To study the influence of B_4C and Al_2O_3 nanoparticles on the Tensile strength and Hardness of AA 7050 Hybrid Composite

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Abstract - **In recent years, it is found that aluminum matrix composites (AMCs) reinforced with multiple reinforcements have improved their performance compared to single-reinforced AMCs. Henceforth, the present study is focused on the fabrication of nano-size B_4C/Al_2O_3 reinforced hybrid AA7050 matrix composites (HAMCs) by the stir casting process. Further, the optimization and influence of different stir casting input parameters such as stirrer speed, stirring duration, and amount of nano-sized B_4C/Al_2O_3 on the mechanical properties of HAMCs are explored using the Taguchi method. The results showed that a small amount of nano-sized B_4C/Al_2O_3 when reinforced, appreciably enhanced the mechanical properties of the fabricated hybrid composite as compared to a higher number of nano reinforcements. The ANOVA results established, stirring speed, as one of the most crucial parameters for higher tensile strength (32.04%) and hardness (31.69%). The optimal tensile strength and hardness were obtained when B_4C-0.5 wt% and Al_2O_3 -0.5 wt% were stirred at the speed of 600 rpm with a stirring time of 10 min. The predictive mathematical models for both mechanical properties produced satisfactory results and the R^2 values of developed regression models for tensile strength and hardness were 90.17% and 92.48% respectively.**

Keywords- AMCs; HAMCs; Stir casting; Al_2O_3 and B_4C nano reinforcement; Hardness; Tensile strength.

I. INTRODUCTION

Currently, the prerequisite for aluminum matrix composites (AMCs) has multiplied in the advanced sectors like aerospace, defence, marine and automobile. Its inimitable traits such as higher mechanical and tribological properties have established it as a subduer when compared to the aluminum alloy [1],[2],[3]. Table 1 highlights the different grades of aluminium alloys (AA) that have been exploited for the fabrication of AMCs in previous years [4]. Amongst the AA 7xxx series, the AA 7050 alloy has been hailed for its structural applications in advanced industries, because of its high specific strength and low density [5],[6]. The higher influx and the continuous advancements in these industries have restricted the application of AA 7050 alloy and raised the bar for the need for lightweight with higher-specific properties materials. However, this was sorted out with the use of AA 7050 metal matrix composites, which can have more tailored properties according to the specific requirements of advanced industries.

Table 1. Different grades of aluminum alloy.

Aluminum alloy series	Important constituents
1***	Pure Aluminum (>99%)
2***	Aluminum- Copper - Magnesium
	Aluminum- Copper -Magnesium- Silicon
3***	Aluminum-Manganese-Magnesium
4***	Aluminum-Silicon
5***	Aluminum-Magnesium
	Aluminum-Magnesium-Manganese
6***	Aluminum-Magnesium-Silicon
7***	Aluminum-Zinc-Magnesium
	Aluminum-Zinc-Magnesium- Copper
8***	Aluminum-Lithium-Copper-Magnesium

The AA 7050 MMCs use different hard reinforcement particles, exhibiting high mechanical and tribological properties, which can withstand higher loads with low wear [7]. This contribution is more attractive for several

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engineering applications in advanced industries. There are different types of reinforcements such as Al_2O_3, SiC, B_4C, TiO_2, TiC, TiB_2, Graphene, CNTs etc which can be used as a reinforcement material in the aluminium matrix to improve its mechanical and tribological properties [8].

These AMCs are fabricated by different methods, which are classified into three broad categories i.e., liquid-state, solid-state, and other processing methods [9],[10],[11]. Amongst these methods, the liquid state-based stir casting method always remains the popular choice for MMCs fabrication. The predominance of stir casting showcases the economical process for mass production and a simple process with high flexibility. [12]. The important stir-casting input parameters which affect the mechanical properties of AMCs are shown in Fig. 1.

S R Mungara et al [13] refined the credible bonding between well-distributed B_4C microparticles with the AA 7050 matrix materials, which enhanced the tensile strength and hardness up to 50% using 8 wt% of B_4C reinforcements. J. Chandrashekar et al [14] elevated the ultimate tensile strength by 20% with the use of 3 wt% B_4C of 50 μm reinforcements. The MMC's property was improved because of the superlative distribution of these hard B_4C microparticles in the aluminum alloy matrix. While, 9% B_4C reinforcement in AA 7050 showed the clustering of these particles, thereby reducing its attributes to a greater extent.

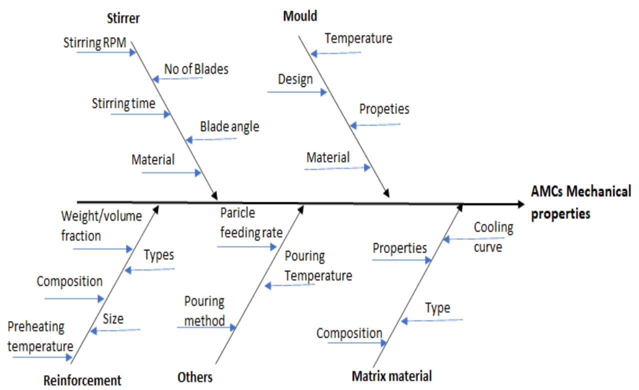

Fig. 1 Important stir casting parameters.

Lihua Zhang et al [15] used an ultrasonic method after the two-step stir casting method for the fabrication of AA 7050/μSiC composite. From the experimental investigation, it was found that tensile strength, elastic modulus and microhardness were significantly increased, while wear rate was decreased with the increase of the ultrasonic processing time. M. Anijdan et al [16] improved the mechanical properties by the uniform distribution of 3% SiC (10-30 μm) particles in the AA 7050 liquid matrix. This was achieved by using the pouring temperature of 800°C with a surface angle of 45°. A. Ranganathan et al [17] distributed TiC (325 μm) reinforcement from 0 to 6 wt% in the matrix of AA 7050 with the use of the stir casting method. The experimental results exhibited a spiked improvement in the tensile strength and hardness of the MMCs by 9% and 10% respectively. While its ductility was reduced by 6% of TiC microparticles when compared to the AA A7050 matrix. S. Venkatesan et al [18] experimentally found that a small amount of nanographene reinforcement of 0.3% was evenly distributed into the AA 7050 composite as compared to a higher percentage of these nanoparticles. Henceforth, a small amount of graphene nanoparticles significantly improved the mechanical properties of the MMC, which was obtained by the stir-casting process. S. Venkatesan et al [19] synthesized nano graphene reinforced AA 7050 matrix composite, and found that the percentage of nanographene particles was the most significant parameter. This leveraged the hardness and tensile strength of the MMC produced by the stir-casting method. Srivallirani et al [20] increased the tensile strength by 27% of AA 7050 composite with 2% h-BN and 5% TiO_2 of 40μm reinforcements. It was noticed that the mechanical properties of the stir-cast MMC were significantly enhanced by Orowan's strengthening mechanism. K. Sekar et al [21] increased the hardness by 27% of AA 7050 hybrid MMC with the use of 1% nano Al_2O_3 and 1.5% micro ZrO_2 reinforcements. It was also explored that the impact strength decreased with the increase of the ZrO_2 percentage content while keeping Al_2O_3 reinforcement constant at 1%. Saminathan et al [22] fabricated AA 7050 composite with different percentages of SiC (40μm) and Granite (60μm), and microparticles using the liquid state stir casting process. Experimentally, it was noticed that the hybrid composite exhibited higher tensile strength and hardness with lower wear rates.

As per the literature survey, it has been found that no work has been accomplished to evaluate the influence of different stir-casting input parameters on the mechanical properties of AA 7050/B_4C/Al_2O_3 hybrid nanocomposites. Hereupon, the present research work focuses on the utilization of Taguchi's method to optimize the HAMCs performance and to find the influence of important parameters like stirring speed, stirring duration and nano B_4C/Al_2O_3 reinforcements content on their mechanical properties.

II. MATERIAL SELECTION AND EXPERIMENTAL METHODOLOGY

The proposed experimental plan is shown in Fig.2, in which two nano reinforcements B_4C (size<80 nm with purity:99.8%) and Al_2O_3 (alpha, size-20-30 nm with min purity: 99.9%) are used to enforce the hardness and tensile strength of the AA 7050 hybrid composite. The present work has been divided into two parts. In the first part, the

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AA 7050 hybrid nanocomposite is fabricated with the use of a stir-casting method. In the second part, mechanical testing is carried out on the fabricated hybrid composites to explore their mechanical behaviour.

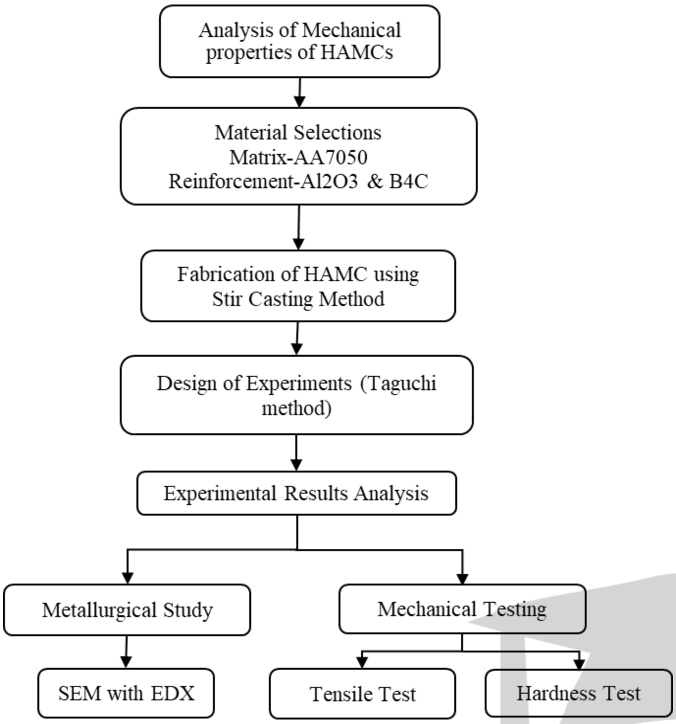

Fig. 2 Experimental methodology of the present work

Different stir-casting process parameters used for the preparation of hybrid nanocomposites are listed in Table 2. The Taguchi analysis is performed using Minitab software and the response table for S/N ratio, means S/N ratio graph, analysis of variance (ANOVA), and regression analysis results are obtained and presented in this study. For the four main factors with three levels, Taguchi L9 orthogonal array, which involves nine experiments is performed randomly as shown in Table 3. Signal-to-noise (S/N) ratio is used to identify the optimum condition, while ANOVA shows the contribution of various input factors to the tensile strength and hardness of the fabricated composite. The S/N ratios are categorized into three types i.e., larger is better, smaller is better and nominal is the best. Here, a larger-is-better S/N ratio is used for higher tensile strength and hardness of the hybrid composite. The mechanical characterization is done by conducting a Tension test (ASTM E8) and Vickers hardness test (ASTM E92), which are shown in Fig. 3. Field Emission Scanning Electron Microscopy (FESEM) is used to analyse the presence of the nano-sized B_4C/Al_2O_3 reinforcement in the AA 7050 matrix. Energy Dispersive Spectroscopy (EDS) is carried out to identify the various elements present in the AA 7050 hybrid composite.

Table 2. Stir casting input parameters used in the present work.

Process parameters	Values
Stirring speed-SS (rpm)	300, 450, 600
Stirring time- ST (min)	5, 10, 15
Al_2O_3 reinforcement (wt%)	0.5, 1.5, 2.5
B_4C reinforcement (wt%)	0.5, 1.5, 2.5
Stirrer blade angle (°)	45
Number of blades	3
Reinforcement preheats temperature (°C)	400
Metallic Die Preheat temperature (°C)	400
Pouring temperature (°C)	800
Degasser -C_2Cl_6 (wt%) in each experiment	0.4%
Magnesium (wt%)	1%

Fig. 3 Standard samples for the Tensile strength and Hardness Test

Table 3. Experimental results and their S/N ratios.

Experiment No.	Stirring Speed (rpm)	Stirring Time (min)	B_4C (wt%)	Al_2O_3 (wt%)	Tensile Strength (MPa)	Hardness (HV)	SNR (TS)	SNR (HV)
1	300	5	0.5	0.5	207	128	46.3194	42.1442
2	300	10	1.5	1.5	198	141	45.9333	42.9844
3	300	15	2.5	2.5	142	106	43.0458	40.5061
4	450	5	1.5	2.5	156	115	43.8625	41.2140
5	450	10	2.5	0.5	236	152	47.4582	43.6369
6	450	15	0.5	1.5	250	176	47.9588	44.9103
7	600	5	2.5	1.5	200	130	46.0206	42.2789
8	600	10	0.5	2.5	258	165	48.2324	44.3497
9	600	15	1.5	0.5	270	189	48.6273	45.5292

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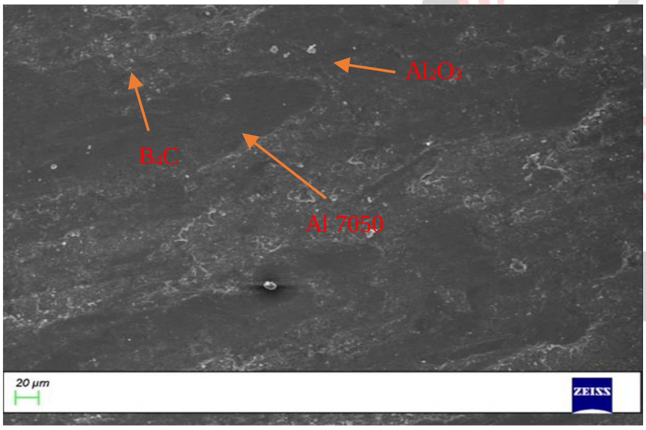
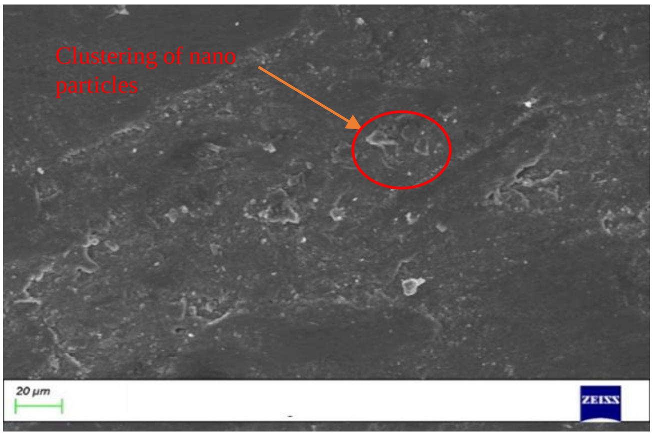
III. RESULTS AND DISCUSSION

3.1 FESEM ANALYSIS

The microstructure analysis of the fabricated AA 7050 nanocomposite is very important because it significantly affects its mechanical properties. For this purpose, FESEM is used to examine the distribution of nano B_4C and Al_2O_3 reinforcement in the AA 7050 matrix material. The FESEM images are shown in Fig 4 (a) and (b), where, B_4C nanoparticles are seen as dark phases and Al_2O_3 nanoparticles are seen as grey phases in the AA 7050 matrix. EDS analysis of the fabricated composite for the test sample-1 with 0.5% B_4C and 0.5% of Al_2O_3 nano reinforcements is shown in Fig. 5, which confirms the presence of B_4C and Al_2O_3 reinforcements in this hybrid composite. From the FESEM images, it can be deduced that a low amount (B_4C 0.5 wt% / Al_2O_3-0.5 wt%) of reinforcements are uniformly distributed in the AA 7050 matrix with good interfacial bonding exists between the matrix material and reinforcing B_4C/Al_2O_3 nanoparticles which are responsible for the higher tensile strength and hardness of the hybrid composite material. While with the increase of nano reinforcement in the Al 7050 matrix, the clustering of the nano reinforcement particles starts. This is responsible for its lower mechanical properties which can be seen in the experimental results in Table 3. Fig 4 (b) shows the agglomeration of nanoparticles at 2.5 % of B_4C / 2.5% of Al_2O_3 concentration in the Al matrix.



(a)



(b)

Fig. 4 FESEM micrographs of AA 7050 composite with (a) B_4C 0.5 wt% / Al_2O_3 0.5 wt% (b) B_4C 2.5 wt%/Al_2O_3 2.5 wt% and

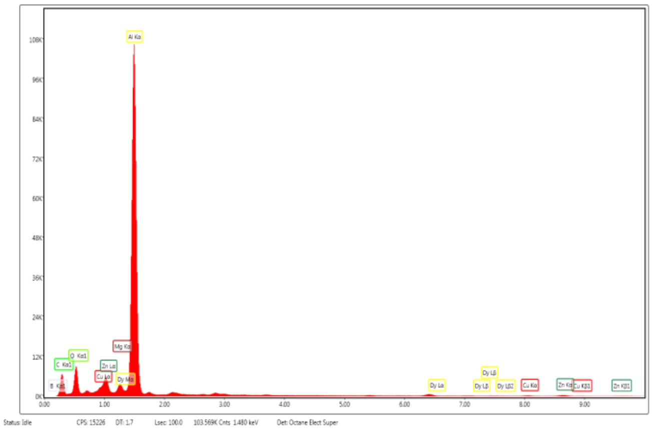


Fig. 5 EDS profile analysis for the composite with 0.5% B_4C and 0.5% of Al_2O_3 nano reinforcements.

3.2 ANALYSIS OF MECHANICAL PROPERTIES

The current study focuses, on the improvement in tensile strength and hardness of the AA 7050 alloy with the use of B_4C and Al_2O_3 nano-sized reinforcements. The introduction of these reinforcements in the AA 7050 matrix was achieved by performing the stir-casting process properly. The hardness and the tensile strength of nanocomposites were studied using standard specimens which were prepared and tested as shown in Fig 3. The results of different experiments and their S/N ratio for hardness and tensile strength are shown in Table 3. Table 3 emphasizes the mechanical properties of the AA 7050 hybrid composites, which were increased with the addition of B_4C and Al_2O_3 nanoparticles. This improvement in the mechanical properties could be due to different strengthening mechanisms for MMC such as the Hall-Petch effect, the Orowan mechanism, the mismatch in modulus of elasticity, the mismatch in different CTEs and load transfer mechanism [23],[24]. From the experimental results, this has been observed that uniformly distributed B_4C and Al_2O_3 nano-sized reinforcements provide restriction to dislocation movement in the AA 7050 matrix. Hence, the mechanical properties of the fabricated hybrid composites have increased significantly even for a small amount of B_4C and Al_2O_3 reinforcement by the Orowan strengthening mechanism [25],[26]. While the hardness and tensile strength of 2.5% Al_2O_3 and 2.5% B_4C reinforced AA 7050 hybrid composite is lower than that of the composite reinforced with the small amount of these nano reinforcements. This could be due to the agglomeration of B_4C and Al_2O_3 nano reinforcements at this high concentration and hence the reduction in mechanical properties [23].

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3.3 S/N RATIO ANALYSIS AND CONFIRMATION TEST

The effect of each input parameter on the tensile strength and hardness can be obtained from the S/N ratio response table which is given in Table 4 and Table 5 respectively. Fig. 6 (a) and (b) exhibit the mean S/N ratio graph for the different responses of the hybrid composite. A higher value of the S/N ratio shows better results due to the smaller variation between the measured output and the desired output. The results observed from the S/N response tables and graphs showed that the optimal condition for both mechanical properties i.e. hardness and tensile strength were identified at SS-3 (600 rpm), ST-2 (10 min), B_4C-1 (0.5 %), Al_2O_3-1m (0.5 %). From the S/N ratio response table, it has been established that SS-3 (47.63 dB) is marked as a chief influencing parameter for tensile strength followed by B_4C 1 (47.50 dB), Al_2O_3 -1 [47.47 dB] and ST-2 [47.21 dB]. Whereas for hardness, SS-3 (44.05 dB) has been a major influencing parameter followed by B_4C -1 (43.80 dB), Al_2O_3-1 [43.77 dB] and ST-2 [43.66 dB].

Table: 4 Mean S/N ratio response for Tensile strength

Level	Stirring Speed (rpm)	Stirring Time (min)	B_4C (wt%)	Al_2O_3 (wt%)
1	45.10	45.40	47.50	47.47
2	46.43	47.21	46.14	46.64
3	47.63	46.54	45.51	45.05
Delta	2.53	1.81	2.00	2.42
Rank	1	4	3	2

Table: 5 Mean S/N ratio response for Hardness

Level	Stirring Speed (rpm)	Stirring Time (min)	B_4C (wt%)	Al_2O_3 (wt%)
1	41.88	41.88	43.80	43.77
2	43.25	43.66	43.24	43.39
3	44.05	43.65	42.14	42.02
Delta	2.17	1.78	1.66	1.75
Rank	1	2	4	3

(a)

(b)

Fig. 6 Mean S/N ratio graphs of (a) Tensile Strength (b) Hardness

Table: 6 Confirmation test results for Tensile Strength and Hardness.

	Optimal stir-casting parameters	
	Experimental value	Predicted value
Levels	SS-600 rpm, ST-10 min, B_4C-0.5%, Al_2O_3-0.5%	
Tensile Strength (MPa)	304	
S/N ratio (dB)	49.6575	50.6538
Hardness (HV)	194	
S/N ratio (dB)	45.7560	46.0965

A confirmation test is required to be performed to validate the predicted optimum conditions by the Taguchi approach. The confirmation experiment was performed at the predicted stir-casting optimum condition for the hybrid composite, and the obtained results were shown in Table 6 for both mechanical properties. The confirmation results showed that S/N ratios for the optimal and predicted conditions are very close for both mechanical properties.

3. ANOVA ANALYSIS FOR DIFFERENT MECHANICAL PROPERTIES

ANOVA exposes the contribution of each stir-casting input parameter on the mechanical properties of the AA 7050 hybrid composite. ANOVA results for tensile strength and hardness were shown in Table 7 (a) and (b) respectively. Table 7 highlights the effect on tensile strength of stirring speed followed by Al_2O_3%, B_4C% and stirring time respectively. The percentage contribution of these input parameters was 32.04%, 30.36%, 20.85% and 16.75% respectively. Similarly, the hardness of fabricated composite was mostly influenced by stirring speed 31.69% followed by stirring time- 27.48%, Al_2O_3% - 22.12% and B_4C% - 18.71 % as shown in Table 8. From the ANOVA

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analysis, it can be seen that stirring speed was the most influencing parameter for both mechanical properties of the AA 7050 hybrid nanocomposites.

Table 7: ANOVA test results for (a) Tensile Strength (b) Hardness

Parameters	DoF	Seq SS	Adj SS	Adj MS	% Contribution
Stirring Speed (rpm)	2	9.59	9.59	4.79	32.04
Stirring Time (min)	2	5.01	5.01	2.51	16.75
B_4C (%)	2	6.24	6.24	3.12	20.85
Al_2O_3 (%)	2	9.08	9.08	4.54	30.36
Total	8	29.92			

(a)

Parameters	**DoF**	**Seq SS**	**Adj SS**	**Adj MS**	**% Contribution**
Stirring Speed (rpm)	2	7.26	7.26	3.63	31.69
Stirring Time (min)	2	6.29	6.29	3.15	27.48
B_4C (%)	2	4.28	4.28	2.14	18.71
Al_2O_3 (%)	2	5.07	5.07	2.53	22.12
Total	8	22.90			

(b)

IV. REGRESSION ANALYSIS

In the present study, the predictive mathematical models for tensile strength and hardness were developed by linear regression analysis. The dependent variable of these models was the function of stirring speed, stirring time, and wt% of B_4C and Al_2O_3. Equations (1) and (2) emphasize the two mathematical models obtained using Minitab software for the two different dependent variables i.e., tensile strength and hardness.

Tensile Strength (MPa) = 163.0 + 0.2011 Stirring Speed (rpm) + 3.30 Stirring Time (min) – 22.83 B_4C (%) - 26.17 Al_2O_3 (%) **(1)**

Hardness (HV) = 98.5 + 0.1211 Stirring Speed (rpm) + 3.267 Stirring Time (min) - 13.50 B_4C (%)- 13.83 Al_2O_3 (%) **(2)**

The capability of the above-mentioned predictive models was examined by using a factor called the coefficient of determination R^2. The determination value varies from zero to one. A higher R^2 value means that there is a good fit between the input and output variables of the stir-casting process. In the present work, R^2 values of the predictive regression models for tensile strength and hardness are 90.17% and 92.48% respectively. Different experimental results were taken randomly from the Taguchi L9 orthogonal array to validate these developed mathematical models for both tensile strengths and hardness. From the validating test, it can be seen that experimental and predicted results from the above-mentioned two mathematical models show close agreement for the given range of stir casting parameters.

Table 9 Validating results for the developed mathematical models.

Test run	**Experimental results**		**Predicted results**		**Error%**	
	Tensile strength (MPa)	Hardness (HV)	Tensile strength (MPa)	Hardness (HV)	Tensile strength (MPa)	Hardness (HV)
1	207	128	215	138	3.86	7.81
5	236	152	216	145	8.47	4.61
7	200	130	204	133	2.00	2.31
9	270	189	285	193	5.55	2.12

V. CONCLUSIONS

AA 7050 hybrid composite reinforced with B_4C and Al_2O_3 nanoparticles was successfully fabricated by the stir casting method. The optimization and the effect of different input parameters were explored using the Taguchi method. FESEM-EDS analysis was used to characterize the composition of AA 7050 hybrid composites. The following general findings were observed:

1) FESEM analysis showed that 0.5 % B_4C and 0.5 % Al_2O_3 nanoparticles were uniformly distributed in the aluminum matrix. But with the increase of the hybrid ratio of 2.5 % B_4C and 2.5 % Al_2O_3 reinforcement, the agglomeration tendency increased. EDS analysis confirmed the presence of B_4C and Al_2O_3 nanoparticles in the matrix of AA 7050.

2) Tensile strength and Hardness of the AA 7050 hybrid composites were increased with the inclusion of nano-size B_4C and Al_2O_3 reinforcements. The superior tensile strength of 304 MPa and Vickers hardness of 194 HV was obtained at an optimal condition of stirring speed of 600 rpm, stirring duration of 10 min, 0.5% of B_4C and 0.5% of Al_2O_3. Thus, better properties were observed even at a lower% of B_4C and Al_2O_3.

3) ANOVA results established the stirring speed as the most significant factor for both tensile strength and hardness with the percentage contribution of 32.04% and 31.69% respectively.

4) From the regression analysis for tensile strength and hardness, satisfactory results were obtained from the developed predictive models as compared to experimental results. The R^2 values of developed regression models for tensile strength and hardness were 90.17% and 92.48% respectively.

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