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INFLUENCE OF ABRASIVE WATER JET MACHINING PARAMETERS ON THE SURFACE ROUGHNESS OF EUTECTIC Al-Si ALLOY– GRAPHITE COMPOSITES

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Abstract. In this study, the influence of abrasive water jet machining (AWJM) parameters such as water pressure, standoff distance, and traverse speed each at three different levels were analyzed on the surface roughness of the Al- graphite composites which are fabricated through the squeeze casting method. The experiments were conducted using L9 Taguchi technique. The percentage contribution of each process parameter on surface roughness was analyzed by means of analysis of variance. The contribution of water pressure on surface roughness was found to be more significant than traverse speed and standoff distance. Linear regression model was developed to predict the surface roughness.

1. Introduction

In the abrasive water jet machining, the water jet stream accelerates abrasive particles and those particles erode the material. Machining of particulate reinforced MMCs using conventional machining processes such as turning, drilling, etc., generally results in excessive tool wear due to the presence of the hard reinforcing particles. Moreover, premature failure of the tool caused poor surface quality and high machining cost. Savrun and Taya [1] investigated the machinability of Al 2124- SiC_w and Al 2124 SiC_w -Al_2O_3 composites with an abrasive water jet machining. The machined surfaces were characterized by SEM, energy dispersive X-ray spectroscopy and profilometry. Liu and Chen [2] analyzed the influence of process parameters on cutting mechanism and performance of granite. Among other unconventional machining processes abrasive water jet (AWJ) machining techniques are employed for the machining of difficult-to-cut materials since it has advantages such as absence of thermal effects, high machining flexibility and little cutting forces [3-6].

It was observed that little attention has been paid to the abrasive water jet machining of metal matrix composite materials. Hence more work is required to analyze the cutting performance and to develop models to predict the cutting performance. Abrasive water jet cutting involves a large number of variables which have an influence on the cutting performance, such as size of the orifice, mixing tube and nozzle, the properties of work piece material, the type of abrasive and its mesh size, the standoff distance, water pressure, the traverse speed, the jet impact angle, and the standoff distance. Surface roughness of the machined surface acts as major role in dimensional accuracy. Hence, the proper selection of process parameters is important in achieving better surface finish. Abrasive water jet machining parameters such as water pressure, standoff distance and traverse speed, were considered in the present study. The traverse speed determines the duration of surface exposure of the abrasive particles in impinging on the material's surface. Other parameters such as abrasive size and mass flow rate of abrasive were considered to be constant. Garnet 80 (150 to 300 μm) abrasive particles with a flow rate of 7.5 g/s was chosen. It is obvious that higher abrasive mass flow rate would increase the strike rate of abrasive particles on the work material since more abrasive particles come into contact with the surface to be machined. Hence it accelerates the material removal process thereby decreases the surface roughness. On the other hand, very high mass flow rate could increase the interference between the particles and lead in decreasing the kinetic energy thereby reduces the cutting efficiency which causes the decrease in surface quality. In this study, the effect of process parameters such as water pressure, standoff distance and traverse speed were analyzed on the surface roughness of the Al- graphite composites which are fabricated through the squeeze casting method using L9 Taguchi technique. Linear regression model was developed to describe the correlation between the cutting parameters and the surface roughness and to select the optimum cutting parameters to obtain the minimum surface roughness.

2. Materials and fabrication of composites

Eutectic Al-Si alloy was used as the matrix material and graphite particles (50 -125 microns) were used as the solid lubricant. Squeeze casting method was employed to fabricate the Al-Gr composites [7]. Al– Gr composite melt was prepared employing stir casting method and poured into the preheated (350 °C) mould cavity. 50 MPa squeeze pressure was applied on the melt for 50 seconds through the preheated punch till solidification was completed. Punch was withdrawn and specimen was removed from the mould assembly.

3. Microstructure analysis

The micrograph of Al-7.5 wt.% Gr composite which is shown in Fig. 1.

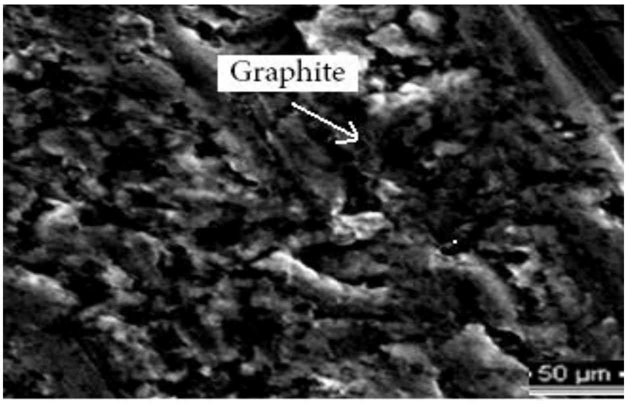

Fig. 1. SEM micrograph of the Al-7.5 wt.% Gr composite.

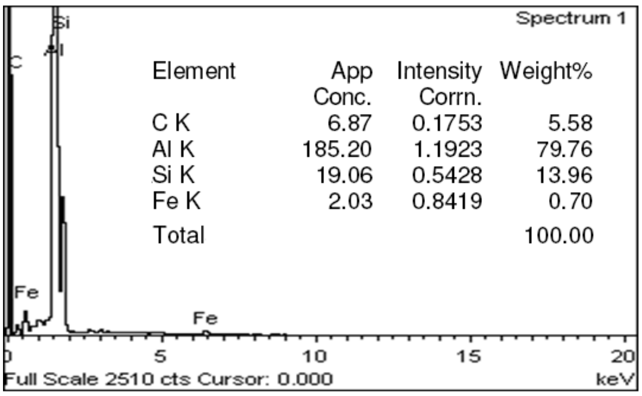

Fig. 2. EDS spectrum of the Al-7.5 wt.% Gr composite.

The dark phases observed in the micrograph are the graphite particles which are being distributed more uniformly in the Al alloy matrix. EDS spectrum of the Al-7.5 wt.% Gr composite specimen is shown in Fig. 2. It indicates the presence of Al, Si and Fe from the Al-Si alloy matrix whereas the existence of C peak confirms the presence of the graphite in the composite.

4. Experimentation

Abrasive cutter was employed for machining the composites. Garnet (angular shape) was chosen as an abrasive material. Sapphire was chosen as primary nozzle (water jet) and tungsten carbide was selected as secondary nozzle (water- abrasive jet). Schematic of an abrasive water jet machining equipment is shown in Fig. 3. During the course of the study, regular checks were made to replace the worn out nozzle in order to enhance the cutting performance. Surface roughness measurement was performed employing SJ-210 – Mitutoya surface roughness tester which is shown in Fig. 4. Surface roughness values were measured at the top, middle and at the bottom of the machined surface and mean value was considered. For all the tests, the other parameters were kept constant using the system standard configuration, i.e. the orifice diameter = 0.33 mm, the mixing (focusing) tube diameter = 0.762 mm, the length of mixing tube = 88.9 mm, the nozzle diameter = 1.02 mm, the nozzle length = 76.2 mm and Jet Impact angle = 90 $^\circ$.

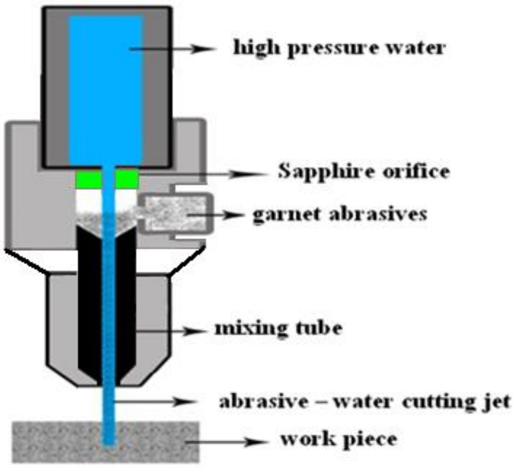

Fig. 3. Schematic of abrasive water jet machining process.

Fig. 4. Surface roughness measurement tester.

5. Taguchi method

Taguchi's parameter design provides a systematic and efficient methodology to find the optimum parameters which have an effect on the process and performance. Taguchi method utilizes orthogonal arrays to study a large number of variables with a minimum number of configurations. In this study, “smaller is better” S/N ratio is used to predict the optimum parameters because a lower surface roughness was desirable. Mathematical equation of the S/N ratio for “smaller is better” is represented in the equation (1):

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum y^2\right], \quad (1)$$

where, y is the observed data and n is the number of observations.

In the present investigation, tests were conducted in the composite material as per the L9 orthogonal array. Accordingly, 9 tests were carried out and each test was repeated thrice in order to reduce the experimental errors. The parameters and the corresponding levels are presented in Table 1. In addition, the experimental results were analyzed using analysis of variance (ANOVA) to study the influence of the parameters on surface roughness.

Table 1.Parameters and levels.

Level	Water pressure, MPa (A)	Standoff distance, mm (B)	Traverse speed, mm/s (C)
I	200	2.5	1.0
II	250	5.0	1.5
III	300	7.5	2.0

Table 2. Measured values and S/N ratios for surface roughness of composites.

Exp.No	Water pressure, MPa (A)	Standoff distance, mm (B)	Traverse speed, mm/s (C)	Surface roughness, microns	S/N ratio
1	200	2.5	1.0	8.20	-18.2763
2	200	5.0	1.5	10.56	-20.4733
3	200	7.5	2.0	11.96	-21.5546
4	250	2.5	1.5	7.05	-16.9638
5	250	5.0	2.0	8.62	-18.7101
6	250	7.5	1.0	7.60	-17.6163
7	300	2.5	2.0	6.60	-16.3909
8	300	5.0	1.0	5.23	-14.37
9	300	7.5	1.5	6.20	-15.8478

Table 3. ANOVA analysis for surface roughness.

Parameters	DoF	Seq.SS	Adj.MS	F value	P value	Pc
Water pressure, MPa (A)	2	27.1107	13.5553	50.98	0.019	74.083
Standoff distance, mm (B)	2	2.6294	1.3147	4.94	0.168	7.185
Traverse speed, mm/s (C)	2	6.3231	3.1615	11.89	0.078	17.278
Error	2	0.5318	0.2659			1.453
Total	8	36.5950				100

DoF - Degrees of Freedom; Seq.SS - Sequential sums of squares; Adj.MS - Adjusted sums of squares; Pc-Percentage of contribution.

6. Results and discussion

6.1 Results of S/N ratio. The S/N ratio for each parameter level is determined by averaging the S/N ratios at the corresponding level. From the response diagram of S/N ratio (Fig. 5), it was found that the optimum parameters were water pressure (300 MPa), standoff distance (2.5 mm) and traverse speed (1 mm/s) for the composites.

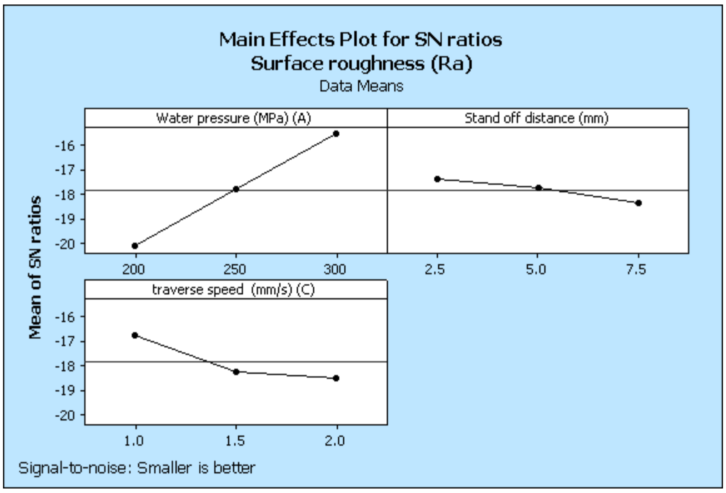

Fig. 5. Response diagram of S/N ratio for surface roughness of Al - Gr composites.

6.2. Results of ANOVA. ANOVA establishes the optimum combination of process parameters more accurately by investigating the relative importance among the parameters. ANOVA was performed with the help of the software MINITAB15 for a level of significance of 5 % to study the contribution of the parameters. In the ANOVA table, there is a P-value for each independent parameter in the model. When the P-value is less than 0.05, then the parameter can be considered as statistically highly significant. It was observed that the water pressure has less than 0.05, which means that it is highly significant at 95 % confidence level. The last column of the table 3 shows the percentage contribution (Pc %) of each variable in the total variation indicating their degree of influence on the surface roughness of the composites. It was observed that the water pressure (74.08 %) was the major contributing parameter followed by traverse speed (17.28 %) and standoff distance (7.18 %) influencing the surface roughness of the Al–7.5 wt.% Gr composite.

6.3. Multiple linear regression model. A multiple linear regression equation was developed to establish the correlation among the parameters on the response. The value of regression coefficient, R^2 (0.9855) is in good agreement with the adjusted R^2 (0.9419). It can be noted that since the value of regression coefficient for the model is 0.9855, the data were not scattered. Since both the values are reasonably close to unity, models provide reasonably good explanation of the relationship between the independent factors and the response (surface roughness).

The regression equation developed for surface roughness is

$$Ra = 14.2 - 0.0423 (A) + 0.261 (B) + 2.05 (C), \tag{2}$$

where Ra = surface roughness; A- water pressure, MPa; B- Standoff distance, mm; C-traverse speed, mm/s.

It can be observed from the Eq. (2) that the coefficient associated with water pressure (A) is negative. It indicates that the surface roughness of the composite decreases with increasing water pressure. Conversely the surface roughnesses of the composite decreases with increasing traverse speed and standoff distance since the co- efficient associated with them are positive.

6.4. Confirmation test. A confirmation test is the final step in the design of experiment process. It was found that the optimum parameters were water pressure (300 MPa), standoff distance (2.5 mm) and traverse speed (1 mm/s) in minimizing the surface roughness of the composites. The confirmation experiments were conducted and results are presented in the Table. 4 and Table 5, respectively. The experimental values and calculated values from the regression equation are nearly same with least error (± 4 %).

Table. 4. Parameters used in the confirmation test.

Test	Water pressure, MPa (A)	Standoff distance, mm (B)	Traverse speed, mm/s (C)
I	225	3	1.2
II	275	5	1.8

Table. 5. Results of confirmation tests.

Material	Test I			Test II		
	Surface roughness					
	Model equation	Expt.	Error, %	Model equation	Expt.	Error, %
Al-Gr composite	7.9255	7.99	0.81	7.5625	7.867	4.02

The resulting equations seem to be capable of predicting the surface roughness to the acceptable level of accuracy. However if number of observations of performance characteristics are increased further these errors can be reduced.

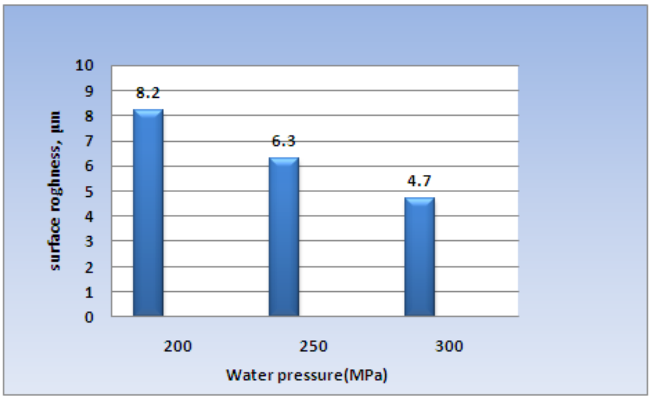

Fig.6. Effect of water pressure on surface roughness.

6.4.1. Effect of the water pressure. For better understanding, surface roughness values were plotted with three different water pressures keeping the other two parameters such as standoff distance (2.5 mm) and traverse speed (1 mm/s) as constants at their optimum values in order to observe the effect of water pressure on the surface roughness. It can be observed from the response diagram of S/N ratio (Fig. 5) that the optimum water pressure was found to be 300 MPa.

Figure 6 depicts that the surface roughness decreases as the water pressure increases. The surface roughness decreased by 43 % when the water pressure was increased from 200 MPa to 300 MPa. It infers that the surface roughness decreased with an increase in water pressure. It can be attributed to the fact that abrasive particles are gaining momentum by allowing the high-pressure water through an orifice of small diameter. An increase in water pressure causes more cutting force of abrasive particles thereby decreasing the surface roughness of the cutting surface. The similar observation was made by the Momber et al. [8]. It was reported that increasing in water pressure improves the surface quality. However, high water jet pressure loses cutting ability of the abrasive particles when they become too fragmented [9].

6.4.2. Effect of the standoff distance. In order to analyze the effect of standoff distance on the surface roughness, surface roughness values were plotted with different standoff distances by keeping the optimum water pressure 300 MPa and traverse speed, 1 mm/s. Figure 7 shows that the surface roughness of composite is apparently to have increasing trend with increase in standoff distance.

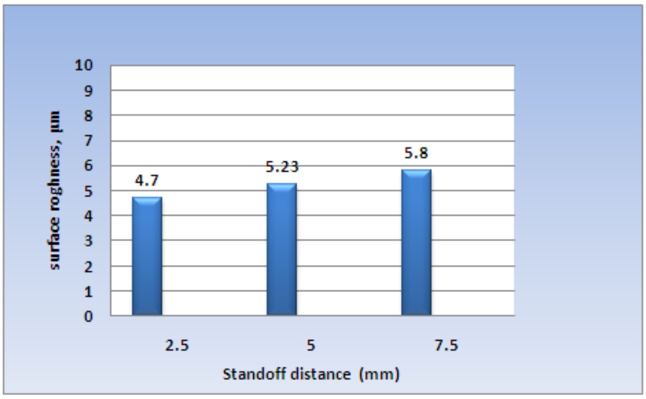

Fig. 7. Effect of standoff distance on surface roughness.

The results revealed that the surface roughness decreased by 19 % when the standoff distance was decreased from 7.5 mm to 2.5 mm at optimum traverse speed (1 mm/s) and water pressure (300 MPa). A lower standoff distance ensures the smoother surface roughness due to increased kinetic energy of the abrasive- water stream. Similar observation was made by John Kechagias et al [10] and they reported that when the standoff distance was increased, the surface roughness increased considerably in machining of TRIP sheet steels.

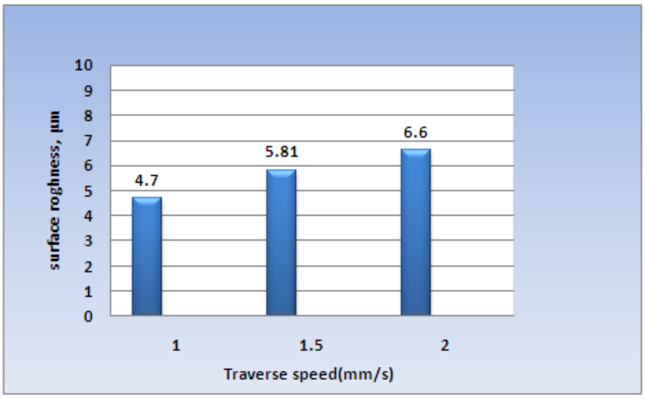

Fig. 8. Effect of traverse speed on surface roughness.

6.4.3. Effect of the traverse speed. Similarly, the average surface roughness value with respect to the three different traverse speeds at optimum water pressure of 300 MPa and traverse speed of 1mm/s is shown in Fig. 8. It demonstrates that a decrease in traverse speed decreases the surface roughness of the machined surface of the composite. Surface roughness decreased from 6.6 µm to 4.7 µm when traverse speed was decreased from 2 mm/s to 1 mm/s. It can be noted that the considerable reduction (29%) in surface roughness is achieved by decreasing the traverse speed. It can be revealed that the lower traverse speed enhance easier removal of material within a short time, resulting in considerable improvement in surface finish.

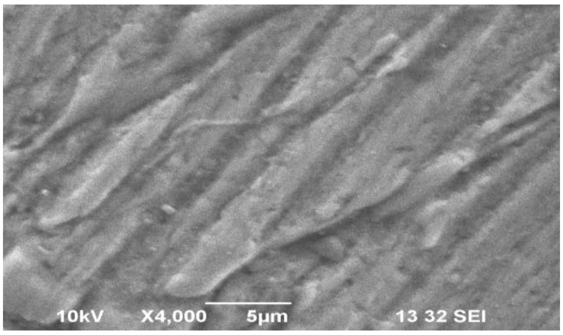

Fig. 9. SEM image showing the machined surface.

A scanning electron microscope was used to investigate the surface quality on the machined surface of Al–Gr composite. Figure 9 shows the surface cut by the optimum parameters (water pressure, standoff distance and traverse speed), keeping other cutting conditions constant. It can be seen from the high magnification SEM image that de-bonding between the graphite particles and Al –Si alloy matrix occurred on the cutting surface where the soft graphite particles pulled out and form a valley on the machined surface of the Al –Gr composite. This could be the cause for higher surface roughness values while machining graphitic reinforced composites.

8. Conclusions

A study of Abrasive Water jet cutting of Al - Gr composites has been presented based on an experimental investigation. It was found that the water pressure is the predominant machining factor followed by traverse speed and the standoff distance. Results showed that surface roughness of composite decreased with increasing water pressure. The lowest surface roughness values occurred at the lowest traverse rate and the standoff distance. The outcomes of investigation show that the water pressure (74.08 %) has the highest influence on surface roughness followed by traverse speed (17.28 %) and standoff distance (7.18 %) in machining of Al-Gr composite. Obtained mathematical modeling can be successfully employed to predict the surface roughness of composites.

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