INFLUENCE OF THE PROCESS CONDITIONS ON THE DIAMETER OF CYLINDRICAL HOLES PRODUCED BY ABRASIVE WATER JET CUTTING

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Abstract

This paper discusses experimental results concerning the geometric accuracy of cylindrical holes made in EN AW-2007 aluminum alloy by a high-pressure jet of water containing almandine garnet as an abrasive substance. The tests were conducted according to a three-level Box-Behnken design using an APW 2010BB water jet cutting machine. Changes in the input parameters during high-pressure abrasive water jet cutting resulted in the occurrence of geometric inaccuracies. The input variables were the cutting speed, the distance between the abrasive water jet nozzle and the workpiece, and the abrasive mass flow rate. The values of the correlation coefficient confirmed that the greatest influence of the cylindrical holes had cutting speed.

Keywords: Cutting of aluminum alloy, abrasive water jet, cutting parameters

1. INTRODUCTION

Demand for a higher surface quality achieved with the smallest possible number of cutting operations has led to the development of alternative methods of cutting, able to produce components that can be very complex in shape. One of the high-end technologies is abrasive water jet cutting (AWJ) [1], which uses a high-pressure high-velocity concentrated jet of water mixed with abrasive material. Abrasive particles are added to water to intensify the machining process. As there is no heat affected zone, the process is considered ‘cold’ [2]. This feature makes it an extremely effective and attractive method of cutting suitable for use where the heating of a workpiece is unacceptable [3]. The whole process of cutting is performed at a relatively small force applied by the water jet.

Benefits of abrasive water jet cutting are numerous. Because of its universality, the method can be used to cut most materials, both thin and thick, into any complex shape; hence its wide range of applications. As such, it can easily compete with the conventional material cutting methods [4]. AWJ is extremely effective for cutting workpieces complex in shape.

2. PARAMETERS

The major parameters of the high-pressure abrasive water jet cutting process can be divided into three categories: [5, 6]

- Hydraulic parameters: water jet pressure, water jet diameter, water jet power.
- Abrasive-related parameters: abrasive material, abrasive mesh size.
- Cutting process parameters: cutting speed, distance between the nozzle and the workpiece, abrasive mass flow rate.

Extensive research is required to analyse the effects of different cutting process parameters on the surface quality of workpieces in abrasive water jet cutting. The data will then be used to develop a model of the cutting process for a selected material [7]. As a result, it will be possible to reduce the excess energy consumed during the cutting process to a minimum, for example, by increasing the cutting speed or the abrasive flow rate when they are too low and therefore economically ineffective.

The surface quality after abrasive water jet cutting should be neither too low nor too high. A good or very good surface quality involves higher and unnecessary costs, and these are always to be avoided if possible. The surface structure after abrasive water jet cutting is generally assessed visually. The surface quality class is expressed by a number from 1 to 5. The lower the number, the worse the structure of the surface produced by cutting. Thus, higher numbers correspond to smoother surfaces. Examples of the surface quality classes are shown in **Figure 1**. The curved groove pattern, characteristic of abrasive water jet cutting, is most visible in the lower quality zone [8].

Figure 1 Surface structure of C45 steel produced by abrasive water jet cutting assessed as: a) Q1, b) Q3, c) Q5 [9]

3. EXPERIMENT

The aim of the experiment was to analyze how certain process parameters affected the diameter of cylindrical holes produced by abrasive water jet cutting. The tests were conducted under different conditions by changing the values of three basic process parameters: the cutting speed (v) (v_1 = 20, v_2 = 60 and v_3 = 100 mm/min), the distance between the water jet nozzle and the workpiece (s) (s_1 = 2, s_2 = 4 and s_3 = 6 mm) and the mass flow rate for the abrasive (m_a) (m_{a1} = 230, m_{a2} = 340 and m_{a3} = 450 g/min).

3.1. Workpiece material

The cutting efficiency is dependent not only on the process parameters but also on the properties of the workpiece material. The most important is the material resistance to erosion. The workpiece thickness is also essential. The material studied was the EN AW-2007 aluminum alloy in the form of 15 mm thick plates. The material has good strength and very good cuttability. Moreover, the material has high fatigue strength and it is not suitable for welding. **Table 1** shows the standard chemical composition of the material studied.

Table 1 Composition of the EN AW-2007 aluminum alloy (wt.%)

Cu	Pb	Mg	Mn	Fe	Si	Zn
3.3-4.6	0.8-1.5	0.4-1.8	0.5-1.0	max 0.8	max 0.8	max 0.8

3.2. Test conditions

The experiments were carried out using an APW 2010 BB with an 18.5 kW pump able to produce a water jet with a maximum cutting pressure of 300 MPa. The machine has a cutting table with an X and Y axis travel of 2000 x 1000 mm. The cutting process was performed using a water jet nozzle with an orifice of 0.30 mm in diameter and an abrasive water jet nozzle with a diameter of 1.02 mm and a length of 75 mm. All the experiments were conducted at a constant working pressure of 280 MPa. The first test was performed for the water jet nozzle and the abrasive water jet nozzle with 30 hours logged. The experiments were conducted at the Division of Materials Science and Munitions Technology of the Kielce University of Technology.

3.3. Abrasive substance

The abrasive used in the cutting process was almandine garnet with a mesh size of 80 and a grade of E. It is a naturally occurring mineral with a chemical formula of $Fe_3Al_2(SiO_4)_3$. The abrasive ranges from light red to almost black in colour. The garnet grains have irregular shapes and sharp edges. Garnet can be purchased graded and sized in 25 kg bags. A water jet cutting abrasive material sized 80 has grains ranging from 88 µm to 250 µm. The abrasive substance used in the experiments exhibited a hardness of 8 Mohs. It had a specific mass of about 4.2 Mg/m^3 and a specific gravity of 2.34 Mg/m^3. The material is shown in **Figure 2**.

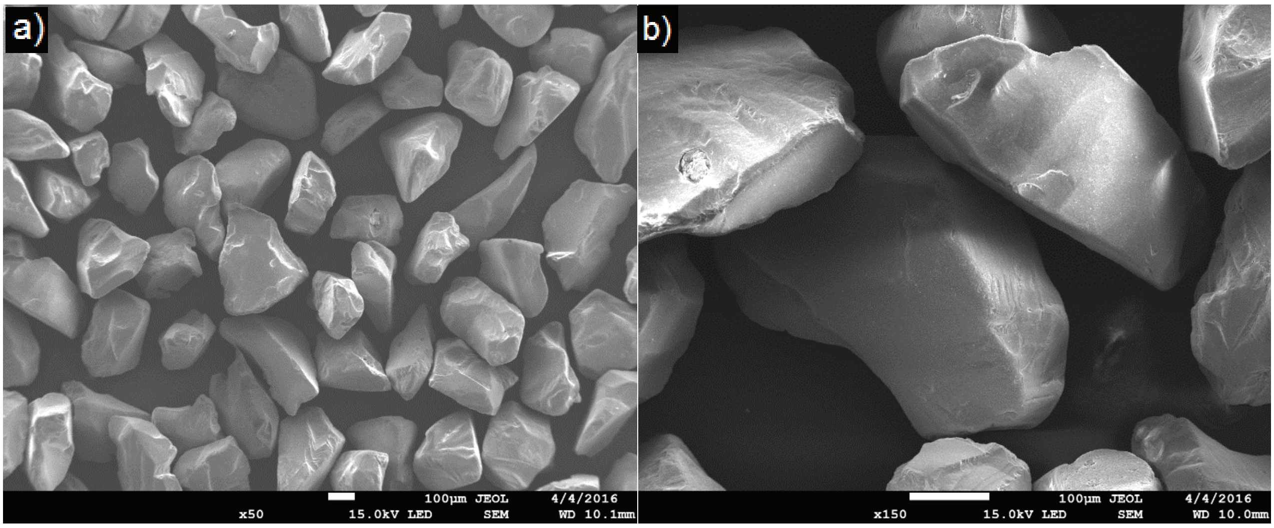

Figure 2 SEM images of the abrasive grains (garnet # 80 E)

3.4. Design of Experiment

The tests were conducted according to a three-level Box-Behnken design to investigate the influence of three input factors (placed at one of three equally spaced values coded as -1, 0 and +1) on the output values. The Statistica 12 Design of Experiment (DOE) module was employed to generate the experimental design for the predetermined conditions and ranges of variability of the input parameters. The ranges of the input parameters for the experiment were established by analyzing the literature and reviewing the results of earlier studies by the authors. The three variables in the cutting process were:

- the cutting speed v,
- the distance between the nozzle and the workpiece s,
- the abrasive mass flow rate m_a.

The experiment involved cutting cylindrical holes [10], each with a predetermined nominal diameter of 30 mm, in an aluminum alloy plate. The diameters of the holes were measured by means of a Zeiss Prismo Navigator coordinate measuring machine. The measurements were performed using a contact ball 2 mm in diameter moving with a rate of 5 mm/s.

4. RESULTS AND DISCUSSION

Table 2 shows the coded and the actual values of the input parameters and the output data, i.e. the diameter of cylindrical holes, d.

Table 2 Design of experiment with the input and output values

Test No.	Input factors (coded values)			Input factors (actual values)			Output values (measured values)
	v (mm/min)	*s* (mm)	m_a (g/min)	*v* (mm/min)	*s* (mm)	m_a (g/min)	*d* (mm)
1	-1	-1	0	20	2	340	30.7894
2	1	-1	0	100	2	340	30.2623
3	-1	1	0	20	6	340	30.7290
4	1	1	0	100	6	340	30.4196
5	-1	0	-1	20	4	230	30.6003
6	1	0	-1	100	4	230	30.2824
7	-1	0	1	20	4	450	30.7491
8	1	0	1	100	4	450	30.4419
9	0	-1	-1	60	2	230	30.3431
10	0	1	-1	60	6	230	30.5143
11	0	-1	1	60	2	450	30.3576
12	0	1	1	60	6	450	30.6556
13	0	0	0	60	4	340	30.4580
14	0	0	0	60	4	340	30.4677
15	0	0	0	60	4	340	30.5025

The experimental results were used to derive regression equations, which were then used to graphically represent the data as three-dimensional plots (see **Figures 3** and **4**). The relationship between the output and input parameters is shown in **Table 3** in the form of a partial correlation coefficient k. The values of the coefficient vary in the range <-1,1>. A correlation is considered significant when the correlation coefficient is k > |0.5|. This condition is satisfied for the parameter v; the partial correlation coefficient is then -0.82. In the case of a negative correlation, an increase in the input parameter leads to a decrease in the output parameter.

Table 3 Values of the partial correlation coefficient for the output parameter according to the input factor

Input parameters	Correlation coefficient for the output parameter
v	-0.82
s	0.32
m_a	0.26

Regression equations to determine straightness:

$$\Delta S_{v,ma} = 30.5288 - 0.0094\, v + 0.0017\, m_a + 3.8436\cdot10^{-5}\, v^2 + 6.0795\cdot10^{-7}\, v\, m_a - 1.7295\cdot10^{-7}\, m_a^2 \quad (1)$$

$$\Delta S_{s,ma} = 30.1796 - 0.0272\, s + 0.0013\, m_a + 0.0017\, s^2 + 0.0001\cdot10^{-7}\, s\, m_a - 2.0523\cdot10^{-7}\, m_a^2 \quad (2)$$

$$\Delta S_{v,s} = 30.956 - 0.0121\, v + 0.0318\, s + 3.9958\cdot10^{-5}\, v^2 + 0.0007\, v\, s + 0.0033\, s^2 \quad (3)$$

Figure 3a) shows the relationship between the diameter of cylindrical holes and the abrasive mass flow rate at s = 4 mm. The diagram indicates that when the cutting speed v increases within the range of variability, there is a decrease in the hole diameter. From the values of the partial correlation coefficient it is clear that this correlation is strong. A change in the abrasive mass flow rate ma has little influence on the value of the output parameter.

Figure 3b) is a graphical representation of the relationship between the hole diameter, the distance between the nozzle and the workpiece s and the abrasive mass flow rate ma (with the predetermined value of the cutting speed *v* being 60 mm/min). The shape of the diagram suggests that for the parameters s and ma the values of the correlation coefficient are similar. An increase in the two input parameters caused a gradual increase in the hole diameter.

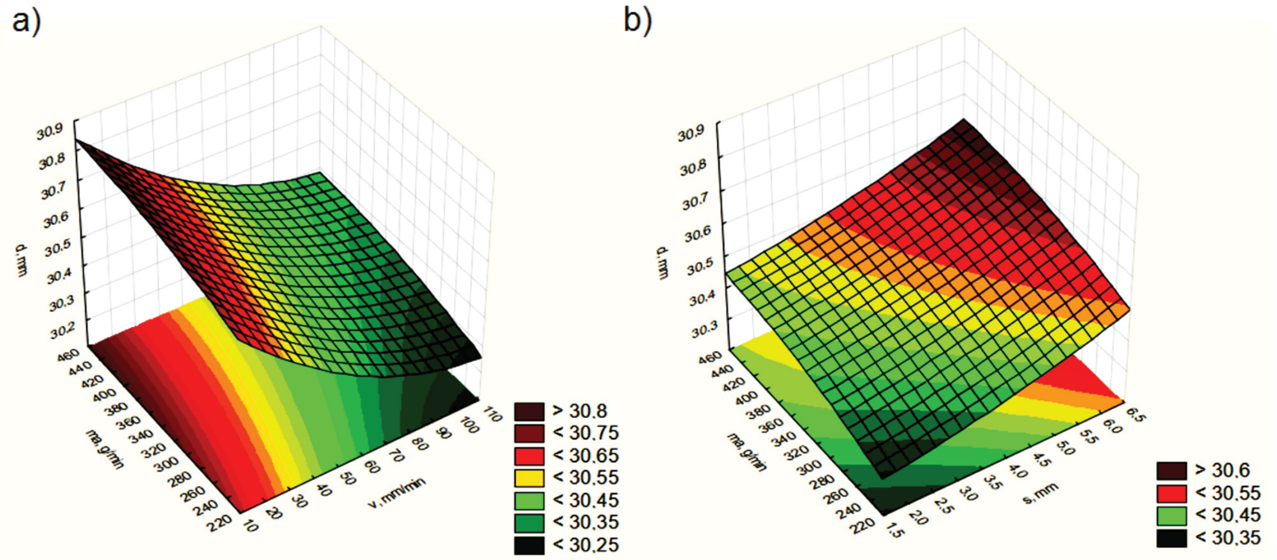

Figure 3 a) Relationship between the hole diameter, the cutting speed and the abrasive mass flow rate at *s* = 4 mm, b) Hole diameter vs. the distance between the nozzle and the workpiece vs. the abrasive mass flow rate at *v* = 60 mm/min

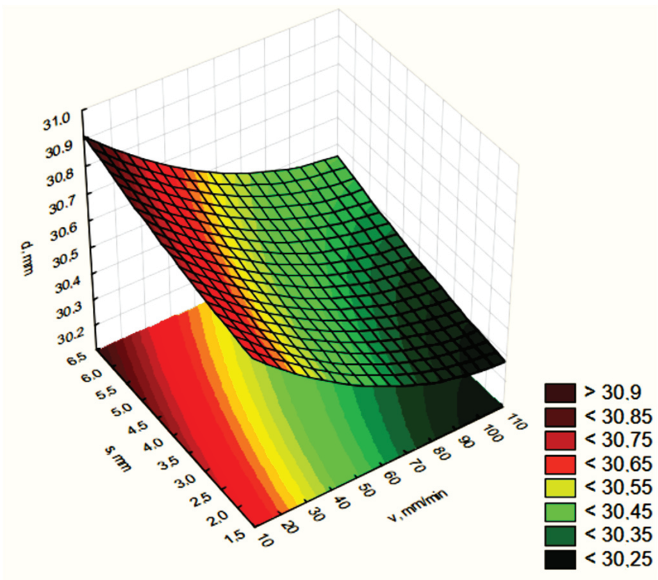

Figure 4 Relationship between the hole diameter, the cutting speed and the distance between the nozzle and the workpiece at m_a = 340 g/min

Figure 4 shows the relationship between the diameter of the holes, the cutting speed and the distance between the nozzle and the workpiece at m_a = 340 g/min. The shape of the plot indicates a substantial influence of the cutting speed v on the hole diameter *d*. With the abrasive mass flow rate m being constant and the other two input parameters changing within the ranges of variability, the input parameter s had a much smaller effect on the output parameter *d*.

5. CONCLUSION

Changes in the input parameters during high-pressure abrasive water jet cutting resulted in the occurrence of geometric inaccuracies, i.e. changes in the nominal value of the hole diameter.

The experimental results were analyzed to determine the influence of three input parameters of the abrasive water jet cutting process (the cutting speed v, the distance between the nozzle and the workpiece s and the abrasive mass flow rate ma) on the diameter of cylindrical holes d.

The values of the partial correlation coefficient confirmed that effect of the cutting speed v on the diameter of the cylindrical holes was considerable. It was a significant negative correlation.

The other input parameters, i.e. the distance between the water jet nozzle and the workpiece s and the abrasive mass flow rate ma with values in the analyzed ranges, had a smaller influence on the diameter of the holes. No significant partial correlation was observed. When these two parameters increased, the diameter of the cylindrical holes increased as well, and this indicates a positive correlation.

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