Abrasive Water Jet Turning of Aluminum-silicon Carbide Metal Matrix Composites

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Abstract

This paper presents a set of studies performed on turning of aluminum-silicon carbide metal matrix composite. The metal matrix composites are prepared by addition of 5, 10, 15% of SiC in aluminum alloy, the specimens are produced by stir casting method. The study is essentially meant to study the turning characteristics during turning of metal matrix specimens. A turning fixture has been designed and developed to carry out the turning experiments on the specimens. Full factorial experiments are carried out on different compositions of cylindrical metal matrix composite specimens by varying traverse speed and nozzle angle. Volume removal and surface roughness are the output parameters studied. Percentage contributions of individual and combined effects of input parameters have been studied using analysis of variance. Traverse rate and nozzle angle have significant influence on volume removal rate with nozzle angle having greater influence. Nozzle angle is found to influence the surface roughness during abrasive water jet turning. Using response surface methodology, statistical model is developed to predict the volume removal rate and surface roughness for abrasive water jet turning of metal matrix composite specimens. Using surface response methodology, optimum values of traverse speed and nozzle angle are found. Finally, both the theoretical results are compared to compute the error. This study emphasizes the need to select suitable values of traverse rate and nozzle angle for effective turning of MMCs using abrasive water jet.

Keywords: Abrasive water jet turning, metal matrix composites, volume removal rate, surface roughness, full factorial experiments

1. INTRODUCTION

Metal matrix composites possess high stiffness, fracture toughness and strength They have high resistance to wear, creep, fatigue and corrosion. MMCs can withstand applications at elevated temperatures in highly corrosive environment than polymer matrix composites. Metal matrix composites are not as widely used as polymer matrix composites despite their favorable thermal and mechanical properties. This is because during conventional machining of MMCs, tool wear is higher due to contact of abrasive reinforcement with the cutting tool. Tool wear results in poor surface finish and higher costs during operation [1]. To overcome the problems encountered during conventional machining of metal matrix composites, nontraditional machining techniques such as Laser beam machining, electro discharge machining, and abrasive water jet machining are employed. Among these nontraditional machining processes, abrasive water jet is the most preferred process. Abrasive water jet machining has become one of the leading machining technologies in a relatively short period. Abrasive water jet machining is a novel machining process; it can cut all type of materials ranging from ductile to brittle materials and fragile to hard materials.

2. PREPARATION AND CHARACTERIZATION OF METAL MATRIX COMPOSITE SPECIMENS

Metal matrix composites are prepared by stir casting process as it is widely used and economical. The Metal Matrix chosen for the preparation of MMC is Aluminum 6061 (Al 6061) and the reinforcement particulate is Silicon Carbide of 80-mesh grade (SiC 80M). The metal matrix composite specimens have been prepared with the following composition.

- 95% Al6061 + 5%SiC 80 Mesh
- 90% Al6061 + 10%SiC 80 Mesh
- 85% Al6061 + 15%SiC 80 Mesh

3. ABRASIVE WATER JET TURNING OF METAL MATRIX COMPOSITES

To study the influence of dynamic parameters and their interactions on the turning characteristics of different compositions of the specimen, full factorial experiment method has been considered. Full factorial experiments are useful in reducing the error variance. To conduct the experiment, the workpiece is rotated using the fixture. The jet is made to impact the workpiece along the length of the workpiece. This resembles conventional turning process where the tool is moved along the length of a rotating workpiece. The water jet is moved along the length of the workpiece; water jet is made to impact on the periphery of the specimen at lower pressure and is offset towards the axis of the specimen by a distance equal to radius of the workpiece. This is done to minimize the errors due to misalignment and to locate the jet at the center of the specimen for normal impact. By changing the angle of impact of the jet, different depth of cuts can be obtained. The angle of impact is changed by offsetting the jet from the center by a distance calculated corresponding to required angle of impact by using equation (1)

$$d = r \cos \alpha \tag{1}$$

d= the distance to be offset from centre (mm)

a =Angle of impact (°)

r= Radius of the specimen (mm)

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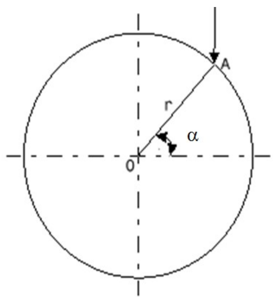

Figure 1 – Geometry of specimen

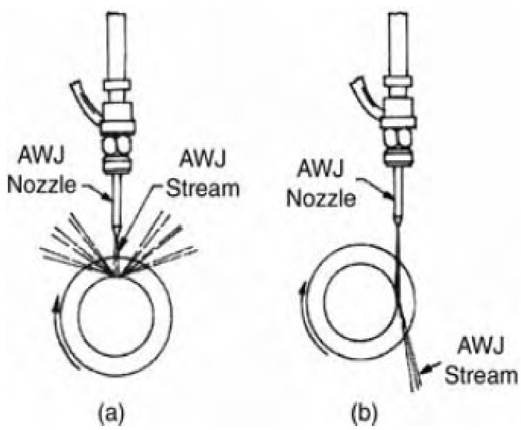

Figure 2 - Schematic representation of impact of abrasive water jet on cylindrical specimen

The normal impact and low impact angle of the jet are shown in figure 2. Figure (a) shows the nozzle impact of abrasive water jet on the cylindrical specimen, figure (b) shows the impact of the jet at lower impact angle on the specimen. Nozzle impact angle is varied in three steps- 30°, 45° and 60°, but the movement of nozzle is restricted to 45° in the machine. Hence nozzle is made to impact at a distance offset from the centre of the specimen. This distance is calculated using equation 1 and denoted in figure 2.

Workpiece is rotated at constant speed using voltage regulator. Abrasive water jet turning of MMC specimens are carried under following conditions. Process parameters for turning of abrasive water jet turning of MMC specimens are as tabulated below in table 1. Nozzle impact angle has been varied in three steps to obtain three distinct depths of cuts. The material is fully removed at normal impact and the depth of cut obtained by angle less than 30° is very less to be studied. Hence the values have been chosen between 30-60°. Speed of rotation of the workpiece has negligible impact on the output parameters. At lower speed, the wobbling of the workpiece is more upon the impact of the jet. Taking into consideration the value of speed of rotation from the literature survey, speed of rotation is fixed at 250 rpm. During literature survey, it has been observed that abrasives of 80 mesh size give higher depth of penetration across all compositions of metal matrix composites (Srinivas and Babu, 2011), abrasives of 80 mesh size have been chosen for this project. Values of water jet pressure, abrasive flow rate, orifice diameter and all other parameters have been decided from literature survey. Figure 3 shows a metal matrix composite specimen being turned by an abrasive water jet.

Table 1- Process parameters for AWJT

Process parameters	Level 1	Level 2	Level 3
Composition of MMC (% of SiC)	5	10	15
Traverse rate, u (mm/min)	2	4	6
Nozzle impact angle, a(°)	30	45	60
Water pressure, P (MPa)		250	
Abrasive flow rate (kg/min)		0.358	
Orifice diameter (mm)		0.3556 and material is sapphire	
Focusing nozzle diameter (mm)		0.7620 and material is Tungsten carbide	
Standoff distance (mm)		2	
Initial diameter of the specimen(mm)		22	
Speed of rotation (rpm)		250	

Figure 3- Abrasive water jet turning of MMC specimen

4. RESULTS AND DISCUSSIONS

The results of all the tests and experiments are presented below, the discussions related to the results have also been provided accordingly.

Abrasive water jet turning of metal matrix composites

The table 4 shows the experimental values after turning the metal matrix composite by abrasive water jet. Volume removal rate is calculated using the equation 2 [2]

$$VRR = \frac{\pi}{4}(D_1^2 - D_2^2)u \qquad (2)$$

VRR= Volume removal rate (mm3/min)

D1= Initial diameter of specimen (mm)

D2= Final diameter of specimen (mm)

u= Traverse rate of water jet (mm/min)

Volume removal rate is found to increase as the nozzle angle increases. Nozzle angle is increased by decreasing the distance to be offset from the centre of the specimen. The depth of cut of the jet increases as the nozzle angle increases. As the depth of cut is increased more material is removed hence the volume removal rate increases. Volume removal rate increases with the increase in traverse rate of the water jet. The exposure time per unit area of the material to the jet is reduced as the traverse rate of the water jet increases. The length of specimen impacted by the jet is higher as the traverse speed of the jet increases. Due to this the volume of material removed increases with increase in traverse speed of the jet, hence volume removal rate is increased. Surface roughness of the material is found to increase with the increase in traverse rate of the water jet. At lower traverse speed, the time of interaction between the abrasives of the water jet and unit surface area of the material is more. Number of abrasives impacting unit area of the specimen is more, this results in lower surface roughness and better surface finish. As the traverse speed is increased, the time of interaction between the jet and the workpiece at an area is reduced. When the pressure of the jet decreases the surface roughness increases. When the kinetic energy of the striking abrasives reduces, surface roughness increases.

Hardness of aluminum 6061 alloy is increased by addition of silicon carbide. Silicon carbide particles get distributed as reinforcement in aluminum 6061 matrices in Al 6061-SiC MMC. SiC particles are present on the surface as well; this increases surface roughness. The effect of silicon carbide on the surface roughness of the specimen is negligible as the difference in surface roughness values with same set of parameters across different composition of SiC is very less.

Upon the addition of SiC in aluminum 6061, the intermolecular bonding between aluminum is reduced. The SiC particles are loosely packed in the metal matrix composite when compared to aluminum. Due to this, more material is removed as the distribution of SiC is increased hence volume removal rate increases with the increase in SiC particles. Due to interaction between the parameters of the process, a second order quadratic function is considered to develop the statistical model for predicting volume removal rate and surface roughness during abrasive water jet turning of metal matrix composites. General form of the quadratic equation is given by

$$f(x,y)= ax^2+by^2+cxy+dx+ey+f+\varepsilon \quad (3)$$

Table 2- Results of AWJT on metal matrix composites

Percentage of SiC	Traverse rate 'u' in mm/min	Nozzle angle in degrees	Initial Diameter 'D1' in mm	Final Diameter 'D2' in mm	Volume removal rate	Surface roughness 'Ra' in µm
5	2	30	22	20.35	109.707	2.65
5	2	45	22	16.45	335.034	3.3
5	2	60	22	11.25	561.176	4.15
5	4	30	22	20.7	174.301	2.75
5	4	45	22	16.9	622.944	3.5
5	4	60	22	11.9	1075.10	4.2
5	6	30	22	19.8	433.131	2.8
5	6	45	22	15.96	1079.90	3.7
5	6	60	22	11.13	1696.18	4.3
10	2	30	22	19.75	147.481	2.7
10	2	45	22	15.9	362.968	3.9
10	2	60	22	10.8	576.755	4.27
10	4	30	22	18.56	438.112	2.8
10	4	45	22	14.75	836.613	3.85
10	4	60	22	9.75	1221.26	4.4
10	6	30	22	20.04	386.208	2.8
10	6	45	22	16.4	1012.83	3.75
10	6	60	22	11.55	1651.31	4.6
15	2	30	22	19.72	149.340	2.9
15	2	45	22	15.75	370.421	3.9
15	2	60	22	10.54	585.466	4.2
15	4	30	22	20.31	224.522	2.8
15	4	45	22	16.4	675.225	3.9
15	4	60	22	11.35	1115.25	4.35
15	6	30	22	19.35	516.11	2.9
15	6	45	22	15.55	1140.75	3.8
15	6	60	22	10.75	1735.31	4.3

In equation 3, a, b, c, d, e are regression coefficients, f is a constant and ε is the error. Traverse speed and nozzle angle are represented by x and y respectively.

Table 3- Regression coefficients for volume removal rate

Coefficients	**Composition of MMC**		
	5% SiC	10% SiC	15% SiC
a	19.6	-35.6	19.48
b	-0.0194	-0.0027	-0.0347
c	6.763	6.965	6.526
d	-277.5	135	-258.9
e	3.75	-0.09	5.31
f	77	-382	58

Table 4- Regression coefficients for surface roughness

Coefficients	Composition of MMC		
	5% SiC	10% SiC	15% SiC
a	0	-0.0033	-0.0042
b	-0.0001	-0.001	-0.0012
c	0	0.0019	0.008
d	0.058	-0.036	-0.004
e	0.0594	0.142	0.1606
f	0.817	-0.589	-0.789

5. CONCLUSION

This paper attempts to study the application of abrasive water jet turning on metal matrix composites. The paper covers the stages of synthesis of material, characterization of material, design and fabrication of fixture, machining of the specimen using abrasive jet, analysis of the effects of process parameters on the material and inter relation between them. Design of fixture emphasizes the need for specialized fixtures to explore the applications of abrasive water jet machining on processes other than cutting. Traverse rate and nozzle angle influence the surface roughness and volume removal rate more than silicon carbide particles. Percentage contribution of both traverse speed and nozzle angle is significant on volume removal rate. On surface roughness, nozzle angle has more percentage contribution when compared to the percentage contribution of traverse speed. From the statistical model, values of surface roughness and volume removal rate can be calculated for desired values of process parameters. Also, for desired values of surface roughness and volume removal rate the required values of process parameters can be calculated using statistical model. The optimum values of the process parameters predicted by the statistical model would serve as a ready reckoner for future studies. This paper would therefore serve as database to study the application of abrasive water jet on a wide range of engineering materials and carry out different machining processes using abrasive water jet. Abrasive water jet is best suited for turning of metal matrix composites as problems encountered during conventional turning like tool wear, reduced tool life and improper surface finish can be overcome by abrasive water jet turning.

Studies on different compositions of metal matrix composites and other engineering materials, application of AWJM in milling and drilling, design of compact and smaller fixtures that support multiple machining processes, experiments with different combinations of input parameters and development of even more accurate statistical model can be considered for future research.

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