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Estimation of Surface Roughness of Aluminum Reinforced Metal Matrix Composites

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Abstract: There is a strong agitation from rocket designer for a highly reinforced metal matrix composites for rocket chamber to curtail the effect of high temperature and pressure from gaseous product of combustion process. This study has been designed to evaluate the surface roughness of an aluminum reinforced metal matrix composites produced by stir casting techniques at constant cutting speed of 1000 rpm, three (3) different feed rates at various aluminum weight ratio. Response surface methodology was adopted to formulate a surface roughness model in terms of metal matrix constituents such as aluminum, barite and zircon under three (3) different feed rate. The model adequacy was verified using analysis of variance. Also, the approach was used to optimize the effect of reinforced materials on surface roughness of the matrix composites. The increase in weight ratio of aluminum matrix reduces the surface roughness and vice versa. However, increase in barite, zircon weight ratios and feed rate increase the surface roughness. The optimum matrix chemical composition ratios of 0.9310, 0.0296, and 0.0394 for aluminum, barite, and zircon respectively with optimal desirability index of 0.903 shows the validity of the design. The F-values obtained at 95% confidence interval revealed that the selected model adequately represent the data for the matrix composites. Therefore, the study confirm the effectiveness of Response Surface Methodology as a tool in predicting surface roughness and provide materials with enhanced mechanical properties.

Keywords: Surface Roughness, Metal Matrix, Composites, Feed Rate, Stir Casting

1. Introduction

In rocketry development, the temperature induced by the combustion process are of the order of 1000°C to 3000°C. However, when metals are continuously and plastically deformed at high temperature, both work hardening and annealing take place simultaneously, and creep in metals occur [1, 10]. High temperature allows metal to deform more easily since atoms can move more freely, hence, greater movement of dislocations. Grain-boundary movement are also possible at higher temperatures [2]. Therefore, engineering alloys utilized at high temperatures is susceptible to creep as well as recrystallization and grain coarsening. In the case of age-hardened metals, over-ageing is feasible, which results in reduced hardness and strength due to the coarsening of the second phase precipitates. Furthermore, metals generally oxidize at high temperatures, thus experiencing creep problems [3].

Generally, The properties of a metal matrix such as high strength to-weight ratio, plasticity, capacity for crucial shape forming along with their ease for joining and good corrosion resistance have become increasingly focused for versatile applications such as design of armour structures, rocket, missile casing, light-weight defense vehicle, cars, and marine structures [4]. Also, varieties of metal matrix composites have been developed by manipulating the compositions and tailoring the fabrication technology to combats the inherent problem [5]. The requirements for producing high-quality matrix composites are inevitably associated with precision metal alloy design, innovative technology development in processing and enhancement of mechanical properties [9].

The development of an aluminum reinforced metal matrix composite is therefore a way to combat these problems and provide materials with enhanced mechanical properties. This is for example, the development of aluminum–barite–zircon matrix composites for aerospace and high-performance applications. Metal matrix composites (MMC) are new class of engineering materials which find its application in automotive, aircraft and defense mainly because of its improved property than alloys. There various matrix and reinforcement available out of which aluminum reinforced with ceramics particles finds to be important [12]. The particles are harder which improve the mechanical properties of the composites. The hard reinforcement makes the composites difficult to machine and get into required shape. Hence, the particles makes the surface rough and increases tools wear. This discourage the use of metal matrix composite in many applications [13]. In order to overcome the difficulty, some amount of soft reinforcement material such as Barite, Zircon are added to form a hybrid MMC. The aluminum-barite-zircon MMC is easier to machine and shape into required specification [11].

Aluminum offers weight saving because of its light weight. The softness of this metal can restrict its use for the engineering purposes [6]. Hence, the strengthening of this metal is required for its use in cars, light-weight armour vehicles, rockets, missiles, and aircraft structures in civil and defense sectors, which demand high strength-to-weight ratio [7]. The strengthening of Aluminum (Al) is principally done by alloying it with elements like Cu, Zn, Mn, Mg, Si, and Li and processing its alloys [8]. The quality of the surface has a very important role in the performance of face milling because a good quality machined surface significantly improves fatigue strength, corrosion resistance and creep life.

Moreover, surface roughness is an important factor in determining the quality of the composites products [14]. The average surface roughness (R_a) is define arithmetically as the departure of profile from centerline along the sampling length in equation (1);

$$R_a = \frac{1}{l}\int \left|(y)\right| x \qquad (1)$$

Where l is the sampling length and y, x are the coordinate of profile curve. The basic objective of rocket chamber development is to produce combustion chamber of high efficiency for containing effects of gaseous product of high temperature and pressure. Metal matrix composite reinforcement is being widely employed for casting aerospace motor casing. In order to improve the rocket chamber capacity, the optimum metrix composite constituents must be achieved. Optimum composite constituents are of great concern in rocketry development, where curtailing the effects of gaseous product from combustion process is of great concern. It is therefore difficult to utilize the highest performance of the composite constituents owing to their many adjustable composite parameters [15].

There were various efforts from different researchers to estimate surface roughness for aluminum reinforced metal matrix composites. Surface roughness of Al alloy is less when compared with Al alloy composite during turning by carbide [16]. The surface roughness value of the K10 was higher than that of the TP30 tool. It increases with an increase in the cutting speed while it decreases with increasing the size and volume fraction of the particles for both tools in all cutting conditions [17]. Also, the feed rate is the one of main factor that influences the surface roughness in machining the matrix composites [18]. Lou *et al*. (1999), investigated the effect of spindle feed, feed rate and depth of cut on the surface roughness of the end milling process. The in-process Surface roughness recognition and a neural fussy system were employed to predict the work piece surface roughness [19]. However, the volume fraction of SiC particles present in the aluminum alloy matrix has a significant effect on the milling characteristics, increasing tool wear and decreasing surface roughness [20]. Ramulu *et al*. (2003), performed an experiment using PCD drills aluminum oxide particles reinforced aluminum-based metal matrix composites. The Response surface methodology was employed to analyze data obtained and formulated regression models. They inferred that drilling forces and average surface roughness values were greatly influenced by the feed rate than the cutting speed [21].

Despite concerted efforts from many researchers on Aluminum reinforced metal matrix composite to enhance its performance, there is little or no information on the casting of Aluminum-Barite-Zircon reinforced composites [22]. This study is being design to investigate the influence of mass fraction and feed rate on the surface roughness in stir casting of aluminum-Barite-Zircon reinforced hybrid composites using Response surface methodology.

2. Materials and Method

2.1. Design Analysis

In this study, Design Expert (6.0.8) software was adopted to design the experiment with the aim of optimizing the response of the metal matrix constituent involving in the experiment using response surface methodology (RSM). This methodology is a collection of statistical techniques and mathematical techniques that used quantitative data from the appropriate experiment to determine regression and model equations and operating condition which was useful for developing, improving and optimizing processes [23].

The design was based on the fact that Surface roughness of the matrix composite is functionally related to its specific composition and attempts were made to fit multiple regression equations describing responses to optimal matrix composition. Table 1 lists constituents in the descending order of importance as an Aluminum reinforced alloy percentage composition. The composition of the matrix has the form: A (Aluminum) + B (Barite) + C (Zircon) = 100%. This equation implies mathematical linear dependence of the variables if the amounts of constituents are used directly as variables, from the equation, the quantity of any constituent is uniquely determined by the amounts of the other [24]. To function in a multiple factor analysis, these constituents may be transformed to ratios, which can be varied independently. For this experiment, the following constituents' ratios were selected as the x_i variables in equations (2) and (3).

$$x_1 = \frac{A}{B+C} = 9 \quad (2)$$

$$x_2 = B/C = 1.5 \quad (3)$$

Table 1. *Metal Matrix Composition at the Design Centre Point.*

Constituents	Centre Point (%) weight
A. Aluminum	90
B. Barite	6
C. Zircon	4
Total	100

The constraint of transforming to ratios complicates interpretation of results but permits a mathematical approximation to the propellant composition relationship. A centre point for the design was selected with constituents at levels expected to yield, at least, satisfactory experimental results. With the centre composition selected based on calculation for percentage weight composition from the Aluminum 6061 reinforced alloy with varying weight fraction, the normal x_i ratios were calculated by using the normal weight composition of 90% Al, 6% Barite and 4% Zircon given in Table 1. The design was depended upon the symmetrical selection of variation increments about the centre composition [25]. These levels of variation were chosen to be within the range of Composition, and the increments were carefully selected, as interpretation of the result was valid only within the experimental limits. The increments of variation for each variable spaced around the centre point ratios, along with the equations relating the actual and coded ratios, are presented in Table 2. By substituting these equations, compositions were coded for solution of the multiple regression equations.

Table 2. *Experimental Increments, Values of Coded levels and Equations relating Actual x_i and Coded X_i Ratios.*

X_i coded levels				
Constituents (X_i)	±Increment	-1	0	1
X_1	±0.5	4.5	9	13.5
X_2	±0.5	0.75	1.5	2.25

Where x_i and coded X_i ratios are related by the following equations (4) and (5):

$$X_1 = \frac{(x_1 - 9)}{0.5} \quad (4)$$

$$X_2 = \frac{(x_2 - 1.5)}{0.5} \quad (5)$$

Before this type of experiment was carried out, the coded X_i ratios for each composition as per experimental design were translated into useful metal matrix composite. The matrix constituent compositions were obtained by systematic algebraic solutions for A, B and C in terms of actual x_i ratios and a unit quantity of a metal matrix. Equations derived for the general case are as follow equations (6) to (8):

$$A = \frac{x_1}{1+x_1} \quad (6)$$

$$B = \frac{x_2(1-A)}{1+x_2} \quad (7)$$

$$C = \frac{1-A}{1+x_2} \quad (8)$$

The resulting design composition is given in Table 3. The composite constituents in this Table were considered for the study.

Table 3. *Central Composite Design Arrangement for Matrix Composite.*

Runs No.	Coded level X_1	X_2	Actual Constituents A	(Weight fraction) B	C
1	0.00	0.00	0.90	0.06	0.04
2	0.00	1.414	0.90	0.07	0.03
3	-1.00	-1.00	0.82	0.08	0.10
4	-1.414	0.00	0.73	0.16	0.11
5	1.414	0.00	0.94	0.04	0.02
6	1.00	-1.00	0.93	0.03	0.04
7	0.00	-1.414	0.90	0.03	0.07
8	-1.00	1.00	0.82	0.12	0.06
9	1.00	1.00	0.93	0.05	0.02

2.2. Matrix Composite Preparation

The material considered for the composite under the study was an Aluminum 6061 reinforced matrix whose chemical composition consist of 73 - 94% Aluminum, 3–16% Barite and 2–11% Zircon (Percentage weight). The experiment was carried out at a constant machine speed of 1000 rpm, feed rate of 50, 75 and 100 mm/min respectively. These compositions were fabricated using Stir casting equipment into twenty seven different specimens. This equipment is being used owing to its simplicity, low cost and commercial viability. The Central composite design arrangement which formed chemical compositions for the reinforced matrix are shown Table 3. Surface Roughness (Ra) reading was taken using a stylus instrument for sampling length of 0.6 mm and a cut off. For evaluation, the mean of five surface roughness reading were considered for each specimen.

2.3. Response Equations for Matrix Composite Properties

The resulting weights for each constituent in different matrix composite composition were generated. A central composite rotatable design was adopted [26]. In this design, experiments were randomized in order to minimize the effects of unexplained variability in any responses due to extraneous factors. In order to analyze the experimental design by response surface methodology, it was assumed that there existed n mathematical functions, $f_h(h=1,2,....,n)$, for each response variable, Y_h in term of m independent metal matrix properties $X_i(i=1,2,....,m)$ (equation (9)).

$$Y_h = f_h(X_1, X_2, ..., X_m). \tag{9}$$

In this experiment, n = 3 and m = 2. In order to approximate this function, a second order polynomial equation was assumed for Surface roughness (equation (10)).

$$Y_h = b_{h_o} + \sum_{i=1}^{m} b_{h_i} X_i + \sum_{i=1}^{m} b_{h_{ii}} X^2{}_i + \sum_{i \neq j=1}^{m} b_{h_{ij}} X_i X_j \tag{10}$$

Where b_{h_o} is the value of fitted response at the centre point of the design, i.e. $(0,0)$, and b_{h_i} , $b_{h_{ii}}$ and b_{ij} are linear, quadratic and cross product regression term respectively.

3. Results and Discussion

3.1. Surface Roughness of Matrix Composite Composition

The effects of various matrix composition and machine feed rate on surface roughness as obtained from Stir Casting Equipment are as shown in Table 4. Based on the three different machine feed rates considered in the study, it's evidently clear from the table that surface roughness increases with increase in feeding rate and however indicated that it decreases with increase in cutting speed. The increases in cutting speed and feed rate proportionally decreases and increases the surface roughness respectively. This shows the importance of cutting speed and feed rate in deciding surface roughness.

Table 4. *Surface Roughness for Matrix Composite.*

Actual Constituents A	(Weight fraction) B	C	Response (µm) Ra @ 50 mm/min	Ra @ 75 mm/min	Ra @ 100 mm/min
0.90	0.06	0.04	1.08	1.14	1.21
0.90	0.07	0.03	1.22	1.27	1.34
0.82	0.08	0.10	1.43	1.50	1.55
0.73	0.16	0.11	1.72	1.79	1.85
0.94	0.04	0.02	0.98	1.06	1.11
0.93	0.03	0.04	0.65	0.72	0.78
0.90	0.03	0.07	0.48	0.56	0.60
0.82	0.12	0.06	1.68	1.74	1.81
0.93	0.05	0.02	1.02	1.08	1.14

3.2. Predicted Coefficients of the Surface Roughness Modes

Multiple regression analyses were conducted to develop surface response models for matrix composite. All main effects, linear, quadratic and interaction were estimated for each model. The coefficients of each factor as well as the coefficient of determination obtained for each model are as given on Table 5. The square of the coefficients of regression (R^2) for the three different feed rates considered are 0.9585, 0.9597 and 0.9587, respectively. These values are quite high for response surfaces and indicated that the fitted quadratic models accounted for more than 95% of the variance in the experimental data. Based on statistical analysis, the regression coefficients that are not significant at 95% were discarded while only those that are significant were selected for the models as given in equations (11)–(13). As depicted in the equations, most of the linear and quadratic terms of the models were significant. The models indicated that the actual composition and the feed rate have effect on surface roughness.

Table 5. *Predicted Coefficients of the Surface Roughness Models.*

Surface Roughness (Ra)	Model Factors	Coefficients	t–values	p - values
Ra @ 50 mm/min	Constant	1.08	1.67500	0.0001*
	X_1	-0.31	-0.22351	< 0.0001*
	X_2	0.21	0.68442	0.0004*
	X_1^2	0.16	7.83951E-003	0.0027*
	X_2^2	-0.091	-0.16222	0.0356*
	$X_1 X_2$	0.030	8.88889E-003	0.5381
			$R^2 = 0.9585$	
Ra @ 75 mm/min	Constant	1.14	1.77707	< 0.0001*
	X_1	-0.31	-0.22868	< 0.0001*

Surface Roughness (Ra)	Model Factors	Coefficients	t–values	p - values
	X_2	0.20	0.66735	0.0004*
	X_1^2	0.17	8.14815E-003	0.0020*
	X_2^2	-0.090	-0.16000	0.0343*
	$X_1 X_2$	0.030	8.88889E-003	0.5287
			$R^2 = 0.9597$	
Ra @ 100 mm/min	Constant	1.21	1.76500	0.0001*
	X_1	-0.31	-0.22129	< 0.0001*
	X_2	0.21	0.72442	0.0004*
	X_1^2	0.16	7.83951E-003	0.0027*
	X_2^2	-0.096	-0.17111	0.0290*
	$X_1 X_2$	0.025	7.40741E-003	0.6063
			$R^2 = 0.9587$	

*Significant at p value < 0.05 at 95% Confidence interval.

$$\text{Ra @ 50 mm/min} = 1.67500 - 0.22351\, X_1 + 0.68442 X_2 + 7.83951\text{E-003}\, X_1^2 - 0.16222 X_2^2 \tag{11}$$

$$\text{Ra @ 75 mm/min} = 1.77707 - 0.22868 X_1 + 0.66735 X_2 + 8.14815\text{E-003} X_1^2 - 0.16000 X_2^2 \tag{12}$$

$$\text{Ra @ 100 mm/min} = 1.76500 - 0.22129 X_1 + 0.72442 X_2 + 7.83951\text{E-00} X_1^2 - 0.17111 X_2^2 \tag{13}$$

3.3. Adequacy Test for Surface Roughness Models

The selected models were tested for adequacy and consistency using Analysis of Variance (ANOVA) and the values of various computation are as given in Table 6. The results from the ANOVA indicated that the F-values for the different three feed rates adopted are 32.30, 33.35 and 32.46, respectively. These are significant at the 95% level. The Surface and Perturbation Plots given in Figures 1–6 reveal that increases in Aluminum weight fraction decreases surface roughness while increases in Barite and Zircon weight fraction increases the surface roughness. Also, it shows that surface roughness proportionally increases with feeding rate and decreases with cutting speed. The investigation carried out by Lou *et al*. (1999) and Palanikumar, and Karthikeya, (2006) also corroborated the finding that the feeding rate, cutting speed and aluminum weight ratio are deciding factors for surface roughness in metal matrix composites. Therefore, Aluminum weight ratio is a deciding factor for surface roughness of matrix composition.

Table 6. *Analysis of Variance (ANOVA) for Surface Roughness (Ra)*

Surface Roughness (Ra)	Source of Variation	Sum of Squares	Mean Squares	F-values	Adjusted R^2
Ra @ 50 mm/min	Regression	1.39	0.28	32.30	0.9288
	Residual	0.060	8.592E-003		
	Total	1.45			
Ra @ 75 mm/min	Regression	1.37	0.27	33.35	0.9309
	Residual	0.057	8.197E-003		
	Total	1.42			
Ra @ 100 mm/min	Regression	1.39	0.28	32.46	0.9291
	Residual	0.060	8.592E-003		
	Total	1.45			

Significant level at p < 0.05.

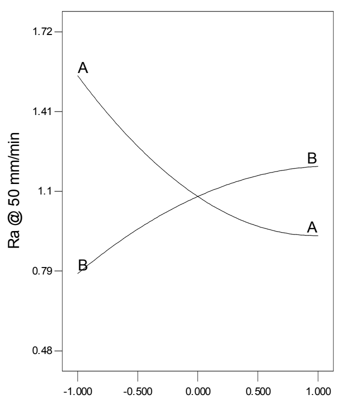

Figure 1. *Surface Plot for Ra @ 50 mm/min*

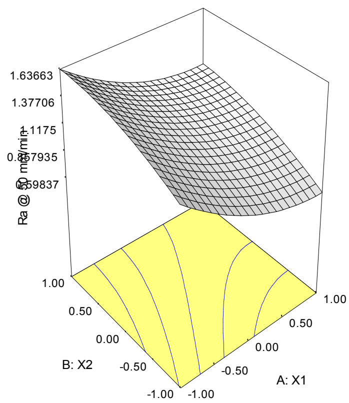

Figure 2. *Paturbation Plot for Ra @ 50 mm/min*

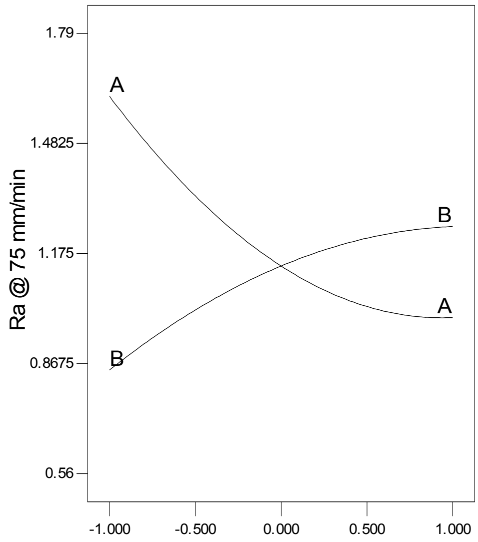

Figure 3. *Surface Plot for Ra @ 75 mm/min*

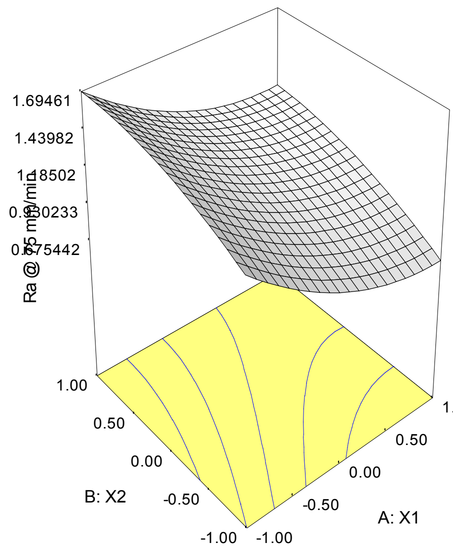

Figure 4. *Paturbation Plot for Ra @ 75 mm/min*

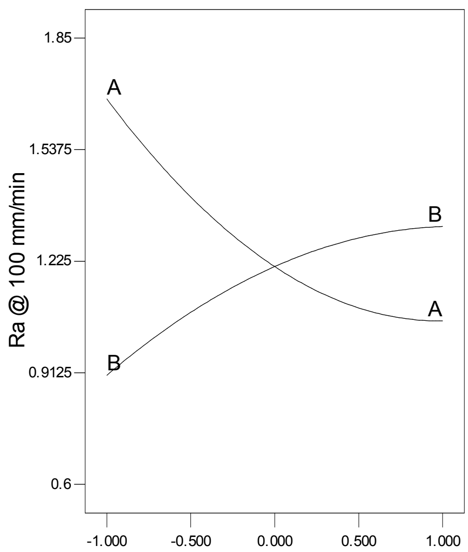

Figure 5. *Surface Plot for Ra @ 100 mm/min.*

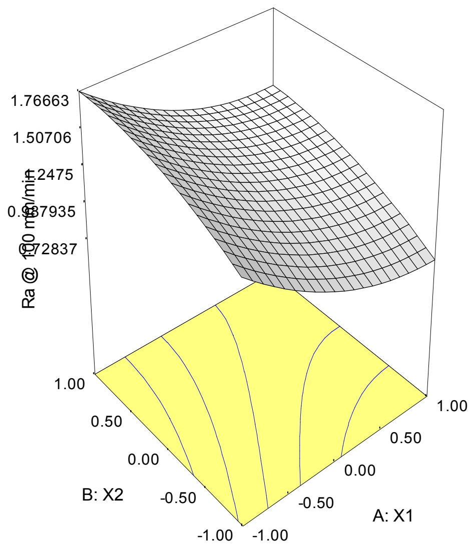

Figure 6. *Paturbation Plot for Ra @ 100 mm/min.*

3.4. Optimization of Matrix Composite Composition

The RSM was used to find the optimum matrix composite composition subject to surface roughness at three different feed rate. The optimum matrix chemical composition obtained were aluminum ratio of 0.9310, barite ratio of 0.0296 and zircon ratio of 0.0394 at surface roughness of 0.598371 µm, 0.675442 µm and 0.728371 µm for feed rate 50 mm/min, 75 mm/min and 100 mm/min respectively. The desirability index obtained for the optimization is 0.903. This indicated the optimality level of the design. Also, the actual values obtained for the analysis were aluminum ratio, 13.5 and barite ratio, 0.75. These were within the experimental range. This shows the validity of the design.

4. Conclusion

This research establishes an optimization procedure to determine the optimal matrix composite for solid rocket chamber. Also, the mathematical models developed depicted the effect of surface roughness on the matrix chemical composition and machine feeding rate. The optimum matrix chemical composition ratios of 0.9310, 0.0296, and 0.0394 for aluminum, barite, and zircon respectively with optimal desirability index of 0.903 shows the validity of the design. The study therefore confirm the effectiveness of RSM as a tool in predicting surface roughness and provide materials with enhanced mechanical properties.

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