface by SEM. It is required to define a metric to distinguish shape of garnet and other materials in the Al alloy, which does not include brittle particles. Thus, intricate stone like shapes are considered as cracked abrasives. The reason 'cracked' term is used is because of mesh size. In the experiments, 80 mesh number Garnet is used having average size around 180 to 200 microns. However, the embedded particles are much smaller than this range. In Figure 4, SEM images of Sample #1, #2 and #3 are shown together with the element specific pictures. In Figure 4a, an embedded grit is shown, where it's material specific pictures in Figure 4b, i.e. second and third columns, demonstrate that it's content is mostly Silicon (2nd row) but around there is Aluminum (3rd row). All EDS results supported the idea of classifying and identifying an embedded grit. One of the other methods to detect where embedment occurred is trying to capture scratched regions on the Aluminum surface. From Figure 4a, a typical scratch, and at the end of it, a groove can be seen clearly. At the 30 microns left upper portion, a particle with similar shape of the groove is stuck, which is a good sign to analyze. At the below part of same figure, zoomed in portion of the particle is analyzed. Figure 4b shows Al dense regions in second row and Si dense regions in third row areas. Also, compositions of other materials can be seen in Figure 4c and Figure 4d, respectively. It is noteworthy to state that Si ratio differs when the screening is done in a zoomed area compared to a zoomed out area. Similar types of embedment are also given in Figure 4e.



(a) Top view of successive kerfs. (b) Typical melt pool (c) EDX plot for melt pool.

Figure 3. Kerf views and melt pool.

In the first experiment, exothermic reaction in the form of sparks are observed, by naked eye. SEM analysis showed some melt pools (see Figure 3b). The composition plot of the corresponding melt pool is shown in Figure 3c, where it is seen that Si ratio is very low compared to Al. The melt pool may occur due to the high kerf depth in cutting. In deeper cuts for AWJ, cutting process results in local temperature increases, where the surface cannot be cooled. As a result, exothermic reaction takes place leading to melting of the material.

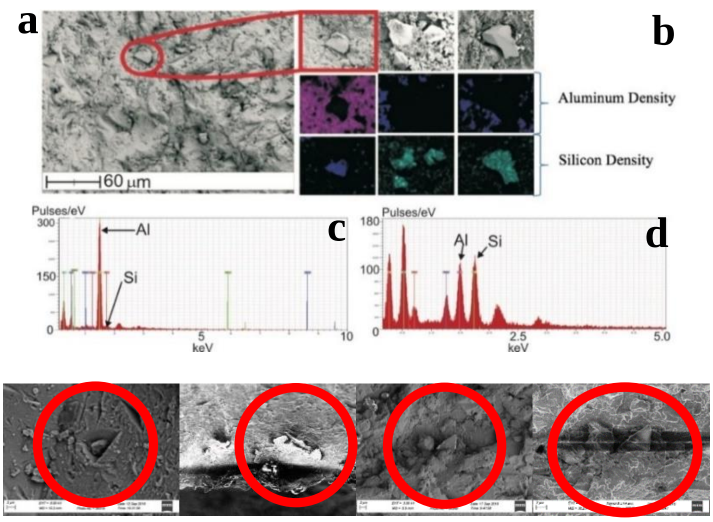


Figure 4. SEM Images for embedded grit (Purple- Al and dark blue - Si)

4 Conclusions

In this paper, early investigations of surface morphology and integrity achieved by AWJ machining was presented. Al6061 T6 was used in the experiments, though industrial application may need to be performed on Ni alloys to demonstrate the real benefits of the process in machinability aspect. The aim of the experiments was to observe the effect of feed rate and jet impact angle on the surface morphology and grit embedment. Feed rate, lead and tilt angles are effective parameters for roughness waviness and erosion rate in controlled depth AWJM. As exposure time decreases with feed rate, the erosion rate and hence the kerf depth decrease. It also decreases the surface waviness but does not affect roughness in feed direction. Tilt angle decreases erosion rate abruptly, due to decrease in effective velocity in z-direction. Also, it has positive effects in waviness along cross feed direction since jet exposure area increases material is removed on kerf sides leading to decreased kerf depth. Lead angle decreases erosion rate due to a similar reason. Lead and tilt angles decrease the roughness in feed direction, but tilt angle is not as significant as lead angle. It was observed that embedded particle size is much smaller than the average size of abrasives, which may be primarily due to fragmentation or only small particles embed. In some cases, melt pools were observed in very small areas.

5 Acknowledgments

The authors acknowledge the support of TUBITAK under grant no 217M704. The efforts of Mr. Ragıp Orkun Seçer and Dr. Leila Haghighi Poudeh for their technical support are also acknowledged.

6 References

[1] Ramulu, M., Raju, S. P., Inoue, H., Zeng, J. 1993. “Hydro-abrasive erosion characteristics of 30vol.%SiCp/6061-T6 Al composite at shallow impact angles”, Wear, cilt 166, sayı 1, s. 55–63.

[2] Fowler, G., Shipway, P. H., Pashby, I. R. 2005. “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, cilt 161, s. 407–414.

[3] Wang, S., Zhang, S., Wu, Y., Yang, F. 2017. “Exploring kerf cut by abrasive waterjet”, International Journal of Advanced Manufacturing Technology, cilt 93, sayı 5–8, s. 2013–2020.

[4] Axinte, D. A., Karpuschewski, B., Kong, M. C., Beaucamp, A. T., Anwar, S., Miller, D., Petzel, M. 2014. “High Energy Fluid Jet Machining (HEFJet-Mach): From scientific and technological advances to niche industrial applications”, CIRP Annals - Manufacturing Technology, cilt 63, sayı 2, s. 751–771.

[5] Stachowiak, G. B., Stachowiak, G. W. 2001. “The effects of particle characteristics on three-body abrasive wear”, Wear, cilt 249, sayı 3–4, s. 201–207.

[6] Shipway, P. H., Fowler, G., Pashby, I. R. 2005. “Characteristics of the surface of a titanium alloy following milling with abrasive waterjets”, Wear.

[7] Kong, M. C., Axinte, D. 2009. “Response of titanium aluminide alloy to abrasive waterjet cutting: Geometrical accuracy and surface integrity issues versus process parameters”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, cilt 223, s. 19–42.

[8] Boud, F., Carpenter, C., Folkes, J., Shipway, P. H. 2010. “Abrasive waterjet cutting of a titanium alloy: The influence of abrasive morphology and mechanical properties on workpiece grit embedment and cut quality”, Journal of Materials Processing Technology, cilt 210, sayı 15, s. 2197–2205.

[9] Getu, H., Ghobeity, A., Spelt, J. K., Papini, M. 2008. “Abrasive jet micromachining of acrylic and polycarbonate polymers at oblique angles of attack”, Wear.

[10] Maruyama, T., Akagi, K., Kobayashi, T. 2006. “Effects of blasting parameters on removability of residual grit”, Proceedings of the International Thermal Spray Conference.

[11] Kong, M. C., Axinte, D., Voice, W. 2011. “Challenges in using waterjet machining of NiTi shape memory alloys: An analysis of controlled-depth milling”, Journal of Materials Processing Technology, cilt 211, sayı 6, s. 959–971.

[12] Kong, M. C., Srinivasu, D., Axinte, D., Voice, W., McGourlay, J., Hon, B. 2013. “On geometrical accuracy and integrity of surfaces in multi-mode abrasive waterjet machining of NiTi shape memory alloys”, CIRP Annals - Manufacturing Technology.