Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 13 (2017) 679–686

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

Manufacturing Engineering Society International Conference 2017, MESIC 2017, 28-30 June 2017, Vigo (Pontevedra), Spain

Analysis of Alloy 718 surfaces milled by abrasive waterjet and post-processed by plain waterjet technology

A. Alberdi[a,*], A. Rivero[a], T. Artaza[a], A. Lamikiz[b]

[a] *Industry and Transport Division, Tecnalia Research & Innovation, Paseo Mikeletegi 7 – Parque Tecnológico, Donostia 20009, Spain*
[b] *Department of Mechanical Engineering, University of Basque Country UPV/EHU, Alameda Urquijo s/n, Bilbao 48013, Spain*

Abstract

This work analyzes the surfaces obtained in Alloy 718 when they are milled by Abrasive Waterjet (AWJ) at different conditions. This analysis revealed that all surfaces have a homogeneous roughness in the transversal and the longitudinal directions, present embedded abrasive particles and have hardened about 50% with respect to the untreated bulk Alloy 718. On the other hand, Plain Waterjet (PWJ) technology was used for removing the abrasive particles embedded in surfaces of Alloy 718 milled previously by AWJ technology. The effect of this process on the surface characteristics is also analyzed. For all tested conditions, this technology removed all the particles embedded in the surface. In addition, the PWJ technology process in general smoothened the surfaces produced by AWJ milling and it also released near-surface stresses.

Keywords: Waterjet, Alloy 718, post-treatment, milling, fatigue

1. Introduction

The number of aircrafts will be highly increased over the next 20 years according to the Airbus Global Market Forecast [1]. Regarding the increase of aircrafts (3.7% per year) resulting from the growth of air traffic per year (4.7% per year), in 2034 more than 38,000 aircrafts are estimated to be in service. Of these, 19,000 are necessary due to

---

* Corresponding author. Tel.: +34-943105115;
E-mail address: amaia.alberdi@tecnalia.com

2351-9789 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.
10.1016/j.promfg.2017.09.163

growth, whereas 13,000 will be replacement of actual airplanes, leading to 32,000 new aircrafts which need to be built.

This leads to a significantly increasing necessity of manufacturing high-temperature resistant materials used in the turbo-machinery. Heat-resistant superalloys such as Alloy 718 are commonly used in the aerospace sector, thanks to their unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance. The ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys. Thus, they are generally referred as difficult-to-cut alloys. Most problems encountered during machining are due to heat generation, mainly during the deformation process and friction at the tool–chip and tool–workpiece interfaces, and the consequent high temperatures associated with it. Other characteristics of aerospace superalloys include their austenitic matrix which make them harden rapidly; their ability to react with tool materials under atmospheric conditions; their tendency to form built-up edge and to weld to cutting tools; and the presence of abrasive carbides in their microstructure [2]. The associated manufacturing cost is high because of low material removal rates and rapid tool wear. The machining of these alloys is characterized by low productivity and low process stability as a result of their physical and mechanical properties [3, 4]. Major problems during the machining of these materials are very high thermal and mechanical tool loads, which results in low applicable cutting speeds due to excessive tool wear and long machining times, and thus, in high manufacturing costs [5-7].

The Abrasive Waterjet (AWJ) technology has a great potential for machining heat-resistant superalloys [8, 9]. Its main advantages for manufacturing these materials are its low tool wear, since it is a non-contact process, and its flexibility for application to different processes like cutting, milling, turning or peening.

One of the disadvantages of the use of AWJ technology for machining metal parts is the embedment of abrasive particles in the machined surface, since it may be detrimental for the fatigue life of the components [10]. In this regard, Huang et al. [11] demonstrated that it is possible to use the Plain Waterjet (PWJ) technology for cleaning the surfaces of Ti-6Al-4V with an alpha case layer machined previously with AWJ technology.

This work analyzes the surfaces obtained in Alloy 718 when they are milled by AWJ at different conditions of pressure (p), stand-off distance (s), traverse feed rate (v) and abrasive mass flow rate ($\dot{m}a$), in terms of surface roughness, sub-surface hardening and the degree of embedded abrasive particles. In addition, PWJ technology was used for removing the abrasive particles embedded in surfaces of Alloy 718 milled previously by AWJ technology. The effect of PWJ post-processing on the surface characteristics is also analyzed.

2. Experimental Procedure

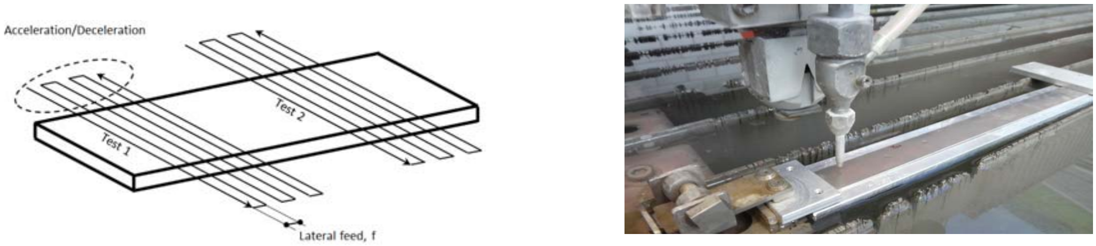
2.1. Materials and equipment

All experimentation was carried out in the Byjet L2030® waterjet cutting machine equipped with the Bypump 50APC® high pressure pump, which can reach a maximum working water pressure of 360 MPa. An orifice nozzle of 0.25mm in diameter and a focusing tube of 0.76mm were used as a tool. Same machine was employed for both AWJ and PWJ technologies, with the difference of not adding any abrasive particle to the waterjet in the case of PWJ.

The material used is annealed Nickel based Alloy 718 sheet with a thickness of 3.2 mm, with an ultimate tensile strength of 965MPa, a yield strength of 562MPa and an elongation of 44%.

2.2. Milling of Alloy 718 surfaces by AWJ

Alloy 718 surface areas of 30x20mm were milled by AWJ using different processing conditions. As a standard test condition, a pressure of 360 MPa, a traversal feed rate of 15 m/min, a mass flow rate of 300 g/min and a stand-off distance of 90 mm were established. In order to analyze the effect of these parameters, each parameter was varied at other two levels different to the standard condition stated in Table 1, which resulted in a total 9 different combinations. The lateral feed (f) of the toolpath was fixed for each stand-off distance in order to maintain similar overlapping areas between two adjacent tracks. In addition, the direction changes were programmed to be made outside the material surface in order to avoid the effects produced by the acceleration and deceleration of the cutting head (Fig. 1).



(a) (b)

Fig. 1. (a)Milling tool paths; (b) Experimental set-up;

2.3. PWJ post-processing

For demonstrating the viability of removing embedded abrasive particles by PWJ technology, first, 9 different areas of 20x30mm were milled in Alloy 718 by AWJ technology employing standard conditions (p=360MPa, s=90mm, v=15m/min and $\dot{m}_a$=300 g/min), whose average area with embedded abrasive particles resulted in 19.4%. Then, these areas were post-processed by PWJ technology. As a standard post-processing condition, a pressure of 360 MPa, a stand-off distance of 10 mm, a traverse feed rate of 500 mm/min, and 1 number of passes (n) was established. In order to analyze the effect of these parameters, each of these parameters were also varied at other two levels different to the standard condition stated in Table 1, resulting again in a total of 9 different test conditions.

Table 1. Definition of levels for each process parameter

Process parameter	Levels for AWJ milling tests			Levels for PWJ post-processing tests		
	1	2	3	1	2	3
$\dot{m}_a$ [g/min]	150	300	450	-	-	-
p [MPa]	160	260	360	160	260	360
v [mm/min]	5000	10000	15000	100	500	900
s [mm]	10 (f=0.2mm)	50 (f=0.6mm)	90 (f=1mm)	10	50	90
n [-]	-	-	-	1	2	4

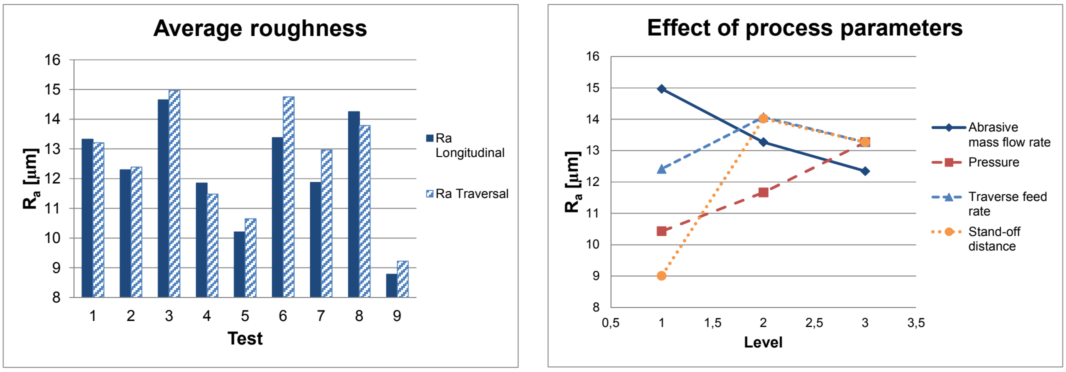
2.4. Surface analysis

The obtained surfaces were measured and analyzed in terms of roughness, sub-surface hardness and the embedment of abrasive particles. For measuring the topography of milled surfaces a Leica DCM 3D optical surface metrology system was used. The surface average roughness was evaluated in longitudinal and traversal direction to the machining path, using a Gaussian filter with a cut-off length of 0.8mm. For measuring the sub-surface hardness, polished cross sections were obtained and a Future Tech FM-800 micro-hardness tester was used starting at 1,500 µm far from the eroded surface up to a distance of about 20 µm close to it. Finally, surfaces were also analyzed by Scanning Electron Microscopy (SEM). Backscattered Electron Images (BEI) were taken for analyzing the percentage of the area embedded by abrasive particles. The images are analyzed using the software ImageJ according to the procedure described by Huang et al. [11], by filtering out the darkest zones corresponding to abrasive particles using a suitable threshold. The images were obtained and analyzed in three different positions of the samples.

3. Results and discussion

3.1. Characteristics of surfaces milled by AWJ

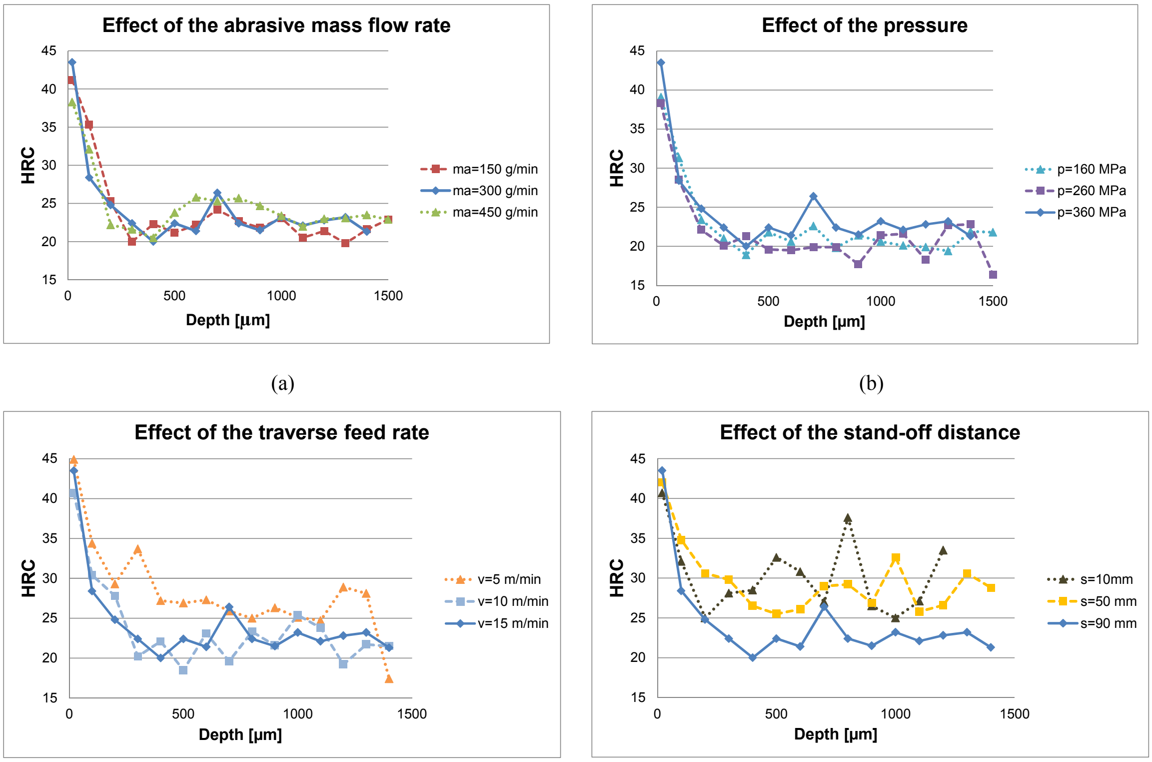
The surfaces milled by AWJ show similar characteristics to grit-blasted surfaces. The obtained average roughness values and the effect of process parameters are shown in Fig. 2. The results showed that the longitudinal and transversal average roughness have similar values, no effects of the tool path are observed. Thus, the surfaces present a homogenous texture. The average roughness of the surfaces varies from 9µm to 15µm, which are in agreement with the results obtained by Sadasivan et al [12] in Alloy 718. In addition, the abrasive mass flow rate, the pressure and the stand-off distance have a significant influence on the average roughness. In this study, the employed AWJ milling conditions corresponds to high traverse feed rates, where the eroded depths are low and thus, particle-substrate impact occurs at normal angles. In this case, the particle performs as an indenter with the depth and area of indentation dependent on the shape and size of the particle and its velocity [13]. Low velocity impact and small particles result in small indentations in the target material and thus, low values of surface roughness. At higher particle velocities and greater particle sizes, the indentations are correspondingly deeper and the surface roughness increases. According to the Bernoulli's law and the simple momentum-transfer model [14], there is a square-root relation between abrasive-particle velocity and the pressure. Therefore, an increase in the pressure leads to an increase in the surface roughness as observed in Fig. 2b. In addition, the results obtained in this study show that when increasing the abrasive mass flow rate, the roughness decreases. This can be explained by taking into account that for greater abrasive mass flow rate, there exist more collisions between different abrasive particles and their kinetic energy is wasted [15]. In addition, this collision also leads to a reduction in the size of the abrasive particles. In the case of the stand-off distance, a significant increase of the roughness was observed when increasing the stand-off distance from 10 to 50 mm. On the contrary, the roughness is reduced when increasing it from 50 to 90 mm. This may indicate that there exists an optimum for the stand-off distance where the momentum transfer from the water jet to the abrasive particles is the maximum, thus, the abrasive particles reach the highest possible velocity. If higher stand-off distances are employed, the abrasive particles start decelerating, decreasing the velocity impact and therefore, the roughness. This statement is in agreement with the model obtained in [16] for milling Aluminum 7075 by AWJ, which indicates that there exists an optimum value for the stand-off distance equal to 33mm which maximizes the Material Removal Rate (MRR) for similar processing conditions (p=360 MPa, $\dot{m}_a$=300g/min and v=800mm/min) used in the present study (p=360 MPa, $\dot{m}_a$=300g/min and v=5000mm/min). In this model it was not possible to use higher values of the traverse feed rate because they were out of the experimental window used in that study. However, similar conclusions would be obtained for higher traverse rates, since the velocity impact and the shape and size of the abrasive particles is independent to the traverse feed rate. The latter, is also reflected in Fig. 2b, which indicates that no clear effect of the traverse feed rate was observed.



(a) (b)

Fig. 2. Average roughness of surfaces milled by AWJ (a) Longitudinal and traversal directions; (b) Effect of the process parameters

According to Fig. 3, a hardness gradient is evident starting from a distance of around 300 µm, and increasing with proximity to the surface up to 40-45 HRC. This increase corresponds to a hardening of about 50% with respect to the untreated bulk Alloy 718 (20-25 HRC). The AWJ process is a combination of erosion and localized plastic deformation produced by abrasive particles impacts. The plastic deformation leads to an increase in the subsurface hardness and to compressive residual stresses. According to the literature [17], it is expected that the hardness gradient coexists with a significant gradient of compressive residual stresses. Although residual stressed were not measured, the curvature of the milled samples indicated a compressive residual stresses in the milled surface. Regarding the effect of process parameters, no significant effects of process parameters were observed within this experimental study. According to Arola et al. [18], the residual stresses are dependent to the pressure and to the abrasive particles size, which means that the same parameters who increase the roughness also increases the residual stresses and the sub-surface hardness. Therefore, a correlation between the surface roughness and sub-surface hardness may be observed. However, neither in this study nor in the study made by Huang et al. [11] this correlation was observed.



(a) (b)

(c) (d)

Fig. 3. Effect of process parameters on the subsurface hardness in surfaces milled by AWJ: (a) abrasive mass flow rate; (b) pressure; (c) traverse feed rate; (d) stand-off distance.

Finally, as occurred in grit blasting process, substrates subjected to AWJ milling also present abrasive embedment. Fig. 4 shows the results obtained and the effect of process parameters on the embedded area. The results show that all surfaces presented embedded abrasive particles, and that the surface area embedded with abrasive particles varies from 5% to 20%. In addition, when increasing the pressure, the traverse feed rate and the stand-off distance, the area percentage with embedded abrasive particles increases. On the other hand, the highest level of particle embedment occurred for an abrasive mass flow rate of 300 g/min.

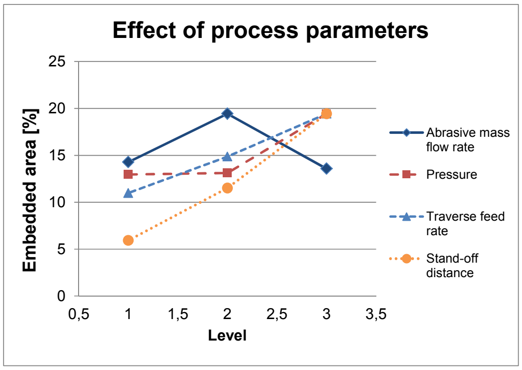
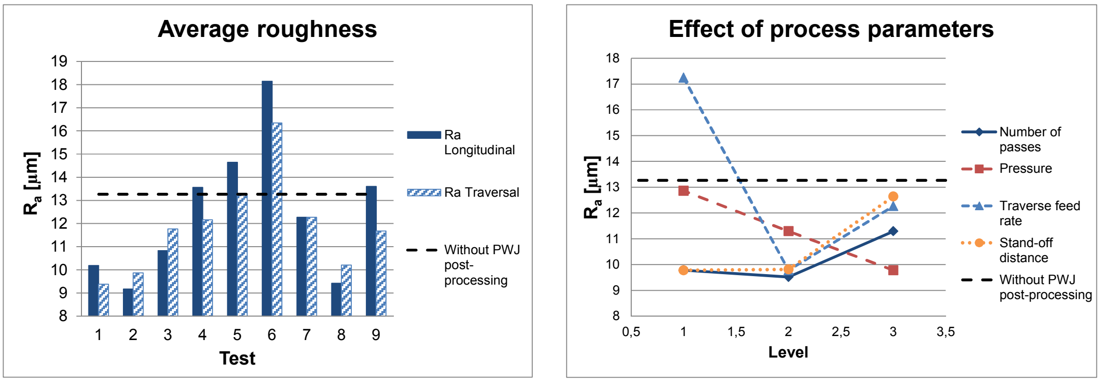


Fig. 4. Effect of the process parameters on abrasive particles embedment when milling by AWJ

3.2. Effect of PWJ post-processing

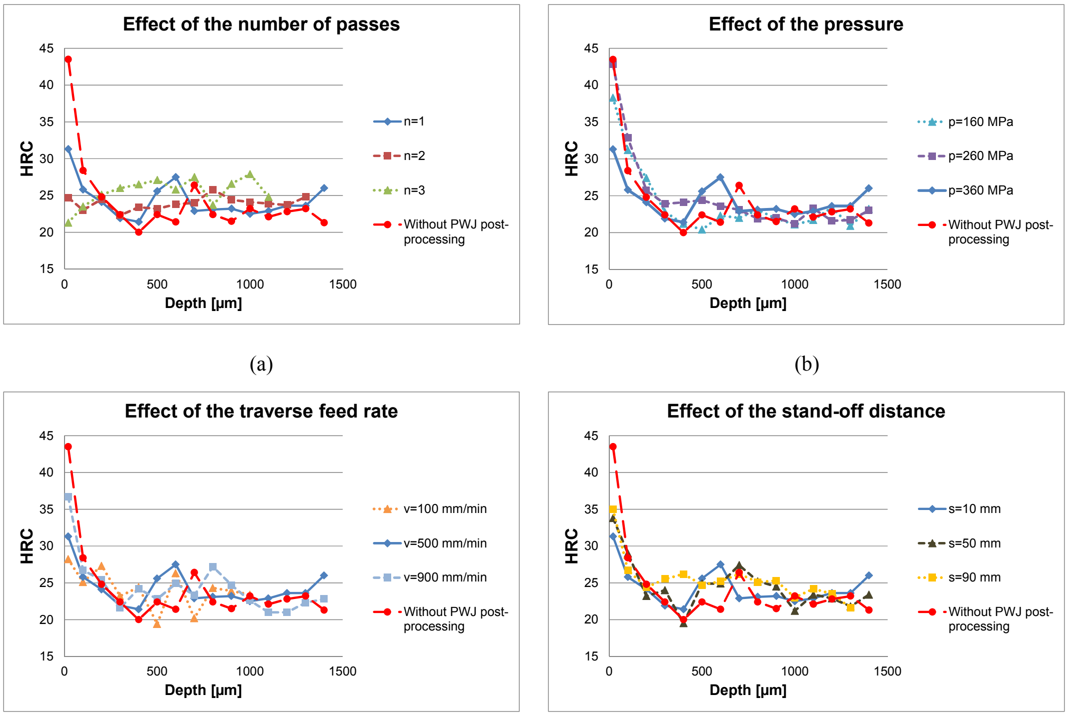
The obtained surfaces are macroscopically similar to the surfaces obtained when milling by AWJ, they present a homogenous texture. The average roughness of the surfaces varies from 9µm to 18µm and in general, the PWJ post-processing reduced the roughness produced during AWJ milling (Fig. 5a*).* This is because water droplets erode and deform the peaks and valleys produced by abrasive particles, which are the most sensitive areas of failure against the impact of water droplets. Thus, the PWJ tends to smoothen the surfaces milled by AWJ. However, this smoothening depends on the process parameters used during PWJ. According to Taylor [19], the roughness in PWJ is proportional to erosion of the substrate, and therefore it is proportional the hydraulic energy of the jet and the exposure time. When using low hydraulic energy (low pressure and high stand-off distance) and low exposure time (high traverse feed rate and low number of passes), the jet is not able to erode and deform the substrate, thus, very little reduction in the roughness is observed (Fig. 5b). On the contrary, when using high hydraulic energy (high pressure and low stand-off distance) and high exposure time (low traverse feed rate and high number of passes), this reduction is more evident since the jet is able to erode and deform more peaks produced by abrasive particles in the previous processing step. An increase in the roughness is observed when very low traverse feed rate is used (100 mm/min). This is because the roughness produced when using these processing conditions is higher than the roughness produced by AWJ milling. Thus, the resulting average roughness is the one corresponding to the PWJ processing.



(a) (b)

Fig. 5. Average roughness of surfaces post-processed by PWJ (a) Longitudinal and traversal directions; (b) Effect of the process parameters

The PWJ post-processing also reduced the subsurface hardness of the samples milled by AWJ. The material removal eroded by water droplets during PWJ post-processing lead to relief near-surface stress, and therefore, this erosion is the responsible of the reduction of the sub-surface hardness (Fig. 6). This reduction is more evident when high hydraulic energies (high pressure and low stand-off distance) and high exposure times (low traverse feed rate and high number of passes) are used.

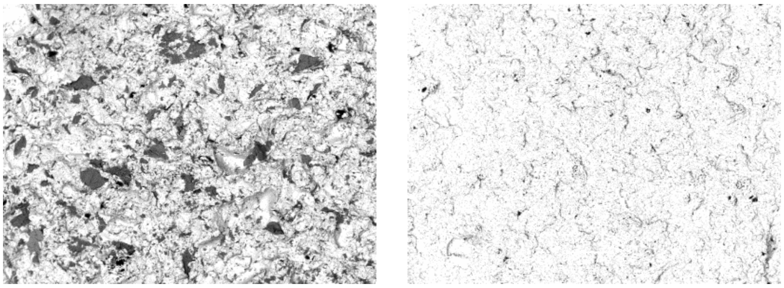


(a) (b)

(c) (d)

Fig. 6. Effect of process parameters on the subsurface hardness in surfaces post-processed by PWJ: (a) abrasive mass flow rate; (b) pressure; (c) traverse feed rate; (d) stand-off distance.

Finally, the images obtained (Fig. 7) and the chemical analysis done by the Energy Dispersive Spectrometer (EDS) reveal that there were no abrasive particles embedded in the surfaces. There are generally two types of embedment: deposited abrasives and submerged abrasives. The latter, are the most difficult to be removed according to Hashish [20]. However, thanks to the erosion produced by PWJ, the PWJ post-processing removed all abrasive particles embedded in the surfaces of Alloy 718 milled by AWJ. In submerged abrasives, the water droplets eroded first the metallic layer from the top of the particles, and then, removed the abrasive particle.



(a) (b)

Fig. 7. BEI images of: (a) AWJ milled surface; (b) PWJ post-processed surface

4. Conclusions

The analysis of milled surfaces revealed that all surfaces have a homogeneous roughness in the transversal and the longitudinal directions, which varies from 8 to 16 µm. In addition, all surfaces presented embedded abrasive particles, which can vary from 5% to 20% of the total surface area depending on process parameters. When increasing the pressure, the traverse feed rate and the stand-off distance, the area percentage with embedded abrasive particles increases. On the other hand, the abrasive mass flow rate does not show a clear effect on the area percentage with embedded abrasive particles. Finally, the milling process also produces a surface hardening of about 50% with respect to the untreated bulk Alloy 718 (20-25 HRC), which may indicate a significant gradient of compressive residual stresses. In this case, no significant effects of process parameters were observed.

The PWJ technology is applied for removing the abrasive particles embedded in the surfaces cut and milled by AWJ. For all tested conditions, this technology removed all the particles embedded in the surface. In addition, this process in general smoothened the surfaces produced by AWJ milling and it also released near-surface stress.

Acknowledgements

The authors acknowledge the support of the Ministry of Economy and Competitiveness of the Spanish Government for support of project EVOCA II (reference DPI2013-45308-P).

References

[1] Global Market Forecast 2015-2034. Airbus, a leading aircraft manufacturer. Available at: http://www.airbus.com/company/market/forecast/.
[2] E. O. Ezugwu, Int. J. Mach. Tools Manuf. 45 (2005) 12–13.
[3] E. O. Ezugwu, J. Bonney, Y. Yamane, J. Mater. Process. Technol. 134 (2003) 233-253.
[4] Q. Bayoun, L. Liang, H. Ning, Proceedings of 4th CIRP International Conference on High Performance Cutting, Gifu, Japan, 2010.
[5] N. Khanna, N. K. Sangwan, Proceedings of 4th CIRP International Conference on High Performance Cutting. Gifu, Japan, 2010.
[6] N. Corduan *et alm,* CIRP Ann. 52 (2003) 73-76.
[7] F. Klocke, H. Sangermann, A. Krämer, D. Lung, J. Eng. Manuf. 225 (2011) 1.
[8] G. A. Escobar-Palafox, R. S. Gault, K. Ridgway, Proc. CIRP. 1 (2012) 404-408.
[9] M. Ay, U. Çaydaş, A. Hasçalik, Mater. Manuf. Process. 25 (2010) 1160-1165.
[10] F. L. Chen, E. Siores, K. Patel, A. W. Momber, Int. J. Mach. Tools Manuf. 42 (2002) 1385-1390 2002.
[11] L. Huang, P. Kinnell, P. H. Shipway, Proc. CIRP. 6 (2013) 594-599.
[12] B. Sadasivam, A. Hizal, D. Arola, Int. J. Mach. Tools Manuf. 49 (2009) 134-141.
[13] P. H. Shipway, G. Fowler, I. R. Pashby, Wear. 258 (2005) 123-132.
[14] A. W. Momber, R. Kovacevic, Principles of Abrasive Water Jet Machining. Springer, 1997
[15] A. Tazibt, F. Parsy, N. Abriak, Comput. Mater. Sci. 5 (1996) 243-254.
[16] A. Alberdi, A. Rivero, L. N. L. de Lacalle, I. Etxeberria, A. Suárez, Int. J. Adv. Manuf. Technol. 51 (2010) 467-480.
[17] D. Arola, A. E. Alade, W. Weber, Mach. Sci. Technol. 10 (2006) 197-218.
[18] D. Arola, M. L. McCain, S. Kunaporn, M. Ramulu, Wear. 249 (2001) 943-950.
[19] T. A. Taylor, Surf. Coatings Technol. 76-77 (1995) 95-100.
[20] M. Hashish, J. Eng. Mater. Technol. 113 (1991) 354-362.