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Investigation of hardness behavior in aluminum matrix composites reinforced with coconut shell ash and red mud using Taguchi analysis

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ABSTRACT

Introduction: in present scenario, light and high strength aluminium metal matrix composite are extensively used due to its high mechanical and tribological properties. Aluminium metal matrix composite reinforced with ceramic and industrial waste can customize its mechanical-chemical behavior. **The purpose of the work:** to create an aluminum matrix composite material using ceramic (primary) and industrial (secondary) waste represented by red mud and coconut shell ash, respectively. The mass fraction of the strengthening phase varied from 5 to 12.5 wt. % respectively with the residual mass percentage of the aluminum alloy. **Method of investigation:** nine specimens of composite materials were prepared by stir casting. Stirring was carried out at a speed of 50 to 100 rpm for 20 minutes at a temperature of 800 °C. **Result and Discussion:** the hardness behavior of the aluminum metal matrix composite was studied at an indentation load of 10, 15 and 20 kN. Taguchi method with *L27* orthogonal array was selected to conduct analysis of variance (*ANOVA*) and regression analysis by selecting the mass percentage of red mud and mass percentage of coconut shell ash. The indentation load was used as an input parameter, and the hardness behavior was taken as an output parameter. The signal-to-noise ratio, response rank table, contour plot, and normal probability plot are investigated and it is found that hardness values improve with the addition of both reinforcing components and indenter load. The results show that the hardness value varies from 33.34 HB to 53.44 HB, and the effect of red mud mass percentage is more significant than the indenter load and coconut shell ash mass percentage.

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Introduction

Currently, Aluminum Metal Matrix Composites (*AL MMC*) are widely used due to its high strength-to-weight ratio and good tribological properties. There are a large number of materials available in manufacturing industry, so we require cost-effective high-performance materials whose mechanical and chemical properties can be changed according to customer requirements. Due to the reinforcing materials in aluminum matrix composites, it is possible to adapt the mechanical, chemical and tribological properties of the latter in accordance with the requirements of the market and the consumer. In the last decade ceramic materials like silica, alumina, rutile etc. have been widely used to reinforce *AL MMC* but it may enhance the manufacturing and processing cost of Composite materials [1]. Industrial and bio wastes such as red mud, iron ore, rice husk ash, bagasse ash, coconut shell ash, etc. have the ability to replace these ceramic materials in the development of cost-effective composite materials by reducing manufacturing cost. In this

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research work, a hybrid *MMC* is prepared using industrial waste red mud and bio-waste coconut shell ash. Previously many researchers utilized coconut shell ash as an adsorbent to remove heavy metals and dyes from aqueous solutions [2], in the development of building materials such as brick tiles [3], cementitious and polymeric composites [4,5] and in the production of activated carbon [6]. Similarly, red mud is used as a coating material [7], as a mortar, aggregate tiles [8], a mineral cementitious material [9], a ceramic material [10] and for heavy metal leaching and wastewater treatment in general [11]. Some of the researchers have used the combination of bio-waste with ceramic material to create and evaluate a hybrid *Al MMC.* In [12] coconut shell ash and graphene are used to evaluate abrasive wear properties. In [13] and [14] a mixture of agricultural waste in the form of coconut shell ash and baggas ash with aluminum oxide was used to evaluate the mechanical properties of the developed hybrid *Al MMC*. In [15] and [16], a mixture of rice husk ash with red mud and alumina was used, respectively, to evaluate the tribomechanical behavior of hybrid *Al MMC* materials.

Hardness

Hardness is an important parameter to check mechanical strength of composite materials. The hardness of composite material depends on various parameters, such as the particle size, heat treatment, the weight ratio of the reinforcing material and the interatomic bonds between the reinforcing material and the parent matrix. Previously, many researchers optimized this hardness parameter and concluded that the hardness of composite increases with decreasing particle size and the heat treatment. Also, the increases to an optimal weight percentage, which varies from reinforcing material to the composite as there is good inter-atomic bonding between the reinforcing material and the matrix but at higher weight percentage the hardness value decreases due to agglomeration of the reinforcing material in the matrix layer, which leads to the formation of pits and cavities. Cavities lead to the propagation of cracks and a decrease in tensile strength and hardness [17].

The hardness values are dependent on many parameters such as reinforcing material weight fraction, indentation load, treatment behavior, inter-atomic bonding etc. For this reason, a large number of composite specimens are required for experiments and determining its characteristics becomes expensive and labor intensive. Therefore, experimental design and *Taguchi* analysis are suitable approaches for optimizing input and output parameters. In this paper, the aluminum composite material obtained through stir casting route and its *Brinell* hardness value are optimized using *ANOVA* and regression analysis. The selected orthogonal array L27 of the experimental plan and the effect of the signal-to-noise ratio, the graph of the normal probability of the remainder, response characteristics, contour diagrams are tabulated for various composite samples.

L27 orthogonal array of design of experiment are chosen and the effect of the signal-to-noise ratio, normal probability plot of residual, response characteristics, contour plots are tabulated for various composite specimens.

Method and Materials

The 5051 series aluminum alloy was chosen as parent material due to high stiffness and strength-to-weight ratio, high corrosion resistance and optimum thermal properties and widespread use in the development of building materials, in the automotive and aerospace industries. Red mud and coconut shell ash were used as reinforcing material to develop a hybrid composite material. Here, red mud is bauxite residue and is used as the primary reinforcing material, the content of which varies from 5 to 12.5 % and is purchased from the *Balco* aluminum refinery. Around 100 coconuts were purchased from various temples in *Jaipur* to obtain ash by burning and sieving. The proportion of coconut shell ash used as a secondary supportive reinforcing material varied from 5 to 12.5 wt. %. Both red mud and coconut shell ash were properly sieved to obtain particles of about 50 μm in size as hardness increases with decreasing particle size.

Composite preparation

Nine aluminum specimens were prepared via stir casting process. Ceramic crucibles were used for casting of aluminum metal. Red mud and coconut shells were preheated to 200 °C to remove moisture before the casting process. Melting and stirring parameters were optimized using the control panel. The following parameter values were set: stirring speed = 50–100 rpm, stirring time = 20 minutes, melting temperature = 800 °C, preheating temperature = 200 °C. A cylindrical mould with a diameter of 20 mm and a length of 250 mm was made for pouring molten metal. Using an orthogonal array ***L9***, nine specimens were prepared, while the weight percentage of red mud and coconut shell ash was selected separately in the amount of 5, 7.5 and 12.5 wt. %. The hardness of each composite was calculated via selecting three values of indentation load of 10, 20 and 30 kN, the control variables table of which is shown below.

Design of Experiment

Material characterization requires an optimal output response to reduce the number of variables and improve the performance and durability of composite specimens. This optimization is achieved by controlling the input parameter over the output response, and *Taguchi* analysis is the optimal platform for characterizing materials [14]. Here, three parameters as weight percentage of red mud, weight percentage of coconut shell ash and indentation load are selected to test the *Brinell* hardness response of the hybrid aluminum composite material. Three levels of input parameters were selected to evaluate the hardness response, therefore, an orthogonal array ***L27*** was selected for *ANOVA* and regression analysis, which is an experimental and predictable result of regression analysis, summarized in Table 1. In this research work, *ANOVA* and regression analysis were performed using *Minitab 17* software to check the hardness value of hybrid aluminum composite specimens. The weight percentage of coconut shell ash (*CSA* weight %), the weight percentage of red mud (*RM* weight %) and the indenter load were accepted as input parameters. The coconut shell ash and red mud levels are assumed to be equal to 5, 7.5 and 12.5 wt. % at loads of 10, 15 and 20 kN. The hardness of composite specimens with different parameters is shown in Table 2.

Figure 1 shows the effect of hardness on the signal-to-noise (*SN*) ratio and here the response is optimized for a larger hardness value and mean of *SN* ratio varies from 31 to 32.6 hardness values, which shows the optimal variability of the output hardness response. The composite material with the highest percentage of red mud and coconut shell ash reinforcing with the highest indentation load has a maximum hardness of 52.44 HB, which is almost 95 % greater than the composite material with the lowest percentage of reinforcing material (5 wt. % coconut shell ash and 5 wt. % red mud) and indenter load (10 kN). Thus, the hardness value improves with increasing volume fraction of the reinforcing material under loading [19].

Hardness behavior

The hardness behavior characterization of a hybrid aluminum composite material reinforced with red mud (*RM*) and coconut shell ash (*CSA*) is presented in Table 2. The hardness increases with increasing percentage of reinforcing martial because the hard and brittle phase of the reinforcing martial creates a lubricating dislocation density and while the application of a dislocation density load leads to the formation of new strain fields that resist the dislocation movement [19]. Also, the difference in melting temperatures between the reinforcing material and the aluminum matrix activates the mechanism of strain hardening due to the transfer of the strain field along the grain boundary, which creates a barrier field along the matrix and hinders the indentation load, therefore increasing the hardness of the composites [20].

Figure 2 shows that the hardness value increases with increasing load, since under high load conditions the lubricating layer (formed due to the thermal mismatch between the reinforcing material and the aluminum

Table 1

Level of Control variables for hardness

Variable	Unit	Level I	Level II	Level III
Red mud	Weight %	5	7.5	12.5
CSA	Weight %	5	7.5	12.5
Load	kN	10	20	30

Table 2

Brinell hardness characterization of aluminum composite specimens

Red Mud (%)	CSA (%)	Load (kN)	Observed hardness	Predicted hardness	Signal-to-noise ratio
5	5	10	33.52	32.78	30.50696
5	5	15	34.75	35.02	30.82105
5	5	20	36.61	37.30	31.27347
5	7.5	10	35.12	35.94	30.91267
5	7.5	15	36.11	38.22	31.15281
5	7.5	20	38.22	40.50	31.64756
5	12.5	10	35.47	35.71	30.99823
5	12.5	15	37.60	37.95	31.50574
5	12.5	20	38.38	40.27	31.68409
7.5	5	10	36.27	34.95	31.1922
7.5	5	15	38.60	37.22	31.73368
7.5	5	20	39.21	39.50	31.8698
7.5	7.5	10	37.64	35.94	31.51387
7.5	7.5	15	38.99	38.22	31.82011
7.5	7.5	20	39.93	40.50	32.02644
7.5	12.5	10	38.09	37.92	31.61843
7.5	12.5	15	39.85	40.20	32.00981
7.5	12.5	20	40.32	42.48	32.11192
12.5	5	10	38.49	39.36	31.70709
12.5	5	15	39.33	41.64	31.89633
12.5	5	20	42.39	43.94	32.54664
12.5	7.5	10	39.04	40.35	31.83158
12.5	7.5	15	40.60	42.63	32.17236
12.5	7.5	20	48.72	44.91	33.75489
12.5	12.5	10	41.53	42.34	32.3691
12.5	12.5	15	43.51	44.62	32.77234
12.5	12.5	20	52.44	46.9	34.39448

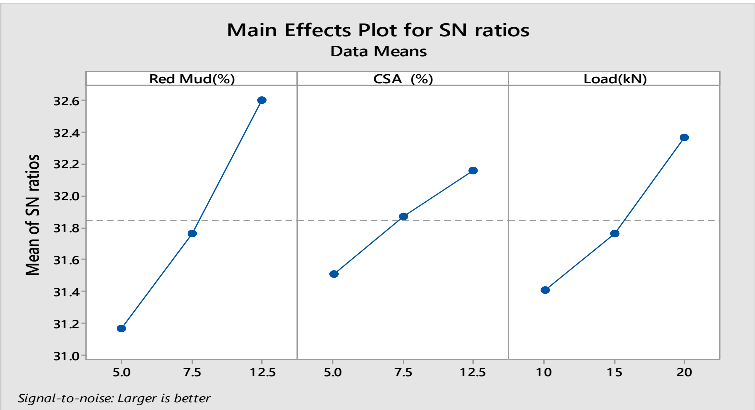


Fig. 1. Mean effect of signal-to-noise ratio on *Brinell* hardness

matrix) creates a strong dislocation strain field along the aluminum grain boundaries, which supports the tendency of increasing hardness. Figure 2 also shows that hardness increases as the percentage of the reinforcing material increases, since the combination of both reinforcing components can refine grain the structure of the composite, and the presence of a hard and brittle phase of silicon oxide, aluminum oxide and iron oxide leads to the formation of a strong inter-atomic bond between the aluminum matrix and the reinforcing material. At the same time, a larger indentation load is required to facilitate scratching hence improves the hardness [21]. According to Table 2, nine specimens were used, while the weight percentage of red mud and coconut shell ash was selected separately in the amount of 5, 7.5 and 12.5 wt. %. In addition, three loads were selected to assess the hardness behavior: 10, 20 and 30 kN. The results of the hardness behavior assessment are given below (Figure 2).

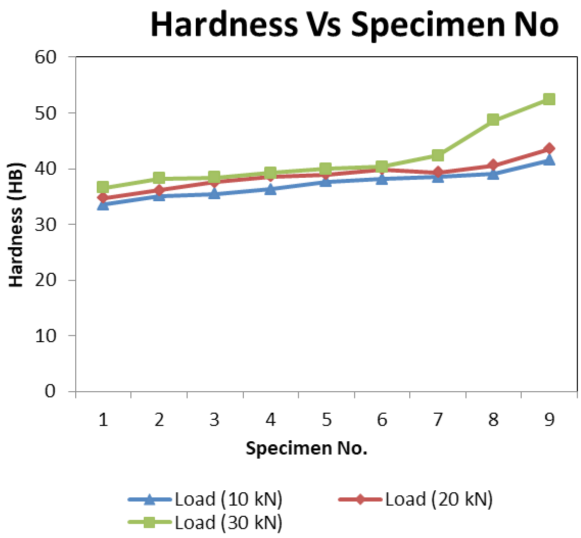


Fig. 2. Hardness variation with respected to load

Result and Discussion

ANOVA

Table 3 presents the output hardness response data and shows that the weight percentage of red mud possesses higher rank than load and coconut shell ash. This is a very useful tool for testing the effect of an input parameter on the output response. Table 4 shows the results of *ANOVA*, which is a very valuable tool for testing the relevance of various input variables to the output results. The contribution of the weight percentage of red mud reaches 48.80 %, the weight percentage of coconut shell ash is 10.41 % and the indenter load is 23.01 %. The same type of results is presented in the response table. The effect of weight percentage of red mud on hardness is superior to the influence of weight percentage of coconut shell ash and indenter load because red mud contains industrial compounds such as Al_2O_3, Fe_2O_3, SiO_2, TiO_2, etc., which support the hardening mechanism of aluminum composite materials [14].

The value of the determination coefficient $\boldsymbol{R^2}$ and the adjusted value $\boldsymbol{R^2}$ drop by 97.02 % and 90.31 %, respectively, which shows the variability of the output response depending on different input parameters. Both $\boldsymbol{R}$ values are within a good range of variability and this analysis is also used to further verify the mechanical hardness of the hybrid aluminum composite material.

Regression Analysis

A linear regression equation was drawn for the hardness value using the parameters for red mud, coconut shell ash and indentation load taken as input parameters and *Brinell* hardness response was analyzed by

Table 3

Response Table for Hardness

Level	Red Mud (%)	CSA (%)	Load (kN)
1	36.20	37.69	37.25
2	38.77	39.38	38.82
3	42.90	40.81	41.56
Delta	6.70	3.11	4.56
Rank	1	3	2

Table 4

***ANOVA* for *Brinell* hardness**

Source	Degree of variance DF	Adjusted value of within-group variability (error variance) Adj SS	Adjusted variance value Adj MS	F-Value	P-Value	Contribution %
Red mud (%)	2	205.446	102.723	65.54	0.000	48.80
CSA (%)	2	43.744	21.872	13.96	0.002	10.41
Load (kN)	2	96.652	48.326	30.83	0.000	23.01
Red Mud (%)* CSA (%)	4	16.548	4.137	2.64	0.113	3.94
Red Mud (%)* Load (kN)	4	40.826	10.206	6.51	0.012	9.73
CSA (%)* Load (kN)	4	4.641	1.160	0.74	0.590	1.15
Error	8	12.539	1.567			2.29
Total	26	420.396				
*Standard deviation S = 1.2519; R^2 = 97.02 %; adjusted R^2 = 90.31 %.						

95 % probability level. Equation 1 shows the regression of hardness and in Table 1 shows the predicted value based on Equation 1 and it is found that the error of the predicted value compared with the experimental value is only 4 %, so this regression equation can be used for further analysis [22–23].

$$\textit{Brinell}\text{ Hardness} = 21.78 + 0.883\text{ Red Mud} + 0.397\ \textit{CSA} + 0.4562\text{ Load} \quad (1)$$

The normal probability plot is drawn for 95 % confidence level and the straight line shows the regression equation line (Figure 3). Using this residual value, it is shown that all hardness deviations are very close to the regression line, out of 27 data, about 4 falls outside the optimal residual value. Therefore, this hybrid compositional combination can be considered suitable for further hardness design analysis.

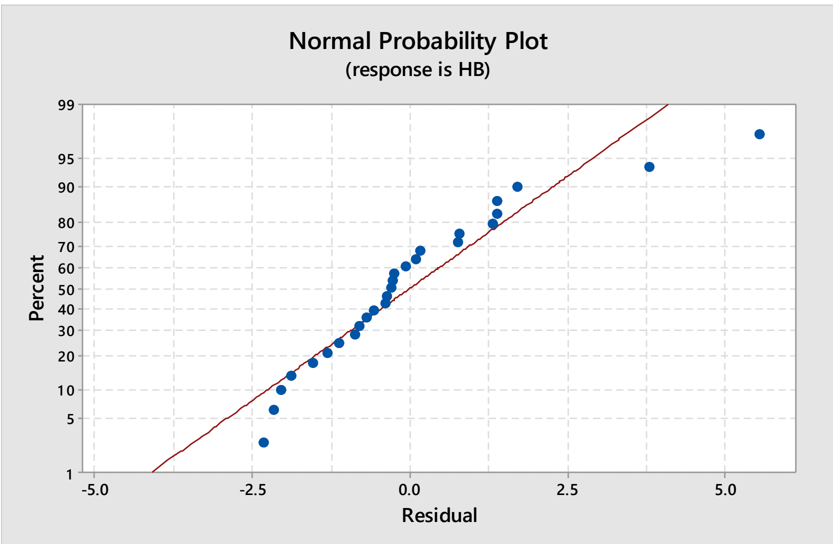
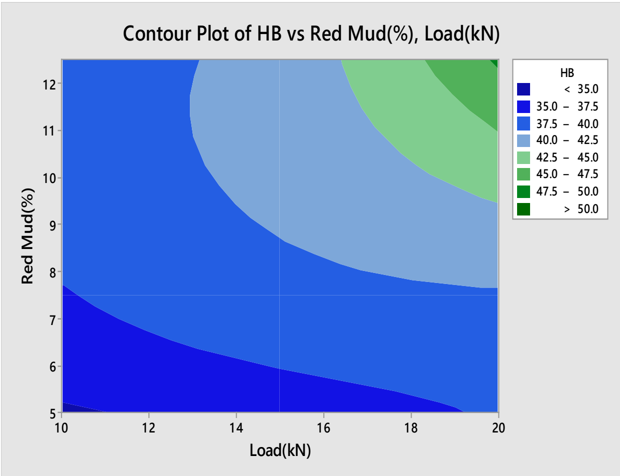


Fig. 3. Normal probability plot for residual on hardness of Hybrid Al composites

Contour plot effect on Hardness

Figure 4 shows contour plot variation of different input factor over Hardness output. The ***X*** and ***Y*** axes display the combination of weight percentages of red mud, coconut shell ash and indentation load. The results show that all combined maximum variations of hardness fall in the range of 37.5–40 HB , while the range of 47.5–50 HB have very low area range. The weight percentage of red mud has more influential effect than the weight percentage of coconut shell ash and the load variation. The hardness value increases with an increase in the weight percentage of red mud and a load variation; a slight increase in hardness occurs with increasing weight percentage of coconut shell ash because the volatile nature of the red mud in the aluminum matrix and the low specific gravity of the coconut shell ash improve the surface contact area along the matrix. Thus, more of the intermediate contact area is available to incorporate the reinforcing component, and due to the sintering effect, the red mud and coconut shell ash are placed in the intermediate area, which acts as a barrier to the deformation movement under indentation load, thereby increasing the hardness [24].



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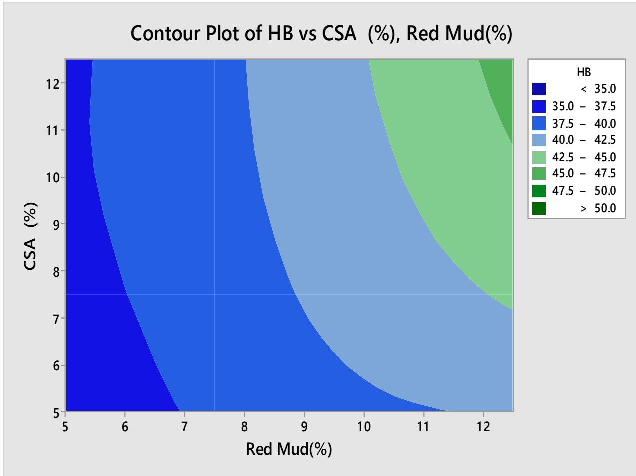

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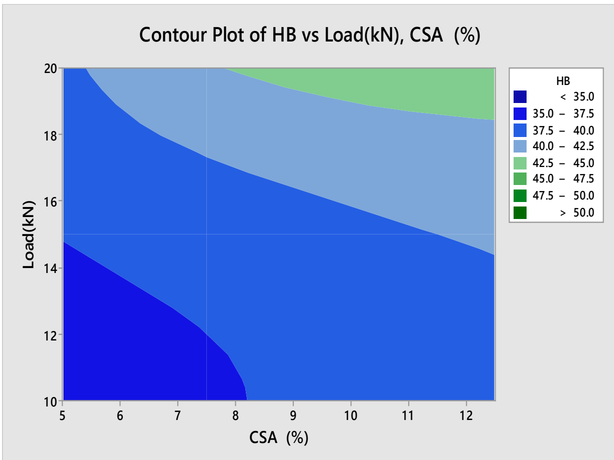

c

Fig 4. Variation of contour plot of Hardness value on (*a*) red mud vs load (*b*) load vs coconut shell ash (*c* Coconut shell ash vs red mud

Conclusion

A hybrid aluminum metal matrix composite has been successfully developed by reinforcing red mud and coconut shell ash through stir casting process while maintaining 800 °C furnace temperature. Nine composite specimens were prepared, and the *Brinell* hardness of the optimized specimens was calculated using a hardness tester. For *ANOVA* and regression analysis, the ***L27*** orthogonal array was used according to the *Taguchi* method. Three parameters were taken as input: weight percentage of red mud, weight percentage of coconut shell ash and indentation load, and hardness was taken as output. As a result of the optimization analysis, it was concluded that the hardness of the composite increases due to an increase in the weight percentage of the reinforcing component and indenter load. According to the response analysis, the weight percentage of red mud has a maximum contribution in the range of 48.80 %, which is superior to the contribution of the weight percentage of coconut ash and the contribution of indentation load. The hardness value shows an error of only 4 % compared to the predicted regression value, and all hardness values falling within the regression equation range show less variability in the residual value.

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Conflicts of Interest

The authors declare no conflict of interest.