Parametric Study for Graphene Reinforced Aluminum Matrix Composites Production Using Box Behnken Design

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Abstract. The production of graphene reinforced aluminum matrix composite through powder metallurgical route requires optimization of process parameters to obtain better performance characteristics. One of the advanced method available for statistical analysis of parameters is Response Surface Methodology (RSM). The statistical analysis was carried out with three parameters, weight percentage of graphene reinforcement W_g (0.05%, 0.1% and 0.2%), stirring time S_T(1h, 2h and 3h) and compaction pressure P_c(16T, 17T and 19T) while sintering temperature T kept constant. The performance of the Box Behnken design was analyzed and optimized using Design Expert software for the effective production of composites. From the results obtained from the analysis, the best set of parameters were considered for the future production of composites.

INTRODUCTION

Graphene is a 2-D material with sp^2 hybridized carbon atoms [1] named as a wonder material for its amazing properties, such as Young's modulus of 1TPa [2], fracture strength of 125 GPa [2] and thermal conductivity of 5000 w/m-K [3]. It can be noted that graphene nano sheets (few layer graphene) possess a capability to outperform carbon nano tubes (CNT's) and have a potential applications in the field of electronics and composites. On the other hand, metal matrix composites (MMC's) have been applied in the field of automobile, aeronautical and electrical industries owing to their combined high strength and low weight [4]. In order to meet the increasing demand for strength and efficiency in industrial applications, CNT/Al composites have been extensively researched. Even though the research is going on from the long time on CNT's, the major problem with this composites lies in the uniform distribution of CNT in the matrix without disrupting the CNT structure. The challenges involved in the production of graphene/Al composites are similar to that of CNT/Al composites. However, in comparison with graphene based polymers and ceramics, metal matrix composites are relatively less researched. In order to use the full potential of graphene as reinforcement a sophisticated methodology should be used to achieve homogeneous distribution of graphene reinforcement in Al matrix composites.

Factorial experiments are commonly used in most of the research areas especially in the area of material synthesis since the material properties are influenced by multiple factors. Therefore the effects should be evaluated at multiple operating conditions in order to obtain more accurate results. Design of experiments (DOE) is the techniques that

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includes the study of influence of various variables on the outcomes of the experiment in the controlled environment. The design is done in two steps, first step involves identifying the independent variables that effect the product or process and second step involves study the effects of independent variables on the dependent variables or response. Figure 1 shows a cube of Box-Behnken design (BBD) consists of central and middle points of the edge and Table 1 shows the coded values of BBD factor level three. Egne et al. [6] have used central composite design (CCD) to optimize the parameters such as particle size, SiC reinforcement and volume fraction of SiC reinforcement on to the strength of composite. Ghozatloo et al. [7] have reported the use of BBD method to optimize the parameters in the synthesis of graphene. Fakhri et al. [8] reported the optimization of process using response surface methodology for the fluoride ion removal using maghemite nano particles. Ferreira et al. [5] explored the application of BBD method for the optimization of analytical methods. It can also be noted that BBD method facilitate avoiding the experiments that are being performed in extreme conditions. Kumar et al. [9] have reported the use of BBD design for the parametric study of process of removing ethane carboxylic acid onto the powder activated carbon.
The present work includes the process parameters optimization of synthesis of graphene oxide reinforced Al matrix composite through powder metallurgical route using BBD with process parameters of wt% reinforcement, stirring time and compaction pressure and the response of strength of composite was noted to optimize the process parameters. This model can be useful in optimization of process parameters and helps in avoiding the complicated experimentation under the controlled experimental conditions.

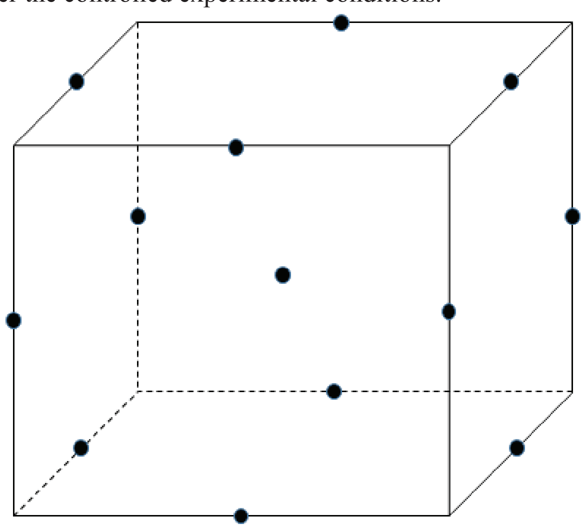

FIGURE 1. Schematic of geometric representation of Box-Behnken design for three factors [5]

TABLE 1. Box- Behnken design for three factors

Run	X	Y	Z
1	-1	1	0
2	1	-1	0
3	-1	-1	0
4	1	1	0
5	-1	0	1
6	1	0	-1
7	-1	0	-1
8	1	0	1
9	0	-1	1
10	0	1	-1
11	0	-1	-1
12	0	1	1
13	0	0	0

METHODOLOGY

Aluminum powder with ~99.9% purity and 35 µm average particle size, used as a matrix material and GO water dispersion (4 mg/ml) used to produce the GO reinforced aluminum matrix composites. The GO aqueous dispersion is sonicated for 15 minutes and then added drop by drop to the Al/IPA solution. The wt% of GO reinforcement used in the present studies include 0.05 wt%, 0.1 wt% and 0.2wt% and the stirring time of 1h, 2h and 4h. Sample powders weights of 0.5g were cold compacted producing specimens of dimensions 20 mm diameter and 0.5 mm thickness. The compaction pressures used for the production of samples are 16T, 17T and 19T. the samples produced were then sintered at 600˚C (88% of melting temperature of Al) [10] and a dwell period of 4hrs. Table 2 shows the description and levels of the parameters being studied in the paper.

TABLE 2. Parameters considered for the present problem

Factor	Description	Units	Low level (-1)	Middle level (0)	High level (1)
X	Wt% of GO	%	0.05	0.1	0.2
Y	Stirring time	Hour	1	2	4
Z	Compaction pressure	Ton	16	17	19

The experimental data is fitted into the linear and second order polynomial to obtain the regression equations and the relationship is given as,

$$Y= f\,(X_1, X_2, X_3 \text{------}) + \varepsilon \tag{1}$$

Where,
f - Real response function with unknown format and
ε - Residual error
A similar software will be used to generate the statistical and response plots. The manual regression will be used to fit the polynomial equation to the experimental data collected. By considering all the terms, the quadratic response model can be given as,

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_{ii}^2 + \sum \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

Where,
β_0 – Constant
β_i - Slope or linear effect of the input factor x_i
β_{ij} - Linear interaction effect between input factors x_i and x_j
β_{ii} - Quadratic effect of the input factor x_i

RESULTS AND DISCUSSION

The most important parameters, which affect the efficiency for the production of GO reinforced Al matrix composite are wt% of GO reinforcement (wt %), stirring time (S_T) and compaction pressure (P_C). In order to study the combined effect of these factors, research was performed for different combinations of the physical parameters using statistically designed experiments. The ranges selected for the input variables are given Table 2. The results of the Y response of efficiency of synthesis was measured according to the design matrix outlined in Table 3 and the measured responses are listed in Table 4.

TABLE 3. Three-level Box-Behnken design of experiments

Run	Wt%	S_T	P_C
1	-1	1	0
2	1	-1	0
3	-1	-1	0
4	1	1	0
5	-1	0	1
6	1	0	-1
7	-1	0	-1
8	1	0	1
9	0	-1	1
10	0	1	-1
11	0	-1	-1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0

TABLE 4. Experimental and predicted values of Yield

Run	Wt%	S_T	P_C	Y_{exp}	Y_{Pred}	ε
1	0.05	1	17	79.53	77.73	1.8
2	0.2	1	17	96.31	97.32	-1.01
3	0.05	4	17	73.21	72.85	0.36
4	0.2	4	17	89.23	91.7	-2.47
5	0.05	2	16	73.34	75.43	-2.09
6	0.2	2	16	96.32	95.31	1.01
7	0.05	2	19	71.2	72.83	-1.63
8	0.2	2	19	93.34	91.52	1.82
9	0.1	1	16	97.83	97.32	0.51
10	0.1	4	16	89.12	88.42	0.7
11	0.1	1	19	90.13	90.81	-0.68
12	0.1	4	19	88.75	88.32	0.43
13	0.1	2	17	89.94	90.35	-0.41
14	0.1	2	17	90.05	90.35	-0.3
15	0.1	2	17	90.21	90.35	-0.14
16	0.1	2	17	89.92	90.35	-0.43
17	0.1	2	17	91.23	90.35	0.88

From the analysis of the measured responses by the Design-Expert software, the fit summary output indicates that the quadratic model is statistically highly significant for the present adsorbate-adsorbent system. The cubic model can be recommended for the statistical analysis, since the Box-Behnken matrix has sufficient data to interpret the outcome of the present system. Figure 2 shows the relation between the actual and predicted response for the composite material using the given process parameters. It can be noted that the developed models are adequate as the prediction residuals of each response are minimum, since residuals are close to the diagonal line.

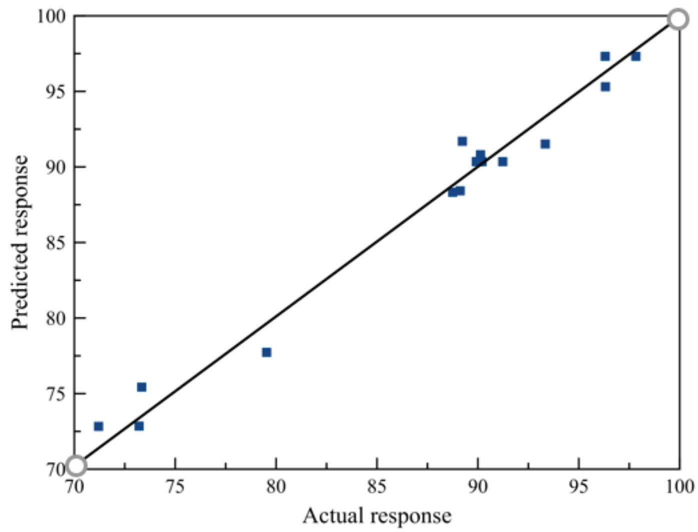

FIGURE 2. Correlation of actual and predicted responses based on the process parameters

CONCLUSIONS

The Box-Behnken design can be employed to develop the mathematical models that can predict the effectiveness of the produced GO/Al composite material. The desired strength of the material is more sensitive to the carbon content. The future work involves the comparison of CCD and BBD for same number of parameters and same number of runs to choose the effective method for optimization. The continuation work will include using ANOVA to find the significance of ratio of mean square variance with the residuals and mean square residual error.

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