Impact of T6 Heat Treatment on the Hardness of Boron Carbide Reinforced Aluminum Composites

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Abstract - *The study examines the effects of T6 heat treatment on the hardness of aluminum composites reinforced with boron carbide (B_4C). Aluminum alloy 2024 (AA2024) served as the matrix material, with boron carbide particles incorporated to enhance its mechanical properties. A standard T6 heat treatment process comprising solutionizing, quenching, and aging was applied to the composite samples. Microstructural analysis revealed significant precipitation hardening and uniform dispersion of B_4C particles as a result of the heat treatment. Compared to as-cast composites, the T6-treated samples exhibited a marked increase in hardness, attributed to the combined effects of matrix strengthening and reinforcement. The findings underscore the synergistic impact of heat treatment and B_4C reinforcement on enhancing the mechanical performance of aluminum composites, paving the way for high-performance applications.*

***Key Words*: Aluminium Matrix Material, Aluminium alloy, Rockwell Hardness, Stir casting, SEM**

1.INTRODUCTION

Over the past two decades, aluminium matrix composites (AMCs) have made significant advancements, demonstrating improved performance characteristics [1]. Aluminium matrix composites possess advanced properties such as low density, excellent electrical and thermal conductivity, exceptional resistance to oxidation and wear, high specific strength and stiffness, and durability at elevated temperatures [2]. These composites are ideal for automotive and aerospace applications, as they are designed to reduce weight while enhancing mechanical properties such as strength and stiffness [3]. Non-metallic ceramic particles such as silicon carbide, boron carbide, and titanium carbide are commonly used as reinforcements in aluminium matrices to produce aluminium matrix composites (AMCs) [4].

Ceramic reinforcement composites have garnered significant attention across various industrial sectors due to their outstanding properties and versatility. These composites typically consist of a metal or ceramic matrix reinforced with ceramic fibers, particles, or whiskers, which significantly enhance their mechanical, thermal, and electrical performance. The addition of ceramic reinforcements improves the composite's hardness, wear resistance, thermal stability, and electrical conductivity, making them ideal for demanding applications in aerospace, automotive, electronics, and energy sectors [5], [6], [7]. Titanium matrix composites (TMCs) reinforced with boron carbide (B_4C) exhibit excellent mechanical properties, including high strain rates and impressive compressive strengths [5]. Ceramic reinforcement composites offer a wide range of possibilities for tailoring material properties to meet specific application needs. The fabrication techniques, such as additive manufacturing, powder metallurgy, and stir casting, play a crucial role in determining the composite's microstructure and performance characteristics [8], [9], [10].

Stir casting is a widely used and cost-effective method for fabricating metal matrix composites (MMCs), particularly AMCs. This process involves mechanically stirring reinforcing particles into molten metal to ensure their uniform distribution throughout the matrix [11], [12]. The stir casting method is preferred for its simplicity, proven effectiveness, and suitability for large-scale production, making it an ideal choice for manufacturing aluminium matrix composites [11]. The quality and properties of stir-cast composites are influenced by several key factors, including the selection of matrix and reinforcing materials, along with parameters such as stirring temperature, speed, and duration. These variables play a crucial role in ensuring a homogeneous distribution of reinforcement and achieving the desired mechanical and tribological properties [12], [13]. Remarkably, when compared to traditional methods, the application of ultrasonic energy during stir casting has shown significant improvements in particle dispersion and the resulting mechanical properties. The use of ultrasound helps break down particle agglomerations and enhances the uniformity of the reinforcement distribution within the matrix, leading to better overall performance of the composite [14]. Nonetheless, challenges such as achieving consistent particle dispersion and ensuring proper wetting of the reinforcement particles remain prevalent [15].

The composition and manufacturing methods of aluminium composite materials significantly influence their Rockwell hardness values. Typically, the addition of reinforcements such as ceramic particles, like boron carbide or silicon carbide, enhances the hardness of aluminium composites when compared to pure aluminium [16], [17],

[18]. Aluminium alloys reinforced with nano-TiO_2 particles through friction stir processing (FSP) exhibit enhanced toughness [19]. Similarly, the addition of ceramic particles like titanium diboride (TiB_2) to aluminium matrices significantly enhances their hardness and other mechanical properties. TiB_2, being a hard ceramic material, contributes to increased wear resistance and hardness [20]. In certain instances, it was discovered that the peak hardness of reinforced composites was either slightly higher than or equivalent to that of unreinforced alloys [21].

2. MATERIAL & METHODOLOGY

2.1 Acquiring of Materials

The AA2024 alloy was procured in block form from a supplier based in Mumbai. Boron carbide was procured in powder form from a supplier based in Mumbai. The average particle size of boron carbide was 40-50 microns.

2.2 Casting & Sample Preparation

The AA2024 block was carefully cleaned to remove impurities and dirt before melting. This step was crucial to ensure the quality of the final alloy and minimize contaminants that could negatively affect the material's properties. The cleaned AA2024 block was placed in a coal-fired furnace. Coal furnaces were chosen for their accessibility and common usage, despite electric or gas furnaces being more prevalent due to their superior temperature control for melting. During the smelting process, slag, a non-metallic waste, and other impurities that had accumulated at the surface of the aluminium melt were removed. This process helped maintain the alloy's purity by eliminating oxides and other contaminants that could negatively impact its mechanical properties.

Boron carbide was added in weight percentages of 8, 10, 12, 14, and 16, and the molten mixture was vigorously stirred to ensure thorough mixing. Stirring is crucial in casting operations as it prevents the formation of localized regions where alloying components could concentrate. Uniform mixing is essential to maintain a consistent microstructure throughout the material, which in turn ensures the uniformity of its mechanical properties. The molten liquid was poured into preheated molds to minimize thermal shock and ensure a steady flow of the molten metal. This approach reduces the formation of internal stresses in the alloy, which could otherwise lead to cracking or deformation due to rapid cooling. The molds were specifically designed to produce circular samples, which were then further processed to create hardness test specimens.

The castings were allowed to cool naturally in ambient air, rather than using forced cooling methods such as water quenching. This approach was chosen to prevent thermal stresses that could lead to cracking or warping of the samples. The slow cooling rate in the ambient air enabled more controlled solidification of the aluminium alloy, ensuring a more uniform and stable microstructure. Once the castings had fully solidified, they were carefully removed from the molds.

After casting, the circular samples were cut for hardness testing. The surfaces of these specimens were smoothed using emery paper and then cleaned with acetone to remove any contaminants.

2.2 Heat Treatment

A specific process known as T6 heat treatment is applied to aluminium alloys to improve their mechanical properties, such as strength and hardness. The composite samples underwent a standard T6 heat treatment process, which involved solutionizing, quenching, and aging.

During the solutionizing process, the aluminium alloy is heated to about 500°C, allowing the soluble alloying elements, such as copper in AA2024, to dissolve into the aluminium matrix and form a solid solution.

After the solution heat treatment, the alloying elements are trapped in the solution by rapidly cooling the material with water. This quenching process prevents the formation of precipitates at room temperature, keeping the material in a supersaturated solid solution.

Following the quenching, the material undergoes artificial aging at a lower temperature, typically around 180°C, for approximately 24 hours. This process allows the precipitates to form and enhance the material's strength and hardness.

3. EXPERIMENT

3.1 Rockwell Hardness Testing

The Rockwell hardness test is a commonly used method to assess the hardness of materials, including alloys. In the Rockwell hardness test, a hardened steel ball indenter is used to apply an initial force of 10 kgf to the specimen. The diameter of the hardened steel ball indenter used in the test was 1/16 inch. This initial force, referred to as the "preload," ensures that the indenter makes contact with the surface of the specimen. Subsequently, a larger test force (major load) of 100 kgf is applied, causing the indenter to penetrate the material. After a predetermined duration, the major load is removed, and only the minor load remains applied to the specimen. The depth of the indentation created under the minor load is then measured. The Rockwell hardness value is determined by measuring the depth of the indentation and applying Equation (1) corresponding to the scale in use.

$$HR = N - \frac{h}{d} \tag{1}$$

Where HR is the Rockwell hardness number, N is a constant based on the scale used (e.g., N=130 for Rockwell B scale), h is the total depth of the indentation after applying the major load, and d is the depth caused by the minor load

In the present study, the B scale of the Rockwell hardness test was used to evaluate the hardness of the prepared aluminium composite. The Digital Rockwell testing machine, as shown in **Fig - 1**, is used to calculate the hardness of the specimen. In this setup, the depth calculations are performed automatically by the machine itself. For each composite sample, around five hardness readings were taken on the surface to ensure accurate and consistent results.

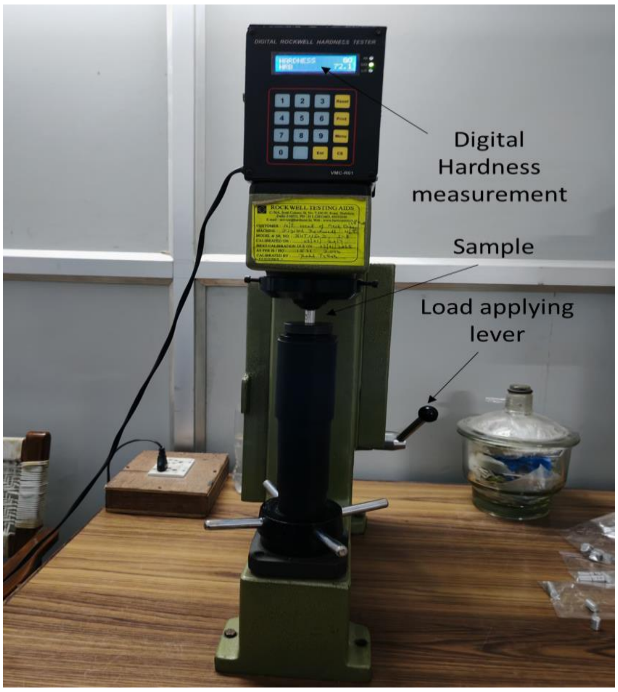

Fig -1: Rockwell Hardness Setup

3.2 Microstructure Analysis

To further analyse the distribution of the reinforcement and matrix material in the composite, Scanning Electron Microscopy (SEM) was utilized to observe the dispersion and distribution. This analysis helps us gain deeper insights into the phenomena driving the observed trends in the properties of the composite. This serves as a valuable indicator for understanding the hardness pattern of the composite. Microstructure analysis also helps us establish the relationship between properties and material distribution. By observing the distribution of boron carbide particles within the aluminum matrix, we can gain insights into how uniformity or clustering of the reinforcement affects the mechanical properties, such as hardness and overall strength of the composite.

4. RESULT AND DISCUSSION

4.1 Hardness

First, composites S1, S2, S3, S4, and S5, reinforced with 8%, 10%, 12%, 14%, and 16% weight of boron carbide, respectively, were tested for hardness using the Rockwell hardness machine. The hardness values of these composites were recorded and are presented in **Table 1.**

Table -1: Hardness of B_4C reinforced composite

Sample	Hardness (HRB)					Average	Std dev.
	1	2	3	4	5		
S1	78.12	71.32	72.56	69.85	74.75	73.32	3.23
S2	76.23	75.11	73.45	78.91	72.45	75.23	2.52
S3	81.94	85.26	88.15	75.19	80.31	82.17	4.94
S4	85.32	78.23	80.45	76.16	83.04	80.64	3.66
S5	81.24	80.27	77.59	81.46	73.84	78.88	3.21

The hardness of T6 heat-treated composites, designated as T1, T2, T3, T4, and T5, with 8%, 10%, 12%, 14%, and 16% weight reinforcement of boron carbide, respectively, was evaluated using the Rockwell hardness machine. The recorded hardness values are presented in **Table 2.**

Table -2: Hardness of B_4C reinforced composite treated with T6 Heat treatment

Sample	Hardness (HRB)					Average	Std dev.
	1	2	3	4	5		
T1	80.44	81.63	77.32	78.26	75.80	78.69	2.35
T2	79.12	81.67	84.24	78.65	82.87	81.31	2.40
T3	81.45	83.89	81.66	86.05	86.05	83.82	2.25
T4	84.98	84.24	83.14	82.82	79.92	83.02	1.94
T5	80.87	81.78	83.21	85.74	79.70	82.26	2.33

To clearly visualize the hardness pattern of the composites, a graph of these values was plotted and compared, as illustrated in **Chart 1.**

The chart clearly indicates that the hardness value increases with an increase in the weight percentage of boron carbide. However, after reaching 14% weight of boron carbide, there is a slight decrease in hardness. This could be attributed to the non-uniform distribution of boron carbide particles at higher concentrations. This decrease in hardness can be mitigated by further optimizing the stir casting parameters, such as increasing the stirring speed, duration, or temperature, to ensure a more uniform distribution of boron carbide particles within the matrix.

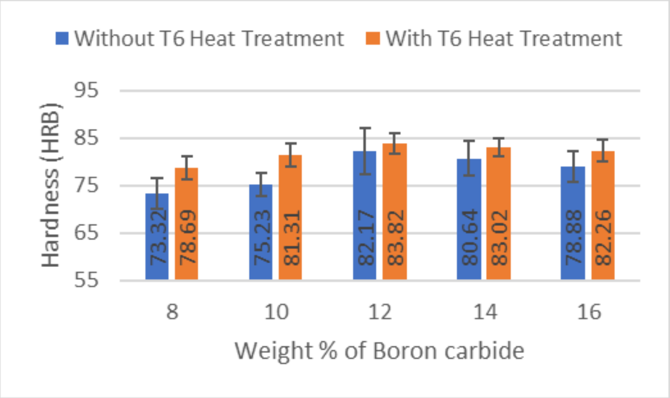

Chart -1: Hardness comparison of composite

4.2 Scanning Electron Microscopy (SEM)

To assess the distribution of boron carbide in the AA2024 composite, SEM analysis was conducted. For this purpose, the specimen surfaces were prepared using fine emery paper and alumina particles. In aluminum composites, boron carbide plays a crucial role in enhancing the composite's load-bearing capacity. If the distribution of boron carbide is homogeneous, this strengthening phenomenon will be more effectively realized. For this analysis, the composite with the highest boron carbide content was selected to examine the distribution as shown in **Fig -2**.

The SEM image clearly reveals a predominantly uniform distribution of boron carbide particles, with only minor clustering observed in certain areas.

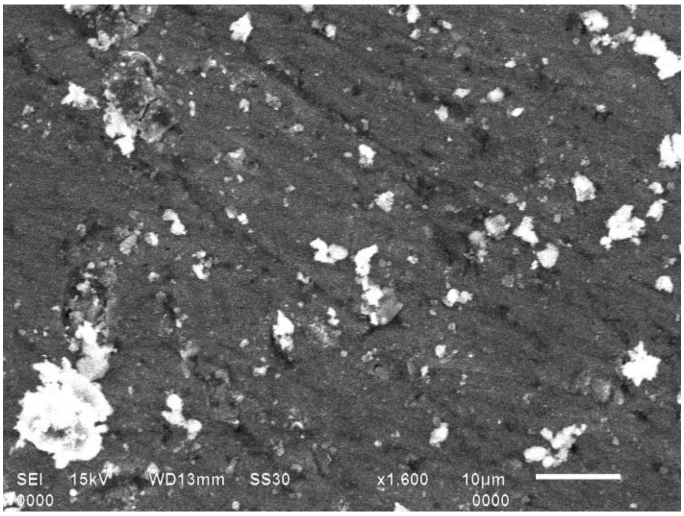

Fig -2: SEM of composite having 16% B_4C

5. CONCLUSIONS

According to this study, the T6 heat treatment substantially enhances the mechanical and microstructural properties of aluminum alloys. The T6 heat treatment results in a maximum increase of 7.32% in hardness. A consistent improvement in hardness is observed for the same weight percent of reinforcement after the T6 heat treatment. These improvements in hardness enhance the composite's lifespan, making it suitable for long-term applications while also providing excellent wear resistance.

Microstructural analysis further confirms the successful casting of aluminum composites with boron carbide reinforcement. The uniform distribution of boron carbide particles observed in the microstructural analysis validates the successful enhancement in hardness and indicates potential improvements in other mechanical properties of the composite.

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