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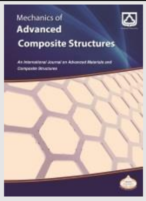

Experimental Study on Surface Roughness and Cutting Force in Turning of Al7032 Reinforced with SiC Using Taguchi Design

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KEYWORDS

Metal matrix composites
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ABSTRACT

Metal matrix composites (MMCs) are now gaining their usage in aerospace, automotive industries because of their excellent engineering properties like low wear rate and high strength to weight ratio. MMCs are hardly machined due to the presence of hard particles in the base phase, such as silicon carbide particles. In this paper, the effect of several factors (spindle speed, depth of cut, feed rate and weight percent of silicon carbide) have been investigated on the parameters of surface roughness and cutting force in the turning operation of AL7032 composite reinforced with SiC. Using the Minitab software and Taguchi method, the design of experiments was carried out in nine experiments in two types of dry machining and machining using mineral oil. Also, analysis of variance and signal-to-noise ratio (S/N) were used to compare the machining conditions and the effect of each input parameter on surface roughness and cutting force. Analysis of variance shows that the weight percentages of silicon carbide and depth of cut have the greatest effect on the surface roughness. On the other hand, the main factors affecting cutting force are the depth of cut and feed rate. It was also found that the use of mineral oil during machining has a significant effect on reducing surface roughness and cutting force.

1. Introduction

Aluminum-based composites are hardly machined due to the presence of hardening reinforcing particles such as silicon carbide [2]. Silicon carbide, boron carbide, and alumina are known as the most popular reinforcements. Aluminum, titanium, and magnesium alloys are often used as metal composites. The density of most metal composites is one-third of the steel [3]. Studies on the metal composites reinforced with alumina and silicon carbide show that the quality of the machining surface is low due to the presence of hard particles [4]. Kumar et al. observed the effect of process parameters on surface roughness in turning of two different composites (AL7075/10wt%SiC and Al7075/7wt%SiC/3wt%Gr). They concluded that graphite plays the role of a solid lubricant, which reduces the heat, friction, and the built-up edge and in result, reduction of surface roughness [5]. Parida et al. examined the optimization of machining conditions for obtaining high surface quality in the graphite-reinforced composite. The results of this research have shown that the minimum cutting speed with the lowest selectable level of feed rate and depth of cut will have the best results to minimize surface roughness [6]. Raj Mohan et al. studied the effect of cutting speed, feed rate, drill type and mass fraction of mica in the drilling process of 356 Aluminum composite reinforced with SiC and mica. They concluded that feed rate had the greatest effect to minimize the thrust force, surface roughness, tool wear, and burr height [7]. Pang et al. optimized the milling parameters of aluminum composite reinforced with epoxy under dry conditions using the Taguchi method. Depth of cut, cutting speed and feed rate were considered as input parameters and surface roughness and machining forces as two output parameters [8]. Zhang modeled the cutting forces by applying the relation between the cutting force and the machining parameters to solve the problem of the short life of tools in composite machining. These experiments were carried out using a tin-coated shear tool for the first time. The results of the analysis have shown that the axial

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and radial depth of cut factors have a significant effect on the compressive forces, which according to the results of the experiments, the effect of radial depth of cut is considered to be more important [9]. Aaron investigated the effect of feed rate, cutting speed, depth of cut and alumina weight percent during milling of three samples of 6061 aluminum composite reinforced with 5, 10 and 15 wt% alumina and 5 wt% graphite produced by stir casting method. They declared that the main factors affecting the cutting force, surface roughness and tool wear are cutting speed and feed rate [10]. Vencatsen et al. examined the turning process of three types of AL356 composites reinforced with 5% boron carbide and different percentages (5, 10 and 15%) of silicon carbide using the diamond tool. They expressed the depth of cut and feed rate had the most effect on cutting force. On the other hand, the depth of cut and the weight percentage of silicon carbide had the most effect on surface roughness [11]. Huang et al. used Polycrystalline diamond (PCD) tools in high-speed milling SiCp/Al composites with higher volume fraction and larger size SiC particles. The results showed that the size of the diamond particle had a great influence on the wear resistance of PCD tools [12]. Chunzheng et al. studied the effects of the different cooling and lubrication conditions on the tool wear in the machining of Al/SiCp composites. The results showed that the minimum quantity lubrication (MQL) and liquid nitrogen (LN2) could be reduced the boundary wear because removing the chips and SiC particles from the boundary zones. In general, MQL is the best cooling and lubrication mode in turning of Al/SiCp [13].

From the literature, it is found that the machining of metal matrix composites is a main field of research in machining, but few researchers have been investigated the effects of several parameters simultaneously on surface roughness and cutting force in dry and wet conditions while machining of MMC. The present study has been carried out to study the effect of spindle speed, feed rate, depth of cut and weight percent of silicon carbide on cutting force and surface roughness in turning of Al/SiC composite. The Taguchi method has been employed to determine the number of tests. After performing the tests, analysis of variance (ANOVA) was applied to determine the most significant control factors in dry and wet conditions.

2. Material and methods

Aluminum composite materials have good properties such as good thermal and electrical conductivity, low thermal expansion coefficient, high shear strength, low density, and high abrasion resistance. This type of composite has wide applications in brake rotor and piston as well as golf carts, bicycles and electronic instruments. Continuous fibers (boron, silicon carbide, alumina, and graphite), discontinuous fibers (alumina and alumina-silica), viscera (silicon carbide) and particles (silicon carbide and boron carbide) are used as reinforcement in aluminum composite structures. Therefore, due to the high application of aluminum composite, the Al7032 composite reinforced with silicon carbide with a grain size of 15 μm was produced by stir casting method. Table 1 shows the chemical composition of Al7032. The Al7032 composite reinforced with 5% and 10% silicon carbide particles and a pure Al7032 were produced in the metal casting laboratory of Semnan University. The Al7032 plain aluminum was melted in an induction electric resistance furnace to a temperature of about 750 ° C. The calculated weight fraction of silicon carbide particles was preheated to 800 ° C. Then molten aluminum and preheated silicon carbide were stirred continuously for 10 minutes in a stir casting furnace as shown in Fig. 1. After mixing, the stirred melt was deposited into a molded steel cylinder of 40 mm diameter and 120 mm in length. After composite completion, a composite specimen of 5% weight fraction was prepared for the X-ray diffraction (XRD) test to detect silicon carbide in the composite, as shown in Fig. 2. Carbide tungsten insert TNMG220412RP made by Kennametal and tool holder Marox MTANR 2525 M22 were applied in all of the experiments. Machining forces in axial (X), radial (Y) and cutting (Z) directions were measured by Kistler 9257 dynamometer. Kistler 9257 has 8 channels and calculates the forces and torques in three directions. Fig. 3 shows the dynamometer mounted on the longitudinal support of the TN50D machine and the force directions. This dynamometer in connecting with an amplifier Kistler 5070 and a Data acquisition can record the output data. The surface roughness was measured by TR200 Roughometer.

Table 1. Chemical composition of Al7032

Symbol of a chemical element	Percentage of participation (%)
Cu	2.11
Mg	2.04
Si	0.357
Fe	0.142
Mn	0.176
Ni	0.008
Zn	3.79
Ti	0.028
Pb	0.015
Cr	0.222

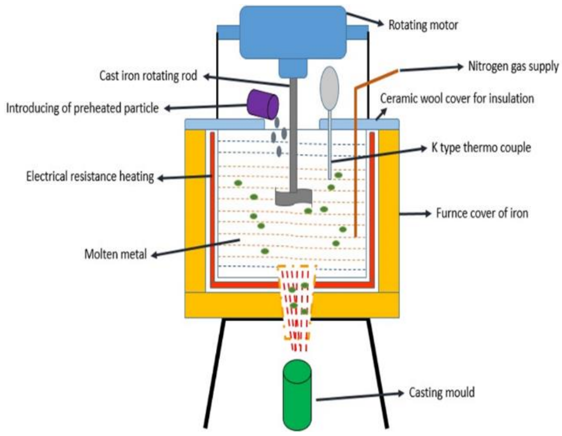

Fig. 1. The schematic of the stir casting furnace

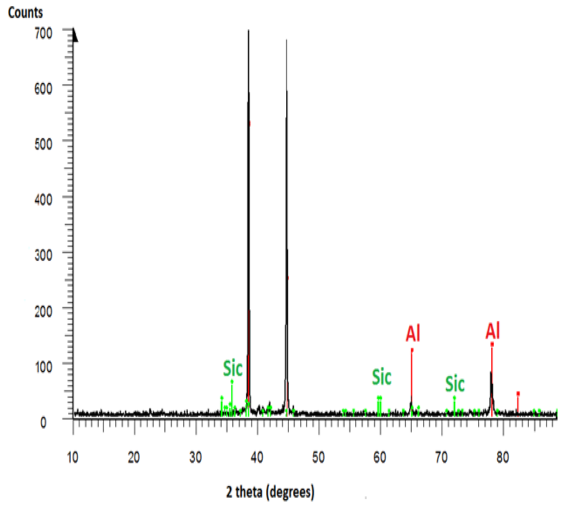

Fig. 2. XRD graph of a 5% AL/SiC

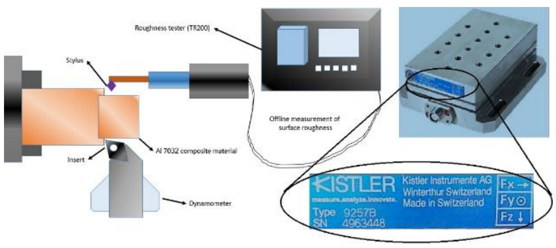

Fig. 3. the schematic of the machining setup

3. Design of experiment based on the Taguchi method

To save time and less waste of raw materials, as well as more accurate statistical analyzes, the design of the experiment (DOE) is used to carry out the experiments. Taguchi is one of the DOE methods used extensively for optimization. In this method, the ANOVA studies the effect of each of the factors on the output parameters separately and S/N ratio interprets the proportion of the desired signal to undesirable random noise. The S/N ratio for each response can be estimated by using the Eq. (1).

$$S/N = -10\, Log_{10}\left(\frac{Y^2{}_1+Y^2{}_2+Y^2{}_3+\cdots+Y^2{}_N}{N}\right) \quad (1)$$

where i = 1,2,... , n (here n = 4) and Yi is the response value for an experimental test. This paper investigates the effect of the weight percent of silicon carbide, spindle speed, feed rate, and depth of cut in three levels by the Taguchi method. Table 2 shows the values and levels of input parameters. The statistical analysis was performed in Minitab software. The number of tests by using the Taguchi method is 9. It should be noted each test has been studied in wet and dry conditions. So, the total number of experiments was 18 tests. Table 3 shows the table of DOE.

4. Results and Discussions

4.1. The Effect of machining parameter on Cutting force

Machining forces were measured in axial (X), radial (Y) and cutting (Z) directions for each test. Since the cutting force (Z direction) is the main term in analyzing the cutting condition, so the results of cutting force were reported in this paper. The S/N ratio was calculated as -40.2336 and -39.3445 for dry and wet conditions respectively. It showed the use of wet condition reduced the cutting force.

Table 2. The Values and levels of input parameters

Symbol	parameters machining	Level 1	Level 2	Level 3
M	Weight percent of silicon carbide (%)	0	5	10
S	Spindle speed (rpm)	500	710	1000
F	feed rate (rev/min)	0.08	0.14	0.20
D	depth of cut (mm)	0.5	1	1.5

Table 3. Design of experiments

experiment	the weight percent of silicon carbide	Spindle speed	feed rate	depth of cut
1	0	500	0.08	0.5
2	0	710	0.14	1
3	0	1000	0.20	1.5
4	5	500	0.14	1.5
5	5	710	0.20	0.5
6	5	1000	0.08	1
7	10	500	0.20	1
8	10	710	0.08	1.5
9	10	1000	0.14	0.5

Also, the S/N ratio for each experiment is shown in Table 4. With respect to Table 4, the first level of the input parameters in wet condition has the minimum amount of cutting force, which is 27.73 N.

The effect of the input factors (the weight percent of silicon carbide, spindle speed, feed rate, and depth of cut) separately on the cutting force in wet and dry condition has been shown in Figs. 4 - 7 respectively. By examining Figs. 4 - 7, it is obvious that the depth of cut and the feed rate have the greatest effect on the cutting force. By increasing the feed rate and the depth of cut, the cutting force is going up due to an increase in the non-deformed chip cross-section area [14]. Also, the increase of the weight percent of silicon carbide goes up the cutting force due to the increase of workpiece hardness. Increasing the spindle speed initially reduces and then increases the cutting force. Of course, according to Figs. 4 and 5, the effect of the reinforcements percentage and spindle speed is not considerable. Also, the wet condition has a better result due to reducing friction in the machining area. The results of ANOVA for the cutting force in dry and wet conditions are shown in Tables 5 and 6. The results are meaningful, whenever P-value is less than 0.05. Therefore, the spindle speed and weight percent of silicon carbide are meaningless with respect to Tables 5 and 6 and must be eliminated in the prediction of the model. After eliminating meaningless factors in both machining conditions, it was found that the depth of cut and feed rate have the greatest effect on cutting force, respectively. The software predicts a linear model without any interaction between the factors. The P-value must be less than 0.05 until the model be meaningful. This means that whatever the P-value of a factor is lower, the factor is more meaningful than the rest of the factors. Following equations can be used to obtain the numerical values in the ANOVA table.

Table 4. The results of the S/N ratio and cutting force for each test

Test	Cutting force in dry (N)	S/N in dry	Cutting force in wet (N)	S/N in wet
1	34.71	-30.8091	27.73	-28.8590
2	82.4	-38.3185	80.9	-38.1590
3	147.5	-43.3758	137.11	-42.7414
4	139.2	-42.8728	104.5	-40.3823
5	71.79	-37.1213	57.01	-35.1190
6	80.65	-38.1321	78.24	-37.8686
7	127.2	-42.0897	124.55	-41.9069
8	116.37	-41.3168	105.07	-40.4296
9	66.84	-36.5007	66.6	-36.4695

$$\text{The total degree of freedom} = f_T = N - 1 \quad (2)$$

$$\textit{Degree of freedom for parameter} = f_S = f_m = f_d = f_f = \text{Number of level} - 1 \quad (3)$$

$$\textit{Degree of freedom for pooled error} = f_e = f_T - (f_S + f_m + f_d + f_f) \quad (4)$$

$$\textit{Sum of squares due to parameter } S = S_S = \frac{S^2{}_1}{N_{S_1}} + \frac{S^2{}_2}{N_{S_2}} + \frac{S^2{}_3}{N_{S_3}} - \frac{T^2}{N} \quad (5)$$

$$\textit{Total Sum of squares} = S_T = \sum_{i=1}^{n} y_i{}^2 - \frac{T^2}{N} \quad (6)$$

$$\textit{Variance to parameter } S = V_S = \frac{S_S}{f_S} \quad (7)$$

$$\textit{Total variance} V_T = \frac{S_T}{f_T} \quad (8)$$

$$\textit{F value to parameter } S = F_S = \frac{V_S}{V_e} \quad (9)$$

$$\textit{Percentage contribution of parameter } S = P_S = S_S \frac{100}{S_T} \quad (10)$$

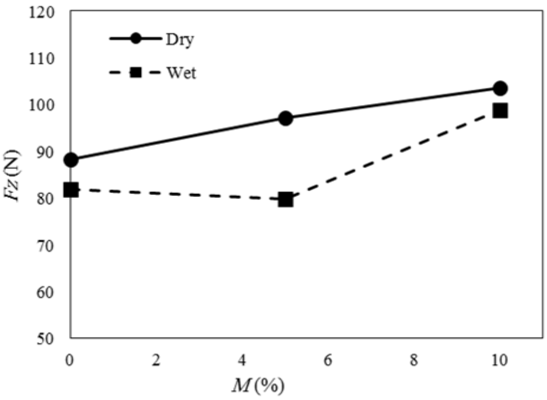

Fig. 4. the effect of reinforcement's percentage on the cutting force

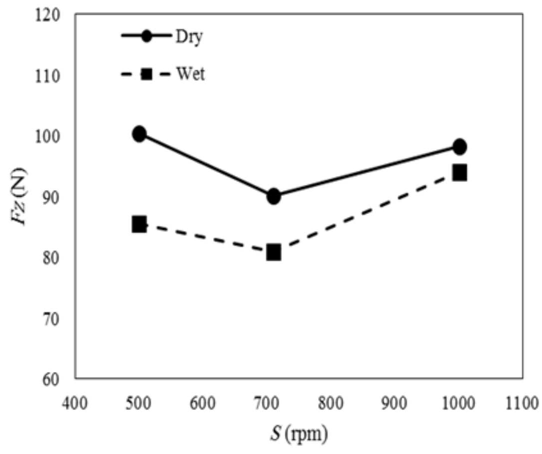

Fig. 5. The effect of spindle speed on the cutting force

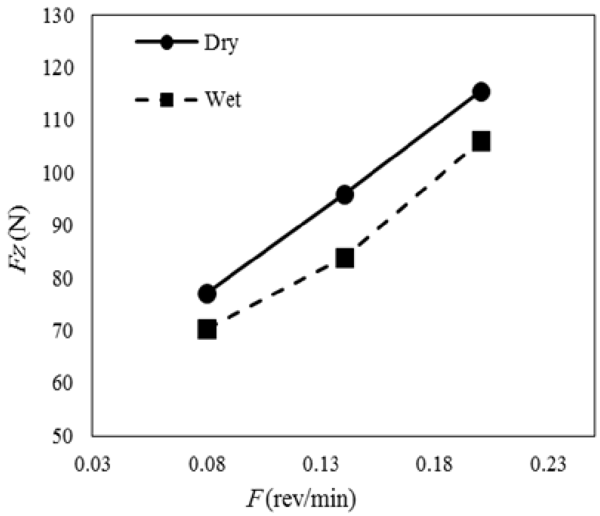

Fig. 6. The Effect of feed rate on the cutting force

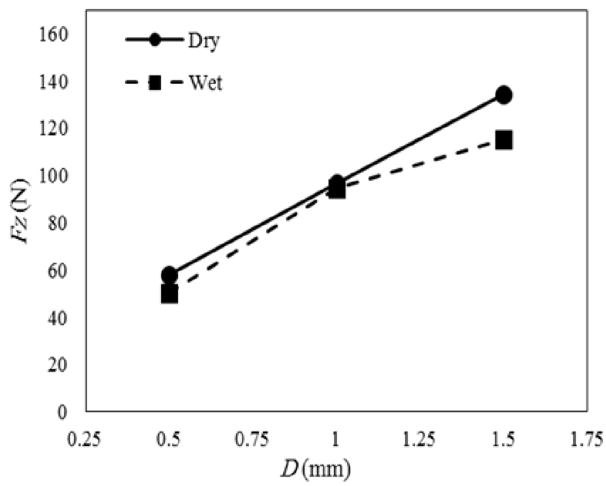

Fig. 7. The effect of depth of cut on the cutting force

Table 5. ANOVA for cutting force in dry machining

Source	DOF	Sum of square	Variance	F value	P value	
Model	4	10991.98	2748.00	20.84	0.0061	significant
S	2	174.17	87.08	0.064	0.9387	Not significant
M	2	553.39	276.69	0.032	0.9690	Not significant
F	2	2195.07	1097.53	8.32	0.0375	
D	2	8796.9	4398.45	33.35	0.0032	
Error	4	527.57	131.89			
T	8	11519.55				

Table 6. ANOVA for Cutting force in wet machining

Source	DOF	Sum of square	Variance	F value	P value	
Model	4	8594.31	2148.58	9.53	0.0253	significant
S	2	260.29	130.14	0.15	0.8659	Not significant
M	2	641.44	230.72	0.061	0.9421	Not significant
F	2	1967.42	983.71	4.36	0.0488	
D	2	6626.88	3313.44	14.69	0.0143	
Error	4	901.73	225.43			
T	8	9496.04				

4.2. Effect of machining parameter on surface roughness

At the end of each experiment, the roughness of the machined sample was measured by a roughometer. The S/N ratio was calculated -6.4795 and -5.3070 for dry and wet conditions respectively. These numerical values indicate a decrease in surface roughness during wet machining. Table 7 shows the S/N ratio for each test. With respect to Table 7, it is obvious that the first level of input parameters in wet condition is the best level for achieving to lowest surface roughness.

Figures 8 to 11 show the effect of the spindle speed, depth of cut, feed rate and weight percent of silicon carbide on surface roughness. With respect to Figs. 8 to 11, the weight percentage of the reinforcement and the depth of cut have the most effects on the surface roughness, respectively. Increasing the percentage of reinforcement in the aluminum phase increases the number of impurities in the material and creates a lack of uniformity in the material. As a result, the tool during the machining process crosses through the soft and hard phases successively and happens the wear of the cutting tool. The wear of cutting edge reduces the surface finish. Also, the increase of depth of cut affects the cross-sectional area of cutting and increases the pressure and vibration on the cutting edge. This factor increases the friction and heat in the cutting area and as a result the reduction of surface finish [3]. By increasing the spindle speed and feed rate, the roughness of the surface increases, but, as shown in Figs. 9 and 10, this increase is negligible and the effect of these two factors can be ignored. Also, the surface roughness has been significantly reduced by changing the machining conditions from dry to wet.

Table 7. The results of Surface roughness of each test

Test	Surface roughness in dry (μm)	S/N in dry	Surface roughness in dry (μm)	S/N in wet
1	0.855	1.3606	0.587	4.6272
2	1.137	-1.1152	0.898	0.9344
3	1.692	-4.5680	1.483	-3.4228
4	2.474	-7.8679	2.244	-7.0204
5	1.806	-5.1343	1.597	-4.0661
6	2.046	-6.2181	1.804	-5.1247
7	2.746	-8.7740	2.238	-6.9972
8	2.940	-9.3669	2.643	-8.4419
9	2.318	-7.3022	2.089	-6.3989

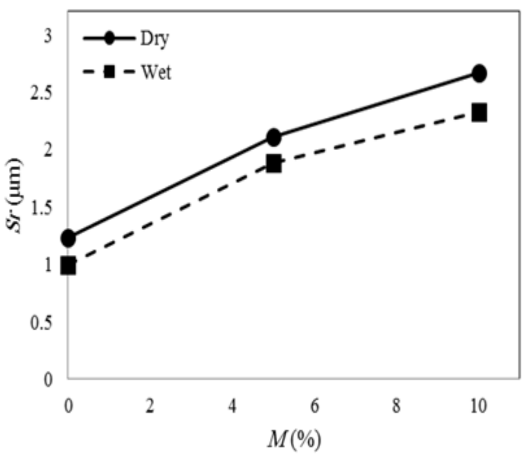

Fig. 8. The Effect of reinforcements percentage on surface roughness

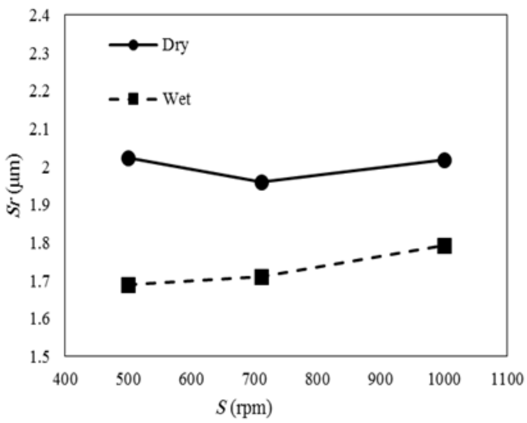

Fig. 9. The Effect of spindle speed on surface roughness

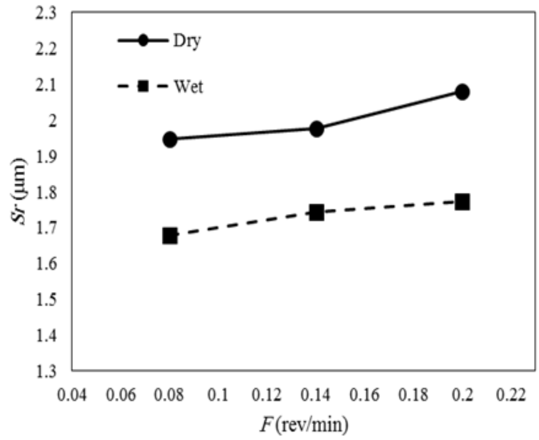

Fig. 10. The Effect of feed rate on surface roughness

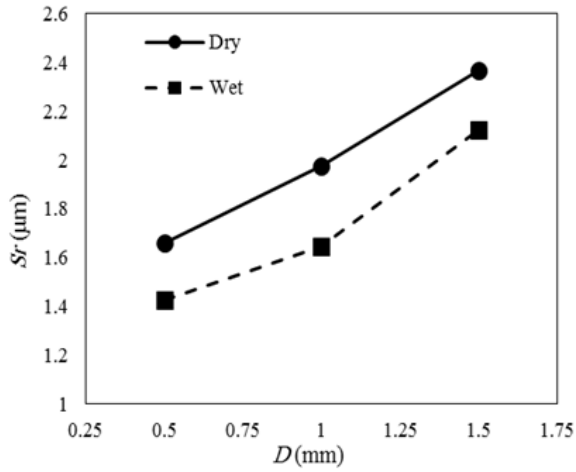

Fig. 11. The Effect of depth of cut on surface roughness

ANOVA for surface roughness in wet and dry condition are shown in Table 8 and 9. This analysis shows that the factors of the reinforcement percentage and the depth of cut are the main factors affecting surface roughness. Concerning Table 8, spindle speed and feed rate have a P-value greater than 0.05 that should be removed from the model. The software predicts a linear model without any interaction between the factors. Also, the predicted model is meaningful because the P-value is less than 0.05.

Table 8. ANOVA for surface roughness in dry machining

Source	DOF	Sum of square	Variance	F value	P value	
Model	4	3.92	0.98	104.80	0.0003	Significant
S	2	0.006	0.003	<0.0001	0.9962	Not significant
M	2	3.16	1.58	169.13	0.0001	
F	2	0.028	0.014	0.015	0.9849	Not significant
D	2	0.77	0.385	40.48	0.0022	
Error	4	0.021	0.0025			
T	8	3.95				

Table 9. ANOVA for surface roughness in wet machining

Source	DOF	Sum of square	Variance	F value	P value	
Model	4	3.54	0.88	112.58	0.0002	Significant
S	2	0.015	0.0075	<0.0001	0.9903	Not significant
M	2	2.77	1.385	176.43	0.0001	
F	2	0.014	0.007	<0.0001	0.9921	Not significant
D	2	0.76	0.38	48.73	0.0016	
Error	4	0.031	0.00925			
T	8	3.56				

5. Results and Discussions

This paper studied the effective parameters during machining of AL7032 with two AL7032 composites reinforced with 5 and 10 wt% silicon carbide. The effects of spindle speed, depth of cut, feed rate and weight percent of silicon carbide were investigated on cutting force and surface roughness and the following results were obtained.

• ANOVA shows that the factors of the depth of cut and feed rate with the percentage of participation of 74.07% and 16.76% in dry condition and 65.03% and 15.97% in wet condition have the greatest effect on cutting force.

• By increasing the parameters of the depth of cut and feed rate, the non-deformed chip cross-sectional area goes up, which increases the cutting force.

• ANOVA shows that the factors of the weight percent of reinforcement and depth of cut with the percentage of participation of 79.61% and 19.32% in dry condition and 77.23% and 20.78%in wet condition have the greatest effect on surface roughness.

• Increasing the percentage of reinforcement in the aluminum phase increases the number of impurities and causes a lack of uniformity in the material of the workpiece. In this case, the tool passes through the soft and hard phase and creates high surface roughness.

• Using the mineral oil during the turning process and the use of the first levels of the input parameters cause to obtain the minimum cutting force and surface roughness. By doing the first level of input parameters, the cutting force and the surface roughness were measured 27.73 N and 0.587 μm respectively.

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