Machining Parameter Optimization of Al/SiC/Gr Hybrid Metal Matrix Composites using ANOVA and Grey Relational Analysis

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This research work focuses on the impact of graphite addition to the Al/SiC hybrid metal matrix composites manufactured by stir casting process. Three specimens were prepared with Al6061 alloy + 5 wt. % SiC and varying weight percent of graphite. Al6061 matrix material is suitable for machining and welding applications commonly used in construction of aircraft wings and fuselages. Machining of composite materials is often required to meet dimensional tolerances, surface roughness and to create holes. A layered SiC/Gr composite material is used in gas turbine combustor can. Machining of Al/SiC/Gr hybrid composite was done in Esteem ETM 356 lathe using tungsten carbide insert. Optimization of three machining parameters cutting speed, feed rate and depth of cut, was done using four levels. From ANOVA results feed rate (35.83%) is the important factor influencing surface roughness. Grey Relational analysis was done for simultaneous improvement of Material Removal Rate and surface roughness.

***Keywords:** Hybrid metal matrix composites, Al6061, SiC, Graphite, Surface roughness, ANOVA, GRA.*

1. INTRODUCTION

Aluminium alloy based composites are widely used in aerospace and automotive industries. Aluminium and its alloys are most economical and attractive due to light weight, fabricability, mechanical properties, and corrosion resistance [1]. Most of the research works on metal matrix composites are done on the following three metals, Aluminium, Magnesium and Titanium.

To improve the properties of MMCs two or more reinforcements are added to the matrix, this leads to the formation of a new hybrid composite. MMCs are composed of a metal matrix and a reinforcement, or filler material. The main matrix materials for MMCs are aluminium and its alloys. To a lesser extent, magnesium, titanium, copper, zinc or lead matrix is also used. MMCs with continuous fiber reinforcements have better mechanical properties than MMCs with discontinuous reinforcements [2].

Commonly used second reinforcement in hybrid composites are Gr, Al_2O_3, B_4C of which Al/SiC/Gr is an important hybrid composite, because SiC is harder than Tungsten carbide (WC) and Graphite particles provide high resistance to wear in the hybrid composite [3,4]. SiC is much easier to synthesize than diamond and can be produced readily in large quantities in a crude form such as powder. SiC-particulate-reinforced aluminium composites have found many applications such as brake discs, bicycle frames, aerospace and automotive industry. Graphite particles present in Al/SiC/Gr composites are solid lubricant and act as a chip breaker, due to this discontinuous chips are produced and tool wear is reduced [5].

Machining process in composite materials cannot be eliminated completely, due to the size and dimensional requirements. A number of researchers have conducted experiments in machining Aluminium metal matrix composites using various machining process. CNC lathe & medium duty lathe under dry turning conditions and machining parameters like cutting speed, feed rate, depth of cut were considered by various researchers for optimization, with surface roughness as their desired target. Tool life is usually shorter due to the abrasive nature of the composite. Traditional high speed steel tool is not suitable for machining MMCs due to rapid growth of tool wear. PCD tools are used for machining carbon-reinforced composites due to high wear resistance [6,7].

Suresh [8] found that higher reinforcement content of Si-Gr promotes brittleness, because of brittleness built-up edge formation disappears. Built-up edge formation leads to tool failures when tools with carbide inserts are reduced, decrees the life of cutting tool. Muthukrishnan [9] studied about the surface roughness of Al-SiC(20 p) by turning using coarse grade PCD insert under different cutting conditions and tested their experimental data with ANOVA and ANN techniques.

Basavarajappa [10] found that graphite in Al 2219 /15 SiCp composite particle increases the surface roughness due to smearing and removal of softer and amorphous graphite particles on the surface of the specimen. Suhasini [11] reviewed machining of MMCs:

slower speeds, higher feeds and depth of cuts contribute to the formation of Built up edge (BUE). Discontinuous chips result in better surface roughness values. Increased reinforced percentages and sizes resulted in increased surface roughness. Cutting forces were much larger for Tungsten carbide tools than PCD tools due to the formation of BUE.

Tian [12] found that surface roughness has a tendency to increase first and then decrease with the increase in cutting speed. For cutting speeds less than 150 m/min, the BUE tends to form and this may lead to increase in surface roughness, whereas for cutting speeds higher than 200 m/min the softening of the work piece material due to increased temperature results in lower temperature.

Toth-Laufer and Richard Horvath [13] investigated surface roughness prediction of fine turning using central composite experimental design. Average surface Roughness R_a and R_z were considered in this study for developing a predictive fuzzy-based model. Lazarevic [3] investigated the influence of cutting speed, feed rate, depth of cut and tool nose radius on main cutting force using L27 Taguchi's orthogonal array. Abdullah [14] investigated the effect of surface roughness on the thermolectric behaviour of friction clutches, developed axisymmetric finite element model for a single-disc clutch system.

Marichamy [15] optimized machining parameters for $\alpha-\beta$ brass manufactured by stir casting process using Taguchi method for abrasive water jet machining. Dhawan [16] developed a new ANN approach to predict drilling-induced thrust force and torque. Sivaiah [17] tested the cryogenic machining of stainless steel; from the ANOVA analysis feed rate is the most influencing process parameter on the performance characteristics.

A review of literatures indicates that the study on machining of Al/SiC/Gr hybrid composites are very limited. Machining parameter optimization with four levels and hybrid composite manufacturing by varying weight percentage of graphite is not carried out by researchers. The present study uses three specimens of Al/SiC/Gr hybrid metal matrix composites manufactured by stir casting method with varying weight percent of graphite. Sixteen experimental runs with three parameters and four levels were conducted in Esteem ETM 356 lathe machine using new tungsten carbide inserts to determine the optimum machining parameters. SEM micrographs and EDAX analysis were done to check the elemental contribution in hybrid metal matrix composites.

2. EXPERIMENTAL PROCEDURES

Hybrid MMCs of type (Al 6061 + 5 % SiC + 2.5 % Gr, Al 6061 + 5 % SiC + 5% Gr and Al6061 + 5 % SiC + 7.5 % Gr) were manufactured using stir casting method. The matrix material used was Al6061 (magnesium and silicon are principal alloying elements), has good resistance to corrosion. The chemical composition of Al6061 alloy is Si 0.4-0.8%, Mg 0.8-1.2%, Fe 0.7, Cu 0.15-0.4%, Mn 0.15%, Cr 0.04-0.35%, Zn 0.25%, Ti 0.15%, Al-balance. Al6061 alloy is widely used in aircraft, defence, automobiles and marine applications. The average particle size of

SiC and Gr used was 40 μm. The SiC and Gr particles were kept in powder particle furnace at 400°C for 3 hours. Al6061 alloy was heated to 800°C in a graphite crucible and the melt was degassed and cleaned to remove impurities, increase wettability and to reduce porosity. SiC and Gr particles were added simultaneously and mixed homogeneously in Al6061 alloy matrix at a stirring speed of 400 rpm. Pouring of molten slurry into the mould is done through the bottom using a remote control switch.

2.1 FESEM Analysis

The microstructure of work material (Al+5% SiC+2.5 %Gr) is shown in Figure 1. The reinforcement (SiC and Gr) particles were evenly distributed within the matrix alloy; it shows that stir casting method can be used for the manufacturing of Al/SiC/Gr composites with improved properties and reduced particle clusters. The graphite takes the form of flakes and the Al particles appear in round and cylindrical shapes, SiC particles have an ellipsoidal shape. The SiC particles appear like cubes; Gr particles are seen as dark regions or as pores formed during polishing of surface. The micrographs indicate perfect bonding between different components of Al composites and absence of cracks. The result of the micro structural analysis revealed a non-uniform distribution of graphite particles takes place at all the three specimens.
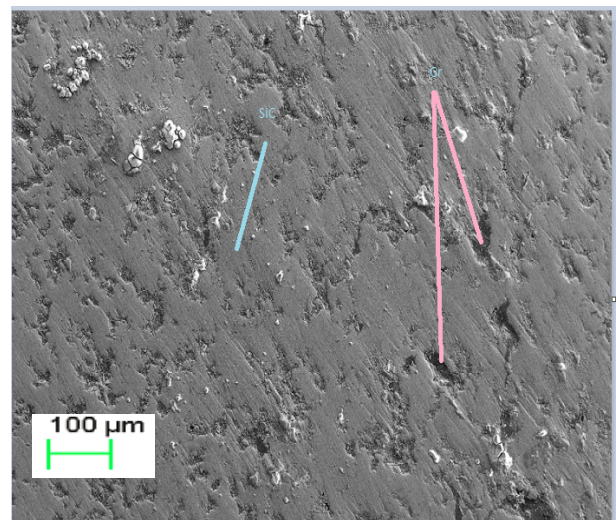

Figure 1. Al + 5% SiC + 2.5 % Gr SEM micrograph

The hardness values of aluminium hybrid composites with 5% SiC and 2.5 % Gr, 5 % Gr, 7.5 % Gr are 83 VHN, 72 VHN and 54 VHN respectively. Hardness of Al/SiC/Gr hybrid composite decreases with increase in weight % of graphite content.

2.2 EDAX Analysis

EDAX (Energy Dispersive X-ray analysis) is done for Al/SiC/Gr specimen. EDAX results in Figure 2 show the presence of Aluminium in major peak & presence of other alloys in minor peaks. Si, C, Mg and other alloys present in Al6061 is also seen. The elemental characterization reveals perfection in the process of fabrication by the method of stir casting.

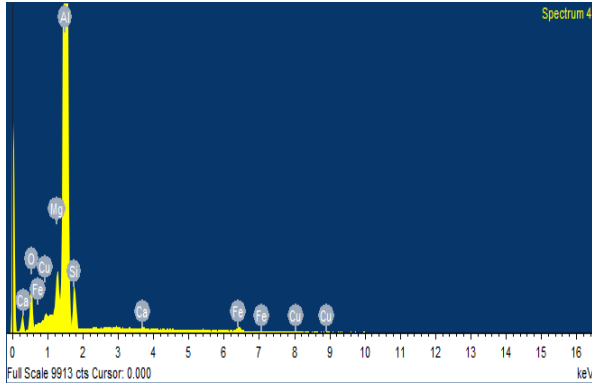| Element	Weight%	Atomic%
O K	10.04	15.94
Mg K	1.19	1.24
Al K	83.86	78.90
Si K	3.73	3.38
Ca K	0.15	0.10
Fe K	0.71	0.32
Cu K	0.31	0.13

Figure 2. EDAX analysis of specimen

Graphite has been completely absorbed due to the phenomenon of diffraction based on the focus of the electron beam. Low intensity oxygen peak was observed due to oxide formation.

Experimental parameters are given in table 1. Esteem ETM 356 lathe machine was used to carry out the experiments. The TNMG 160408 tungsten carbide inserts were used to turn the 50 mm diameter, 300 mm length specimen. The Al/SiC/Gr hybrid specimens are machined at four different cutting speeds, feed rate and depth of cut. The average surface finish (R_a) was measured in the machined surface using Mitutoyo Surf test SJ-201 with a cut off and traverse length of 0.8 and 5 mm, respectively.

Table 1. Experimental conditions

Machine	Esteem ETM 356 lathe machine
Tool insert	Tungsten carbide tool insert TNMG 160408
Tool holder	ETJNL – 2020K16
Machining parameters	Cutting speed : 26, 40,60 and 92 m/min Feed rate : 0.256,0.373, 0.466 and 0.561 mm/rev Depth of Cut : 0.2, 0.4, 0.6 and 0.8 mm
Surface Roughness equipment	Mitutoyo Surf test – 201
Coolant	Dry machining

3. EXPERIMENTAL DATA

The experimental data consists of four replicates. The experiments were designed using Taguchi's L_{16} orthogonal array with 16 experiments [18]. Machining parameters and surface roughness measured for various experiments are shown in table 2.

From table 2, it is observed that at cutting speed of 26 m/min, feed rate 0.256 mm/rev and 0.2 mm surface roughness is low and at high cutting speed 92 m/min, feed rate 0.561 mm/rev and 0.2 mm depth of cut MRR is high.

Table 2 Experimental results using L_{16} orthogonal array

Experiment No	Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Specimen	Surface Roughness Ra Value (μm)	MRR (g/min)
1	26	0.256	0.2	1	**6.19**	**1.33**
2	26	0.373	0.4	2	10.49	3.87
3	26	0.466	0.6	3	12.05	7.24
4	26	0.561	0.8	2	11.02	11.63
5	40	0.256	0.4	3	9.68	4.10
6	40	0.373	0.2	3	9.25	2.99
7	40	0.466	0.8	1	9.66	14.93
8	40	0.561	0.6	2	13.36	13.48
9	60	0.256	0.6	2	13.82	9.28
10	60	0.373	0.8	3	7.99	18.04
11	60	0.466	0.2	2	12.27	5.63
12	60	0.561	0.4	1	**14.07**	13.56
13	92	0.256	0.8	2	6.61	18.81
14	92	0.373	0.6	1	6.74	**20.55**
15	92	0.466	0.4	1	7.41	17.12
16	92	0.561	0.2	3	11.76	10.31

3.1 Analysis of variance

The ANOVA analysis was done to statistically analyze the relative significance of the machining parameters such as cutting speed (A), feed rate (B), and depth of cut (C) on the response variable (surface roughness R_a). The model has been developed for 95% level of confidence. Based on the experimental results of the responses, a first order model has been developed for surface roughness using Minitab software.

Regression Equation

Ra = 10.148 - 0.211 Speed_26 + 0.339 Speed_40
+ 1.889 Speed_60 - 2.018 Speed_92
- 1.073 Feed_0.256 - 1.531 Feed_0.373
+ 0.199 Feed_0.466 + 2.404 Feed_0.561
- 0.281 DOC_0.2 + 0.264 DOC_0.4 + 1.344 DOC_0.6 - 1.328 DOC_0.8   (1)

Table 3 Analysis of variance of Surface Roughness

Machining parameter	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value	Contribution %
Cutting speed	3	31.21	10.403	3.02	0.115	30.01
Feed rate	3	37.26	12.420	3.61	0.085	35.83
Depth of cut	3	14.88	4.96	1.44	0.321	14.3
Error	6	20.65	3.441			19.85
Total	15	103.99				100

From ANOVA table 3, the cutting speed and feed rate have major influence on the roughness value, whereas depth of cut has minor effect on the surface roughness.

3.2 Determination of optimum factor level combination

The optimum machining parameters for conducting confirmation experiment using S/N ratio is $A_3B_4C_3D_1$.

The parameter for which the line has highest inclination has greatest effect, whereas the line which is near horizontal means, the parameter has little effect on surface roughness. From Figure 3, cutting speed and feed rate has major effect on surface roughness, compared to depth of cut.
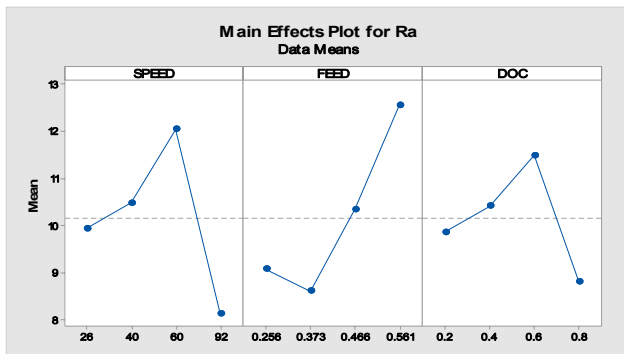

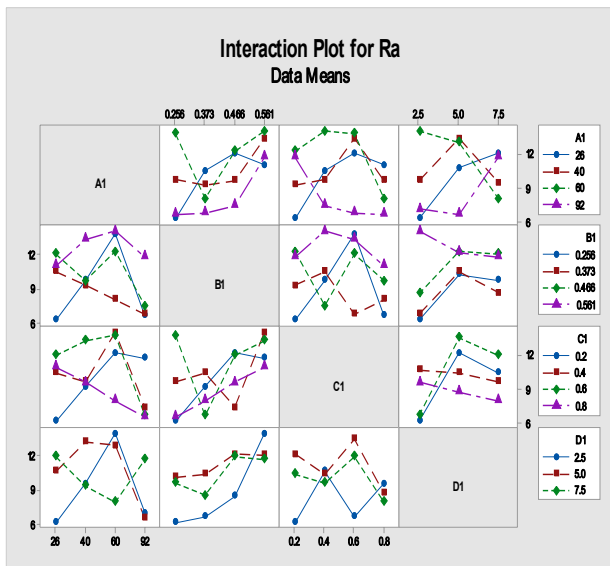
Figure 3. Main Effects plot for SN Ratio

Figure 4. Interaction plot for Surface Roughness

In the interaction plot, if lines are parallel to each other there is no interaction between elements. If the lines are not parallel to each other, an interaction may be present. If we have three or more factors, interaction plot will be displayed in matrix. The greater the difference in slope between the lines, the higher the degree of interaction. From Figure 4, cutting speed of 92 m/min, with feed rate of 0.561 mm/rev is better for getting minimum R_a.

Table 4. Taguchi response table for S/N ratio

Factors	S/N ratio (dB)			
	Level 1	Level 2	Level 3	Level 4
Cutting speed A(m/min)	-19.677	-20.313	-21.4	-17.94[@]
Feed rate B (mm/rev)	-18.691	-18.59[@]	-20.122	-21.993
Depth of cut C (mm)	-19.584	-20.123	-20.87	-18.658[@]
% reinforcement of Graphite (D)	-18.493[@]	-20.794	-20.02	-

@ - Optimum results of minimum Ra

Taguchi response shown in table 4 was determined to find out the optimum factors which influence the surface roughness. The optimum machining conditions cutting speed 92 m/min, feed rate 0.373 mm/rev, depth of cut 0.8 mm and Al+5%SiC+2.5 % Gr respectively.
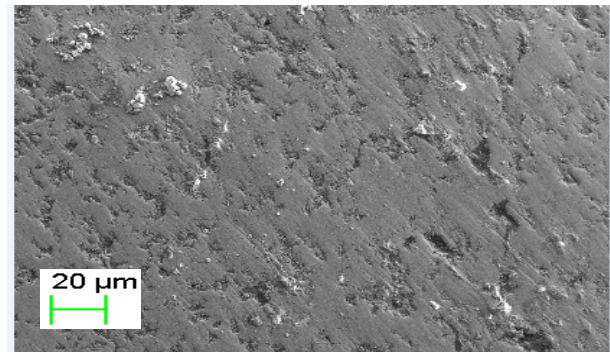

Figure 5. SEM micrograph of machined surface at optimum machining conditions ($A_4B_2C_4D_1$)

The SEM micrograph of machined surface under optimized process parameter ($A_4B_2C_4D_1$) is shown in Figure 5. The surface of the machined work piece contains small surface cracks and tiny pit holes. The white particles show the transformation of aluminium during machining of Al/SiC/Gr composite.

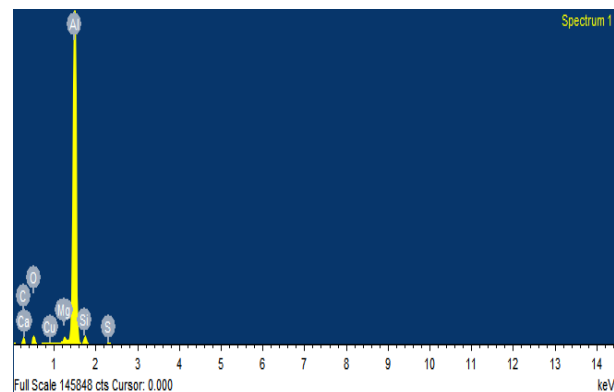| Element	Weight%	Atomic%
C K	27.17	43.05
O K	12.22	14.53
Mg K	0.69	0.54
Al K	55.95	39.46
Si K	2.89	1.96
S K	0.32	0.19
Ca K	0.09	0.04
Fe K	0.42	0.14
Cu K	0.24	0.07

Figure 6. EDAX analysis of machined surface at optimum machining conditions ($A_4B_2C_4D_1$)

The EDAX spectra shown in Figure 6 are analysed to check the presence of elements on the machined surface of the work piece. The EDAX spectra show the presence of carbon after machining using tungsten carbide insert, which is not in the EDAX spectra before machining. EDAX results in fig 6 show the presence of Aluminium in major peak & presence of other alloys in minor peaks. Si, C, Mg and other alloys present in Al6061 is also seen. The presence of low intensity oxygen peak was observed due to oxide formation.

3.3 Predicting the optimum performance

After selecting the optimal level from main effect plots in Figure 3, prediction of R_a value was done by Taguchi design analysis using Minitab software. A confirmation experiment is required to do the optimization, since lesser number of data are available. The confirmation experiment is used to verify the development in quality characteristics.

3.4 Verification of optimal parameters by confirmation test

After determining the optimum machining parameter levels, a new experiment was conducted. The results of the confirmation experiment are compared with the results of the orthogonal array in table 5. The result shows that the surface roughness reduces from 6.19 to 4.714 µm. Predicted values were close to experimental values and they are within the confidence limits.

Table 5. R_a values for starting and optimal process parameters

Output response	Starting parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	$A_1B_1C_1D_1$	$A_4B_2C_4D_1$	$A_4B_2C_4D_1$
Surface Roughness R_a (µm)	6.19	5.271	4.714
S/N ratio	-15.833	-14.437	-13.467

The process of calculating signal to noise ratio depends on whether the quality characteristics has smaller-the-best, larger-the-better or normal-the-better.

$$S/N = -10 \log_{10}(R_a^2) \quad (2)$$

where Ra is the average surface roughness value.

4. RESULTS AND DISCUSSION

The higher level of graphite addition leads to decreased vicker's hardness of Al/SiC/Gr hybrid composite.The surface roughness attained at the starting parameters and optimum condition using tungsten carbide insert are 6.19 and 4.714 µm respectively, which is better than the desired surface roughness results obtained by earlier researchers. The increase in Gr content, tungsten carbide tool insert increases the surface roughness. Smudge and removal of softer and amorphous graphite particles on the surface of the specimen, leads to increased surface roughness values.

The multi-objective problem of getting lower surface roughness and higher material removal rate is changeed into a single-objective optimization problem using grey relational analysis. Grey relational analysis consists of three steps: Data Preprocessing, Grey relational coefficient and Grey relational grade.

Data Preprocessing is required since the range and unit in one data sequence may differ from others. Normalization is a processing step carried out to offset the effect of response units and data ranges for comparison. Equations used for data processing are:

Smaller the better

$$X_i^*(k) = \max X_i^\circ(k) - X_i^\circ(k) / \max X_i^\circ(k) - \min X_i^\circ(k) \quad (3)$$

Higher the better

$$X_i^*(k) = Xi^\circ(k) - \min X_i^\circ(k) / \max X_i^\circ(k) - \min X_i^\circ(k) \quad (4)$$

After data processing, Reference sequence or deviation sequence is calculated

$$\Delta_{oi}(k) = | X_0^*(k) - X_i^*(k)| \quad (5)$$

where $\Delta_{max} = 1$ and $\Delta_{min} = 0$

Calculation of grey relational coefficient

$$\xi_i(k) = \Delta_{min} + \xi. \Delta_{max} / \Delta_{oi}(k) + \xi. \Delta_{max} \quad (6)$$

In the current study $\xi = 0.5$ was considered

Calculation of grey relational grade

Grey relational grade is the average of all grey relational coefficients of the performance characteristics. Grey relational coefficients and grey relational grades are shown in table 6.

4.1 Grey relational Analysis

Table 6. Grey Relational Coefficients and grey relational grades for machining experiments

EXP NO.	Grey Relational coefficients		Grey Relational Grade	order
	R_a(µm)	MRR (g/min)		
1	1.00	0.33	0.67	5
2	0.48	0.37	0.42	13
3	0.40	0.42	0.41	14
4	0.45	0.52	0.48	7
5	0.53	0.37	0.45	12
6	0.56	0.35	0.46	10
7	0.53	0.63	0.58	6
8	0.35	0.58	0.47	8
9	0.34	0.46	0.40	15
10	0.69	0.79	0.74	4
11	0.39	0.39	0.39	16
12	0.33	0.58	0.46	9
13	0.90	0.85	0.88	2
14	0.88	1.00	0.94	1
15	0.76	0.74	0.75	3
16	0.41	0.48	0.45	11

Table 7. Response table for grey relational grade

Process parameters	Grey relational grade					
	Level 1	Level 2	Level 3	Level 4	Delta	Rank
Cutting speed (m/min)	0.495	0.49	0.497	0.755	0.265	1
Feed rate (mm/rev)	0.6	0.64	0.5325	0.465	0.175	3
Depth of cut (mm)	0.493	0.52	0.555	0.67	0.177	2

Means of grey relational grade for each level of process parameters are obtained and results are shown in table 7.

5. CONCLUSIONS

In this research work, the effect of graphite addition to Al/SiC hybrid metal matrix composite is studied with surface roughness as the desired response, while

machining using tungsten carbide insert. The addition of graphite in Al/SiC/Gr composite increases the surface roughness, when machining with tungsten carbide insert. Al/SiC/Gr composite produced discontinuous elemental chips, which leads to easier machining, due to the lubricant property of graphite particles. The higher percentage of graphite results in decreased hardness of Al/SiC/Gr hybrid composite. The Vicker's hardness values of aluminium hybrid composites with 5% SiC and 2.5 % Gr, 5 % Gr, 7.5 % Gr are 83, 72 and 54 VHN respectively. The major influencing factors based on Analysis of Variance towards surface roughness is feed rate(35.83%) and, cutting speed(30.01%) while depth of cut(14.3%) has minor effect on surface roughness. The surface roughness obtained at the starting parameters and optimum condition using tungsten carbide insert are 6.19 and 4.714 μm respectively. Grey relational analysis was done for the surface roughness and MRR performance characteristics. The surface finish is better when feed rate and reinforcement of Gr is at 2.5 % level. Further research in this area can be carried out by developing a fuzzy based model, by incorporating the expert knowledge. This model will reduce the cost and time for surface roughness prediction.

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ОПТИМИЗАЦИЈА ПАРАМЕТАРА ОБРАДЕ КОД ХИБРИДНОГ КОМПОЗИТА ОЈАЧАНОГ Al/SiC/Gr ПРИМЕНОМ АНАЛИЗЕ ANOVA И ГРЕЈ РЕЛАЦИОНЕ АНАЛИЗЕ

М. Еланго, К. Анамалаи

Изучава се утицај додавања графита композиту ојачаном Al/SiC који је добијен мешањем уливањем. Припремљена су три узорка од легуре Al6061 + 5 теж.проц. SiC и променљивим процентом графита. Наведена легура је погодна за обраду и заваривање и најчешће се користи за израду крила и трупа летелица. Захтеви које поставља обрада композита су толеранција димензија, храпавост површине и израда рупа. Слојевити композит ојачан Al/SiC/Gr се користи код коморе за сагоревање гасне турбине. Обрада хибридног композита је обављена на

токарском уређају Esteem ETM 356 помоћу волфрамског карбидног уметка. Оптимизација три параметра обраде: брзина резања, брзина помоћног кретања и дубина резања обављена је на четири нивоа. На основу резултата добијених ANOVA анализом брзине помоћног кретања (35,83%) утврђено је да има значајног утицаја на површинску храпавост. Греј релациона анализа је примењена за истовремено побољшање уклањања материјала и храпавости.