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Enhancing and Predicting Microhardness of Al 7075 Hybrid Composites Reinforced with TiC and Graphite Using ANOVA and Regression

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Abstract:

The mechanical behavior of metal matrix composites (MMCs) is significantly influenced by the type and proportion of reinforcements used. This study investigates the hardness characteristics of Al 7075 hybrid composites reinforced with Titanium Carbide (TiC) and Graphite through a structured factorial design approach. Ten distinct composite formulations were prepared by varying TiC (1, 3, 5 wt.%) and Graphite (1, 3, 5 wt.%) contents, including an unreinforced control sample. The composites were fabricated using the bottom-pouring stir casting technique, ensuring uniform dispersion of reinforcements. Vickers micro hardness testing was conducted to evaluate surface hardness, and the results revealed values ranging from 66 HV to 85 HV. The maximum hardness was recorded for the composite containing 5 wt.% TiC and 5 wt.% Graphite. The experimental design was statistically validated using regression modeling and ANOVA, with a coefficient of determination (R^2) of 0.8233 and Adeq Precision of 8.42, indicating a strong predictive model and good signal-to-noise ratio. The results confirmed that both TiC and Graphite significantly enhance hardness through mechanisms such as grain refinement, dislocation generation, and load-bearing reinforcement. The factorial design approach proved effective for analyzing individual and interaction effects, offering an optimized route for developing high-performance hybrid composites.

Keywords: Al 7075, TiC, Graphite, Microhardness, Hybrid composites, Factorial design

Introduction

Aluminum matrix composites (AMCs) have emerged as promising materials for aerospace, automotive, and defense applications due to their superior mechanical properties, excellent corrosion resistance, and lightweight nature compared to conventional metals [1], [2]. Among them, Al 7075 is a widely used high-strength aluminum alloy prized for its exceptional strength-to-weight ratio and structural integrity. However, its relatively low surface hardness and wear resistance hinder its broader application in high-friction environments [3].

To address these limitations, ceramic reinforcements such as Titanium Carbide (TiC) have been investigated. TiC offers high hardness, excellent thermal stability, and good interfacial compatibility with aluminum matrices, making it an effective reinforcement for improving surface hardness and wear resistance [4], [5]. In parallel, solid lubricants like Graphite have gained attention for their ability to reduce friction and enhance wear resistance in composites [6]. Nevertheless, the inherent softness of Graphite may compromise overall hardness if its content is not optimally balanced [7].

While TiC and Graphite have been studied individually, the synergistic effect of their combination within an Al 7075 matrix remains underexplored—particularly in relation to mechanical hardness. Furthermore, the simultaneous influence of these reinforcements demands a statistically guided investigation to identify optimal combinations. The Design of Experiments (DoE), especially full factorial design, provides a robust framework to evaluate such multivariate interactions and to develop predictive models for property optimization [8].

This study aims to investigate the influence of varying weight percentages of TiC and Graphite on the hardness of Al 7075 composites. Using a full factorial experimental design, the individual and interaction effects of these reinforcements are modeled and analyzed. The goal is to determine the optimal reinforcement configuration that maximizes hardness and to develop a statistically validated regression model to predict hardness within the experimental domain.

Experimental Procedure

In this study, aluminum alloy 7075 (Al 7075) was selected as the matrix material owing to its high strength-to-weight ratio and widespread application in aerospace and structural industries [9]. The composites were reinforced with a constant 3 wt.% of Titanium Carbide (TiC) and varying amounts of Graphite (1 wt.%, 3 wt.%, and 5 wt.%) to examine the effect of hybrid reinforcement on hardness characteristics. The chemical composition of Al 7075 is provided in Table 1.

Table 1: Composition for aluminium alloy 7075

Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
1.12	0.35	1.4	0.81	2.4	5.8	0.25	0.56	leftover

The composites were fabricated using the bottom-pouring stir casting technique, a well-established process for producing particle-reinforced metal matrix composites due to its simplicity, scalability, and cost-effectiveness [10], [11]. A schematic and photographic view of the stir casting setup is presented in Figure 1.

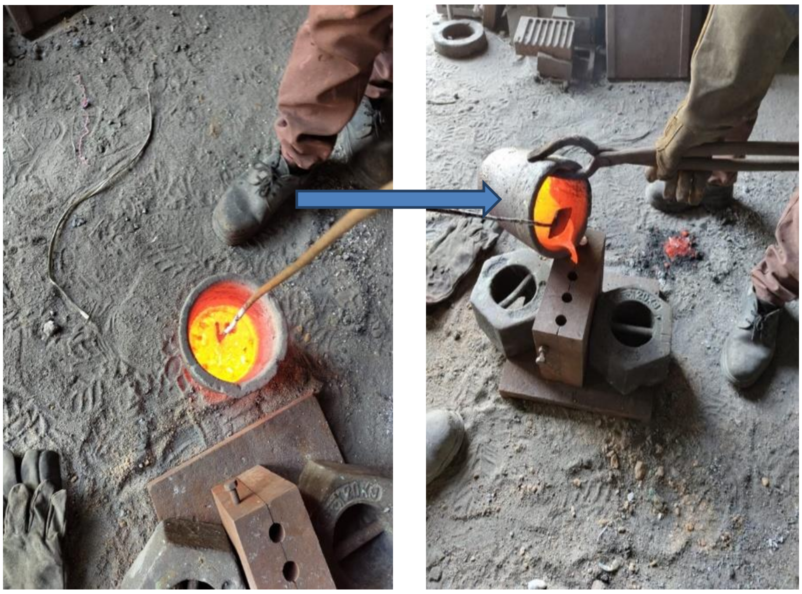


Fig.1. A schematic and photographic view of the experimental setup

During the fabrication process, Al 7075 ingots were first melted in a graphite crucible using an electric resistance furnace at approximately 750 ± 10 °C. The TiC and Graphite powders, both of high purity (>99%) and fine particle size (typically <50 µm), were preheated separately to around 250–300 °C to eliminate moisture and prevent thermal shock. These reinforcements were then gradually added to the molten aluminum under continuous mechanical stirring at 400–600 rpm for 10–15 minutes, ensuring uniform dispersion.

Before reinforcement addition, slag was removed from the melt surface to improve interfacial bonding. TiC particles were preheated to 300–400 °C to remove moisture and improve wettability—a critical step in minimizing agglomeration and enhancing the particle–matrix interface [13]. A fixed 3 wt.% of TiC was introduced slowly into the vortex, followed by the controlled addition of Graphite at the specified weight percentages.

The composite melt was then transferred via a bottom-pouring setup into a preheated permanent steel mold of 20 mm diameter and 150 mm length, as shown in Figure 2. Bottom pouring helped reduce oxidation, gas entrapment, and slag inclusions, which are critical for achieving a high-quality composite [14].

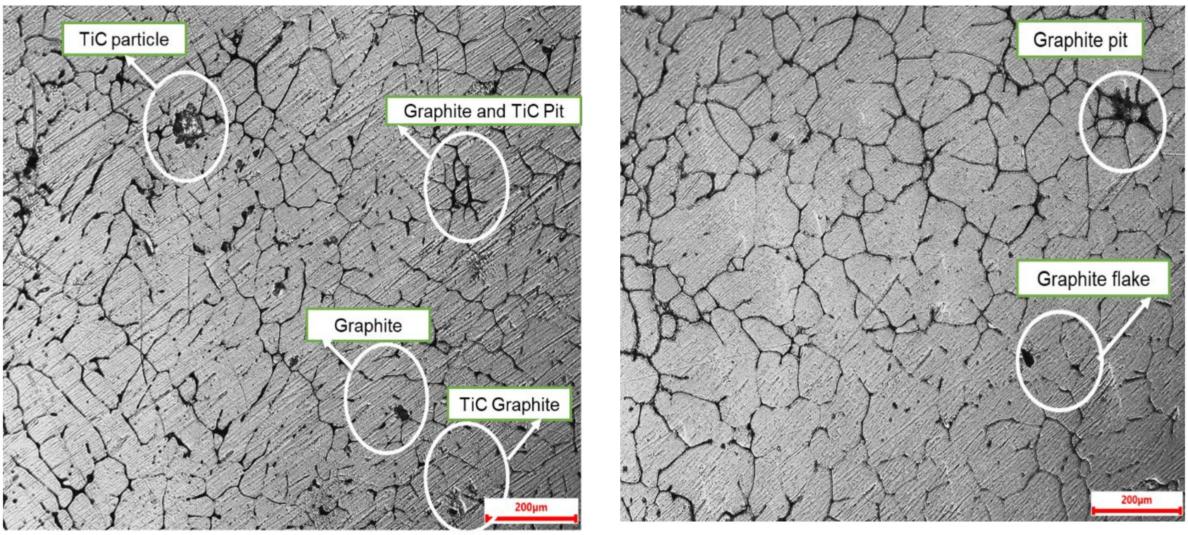
Figure 2: Specimens Prepared

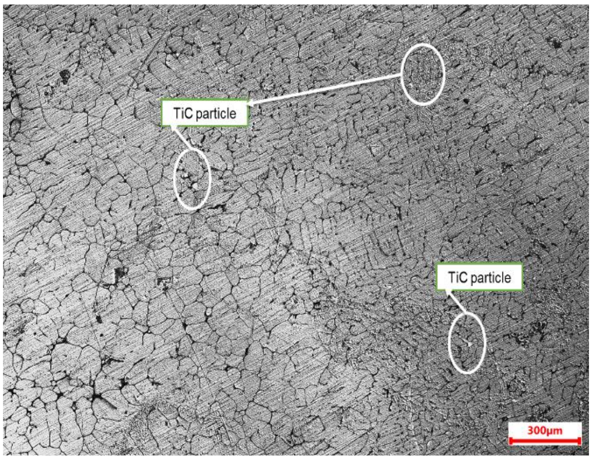
The cast ingots were allowed to cool under ambient conditions and were later machined into standard cylindrical specimens (10 mm diameter × 10 mm height) for hardness testing. Hardness measurements were carried out using a Rockwell hardness tester following ASTM E18 standards. Each specimen was indented at three different locations, and the average value was reported to minimize experimental variation.

Results and discussion:

Microstructural Characterization and Analysis

The microstructure of the fabricated Al 7075/TiC/Graphite composites provides valuable insights into the morphology, dispersion, and interfacial interaction of reinforcements within the aluminum matrix. Representative optical micrographs are presented in Figure 3.





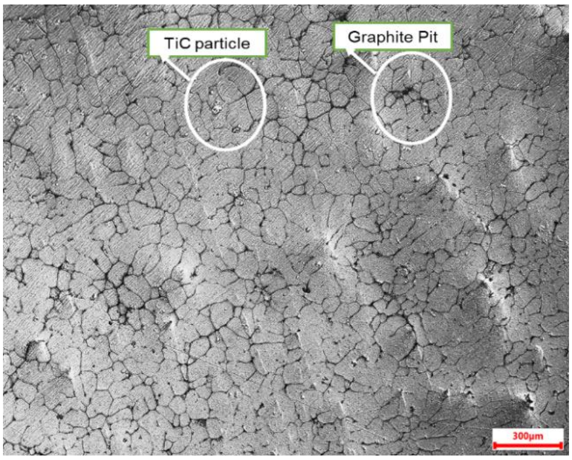


Figure 3. Microstructures of Al 7075 with 3wt.% TiC (a) 0 wt.% Gr, (b) 1 wt.% Gr, (c) 3 wt.% Gr and (d) 5 wt.% Gr

The images reveal a dendritic α-Al matrix interspersed with **discrete TiC particles** and Graphite phases, located along both grain boundaries and matrix interiors. The TiC particles are distinguishable as dark, angular, and well-distributed entities across the matrix (visible in the lower left and lower right images of Figure 3). These reinforcements act as heterogeneous nucleation sites during solidification, contributing to grain refinement and thereby improving hardness and mechanical integrity [19]. Their sharp morphology and intrinsic hardness enhance the load-bearing capability and inhibit plastic deformation [20].

Graphite, on the other hand, is observed in the form of discontinuous flakes or pits, predominantly aligned along grain boundaries or dispersed within the matrix (as seen in the top right and top left images). Graphite serves as a solid lubricant, effectively lowering friction and enhancing wear resistance [21]. However, excessive Graphite content or poor wettability may lead to porosity and interfacial weaknesses, evidenced by the presence of Graphite-induced pits in Figure 3 [22].

Interestingly, the micrographs also show localized zones where TiC and Graphite coexist, indicating partial clustering or agglomeration (top left image). While TiC exhibits good interfacial bonding—attributable to preheating and surface activation—Graphite may show partial detachment, resulting in micro-voids. This phenomenon is commonly observed in hybrid composites with both ceramic and soft-phase reinforcements, and can influence local mechanical properties [23].

The matrix itself displays a fine dendritic structure, suggesting effective grain refinement. This is likely due to thermal mismatch-induced dislocation zones around TiC particles and the growth-interruption effect of both reinforcements during solidification [24]. The relatively uniform dispersion and minimal agglomeration observed validate the optimized stirring parameters and bottom-pouring casting process, ensuring composite homogeneity and repeatability in mechanical behavior.

Hardness Testing

The Vickers microhardness test was employed to evaluate the surface hardness of the fabricated Al 7075-based hybrid metal matrix composites. Prior to testing, the specimens (Figure 4) were carefully sectioned and metallographically polished. The surface preparation involved sequential grinding with silicon carbide abrasive papers of increasing fineness, followed by final polishing using a 1 μm diamond suspension to achieve a smooth, mirror-like finish.

Hardness measurements were conducted using a Vickers microhardness tester equipped with a diamond pyramidal indenter having an included angle of 136° between opposite faces. A test load of 0.1 kgf (100 grams) was applied for a dwell time of 10 seconds, allowing precise indentation while minimizing the effects of substrate deformation or work hardening.

Indentations were performed at multiple, well-separated locations on the polished surface to prevent any interference or stress field overlap between adjacent marks. The diagonals of each indentation were measured using the tester's built-in optical microscope, and the Vickers hardness number (HV) was computed using the standard formula:

$HV=1.8544\times F/ d^2$

where:

- "F" is the applied load in kilogram-force (kg-f),
- "d" is the average length of the two diagonals in millimeters (mm).

To ensure accuracy and reproducibility, five measurements were taken for each specimen, and the average HV value was reported.

This testing procedure enabled a comprehensive understanding of how TiC and Graphite reinforcements influence the surface hardness behavior of the hybrid composite. The results served as a critical input for further statistical analysis and regression modeling.

The enhancement in surface hardness of the Al 7075-based hybrid composites can be attributed to multiple reinforcing mechanisms. Primarily, the incorporation of hard and thermally stable Titanium Carbide (TiC) ceramic particles serves as a strong barrier to dislocation motion, thereby increasing dislocation density within the aluminum matrix [16]. In addition, the thermal mismatch between the Al 7075 matrix and the reinforcements generates plastic strain during the solidification process. This mismatch leads to grain refinement**,** which contributes to hardness improvement through the well-established Hall–Petch effect [17].

Another contributing factor is the effective interfacial bonding between the α-Al matrix and the dispersed TiC and Graphite particles. This strong matrix–reinforcement interface enhances load transfer capabilities**,** thereby resisting plastic deformation and improving the composite's overall mechanical response [18]. Collectively, these microstructural improvements particle strengthening, grain boundary refinement, and load-sharing mechanisms, explain the significant increase in hardness observed across the composite samples.

The Vickers hardness values obtained from 16 experimental trials ranged from 66 HV to 85 HV**,** indicating a considerable influence of the hybrid reinforcement combination. The maximum hardness was recorded for the composite reinforced with 5 wt.% TiC and 5 wt.% Graphite**,** as illustrated in Figure 5**,** demonstrating a synergistic effect of the dual-phase reinforcement when present in higher proportions.

The graph shows the variation in microhardness (VHN) of Al 7075 composites reinforced with different weight percentages of graphite (Gr%) and fixed weight percentages of TiC (1, 3, and 5 wt.%).

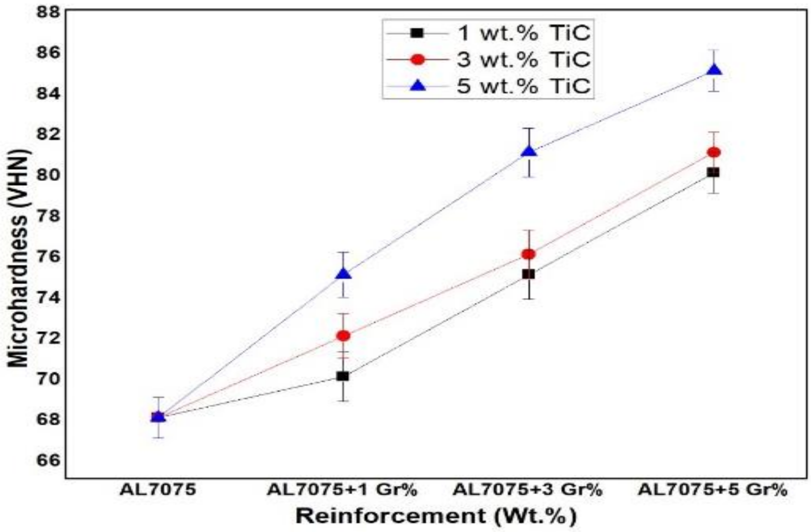


Figure 4. Effect of varying Graphite content (Gr wt. %) on the microhardness of Al7075 composites at different TiC reinforcement levels (1 wt.%, 3 wt.%, and 5 wt.%).

Figure 4 illustrates the influence of varying Graphite reinforcement (Gr wt.%) on the microhardness of Al 7075 composites containing three different TiC weight percentages (1 wt.%, 3 wt.%, and 5 wt.%). It is evident from the graph that the microhardness increases progressively with the addition of graphite for all three TiC concentrations. Among the samples, the composite with 5 wt.% TiC and 5 wt.% Gr exhibited the highest microhardness value, reaching approximately 85 VHN. This enhancement in hardness is primarily attributed to the uniform dispersion and synergistic hardening effect of TiC and Gr particles in the Al7075 matrix. The reinforcing effect becomes more significant at higher TiC contents, indicating the role of ceramic particles in hindering dislocation motion and improving the composite's resistance to deformation.

Optimization of Hardness using Design expert with ANOVA technique:

Table 2: ANOVA table with full factorial design for Hardness

		TiC	Graphite	Response
Std	Run	A:A	B:B	Micro-Hardness
12	1	1	0	70
15	2	0	0	68
13	3	0	5	71
11	4	3	1	75
1	5	0	3	66
8	6	5	0	69
7	7	1	1	70
6	8	5	1	80
3	9	5	3	76
14	10	3	5	81

9	11	5	5	85
4	12	3	0	76
16	13	1	5	75
10	14	3	3	79
2	15	0	1	69
5	16	1	3	70

A = TiC wt.%
B = Graphite wt.%

The experimental results for microhardness of Al 7075 composites reinforced with varying weight percentages of TiC and Graphite are tabulated above Table 4.8. The base alloy (Al 7075 without reinforcement) exhibited a hardness of 68 VHN. With the introduction of TiC or Graphite individually, a marginal increase in hardness was observed. For instance, a composite with 1 wt.% TiC showed an increase to 70 VHN, while 1 wt.% graphite resulted in 69 VHN. The highest hardness value of 85 VHN was recorded for the composite with 5 wt.% TiC and 5 wt.% Gr, indicating a clear synergistic effect of dual reinforcement. Across the dataset, it is evident that both TiC and Gr positively contribute to hardness enhancement, with TiC having a more pronounced effect due to its ceramic nature. Furthermore, when both reinforcements were combined, the microhardness increased significantly with higher weight percentages. These results are consistent with the trend observed in Figure 4.20**,** where microhardness improves systematically with increasing reinforcement content, particularly when TiC is present in higher concentrations.

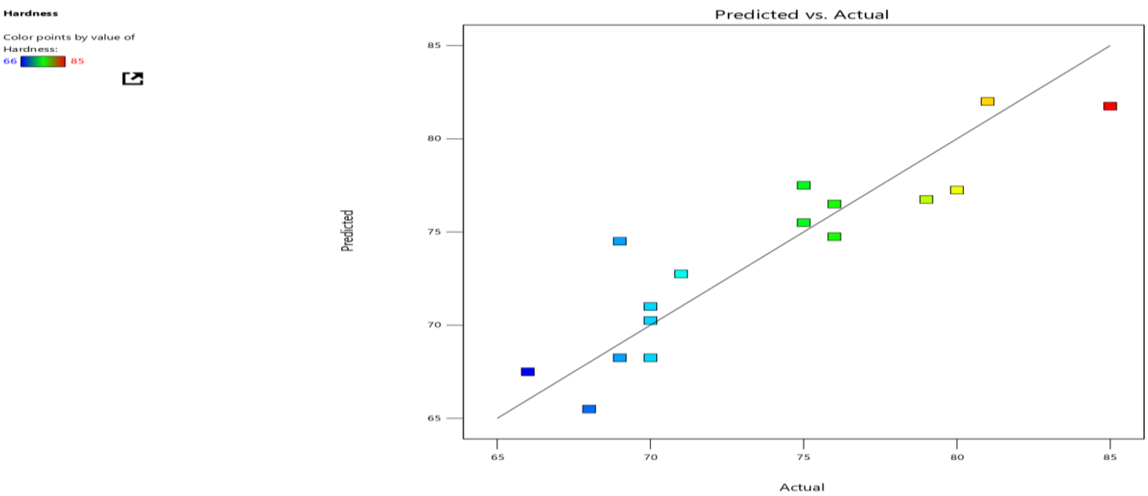


Figure 5. Effect of varying Graphite content (Gr wt. %) on the microhardness of Al7075 composites at different TiC reinforcement with predicted and actual values.

The optimization of microhardness was carried out using a full factorial design of experiments with two input variables: A – TiC wt.% and B – Graphite wt.%, each varied at four levels. The experimental matrix was analyzed using the Analysis of Variance (ANOVA) technique in Design-Expert® software to evaluate the significance of individual parameters on hardness response.

The ANOVA results (Table 4.8) indicate that both TiC (A) and Graphite (B) significantly influence the microhardness of the Al7075 matrix composites. The P-value for TiC was 0.0035, which is well below the 0.05 threshold, confirming a strong and statistically significant effect on hardness. Similarly, Graphite also exhibited a significant influence with a P-value of 0.0391. The F-values for TiC and Graphite were 9.70 and 4.27 respectively, further establishing the dominant role of TiC in improving hardness due to its ceramic nature, while graphite contributes through solid lubrication and matrix strengthening.

Table 3: ANOVA Table for Microhardness (Full Factorial Design – Main Effects Model)

Source	**Sum of Squares**	**DF**	**F-Value**	**P-Value**
A – TiC	255.5	3	9.7025	0.0035
B – Graphite	112.5	3	4.2722	0.0391
Residual	79	9		

This analysis confirms that increasing the weight percentages of TiC and graphite in the Al 7075 alloy matrix contributes significantly to the enhancement of microhardness. The optimized combination resulting in maximum hardness (85 VHN) was achieved at 5 wt.% TiC and 5 wt.% Graphite, validating the statistical findings from the model.

ANOVA and Model Adequacy

The Analysis of Variance (ANOVA) was employed to assess the statistical significance and adequacy of the developed model for predicting the microhardness of Al7075–TiC–Gr composites. The results confirmed that the selected model is statistically significant, with a model F-value of 6.99 and a p-value of 0.0054, which is well below the 0.05 significance threshold. This indicates that the probability of the model's output being due to noise is very low. Further analysis revealed that both input parameters—Factor A (TiC) and Factor B (Graphite) have significant effects on the response. TiC demonstrated a stronger influence on microhardness, with an F-value of 9.70 and a p-value of 0.0035, indicating a high level of statistical significance. Graphite also showed a meaningful effect, with an F-value of 4.27 and a p-value of 0.0391. These results validate that the microhardness of the composite is significantly enhanced by increasing the content of both TiC and graphite reinforcements. The model thus adequately represents the behavior of the system and can be reliably used for optimization and prediction.

Model Adequacy and Fit Statistics

The adequacy of the developed regression model was further validated using various statistical metrics. The standard deviation (Std. Dev.) of the model was found to be 2.96, and the mean response (microhardness) across all experiments was 73.75 VHN, resulting in a coefficient of variation (C.V.%) of 4.02%, which indicates good model precision and low variability in the experimental data.

Table 4: Fit Statistics

Std. Dev.	2.96	**R^2**	0.8233
Mean	73.75	**Adjusted R^2**	0.7054
C.V. %	4.02	**Predicted R^2**	0.4414
		Adeq Precision	8.4198

The coefficient of determination (R^2) was 0.8233, signifying that approximately 82.33% of the variability in microhardness is explained by the model. The Adjusted R^2 value of 0.7054 further confirms that the model remains robust after adjusting for the number of predictors. However, the Predicted R^2 value was 0.4414, indicating some discrepancy between the predicted and observed values, which could be due to unmodeled higher-order interactions or experimental noise. Nonetheless, the model exhibited an Adequate Precision value of 8.4198, which is well above the desired threshold of 4, confirming that the model has a sufficient signal-to-noise ratio and can be effectively used to navigate the design space.

Collectively, these statistics confirm the adequacy of the developed model in representing the microhardness behavior of Al 7075 composites reinforced with TiC and graphite, making it suitable for predictive and optimization purposes.

Regression Coefficients and Model Interpretation

Table 5: Fit Statistics

Term	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High
Intercept	73.75	1	0.7407	72.07	75.43
A[1]	-5.25	1	1.28	-8.15	-2.35
A[2]	-2.50	1	1.28	-5.40	0.4021
A[3]	4.00	1	1.28	1.10	6.90
B[1]	-3.00	1	1.28	-5.90	-0.0979
B[2]	-0.2500	1	1.28	-3.15	2.65
B[3]	-1.0000	1	1.28	-3.90	1.90

The coefficients of the fitted model, calculated in terms of coded factors, provide insights into how each level of the factors TiC (A) and Graphite (B) affects the microhardness of the Al7075 composite. The intercept was estimated as 73.75, which represents the overall average response across all experimental runs in this orthogonal design.

For factor **A (TiC)**, the level-wise coefficients indicate that:

- A[1] (1 wt.% TiC) has a significant negative effect on hardness (–5.25, $p < 0.05$), with a 95% confidence interval from –8.15 to –2.35.
- A[2] (3 wt.% TiC) shows a smaller negative effect (–2.50) but is not statistically significant at the 5% level.
- A[3] (5 wt.% TiC) contributes a positive and statistically significant effect (+4.00, 95% CI: 1.10 to 6.90), indicating substantial improvement in hardness at higher TiC content.

For factor B (Graphite):

- B[1] (1 wt.% Gr) also has a negative and statistically significant effect on hardness (–3.00, 95% CI: –5.90 to –0.0979).
- B[2] (3 wt.%) and B[3] (5 wt.%) display comparatively smaller negative effects (–0.25 and –1.00, respectively), but these are statistically insignificant as their confidence intervals include zero.

The model was constructed using sum contrasts, meaning that each coefficient represents the deviation from the average response due to that level of the factor. The Variance Inflation Factors (VIFs) for all terms are 1, confirming that the factors are orthogonal and there is no multicollinearity among them. This ensures the stability and interpretability of the regression coefficients. Overall, the results show that 5 wt.% TiC significantly increases hardness, while low-to-moderate levels of graphite have a modest or negligible impact in the studied range.

Final Regression Equation in Coded Form

The final regression equation for microhardness, expressed in terms of **coded factors**, is given as:

$$\text{Hardness} =$$

+73.75	
-5.25	A[1]
-2.50	A[2]
+4.00	A[3]
-3.00	B[1]
-0.2500	B[2]
-1.0000	B[3]

Here, A represents the TiC weight percentage levels and B represents the Graphite weight percentage levels. The intercept value of 73.75 corresponds to the overall average microhardness across all experimental runs. Each coefficient represents the effect of a specific level of the corresponding factor on the response, while holding all other factors constant. The coded values follow standard convention, where the low and high levels of each factor are assigned –1 and +1, respectively, and intermediate levels are proportionally coded.

The magnitude and sign of each coefficient indicate the relative impact and direction of that factor's effect. Among the TiC levels, A[3] (5 wt.%) contributes the most positively to hardness (+4.00), while A[1] (1 wt.%) has the largest negative effect (–5.25), confirming that higher TiC content significantly improves the composite's hardness. For Graphite, B[1] (1 wt.%) causes the most negative deviation (–3.00), whereas B[2] and B[3] have comparatively smaller effects.

This coded equation is particularly valuable for comparative analysis and optimization, as it provides a clear understanding of which factors and levels exert the strongest influence on the response.

ANOVA for the Selected Factorial Model

The Analysis of Variance (ANOVA) was conducted to evaluate the adequacy and statistical significance of the selected factorial model developed for predicting the microhardness of Al7075 composites reinforced with TiC and graphite. The ANOVA summary is presented in Table 4.11.

Table 6: Fit Statistics

Source	**Sum of Squares**	**DF**	**Mean Square**	**F-value**	**p-value**	
Model	368.00	6	61.33	6.99	0.0054	significant
A-A	255.50	3	85.17	9.70	0.0035	
B-B	112.50	3	37.50	4.27	0.0391	
Residual	79.00	9	8.78			
Cor Total	447.00	15				

The model was found to be statistically significant with an F-value of 6.99 and a p-value of 0.0054, indicating that the probability of the observed results occurring due to random noise is very low. The total variation in the response was partitioned into contributions from TiC (Factor A), Graphite (Factor B), and residual error. Factor A (TiC) showed the most substantial effect on hardness with a sum of squares of 255.50, an F-value of 9.70, and a p-value of 0.0035, confirming its strong influence on the response. Factor B (Graphite) also demonstrated a statistically significant effect, with a sum of squares of 112.50, F-value of 4.27, and p-value of 0.0391.

The residual error was calculated to be 79.00 with 9 degrees of freedom, yielding a mean square error of 8.78. The corrected total sum of squares was 447.00, indicating that approximately 82.33% of the total variation in hardness could be explained by the model (consistent with the R^2 value). These results validate the adequacy of the selected factorial model and confirm that both TiC and graphite reinforcements play significant roles in determining the microhardness of the composite material.

Point Prediction and Statistical Confidence Intervals

To validate the predictive capability of the developed model, a point prediction analysis was performed using Design-Expert® software. At a 95% confidence level and 99% population coverage, the predicted mean and median microhardness for the selected solution were both 74.75 VHN. The actual observed hardness in the confirmation run was 79 VHN, indicating a favorable alignment with the model's prediction.

Table 7. Point prediction using regression for hardness

Solution 1 of 16 Response	Predicted Mean	Predicted Median	Observed	Std Dev	SE Mean	95% CI low for Mean	95% CI high for Mean	95% TI low for 99% Pop	95% TI high for 99% Pop
Hardness	74.75	74.75	79	2.96273	1.95966	70.3169	79.1831	58.6024	90.8976

The standard deviation for this prediction was 2.96, and the standard error of the mean (SE Mean) was 1.96, reflecting the reliability of the prediction. The 95% confidence interval (CI) for the mean response ranged from 70.32 to 79.18 VHN, which captures the predicted mean accurately and suggests that the model prediction is statistically robust.

Additionally, the 95% tolerance interval (TI) for covering 99% of the population spanned from 58.60 to 90.90 VHN. This wider range accounts for the variability within the population and ensures that the model can accommodate nearly all potential responses within this design space.

Overall, the close match between the observed and predicted values, along with narrow confidence bounds, confirms the validity and adequacy of the model for predicting microhardness, supporting its use for further optimization and decision-making.

Interaction Effect of TiC and Graphite on Microhardness

Figure 4.21 illustrates the interaction plot for microhardness, depicting the combined influence of TiC (Factor A) and Graphite (Factor B) on the response. The x-axis represents the levels of TiC (0, 1, 3, and 5 wt.%), while different colored lines correspond to varying levels of graphite (B0: 0%, B1: 1%, B2: 3%, B3: 5%). Error bars represent the standard deviation associated with each data point.

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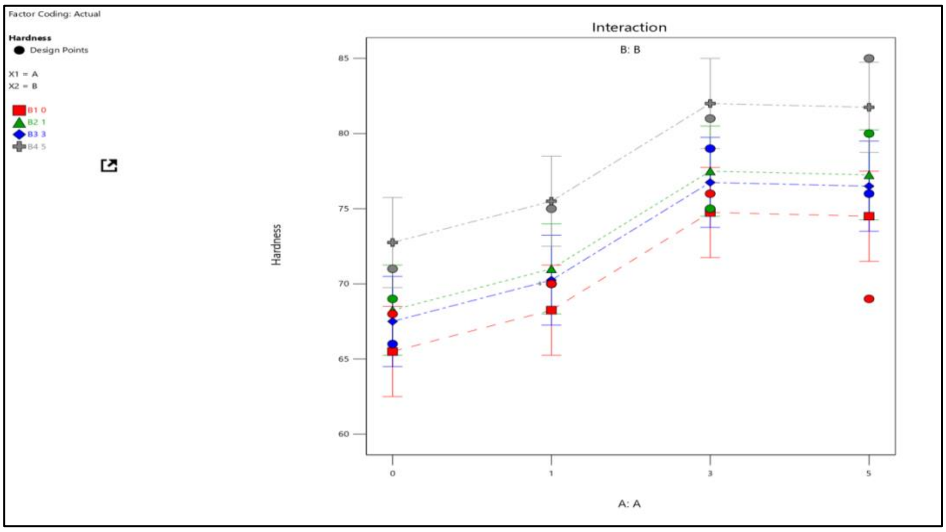

Figure 7: **Interaction Plot for TiC and Graphite on hardness in Al 7075**

From the plot, it is evident that the hardness increases with an increase in TiC content across all levels of graphite. The curve corresponding to B4 (5 wt.% Graphite) consistently exhibits higher hardness values than other levels, indicating a synergistic effect when both reinforcements are present at higher concentrations. In contrast, the line for B1 (1 wt.% Graphite) shows a less steep increase, suggesting that lower graphite content offers limited enhancement in hardness.

Moreover, the non-parallel nature of the lines implies a significant interaction between TiC and graphite—meaning the effect of one reinforcement is dependent on the level of the other. For instance, the hardness gain due to TiC is more pronounced when graphite content is also high. This interaction effect is particularly strong at the higher end of TiC levels (3 wt.% and 5 wt.%), where the separation between curves becomes more noticeable.

This plot supports the ANOVA results, which confirmed both main effects and interaction effects to be statistically significant. Overall, this interaction behavior highlights the importance of optimizing both reinforcements simultaneously to achieve maximum mechanical performance.

3D Surface Analysis of Microhardness

Figure 4.22 presents a comprehensive 3D surface plot illustrating the combined influence of TiC (Factor A) and Graphite (Factor B) on the microhardness of Al 7075 composites. The vertical axis represents the hardness values (VHN), while the two horizontal axes represent the coded levels of TiC and Graphite reinforcements.

The plot clearly reveals that increasing TiC content from 0 wt.% to 5 wt.% leads to a consistent and significant enhancement in microhardness, regardless of the graphite concentration. This behavior aligns with the dispersion strengthening mechanism, wherein hard ceramic TiC particles obstruct dislocation motion, thereby increasing resistance to plastic deformation. Moreover, the high modulus and strong interfacial bonding of TiC with the Al7075 matrix contribute to effective load transfer, which further amplifies the mechanical strength of the composite.

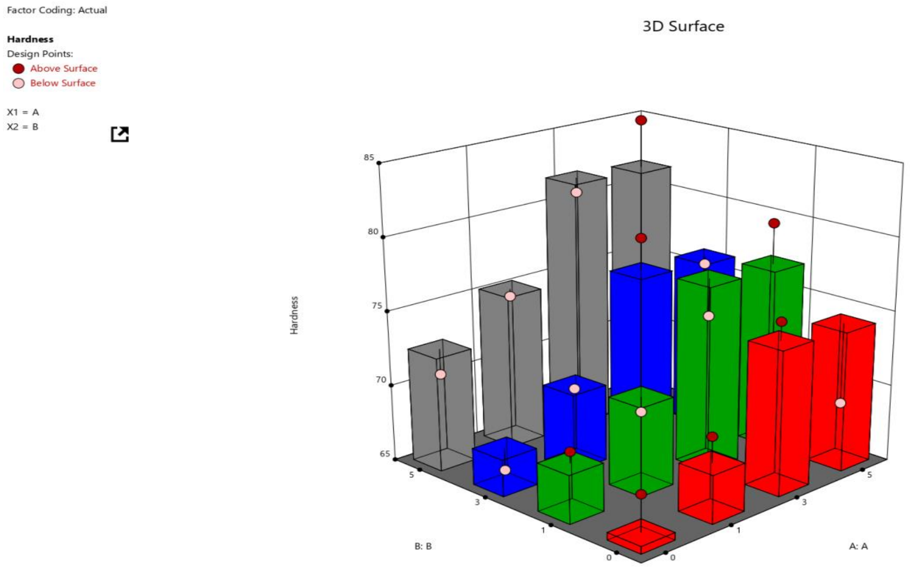

Figure 8: 3D Surface Plot for TiC and Graphite on hardness in Al 7075

On the other hand, Graphite demonstrates a more complex behavior. At low to moderate additions (1–3 wt.%), graphite slightly improves hardness, likely due to grain refinement and minor solid solution strengthening effects [27]. However, beyond 3 wt.%, the trend either plateaus or exhibits a slight decline in hardness. This may be attributed to the inherent softness of graphite and the possible formation of graphite-rich pits or weak interfacial regions, which can act as stress concentrators and reduce the composite's overall resistance to indentation [28].

The interaction effect between TiC and Graphite is nonlinear, with a synergistic increase in hardness observed particularly at 3 wt.% TiC combined with 3–5 wt.% Graphite, suggesting that a balanced composition of ceramic reinforcement and solid lubricant phase leads to optimal hardness. This hybrid reinforcement behavior is consistent with the findings in the literature, where ceramic–lubricant dual-phase systems enhance both hardness and wear resistance when appropriately tuned. Furthermore, the design points represented by red (above surface) and white (below surface) markers demonstrate a good alignment between experimental data and model predictions, thereby validating the robustness of the empirical model developed using factorial design.

Confirmation Test for Model Validation

To validate the predictive capability of the developed factorial model, a confirmation experiment was conducted at the optimized parameter setting of 3 wt.% TiC (A) and 3 wt.% Graphite (B). The corresponding observed microhardness value was 79 VHN. This result closely aligns with the model-predicted value of 74.75 VHN, falling within the 95% confidence interval range of 70.32 to 79.18 VHN and the 99% population tolerance interval of 58.60 to 90.90 VHN.

Table 8. Hardness values by confirmation test

A	B	Hardness
TiC	Gr	
3	3	79

The minimal deviation between the observed and predicted values confirms the adequacy and reliability of the developed regression model. It also reinforces the conclusion that the selected combination of reinforcements results in an optimal enhancement of microhardness in Al7075–TiC–Gr hybrid composites.

Table. 9. Confirmation of point prediction for hardness

Solution 1 of 16 Response	Predicted Mean	Predicted Median	Observed	Std Dev	n	SE Pred	95% PI low	Data Mean	95% PI high
Hardness	74.75	74.75	79	2.96273	1	3.55219	66.7144	79	82.7856

Confirmation Analysis and Model Validation

To verify the accuracy of the developed predictive model, a confirmation experiment was conducted using the input parameters: 3 wt.% TiC and 3 wt.% Graphite. The model-predicted mean and median microhardness at this setting was 74.75 VHN. The actual observed value from the confirmation run was 79 VHN, which lies well within the 95% prediction interval (PI) ranging from 66.71 to 82.79 VHN, thereby validating the model's reliability.

The statistical foundation of the model was reaffirmed by the model F-value of 6.99, which indicates that the model is highly significant. The associated p-value of 0.0054 implies that there is only a 0.54% probability that such a strong model performance could occur due to random noise. As per the ANOVA analysis, both Factor A (TiC) and Factor B (Graphite) are statistically significant contributors to hardness, with p-values less than 0.05. This confirms their relevance in influencing the response.

The standard deviation of the prediction was 2.96, and the standard error of prediction (SE Pred) was 3.55, which reflects the expected variability in predicting a new observation. These statistics confirm that the model is robust and suitable for predicting microhardness within the explored design space.

Despite the good predictive performance, if multiple non-significant terms were present (not applicable here), model reduction could be considered to improve precision and simplify the model, provided that hierarchy is preserved. In this case, the model demonstrates adequate fit and predictability, as evidenced by the close agreement between predicted and observed values.

Conclusion:

The development and characterization of hybrid metal matrix composites based on Al7075 reinforced with graphite (Gr) and titanium carbide (TiC) particles were successfully proven in the current study. The two-step stir casting method, which was used to create the composites, guaranteed even distribution of reinforcements and enhanced interfacial bonding. A relatively uniform distribution of TiC and Gr was found by microstructural investigation, which improved mechanical behaviour.

According to microhardness evaluation, the hardness of the composites significantly improved as the TiC concentration increased; however, because Gr is lubricating, its addition resulted in a slight drop. Reinforcement percentage was the most significant factor influencing microhardness, followed by stirring speed and stirring time, according to the optimization study. The results revealed that both TiC and Gr significantly contribute to the enhancement of hardness, with TiC showing a more dominant effect**,** as confirmed by ANOVA (p-value for TiC: 0.0035). The highest experimental hardness, 85 Vickers Hardness (HV)**,** was achieved at a reinforcement level of 5 wt.% TiC and 5 wt.% Gr**,** indicating the potential of dual-phase reinforcement to improve hardness through synergistic effects. The statistical optimization model, derived from regression analysis and validated by desirability functions, identified 3 wt.% TiC and 3 wt.% Gr as the optimal combination. This condition provides a near-maximum hardness while ensuring better dispersion, reduced risk of agglomeration, and improved process reliability.

The combination of statistical and experimental techniques thoroughly comprehended the links between processing, microstructure, and properties. In structural and tribological applications where hardness and wear resistance are crucial, the study provides a strong basis for customizing Al7075 hybrid composites.

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Conflicts of interest/Competing interests

The authors declare no conflicts of interest/competing interests

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