Multi-Objective Optimization in Hot Machining of Al/SiCp Metal Matrix Composites

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Abstract. Metal Matrix Composites (MMCs) have been found to be useful in a number of engineering applications and particle reinforced MMCs have received considerable attention due to their excellent engineering properties. These materials are generally regarded as extremely difficult to machine, because of the abrasive characteristics of the reinforced particulates. These characteristics of MMCs affect the machined surface quality and integrity. This paper presents use of Taguchi Grey Relational Analyses (GRA) for optimization of Al/SiCp/10p (220 and 600 mesh) MMCs produced by stir casting. Experiments are performed using L16 orthogonal array by using hot machining technique. The objective of this study is to identify the optimum process parameters to improve the surface integrity on Al/SiCp MMCs. The machined surface integrity has been analyzed by process parameters such as speed, feed, depth of cut and preheating temperature. The significance of the process parameters on surface integrity has been evaluated quantitatively by the analysis of variance (ANOVA) method and AOM plots. The grey relational analysis shows optimum machining conditions as 0.05 mm/rev feed, 0.4 mm depth of cut and 60 °C preheating temperature to enhance surface integrity for both Al/SiCp/10p (220 and 600 mesh) MMCs except for cutting speed 50 and 25 m/min respectively.

Keywords: Metal matrix composites, force components, surface finish, flank wear, Taguchi Method, Grey Relational Analysis

1. Introduction:

Metal matrix composites (MMCs) materials are well known composites because they possess superior properties such as high strength to weight ratio, hardness, stiffness, wear and corrosion resistance etc. over conventional materials. Aluminum alloy reinforced with silicon carbide particles are one class of such MMCs. The conventional materials are replaced by these MMCs in many applications, especially in the automobile and aerospace industries. The conventional material may not always be capable of working in environments like cryogenic condition, vacuum in space and high hydrostatic pressure in sea. Hence for meeting these performance requirements, these types of materials are developed [1, 2]. Now a day's commercial aero plane, automotive, electronics and recreation industries (bicycles and golf clubs), are also- working with these composites. The force behind the development of these composites is their ability to produce tailored mechanical and physical properties for specific applications [3]. Aluminum alloys reinforced with silicon carbide particles (Al/SiCp) are low cost composite, provide higher strength and stiffness with a minimal increase in density over the base alloy. SiC particles are normally harder and stiffer than the aluminum matrix. Due to addition of SiC particles into Aluminum matrix, machining becomes more difficult than in the case of conventional materials [2]. Very hard abrasive reinforcement particles cause extensive tool wear which is the main problem while machining of such MMCs. Debonding, pull-out and fracturing of SiC particles may cause during conventional turning of Al/SiCp. Machinability can be improved by hot machining of Al/SiCp composites at low temperature prior to machining. Heat is supplied from external sources in the vicinity of the shear zone, reducing the shear strength of the work material due to which material becomes soft. This leads in reduction of the mechanical processing energy on the tool [4]. In order to minimize these machining problems, scientific methods based on Taguchi design of experiments were used [5]. However, the original Taguchi method has been designed to optimize a single performance characteristic and is not appropriate for multiple-performance optimization [6]. Therefore, it requires further research efforts to handle multiple performance characteristics. If there are multiple response variables for the same conditions of independent variables, the methodology provides optimal operating conditions for each response variable, but these conditions could be different from each other. Therefore, an improvement of one performance characteristic may cause a deterioration of another performance characteristic. Hence, optimization of the multiple performance characteristics is more complicated than optimization of a single performance characteristic [7].

2.Literature review

Dabade and Joshi [3] made attempts to improve the machinability of MMCs and surface quality by hot machining using wiper inserts. Experimental results indicate that the moderate heating of Al/SiCp composite material prior to machining (60- 90°C) reduces the machining forces and improves the surface quality by minimizing, debonding, fracture and pull-out of reinforcement particles from the matrix material. The wiper inserts give better results with a priory heating of work surfaces to 60ºC for finer reinforcement composites and 60 to 90ºC for coarser reinforcement composites. Dabade [7] found that surface roughness is more sensitive to a change in size than a change in volume fraction of reinforcement. The grey relational analysis shows that wiper insert geometry with 0.8 mm tool nose radius, 0.05 mm/rev feed, 40 m/min cutting speed and 0.2 mm depth of cut are optimized machining conditions that enhance the surface integrity on Al/SiCp composite. Manna and Bhattacharyya [8] observed formation of built-up edge and reduction in the cutting force components i.e. feed force and cutting force gradually by increasing cutting speed during turning of Al/SiC−MMCs. Reddy and Sriramakrishna [9] observed similar results. Further Manna and Bhattacharyya [8] added that the feed force and cutting force both increases with the increase in depth of cut and feed rate.

Dabade and Joshi [10] performed experiments on three materials Al-matrix, Al/SiC/10p and Al/SiC/30p composites using CBN inserts of wiper geometry and wiperless geometry. They observed that wiper inserts required less cutting force and roughness get improved by about 35-38% than wiperless inserts for all materials. Muthukrishnan et al. [2] carried out the study of the tool wear mechanism by machining of Al/SiC/10p and Al/SiC/20p (grain size ranging from 55 to 85 μm) for duration of 100 minutes with PCD insert. The result indicates that the tool flank wear is more while machining 20% of the SiC reinforced MMCs compared with 10% of the SiC reinforced MMCs. Ibrahim et al.[11] found that coated cutting tools performed better than uncoated cutting tools in terms of tool wear for SiCp reinforced particle size (30, 45 and 110 μm) MMCs. Dabade et al. [12] observed that cutting and feed force components show very little (10–15%) dependence on the change in composition of composites whereas the radial forces in machining of coarser reinforcement composite increase by (40–50%) over the finer reinforcement composite for the same volume fraction while machining of four Aluminum-based composite materials with two levels each of volume fraction (20% and 30%) and size (mesh size: 220 and 600) of SiC reinforcements. They also observed higher surface roughness for coarser reinforcement than finer reinforcement. Bhushan [13] developed a regression model for flank wear, crater wear, and MRR with the process parameters. They observed that in most of the cases, cutting speed, feed, depth of cut, and nose radius are the significant parameters. For simultaneously minimize the flank wear, crater wear and to maximize the MRR Multi-objective optimization of machining parameters was done by desirability analysis. The optimum values of the cutting speed 210 m/min, feed 0.16 mm/ rev, depth of cut 0.42 mm, and nose radius 0.40 mm. Sahoo et al. [14] added that multi- layer TiN coated carbide insert gives better machining performance (lower tool wear and smoother surface finish) as lubricity provided by TiN coated layer reduces the friction and prevents the interface temperature and diffusion at higher cutting speed thus delaying the growth of wear. Dabade et al. [15] found that during machining of Al/SiC/10p composites, the surface finish is better at higher cutting speed, whereas in the case of Al/SiC/30p composites, better at lower cutting speed. Further they added that the feed marks, pits and cracks on the machined surfaces of Al/SiCp/30p were significantly reduced using wiper insert. Kannan and Kishawy [16] observed that application of the coolant causes the loosely bonded particulates to be flushed away resulting in higher percentage of voids and pits that deteriorate the quality of the finished surface during wet turning of 7075 Alumina-reinforced (10%) Aluminum composites using coated Tungsten Carbide cutting tools.

The objective of the research work is to improve the surface integrity of machined surface by pre heating before machining of Al/SiCp MMCs. Surface integrity is influenced by various parameters such as cutting force, feed force, radial force, flank wear and surface roughness on machined surface and hence these parameters are considered as response variables. The literature indicates that the selected response variables are influenced by the process parameters such as cutting speed, feed, depth of cut and pre heating temperature. This paper presents use of Taguchi Grey Relational Analyses (GRA) for optimization of Al/SiCp/10p (220 and 600 mesh) MMCs produced by stir casting. Experiments are performed using L16 orthogonal array by using hot machining technique. The significance of the process parameters on surface integrity has been evaluated quantitatively by the analysis of variance (ANOVA) and AOM plots.

3. Experimental details

In the current work, Stir casting method was used to prepare MMCs which is liquid metallurgy technique and the most economical of all the available routes for metal matrix composite production. Al–SiC MMC work piece specimens having aluminum alloy 2024 as the matrix and containing 10 % weight fraction of silicon carbide particles of both finer and coarser reinforcements of size 15µm (600 mesh size) and 65 µm (220 mesh size). MMCs of SiC reinforcement of two mesh size i.e. 220 and 600 were used (Al/SiC/10p/220, Al/SiC/10p/600). Figure 1 shows the Photo micrographic image of Al-SiCp.

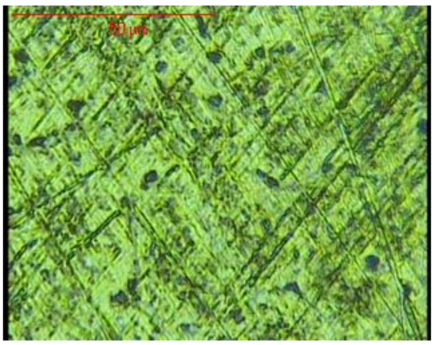


Figure 1. Photo micrographic image of Al-SiCp.

The size of specimen was 60 mm in length and 22 mm in diameter. The turning length was 15 mm. The experimental studies were carried out on a MTAB MAXTURN CNC turning center. All the experiments were conducted under resistance preheating conditions (RT, 60°C, 80°C, and 100°C). Sandvik make PVD coated CNMG 12 04 08 insert was used for experimentation purpose. A Taguchi method-based design of experiment involving L16 orthogonal array was chosen for this experimentation. Accordingly, 16 experiments were performed on each composite material; hence total of 32 experiments were performed. The process parameters and the levels of each parameter are given in table 1. For every experimental run, a fresh insert cutting edge was used for making suitable analysis and comparison. During turning experiments, force components were measured using a 3-component piezo-electric force dynamometer (Kistler make, model 9257). The dynamometer was set on the turret face of the turning centre using a fixture. A photograph of the force measurement system used during machining is shown in figure 2. The surface roughness was measured using a Mitutoyo SJ-201 with cut-off length of 0.8 mm. The surface roughness was measured at three points on the specimen and average of that was taken as final roughness value. Tool wear measurements were carried out by using Mitutoyo make tool wear microscope to determine the degree of flank wear on worn cutting tool after each test.

Table 1. Machining parameters and their levels.

	Levels			
Process parameters	1	2	3	4
Cutting speed (m/min)	25	50	75	100
Feed (mm/rev)	0.05	0.1	0.15	0.2
Depth of cut (mm)	0.4	0.6	0.8	1
Preheating temp.(^{0}C)	RT	60	80	100

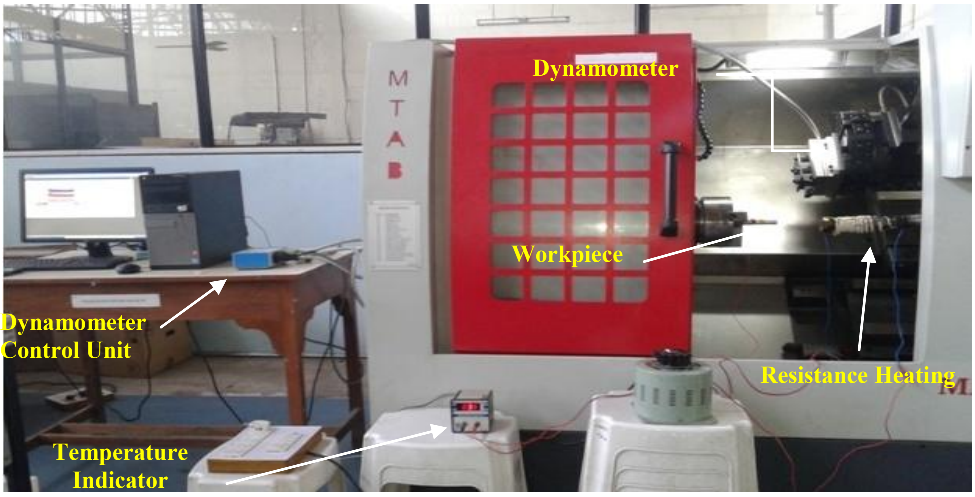


Figure 2. Experimental setup.

4. Grey Relational Analysis (GRA)

In grey relational analysis, black represents having no information and white represents having all information. A grey system has a level of information between black and white. In other words, in a grey system, some information is known and some information is unknown. In a white system, the relationships among factors in the system are certain; in a grey system, the relationships are uncertain [17]. The optimization of multiple performance characteristics using GRA include following steps:

- Identification of performance characteristics and process parameters to be evaluated.
- Selection of process parameter levels.
- Selection of orthogonal array and assign the process parameters to the array.
- Experimentation as per the orthogonal array.
- Normalization of the experimental results
- Determination of deviation sequences.

- Determination of grey relational coefficient (GRC).
- Determination of grey relational grade (GRG).
- Determination of optimal parameters.
- Prediction of GRG under optimal parameters

4.1 Normalization of the experimental results

In GRA, data processing is first performed in order to normalize the raw data for analysis. Normalization in the range between zero and unity is also called as the grey relational generation. In this case machining forces, surface roughness and flank wear are response variables said to be better if their values are smaller (i.e. smaller is better). Hence that experiment will be ranked one which will have smaller values of machining forces; surface roughness and flank wear response variables. The larger value of normalized results indicates the better performance characteristic and the best normalized result will be equal to one. In this investigation "smaller-the-better" criterion is used for normalization of all the responses as given by equation 1.

$$x_i^* (k) = \frac{\max x_i^{(o)}(k) - x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)} \quad (1)$$

4.2 Determination of deviation sequence

The deviation sequence $\Delta 0_i\ (k)$ is the absolute difference between the reference sequence $x_0{}^*(k)$ and the comparability sequence $x_i{}^*(k)$after normalization. It is determined using equation 2.

$$\Delta 0_i\ (k) = |x_0^*(k) - x_i^*(k)| \quad (2)$$

4.3 Determination of Grey Relational Coefficient

GRC for all the sequences expresses the relationship between the ideal (best) and actual normalized result. If the two sequences agree at all points, then their grey relational coefficient is 1. The grey relational coefficient $\gamma(x_0(k), x_i(k))$ can be expressed by equation 3 [7].

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{min} + \zeta\ \Delta_{max}}{\Delta_{0i}\ (k) + \zeta\ \Delta_{max}} \quad (3)$$

Where, Δ min is the smallest value of $\Delta 0_i\ (k) = min\ _i\ min\ _k |x_0{}^*(k) - x_i{}^*(k)|$ and Δ max is the largest value of $\Delta 0_i\ (k) = max\ _i\ max\ _k |x_0{}^*(k) - x_i{}^*(k)|$, $x_0{}^*(k)$ is the ideal normalized result, $x_i{}^*(k)$ is the normalized comparability sequence, and ζ is the distinguishing coefficient. The value of ζ can be adjusted with the systematic actual need and defined in the range between 0 and 1; here it is taken as 0.5 [7].

4.4 Determination of Grey Relational Grade

The overall evaluation of the multiple performance characteristics is based on the grey relational grade. The grey relational grade is an average sum of the grey relational coefficients which is calculated using equation 4 [6].

$$\gamma\ (x_{o,}x_i) = \frac{1}{m} \sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \quad (4)$$

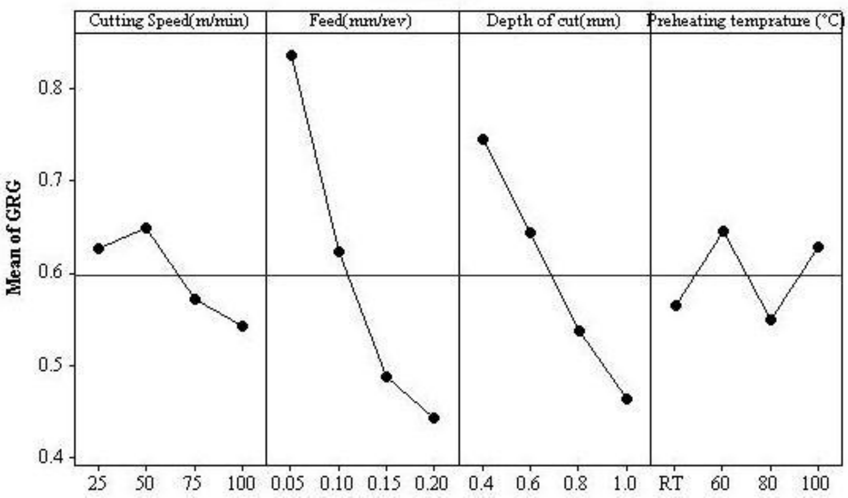
Where, γ(x0, xi) is GRG for the j^{th} experiment and m the number of performance characteristics. The order of the experiments according to the magnitude of GRG is depicted in table 2.

Table 2. Grey relational grades and their orders for Al/SiC/10p/220 and Al/SiC/10p/600.

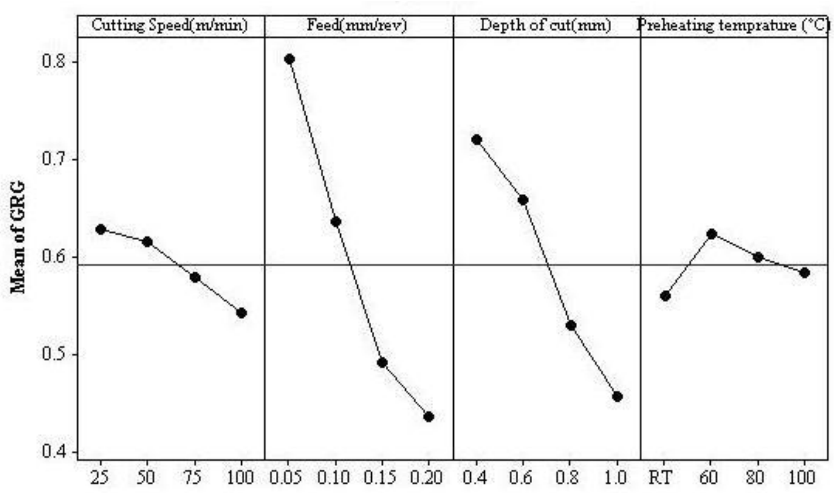
Orthogonal array No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Preheating temperature (^{0}C)	Al/SiC/10p/220 GRG	Al/SiC/10p/220 Order	Al/SiC/10p/600 GRG	Al/SiC/10p/600 Order
1	25	0.05	0.4	RT	1	1	0.901	2
2	25	0.1	0.6	60	0.75	5	0.8	3
3	25	0.15	0.8	80	0.42	14	0.468	10
4	25	0.2	1	100	0.34	16	0.349	16
5	50	0.05	0.6	80	0.85	3	0.92	1
6	50	0.1	0.4	100	0.87	2	0.775	4
7	50	0.15	1	RT	0.37	15	0.377	15
8	50	0.2	0.8	60	0.5	9	0.393	14
9	75	0.05	0.8	100	0.78	4	0.751	5
10	75	0.1	1	80	0.44	13	0.46	12
11	75	0.15	0.4	60	0.63	7	0.659	6
12	75	0.2	0.6	RT	0.45	11	0.453	13
13	100	0.05	1	60	0.71	6	0.643	7
14	100	0.1	0.8	RT	0.44	12	0.511	9
15	100	0.15	0.6	100	0.53	8	0.465	11
16	100	0.2	0.4	80	0.49	10	0.552	8

4.5 Determination of optimal parameters

The grey relational grade calculated for each sequence is taken as a response for the further analysis. The larger-the-better quality characteristic was used for analyzing the GRG, since a larger value indicates the better performance of the process. The GRG obtained is analyzed using ANOVA and analysis of mean (AOM) plots. ANOVA is used to identify the statistical significance of individual parameter on a particular response. The response table of Taguchi method was employed here to calculate the average grey relational grade for each factor level. In this, the grouping of the grey relational grades was done initially by the factor level for each column in the orthogonal array and then by averaging them. The average sum of these values will be the corresponding response grade. The AOM plots for GRG are shown in figures 3(a-b), and mean response table for the overall GRG is presented in table 3 and the corresponding F and P values of ANOVA for GRG are given in table 4.



(a) Al/SiC/10p/220



(b) Al/SiC/10p/600

Figure 3. AOM plots for GRG of hot machined Al/SiCp MMCs.

Table 3. Mean response table for grey relational grades.

Level	(a) Al/SiC/10p/220			
	CS (m/mi	FR (mm/rev	DOC (mm)	PT(^{0}C)
1	0.626	0.8361	0.745	0.565
2	0.649	0.6236	0.644	0.646
3	0.572	0.4874	0.537	0.550
4	0.543	0.4438	0.464	0.628
Max-Min	0.106	0.3923	0.281	0.095
Ranking	3	1	2	4
	Total mean value of GRG is 0.5978			

Level	(b) Al/SiC/10p/600			
	CS (m/min)	FR (mm/rev)	DOC (mm)	PT (^{0}C)
1	0.6293	0.8038	0.721	0.56
2	0.6162	0.6364	0.659	0.62
3	0.5738	0.4921	0.530	0.59
4	0.5428	0.4366	0.457	0.58
Max-Min	0.0865	0.3673	0.264	0.06
Ranking	3	1	2	4
	Total mean value of GRG is 0.5922			

(CS: cutting speed, FR: feed rate, DOC: depth of cut, PT: Preheating temperature)

From figure 3 it is clear that as cutting speed, feed and depth of cut increases, the corresponding machining forces and flank wear grey relational grade rank increases. It is because due to an increase in the area of undeformed chip cross-section, given by: $A_c = feed \times depth\ of\ cut$. Similar results are obtained from classical relation of surface roughness, feed rate and tool nose radius given by: $Ra = f^2 / 32r$. But as pre heating temperature increases up to 60°C grey relational grade decreases due annealing of the work may causing softening close to the surface. Further increase in preheating temperature grey relational grade rank increases due to excessive thermal softening of matrix material in composites (causes formation of built-up-edge on tool rake surface refer SEM photograph in figure 4) which deteriorates the quality of the machined surface, gives higher magnitude of machining forces, surface roughness and flank wear. Similar results were reported by Dabade and Joshi [3]. Results of ANOVA in tables 4 indicate that feed rate and depth of cut are the statistically significant turning process parameters that affect the response variables chosen for this experiments or overall performance characteristics. These are, therefore, the noticeable parameters to improve the surface quality/integrity on Al/SiCp composites. From the AOM plots of GRG in figures 3, the optimal parametric combinations are determined, refer table 5

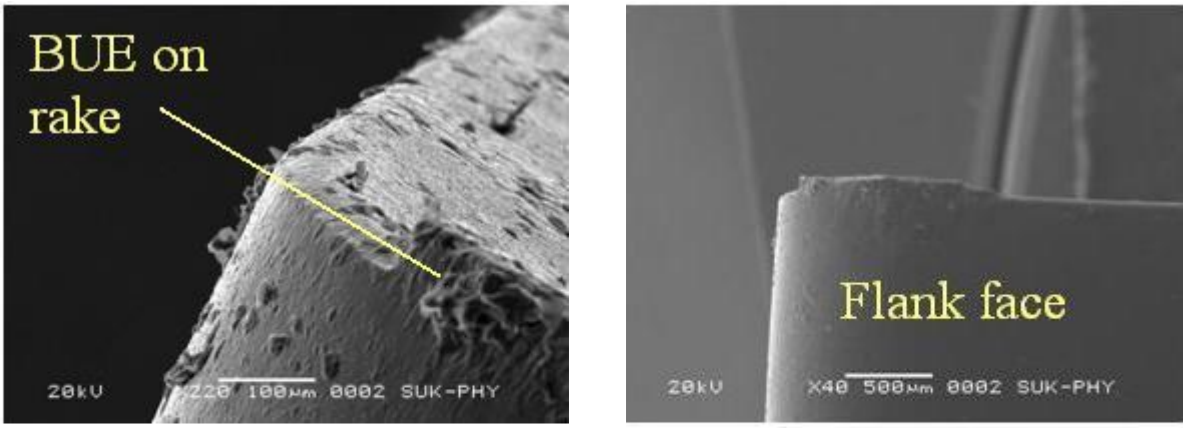


Figure 4. SEM of built up edge on tool rake surface formed: Al/SiC/10p/600 (cutting speed=75 m/min, feed=0.10 mm/rev, depth of cut= 1.0, preheating temperature= 80°C).

Table 4. Summarized F and P values of ANOVA for GRG.

Parameter	DOF	Al/SiC/10p/220		Al/SiC/10p/600	
		F	P	F	P
Cutting speed (m/min)	3	4.53	0.123	1.77	0.326
Feed (mm/rev)	3	59.87	**0.004**	31.58	**0.009**
Depth of cut(mm)	3	29.18	**0.01**	16.9	**0.022**
Preheating temperature (°C.)	3	4.2	0.135	0.83	0.56
		R^2 = 98.99%		R^2 = 98.08%	
		R^2 (adj) = 94.94%		R^2(adj) = 90.40%	

Table 5. Multiple-performance optimized conditions using grey relational analysis.

MMC material	Cutting speed (m/min)	Feed	Depth of cut	Preheating temp. (°C)
Al/SiC/10p/220	50	0.05	0.4	60
Al/SiC/10p/600	25	0.05	0.4	60

4.6 Prediction of grey relational grade under optimum parameters

After evaluating the optimal parameter settings, the next step is to predict and verify the improvement of quality characteristics using the optimal parametric combination. The predicted grey relational grade by using the optimal level of the machining parameters can be calculated as

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{0}(\gamma^{-} - \gamma_m) \qquad (5)$$

Where γ_m is the total mean grey relational grade, γ^{-} is the mean grey relational grade at the optimal level, and q is the number of the parameters that affect the quality characteristics. The predicted or estimated grey relational grade (optimal) is equal to the mean grey relational grade plus the summation of the difference between the overall mean grey relational grade and the mean grey relational grade for each of the significant factors at optimal level. The results of the confirmation experiments using the optimal machining parameters are presented in tables 6. It is found that there is a good agreement between predicted and experimental GRG. This ensures the usefulness of grey relational approach in relation to product/process optimization, where multiple quality criteria have to be fulfilled simultaneously.

Table 6. Results of machining performance using the initial and optimal machining parameters.

Al/SiC/10p/220	**Initial parameter setting**	**Optimum parameter level**	
		Prediction	**Expt.**
Setting level	$A_2B_2C_1D_4$	$A_2B_1C_1D_2$	$A_2B_1C_1D_2$
Cutting force (N)	38.81		28
Radial force (N)	12.79		21
Feed force (N)	24.74		12
Surface roughness (µm)	1.021		0.583
Flank wear (mm)	0.100		0.150
GRG	0.8666	0.8634	0.9444
Improvement in grey relation grade = 0.0778			

Al/SiC/10p/600	**Initial parameter setting**	**Optimum parameter level**	
		Prediction	**Expt.**
Setting level	$A_2B_1C_2D_3$	$A_1B_1C_1D_2$	$A_1B_1C_1D_2$
Cutting force (N)	28.74		25.50
Radial force (N)	10.08		16.10
Feed force (N)	17.22		08.55
Surface roughness (µm)	0.87		0.90
Flank wear (mm)	0.020		0.015
GRG	0.8969	0.8860	0.9111
Improvement in grey relation grade = 0.0142			

5.Conclusion

- During this work, Al/SiCp/10p/220 and Al/SiCp/10p/600 metal matrix composites are prepared using stir casting method to see the effect of preheating prior to machining. Experiments are performed using L16 orthogonal array as per Taguchi method for both types of metal matrix composites.
- GRA is an effective and efficient method for multi response optimisation. The process parameters for machining of metal matrix composites are optimised with L16 orthogonal array and GRA.
- From analysis of variances, it is found that feed rate and depth of cut is the most significant parameters where as cutting speed and preheating temperature are observed as least influencing parameters.
- The SEM analysis of the flank wear shows generation of built-up-edge due to excessive thermal softening at higher temperature range 80°C and 100°C which deteriorates the surface quality of Al/SiCp composites.
- The best optimized combination of machining conditions to enhance the surface quality/integrity on machined surfaces of Al/SiCp/10p/220 composite is use of $\mathbf{A_2B_1C_1D_2}$ and $\mathbf{A_1B_1C_1D_2}$ **for** Al/SiCp/10p/600 composites to minimize machining forces, surface roughness and tool flank wear.

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