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A precursor experimental study on corrosion resistant AA6061-SiC_p MMC prepared through PM process using ANOVA and Grey relational analysis - A novel approach

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Abstract

The present investigation focuses on finding the optimal powder metallurgical process parameters to prepare corrosion resistant AA6061-SiC_p metal matrix composite. AA6061 alloy powder was homogenously mixed with various weight percentages of SiC_p (5-15 wt %) and compacted at a pressure ranging from 350 to 550 MPa. The green compacts were sintered at temperatures between 400°C and 600°C with sintering time ranging from 1 to 3 hours. Taguchi's L27 orthogonal array of experimental design was used. The effect of processing parameters such as reinforcement percentage, compacting pressure, sintering temperature and sintering time on the performance characteristics of sintered density and micro hardness were studied. Optimal levels of parameters were identified using grey relational analysis, and significant parameter was determined by analysis of variance. Experimental results

indicate that multi-response characteristics such as density and micro hardness can be improved effectively through this approach.

Keywords: Powder metallurgy; Metal matrix composites; Corrosion; Multi-response optimization; ANOVA; Grey relational analysis.

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1. Introduction

Metal matrix composites (MMCs) have progressed as a grandiose material, which are widely used in current decade. Metal matrix composites have become necessary in various engineering applications, such as aerospace, marine, automobile, and applications because of their low density, specific strength and stiffness [1,2]. Nikhilesh Chawla and his co worker [3] investigated particulate reinforced aluminium metal matrix composite is one of the important composites among the metal matrix composites due to their low cost when compared to long fibre reinforced MMCs and due to their better properties than those of monolithic alloys Though lot of research and development has taken place in the filed of metal matrix composites by liquid processing the growth in composite manufacturing by powder metallurgy processing has not grown to that extent. In powder metallurgy technique, the reinforcements have been homogeneously mixed in the matrix. Functional performance and mass production was enhanced on account of homogeneity as reported by J.M.Torralbo et al

[4]. have studied the sintering process for aluminium-based composite in nitrogen atmosphere However, vacuum atmosphere was also used for sintering because sintering in air leads to oxidation, which reduces the strength of the composite [5, 6]. Powder processing of Aluminium matrix composites has the advantage over other processes due to its low tool consumption as reported by S.Muller et al [7]. It has already established that PM process is an effective from the point cost and power it is widely used to manufacture intricate mass production parts. The current study aims to use grey relational analysis for finding the optimum levels of parameters like reinforcement percentage, compacting pressure, sintering temperature and sintering time for maximum sintered density and micro hardness as first time in powder metallurgy processing of Al-SiCp MMC. These two properties are essential for understating from the point of enhancement of strength and wear resistance of MMCs and facilitate applications for a wide spectrum of industries.

2. Experimental details

2.1. Materials

In this investigation a gas atomized Aluminium alloy powder as per AA6061 (average size of 35 microns) and SiC particles (average size of 35 microns) were used for production of Al-SiCp metal matrix composites (MMCs). The powders were mixed to achieve uniform distribution and then weighed with reinforcement percentage by weight of 5%, 10% and 15% of matrix alloy powder. The powder mixture was

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mechanically alloyed in a ball mill in 15 hrs and with ball to powder ratio of 1:10. The mixed powders were compacted in a universal testing machine of 60T capacity uniaxially with hardened steel die and punch. The steel die wall and the punch were uniformly coated with Zinc stearate along with acetone to reduce wall friction. No lubricant was added with powders to avoid reduction in sintered density. Sintering was carried out in muffle furnace and under neutral atmosphere with nitrogen of 99 % purity. Sintering temperatures employed are 400°C, 500°C and 600°C with sintering time from 1hr to 3 hr. Sintered density was measured as per ASTM B962 - 08. Measuring hardness of composites was carried out using Vicker's micro hardness tester. Figure-1 shows the micrograph of the sintered Al-SiCp MMC sample work piece. The uniform distribution of SiCp in these com*posites* was clearly visible.

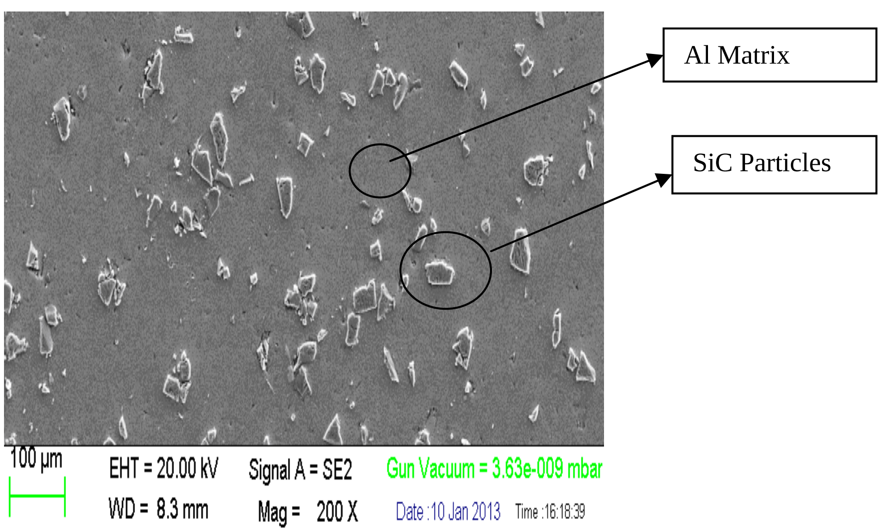

Fig. 1. Micrograph of Sintered Al-SiC_p MMC Sample

2.2. Methods

In recent years, Taguchi method is used because of its economical and effective technique for improving productivity as well as to get robust design in order to manufacture high quality products rapidly . A special design of orthogonal arrays for four factors at three levels can be applied to study the entire parameters with minimal experiment requirements [15]. The process parameters and levels are listed in Table 1. Each of the 27 trials / process designs was replicated twice and the average response values were used for the analysis. Table 2 showed the experimental arrangement and test results.

Table 1 Process parameters and their levels

Parameter	Unit	Level	Level	Level
% Reinforcement	Wt	5	10	15
Compacting	MPa	350	450	550
Sintering	° C	400	500	600
Sintering Time	Hrs	1	2	3

3. Determination of optimal machining parameters

3.1. Grey Relational Analysis (GRA)

Preliminary trials were conducted in order to normalize the raw data for the analysis . A linear normalization of the experimental findings for sintered density and micro hardness were performed in the range between zero and one (Table 2) , which is also called grey relational generation. The normalized experimental results X_{ij} can be expressed as:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \quad (1)$$

Y_{ij} for the i^{th} experimental results in the j^{th} experiment. Table 3 shows the normalized results for sintered density and micro hardness. Basically, larger normalized results correspond to the improved performance of MMC's and the best-normalized results should be equal to unity.

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Table 2 Experimental layout using an L27 orthogonal array and corresponding results

Exp No.	Process parameter(s)				Mean value of response(s)	
	Reinforcement %	Compaction Pressure	Sintering Temperature	Sintering Time	Density (gms/cc)	Micro hardness ($HV_{0.5}$)
1	5	350	400	1	2.540	51.31
2	10	450	500	2	2.449	47.37
3	15	550	600	3	2.443	56.88
4	5	450	500	2	2.168	49.27
5	10	550	600	3	2.421	41.50
6	15	350	400	1	2.284	47.44
7	5	550	600	3	2.482	62.05
8	10	350	400	1	2.205	36.00
9	15	450	500	2	2.331	52.70
10	15	350	500	3	2.130	38.84
11	5	450	600	1	2.310	46.05
12	10	550	400	2	2.662	65.98
13	15	450	600	1	2.475	46.90
14	5	550	400	2	2.508	65.40
15	10	350	500	3	2.255	39.70
16	15	550	400	2	2.486	56.01
17	5	350	500	3	2.332	40.70
18	10	450	600	1	2.431	57.02
19	10	350	600	2	2.211	42.50
20	15	450	400	3	2.432	56.08
21	5	550	500	1	2.497	59.40
22	10	450	400	3	2.585	50.40
23	15	550	500	1	2.563	61.64
24	5	350	600	2	2.277	38.67
25	10	550	500	1	2.563	67.31
26	15	350	600	2	2.288	31.67
27	5	450	400	3	2.453	54.94

Also, the grey relational coefficient was calculated to express the relationship between the ideal (best) and the actual normalized experimental results. The grey relational coefficient ξ_{ij} can be written as:

$$\xi_{ij} = \frac{\min_i \min_j \left|x_i^o - x_{ij}\right| + \xi \max_i \max_j \left|x_i^o - x_{ij}\right|}{\left|x_i^o - x_{ij}\right| + \xi \max_i \max_j \left|x_i^o - x_{ij}\right|}$$

(2)

Where x_i^0 is the ideal normalized results for the i^{th} performance characteristics and ξ is the distinguishing coefficient which is defined in the range $0 \leq \xi \leq 1$. In the present study the value of ξ is assumed as 0.5 to give equal weightage for the responses.

The grey relational grade is obtained after computing the average grey relational coefficient corresponding to each performance characteristics. The overall evaluation of the performance response is based on the grey relational grade, that is:

(3)

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m}\xi_{ij}$$

Where γ_j is the grey relational grade for the j^{th} experiment and m is the number of performance characteristics.

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Table 3. Evaluated Grey relational coefficient and Grade for 27 groups

Exp. No	Normalized Values		Grey relational Coefficients		Grey relational grade	
	Density	Micro Hardness	Density	Micro Hardness	Grey grade	Rank
1	0.7706	0.5511	0.6855	0.5269	0.6062	9
2	0.5997	0.4405	0.5554	0.4719	0.5136	15
3	0.5884	0.7074	0.5485	0.6308	0.5896	10
4	0.0710	0.4938	0.3499	0.4969	0.4234	21
5	0.5465	0.2758	0.5244	0.4084	0.4664	17
6	0.2902	0.4425	0.4133	0.4728	0.4430	19
7	0.6622	0.8524	0.5968	0.7721	0.6845	5
8	0.1417	0.3740	0.3681	0.4441	0.4061	22
9	0.3786	0.5901	0.4459	0.5495	0.4977	16
10	0.0000	0.2012	0.3333	0.3850	0.3591	27
11	0.3383	0.4035	0.4304	0.4560	0.4432	18
12	1.0000	0.9627	1.0000	0.9305	0.9653	1
13	0.6485	0.4273	0.5872	0.4661	0.5267	14
14	0.7105	0.9464	0.6333	0.9032	0.7683	3
15	0.2350	0.2253	0.3952	0.3923	0.3937	25
16	0.6692	0.6829	0.6018	0.6120	0.6069	8
17	0.3797	0.2534	0.4463	0.4011	0.4237	20
18	0.5658	0.7113	0.5352	0.6339	0.5846	11
19	0.1523	0.3039	0.3710	0.4180	0.3945	24
20	0.5677	0.6849	0.5363	0.6134	0.5749	13
21	0.6898	0.7781	0.6172	0.6926	0.6549	6
22	0.8553	0.5255	0.7755	0.5131	0.6443	7
23	0.8139	0.8409	0.7288	0.7586	0.7437	4
24	0.2763	0.1964	0.4086	0.3836	0.3961	23
25	0.8139	1.0000	0.7288	1.0000	0.8644	2
26	0.2970	0.0000	0.4156	0.3333	0.3745	26
27	0.6071	0.6529	0.5600	0.5903	0.5751	12

Table 3 shows the grey relational grade for each experiment using L27 orthogonal array. The higher grey relational grade implies the better product quality; therefore, on the basis of grey relational grade, the process parameters influence can be predicted and the suitable values for each influencing factor may also be estimated.. The mean of the grey relational grade for each level of the parameter is summarized and shown in Table 4. In addition, the total mean of the grey relational grade for the 27 experiments is also calculated and listed in Table 4. The grey relational grade graph for the levels of the processing parameters (fig.2). Basically, the larger the grey relational grade, the better is the performance response.

Table 4 Response table for the grey relational grade

Processing Parameter	Grey relational grade				
	Level 1	Level 2	Level 3	Max-Min	Rank
% Reinforcement	0.5528	0.5814*	0.5240	0.0574	4
Compacting	0.4219	0.5315	0.7049*	0.2830	1
Sintering	0.6211*	0.5416	0.4956	0.1256	2
Sintering Time	0.5859*	0.5489	0.5235	0.0624	3
Total Mean Value of the Grey Relational Grade = 0.5528					

3.2. Analysis of Variance

The purpose of the variation analysis is to study the influence of processing factors that contribute the important characteristics [19]. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each machining parameter and the error. First, the total sum of the squared deviations SS_T from the total mean of the grey relational grade γ_m can be calculated as:

$$SS_T = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2 \tag{4}$$

Where p is the number of experiments in the orthogonal array and γ_j is the mean grey relational grade for the j^{th} experiment.

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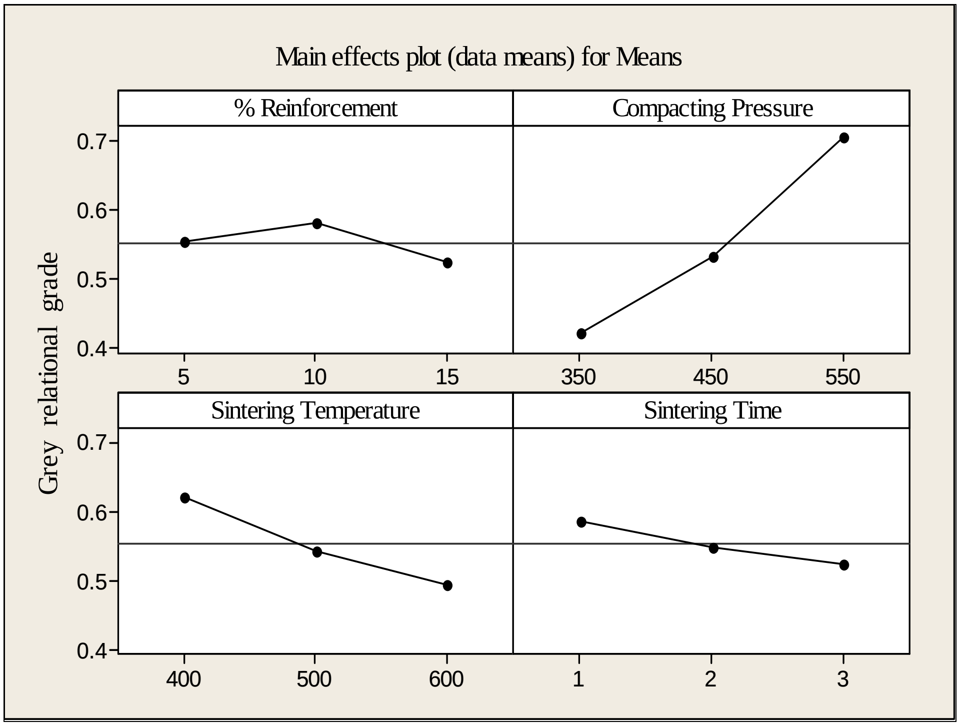

Fig. 2. Main effects plot for Grey relational grade

The cumulative addition of the square of the deviation SS_T is classified into two factors Viz., consolidated processing parameter and its interaction effects and the square of the error . The actual part of each of the processing parameter in the total sum of the squared deviations SS_T may be utilized to assess the contribution of the processing parameter deviation results of this analysis. F- test [20] can also be used to determine which machining parameters have a significant effect on the performance characteristic. Table 7 shows the results of ANOVA analysis[16-19].

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Table 5 Results of the analysis of variance

Source	df	SS	MS	F	%
% Reinforcement	2	0.01484	0.0074	0.84	2.35
Compacting Pressure	2	0.3664	0.1832	20.66	58.05
Sintering Temperature	2	0.0726	0.0363	4.09	11.51
Sintering Time	2	0.0177	0.0088	1.00	2.80
Error	18	0.1596	0.0088		25.28
Total	26	0.6312			100.0

Results of analysis of variance (Table – 7) indicate that depth of cut is the most significant machining parameter for affecting the multiple performance characteristics (32.23%).

3.3. Confirmation Experiment

Once the optimal level of processing parameters is selected the prediction and verification of predicted parameter level is carried out and the improvement of the performance characteristics using the optimal level of the processing parameters is evaluated. The estimated grey relational grade $\hat{\gamma}$ using the optimum level of the machining parameters can be calculated as

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

Where γ_m is the total mean of the grey relational grade, $\bar{\gamma}_j$ is the mean of the grey relational grade at the optimum level and q is the number of processing parameters that significantly affects the multiple performance characteristics.

Based on Eq (5) the estimated grey relational grade using the optimal processing parameters can then be obtained. The results of the confirmation experiment using the optimal processing parameters sintered density was 2.692 and the microhardness was 71.98 $HV_{0.5}$ and the grey relational grade value is 0.8611 which is 3.12% higher than the predicted mean value. It is clearly shown that multiple performance characteristics in the Al-SiC are greatly improved through this study.

The contour plots obtained using the experimental data presented in fig 3 and 4 also inline with the grey analysis that the compacting pressure and sintering temperature which are significant process parameters yield maximum sintered density and microhardness. The results are have given understanding that higher reinforcement percentage and higher sintering temperature do not give maximum sintered density and microhardness, This is on account of the fact that as the reinforcement percentage increases compressibility is becoming poor and also higher sintering temperature combined with higher reinforcement leads reduction in inter particle distance of SiC which leads to poor bonding and probability of defect formation and increased porosity which hampers achieving the maximum sintered density and microhardness.[20,21]

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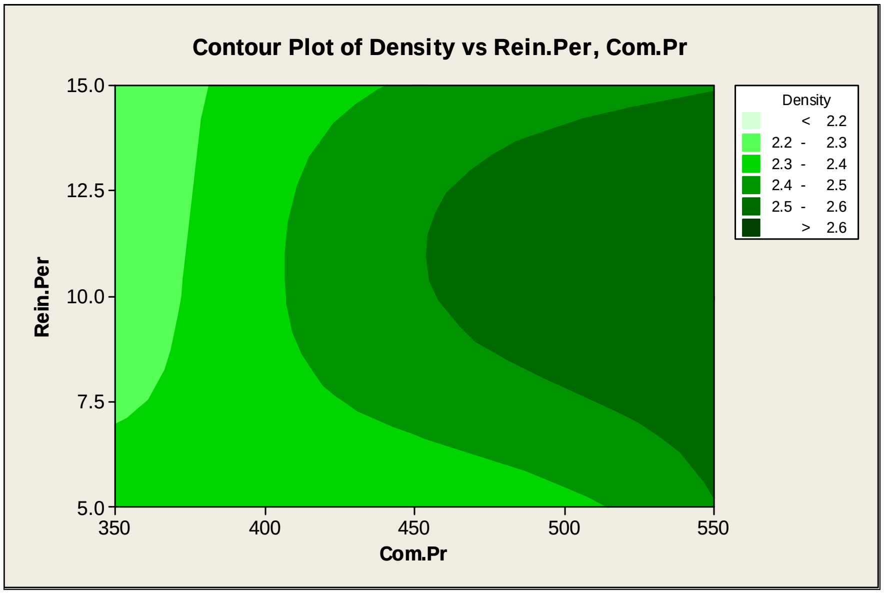

Fig.3. Contour plot for Density Vs Reinforcement and compacting pressure.

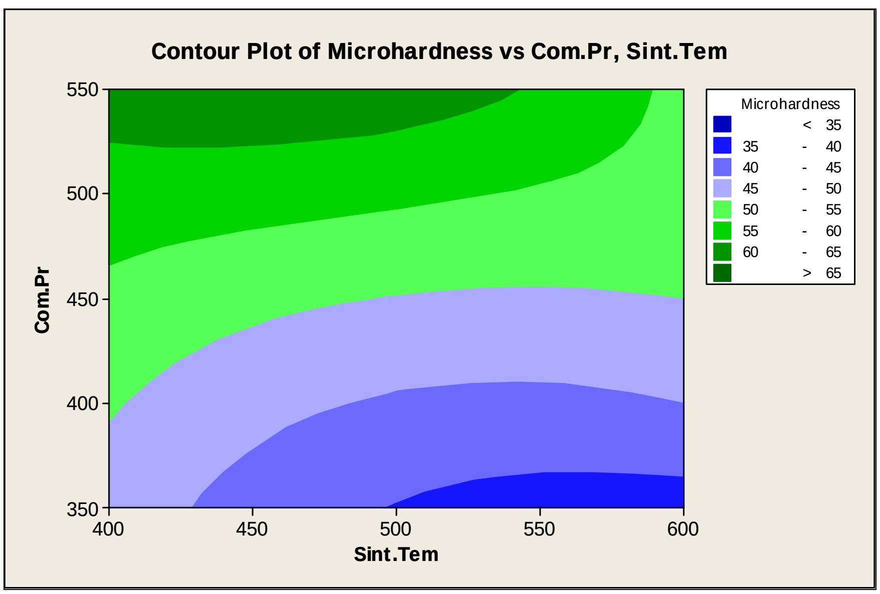

Fig.4 Contour Plot for Microhardness Vs compacting pressure and sintered temperature

4. Conclusion

A precursor experimental analysis for obtaining corrosion resistant composites were tried out successfully using grey relational analysis for developing metal matrix composites by powder processing route. It has been also justified that 10% reinforcement with 550 MPa sintered at 400°C for one hour resulted in maximizing the sintered density and microhardness. This encouraged applying the grey concept for optimizing multi response processing with multiple factors. ANOVA also showed that compacting pressure, sintering temperature, sintering time and reinforcement are impacting the objective achieving the sintered density and microhardness in the order. This justified that with optimization of the processing parameters yielded the desired results for obtaining corrosion resistant Al-SiC composites.

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