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On The Optimization Of The Machinability Characteristics Of Al-Si/Al_2O_3 AND Al-Si/MWCNTs METAL MATRIX NANOCOMPOSITES

M. Al-Kandary, S. S. Habib, E.H.Mansour, T. S. Mahmoud

Mechanical Engineering Department, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.

ABSTRACT

This paper presents the results of experimental investigation on the machinability characteristics in conventional turning process of two different Al-Si alloy-based metal matrix nanocomposites (MMNCs), containing 0.5 vol.-% of Al_2O_3 nanoparticles and 0.5 vol.-% multi-wall carbon nanotubes (MWCNTs). The MMNCs were fabricated using stir casting technique. The influence of the nanofiller type as well as the turning machining parameters, typically, the cutting speed, feed rate and the rake angle of the cutting tool on the machinability characteristics, typically, the surface roughness, roundness error and material removal rate (MRR) were studied. The results revealed that cutting speed has the most significant effect on the roundness error and MRR of the nanocomposites. While, the rank angle is the most influential factor that affect the surface roughness of the nanocomposites.

KEYWORDS: Metal matrix nanocomposites, Optimization, Machinability, Aluminum Alloys, Analysis of Variance (ANOVA).

1. INTRODUCTION

Metal matrix nanocomposites (MMNCs) are new category of engineering materials with increasing applications in industry especially in automotive and aerospace industries. Typical application of MMNCs include engine parts, brake system, pump housing and supercharger compressor [1]. The main advantage of these materials is the ability of tailoring material characteristics by altering the matrix alloys and nanofiller phase proportions. One main class of MMNCs is aluminum-alloy matrix nanocomposites reinforced with ceramics nanoparticulates, such as graphene, SiC, TiO_2 and alumina, or nanotubes such as carbon nanotubes (CNTs) and multiwall carbon nanotubes (MWCNTs) [2,3].

Despite the superior mechanical and physical characteristics as well as the low production cost, the nanoparticulate reinforced MMNCs are not extensively used in industry due to their poor machinability. The presence of hard nanoparticles phase, such as alumina (Al_2O_3) or silicon carbide (SiC) makes the machining process difficult [4,5]. So, many investigators have worked to unraveling the various aspects of machining these materials.

Turning is a process used to machine round products. In turning process, the workpiece rotates in high speed, and a cutting tool is used to remove away the unwanted material. The productivity of such process depends on many factors such as material removal rate (MRR), cutting forces and power consumption, tool life and wear. Various parameters such as nature of workpiece material, cutting edge geometry, rake angle, tool material, cutting speed, feed rate and depth of cut can affect the aforementioned factors [6,7]. Accordingly, it is important to choose the proper machining conditions to improve cutting efficiency [8,9].

In the present investigations the optimization of the MMR, surface roughness and roundness error during Turning of Al-based nanocomposites was carried out. Two different nanocomposites were fabricated, typical, Al/0.5%Al_2O_3 and Al/0.5%MWCNTs, using stir casting technique. This technique has several advantages such as the simplicity, low cost and high productivity [10]. Taguchi design of experiment technique was performed to investigate the effect of the turning process parameters typically the cutting speed, feed rate and the rake angle of the cutting tool on the aforementioned machinability characteristics. The optimum process parameters combinations were determined using the analysis of signal-to-noise (S/N) ratios. The levels of importance of the turning process parameters on the machinability characteristics were determined by analysis of variance (ANOVA) statistical approach.

2. EXPERIMENTAL PROCEDURES

In the present investigation, the Al-Si aluminum alloy was used as a matrix. The chemical composition is shown in Table 1. Nano-Al_2O_3 particulates and multi-wall carbon nanotubes (MWCNTs) were used as reinforcing agents. The Al_2O_3 nanoparticles have average size of 50 nm, while the MWCNTs have inner and outer diameters of 10 and 30 nm, respectively. The aforementioned nanofillers were dispersed in the Al-Si matrix by 0.5 vol.-% using stir casting technique. The nanocomposites were poured into steel die that has a cylindrical shape cavity with a diameter of 40 mm and length of 210 mm.

Table.1 The chemical composition of the Al-Si matrix alloy.

Alloy	Fe	Si	Mn	Ni	Ti
Al-Si	0.221	5.50	0.014	0.62	0.14

Figure 1. The turning process of the nanocomposites.

The turning experiments were conducted using a conventional center lathe machine with the following general specification: length between chuck center to dead center is 750 mm, maximum diameter is 420 mm, power is 5 HP, speed up to 1250 rpm and feed motion range (up to 1.30 mm). Three cutting tools with different rake angles, typically, 4, 8 and 12º were used to machine the nanocomposites. The tools are made from k100 tool steel. Figure 1 show a photograph of the turning process carried out in the present investigation.

The roughness (R_a) of the workpiece surafce was measured using Mitutoyo Surftest SJ-310 surface roughness tester. The roundness error of the machined workpieces was measured using Taylor-Hobson talyrond 73 roundness tester. The machining experiments were designed using Taguchi design of experiments approach. The Taguchi's L27 orthogonal array (OA) was adopted in the present work. The L27 OA include 27 experiments. The input (independent) parameters are the cutting speed, feed rate and rake angle as well as the nanofiller type. The output (dependent) parameters are the surface roughness, roundness error and material removal rate (MRR). Table 2 lists the parameters and level values used for L27 orthogonal array.

Table 2. The turning process parameters levels.

Parameter	Unit	Parameter Level		
		Level 1	Level 2	Level 3
Nanofiller (A)	-	0 %	0.5A %	0.5C %
Cutting speed (B)	(mm/sec.)	500	712	970
Feed rate (C)	(mm/rev.)	0.06	0.08	0.10
Rake angle (D)	-	4º	8º	12º

The signal-to-noise (S/N) ratio was estimated. The "larger-the-better" quality characteristics was considered for the MRR while the "lower-the-better" was considered for both the surface roughness and roundness error. Finally, the analysis of variance (ANOVA) statistical approach was performed to find which process parameters are statistically significant. Using the S/N ratio and ANOVA analyzes, the optimal combination of the machining process parameters can be predicted. The ANOVA calculations were performed using MiniTab statistical commercial software.

3. RESULTS AND DISCUSSION

As mentioned earlier, in the present investigation L27 OA was used to carry out the machining experiments and the results were analyzed using Taguchi approach. Table 3 lists the L27 OA and the observed experimental values.

3.1. Effect of Machining parameters on The MRR of the Nanocomposites.

Figure 2 shows the mean values of MMR for each parameter at levels 1, 2 and 3 for S/N data. The results show that both of the nanofiller type (A) and the rake angle (D) have no influence on the MRR of the Al-Si monolithic alloy as well as the Al/0.5%Al_2O_3 and Al/0.5%MWCNTs nanocomposites. Table 4 lists the mean of each response parameters for each level of each factor. The table lists the ranks of the response factors based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest mean for each factor. The table assigns the ranks based on delta-values; rank 1 is to the highest delta value, rank 2 is to the second highest, and so on. The ranks show the relative importance of each parameter to the response. From Table 4, it is clear that the cutting speed (B) has the highest influence on MMR of the nanocomposites and is followed by feed rate (C). The optimal machining process parameter combination is the one that produces individual maximum mean S/N ratio. Accordingly, for maximum MRR this combination is A1B3C3D1.

Table 3. The L27 OA with the machining processes parameters and experimental results.

Exp. No.	Nanofiller	Cutting speed (mm/sec)	Feed rate (mm/rev)	Rake angle (Degree)	MRR (mm^3/sec)	Mean Ra (μm)	Mean round error (μm)
1	0%	500	0.06	4	15.00	4.92	37.65
2	0%	500	0.06	4	15.00	4.242	36.58
3	0%	500	0.06	4	15.00	3.998	35.60
4	0%	712	0.08	8	28.48	3.111	22.36
5	0%	712	0.08	8	28.48	3.354	24.81
6	0%	712	0.08	8	28.48	3.696	31.28
7	0%	970	0.1	12	48.50	3.439	34.72
8	0%	970	0.1	12	48.50	3.408	35.54
9	0%	970	0.1	12	48.50	3.491	36.19
10	0%	500	0.08	12	20.00	4.250	37.59
11	0.5A%	500	0.08	12	20.00	4.026	38.90
12	0.5A%	500	0.08	12	20.00	4.265	38.05
13	0.5A%	970	0.1	4	35.60	5.232	40.05
14	0.5A%	970	0.1	4	35.60	5.398	40.96
15	0.5A%	970	0.1	4	35.60	5.273	41.43
16	0.5A%	970	0.06	8	29.10	3.596	35.58
17	0.5A%	970	0.06	8	29.10	3.615	34.81
18	0.5A%	970	0.06	8	29.10	3.723	35.49
19	0.5c%	500	0.1	8	25.00	4.858	39.19
20	0.5c%	500	0.1	8	25.00	4.447	38.31
21	0.5c%	500	0.1	8	25.00	4.463	38.31
22	0.5c%	712	0.06	12	21.36	2.257	20.82
23	0.5c%	712	0.06	12	21.36	2.833	21.18
24	0.5c%	712	0.06	12	21.36	3.060	25.28
25	0.5c%	970	0.08	4	38.80	4.662	38.47
26	0.5c%	970	0.08	4	38.80	4.587	38.91
27	0.5c%	970	0.08	4	38.80	4.399	37.67

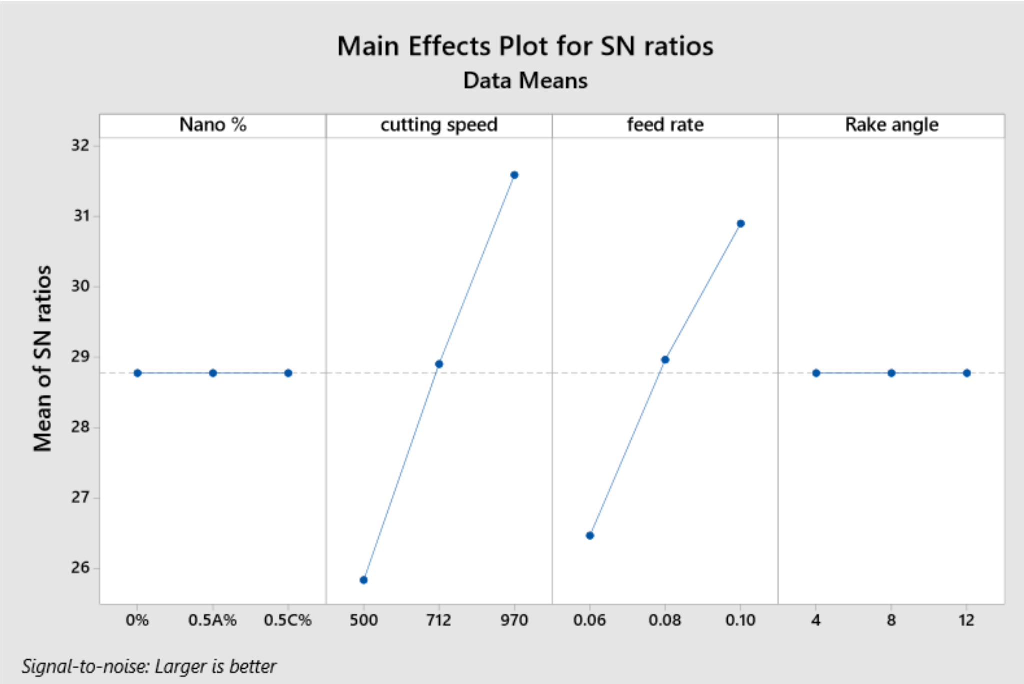

Figure 2. Main effects for S/N ratios of MRR of nanocomposites.

Table 4. Response for S/N ratios for MRR (Larger is better).

Level	Nanofiller	Cutting speed	Feed rate	Rake angle
1	28.78	25.83	26.46	28.78
2	28.78	28.90	28.96	28.78
3	28.78	31.59	30.90	28.78
Delta	0.00	5.76	4.44	0.00
Rank	3	1	2	4

The ANOVA results for the MRR of the nanocomposites are shown in Table 5. The ANOVA table shows the percentage contribution of each of the machining parameters. As mentioned earlier, for the main effect plots (Fig. 2), a similar trend can be noticed for the investigated machining parameters, i.e., the parameter B (cutting speed) and C (feed rate), showed the most significant influence on MRR while parameters A (nanofiller type) and D (rake angle) were not significant within the investigated experimental range. The cutting speed and feed rate exhibited percentage of contribution values of 61.03% and 36.43%, respectively. While the nanofiller type and rake angle parameters exhibited an equal value of the percentage of contribution of 1.27%.

Table 5. ANOVA results for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Nanofiller	2	33.24	16.620	-	-	01.27 %
Cutting speed	2	1595.56	797.779	-	-	61.03 %
Feed rate	2	952.22	476.112	-	-	36.43 %
Rake angle	2	33.24	16.620	-	-	01.27 %
Error	18	0.00	0.000	-	-	00.00 %
Total	26	2614.26	-	-	-	100 %

3.2. Effect of Machining parameters on The Surface Roughness of the Nanocomposites.

The mean values of surface roughness for each parameter for S/N data is illustrated in Fig. 3. Table 6 and Table 7 lists the response for S/N ratios and ANOVA results for the surface roughness of the nanocomposites. The results revealed the rake angle (D) is the most influential factor on the surface roughness of the nanocomposites followed by the feed rate (C), nanofiller type (A) and cutting speed, respectively (see Table 6). The rake angle, feed rate, nanofiller type and cutting speed parameters exhibited percentage of contribution values of 44.06%, 27.05%, 15.23% and 8.22%, respectively (see Table 7). Using the minimum-is-better concept for the surface roughness, the optimum levels of the investigated parameters are A2B1C3D1.

3.2. Effect of Machining parameters on The Roundness Error of the Nanocomposites.

The mean values of roundness error (in µm) for each machining parameter for S/N results is illustrated in Fig. 4. Table 8 lists the response for S/N ratios for the roundness error of the nanocomposite workpieces. Table 9 lists ANOVA results for the roundness error of the nanocomposite workpieces. The results revealed the cutting speed (B) is the most influential factor on the roundness error of the nanocomposites followed by the rake angle (D), feed rate (C) and nanofiller type (A), respectively (see Table 8). The cutting speed, rake angle, feed rate and nanofiller type parameters showed percentage of contribution values of 33.44%, 22.09%, 21.84% and 16.38%, respectively (see Table 9). Using the smaller-is-better concept for the roundness error, the optimum levels of the investigated parameters are A2B1C3D1.

Table 6. Response Table for S/N ratios for surface roughness (Smaller is better)

Level	Nanofiller	Cutting speed	Feed rate	Rake angle
1	-11.22	-12.65	-10.75	-13.31
2	-12.72	-11.71	-12.07	-11.70
3	-11.72	-11.71	-12.83	-10.64
Delta	1.50	1.37	2.07	2.67
Rank	3	4	2	1

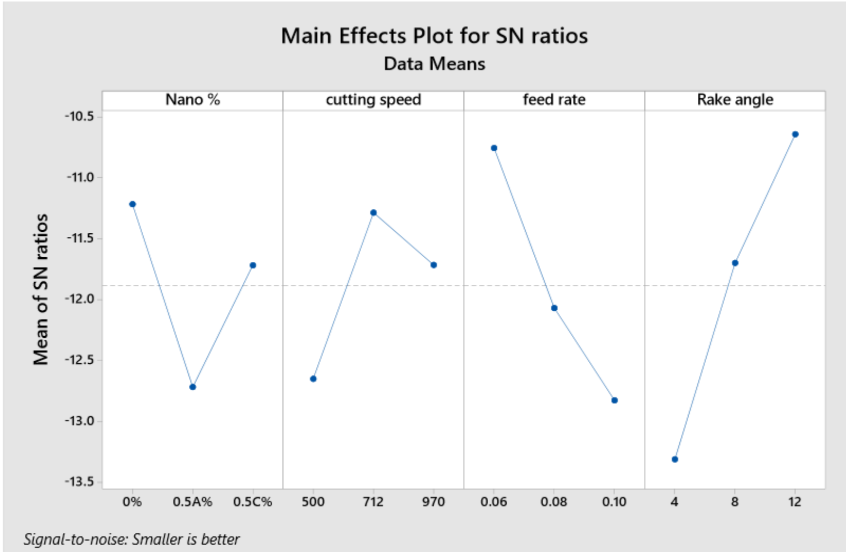

Figure 3. Main effects for S/N ratios of surface roughness of nanocomposites.

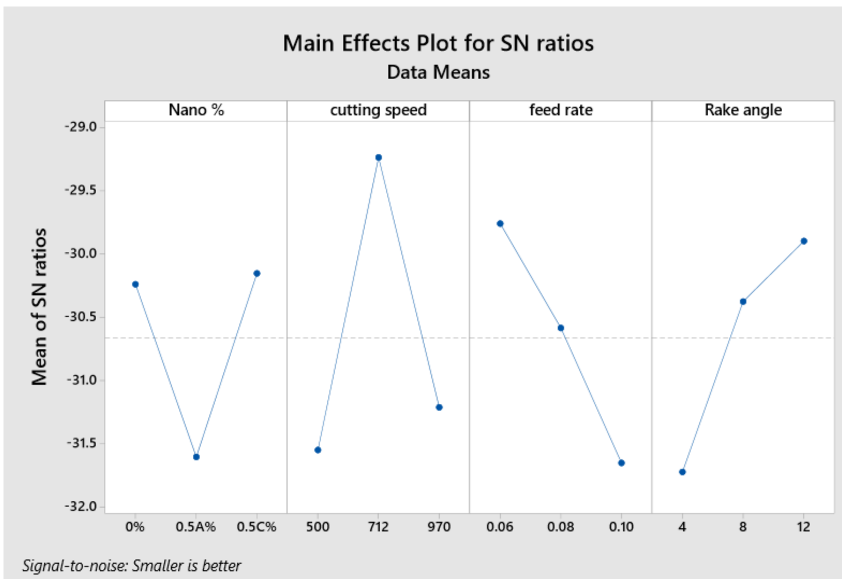

Figure 4. Main effects plot for S/N ratios of roundness error of the nanocomposite workpices.

Table 7. ANOVA for surface roughness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Nanofiller	2	2.4032	1.20159	28.61	0.000	15.23 %
Cutting speed	2	1.5264	0.62821	14.96	0.000	08.22 %
Feed rate	2	4.1339	2.06693	49.22	0.000	27.05 %
Rake angle	2	6.7329	3.36647	80.17	0.000	44.06 %
Error	18	0.7559	0.04199	-	-	04.95 %
Total	26	15.2823	-	-	-	100 %

Table 8. Response Table for S/N ratios for roundness error (Smaller is better)

Level	Nano%	Cutting speed	Feed rate	Rake angle
1	-30.24	-31.55	-29.76	-31.72
2	-31.60	-29.24	-30.58	-30.38
3	-30.15	-31.21	-31.65	-29.90
Delta	1.45	2.31	1.89	1.83
Rank	4	1	2	3

Table 9. The ANOVA for roundness error

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Nanofiller	2	160.45	80.223	23.49	0.000	16.38 %
Cutting speed	2	327.99	163.994	48.03	0.000	33.44 %
Feed rate	2	214.23	107.114	31.37	0.000	21.84 %
Rake angle	2	216.74	108.372	31.74	0.000	22.09 %
Error	18	61.47	3.415	-	-	06.26 %
Total	26	980.87	-	-	-	100

CONCLUSIONS

In the present unvestigation, a study had been carried out to optimize the machining process parameters in turning of Al/0.5%Al_2O_3 and Al/0.5%MWCNTs fabricated using stir casting technique. The effects of the machining parameters, typically, cutting speed (B), feed rate (C) and rake angle (D) of the cutting tool as well as the effect of the nanofiller type (A) dispersed in the Al-Si matrix, on the material renoval rate (MRR), surface roughness and the roudness error of the nanocomposite workpieces were evaluated. The experiments were designed and analyzed using Taguchi method and ANOVA statistical analysis. The optimum parameter levels were determined for maximum MRR, minimum surface roughness and roudness error. The analysis showed that cutting speed has the most significant effect on the roundness error and MRR of the nanocomposites. While, the rank angle is the most influential factor that affect the surface roughness of the nanocomposites.

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