Jurnal
Teknologi

Full paper

Optimization of Cutting Parameters of Multiple Performance Characteristics in End Milling of AlSi/AlN MMC – Taguchi Method and Grey Relational Analysis

S. H. Tomadi[a,b*], J. A. Ghani[a], C. H. Che Haron[a], M. S. Kasim[c], A. R. Daud[d]

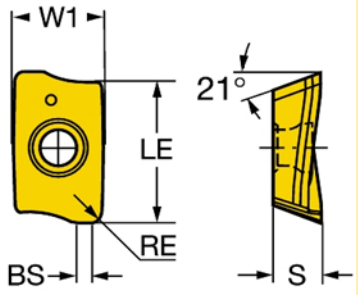
[a]*Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia*
[b]*Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*
[c]*Department of Manufacturing Process Engineering, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia*
[d]*School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia*

*Corresponding author: sharyani@ump.edu.my

Article history

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

Graphical abstract



Abstract

The main objective of this paper is to investigate and optimize the cutting parameters on multiple performance characteristics in end milling of Aluminium Silicon alloy reinforced with Aluminium Nitride (AlSi/AlN MMC) using Taguchi method and Grey relational analysis (GRA). The fabrication of AlSi/AlN MMC was made via stir casting with various volume fraction of particles reinforcement (10%, 15% and 20%). End milling machining was done under dry cutting condition by using two types of cutting tool (uncoated & PVD TiAlN coated carbide). Eighteen experiments (L18) orthogonal array with five factors (type of tool, cutting speed, feed rate, depth of cut, and volume fraction of particles reinforcement) were implemented. The analysis of optimization using GRA concludes that the better results for the combination of lower surface roughness, longer tool life, lower cutting force and higher material removal could be achieved when using uncoated carbide with cutting speed 240m/min, feed 0.4mm/tooth, depth of cut 0.3mm and 15% volume fraction of AlN particles reinforcement. The study confirmed that with a minimum number of experiments, Taguchi method is capable to design the experiments and optimized the cutting parameters for these performance characteristics using GRA for this newly develop material under investigation.

Keywords: AlSi/AlN MMC; carbide tools; surface roughness; tool life; cutting force; material removal; Taguchi method; grey relational analysis

Abstrak

Objektif utama kertas kerja ini adalah untuk menganalisis dan mengoptimumkan parameter pemotongan terhadap pelbagai ciri prestasi dalam proses kisar aloi aluminium diperkuatkan aluminium nitrida (AlSi/AlN MMC) menggunakan kaedah Taguchi dan *Grey Relational Analysis* (GRA). Proses fabrikasi AlSi/AlN MMC menggunakan kaedah tuangan aduk dengan peratus zarah bahan penguat yang berbeza (10%, 15% dan 20%). Pemesinan kisar dilakukan di bawah keadaan pemotongan kering menggunakan dua jenis mata alat pemotongan (karbida tidak bersalut dan karbida bersalut PVD TiAlN). Lapan belas ujikaji bersusunan ortogan (L18) dengan lima faktor pemotongan (jenis mata alat, laju pemotongan, kadar suapan, dalam potongan dan % bahan penguat) dilakukan. Analisis pengoptimuman menggunakan GRA menyimpulkan bahawa keputusan yang lebih baik untuk kombinasi kekasaran permukaaan yang rendah, hayat mata alat yang panjang, daya pemotongan yang rendah, dan isipadu bahan terbuang yang tinggi diperolehi dengan menggunakan mata alat karbida tidak bersalut, laju pemotongan 240 m/min, kadar suapan 0.4 mm/gigi, dalam pemotongan 0.3 mm, dan % bahan penguat AlN sebanyak 15%. Kajian ini mengesahkan bahawa dengan bilangan ujikaji yang sedikit, kaedah Taguchi berupaya mengoptimumkan parameter pemotongan menggunakan GRA untuk bahan yang baru dibangunkan yang masih di bawah proses penyelidikan.

Kata kunci: AlSi/AlN MMC; mata alat karbida; kekasaran permukaan; hayat mata alat; daya pemotongan; isipadu bahan terbuang; kaedah Taguchi; *grey relational analysis*

■1.0 INTRODUCTION

Metal matrix composites has many potential in engineering application such as in automotive and aerospace due to their superior mechanical properties including high strength, high hardness, good wear resistance and excellent strength to weight ratio [1]. However, the highly abrasive due to larger sizes of particle reinforcement and irregular nature of the reinforcement causes the machinability of MMCs facing difficulties. Diamond tools are considered the most significantly for the machining of MMCs [2, 3]. Polycrystalline diamond (PCD) also shows better wear resistance and produced better surface finish than carbide or alumina tools when machining of MMCs [2, 4, 5]. However, the innovation of carbide tools shows that the kind of tools be able to be used in machining of MMCs with a good quality of products.

Nowadays, most of manufacturing industries are facing great challenges in achieving high quality products with maximum productivity and economically. Though the engineering components made from MMCs are primarily manufactured in near-net-shape, the finishing process of components is always essential for the better quality of product. The quality of product surfaces is one of the great importances for product quality and its function [6]. For example Toyota has developed a metal matrix composite (MMC) diesel engine piston but they still need secondary machining operations for finishing purposes [7, 8]. In obtaining better surface finish, decreasing of BUE formation at flank face of cutting tool is needed and it will relate to the cutting force which the cutting force is gradually decreased by increasing cutting speed due to gradual decreased of BUE formation [10]. In meantime, higher material removal, Q will ensure the higher productivity in terms of production rate and cost [9].

Polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) tools shows better performance due the highest fracture resistance [11], but compared these two tools, PCD showed higher wear resistance and lower propensity for work material adhesion. The cost of PCD is much higher and it will increase the cost of production so it is necessary to carry out basic machinability studies in order to find cutting conditions using tungsten carbide tools, which can result in high productivity at low cost. In end milling, optimization of cutting parameters; cutting speed (V), feed rate (f), axial depth of cut (DOC) and volume fraction of reinforcement is a must to ensure all the performance characteristics (lower surface roughness, longer tool life, lower cutting force and higher material removal) meets the requirements.

Design of experiment (DOE) methods is widely used in experimental approaches such as full factorial, response surface methodology (RSM) and Taguchi method. Taguchi method or robust design is an engineering methodology, appropriate for improving productivity during research and development [12]. High quality products can be produced in a short time and at low cost by using a matrix experiment. Ghani *et al.* [13] determined the optimum cutting parameters in end milling when machining hardened steel AISI H13 with a TiN coated P10 carbide insert tool under semi-finishing and finishing conditions of high cutting speed. They found that the optimization of the combination for the low resultant cutting force and a good surface finish are high cutting speed, low feed rate and low depth of cut. Oktem *et al.* [14] developed a Taguchi optimization method for low surface roughness in terms of process parameters when milling the mould surfaces of 7075-T6 aluminium material. They concluded that the Taguchi method is very suitable in solving the surface quality problem of mould surfaces. Shetty *et al.* [15] analyzed the influence of speed, feed, depth of cut, nozzle diameter and steam pressure in the turning of age hardened Al6061-15% vol. SiC 25 μm particle size MMC with cubic boron nitride inserts, CBN. They determined the multi-performance of the machining characteristics and indicated that, among the parameters, steam pressure is the most significant parameter. Nalbant *et al.* [16] analyzed the optimum of three cutting parameters; insert radius, feed rate, and depth of cut in machining of AISI 1030 steel bars. They demonstrated that the radius of insert and feed rate are the main parameters that influence the surface roughness of machined material. Ramanujam *et al.* [17] determined the optimum cutting parameters for turning Al-SiC(10p) MMC using ANOVA and grey relational analysis. They concluded that the performance characteristics of the Al-SiC (10p) MMC machining process, such as surface roughness and specific power, are improved by using the Taguchi method.

Grey relational analysis has been introduced in optimizing the control parameters which having multi-responses through grey relational grade by Deng in 1989 [18]. Grey relational analysis was applied in this experiment to find the most influential factor among the end milling cutting parameters that affects the surface roughness, tool life, cutting force and material removal. Data preprocessing was employed based on 'smaller-the-better' for surface roughness and cutting force, and 'larger-the better' for tool life and material removal. To obtain the grey relational coefficients, the deviation sequences were calculated. In addition, the grey relational coefficients were averaged using equal weighting to obtain grey relational grade.

The main objective of this paper is to investigate and optimize the cutting parameters on multiple performance characteristics such as; surface roughness, tool life, cutting force and material removal. Taguchi method with orthogonal array [12] was utilized as DOE for experimental investigation during end milling of AlSi/AlN MMC. Grey relational analysis (GRA) was employed for optimization purposes by measuring the degree of relationship between machining characteristics with specific steps [19]. This new material is under investigation in terms of its machinability and the effects of the cutting parameters.

■2.0 EXPERIMENTAL

2.1 Work Material

The work material used for the experiment was a 100 mm × 150 mm × 50 mm block of age treated AlSi/AlN MMC. The chemical composition of the AlSi alloy, as shown in Table I, was determined by a glow discharge profiler (Model-Horiba Jobin Yyon). The mean size of the reinforcement particles is <10 μm and the purity >98%. The AlSi/AlN MMC work material passed through a double ageing process and was hardened at 540 °C for 6 hours. The process followed by water solution treatment. It was then reheated for another 4 hours at 180 °C, immediately cooled in open air at room temperature. The purpose of the heat treatment process is to increase the mechanical properties such as strength and hardness.

Table 1 Chemical composition of Al-Si 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	

2.2 Machining of Work Material

The milling test was conducted using uncoated carbide and PVD TiAlN coated carbide inserts under dry cutting conditions. Cutting inserts were mounted on a tool body with a diameter of 20 mm. Figure 1 shows an illustration of the cutting tool geometry and the specification of the cutting tool is shown in Table 2. There are five factors to be investigated. The first factor is considered at two levels, and a further four factors are considered at three levels. Table 3 shows the experimental factors or cutting parameters to be designed and their levels designations.

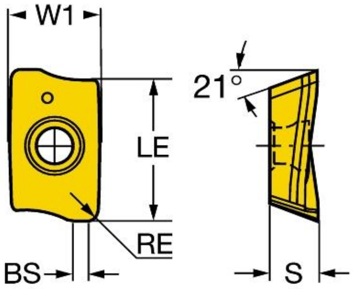


Figure 1 Geometry of cutting insert

Table 2 Cutting tool specification

Tool type	Uncoated and PVD TiAlN coated carbide (2.2 µm coating thickness)
Manufacturer	Sandvik
Rake	Positive
Nose radius	0.2 mm
W1	6.8 mm
BS	0.7 mm
LE	11.0 mm
S	3.59 mm
Lead angle	90°
Base Material	EH520, fine-grained carbide, WC-10%CO

Table 3 Cutting parameters and levels

Parameter	**Factor**	**level**		
		1	***2***	***3***
Type of insert	A	uncoated	coated	
Cutting speed (m/min)	B	240	320	400
Feed rate (mm/tooth)	C	0.3	0.4	0.5
Axial depth of cut (mm)	D	0.3	0.4	0.5
Volume fraction of reinforcement (%)	E	10	15	20

2.3 Design of Experiment (DOE)

The Taguchi method was used to design the experiments based on the orthogonal array L18 in order to obtain the maximum number of parameters with minimum experiments. The number of experiments is very low compared to other designs, such as full factorial or RSM design which required many experiments with the increased number of cutting parameters. The results for each experiment were then summarized to calculate the signal-to noise (S/N) ratio η. Generally, there are three categories of performance characteristics that are commonly used in the analysis of the S/N ratio; smaller-the-better, nominal-the better and larger-the-better. The optimal cutting parameters were then been predicted. The S/N ratio η for each category was calculated as follows:

Smaller-the-better S/N,

$$\eta = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \qquad (1)$$

Nominal-the-better S/N,

$$\eta = 10log_{10}\left(\frac{\mu^2}{\sigma^2}\right) \qquad (2)$$

Larger-the-better S/N,

$$\eta = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \qquad (3)$$

Where μ^2 is the mean of the observed data, σ^2 is the variance of observed data (y), and n is the number of observed data. In this study, the S/N ratio for smaller-the-better was used to minimize the surface roughness and resultant cutting force while larger-the-better was used to maximize the tool life and material removal. Grey relational analysis (GRA) was used for the optimization analysis for multiple performance characteristics. The calculation started with the calculation of data pre-processing. For surface roughness and cutting force, the data will be pre-processed as ‘smaller-the-better’. The equation used as follow;

$$x_i(j) = \frac{\max xi(0)(j) - xi(0)(j)}{max\ xi(0)(j) - min\ xi(0)(j)} \qquad (4)$$

For the tool life and material removal, the data will be pre-processed as ‘larger-the-better’. The equation used was different compared to the previous equation. The equation stated as follows;

$$x_i(j) = \frac{xi(0)(j) - min\ xi(0)(j)}{max\ xi(0)(j) - min\ xi(0)(j)} \qquad (5)$$

Where; $x_i(j)$ was the normalized value, $xi(0)(j)$ was the data obtained from the experiment, $min\ xi(0)(j)$ was the minimum value of data obtained, and $max\ xi(0)(j)$ was the maximum value of data obtained for each experiment.

Next, the deviation sequences will be calculated using the following equation;

$$\Delta x_{i(j)} = |x_0(j) - x_i(j)| \qquad (6)$$

Where; $x_0(j)$ were the reference sequences for each performances and specified to be at 1.000.

The next step is to determine the grey relational coefficient by using the following equation;

$$\zeta_{0,i}(j) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta x_{i(j)} + \zeta\Delta_{max}} \qquad (7)$$

Where; Δ_{min} was the minimum value of deviation sequence and equal to 0, Δ_{max} was the maximum value of deviation sequence and equal to 1, and ζ was identification coefficient and in general, it takes the value of 0.5.

Then, the grey relational grade was computed by averaging the grey relational coefficient corresponding to each performance characteristics. The overall evaluation of the multiple performances is based on the grey relational grade γ_j, that is:

$$\gamma_j = \frac{1}{n}\sum_{i=1}^{n} \zeta_{0,i}(j) \qquad (8)$$

3.0 RESULTS AND DISCUSSION

3.1 Optimization of Cutting Parameters for Tool Life and Material Removal using Taguchi Method

The type of milling performed in this experimental investigation is “down milling”. The radial depth of each pass was kept constant at 5 mm. The value of radial depth was set according to ISO 8688-2 [20] which stated that the radial depth of cut should be at least 25% of the cutting tool diameter. In this experimental investigation, one factor is determined as noise; a different batch of material. Two replicates were conducted for each experiment and the average values of all performance characteristics are calculated. Flank wear is a measurement that most often used to assess tool condition. It was measured using a two-axis toolmaker’s microscope with an attached digital micrometer for the x-axis and y-axis in 0.001 mm resolution. Based on the ISO 8688-2 [20] standard, they specified that a flank wear for semi-finishing and finishing process in end milling machining is 0.3 mm. The cutting insert was examined after every 750 mm of cutting travel. It was took about 5-8 sec for each path of cutting (150 mm). After reached 0.3 mm worn out, machining process will stop and worn out insert was changed to the new insert and new experiment was started. Data in Table 4 shows the time taken when each cutting insert reached 0.3 mm worn out. In meantime, material removal was calculated using the following equation;

$$Q\,(\mathrm{cm}^3) = a_d\, a_e\, t\, V_f /1000 \qquad (7)$$

Where, f was the feed rate (mm/min), a_d was the axial depth of cut, a_e was radial depth of cut and t was the tool life for each experiment. Also, the S/N ratio was calculated using the condition larger-the-better for both tool life and material removal (Equation 3).

Table 4 Data and S/N ratio for tool life and material removal

Exp no.	Tool life (min)	S/N ratio	Material removal (cm^3)	S/N ratio
1	72.00	37.147	123.768	41.852
2	59.90	35.549	183.0544	45.252
3	48.92	33.790	233.5691	47.368
4	60.90	35.692	139.5828	42.897
5	50.08	33.993	204.0259	46.194
6	31.67	30.013	201.6112	46.090
7	26.67	28.520	101.8794	40.162
8	27.93	28.921	177.8024	44.999
9	27.95	28.928	133.4613	42.507
10	49.33	33.862	141.3305	43.005
11	63.90	36.110	146.4588	43.314
12	53.33	34.539	203.7206	46.181
13	47.90	33.607	146.3824	43.310
14	35.00	30.881	178.255	45.021
15	44.00	32.869	168.08	44.510
16	26.67	28.520	127.3493	42.100
17	33.93	30.612	129.6126	42.253
18	23.00	27.235	146.418	43.312

Due to the orthogonal experimental design, the effects of each parameter were separated at different levels. For example, the mean S/N ratio for the type of insert at levels 1 and 2 were calculated by averaging the S/N ratios for the experiments 1–9, and 10–18 respectively. The mean values of the S/N ratio for each cutting parameter were calculated and summarized in Table 5 and Table 6. Also, the mean values of the S/N ratio for the five control factors or cutting parameters at each level are shown in Figure 2 and 3. The highest mean value of the S/N ratio for each parameter was chosen, representing the optimum condition.

Table 5 Mean values of S/N ratio for tool life

Level/Factor	A	B	C	D	E
1	32.51	35.17	32.89	33.56	31.65
2	32.03	32.84	32.68	32.24	32.68
3		28.79	31.23	31	32.47

Table 6 Mean values of S/N ratio for material removal

Level/Factor	A	B	C	D	E
1	44.15	44.5	42.22	42.89	43.29
2	43.67	44.67	44.51	44.07	44.32
3		42.56	44.99	44.76	44.11

It can be seen from Figure 2 that the optimum levels for maximum tool life were; A1 (uncoated cutting tool), B1 (cutting speed: 240 m/min), C1 (feed rate: 0.3 mm/tooth), D1 (axial depth: 0.3 mm) and E2 (15% reinforcement). At the mean time, Figure 3 shows the optimum levels for maximum material removal; A1 (uncoated cutting tool), B2 (cutting speed: 320 m/min), C3 (feed rate: 0.5 mm/tooth), D3 (axial depth: 0.5 mm) and E2 (15% reinforcement) respectively.

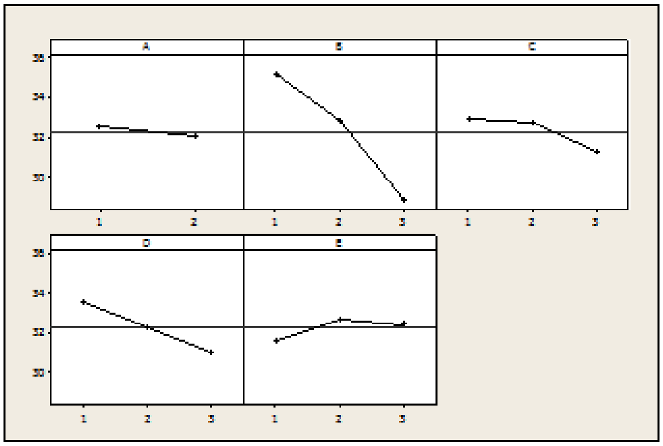


Figure 2 Effect of cutting parameters on mean value S/N ratio for tool life for each cutting parameter, A-E

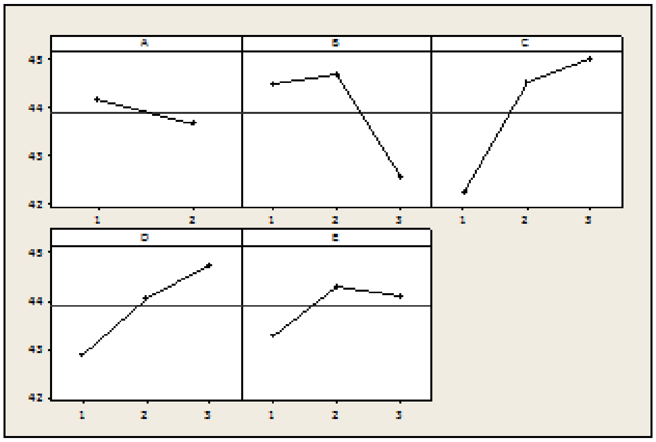


Figure 3 Effect of cutting parameters on mean value S/N ratio for material removal for each cutting parameter, A-E

3.2 Optimization of Cutting Parameters for Surface Roughness and Cutting Force using Taguchi Method

The surface roughness value (Ra) was measured using a contact-type stylus profilometer: Mahr Perthometer M1. The stylus traversing length, Lt, was set to 5.4 mm with the cut off, λc, at 0.8 mm. For each experiment, the average of at least five surface roughness measurements was taken and recorded. The measurement for cutting force was recorded using KISTLER dynamometer which attached to the workpiece AlSi/AlN MMC and connected to the DynoWare software. Table 7 shows the data taken for surface roughness and cutting force. S/N ratio was calculated for each characteristic using the condition smaller-the-better for both surface roughness and cutting force (Equation 1).

Table 7 Data and S/N ratio for surface roughness and cutting force

Exp no.	Surface roughness (µm)	S/N ratio	Cutting force (N)	S/N ratio
1	0.405	7.851	128.116	-42.152
2	0.3825	8.347	200.596	-46.046
3	0.6075	4.329	288.621	-49.207
4	0.5125	5.806	125.649	-41.983
5	0.437	7.190	226.499	-47.101
6	0.51	5.849	250.147	-47.964
7	0.425	7.432	186.989	-45.436
8	0.355	8.995	214.210	-46.617
9	0.565	4.959	204.464	-46.212
10	0.745	2.557	225.386	-47.059
11	0.655	3.675	182.357	-45.218
12	0.56	5.036	273.216	-48.730
13	0.5375	5.392	168.009	-44.507
14	0.47	6.558	258.460	-48.248
15	0.6725	3.446	169.006	-44.558
16	0.6325	3.979	223.153	-46.9721
17	0.744	2.557	143.504	-43.137
18	0.4975	6.064	246.924	-47.851

The effects of each parameter to surface roughness and cutting force were separated at different levels. For example, the mean S/N ratio for the type of insert at levels 1 and 2 were calculated by averaging the S/N ratios for the experiments 1–9, and 10–18 respectively. The mean S/N ratio for the cutting speed at level 1 was calculated by averaging the S/N ratio for experiments 1–3 and 10–12. The mean S/N ratio for the cutting speed at level 2 was calculated by averaging the S/N ratio for experiments 4–6 and 13–15, and the mean S/N ratio for the cutting speed at level 3 was calculated by averaging the S/N ratio for experiments 7–9 and 16–18. The mean values of the S/N ratio for each cutting parameter were summarized in Table 8 and Table 9. Also, it shows in Figure 4 and 5. The highest mean value of the S/N ratio for each parameter was chosen, representing the optimum condition.

Table 8 Mean values of S/N ratio for surface roughness

Level/ Factor	A	B	C	D	E
1	6.751	5.299	5.503	4.718	6.238
2	4.364	5.707	6.222	6.577	5.935
3		5.666	4.947	5.378	4.499

Table 9 Mean values of S/N ratio for cutting force

Level/ Factor	A	B	C	D	E
1	-45.790	-46.400	-44.680	-43.880	-46.140
2	-46.320	-45.730	-46.160	-46.610	-45.820
3		-46.040	-47.330	-47.680	-46.200

It can be seen from Figure 4 that the optimum levels for minimum surface roughness were; A1 (uncoated cutting tool), B2 (cutting speed: 320 m/min), C2 (feed rate: 0.4 mm/tooth), D2 (axial depth: 0.4 mm) and E1 (10% reinforcement). At the mean time, Figure 5 shows the optimum levels for maximum material removal; A1 (uncoated cutting tool), B2 (cutting speed: 320 m/min), C1 (feed rate: 0.3 mm/tooth), D1 (axial depth: 0.3 mm) and E2 (15% reinforcement) respectively.

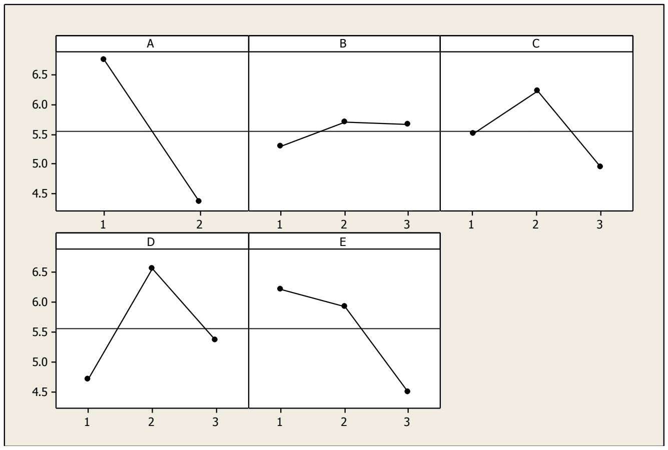


Figure 4 Effect of cutting parameters on mean value S/N ratio for surface roughness for each cutting parameter, A-E

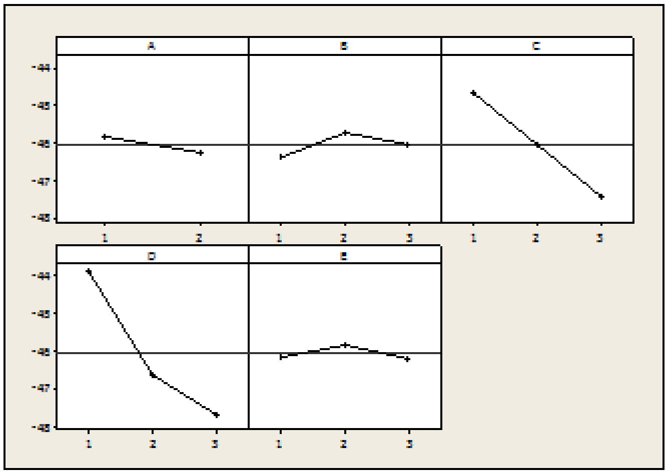


Figure 5 Effect of cutting parameters on mean value S/N ratio for cutting force for each cutting parameter, A-E

3.3 Optimization of Cutting Parameters on Multiple Performance Characteristics using Grey Relational Analysis (GRA)

All data was presented in Table 10. Grey relational analysis (GRA) was applied for the optimization on the multiple performance characteristics including; tool life, surface roughness, cutting force and material removal. For surface roughness and cutting force, the data will be pre-processed as 'smaller-the-better' as mentioned in Equation 4. While for tool life and material removal, the data will be pre-processed as 'larger-the-better' as mentioned in Equation 5.

Table 10 Data for all performance characteristics

Exp no.	Tool life (min)	Surface roughness (µm)	Cutting force (N)	Material removal (cm^3)
1	72.00	0.405	128.116	123.768
2	59.90	0.3825	200.596	183.0544
3	48.92	0.6075	288.621	233.5691
4	60.90	0.5125	125.649	139.5828
5	50.08	0.437	226.499	204.0259
6	31.67	0.51	250.147	201.6112
7	26.67	0.425	186.989	101.8794
8	27.93	0.355	214.210	177.8024
9	27.95	0.565	204.464	133.4613
10	49.33	0.745	225.386	141.3305
11	63.90	0.655	182.357	146.4588
12	53.33	0.56	273.216	203.7206
13	47.90	0.5375	168.009	146.3824
14	35.00	0.47	258.460	178.255
15	44.00	0.6725	169.006	168.08
16	26.67	0.6325	223.153	127.3493
17	33.93	0.744	143.504	129.6126
18	23.00	0.4975	246.924	146.418

All the calculation results is summarized and shown in Table 11.

Table 11 Performance characteristics after pre-processing sequences

Exp no.	pre-processing sequences results			
	Tool life	*Surface roughness*	*Cutting force*	*Material removal*
1	1.000	0.872	0.985	0.166
2	0.753	0.929	0.540	0.616
3	0.529	0.353	0.000	1.000
4	0.773	0.596	1.000	0.286
5	0.553	0.790	0.381	0.776
6	0.177	0.603	0.236	0.757
7	0.075	0.821	0.624	0.000
8	0.101	1.000	0.457	0.577
9	0.101	0.462	0.516	0.240
10	0.537	0.000	0.388	0.300
11	0.835	0.231	0.652	0.339
12	0.619	0.474	0.095	0.773
13	0.508	0.532	0.740	0.338
14	0.245	0.705	0.185	0.580
15	0.429	0.186	0.734	0.503
16	0.075	0.288	0.402	0.193
17	0.223	0.003	0.890	0.211
18	0.000	0.635	0.256	0.338

Deviation sequences was then been calculated according to Equation 6. As mentioned before, the reference sequence for each performance characteristic was specified to be at 1.000. All data was presented in Table 12.

Table 12 Performance characteristics after deviation sequences

Exp no.	Deviation sequences			
	Tool life	*Surface roughness*	*Cutting force*	*Material removal*
	1.000	*1.000*	*1.000*	*1.000*
1	0.000	0.128	0.015	0.834
2	0.247	0.071	0.460	0.384
3	0.471	0.647	1.000	0.000
4	0.227	0.404	0.000	0.714
5	0.447	0.210	0.619	0.224
6	0.823	0.397	0.764	0.243
7	0.925	0.179	0.376	1.000
8	0.899	0.000	0.543	0.423
9	0.899	0.538	0.484	0.760
10	0.463	1.000	0.612	0.700
11	0.165	0.769	0.348	0.661
12	0.381	0.526	0.905	0.227
13	0.492	0.468	0.260	0.662
14	0.755	0.295	0.815	0.420
15	0.571	0.814	0.266	0.497
16	0.925	0.712	0.598	0.807
17	0.777	0.997	0.110	0.789
18	1.000	0.365	0.744	0.662

Table 13 shows the grey relational coefficient and grey relational grade. Grey relational coefficient was calculated by using Equation 7 and grey relational grade was calculated by averaging all four grey relational coefficients for each experiment; as mentioned in Equation 8.

Table 13 Performance characteristics after calculation of grey relational coefficient & grey relational grade

Exp no.	Grey relational coefficient				Grey relational grade
	Tool life	*Surface roughness*	*Cutting force*	*Material removal*	
1	1.000	0.796	0.971	0.375	0.785
2	0.669	0.876	0.521	0.566	0.658
3	0.515	0.436	0.333	1.000	0.571
4	0.688	0.553	1.000	0.412	0.663
5	0.528	0.704	0.447	0.690	0.592
6	0.378	0.557	0.396	0.673	0.501
7	0.351	0.736	0.571	0.333	0.498
8	0.357	1.000	0.479	0.541	0.594
9	0.357	0.481	0.508	0.397	0.436
10	0.519	0.333	0.450	0.417	0.430
11	0.752	0.394	0.590	0.430	0.541
12	0.568	0.488	0.356	0.688	0.525
13	0.504	0.517	0.658	0.430	0.527
14	0.398	0.629	0.380	0.543	0.488
15	0.467	0.380	0.653	0.501	0.500
16	0.351	0.413	0.455	0.383	0.400
17	0.392	0.334	0.820	0.388	0.483
18	0.333	0.578	0.402	0.430	0.436

Grade order was sorted and filtered in descending order. The higher of grey relational grade means the better corresponding to multiple performance characteristics. From Table 14, it shows that experiment 1 indicated the higher grey relational grade, means the cutting parameters in experiment 1 is said to be closed to the optimal. It also could be seen clearly in Figure 6.

Table 14 Grey relational grade & grade order

Exp no.	Grey relational grade	Grade order
1	0.785	1
2	0.658	3
3	0.571	6
4	0.663	2
5	0.592	5
6	0.501	10
7	0.498	12
8	0.594	4
9	0.436	15
10	0.430	17
11	0.541	7
12	0.525	9
13	0.527	8
14	0.488	13
15	0.500	11
16	0.400	18
17	0.483	14
18	0.436	16

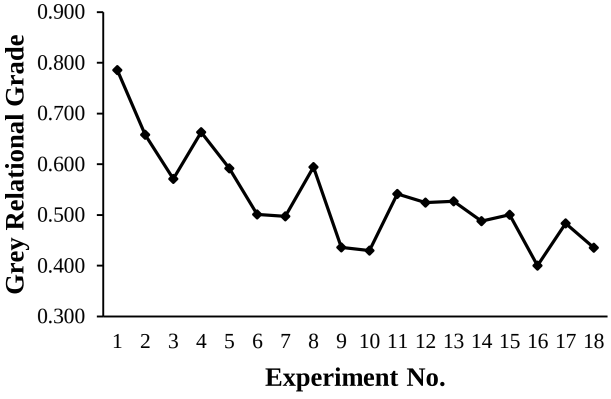


Figure 6 Grey relational grade (the higher grade the better)

The effects of each parameter were separated at different levels. For example, the mean of grey relational grade (GRG) for the type of coating at levels 1 and 2 were calculated by averaging the GRG for experiments 1–9 and 10–18, respectively. The mean of GRG for the cutting speed at level 1 was calculated by averaging the GRG for experiments 1–3 and 10–12. The mean of GRG for the cutting speed at level 2 was calculated by averaging the GRG for experiments 4–6 and 13–15, and the mean GRG for the cutting speed at level 3 was calculated by averaging the GRG for experiments 7–9 and 16–18. The mean values of the GRG for each cutting parameter were calculated and summarized in Table 15 and Figure 7.

Table 15 Mean response table for grey relational grade

Response table for grey relational grade					
Level/Factor	*A*	*B*	*C*	*D*	*E*
1	**0.589**	**0.585**	0.551	**0.568**	0.541
2	0.481	0.545	**0.560**	0.539	**0.557**
3		0.475	0.495	0.497	0.507
diff Δ	0.108	0.11	0.065	0.071	0.05

From Figure 7, the optimum levels for multiple performance characteristics was presented as the higher value of mean response. It was; A1 (uncoated carbide insert), B1 (cutting speed: 240 m/min), C2 (feed rate: 0.4mm/tooth), D1 (axial depth: 0.3 mm) and E2 (15% volume fraction of reinforcement).

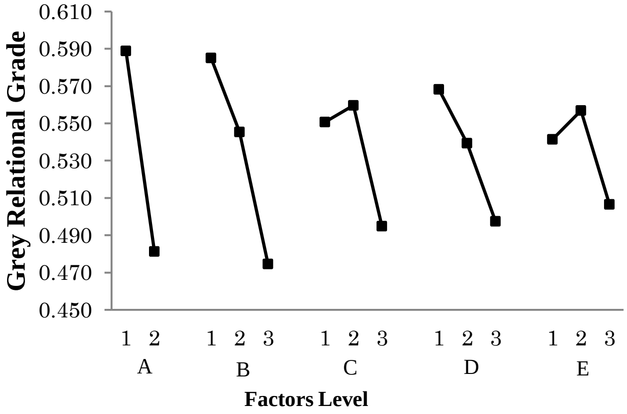


Figure 7 Effect of cutting parameters level to the multiple performance characteristics

3.4 Confirmation Test

The optimum level of each machining parameter was selected using GRA. Then, the final step is to verify the improvement of the multiple performance characteristics using the optimal level of the machining parameters. The $A_1B_1C_2D_1E_2$ is an optimal combination of machining parameters using end milling process through the GRA. Therefore, these parameters condition was treated as a confirmation test. Table 16 shows the improvement of the performance characteristics by using GRA.

Table 16 Comparison between initial and optimal machining parameters

	Initial machining parameters	**Optimal machining parameters (Experiment)**
Best combination	$A_1B_1C_1D_1E_1$	$A_1B_1C_2D_1E_2$
Tool life (min)	72	70
Surface roughness (µm)	0.405	0.368
Cutting force (N)	128.116	146.07
Material removal (cm^3)	123.768	167.316
Grey relational grade	0.785	0.797
Improvement in GRG = 0.012		

The surface roughness is improved from 0.405 to 0.368 µm, tool life is slightly dropped from 72 to 70 min, cutting force increased from 128.116 to 146.07N and the material removal is increased from 123.768 to 167.316 cm^3. It is clearly shown that multiple performance characteristics in the end milling of AlSi/AlN MMC are significantly improved through this study.

■4.0 CONCLUSION

Taguchi method and Grey relational analysis was applied in this experimental investigation. The aim of this paper is to determine the optimum cutting parameters for multiple performance characteristics; surface roughness, tool life, cutting force and material removal while milling AlSi/AlN MMC. The following observations were made:

1. Based on the Grey Relational Analysis (GRA), the mean response for GRA as shown in Table 15 and Figure 7 shows the effect of cutting parameters to the multiple performance characteristics respectively. Therefore these parameters $A_1B_1C_2D_1E_2$ with uncoated carbide insert, cutting speed of 240m/min, feed rate of 0.4mm/tooth, axial depth of 0.3mm, and 15% volume fraction of AlN reinforcement are the optimum combination of cutting parameters for the designated experiment.
2. The improvement of GRG can be seen clearly by using the optimal machining parameters compared to initial machining parameters. The surface roughness Ra is improved from 0.405 to 0.368 µm, tool life is slightly dropped from 72 to 70 min, cutting force increased from 128.116 to 146.07 N and the material removal is increased from 123.768 to 167.316 cm^3.
3. The Taguchi method is suitable not only for the optimization of cutting parameters in a milling operation, so it can also be used for other operations; turning, grinding etc.

Acknowledgement

The authors are grateful to the Universiti Kebangsaan Malaysia, Universiti Malaysia Pahang and the Ministry of Higher Education for funding this research project. The authors would also like to thank the staff at the Department of Mechanical and Material Engineering, Faculty of Engineering and Built Environment at UKM, for their technical assistance.

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