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Experimental Investigation of Boron Carbide Reinforced Al-Mg-Si Alloy Nano Composites by the Stir Casting Method Using Machine Learning Algorithm

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Abstract

For the purpose of this experiment, Al-Mg-Si alloys were manufactured with the use of the stir casting process with a metal mold. The alloys had different weight percentages of nano boron carbide, which ranged from 0 to 4% by weight. The intervals between the percentages were 0.5. Following that, the microstructural and mechanical parameters of the as-cast alloy and the nano composites were compared and contrasted according to ASTM Standards in order to assess the impact of B_4C. The results of a microstructural analysis showed that the B_4C nanoparticles were distributed virtually equally throughout the Al-Mg-Si matrix. Additionally, the manufacturing procedure can be considered to have been effective due to the fact that the stir casting technique only resulted in an insignificant number of pores that remained after the operation. The inclusion of nano boron carbide (nB_4C) caused a substantial change in the mechanical characteristics of the alloy while it was in its as-cast form. The fabricated composites had a higher compressive strength (7.84%), ultimate tensile strength (22.75%), and hardness (25%) than the base material. The Python programming language was used to look at the graphical methods of mechanical properties.

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INTRODUCTION

Metal matrix composites (MMCs) are a major type of material that is being used more and more in many different fields because they have better properties than regular monolithic metals. [1–3]. MMCs are engineered materials comprising a metallic matrix reinforced with another material, which may be in the form of fibers, particles, or whiskers [4]. The strategic combination of a metal matrix with a reinforcing phase aims to create materials that leverage the desirable characteristics of both constituents [5]. The metal matrix usually has properties like ductility, toughness, and thermal conductivity, while the reinforcement makes the metal stronger, stiffer, more resistant to wear, and better at high temperatures [6]. MMC's are used in airplane parts because they have a high strength-to-weight ratio and resistance to high temperatures [7]. In the automotive sector, MMCs are employed in engine components, brake rotors, and other parts requiring high wear resistance and thermal management [8]. MMCs are also utilized in structural, marine, defense, biomedical, and sports equipment industries, showcasing their versatility and performance.

AA6063 aluminum alloy, known for its good corrosion resistance, medium strength, and excellent extrudability, is a widely used material in various applications, including architectural extrusions and automotive components [9,10]. To further enhance its mechanical and tribological properties, AA6063 is often reinforced with ceramic particles such as boron carbide (B_4C) [11]. The resulting AA6063/B_4C metal matrix composites (MMCs) exhibit enhanced hardness, wear resistance, and tensile strength, rendering them suitable for demanding engineering applications. The stir casting method is commonly employed to fabricate AA6063/B_4C composites, ensuring a uniform dispersion of the B_4C particles within the aluminum matrix. This technique involves mechanically mixing the reinforcement particles into the molten aluminum alloy, followed by solidification. The properties of the resulting composite material can be tailored by varying the weight percentage of B_4C. AA6063 hybrid composites with 4% graphite and varying weight percentages (3, 6, 9, and 12%) of B_4C microparticles using the stir casting method [12]. AA6063/ZrO_2 metal matrix composites have been created using the stir casting method to study mechanical properties [13]. Experimental investigations into boron carbide (B_4C) reinforced aluminium-magnesium-silicon (Al-Mg-Si) alloy nanocomposites aim to improve mechanical characteristics, with machine learning algorithms playing a crucial role in optimizing fabrication and characterization processes [14]. Al6063/SiC composites fabricated using electromagnetic stir casting showed improvements of 17% in hardness, 18% in UTS, and 37% in yield strength compared to the base AA6063 alloy [15].The hardness of B4C/Al-Mg-Si composites has been shown to increase with increasing B4C content, reaching approximately 98 HV at 17.5% B_4C compared to 45 HV for the unreinforced alloy [16]. Researchers have explored varying weight percentages of B4C, typically ranging from 3% to 17.5%, to optimize mechanical performance. The incorporation of B4C particles improves hardness, tensile strength, and wear resistance [17]. When these alloys are used with atomistic simulations, data analysis, or materials design methods, Python programming is usually what is used. The 6XXX line of Al-Mg-Si alloys is a well-known type of aluminium alloy valued for its low weight and good mechanical properties, which can be further improved through engineered precipitation [18–20].

In this research work, Al-Mg-Si with varying weight % of nB_4C (0 ,0.5,1,1.5,2,2.5,3,3.5,4) reinforced composite materials were produced by stir casting with a speed range of 250 to 500 rpm and the entire composite was stirred for 30 minutes. We studied Morphological analysis and mechanical characterization. The output values were assessed by Python programming.

MATERIALS AND METHODOLOGY

The base material for fabricating aluminium alloy hybrid composites via the stir casting technique is an Aluminium Magnesium Silicon alloy (AA6063). Table 1 illustrates their chemical compositions.

AA6063 (Aluminium Alloy) was purchased in the local shops of Hyderabad. Currently, these alloys are utilized in transportation applications where weight reduction is crucial. Additionally, when compared to other aluminium alloys, it exhibits enhanced physical properties. The incorporation of reinforcing ceramic particles into the base materials is thought to be ineffective in improving the density of the resulting composites because of the uneven weight reduction properties for functional use. The current study utilized commercially available nano-ceramic strengthening particulates of B_4C (2.24 g/cm^3) with a particle size of 80 nm (Sigma Aldrich). B_4C serves as the principal hard ceramic reinforcement particle for homogenizing the mixture. Boron carbide (B_4C) possesses superior physical properties, including hardness, flexural strength, elastic modulus, wear resistance, reduced density, and enhanced chemical and thermal stability.

Table 1. AA6063 chemical composition.

Al	Mg	Si	Fe	Cr	Cu	Mn	Ti	Zn	Others
98.8	0.46	0.25	0.15	0.08	0.07	0.06	0.05	0.05	0.23

Stir Casting

The aluminum, magnesium, and silicon alloy was put in a resistive heating oven and heated to 700°C for 10 minutes. The speed of the stirring was kept at 250 rpm to make sure that the metal was completely melted. Nano boron carbide (nB_4C) reinforcement particles of different weights (0% to 4%) are heated at 250°C to get rid of any wetness and make the matrix and reinforcement particles more wettable. The melting point was raised to 740°C, and the reinforcement was added to the melt. The stirring speed of the molten slurry is elevated to 500 rpm to prevent particle aggregation. The breakdown of the chemical reaction between the matrix and reinforcement particles creates a vortex that stops strengthening nanoparticles from preventing agglomeration.

This influences the consistent distribution of reinforcement maintained within the molten slurry. Furthermore, the molten metal's temperature was elevated to 775°C, which reduced the viscosity of the composite slurry and facilitated the dispersion of the ceramic reinforcement particles throughout the liquid during the stirring process. The stirring speed was elevated to 500 rpm, and the duration was extended to 15 minutes. It was observed that elevating the concentration of micro boron carbide (4 wt%) leads to the agglomeration of ceramic particulates, despite the implementation of effective processing techniques.

Consequently, it was determined to restrict the concentration of these ceramic particulates to 3.5wt%. The die underwent heating to remove any entrapped gas prior to the introduction of the molten slurry into the die cavity, thereby minimizing the impact of matrix porosity.

The molten slurry was introduced into the die cavity and allowed to solidify at ambient temperature. Performance metrics for Al-Mg-Si alloy nano composites were established using ASTM standards, specifically ASTM E8, E9, E23, and D790. An optical microscope was used to study the microstructure of aluminum hybrid composites. The morphology of the distribution of reinforcing particles within the matrix alloy was examined using scanning electron microscopy. Aluminum alloy hybrid composites' tensile, compressive, flexural, and impact resistance characteristics are investigated.

RESULTS AND DISCUSSION:

Microstructural Analysis

The behavior of the reinforcing particles in the aluminum nanocomposites was examined utilizing a scanning electron microscope (SEM), with specific attention directed towards Figures 1 to 3 of the results. Furthermore, it examines the unique properties exhibited by boron carbide particles and the development of an aluminum dendritic structure throughout the solidification process. The accumulation of strengthening particles occurs in specific locations as a result of an increased fraction of ceramic particulates, despite the elevation of process parameters, as observed in the scanning electron microscope (SEM) analysis of aluminum nanocomposites.

When the number of ceramic particulates in the composite is increased, the data that was acquired by the SEM showed that the strengthening particles tend to cluster or pile up in specific regions within the composite. This tendency was observed when the amount of ceramic particulates was increased. This suggests that when the number of ceramic particles that are present in the composite increases, the distribution of those ceramic particles becomes less uniform, and the ceramic particles have a tendency to cluster together in some regions is shown in Figure 3.

The structure of boron carbide particles is proposed to resemble that of sharp edges, and it is also suggested that these particles possess the capability to endure exceptionally high temperatures. The non-uniformity is evident, with ceramic particles exhibiting a propensity to aggregate in certain areas, as illustrated in Figure 3.

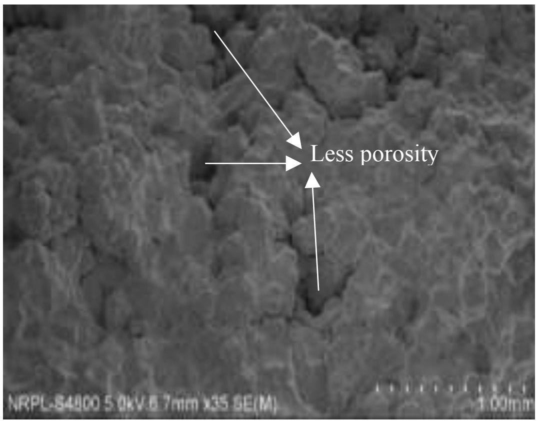

Figure 1. AA6063-3% nB_4C.

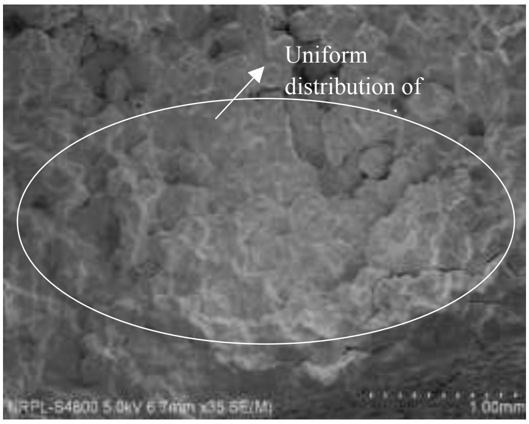

Figure 2. AA6063-3.5% nB_4C.

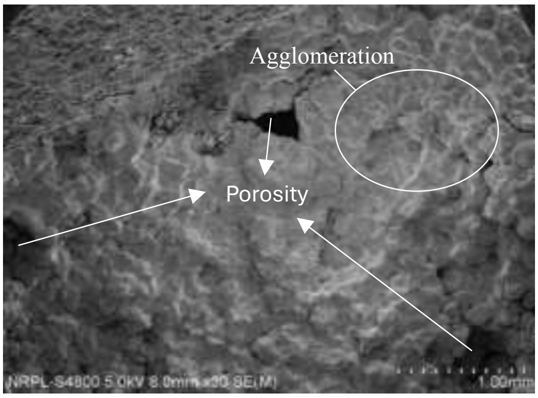

Figure 3. AA6063-4% nB_4C.

Table 2. Experiment data.

S.N.	Temperature	Time (seconds)	Speed in RPM
0	650	600	250
1	720	720	400
2	770	900	500
3	800	1200	600

Table 3. Experiment data summary statistics.

Description	Temperature	Time (seconds)	Speed in RPM
Count	4.000000	4.000000	4.000000
mean	735.000000	855.000000	437.500000
std	65.574385	260.959767	149.303941
min	650.000000	600.000000	250.000000
25%	702.500000	690.000000	362.500000
50%	745.000000	810.000000	450.000000
75%	777.500000	975.000000	525.000000
max	800.000000	1200.000000	600.000000

Mechanical Characterization

Through Python programming, mechanical characterization was assessed, and the results are given below. Tables and Graphs were drawn using Python.

Table 2 shows the experimental data, and Table 3 shows the summary statistics of the experimental data.

Code and OutPut

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns

experiment_data = pd.read_excel('/content/Experiment.xlsx')
# Display the first few rows of each dataset
print("Experiment Data:")
print(experiment_data.head())

# Analyze Experiment Data
experiment_summary = experiment_data.describe()
print("\nExperiment Data Summary Statistics:")
print(experiment_summary)
```

Output:

```
# Print column names to check for discrepancies
print(experiment_data.columns)
```

o/p:

Index(['Temperature', 'Time(Seconds)', 'Speed in RPM'], dtype='object')

Through python programming graph was drawn Temperature vs. Time is shown in Figure 4

```
import matplotlib.pyplot as plt

# Line plot for Temperature vs. Time
plt.figure(figsize=(10, 6))
plt.plot(experiment_data['Temperature'], experiment_data['Time(Seconds)'], marker='o', linestyle='-')
plt.title('Temperature vs. Time')
plt.xlabel('Temperature (K)')
plt.ylabel('Time (Seconds)')
plt.grid(True)
plt.show()
```

o/p:

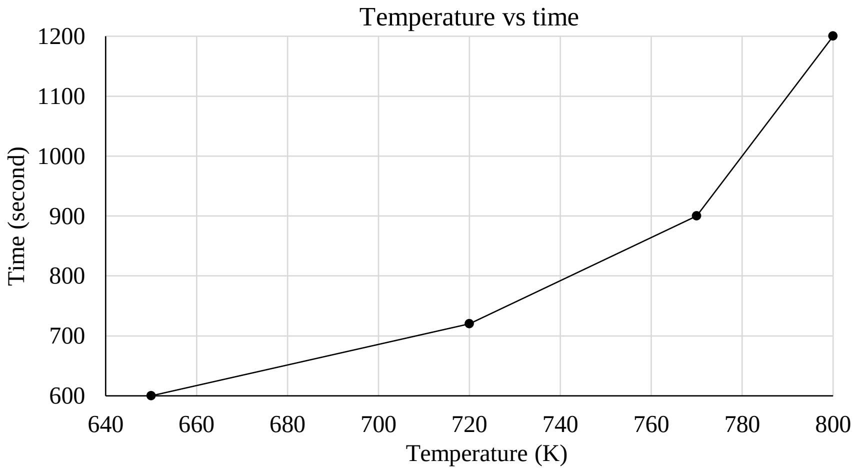

Figure 4. Temperature vs time graph of composites.

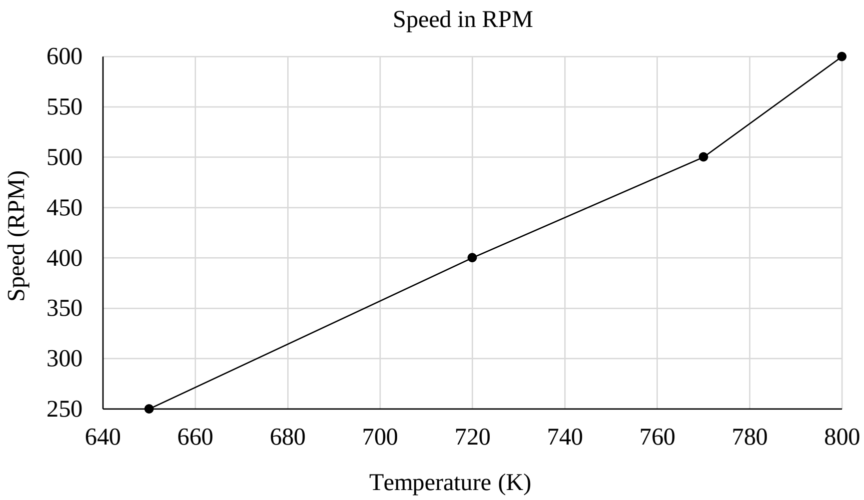

Figure 5. Speed vs time graph of composites.

Through Python programming, a graph was drawn. Speed vs Temperature is shown in Figure 5.

```
# Line plot for Speed vs. Temperature
plt.figure(figsize=(10, 6))
plt.plot(experiment_data['Temperature'], experiment_data['Speed in RPM'], marker='o', linestyle='-')
plt.title('Speed vs. Temperature')
plt.xlabel('Temperature (K)')
plt.ylabel('Speed (RPM)')
plt.grid(True)
plt.show()
```

The correlation heat map drawn through the code of Python is shown in Figure 6.

```
import seaborn as sns
# Correlation matrix
correlation matrix = experiment_data.corr()
plt.figure(figsize=(8, 6))
sns.heatmap(correlation_matrix, annot=True, cmap='coolwarm', fmt=".2f")
plt.title('Correlation Heatmap')
plt.show()
```

The descriptive statistics for the compression test are shown in Table 4.

```
import pandas as pd
import matplotlib.pyplot as plt

# Load the Excel files
compression_test_file = '/content/CompressionStrength.xlsx' # Update with your file path
hardness_bhn_file = '/content/HardnessBHN.xlsx' # Update with your file path
tensile_strength_file = '/content/UltimateTensileStrength.xlsx' # Update with your file path

# Reading the data from each file
compression_test_sheet = pd.read_excel(compression_test_file)
hardness_bhn_sheet = pd.read_excel(hardness_bhn_file)
```

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```
tensile_strength_sheet = pd.read_excel(tensile_strength_file)
# Descriptive statistics for each test
compression_stats = compression_test_sheet.describe()
hardness_stats = hardness_bhn_sheet.describe()
tensile_strength_stats = tensile_strength_sheet.describe()

print("Compression Test Descriptive Statistics:")

print(compression_stats)

o/p:

plt.title('Mean Compression Test Results')
plt.ylabel('Compression Strength')
plt.xlabel('Material')
for i in plt.gca().patches:
  plt.text(i.get_x() + i.get_width()/2, i.get_height() + 0.2, f'{i.get_height():.2f}', ha='center', va='bottom')
plt.tight_layout()
plt.show()
```

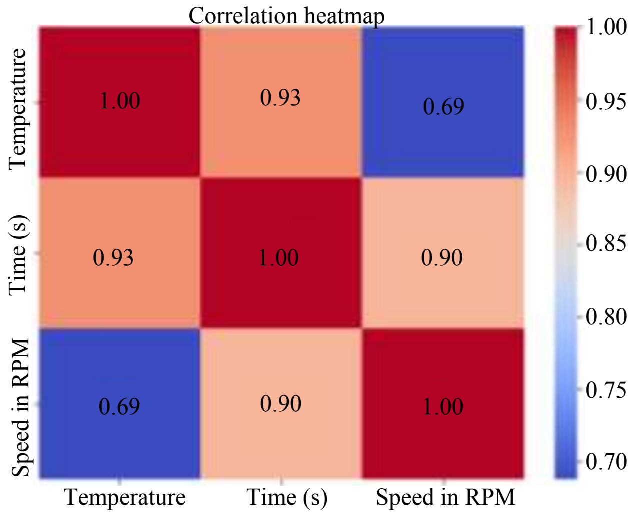

Figure 6. Correlation heat map of AA6063-nB_4C composites.

Table 4. Compression test descriptive statistics.

Description / Composition	Count	Mean	std	Min	25%	50%	75%	Max
AA 6063	8.0000	364.00	2.138	361.00	362.50	364.50	366.00	366.00
AA6063 +.5% nB_4C	8.0000	368.00	1.069	367.00	367.00	368.00	368.25	370.00
AA6063 + 1% nB_4C	8.0000	372.00	1.603	370.00	370.75	372.00	373.25	374.00
AA6063 + 1.5 % nB_4C	8.0000	376.00	1.309	374.00	375.00	376.00	377.00	378.00
AA6063 + 2 % nB_4C	8.0000	381.00	1.309	381.00	380.00	381.00	382.00	383.00
AA6063 + 2.5 % nB_4C	8.0000	384.00	1.414	384.00	383.00	383.50	384.25	387.00
AA6063 + 3 % nB_4C	8.0000	386.00	1.414	388.00	387.50	388.00	389.00	390.00
AA6063 + 3.5 % nB_4C	8.0000	395.00	1.414	394.00	394.00	394.50	395.25	398.00
AA6063 + 4 % nB_4C	8.0000	389.00	1.309	387.00	388.00	389.00	390.00	391.00

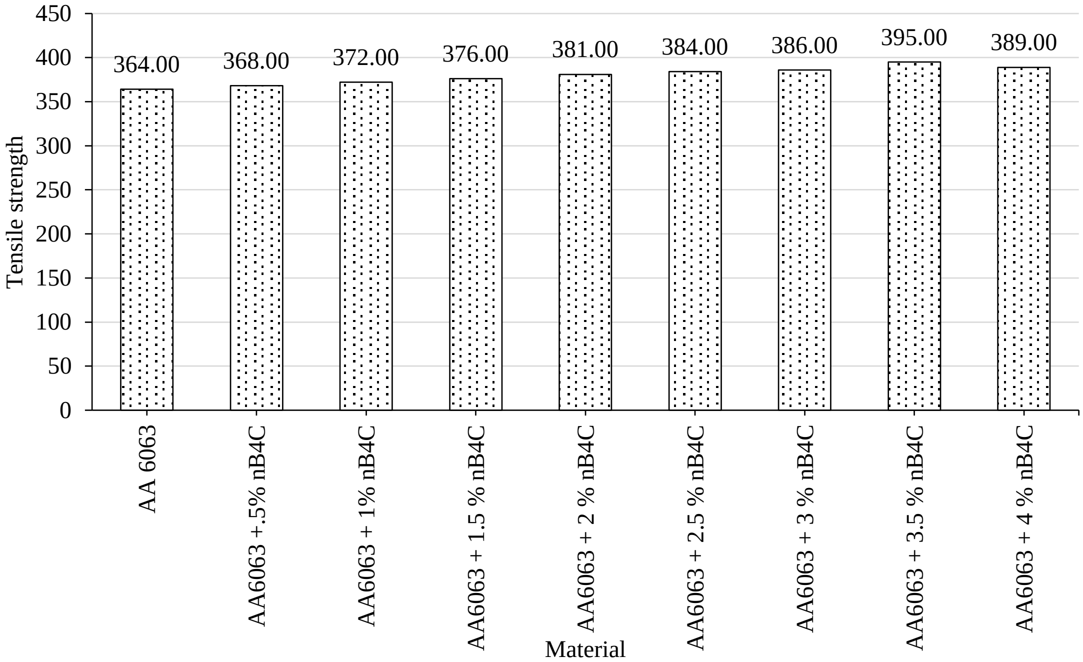

Figure 7. Mean compression strength of AA6063, AA6063 nanocomposites.

Description / Composition	Count	Mean	std	Min	25%	50%	75%	Max
AA 6063	8.000	60.00	1.69	57.00	59.50	60.50	61.00	62.00
AA6063 +.5% nB_4C	8.000	63.00	0.92	62.00	62.00	63.00	64.00	64.00
AA6063 + 1% nB_4C	8.000	66.00	1.30	64.00	65.00	66.00	67.00	68.00
AA6063 + 1.5 % nB_4C	8.000	68.00	1.51	66.00	67.00	67.50	69.25	70.00
AA6063 + 2 % nB_4C	8.000	71.00	1.06	70.00	70.00	71.00	71.25	73.00
AA6063 + 2.5 % nB_4C	8.000	73.00	1.85	70.00	71.75	73.50	74.25	75.00
AA6063 + 3 % nB_4C	8.000	76.00	1.30	74.00	75.00	76.00	77.00	78.00
AA6063 + 3.5 % nB_4C	8.000	80.00	1.30	78.00	79.00	80.00	81.00	82.00
AA6063 + 4 % nB_4C	8.000	76.00	1.30	74.00	75.00	76.00	77.00	78.00

```
# Compression Test Bar Plot
plt.figure(figsize=(10, 6))
compression_test_sheet.mean().plot(kind='bar', color='skyblue', edgecolor='black')
```

Mean Compression strength of AA6063 and AA6063 nanocomposites is shown in Figure 7.

```
print("\nHardness BHN Descriptive Statistics:")
print(hardness_stats)
o/p:
Hardness BHN Descriptive Statistics:

# Hardness BHN Bar Plot
plt.figure(figsize=(10, 6))
hardness_bhn_sheet.mean().plot(kind='bar', color='lightgreen', edgecolor='black')
plt.title('Mean Hardness BHN Results')
plt.ylabel('Hardness (BHN)')
plt.xlabel('Material')
```



```
for i in plt.gca().patches:
    plt.text(i.get_x() + i.get_width()/2, i.get_height() + 0.2, f'{i.get_height():.2f}', ha='center', va='bottom')
plt.tight_layout()
plt.show()
```

Figure 8 shows the hardness values of AA6063 alloy nanocomposites.

```
# Ultimate Tensile Strength Bar Plot
plt.figure(figsize=(10, 6))
tensile_strength_sheet.mean().plot(kind='bar', color='lightcoral', edgecolor='black')
plt.title('Mean Ultimate Tensile Strength Results')
plt.ylabel('Tensile Strength')
plt.xlabel('Material')
for i in plt.gca().patches:
    plt.text(i.get_x() + i.get_width()/2, i.get_height() + 0.2, f'{i.get_height():.2f}', ha='center', va='bottom')
plt.tight_layout()
plt.show()
```

Figure 9 shows the ultimate tensile strength bar plot of AA6063 nanocomposites.

```
import pandas as pd
import matplotlib.pyplot as plt
import numpy as np
```

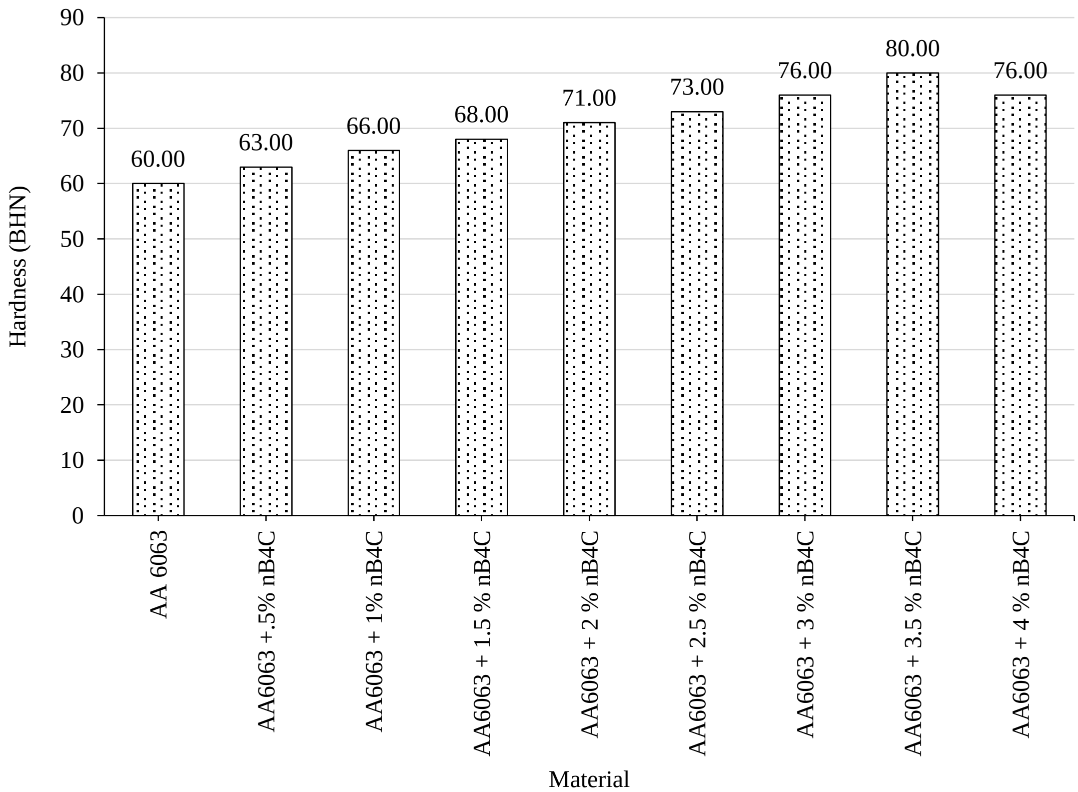

Figure 8. Mean Hardness of AA6063, AA6063 nanocomposites.

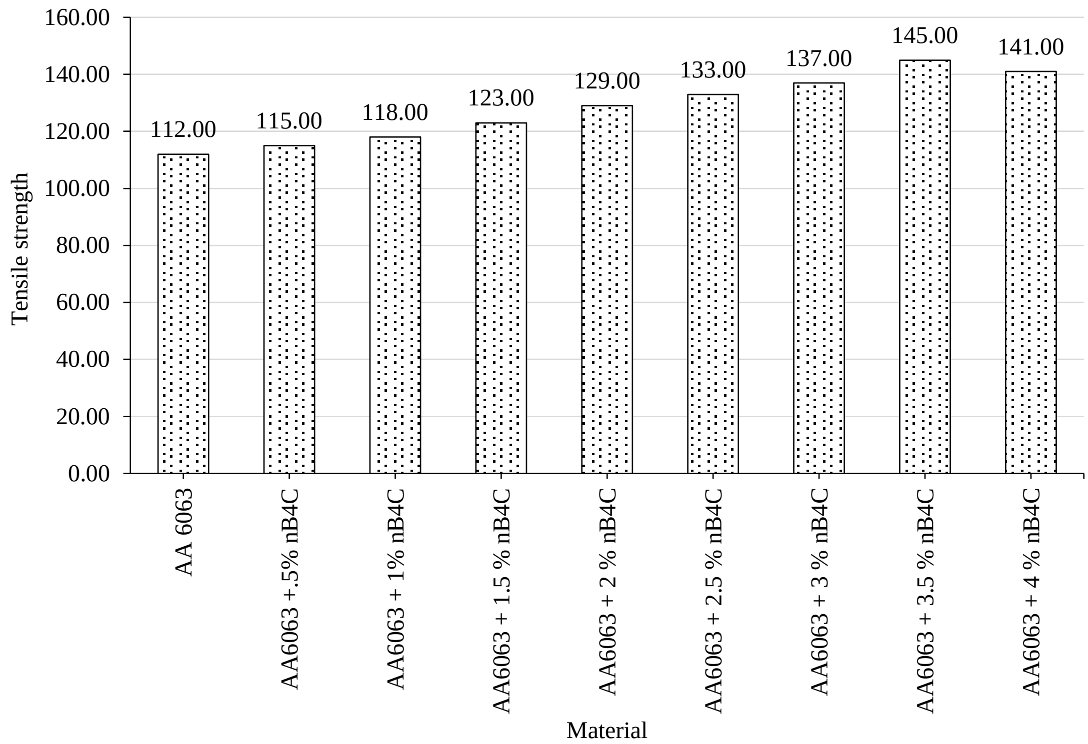

Figure 9. Mean Ultimate Tensile Strength of AA6063, AA6063 nanocomposites.

```
# Function to create the boxplot with separate legends
def plot_boxplot(data, title, ylabel, xlabel, sample_names):
  plt.figure(figsize=(10, 6))
  data.boxplot()
  plt.title(title)
  plt.ylabel(ylabel)
  plt.xlabel(xlabel)

  # Add legend for each plot
  handles = [plt.Line2D([0], [0], color='black', label=f'{key}: {value}') for key, value in sample_names.items()]
  plt.legend(handles=handles, loc='lower right', fontsize='small')

  plt.tight_layout()
  plt.show()

# Create a dictionary for the sample names
sample_names = {
  's1': 'AA6063',
  's2': 'AA6063 + 0.5% nB4C',
  's3': 'AA6063 + 1% nB4C',
  's4': 'AA6063 + 1.5% nB4C',
  's5': 'AA6063 + 2% nB4C',
  's6': 'AA6063 + 2.5% nB4C',
  's7': 'AA6063 + 3% nB4C',
  's8': 'AA6063 + 3.5% nB4C',
  's9': 'AA6063 + 4% nB4C'
}
```



```
# Update sample names in the data
compression_test_sheet.columns = list(sample_names.keys())
hardness_bhn_sheet.columns = list(sample_names.keys())
tensile_strength_sheet.columns = list(sample_names.keys())

# Plot Compression Test Box Plot separately with legend
plot_boxplot(
  compression_test_sheet,
  title='Compression Test Results',
  ylabel='Compression Strength',
  xlabel='Material',
  sample_names=sample_names
)
```

The compression test boxplot of AA6063 nanocomposites is shown in Figure 10.

```
# Plot Hardness BHN Box Plot separately with legend
plot_boxplot(
  hardness_bhn_sheet,
  title='Hardness BHN Results',
  ylabel='Hardness (BHN)',
  xlabel='Material',
  sample_names=sample_names
)
```

Figure 11 shows the hardness box plot of AA6063 with varying weight proportions of nano boron carbide.

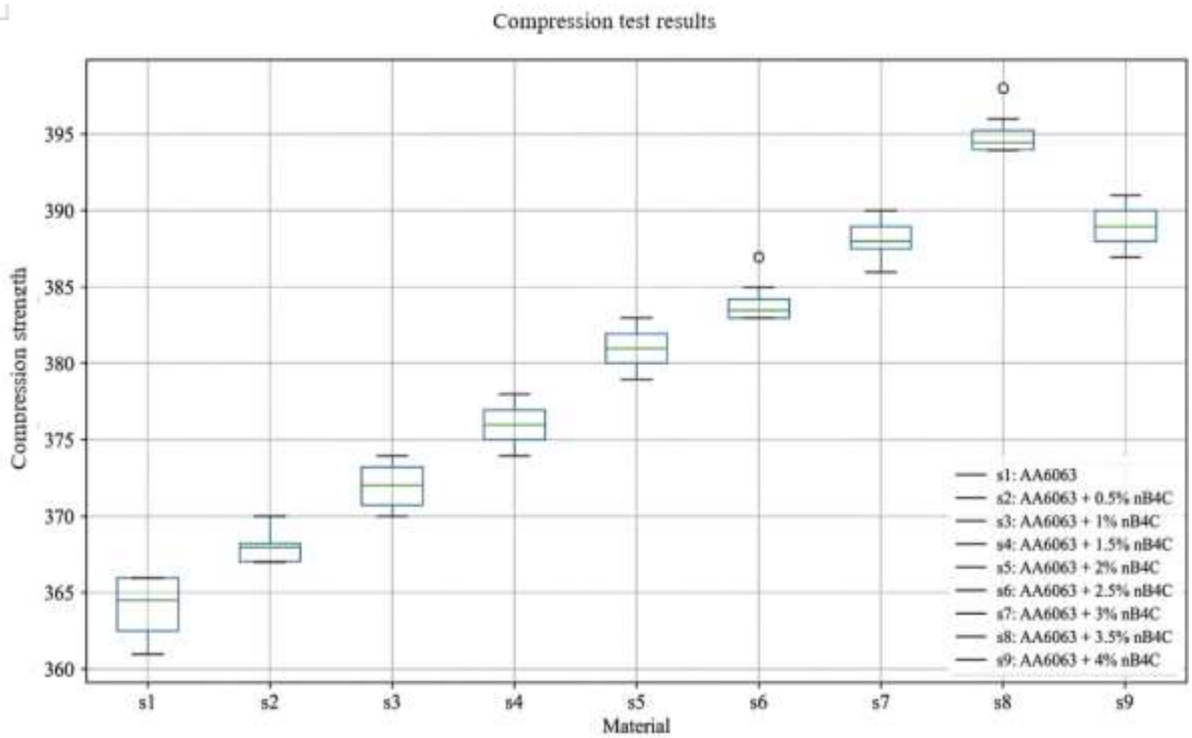

Figure 10. Compression test result of AA6063-nB_4C composites by boxplot.

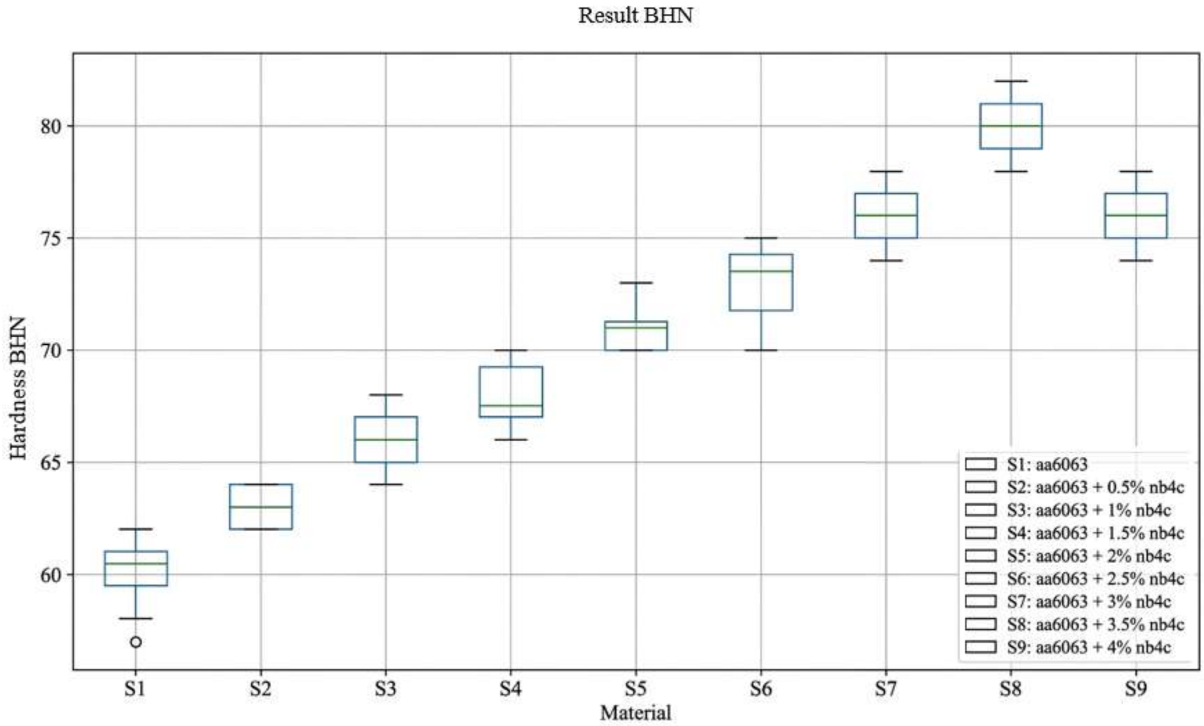

Figure 11. Hardness of AA6063-nB_4C composites by boxplot.

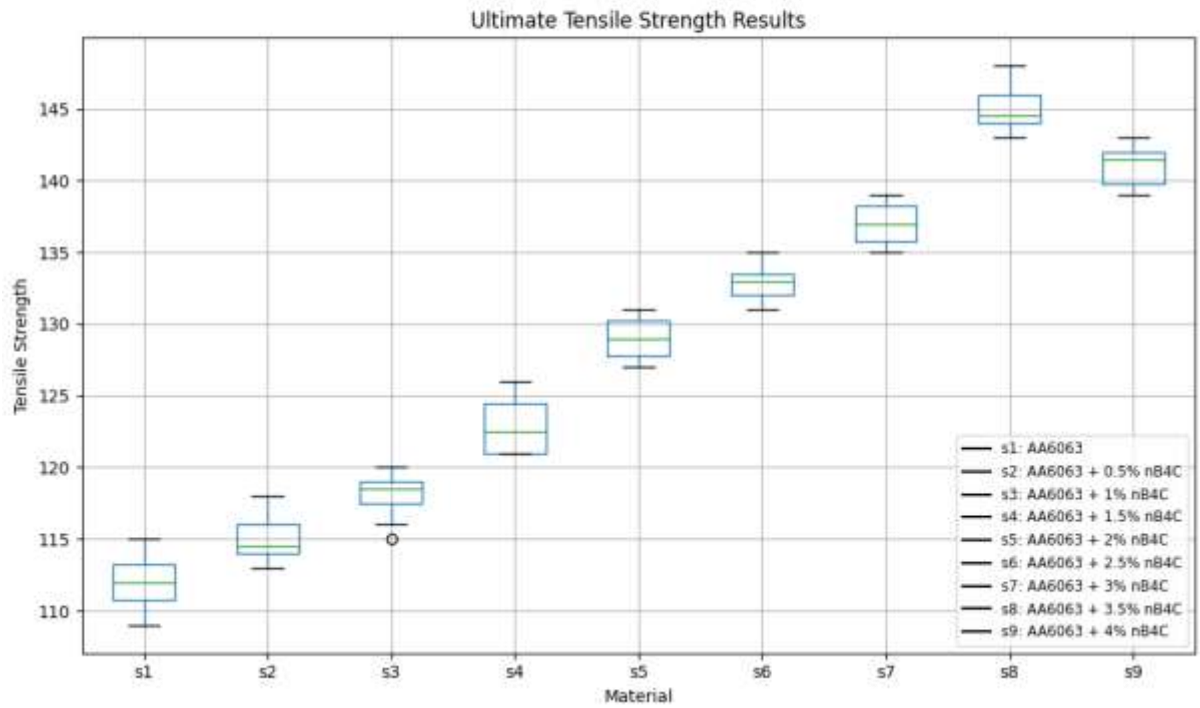

Figure 12. Ultimate tensile strength of AA6063-nB_4C composites by boxplot.

Figure 12 shows the ultimate tensile strength of AA6063 with varying weight proportions of nano boron carbide.

```
# Plot Ultimate Tensile Strength Box Plot separately with legend
plot_boxplot(
```

```
    tensile_strength_sheet,
    title='Ultimate Tensile Strength Results',
    ylabel='Tensile Strength',
    xlabel='Material',
    sample_names=sample_names
)
```

CONCLUSION

The Microstructural analysis and mechanical properties of varying weight % nano-boron carbide (0.5% to 4% with an interval of 0.5), reinforced Al-Mg-Si alloy composites were successfully produced by stir casting.

1. SEM reveals that Nano particles are uniformly distributed throughout the matrix, leading to very little residual porosity and their agglomeration is detected at 4wt% nano addition.
2. Comparing to as-cast, nano-reinforced AA6063 composites reveals better Mechanical properties.
3. The Hardness, ultimate tensile strength, and compression strength of AA6063-3.5 % nB_4C show better performance compared to the remaining composite materials.

Conflicts of Interest

The authors declared that there is no conflicts of Interest

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