Machining Performance of AlSi/10% AlN Metal Matrix Composite Material in Milling Process Using Uncoated Insert

Nurul Na'imy Wan, Mohamad Sazali Said, Norzalina Othman, Ahmad Razlee Ab Kadir and Baizura Zubir

Abstract This paper presents the machining performance of aluminum silicon alloy (AlSi) metal matrix composite which has been reinforced with aluminum nitride (AlN) using the uncoated tool of inserts. Experiments were conducted at various cutting speeds, feed rates, and depths of cut, according to a fractional factorial array L_9 of Taguchi method for both cutting tools. Statistical analysis including the signal-to-noise (S/N) ratio and analysis of variance is applied to study the characteristic performance of cutting speeds, feed rates and depths of cut during the milling operation. The machining performances are observed through surface roughness, and tool wear and these measurements are analyzed using the Taguchi method. From the Taguchi analysis, it was found that cutting speed of 230 m/min, feed rate of 0.4 mm/tooth, a depth of cut of 0.3 mm were the optimum machining parameters for surface roughness and tool wear, indicated that lower level for all machining parameters gave the best result in machining of AlSi/10%AlN metal matrix composite.

Keywords Metal matrix composite · Milling process · Surface roughness Taguchi method

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1 Introduction

Metal matrix composites (MMCs) are composite materials widely used in aerospace, automotive, electronics, and medical industries. These materials possess outstanding properties such as high strength, low weight, high modules, low ductility, high wear resistance, high thermal conductivity, and low thermal expansion. These desirable properties are mainly manipulated by the matrix, the reinforcement element, and interface [1]. MMCs exhibit poor machinability because of the hard and abrasive reinforcement used [2]. These materials are usually applied in bearings, automobile pistons, cylinder liners, and piston rings, connecting rods, sliding electrical contacts, turbocharger impellers, and space structures. The most popular reinforcements are silicon carbide (SiC) and alumina (Al_2O_3). Aluminum, titanium, and magnesium alloys are commonly used as the matrix phase [1].

MMCs possess the combined properties of metals and ceramics [3, 4]. The structure and properties of MMCs are affected by the type and properties of the matrix, reinforcement, and interface [5]. Thus, these materials have been increasingly used to replace conventional materials in numerous applications [4]. Surface roughness has been given significant attention for many years [6] and has been considered in fatigue load, precision fits, fasteners hole, and aesthetic requirements. In addition to tolerance, surface roughness imposes one of the most critical aspects in the selection of machine and cutting parameter in the planning process [6, 7].

In general, optimization of the cutting parameters is determined by the researcher's experience and knowledge or by the Design of the Experiment (DOE) [8]. DOE is a powerful statistical tool used to study the effect of multiple variables simultaneously, and the technique provides an approach to efficiency design real-time experiments which will improve the understanding of the relationship between product and process parameters with the desired performance characteristic [9]. Also, a statistical analysis of variance (ANOVA) was performed to see which parameters were significant. The optimal cutting parameters were then predicted. Meanwhile, Taguchi's parameter design is an important tool for a robust design. It offers a simple and systematic approach to optimize designs for performance, quality, and cost.

Taguchi's approach is wholly based on the statistical design of experiments [10]. This can economically satisfy the needs of problem solving and product or process design optimization. Several previous works have used the Taguchi method as a design tool for experiments in various areas, including metal cutting, are listed in the references section [11, 12]. Factors should be included as many as possible; the method also can identify non-significant variables at the earliest possible opportunity. Taguchi creates a standard orthogonal array to accommodate this requirement. Depending on the number of factors, interactions, and levels needed, the choice is left to the user to select the standard, column-merging, or idle-column method, etc. Two of the applications, within which the concept of S/N ratio is useful, are the improvement of quality through variability reduction and the improvement of measurement. S/N ratio characteristics can be divided into three categories; when the characteristic is continuous [10]:

$$\text{Nominal is the best characteristic;}\quad S/N = 10\log\frac{\bar{y}}{s_y^2} \tag{1}$$

$$\text{Smaller is better characteristics;}\quad S/N = -10\log\frac{1}{n}\left(\sum y^2\right) \tag{2}$$

$$\text{Larger is better characteristics;}\quad S/N = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \tag{3}$$

2 Methodology

2.1 Surface Roughness and Tool Wear Measurement

In machining process, it is necessary to obtain a good surface finish on the surface of the material, whereby for tool wear can be measured through machining time for a tool of an insert used to wear at the certain height. These surface roughness and tool wear values are measured through various cutting speeds, feed rate and depth of cut are shown in Table 1.

2.2 Materials and the Milling Process

AlN reinforced Al–Si alloy matrix composite was fabricated using the stir casting method, where Al–Si alloy ingot, called the matrix material, was reinforced with AlN particles of 10wt% reinforcement. The experimental study was carried out in a CNC Vertical Milling Center Lagun-GVC1000 milling machine. Cutting inserts were attached to the tool with a body diameter of ∅20 mm. The tool holder used was CoroMill R390-020C4-11L and the tool inserts was uncoated cemented carbide ISO catalog no: R390-11T08E-NL. The experiment has three different cutting speeds (230, 300 and 370 m/min) with constant feed rate (0.4, 0.6, 0.8 mm/rev) and depth of cut (0.3, 0.4 and 0.5 mm) under dry cutting condition. The worked material was fabricated in the form of block 120 mm length × 50 mm width × 50 mm thickness.

Table 1 Factors and levels used in the experiment

Factor/level	Low	Medium	High
A—cutting speed (m/min)	230	300	370
B—feed rate (mm/tooth)	0.4	0.6	0.8
C—depth of cut (mm)	0.3	0.4	0.5

2.3 Taguchi Method

In this experiment, with three factors (each with three levels), the fractional factorial design used was a standard L_9 (3^3) orthogonal array. The orthogonal array was chosen because of its minimum number of required experimental trials. Each row of the matrix represented one trial [13]. The smaller, the better characteristic is used to optimize the surface roughness and for the tool wear measurement is analyzed using the larger, the better characteristic in the milling process of aluminum silicon metal matrix composite.

3 Results and Discussion

3.1 Machining Performance and S/N Ratio

Machining performance of AlSi/10%AlN was analyzed based on the Taguchi method and S/N ratio as in Table 2. The surface roughness was analyzed according to Taguchi's smaller-is-better characteristic while the analysis for tool wear was conducted using the larger-is-better characteristic.

3.2 Optimization of Machining Conditions Using the Taguchi Method

This study was conducted to determine the optimum condition for surface roughness and tool wear when AlSi/10%AlN metal matrix composite is cut using uncoated. In Taguchi method, the analysis focuses on process optimization through

Table 2 Experimental design with the L_9 orthogonal array and the *S/N* ratios for Uncoated cutting tools

Test no.	Cutting speed	Feed rate	Depth of cut	SR (μm)	S/N ratio	Tool wear (min)	S/N ratio
1	230	0.4	0.3	0.430	7.33063	75.33	37.5394
2	230	0.6	0.4	0.528	5.54732	82.43	38.3217
3	230	0.8	0.5	0.702	3.07326	94.59	39.5169
4	300	0.4	0.4	0.648	3.76850	67.86	36.6323
5	300	0.6	0.5	0.785	2.10261	66.31	36.4316
6	300	0.8	0.3	0.842	1.49376	82.02	38.2784
7	370	0.4	0.5	0.791	2.03647	50.79	34.1156
8	370	0.6	0.3	0.848	1.45259	47.95	33.6158
9	370	0.8	0.4	0.907	0.84785	75.61	37.5716

S/N ratio, and the result will be supported by the analysis of variance. Both analyses for surface roughness and tool wear using the uncoated tool obtained using Minitab 17.

3.3 Surface Roughness

Figures 1 and 2 show the mean S/N ratio and means of surface roughness using uncoated tool obtained. The slope of the graphs clearly shows that the cutting speed is the most significant factor, followed by the feed rate, and depth of cut. Based on Fig. 1, the optimum parameters for surface roughness is cutting speed of 230 m/min; feed rate of 0.4 mm/tooth and depth of cut of 0.3 mm. It indicated that the best surface finish in the milling process of AlSi/10%AlN was at the lower level of the machining parameters.

3.4 Tool Wear

Figures 3 and 4 show the mean S/N ratio and means of tool wear using the uncoated cutting tool in the milling process. The slopes of the graphs also clearly show that the cutting speed is the most significant factor, followed by the feed rate and depth of cut. Based on Fig. 3, the optimum parameters for surface roughness is disclosed at cutting speed of 230 m/min; feed rate of 0.8 mm/tooth and depth of cut of 0.4 mm.

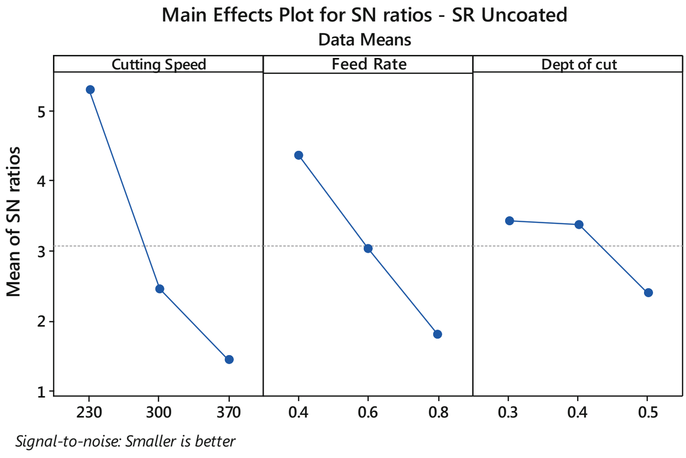

Fig. 1 Main effect plot for S/N ratios of surface roughness

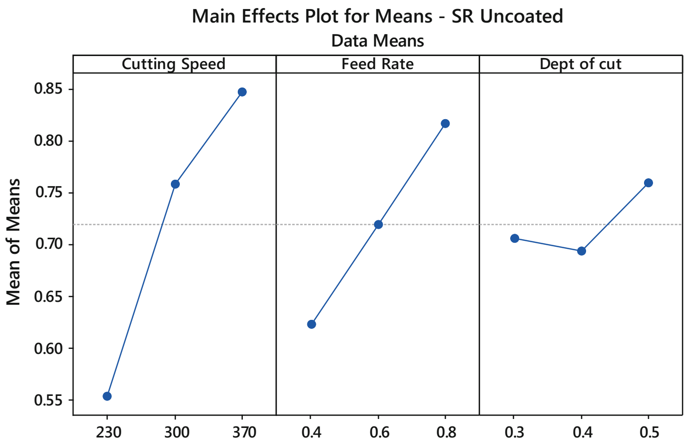

Fig. 2 Main effect plot for means of surface roughness

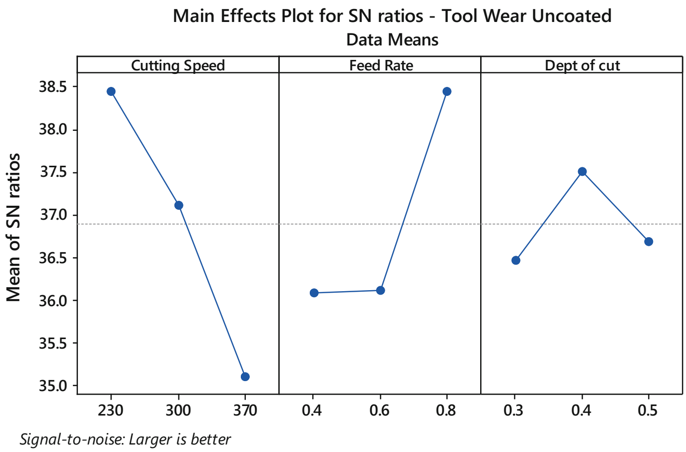

Fig. 3 Main effect plot for S/N ratios of tool wear

3.5 Analysis of Variance (ANOVA)

The analysis of variance was conducted to determine which machining parameters significantly affect the tool life. ANOVA was performed to find whether individual factors that affect the material removal rate and cutting force were meaningful. From the ANOVA results of S/N ratio presented in Table 3, the factor of feed rate and depth of cut significantly affected the surface roughness of AlSi/10%AlN composite which its P-value were less than 0.05. From Table 3, the most influential factor was found to be the depth of cut with 65.72%, followed by feed rate with

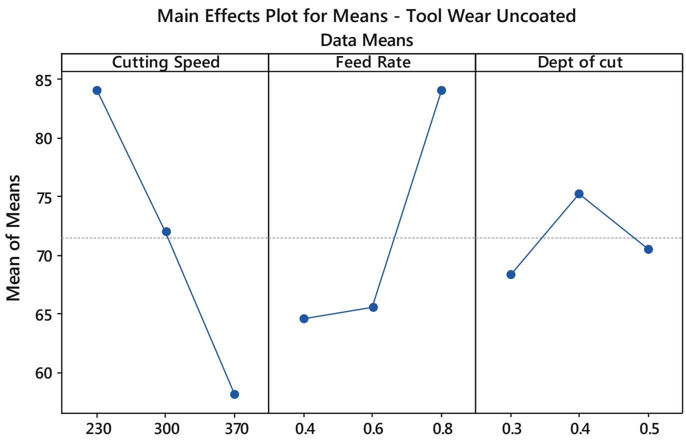

Fig. 4 Main effect plot for means of tool wear

Table 3 ANOVA of S/N ratio for surface roughness

Factors	DF	SS	MS	F	*P**	PD
Cutting speed	2	24.1984	12.0992	36.34	0.027	65.72
Feed rate	2	9.9416	4.9708	14.89	0.063	27.00
Depth of cut	2	2.0128	1.0064	3.01	0.249	5.67
Residual error	2	0.6677	0.3338			1.81
Total	8	36.8205				100

DF Degree of freedom, *SS* sum of square, *MS* mean of square, *PD* percentage distribution
*Significance level = 0.05

27.00% and the remaining percentage were explained by cutting speed and residual error. This contribution has been supported by the value of S/N ratios in Table 4.

Tables 5 and 6 represented the ANOVA results and response values of S/N ratio for tool ware. Based on Table 5, the factor of cutting speed and feed rate significantly affected the tool wear in the machining process of the composite as its *P*-value was less than 0.05. Based on the percentage contribution from Table 4, the most influential factor was found to be the cutting speed with 56.27%, followed by feed rate and depth of cut with 36.15 and 5.85% respectively.

Table 4 Response table for S/N ratios (smaller is better) of surface roughness

Level	Cutting speed V (m/min)	Feed rate f (mm/tooth)	Depth of cut d (mm)
1	5.317	4.379	3.426
2	2.455	3.034	3.388
3	1.446	1.805	2.404
Rank	1	2	3

Table 5 ANOVA of S/N ratio for tool wear

Factors	DF	SS	MS	F	*P**	PD
Cutting speed	2	17.1408	8.5704	32.50	0.030	56.27
Feed rate	2	11.0109	5.5055	20.87	0.046	36.15
Depth of cut	2	1.7797	0.8899	3.37	0.229	5.85
Residual error	2	0.5275	0.2637			1.73
Total	8	30.4589				100

DF Degree of freedom, *SS* Sum of square, *MS* Mean of square, *PD* percentage distribution
*Significance level = 0.05

Table 6 Response table for S/N ratios (larger is better) of tool wear

Level	Cutting speed V (m/min)	Feed rate f (mm/tooth)	Depth of cut d (mm)
1	38.46	36.10	36.48
2	37.11	36.12	37.51
3	35.10	38.46	36.69
Rank	1	2	3

4 Conclusion

The Taguchi method was applied in experimental design to optimize multi-response process parameters of end milling, while the machining of AlSi/AlN MMC was optimized using an L_9 orthogonal array. The results of this study were drawn based on the experiments. The optimum machining parameters found for surface roughness were: cutting speed, 230 m/min; feed rate 0.4 mm/tooth; and depth of cut, 0.3 mm; and the optimum parameters for tool wear were: cutting speed, 230 m/min; feed rate 0.8 mm/tooth; and depth of cut, 0.4 mm. These optimum parameters obtained will help the automotive industry to have a competitive machining operation from economic and manufacturing perspective.

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