Effect of Process Parameters on Abrasive Water Jet Plain Milling

S. J. Ebeid[1], M. R. A. Atia[2], M. M. Sayed[1]
1. Design and Production Dept., Faculty of Engineering, Ain Shams University, Egypt.
2. Mechanical Engineering Dept., Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport (AASTMT), Sheraton, Cairo, Egypt.

1 Abstract

One of the most recent non-conventional shaping processes is the abrasive water jet shaping process. Abrasive water jet shaping has many beneficial parameters such as shaping the various materials; hard to soft; electrically conductive to insulators, flexibility in shaping, small cutting forces and rapid to shape. The abrasive water jet shaping of materials has various variables and parameters. This work focuses on which of the process variables affect the plain water jet (PWJ) milling process of pockets. In the focusing, machining process variables such as water jet traverse speed, water jet pressure, stand-off distance and abrasive flow rate have been investigated to study the effect of each on the PWJ milling process parameters. The water jet milling process is evaluated by examining the pockets' process parameters; namely depth of cut, surface roughness and material removal rate. The material used in the experimental investigation in this work is Aluminum alloy called Alumec 89.The analysis of the experimental results clears that the increase of the jet traverse speed yields a good surface roughness but inversely decreases the depth of cut. Moreover, it shows that the water jet pressure and the stand-off distance have no effect in the tested range. In addition, the *surface roughness*, the *depth of cut* and the *material removal rate* are widely affected by the abrasive flow rate. The increase of abrasive flow rate yields an increase of the depth of cut and the material removal rate but decreases the surface roughness.

KEYWORDS: Abrasive water jet (AWJ), Plain water jet (PWJ) milling, Controlled depth milling (CDM), Surface roughness, Depth of cut, Material removal rate.

2 Nomenclature

f: Jet traverse speed (m/min)
p: Jet pressure (bar)
m_a: Abrasive flow rate (g/min)
d: Nozzle diameter (mm)
θ: Impingement angle (degrees)
s: Stand-off distance (mm)
i: Pass increment (mm)
R_a: Surface roughness (μm)
MRR: Material removal rate (mm^3/min)

3 Introduction

The global economy is becoming one of the more benefit targets in the manufacturing industry. Nowadays the need of manufacturing industry for rapid prototyping and small production batches is increasing. These trends have placed an increase on the use of new and advanced technologies for quickly turning raw materials into usable goods; with no time being required for tooling [1].

The most recent technology, which develops new non-traditional methods, is the abrasive water jet machining (AWJ). It is used in industry for material processing with many advantages such as; no thermal distortion, high machining versatility, high flexibility, quick machining and small cutting forces [2]. It can be even a more attracting technology if plain water jet (PWJ) milling is employed due to reduced running costs caused by the absence of abrasives and the elimination of surface contaminations with grit embedment [3].

Related to these capabilities, AWJ makes an important contribution to machining materials with higher performance being more cost-effective than traditional and some non-traditional machining processes. AWJ is widely used in the machining of materials such as steel, stone, brass, titanium, aluminum, inconel in addition to any kind of glass and composites [4].The intensity and the efficiency of the machining process depend on several AWJ process variables which may be classified as hydraulic, abrasive, work material and cutting variables [6].

Most of the studies dispute the hydrodynamic characteristics of abrasive jets, hence achieving the influence of all operational variables on the process effectiveness including abrasive type, size and concentration, impact speed and angle of impingement. Other studies investigated and studied the nozzle shape size and wear, jet velocity and pressure, stand-off distance (SOD). The result of these studies were the overall process performance in terms of material removal rate, geometrical tolerances and surface finishing of work pieces [7]. In order to predict the depth of cut, the experiments were conducted in varying water pressure, nozzle traverse speed, abrasive mass flow rate and stand-off distance for cutting granite tiles using abrasive water jet cutting process [8].

Most of the work done by researchers is to study the creation of through pockets by milling with AWJ. Also other researchers investigated the milling with abrasive water jet. Recently, researchers have also started experimenting on generating blind pockets using AWJ. This process is called controlled depth milling (CDM) [9].

Surface roughness, which is used to determine and to evaluate the quality of a product, is one of the major quality parameters of the plain water jet (PWJ) milling product, where arithmetic mean of surface roughness, maximum roughness of profile height and mean spacing of profile irregularity are the dependent output variables [10]. In addition, the depth of cut is an important parameter which evaluates the process quality and effectiveness [11,13 and13]. Finally, milling time and material removal rate have been taken into consideration to evaluate the economical approach of the PWJ milling [14].

4 Aim of the work

The aim of the present work is to investigate the plain milling of pocket using PWJ. The investigation focuses on identifying the process variables, which influence the process parameters in interest. The considered process variables are traverse speed, jet pressure, abrasive flow rate and stand-off distance. The process parameters in interest are surface roughness, depth of cut and rate of metal removal. The experimental work was applied using aluminum specimens. The experimental methodology is explained in detail in section 5. The experimental results are presented and discussed in section 6, while the conclusions are summarized in section 7.

5 Experimental work

The main objectives of the present research are extracting the influencing AWJ milling variables and obtaining their relations with process variables. Table 1 shows the cutting variables and their ranges. To achieve these objectives, experimental work was conducted. In this work, real cutting operations had been accomplished using an industrial computer numerically controlled AWJ machine [15]. The machine general specifications are shown in Table 2 and a photo for the machine is shown in Figure 1. The tests were applied on Alumec 89 [16] specimens. Alumec 89 is a high strength aluminum alloy supplied in the form of hot rolled, heat treated plate (30×120×250mm). The alloy properties are listed in Table 3 while the chemical composition is shown in Table 4. The machining operations were conducted using the abrasive material [17], where its physical properties and chemical composition are shown in Table 5.

Table 1 Process variables

Process variable	**Value**	**Type**
Jet traverse speed , f	From 1000 to 2000 mm/min	variable
Jet pressure, p	From 20 to 100 MPa	variable
Abrasive flow rate, m_a	From 60 to 220 g/min	variable
Stand-off distance, s	2, 3, 4, 5 mm	variable
Nozzle diameter, d	1.2 mm	Fixed
jet impingement angle	90°	Fixed
Abrasive material	As shown in Table 5	Fixed
Jet increment	0.3 mm	Fixed
Path shape	Zigzag	Fixed
Jet speed	-------	Fixed
Work material	Aluminum alloy	Fixed

Table 2 General specifications of the used AWJ machine

Item	**Identification**
Machine model	SOITAAB
Intensifier	ACCUSTREAM
Table size	2000 x 4000 mm
Nozzle diameter	1.2 mm
Jet impingement angle	90°
Max. Pressure	400 MPa
Max. Feed	4000 mm/min
Max. Abrasive flow rate	520 g/min
Stand-off distance	More than 1mm
Vertical cut height	300 mm

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Figure 1 AWJ machine and cutting nozzle

Table 3 Alumec 89 alloy properties

Property	**Identification**
Density (kg/m^3)	2830
Modulus of elasticity (GPa)	71.5
Tensile strength (MPa)	590
Yield strength (MPa)	550
Brinell hardness (BHN)	160

Table 4 Alumec 89 alloy chemical composition

Element	Cu	Mn	Mg	Cr	Zn	AL
Content (%)	0.7	0.1	2.6	0.13	4.3	Rest

Table 5 Physical properties and chemical composition of used abrasive material

Physical Properties	**Typical chemical composition**
* Color: Reddish brown * Hardness: 7.5 – 8.0 per Moh's scale * Specific Gravity: 4.0 – 4.2 * Grain Shape: Angular to sub-angular * Melting Point: ~ 1315° C * Free Crystalline Silica: < 1% * Size: # 80 mesh (U.S. standard screen)	* Silicon dioxide (SiO_2) 38% (non-crystalline) * Ferric oxide (Fe_2O_3) 29% * Aluminum oxide (Al_2O_3) 23% * Magnesium oxide (MgO) 5% * Calcium oxide (CaO) 2% * Manganese oxide (MnO) <1%

The machining tests were conducted as a blind pocket milling operation. The pocket size is 10×30mm. The pocket depth value is one of the process parameters. Figure 2 shows the tool path configuration during the pocketing operation. The tool path type is of a rectangular zigzag with a fixed side path of 0.3 mm, which represents the jet increment in AWJ milling. Figure 3 shows the machined pockets in the test specimens.

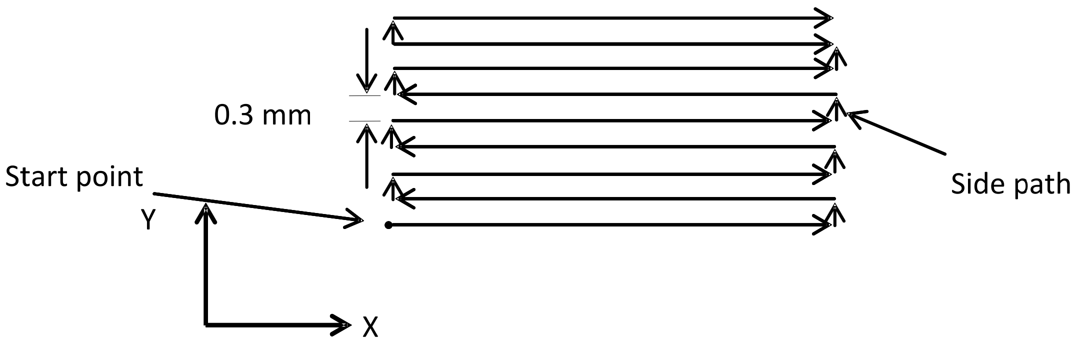

Figure 2 Path configuration of milling pocket

Figure 3 The machined pockets in the test specimen

Surface roughness, as a process parameter, was measured using a portable surface roughness tester. The arithmetic mean (Ra) in micrometer was considered as the surface roughness parameter. The measures were taken in a direction perpendicular to longitudinal tool path with cut-off length of 0.8 mm. The depth of cut and rate of metal removal process parameters were assessed based on measuring of the pocket depth using a depth micrometer with scale value of 0.01 mm.

6 RESULTS AND DISCUSSION

The tests were carried out as explained earlier. The test results are illustrated and explained in the next sections. The results are arranged to describe the effects of cutting variables on cutting parameters. Therefore, the test results are categorized by cutting parameters. During the tests only one variable is considered at a time while the other variables are fixed. Some of the tests were repeated in two values of the fixed variables. The values of the fixed variables are set as for jet pressure being 100 MPa, jet traverse speeds being 1600 and 2000 mm/min, abrasive flow rates being 100 and 150 g/min and a stand-off distance of 2 mm.

6.1 Depth of cut

6.1.1 Effect of traverse speed on depth of cut

The depth of cut was measured at different traverse speeds (f), ranging from 1000 to 2000 mm/min. Tests were repeated for two abrasive flow rates of 100 and 150 g/min. The relation between depth of cut and traverse speed is illustrated in Figure 4. The figure shows that depth of cut decreases with the increase of traverse speed. This is because the exposure time of the workpiece unit area to the cutting abrasive jet is reduced. The relation is of a power function form with a high regression ratio R^2. This relation is nearly similar irrespective of the considered abrasive flow rates.

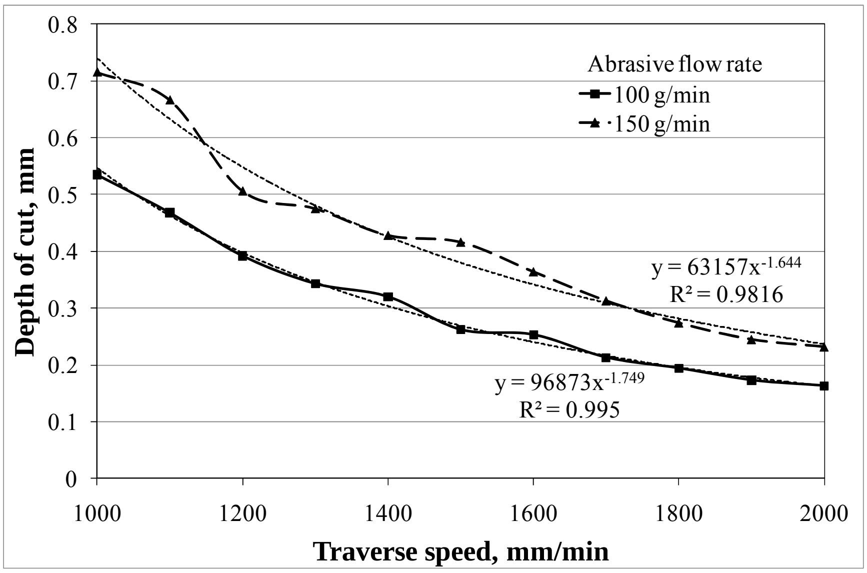

Figure 4 The effect of traverse speed on depth of cut at different abrasive flow rates

6.1.2 Effect of jet pressure on depth of cut

The effect of jet pressure (P) on depth of cut was tested at different pressures, ranging from 20 to 100 MPa. Tests were repeated for two abrasive flow rates of 100 and 150 g/min. The relation between jet pressure and depth of cut is shown in Figure 5. The figure shows that when the jet pressure increases the depth of cut has slight random changes around a fixed value. This means that the jet pressure has no effect on the depth of cut in the test range.

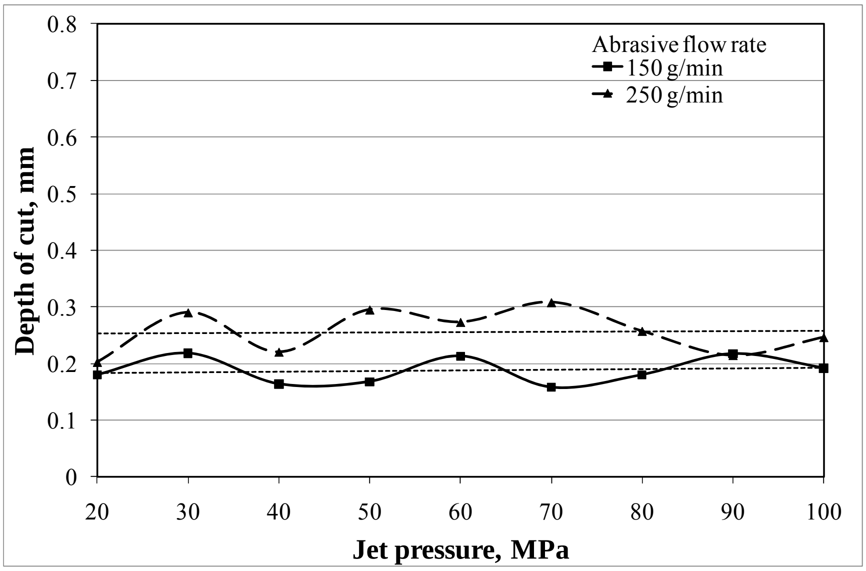

Figure 5 The effect of jet pressure on depth of cut at different abrasive flow rates

6.1.3 Effect of abrasive flow rate on depth of cut

The effect of abrasive flow rate (m_a) on depth of cut was tested. The tests were conducted at different abrasive flow rates from 60 to 120 g/min. The tests were repeated at traverse speeds of 1600 and 2000 mm/min. Figure 6 shows the test results and the trend curves. It is found that the increase of abrasive flow rate increases the depth of cut. The general trend of this relation is a polynomial function with high regression ratio R^2.

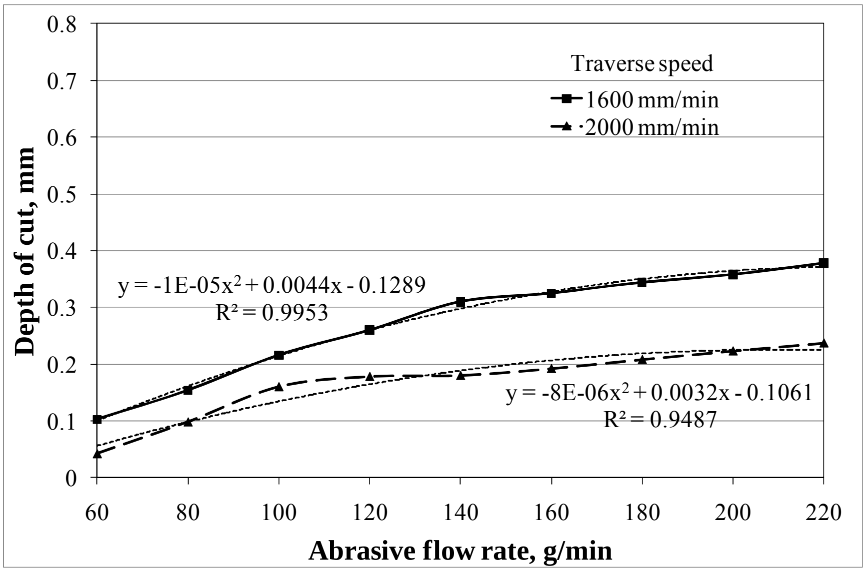

Figure 6 The effect of abrasive flow rate on depth of cut at different traverse speed

6.1.4 Effect of stand-off distance on depth of cut

The effect of stand-off distance on depth of cut was tested. The test was conducted at four different stand-off distances and repeated at three abrasive flow rate values. The results are illustrated in Figure 7. The depth of cut values change barely with the increase of the stand-off distance. Therefore, it is concluded that the stand-off distance has no effect on depth of cut in the range of the tests.

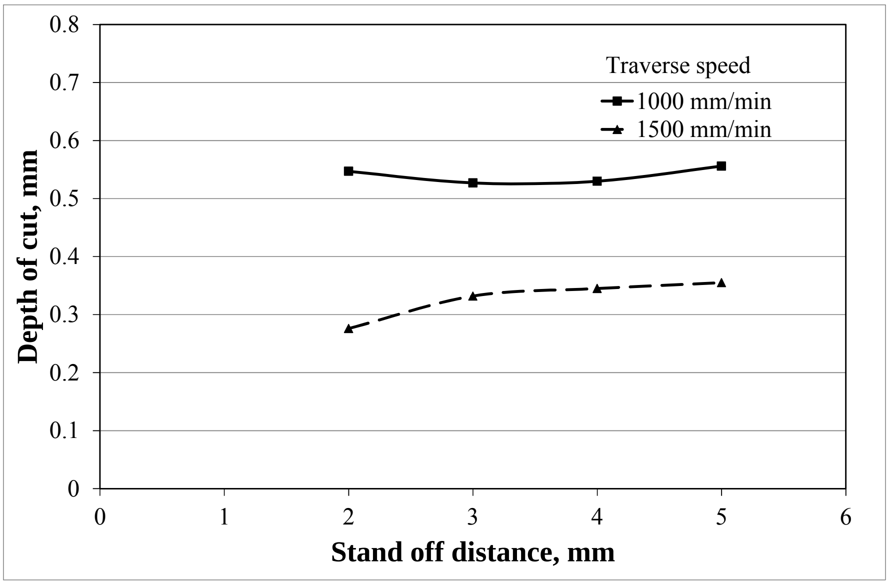

Figure 7 The effect of stand-off distance on depth of cut at different abrasive flow rates

6.2 Material removal rate (MRR)

6.2.1 Effect of traverse speed on MRR

A number of experiments were carried out to find the relation between the traverse speed and MRR. During these tests the traverse speed is varied from 1000 to 2000 mm/min. and the testes were repeated for abrasive flow rates of 100 and 150 g/min. Figure 8 shows the test results and their trend curves. It shows that MRR decreases with the increase of traverse speed. The trend is of a polynomial function with high regression ratio R^2.

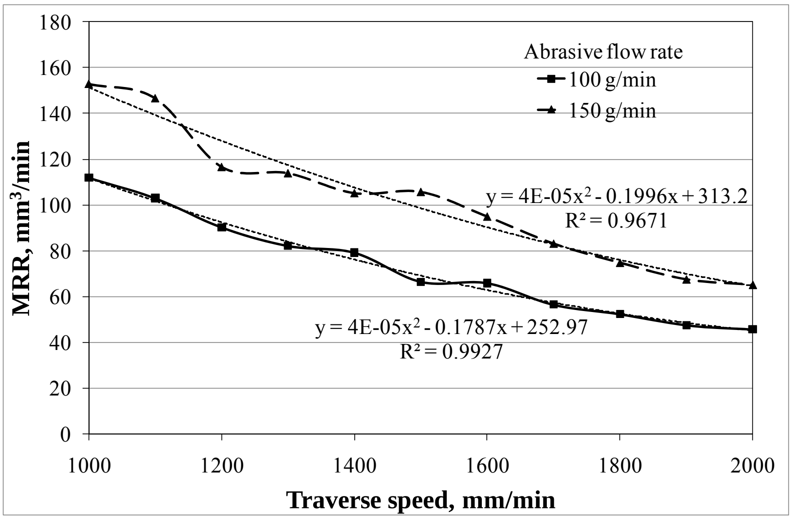

Figure 8 The effect of traverse speed on MMR at different abrasive flow rates

6.2.2 Effect of jet pressure on MRR

The effect of jet pressure on MMR was tested in range of pressures from 20 to 100 MPa. In this range it was found that when the jet pressure increased the MRR was almost of a fixed value. The tests were repeated at two abrasive flow rates. Therefore, it is concluded that jet pressure has no effect on MMR in the test range. Figure 9 shows the test results of the effect of jet pressure on the MMR at different abrasive flow rates.

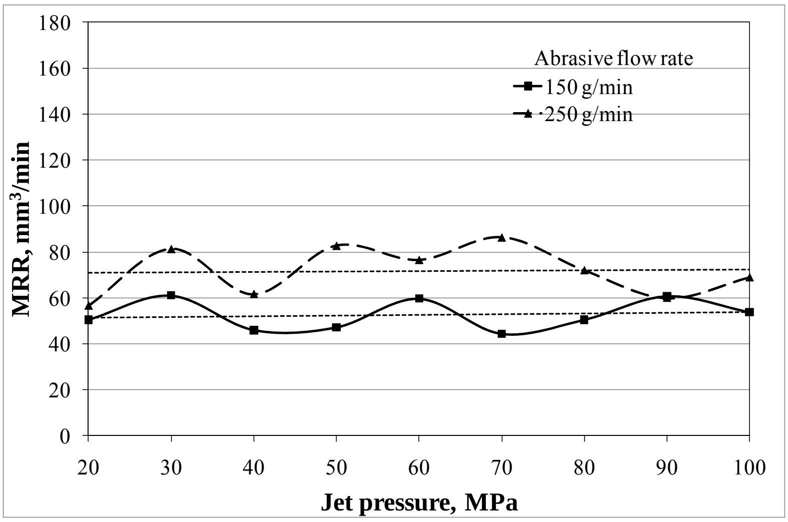

Figure 9 The effect of jet pressure on MMR at different abrasive flow rates

6.2.3 Effect of abrasive flow rate on MRR

A number of experiments were carried out to find the relation between the abrasive flow rate and MRR. During these tests the abrasive flow rate varied from 60 to 220 g/min. and the testes were repeated for two traverse speeds. Figure 10 shows the test results with their trend curves. It shows that MRR increases with the increase of abrasive flow rate. The trend is of a polynomial function with high regression ratio R^2.

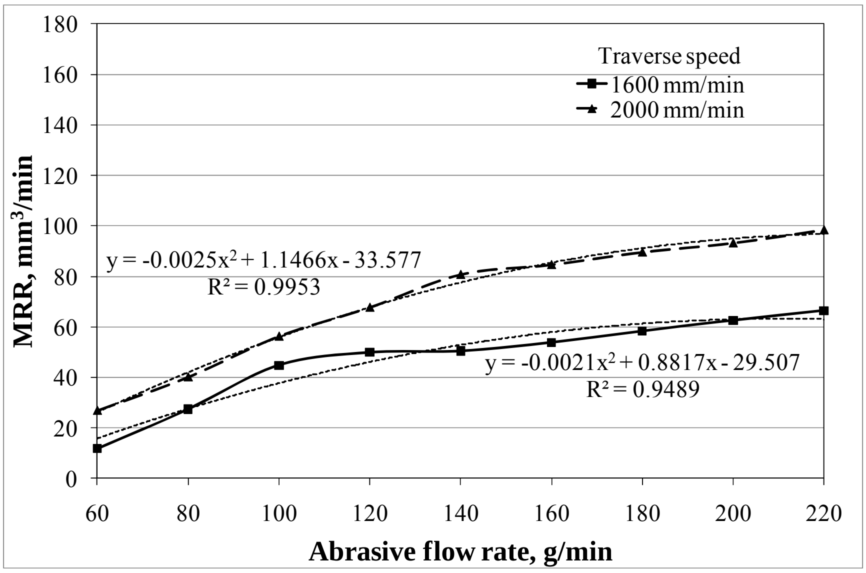

Figure 10 The effect of abrasive flow rate on MRR at different traverse speed

6.2.4 Effect of stand-off distance on MRR

The MRR values were tested at four different stand-off distances. The tests were repeated at three different traverse speeds. The test results are illustrated in Figure 11. The tests show that the MRR values are nearly constant at different stand-off distances. Therefore, it is concluded that the stand-off distance has no effect on MRR value.

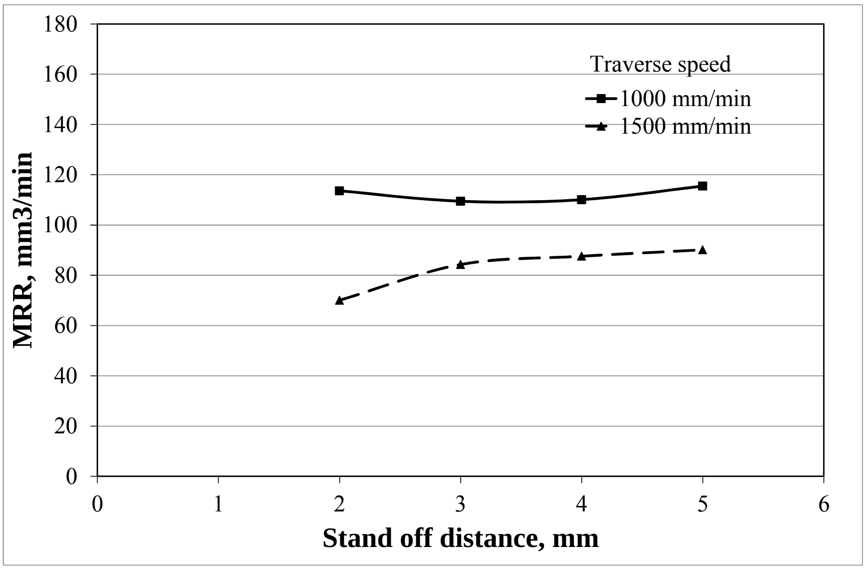

Figure 11 The effect of stand-off distance on MRR at different traverse speeds

6.3 Surface Roughness

6.3.1 Effect of traverse speed on surface roughness:

The surface roughness Ra parameter values were measured at different traverse speeds in the range from 1000 to 2000 mm/min. and this test was repeated for two different abrasive flow rates. The test results show that with the increase of traverse speed, surface roughness decreases. The relation trend is of a power function with medium regression ratio R^2. Figure 12 shows the test results and their trend curves.

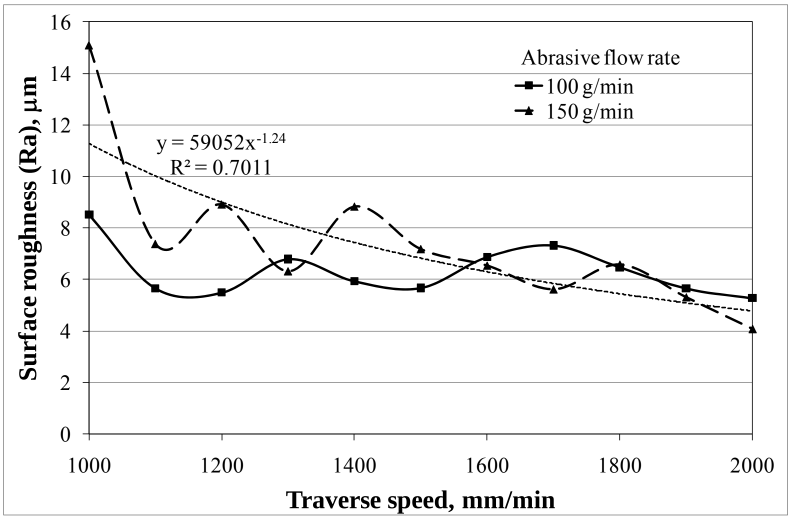

Figure 12 The effect of traverse speed on surface roughness at different abrasive flow rates

6.3.2 Effect of the jet pressure on the surface roughness:

The effect of jet pressure on surface roughness Ra parameter was tested under ranges of pressures from 20 to 100 MPa. In this range it was found that when the jet pressure increased the surface roughness Ra parameter was almost of a fixed value. The tests were repeated at two abrasive flow rates. Therefore, it is concluded that jet pressure has no effect on surface roughness Ra parameter in the test range. Figure 13 shows the test results of the effect of jet pressure on the surface roughness Ra parameter at different abrasive flow rates.

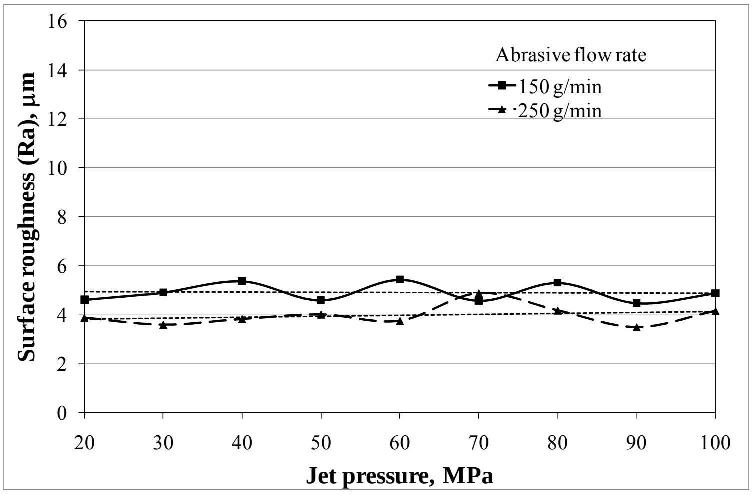

Figure 13 The effect of jet pressure on surface roughness at different abrasive flow rates

6.3.3 Effect of abrasive flow rate on surface roughness:

The surface roughness Ra parameter values were tested at a range of abrasive flow rate from 60 to 220 g/min. The tests were repeated at two different traverse speeds. The test results are illustrated in Figure 14. The tests show that the surface roughness Ra values are nearly constant at different abrasive flow rates. The higher the traverse speed yields that the surface roughness is decreasing by increasing the abrasive flow rate.

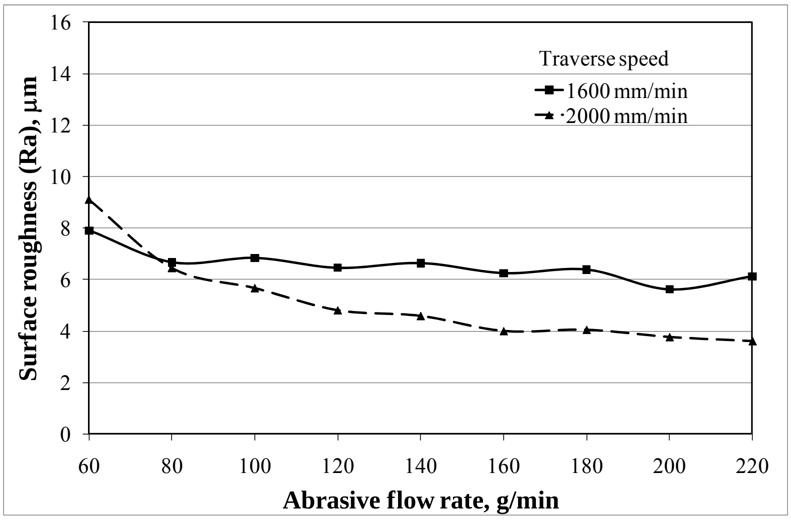

Figure 14 The effect of abrasive flow rate on surface roughness at different traverse speeds.

6.3.4 Effect of the stand-off distance on the surface roughness:

The effect of stand-off distance on the surface roughness was tested. The test was conducted at four different stand-off distances and repeated at two traverse speeds. The results are illustrated in Figure 15. The surface roughness parameter Ra values change barely with the increase of the stand-off distance. Therefore, it is concluded that the stand-off distance has no effect on depth of cut in the range of the tests.

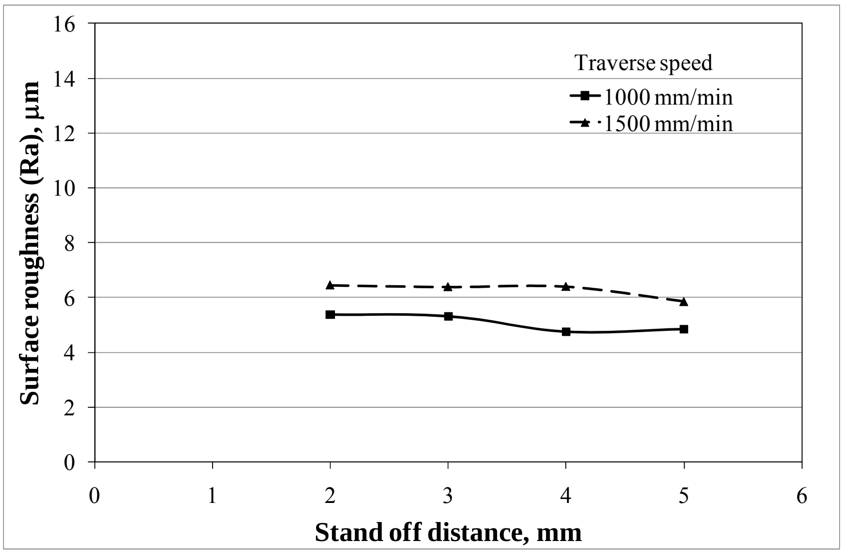

Figure 15 The effect of stand-off distance on surface roughness at different traverse speeds.

7 CONCLUSIONS

This paper is a step towards better understanding for AWJ pocketing operations. The main objective of the present paper is to illustrate the effect of the water jet pocketing variables on the resulting process parameters. To achieve this objective a series of tests were conducted using an industrial AWJ machine to generate rectangular pockets in Aluminum alloy specimens. The considered process parameters are depth of cut, metal removal rate and surface roughness. The considered process variables are traverse speed, jet pressure, abrasive flow rate and stand-off distance. The summary of the results is shown in Table 6.

Table 6 Summary of the effects of AWJ process variables on process parameters

Process variable	Process variable range	Effect of variable increase on process parameters		
		Depth of cut	MRR	Surface roughness
Traverse speed	From 1000 to 2000 mm/min	Decrease	Decrease	Decrease
Jet pressure	From 20 to 100 MPa	No effect	No effect	No effect
Abrasive flow rate	From 60 to 220 g/min	Increase	Increase	Decrease
Stand-off distance	2, 3, 4, 5 mm	No effect	No effect	No effect

The results show that the increase of traverse speed decreases depth of cut, MRR and surface roughness. This leads to longer machining time operation but lower surface quality. Moreover, depth of cut and material removal rate (MRR) depend on abrasive flow rate. Increasing abrasive flow rate increases both depth of cut and MRR, where more abrasive particles yielding more impinging and erosion of the material. This reduces the machining operation time. Moreover, increases the abrasive flow rate has no significant effect on the surface roughness and consequently the surface quality, where the unit surface area will be completely impinged by a certain number of the abrasive particles, so more of the particles have no chance to impinge this surface area. However, increasing abrasive flow rate means more material cost.

The above summary shows that some process variables have no effect on the considered process parameters. This yields to discard these variables in any process control operation, which targets this parameter in the considered process variable range. In addition, this result has an important effect on selecting or designing AWJ machines for pocketing operations. As the jet pressure has no effect on the considered AWJ pocketing process parameters, low pressure water system including pump and valves can be used instead of the intensifier system which is more complicated and expensive. Moreover, since the stand-off distance has no noticeable effect on process parameters, it is better to select a longer value to prevent the nozzle front from damaging by the reflection of the water stream and abrasive.

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