Jurnal Teknologi

Full paper

Surface Roughness and Chip Formation of AlSi/AIN Metal Matrix Composite by End Milling Machining using the Taguchi Method

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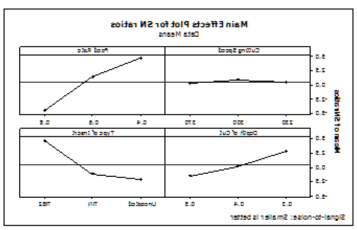
Article history

Received :29 July 2013
Received in revised form :
23 September 2013
Accepted :25 February 2014

Graphical abstract



Abstract

The purpose of this research is to demonstrate surface roughness and chip formation by the machining of Aluminium silicon alloy (AlSic) matrix composite, reinforced with aluminium nitride (AlN), with three types of carbide inserts present. Experiments were conducted at various cutting speeds, feed rates, and depths of cut, according to the Taguchi method, using a standard orthogonal array L_9 (3^4). The effects of cutting speeds, feed rates, depths of cut, and types of tool on surface roughness during the milling operation were evaluated using Taguchi optimization methodology, using the signal-to-noise (S/N) ratio. The surface finish produced is very important in determining whether the quality of the machined part is within specification and permissible tolerance limits. It is understood that chip formation is a fundamental element that influences tool performance. The analysis of chip formation was done using a Sometech SV-35 video microscope. The analysis of results, using the S/N ratio, concluded that a combination of low feed rate, low depth of cut, medium cutting speed, and an uncoated tool, gave a remarkable surface finish. The chips formed from the experiment varied from semi–continuous to discontinuous.

Keywords: Taguchi method; machining process; surface roughness; chip formation

Abstrak

Tujuan kajian ini adalah untuk menganalisis kekasaran permukaan dan pembentukan cip dari proses pemesenan komposit matriks aloi Aluminium silikon (AlSic), diperkukuhkan dengan aluminium nitride (AlN), dari tiga jenis cucuhan karbid. Eksperimen dijalankan pada pelbagai kelajuan pemotongan, kadar suapan, dan kedalaman pemotongan mengikut kaedah Taguchi menggunakan orthogonal array L_9 (3^4). Kesan kelajuan pemotongan, kadar suapan, kedalaman pemotongan dan jenis peralatan untuk kekasaran permukaan ketika operasi milling dinilaikan melalui pengoptimuman kaedah Taguchi dan pendekatan nisbah Signal-to-Noise. Kekasaran permukaan adalah penting dalam menentukan kualiti produk yang dihasilkan adalah dalam julat tolerans yang dibenarkan. Adalah diketahui bahawa penghasilan cip adalah elemen penting yang mempengaruhi performen peralatan. Analisis penghasilan cip dilakukan menggunakan Sometech SV-35 video mikroskop. Analisis menyimpulkan bahawa kombinasi kadar suapan yang rendah, kedalam pemotongan yang rendah, kelajuan pemotongan sederhana dan peralatan yang tidak diselaputi memberikan keputusan yang memberangsangkan. Cip yang dihasilkan dari eksperimen adalah pelbagai dari separa–*continuous* kepada *discontinuous.*

Kata kunci: Kaedah Taguchi; proses pemesenan; kekasaran permukaan; pembentukan cip

1.0 INTRODUCTION

Metal Matrix Composites (MMCs) have many potential engineering applications, such as in automotive and aerospace industries, due to their superior mechanical properties that include high strength, high hardness, good wear resistance, and excellent weight ratio [1-2]. 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 [8]. For this reason, their ability to replace conventional materials in many applications is increasing [4].

Although only a few reports on the use of AlN as the reinforcement for Al alloy composites have been published, the lack of knowledge concerning the characteristics of these new materials; especially the surface roughness and performance of coated and uncoated carbide tools and wear mechanism in machining, has often hindered their wider utilization [9] and chip formation. Many claim that MMCs are harder and stiffer than conventional materials, further leading to the cutting tool being more easily broken and wearing out [10]. Surface roughness is generally known to be highly affected by feed rate; followed by cutting speed and axial depth of cut [13-14]. The geometrical shape of the insert is another factor that has been considered in studies on surface roughness [15-16]. The material inclination angle; followed by the radial depth of cut, were found to be parameters that most significantly affected surface finish after machining [7]. Tool wear influences the surface roughness of the work piece. As such, the surface roughness value is one of the main parameters used to establish the right moment to change the finish milling tool [11]. Chip formation depends on both the characteristics of the material and the machining. The mechanism of chip formation is of fundamental importance, because it relates to the properties of surface integrity, machinability, and other machining characteristics [12]. Three types of chips are produced in machining [5]: 1) discontinuous chips are formed with multiple segments and are produced when machining brittle materials at low cutting speeds, 2) continuous chips are produced when machining ductile materials at high cutting speeds and low feed rates [6], and 3) continuous with built-up edges are produced from ductile materials at low cutting edges. The chips produced can be divided into two categories, namely acceptable and unacceptable chips [7]. Acceptable chips may not disturb work or the machine, but do cause problems in chip removal; while unacceptable chips will disrupt manufacturing operations since their tendency is to shrink around the tool and the work piece, and inflict safety problems to employees [7]. 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. Two major tools used in robust designs are [18, 20-21]:

- Signal to noise ratio - which measures quality with emphasis on variation, and
- Orthogonal arrays - which accommodate many design factors simultaneously.

Taguchi's approach is totally based on the statistical design of experiments [18]. This can economically satisfy the needs of problem solving and product or process design optimization [19]. Several previous works that used the Taguchi method as a design tool for experiments in various areas, including metal cutting [22-23]. As many factors as possible should be included, so as to identify non-significant variables at the earliest possible opportunity and a standard orthogonal array is used 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 [18]:

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

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

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

Where, $\bar{y}$ is the average of the observed data, s_y^2 is the variance of y, n is the number of observations, and y is the observed data. For each type of characteristic, with the above S/N ratio transformation, the higher the S/N ratio the better is the result.

This study will utilize the Taguchi method to determine the optimum condition for surface roughness and chip formation in machining AlSi/AlN MMCs, using smaller is the better characteristic.

2.0 EXPERIMENTAL

2.1 Taguchi Method

In this experiment, with three factors (each with three levels), the fractional factorial design used was a standard L_9 (3^4) orthogonal array [14]. That orthogonal array was chosen because of its minimum number of required experimental trials. Each row of the matrix represented one trial.

Table1 Factors and levels used in the experiment

Factor / Level	0	1	2
A – speed (m/min)	230	300	370
B – feed (mm/tooth)	0.4	0.6	0.8
C – depth of cut (mm)	0.3	0.4	0.5
D – types of tool	Uncoated	TiN	TiB2

The sequence in which those trials were carried out was random. The three levels of each factor were represented by a '0', a '1', or a '2' in the matrix. The factors and levels were assigned (as shown in Table 1) according to roughing and semi-finishing conditions for the said material.

In the standard L_9 (3^4) orthogonal array, factors A, B, C, and D are arranged in columns 1, 2, 3, and 4, respectively.

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 chemical composition of Al-Si alloy was determined using a Glow Discharge Profiler (Model-Horiba Jobin Yyon) (as shown in Table 2). The mean size of reinforcement particles was <10 μm, with a purity of >98%.

Table 2 Chemical composition of AlSi alloy

Elements	Fe	Si	Zn	Mg	Cu	Ni
Wt%	0.42	11.1	0.02	0.01	0.02	0.001
Elements	Sn	Co	Ti	Cr	Al	
Wt%	0.016	0.004	0.0085	0.008	Balance	

The experimental study was carried out in a DMC635V eco DMGECOLINE vertical milling machine. Cutting inserts were attached to the tool with a body diameter of ∅12mm. The surface roughness of the machined surface was observed using a Roughness Tester (Mpi Mahr Perthometer).

The surface roughness of the work piece was measured at several locations along the length of the cut using a portable surface roughness tester (model Mpi Mahr Perthometer). The length of each cutting path measured 0.103 m.

3.0 RESULTS AND DISCUSSION

3.1 Surface Roughness

Table 3 shows the surface roughness results. The uncoated tool, combined with a high feed rate and a medium depth of cut, produced a high Ra i.e., a rough machined surface. A previous study [15] also found that the feed rate was the most significant factor in controlling surface finish. Martelotti [15] describes the chip thickness model as follows:

$t = s\sin b$; where, *s* and *b* represent feed per tooth and tool angular position, respectively. Meanwhile, the height of the tooth mark is given by the following:

$$h = \frac{s^2}{8[R + (sxN/\pi)} \tag{1}$$

Where, *h* is the height of tooth mark above the point of the lowest level, mm; *s* is the feed per tooth, mm; *R* is the radius of the cutter, mm; *N* is the number of teeth in the cutter. The height of the tooth mark can be reduced by increasing the radius of the cutter and by decreasing the feed per tooth until the tooth mark becomes scarcely distinguishable; particularly at lower feed rates.

The coated tool normally produces better Ra, because the coating material used will act as a dry lubrication. Similar results were found by previous researchers [16-17].

Table 3 Surface roughness test results

No.	Cutting speed *V*(m/min)	Feed rate *f* (mm/tooth)	Depth of cut *d*(mm)	Type of insert	Surface Roughness, *Ra* (*μm*)		
1	230	0.4	0.3	Uncoated	0.57	0.74	0.5
2	230	0.6	0.4	TiN	1.13	1.05	1.05
3	230	0.8	0.5	TiB2	1.33	1.28	1.43
4	300	0.4	0.4	TiB2	0.35	0.33	0.39
5	300	0.6	0.5	Uncoated	1.28	1.59	1.26
6	300	0.8	0.3	TiN	1.50	1.47	1.48
7	370	0.4	0.5	TiN	0.75	1.09	0.93
8	370	0.6	0.3	TiB2	0.34	0.46	0.45
9	370	0.8	0.4	Uncoated	2.31	2.18	2.93

3.2 Optimization of Machining Condition Using The Taguchi Method

The aim of this study is to determine the optimum condition for surface roughness when cutting AlSi/AlN using three types of cutting tools. One of the methods used to analyse data for process optimization uses SN ratio. Figure 1 shows the mean of SN ratio for smaller the better characteristics of surface roughness obtained using Minitab 15. The slope of the graphs clearly show that feed rate is the most significant factor, followed by the type of coating material, depth of cut, and cutting speed. Similar results were obtained from the Response Table for Signal to Noise Ratios Smaller is better in Table 4. This is supported by the results of the sensitivity graph for the smaller the better characteristics of the mean surface roughness and response for mean (as shown in Figure 2 and Table 5).

Table 4 Response table for signal to noise ratios smaller is better

Level	Cutting speed V(m/min) cut	Feed rate f (mm/tooth)	Depth of cut d(mm)	Type of insert
1	0.4357	4.7600	2.9968	-2.0505
2	0.9930	1.5456	0.2257	-1.0896
3	0.2764	-4.6004	-1.5174	4.8451
Rank	4	1	3	2

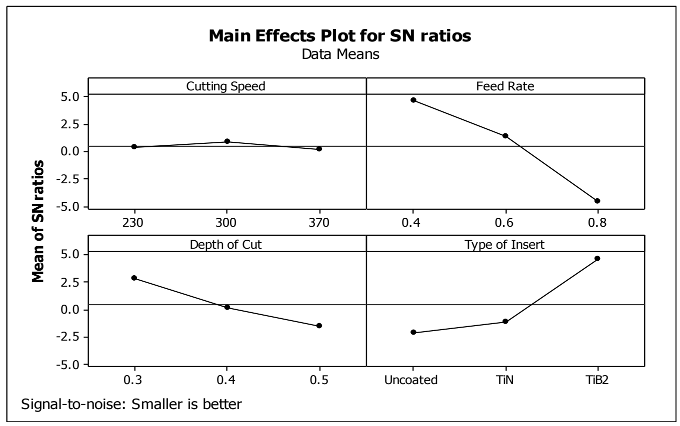


Figure 1 Mean of SN ratio for smaller the better characteristics of surface roughness

The optimum condition is determined by the highest mean SN values. Therefore, the optimum condition is A1 (300 m/min), B0 (0.4 mm/rev), C0 (0.3 mm), and the TiB2 tool.

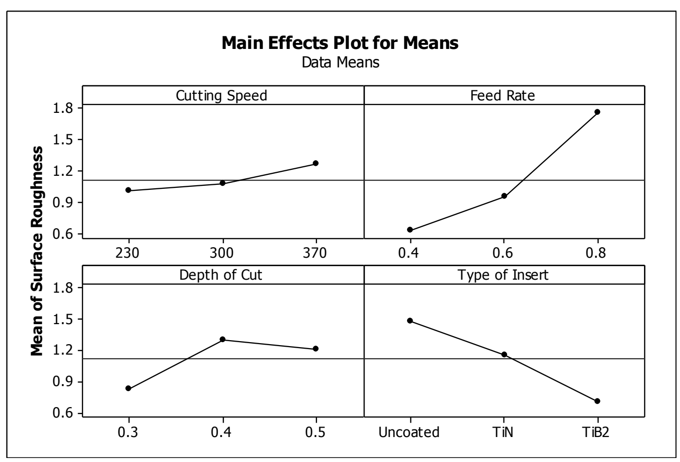


Figure 2 Sensitivity graph for smaller the better characteristics of surface roughness

Table 5 Response table of means

Level	Cutting speed V(m/min) cut	Feed rate f (mm/tooth)	Depth of cut d(mm)	Type of insert
1	1.0033	0.6233	0.8267	1.4800
2	1.0667	0.9467	1.2967	1.1567
3	1.2633	1.7633	1.2100	0.6967
Rank	4	1	3	2

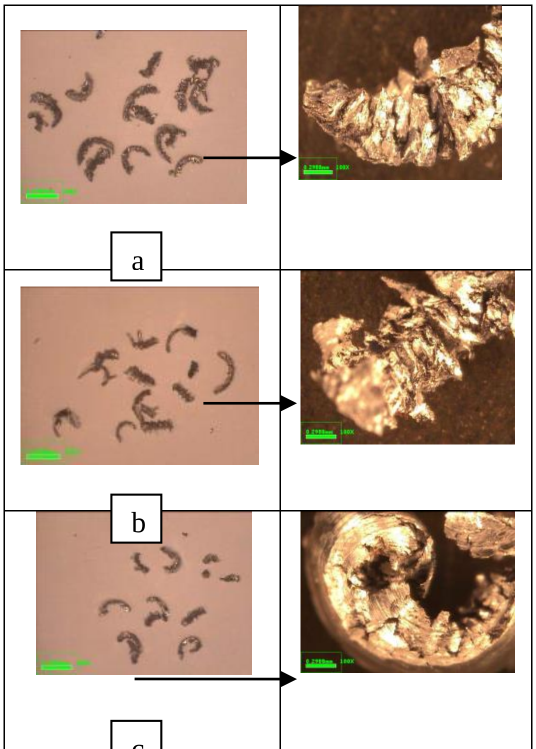


Figure 3 AlSi/AlN MMC chip machined using uncoated at different cutting speeds of (a) 230 m/min, (b) 300 m/min, and (c) 370 m/min

3.3 Chip Formation

Chips are formed due to a shear between the work piece and the cutting edge. During rotation of the end mill, it can be seen that chips were formed as both semi-continuous and discontinuous chips. Figures 3(a), (b), and (c), show shapes for cutting speeds 230, 300, and 370 m/min, for the uncoated insert. Shown are the saw shaped burr of chips formed during dry milling with 0.3.0.5 and 0.4mm depths of cut and feed rates of 0.4, 0.6, and 0.8, respectively. Figure 3(c) shows that circular chips are formed as through curling during machining and broken into semi-continuous chip forms i.e., ½ - ¾ of the circle with a comparatively small radius.

As seen in the TiN insert, with a cutting speed of 370 m/min, a 0.5mm depth of cut, and a feed rate of 0.4mm/tooth (as shown in Figure 4 (c)). Meanwhile, Figures 4(a) and (b), for cutting speeds of 230 and 300 m/min, also showed a saw shaped burr pattern. The saw shaped burrs were closer to each other than the form of shape at the TiB2 insert shown in Figures 5 (b) and (c). Figure 5 (a), with a cutting speed of 230 m/min, showed a saw tooth type form of chip that were small in length.

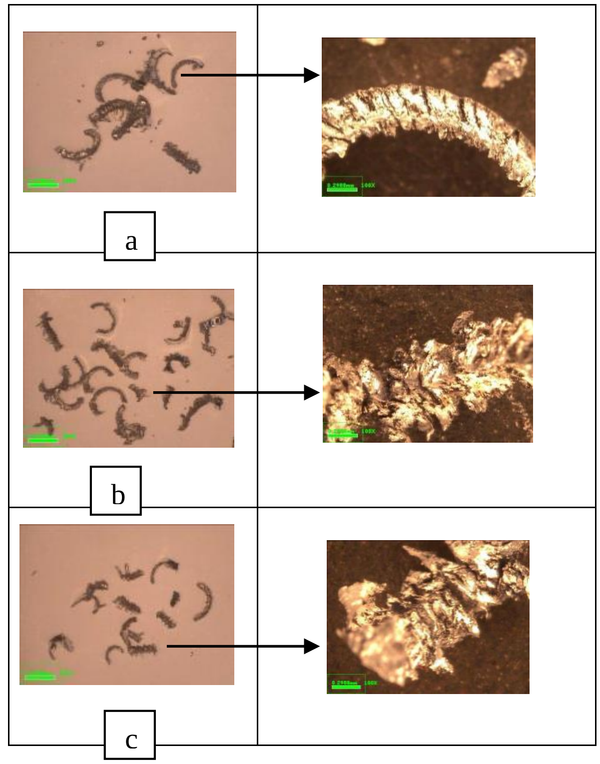


Figure 4 AlSi/AlN MMC chips, machined using a coated insert TiN, at different cutting speeds of (a) 230 m/min, (b) 300 m/min, and (c) 370 m/min

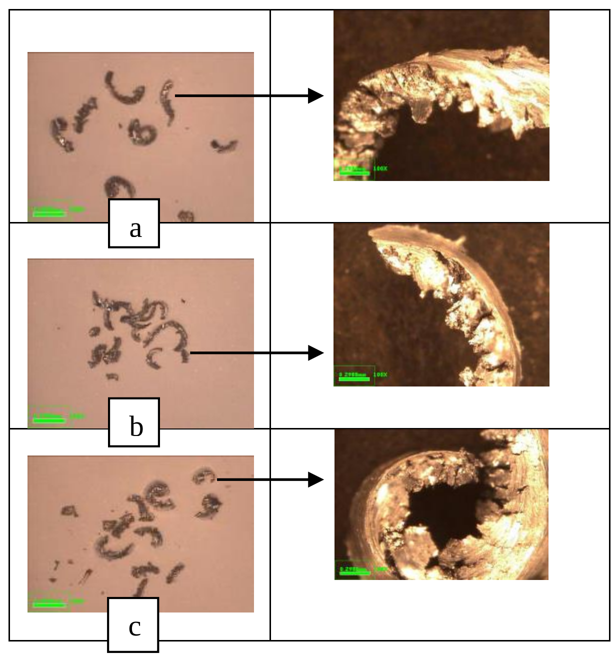


Figure 5 AlSi/AlN MMC chips, machined using a coated insert TiB2 at different cutting speeds of (a) 230 m/min, (b) 300 m/min, and (c) 370 m/min

■4.0 CONCLUSION

Taguchi method of experimental design was applied to optimize multi response process parameters of end milling, while the machining of AlSi/AlN MMC was optimized using an L9 orthogonal array. The results of this study were drawn based on the experiments conducted. The best parameters found for surface roughness were: cutting speed, 300m/min; feed, 0.4mm/tooth; depth of cut, 0.3mm; and TiB2 tool insert. The optimum surface roughness produced a saw shaped burr and the chips formed were both semi-continuous and discontinuous (as shown in Figure 3 (a)).

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