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Prediction of hardness of forged Al7075/Al_2O_3 composites using factorial design of experiments

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ABSTRACT

Aluminium based Metal Matrix Composites (MMCs) with aluminium matrix and non-metallic reinforcements are finding extensive applications in automotive, aerospace and defense fields because of their high strength-to-weight ratio, high stiffness, hardness, wear resistance, high-temperature resistance, etc. compared to their monolithic counterparts. They are generally manufactured by melt casting route and powder metallurgy techniques. Often, they are subjected to secondary manufacturing processes like extrusion, rolling, forging, etc. to obtain the final components. There are no standard methods for selecting the correct proportion of the constituent matrix and reinforcement materials for producing these composites, particularly, in their forged condition. Mathematical modeling using factorial design of experiments (DoE) is found to be very useful in predicting the mechanical/tribological properties of these composites in the face of process parameters. This paper presents the details of modeling the hardness of forged composites made-up of Al-7075 matrix, reinforced with Al_2O_3 particulates produced by stir-casting. Factorial DoE is used to develop the mathematical model to predict the influence of four process parameters, viz., size of reinforcement, weight percent, forging temperature and reduction in size due to forging, on micro-hardness of these composites.

Keywords: **MMCs, Stir-casting, Forging, DoE, Hardness, Modeling**

I. INTRODUCTION

Monolithic alloys are slowly being replaced by composites, which combine ductility and toughness of the matrix materials and higher strength, hardness, wear resistance, etc. of the reinforcements. Metal Matrix Composites (MMCs) are being extensively used in automotive, aerospace and mining engineering, etc. as they are reported to possess high strength–to-weight ratio at elevated temperatures, improved shock-resistance properties, relatively higher wear resistance, toughness, etc [1-6]. In order to shape these composites, often they are subjected to secondary processing methods such as extrusion, rolling and forging. Al-7075 alloys reinforced with particulates of Al_2O_3 are reported to exhibit higher hardness, wear resistance, tensile strength, etc, not only in the as-cast condition, but also in the forged condition as well [7]. However, a deeper understanding of these alloys in respect of their production and mechanical properties is mandatory to enhance their applicability. Recently, factorial design of experiments (DoE) has emerged as an important tool to analyze multi-parameter, complex processes [8-11]. A number of researchers have employed this methodology and developed mathematical models for various properties of MMCs [12-14]. For example, D.P. Mondal et al [12] have studied the erosive-corrosive wear of Al-Si alloy based, 10%SiC reinforced, aluminium metal matrix composites. The wear model developed by them indicates that radial distance among other parameters has the maximum effect on the wear resistance. Abrasive wear behavior of Al-Cu based alloy (Al 2011) matrix dispersed with SiC and manufactured by liquid metallurgy route has been investigated by Y. Sahin [13] using a 2- level factorial design. He has developed a polynomial equation for wear rate of composite in terms abrasive size, sliding distance and applied load. Huda et al [14] have developed a mathematical model for predicting hardness of an Al/Al_2O_3 composite, using response surface methodology and observed that the effect of volume fraction of reinforcement was very dominant. Indumati B.D. and G.K. Purohit [15] have used four factors, five levels factorial design to develop the micro-hardness model for Al7075 matrix, Al_2O_3 reinforced metal matrix composite fabricated by stir-casting. Reinforcement size and weight fraction of reinforcement, among other factors, are observed to affect the hardness more severely.

In our view, the properties of aluminium composites such as strength, tensile properties, wear resistance, hardness etc. are not well documented. Knowledge of hardness of composites is paramount from the stand point of wear resistance, crack initiation and growth, scratch resistance, etc. However, it is noticed from the literature that there is no systematic approach to model the hardness of aluminium based, alumina reinforced composites, particularly in their forged condition. This paper reports the application of DoE for predicting the hardness of Al7075/Al_2O_3 composites fabricated by stir-casting. Influence of reinforcement size, weight percent, forging temperature and reduction in size due to forging on the hardness of Al7075/Al_2O_3 composites was studied and reported. Analysis of Variance (ANOVA) was performed to determine the effectiveness of parameters on their hardness. Fisher's F-test was carried out to arrive at the adequate model that can be used to produce the composites of desired hardness within the range of parameters selected for this study and also predict the combination of input-parameters that give composites of desired hardness within the framework of the experimental values studied.

II. MATERIALS

Table 1a and 1b present the chemical composition and other important properties of the Al7075 matrix material, respectively.

III. EXPERIMENTAL PROGRAM

The experimental work comprised (i) finding the range of the identified parameters viz. size of reinforcement (D), % weight of reinforcement (W), forging temperature (T_f) and % reduction of forging area R_f in mm, (ii) developing the central composite design matrix, (iii) producing the stir cast and forged specimens as per design matrix and extracting the hardness specimens from defect-free regions of the specimens, (iv) conducting hardness survey and recording the hardness values.

Table 2 gives the range of process parameters. Following the design matrix Table 3, 31 composite rods measuring 25 mm diameter and 280mm long were stir-cast. Fig. 1 shows the close up view of the stir casting set-up. The details of stir-casting process are presented elsewhere [16, 17]. The cast rods were subjected to forging as per the design matrix at temperatures ranging from 385˚C to 425˚C to produce samples with reduction in area in the range of 10-50%. For performing hardness survey, test samples were extracted from defect-free regions of the forged composites and a minimum of five indentations were made on the samples using Micro-Vickers hardness tester (Fig. 2).

Mathematical model for hardness is a function of all the process variables and is given by the 2nd order equation (1)

$$Y= b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_1X_1^2 + b_2X_2^2 + b_3X_3^2 + b_4X_4^2 + b_{12}X_{12} + b_{13}X_{13} + b_{14}X_{14} + b_{23}X_{23} + b_{24}X_{24} + b_{34}X_{34} \qquad (2)$$

Where, b_0 is the coefficient corresponding to the first column with all the values, b_1, b_2, b_3 and b_4 are the coefficients corresponding to the 4 selected process parameters, b_{11}, b_{22}, b_{33} & b_{44} refer to quadratic terms, and b_{12}, b_{13}, b_{14}, b_{23}, $b_{24,}$ b_{34} indicate coefficients corresponding to 2-factor interaction - b_{12} meaning coefficient of factors 1 and 2, b_{13} meaning coefficient of factors 1 and 3, etc. The values of these coefficients, determined as per ref [18] were used to write the hardness model. The model is presented in Eqn (3):

$$Hv = 131.574 + 0.5416D_1 + 1.792W_2 + 2.791T_3 + 2.625t_4 - 1.925D_1^2 - 0.925W_2^2 + 0.199T_3^2 - 1.050t_4^2 - 0.313D*W - 0.438D*T + 0.063D*t - 0.813W*T + 0.188W*t + 0.063T*t \qquad (3)$$

The effect of parameters on the response and adequacy of hardness model developed were tested by employing ANOVA and Fisher's F-test. The results are presented in Table 4.

IV. RESULTS AND DISCUSSION

The average micro-hardness of stir-cast and forged composites is almost double that of the aluminium matrix. It is observed from Eqn. (1) that individually all the process parameters have positive sign and hence contribute significantly, in improving the hardness. The effect of reinforcement size is more pronounced up to 60µm and after that it has a tendency to reduce the hardness. Maximum hardness is obtained at 50µm. Similarly, at 15% weight proportion, maximum hardness is obtained (140VHN). At 425°C and corresponding to 15% reduction in area due to forging, the micro-hardness is around 135-140VHN.

The effects of 2-factor interactions are not uniform and there exists a point of inflexion. The improvement in hardness of forged composites may be attributed, primarily to the addition of harder Al_2O_3 as well as the ability of the forging process to close the voids and other discontinuities present in the as-cast composites. This is in line with similar observations made by Ceschini et al [19]. Further, the application of a secondary process like forging will bring about significant grain refinement of as-cast composites.

The F-ratio for the model is more than the tabulated one indicating that the model is adequate. The R-squared and adjusted R-squared values show that the process parameters are quite influential in deciding their effectiveness on hardness at 95% confidence level.

V. CONCLUSION

The following conclusions can be drawn from the present work.

1. Factorial design of experiments (DoE) can be successfully employed to model the hardness behavior of forged composites.
2. Components produced by stir casting and forging of $Al7075/Al_2O_3$ composites possess almost two times the average hardness as compared to those obtained by their monolithic matrix based counter parts.
3. Parts possessing maximum micro-hardness of 140VHN can be produced using 15% by weight of 60µm diameter Al_2O_3 at forging temperature of 425°C and a reduction in area of 55% after forging.
4. It is essential to consider 2-factor interaction effects of the process variables along with main factors to arrive at the model.
5. The model developed can be used to produce $Al7075/Al_2O_3$ composites of desired micro-hardness and also to predict the hardness of the composites knowing the proportions of the same.

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Table 1a Chemical Composition of Al7075

Cr	Cu	Mg	Zn	Al	Density g/cc at 20°C
0.22	1.60	2.80	5.50	Balance	2.89

Table 1b Details of other important properties of Al7075

Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness VHN	Thermal Conductivity Cal/Cm^2/Cm/°C at 25°C	Elect. Resistivity µΩ-Cm at 20°C
228	104	17	79	0.29	5.74

Table 2 Coded values of input variables at different levels

Coded values	Input parameters	Notation	Units	Lower level		Middle	Upper level	
				-2	-1	0	+1	+2
X_1	Size of Al_2O_3	D	µm	36	45	54	63	72
X_2	% Wt of Al_2O_3	W	---	5	7.5	10	12.5	15
X_3	Forging temperature	T_f	°C	385	395	405	415	425
X_4	Reduction in forging area	R_f	%	10	20	30	40	50

Table 3 Design Matrix for Preparation of Stir cast & Forged Samples along with Responses

Trial No.	**Input Parameters**				**Response**
	X_1 Reinforcement size, *D* (µm)	X_2 %Weight of seinforcement, *W*	X_3 Forging temperature, T_f (°C)	X_4 Reduction in size due to forging, R_f (%)	Vickers hardness, *Hv* (VHN)
1	-1	-1	-1	-1	110
2	+1	-1	-1	-1	115
3	-1	+1	-1	-1	120
4	+1	+1	-1	-1	122
5	-1	-1	+1	-1	124
6	+1	-1	+1	-1	125
7	-1	+1	+1	-1	127
8	+1	+1	+1	-1	123
9	-1	-1	-1	+1	120
10	+1	-1	-1	+1	123
11	-1	+1	-1	+1	127
12	+1	+1	-1	+1	125
13	-1	-1	+1	+1	130
14	+1	-1	+1	+1	128
15	-1	+1	+1	+1	132
16	+1	+1	+1	+1	138
17	-2	0	0	0	130
18	+2	0	0	0	132
19	0	-2	0	0	134
20	0	+2	0	0	136
21	0	0	-2	0	139
22	0	0	+2	0	140
23	0	0	0	-2	133
24	0	0	0	+2	136
25	0	0	0	0	135
26	0	0	0	0	131
27	0	0	0	0	132
28	0	0	0	0	133
29	0	0	0	0	130
30	0	0	0	0	131
31	0	0	0	0	129

Table 4 Analysis of variance

S.No.	Source	DF	SS	MS	F_{model}	R^2	$Radj^2$
Hardness Hv in VHN	I & II Order terms	14	595.5686	42.5406	10.764	98.35	98.09
	Lack of fit	10	815.1045				
	Residual error	6	23.714	3.952			
Total		30	1434.3871	46.4926	10.764	98.35	98.09

As per Table (14, 6, 0.05) $F_{tabulated}$ = 4.07. Hence, the model is adequate.

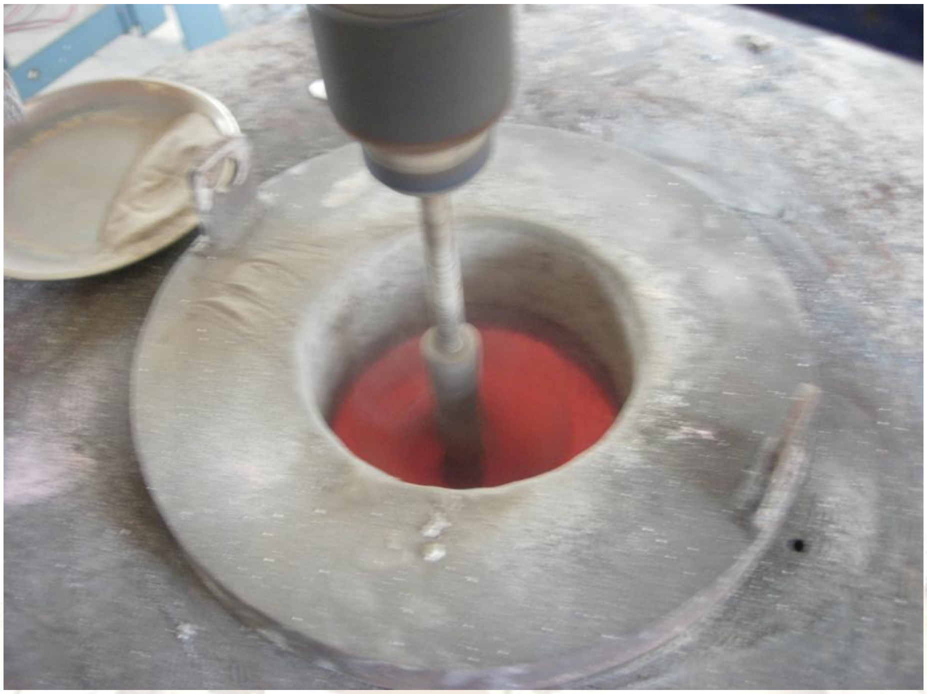

Figure1: Close-up view of stir-casting set-up. Al_2O_3 particulates of various sizes are added to the melt at 730°C which is continuously stirred using a motorized ceramic coated stainless steel rod.

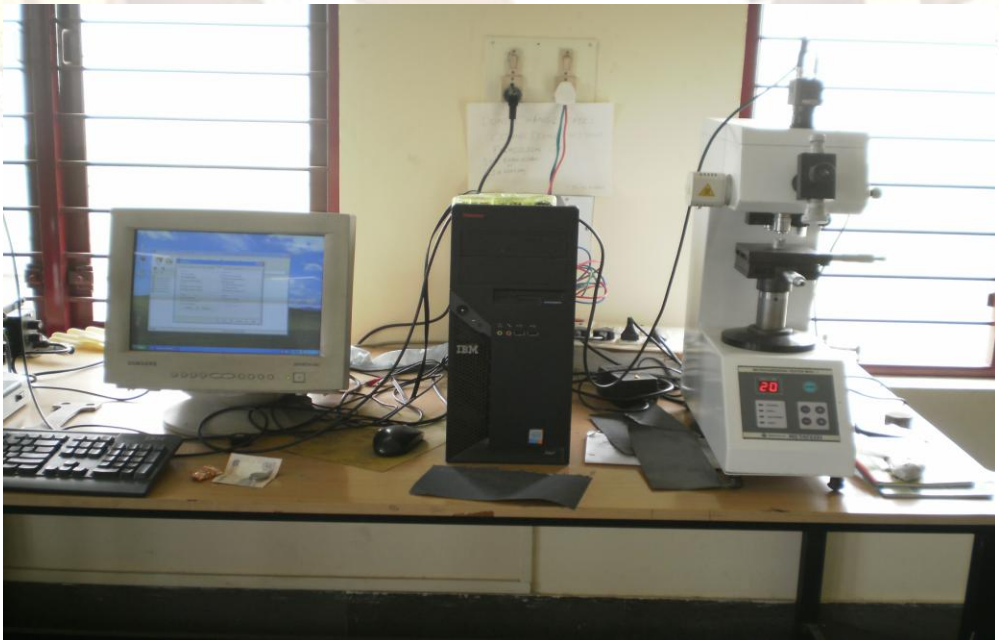

Figure 2: Micro-Vickers hardness tester MVH-I