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EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF MECHANICAL PROPERTIES OF NITINOL REINFORCED COMPOSITES

Metal matrix composites (MMCs) have elevated properties when compared to their parent metals. Aluminium, due to its light weight has a versatile set of applications. In the present work, the 2024 aluminium alloy was chosen as the metal matrix, was melted and stir cast at a temperature of around 900°C along with an addition of a nickel-titanium (Ni-Ti) in powder form as the reinforcement in varying proportions (2, 4, 6, 8% weight fractions). Tests were conducted to analyse the tensile strength, impact strength, elongation and microstructure of the produced specimens. SEM micrographs revealed that the MMCs with 2 and 4 wt.% reinforcement exhibited better dispersion of the reinforcement. The composites having the 4 and 6 wt.% additions of Ni-Ti powder exhibited better ultimate tensile strength when compared to the other specimens, whereas the one with the 8 wt.% addition of Ni-Ti powder revealed better impact strength. Some agglomerations of the Ni-Ti particles were observed on the fractured surface. When evaluating the optimum result using design expert or the design of experiments, it is understood that when the data points are evenly split, either transformation or a higher order model can improve the fit to obtain the optimum result. The yield strength of the metal matrix composite which indicates the ability of the material to withstand permanent deformation varies with respect to the additions of Ni-Ti powder. It occurred that the MMCs with the 4 and 6 wt.% reinforcement produced better results when compared with the 2 and 8 wt.% ones, respectively. The impact strength of the composite containing the 8 wt.% addition exhibited better resistance when compared with the 2, 4 and 6 wt.% reinforced MMCs. It was revealed that the 8 wt.% addition of Ni-Ti powder to the metal matrix resisted fracture due to the applied load. The lower limit for the ultimate tensile strength is 186 MPa and for the upper limit it is 212.14 MPa, which are within the acceptable range; therefore, the optimum results are within the limits.

Keywords: Ni-Ti powder, metal matrix composite, reinforcement, SEM, stir casting

INTRODUCTION

Metal matrix composites are materials which combine the properties of metal materials with reinforcements to produce metal matrix composites possessing extraordinary properties. Aluminium metal matrix composites can be considered as high performance materials even though they are light-weight [1]. They are a valuable addition to the field of engineering, and hence most widely preferred in the fields of automobile, marine and aerospace applications [2]. Nickel-titanium alloys are a kind of smart materials which retain their shape even after being subjected to vibrations [3]. An investigation of Al 2024 with reinforcements was carried out by fabricating it with different weight fractions of the reinforcement using the stir casting technique. SEM analysis was performed to observe the microstructure on the surface of the composites [4]. Low density metals or alloys are considered to be the best amongst others in terms of strength, and reinforcements play a major role when fabricating a composite [5, 6]. Significant weight reduction in the material has been identified as an important factor which gives a wide scope in the design and development of commercial vehicles and aircraft [7]. During the fabrication of metal matrix composites using the stir casting technique, the best effect of the reinforcement on the composites can be observed. Two stage stir casting can enhance the mechanical properties of a composite [8, 9]. Alloys with machinability and good formability are chosen to conduct tensile and impact tests. It is evident that the suitability of aluminium alloys depends on the weight and density of the desired composite [10, 11]. Stir casting has been considered the best method to fabricate Al MMCs as it is less expensive. Investigations made on AMMCs containing wrought aluminium alloy with different weight fractions of Al_2O_3 revealed better tensile and impact strength properties than of other composites. When a composite is loaded cyclically, the developed incompatibility between the fiber and matrix can be reduced by creating a bridge between the components; hence, there are chances to enhance its strength

[12, 13]. The presence of cleavage planes, stress induced cracks, porosities and the increase in strains are evident in the fractured surfaces [14]. The main aim of the design of experiments is to determine the optimum production parameters with their levels in the production of a metal matrix composite reinforced by Ni-Ti powder using the stir casting technique [15].

EXPERIMENTAL PROCEDURE

Materials

The matrix material, Al 2024, and the reinforcement, nickel-titanium were acquired from the PMC corporation, Bangalore and Nilesh Chand Co. Ltd., Mumbai, respectively. The reinforcement materials were ground into powder of 150 microns. The density of the Al 2024 is 2800 kg/m^3 and Ni-Ti is 6450 kg/m^3. The matrix material was mixed with the reinforcement in proportions of 2, 4, 6 and 8 wt.%.

Composite fabrication

The composite was prepared by melting Al 2024 and mixing with Ni-Ti powder in different proportions by the stir casting process (Fig. 1). The composites containing various weight fractions of 2, 4, 6 and 8 wt.% of the reinforcement material were denoted as sample numbers S1, S2, S3 and S4, respectively. The casting temperature of the specimens in the mould was maintained between 1000±15°C with the help of an electronic controller, and the melt was homogenized at 900°C. Graphite paste was used as the mould releasing agent, which was preheated to a temperature of 200°C. The cold rolling process was carried out after casting so as to enhance the compactness within the cast plate. The plates were cut into 150 mm x 150 mm x 6 mm specimens using water jet machining. All the composites underwent spectrochemical analysis to discover their exact chemical composition, which are given in Table 1.

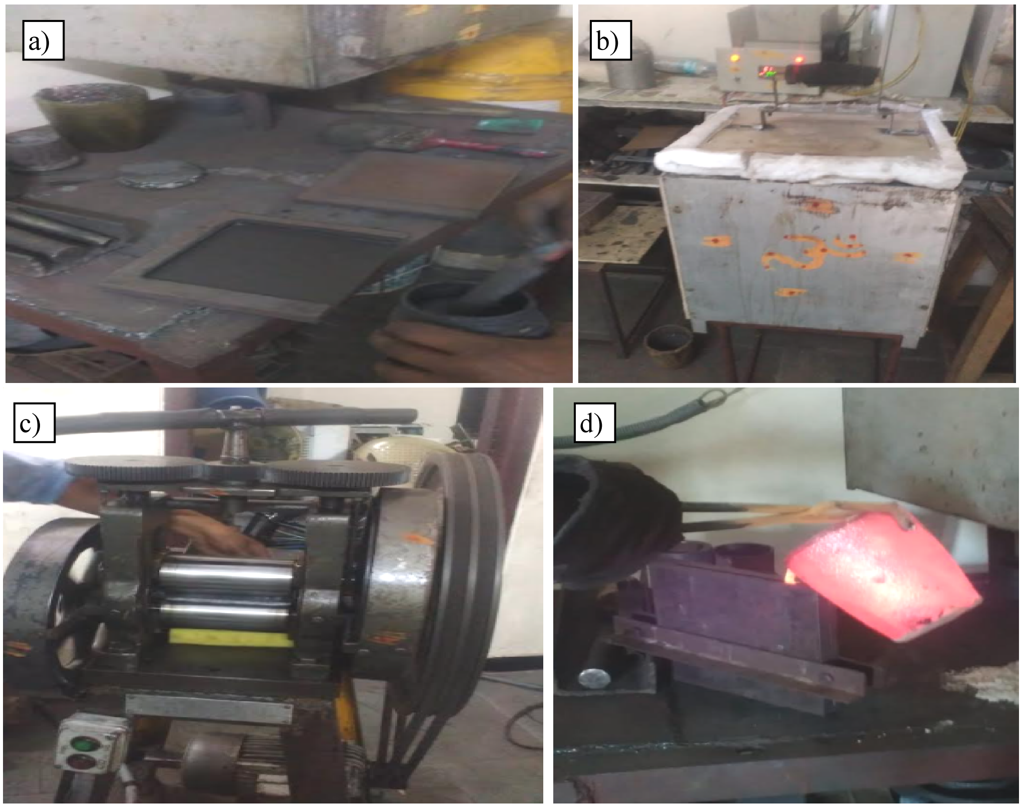

Fig. 1. Stir casting equipment (a), graphite paste coating (b), pouring molten metal in to mould (c), cold rolling (d)

TABLE 1. **Chemical composition of matrix material and different weight fractions of composite**

	Constituent [%]											
Material	Cu	Mg	Mn	Fe	Si	Zn	Ni	Cr	Pb	Sn	Ti	Li	Balance
Al 2024	4.41	1.36	0.54	0.23	0.07	0.04	0.02	0.022	0.013	0.008	0.04	0.001	Al
S1	4.52	1.47	0.51	0.20	0.13	0.04	0.85	0.017	0.007	0.001	0.91	0.001	Al
S2	4.42	1.3	0.48	0.24	0.05	0.06	1.54	0.017	0.009	0.004	1.43	0.001	Al
S3	4.11	1.04	0.47	0.24	0.07	0.07	2.2	0.019	0.009	0.004	1.44	0.001	Al
S4	3.91	0.73	0.28	0.12	0.05	0.003	2.81	0.054	0.02	0.026	1.98	0.001	Al

Tensile test

Dog bone shaped specimens of 150 mm x 20 mm x 6 mm as per the ASTM E8 standard were cut from the rectangular plates of the Ni-Ti reinforced Al 2024 composites for different weight fractions of reinforcement using water jet machining. These specimens were tested by means of an INSTRON-8801 computerized universal testing machine.

Impact strength

Specimens of a size as per the ASTM E23-86 standard were cut from the Al 2024 Ni-Ti reinforced composites for the different weight fractions of reinforcemen: 55 mm x 10 mm x 6 mm from the plates using water jet machining. These specimens were tested by a pendulum impact testing machine, model KT300, with maximum impact energy of the pendulum of 168 J by Krystol Elmec.

Scanning electron microscopy

Microstructural studies of the aluminium metal matrix composites were performed employing a scanning electron microscope on 15 mm x 15 mm x 6 mm as per ASTM standards (Fig 2).

Fig. 2. Scanning electron microscope

RESULTS AND DISCUSSIONS

Tensile strength

Figure 4 represents the plot of the ultimate tensile strength to weight percentage of nickel-titanium powder. As the inclusion of the additive increases to 2 wt.% the ultimate tensile strength falls; at 4 wt.% of the additive the ultimate tensile strength increased and with further inclusions the UTS dropped. The Al MMC with the 6 wt.% addition of Ni-Ti powder exhibited an ultimate tensile strength of 212.14 MPa when compared with the 2, 4 and 8 wt.%. As the weight percentage of the additive increases, the porosity rises by 0.909% [16] resulting in a reduction in strength, performance and quality of the composite.

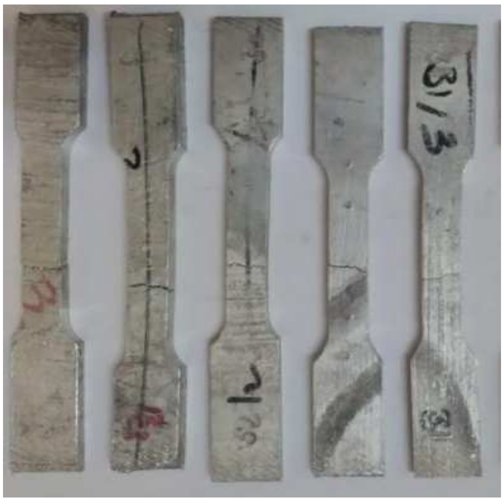

Fig. 3. Specimens after ultimate tensile strength test

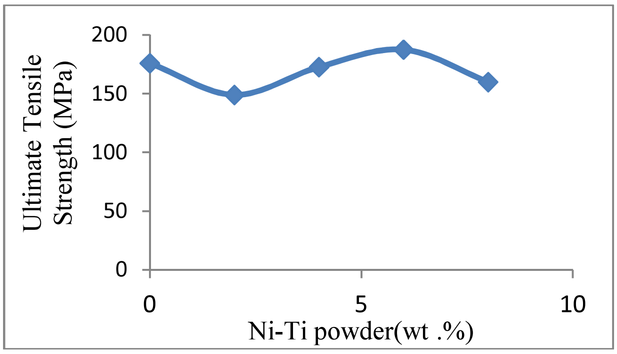

Fig. 4. Ultimate tensile strength vs wt.% Ni-Ti powder

Impact strength

(Figs. 5 and 6)

Fig. 5. Specimen before impact test

Fig. 6. Specimen after impact test

Figure 7 presents the plot for the impact strength to weight percentage of the nickel-titanium powder. The impact strength of the Al metal matrix composite rose with the increase in the weight percentage of Ni-Ti powder. The MMC with the 8 wt.% addition of Ni-Ti powder exhibited better results when we compare it with the 2, 4 and 6 wt.% reinforcement of Ni-Ti powder.

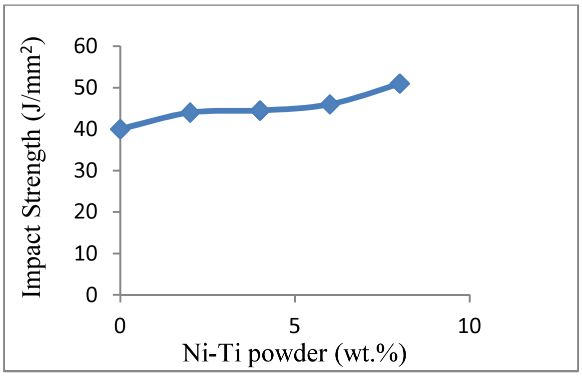

Fig. 7. Impact strength vs wt.% Ni-Ti powder

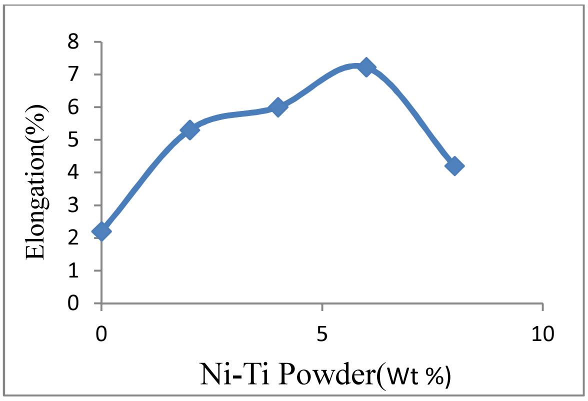

Fig. 8. Elongation vs wt.% Ni-Ti powder

Figure 8 shows the plot for the elongation to weight percentage of the nickel-titanium powder. As the additive to the Al matrix metal increases, the elongation factor increases, and consequently, it raises the ability of the material to withstand changes in temperature. The above graph illustrates that the 6 wt.% reinforcement results in better elongation when compared with the 2, 4 and 8 wt.% additions.

Scanning Electron Microscopy

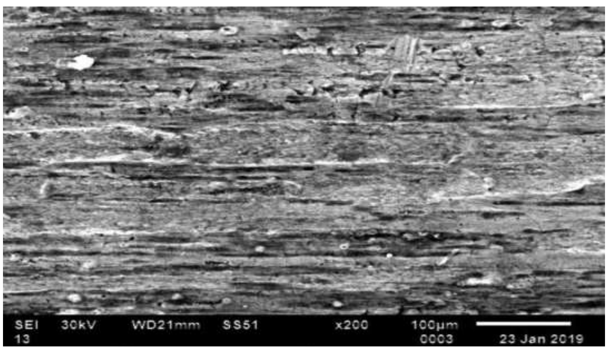

Fig. 9. SEM micrograph of Al 2024

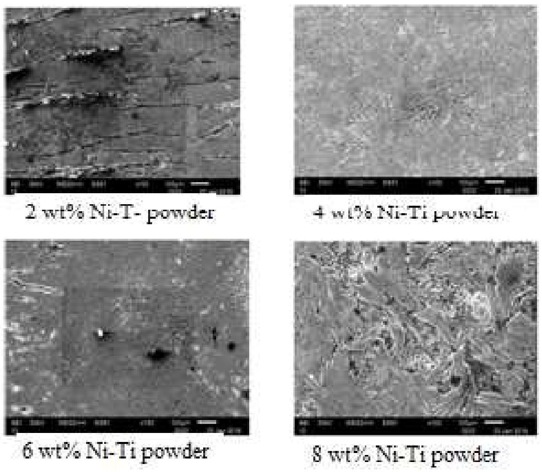

Fig. 10. SEM micrographs of Al MMCs

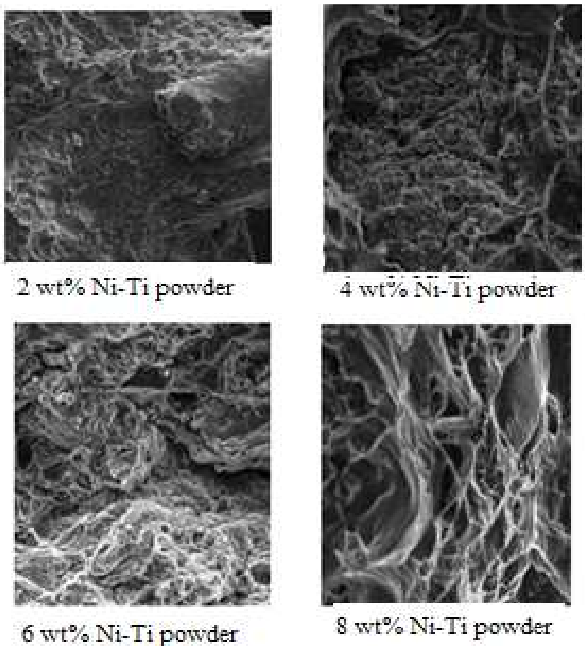

Fig. 11. SEM micrograph of Al MMCs after fracture in tensile test

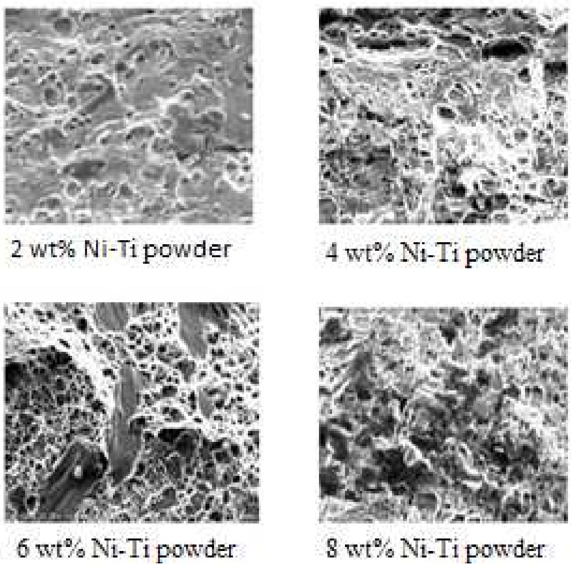

Fig. 12. SEM micrographs of Al MMCs after fracture in impact test

The microstructure of the 2024 aluminium alloy reinforced with Ni-Ti powder in different weight fractions were observed using a scanning electron microscope (Fig. 9). The microstructural study of the MMCs (Fig. 10) proved that the Al MMCs (Fig. 11) with the 4 wt.% and 8 wt.% additions of Ni-Ti powder have a silvery grey-white metallic appearance when compared with the other specimens. The 2 wt.% and 6 wt.% reinforcement of Nitinol powder exhibit better and more uniform dispersion, which result in an increase in the strength and hardness of the specimen. The micrographs of the fracture surface determines that the addition of Ni-Ti to the metal matrix composite exhibited better impact strength (Fig. 12). A dimpled fracture surface is observed with the 6 wt.% addition, characterized by the formation of micro voids that accumulate along the grain boundaries of the specimen.

Design expert

Design expert is a statistical software package used to perform comparative tests, characterization, and optimization of mixture designs and combined designs. The present work focused on evaluating the suggested value during the design stage, which can be used further to optimize the quality, cost and method of design for an overall benefit. During the optimization of certain parameters, the UTS of 212.14 MPa for the metal matrix composite with the 6 wt.% addition of Ni-Ti is taken into consideration for the optimal output.

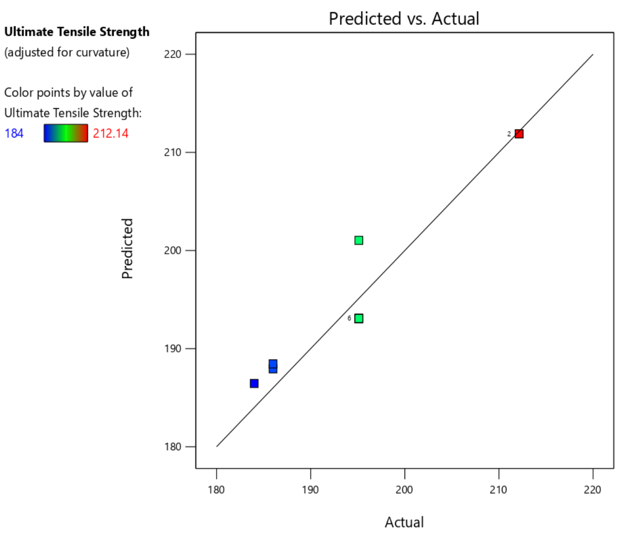

Fig. 13. Predicted vs actual ultimate tensile strength

Figure 13 presents the predicted vs actual values of the ultimate tensile strength. It helps to detect the points that are not exactly predicted by the model. The data points that are specified should be evenly split with respect to the 45 degree line. The figure shows that a higher order model or transformation can improve the fit as the points in the figure are not evenly split.

Figure 14 displays the 3D model for the weight percentage vs ultimate tensile strength vs load. The model determines that the maximum tensile load which can be withstood by the metal matrix composite is approximately 212.14 MPa. The design points in the model indicate the strength defining factor for the specimen.

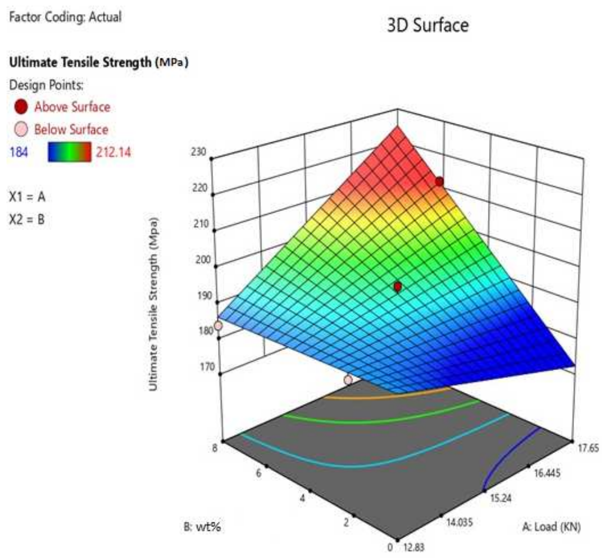

Fig. 14. Ultimate tensile strength vs wt.% vs load

ANOVA for 2FI model

TABLE 2. **Response 1 Ultimate tensile strength**

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	791.56	3	263.85	27.78	0.0001	significant
A-Load	192.81	1	192.81	20.30	0.0020	
B-Weight Percentage	153.41	1	153.41	16.15	0.0038	
AB	215.81	1	215.81	22.72	0.0014	
Residual	75.98	8	9.50			
Lack of Fit	75.98	2	37.99			
Pure Error	0.0000	6	0.0000			
Total	867.54	11				

TABLE 3. **Fit Statistics**

Std. Dev.	3.08	**R^2**	0.9124
Mean	195.51	**Adjusted R^2**	0.8796
C.V.%	1.58	**Predicted R^2**	−0.3422
		Adeq Precision	14.2953

TABLE 4. **Coefficients in terms of coded factors**

Factor	Coefficient estimate	df	Standard error	95% CI low	95% CI high	VIF
Intercept	193.08	1	1.02	190.72	195.44	
A-Load	5.63	1	1.25	2.75	8.51	1.31
B-wt.%	12.68	1	3.16	5.41	19.96	2.01
AB	13.68	1	2.87	7.06	20.30	1.85

TABLE 5. **Final equation in terms of coded factors**

Ultimate tensile strength =
+193.08
+5.63 * A
+12.68 * B
+13.68 *AB

TABLE 6. **Final equation in terms of actual factors**

Ultimate tensile strength =
+231.30357
–3.34045 * Load
–18.45506 * wt.%
+1.41900 * Load * wt.%

Fit Summary

The design of experiments identifies the suggested model which exactly fits in the summary so that the best possible outcome can be obtained (Tables 3 and 4). After examining the summary statistics, we can choose the model which fits the design or we can select different models as per the requirement (Tables 5 and 6).

The two-factor interaction which includes two independent variables that actually fit in each point in the design, suggests that 215.81 MPa is the ultimate tensile strength (Tables 7-9).

Table 10 contains one row of each response; p-values less than 0.01 suggest that the optimum design is significant and are colour coded red. If the same p-values are greater than 0.01 they can be considered as very significant and hence are colour coded green. Hence, the two-factor interaction suggests that 215.81 MPa can be chosen as the optimum value to obtain the ultimate tensile strength.

TABLE 7. **Response 1 ultimate tensile strength**

Source	Sequential p-value	Lack of it p-value	Adjusted R^2	Predicted R^2	
Linear	0.0074		0.5889	–1.8696	
2FI	0.0014		0.8796	–0.3422	Suggested
Quadratic			1.0000		
Cubic					

TABLE 8. **Sum of squares sequential model [Type I]**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs total	4.587E+05	1	4.587E+05			
Linear vs mean	575.75	2	287.87	8.88	0.0074	
2FI vs linear	215.81	1	215.81	22.72	0.0014	Suggested
Quadratic vs 2FI	75.98	2	37.99			
Cubic vs quadratic	0.0000	0				
Residual	0.0000	6	0.0000			
Total	4.596E+05	12	38296.45			

TABLE 9. **Model summary statistics**

Source	Std Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	5.69	0.6637	0.5889	-1.8696	2489.47	
2FI	3.08	0.9124	0.8796	-0.3422	1164.44	Suggested
Quadratic	0.0000	1.0000	1.0000			
Cubic						

TABLE 10. **Coefficients table**

	Intercept	A	B	AB	A^2	B^2
Ultimate tensile strength	193.077	5.62868	12.6821	13.6792		
p-values		0.0020	0.0038	0.0014		
Elongation	5.26738	1.97978	–0.268594			
p-values		0.0007	0.7451			

CONCLUSIONS

In the present work, the Al 2024 alloy was stir casted at a temperature of around 900°C with Ni-Ti powder as the reinforcement in weight proportions of 2, 4, 6 and 8% respectively. From the research results it can be concluded that the reinforcement has a vital role to play in determining the mechanical and microstructural properties of the metal matrix composite. The microstructure of Al 2024 reinforced with Ni-Ti powder after fracture was observed. The fracture surface reveals that the 4 and 6 wt.% Ni-Ti composites have brittle and transgranular failure and the 2 and 8 wt.% Ni-Ti composites have brittle and intergranular failure. It is suggested that two factor interaction using the design of experiments can certainly improve the ultimate tensile strength and further can enhance the elongation of the given material. The results conclude that based on the obtained p-values the optimum result can be identified.

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