Optimization of ductility and yield strength on Al2024/B₄C composite material using Taguchi Technique

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Abstract: In the present investigation, Al2024 alloy reinforced with boron carbide particulates with three different mesh size (100, 200 and 300) have been chosen for the preparation of MMCs. Stir casting route was adopted by varying weight percentage of boron carbide particulates by 1 wt.%, 3 wt.% and 5 wt.%. The cast component was machined through conventional lathe machine tool as per ASTM E8-16a size for tensile test specimen. The tensile test specimens have been subjected to solutionizing treatment at 520 °C for 24 hours followed by water quenching. The quenched test specimens are then subjected to artificial ageing at 175 °C for holding duration of 1 hr., 3 hrs. and 5 hrs. The tensile specimens after artificial ageing were tested using UTM to evaluate the ductility and yield strength of the formed composite material. It is noticed that ductility found to be decreased with increase in wt.% of boron carbide in the Al2024 alloy, whereas yield strength was found to be improved. Taguchi Technique was adopted to evaluate the S/N ratio, optimization, influence of process parameter and regression equation were derived for the confirmation of experimental results through Minitab software. SEM images reveal the uniform distribution of boron carbide in Al2024 alloy. Ductile tearing was observed in pure Al2024 alloy and the formed composite material.

1. Introduction
From the past three eras, there has been arigorous effort were made towards the formation and evaluation of the metal matrix composites. Evaluated MMCs exhibited high strength to weight ratio and better performance characteristics of these composite materials especially in the applications of the aerospace industry. Among various MMCs, Aluminum and its alloys play the more attention which is due to their extensive use in the engineering applications.
As the Pre-heating temperature of the mould increases the impact strength, tensile strength and hardness decreases which are due to the radiative heat transfer coefficient. When pouring temperature of the molten alloy increases, the hardness, tensile strength and impact strength was found to be decreased which is due to increase of the metal hydrogen content followed by picking up the moisture in the form of vapours from the mould[1]. For 3wt.% of B4C and 10 wt.% of SiC in Al7075 alloy can achieve a good toughness and high hardness. Therefore, 3 wt.% of B4C and 10 wt.% of SiC in the Al7075 matrix material maybe considered as the optimal weight percentage for heavy vehicle applications [2]. Hardness and UTS of Al-Cu-Mg alloy can be improved by volume fraction of magnesium and it has a major contribution when compared with the ageing duration, solution temperature and ageing temperature [3]. Large grain refinement can be achieved for Al2024 alloy up to five turn by high-pressure torsion by applying a 6Gpa pressure at room temperature, which is due to the high volume of straining attained by the combined effect of torsion and succeeding compression [4]. Nano-sized SiC in the form of semisolid slurries are used to the fabrication of Al7075 matrix through the advance process so called ultrasonic-assisted semisolid stirring. In order to disperse the SiC nano sized particles in the matrix of Al7075 alloy, semisolid stirring and ultrasonic treatment were combined. Ductile fracture characteristics exhibit for the tensile fracture of the rheo formed composite and steadiness with the ductility of the formed composite material [5].

Stir casting route was adopted to fabricate the Al6061/10 wt.% of Si3N4 by using electrical resistance furnace with a power of 6KW. Nickel coating was done for the surface of Si3N4 particles, before the formation of composite material to improve the wet ability in the Al6061 alloy molten metal. Micro hardness was found to be improved for hot forged heat treatment material when compare to Al6061-10 wt.% Si3N4 composites and Al6061 alloy alone [6]. Addition of the boron carbide particles in Al-Zn-Mg alloy matrix, accelerate the ageing kinetics when compare with the unreinforced material. Presence of B4C reinforcement in the composite material shows the strain concentration, whereas the non uniform distribution of dislocation was observed at the Al/B4C interface[7]. Al6061/B4C composite shows the increase in wear resistance, tensile strength and hardness with an increase in reinforcement content. Testing speed (rpm) contribute (%) highest wear loss for the Al6061/B4C composite, whereas the lowest contribution (%) for the reinforcement[8].

Al2O3 has a major significant contribution (%) on Al7075/Al2O3/SiC composite followed by Silicon carbide and heat treatment temperature. Optimum process parameter for attaining maximum hardness for Al7075/Al2O3/SiC composite are Al2O3 at 6 wt.%, SiC at 9% and heat treatment temperature at 180 °C. [9]. Al/TiB2 composites were fabricated using stir casting technique by varying 3, 6 and 9 wt.% of reinforcement in the matrix material. With the increase in volume fraction of TiB2 in theAl6061 alloy tensile strength was found to be improved without any substantial decrease in the elongation of the composite material. The ductile fracture was occurred at the fractured surface of the tensile specimens of all the formed composite material by the combination of microvoids and nucleation [10]. Improvement on the hardness of Al2024 alloy with T3 conduction was observed with an increase of ageing time. Precipitation was observed through microstructure which causes the increase in hardness of Al2024 alloy and grains are smoothened [11]. Al7075/TiB2 composites exhibit 3.29 % higher ultimate tensile strength and 4.93 % higher hardness when compared with Al7075/SiC composites. Addition of TiB2 and SiC in the matrix of Al7075 alloy increases the UTS and micro hardness which is due to hard reinforcement particles. The ductile fracture was observed at the fracture surface of tensile specimens, due to micro voids and formation of nucleation in the composite material [12].

From the exhaustive literature survey, it is observed that many investigators have worked on the characterization of Metal Matrix Composites and hybrid composite material by varying wt.% of reinforcement material and selecting different casting technique. Mechanical and tribological properties were evaluated for the formed composite materials, it was found that the strength of composite material was increased whereas the ductility was found to be decreased. With increase in weight % of reinforcement in the matrix material, wear resistance was found to be improved. Several researchers used Taguchi Technique to evaluate the optimal process parameter, S/N ratio, regression equations and percentage of contribution by ANOVA.

By this circumstantial, the objective of the current investigation includes i) Formation of Al2024/B4C composites by varying 1, 3 and 5 wt.% with 100, 200 and 300 mesh size ii) Evaluation of yield strength and ductility for the formed composite material. Also, an effort has been made i) To know optimal process parameter and S/N ratio of the formed composites ii) To derive the regression equation and percentage of contribution by ANOVA through Minitab software.
2. Experimentation Details

2.1 Selection of Materials
For the current research work, Al2024 alloy has been chosen as matrix material which exhibits reasonable strength, extremely corrosion-resistant material and heat treatable. In the opinion of this, commercially available Al2024 alloy was selected in the form of Ingot shape as shown in figure 1. Chemical composition of the Al2024 alloy in weight percentage is represented in the table 1. B4C particles have been chosen as reinforcing material with three different mesh sizes as shown in figure 2 (a), (b) and (c). The Al2024/B4C composite material is highly familiar in industrial applications which is due to high hardness, thermal and chemical stability.

![Figure 1: Ingot of Al2024 alloy](image1.png)

![Figure 2: (a) 100 B4C (b) 200 B4C (c) 300 B4C](image2.png)

| Element | Fe   | Si   | Cu   | Mn   | Mg   | Zn   | V    | Al   |
|---------|------|------|------|------|------|------|------|------|
| Amount (Wt.%) | 0.42 | 0.16 | 4.48 | 0.81 | 0.81 | 0.15 | 0.02 | 93.15 |

2.2 Formation of composites
Composite materials are formed by using an electric pit furnace as shown in figure 3(a). The split die in the form of cylindrical shape which is made up of cast iron material was chosen and their edges were preheated to a temperature of 175°C by clamping at the four corners as shown in figure 3(b). The degassing tablet having chemical composition hexachloro-ethane (C2Cl6) as shown in figure 3(c). This degassing tablet was added to the vortex to release all the observed gases from the molten metal to prevent blowholes, porosity during the formation of composite material. Metal Matrix Composites (MMCs) was prepared by addition of 1, 3 and 5 wt.% of boron carbide particles with three mesh sizes. The boron carbide particles were pre-heated to 320°C for 25minutes in order to take out the volatile substance and impurities present in it. The pre-heated B4C particles were introduced into the molten metal manually at controlled rate, while molten metal being stirred. Mechanical stirring was done at the rate of ~500 rpm speed for nearly 8 to 10 min. to achieve the homogeneous mixture of reinforcement throughout the matrix. Figure 3(d) Show the pouring of metal matrix composite into the die cavity. After pouring, the cast product was allowed to solidify about 20 minutes and the die was allowed to cool naturally to ambient temperature. The cast composite have a dimension of 25 mm diameter and length of 210 mm.

![Figure 3:(a) Electric Pit Furnace (b)Clamping of die and pre-heating](image3.png)
Machining and heat treatment

The cast composites were machined by using conventional lathe machine tool as per ASTM E8-16 a standard. After the preparation of test specimens, heat treatment was done in two stages. Stage 1: solutionizing at 520 for 24 hrs. and then water quenched to room temperature. Stage 2: Single-step ageing was done at 175 for the holding time of 1 hr., 3 hrs. and 5 hrs. Ductility and yield strength of the composite material were evaluated by destructive testing method.

Design of Experiments

In the current work, optimization of ductility and yield strength of Al2024/B4C composite materials have done by using L9 orthogonal array. S/N ratio was evaluated for the formed composite materials by considering the 3 factors (wt.% of B4C, ageing duration and mesh size) at 3 levels each. Analysis of variance (ANOVA) is a significant analyzing tool adopted to identify the importance of individual parameter on the output response. ANOVA was done to know the percentage contribution of each factor on ductility and yield strength of the formed metal matrix composites. To validate the experimental values, a regression equation was derived by using Minitab software and compared. The factors and levels selected for the study are represented in the Table 2.

| Table 2: Factors and levels selected. |
|---------------------------------------|
| Sl.No. | Factors  | Levels          |
|--------|----------|-----------------|
| A      | Boron carbide (B4C) | 1, 3 and 5 (wt.%) |
| B      | Ageing duration  | 1, 3 and 5 (hrs.)  |
| C      | Mesh size     | 100, 200 and 300 |

Results and Discussion

Optimization of wt.% of B4C, ageing duration and mesh size parameters on ductility.

| Table 3: (a)Experimental Layout for ductility and their S/N ratio by using L9 (3⁴) orthogonal array. |
|-----------------------------------------------------------------------------------------------|
| Exp. No. / Runs | Wt % of Boron Carbide (A) | Ageing Duration in hrs (B) | Mesh Size (C) | Ductility (%) | Average Ductility (%) | S/N ratio |
|-----------------|--------------------------|---------------------------|--------------|--------------|-----------------------|-----------|
| 1               | 1                        | 1                         | 100          | 8.53         | 9.68                  | 9.3       | 19.24     |
| 2               | 1                        | 3                         | 200          | 10.56        | 10.76                 | 11.2      | 20.70     |
| 3               | 1                        | 5                         | 300          | 10.56        | 10.21                 | 9.95      | 10.24     |
| 4               | 3                        | 1                         | 200          | 9.36         | 9.89                  | 9.37      | 9.54      | 19.59     |
| 5               | 3                        | 3                         | 300          | 9.87         | 9.75                  | 9.81      | 9.81      | 19.83     |
| 6               | 3                        | 5                         | 100          | 7.36         | 7.96                  | 6.55      | 7.29      | 17.25     |
| 7               | 5                        | 1                         | 300          | 8.2          | 9.65                  | 9.87      | 9.24      | 19.31     |
| 8               | 5                        | 3                         | 100          | 6.87         | 6.61                  | 6.95      | 6.81      | 16.66     |
| 9               | 5                        | 5                         | 200          | 6.26         | 6.78                  | 6.58      | 6.54      | 16.31     |
Table 3 (a) represents the variation of ductility with wt.% of boron carbide, ageing duration and mesh size. S/N ratio is better for the 2nd run having 1 wt% of B₄C, 3 hrs ageing duration with 200 mesh size. i.e 20.70 (Larger is better)

### Table 3: (b) Experimental Layout for yield strength and their S/N ratio by using L₉ (3⁴) Orthogonal array.

| Exp.No. | Runs | Wt % of Boron Carbide (A) | Ageing Duration in hrs (B) | Mesh Size (C) | Yield strength (N/mm²) Trail 1 | Trail 2 | Trail 3 | Average Yield Strength (N/mm²) | S/N ratio |
|---------|------|---------------------------|-----------------------------|---------------|----------------------------------|--------|--------|---------------------------------|----------|
| 1       | 1    | 1                         | 100                         | 1             | 178.26 179.56 178.64             |        |        | 178.82                          | 45.04    |
| 2       | 1    | 3                         | 200                         | 3             | 185.26 183.25 184.24             |        |        | 184.25                          | 45.30    |
| 3       | 1    | 5                         | 300                         | 1             | 193.48 195.21 194.54             |        |        | 194.41                          | 45.77    |
| 4       | 3    | 1                         | 200                         | 1             | 178.26 176.26 181.82             |        |        | 178.78                          | 45.04    |
| 5       | 3    | 3                         | 300                         | 1             | 185.26 187.56 186.23             |        |        | 186.35                          | 45.40    |
| 6       | 3    | 5                         | 100                         | 1             | 220.65 221.36 219.91             |        |        | 220.64                          | 46.87    |
| 7       | 5    | 1                         | 300                         | 1             | 159.36 159.34 156.35             |        |        | 158.35                          | 43.99    |
| 8       | 5    | 3                         | 100                         | 1             | 220.36 220.69 220                 |        |        | 220.35                          | 46.86    |
| 9       | 5    | 5                         | 200                         | 1             | 215.74 216.36 215.36             |        |        | 215.82                          | 46.87    |

Table 3 (b) shows the variation of yield strength with wt% of boron carbide, ageing duration and mesh size. S/N ratio is better for the 6th run having 3 wt% of B₄C, 5 hrs ageing duration with 100 mesh size. i.e 46.87 (Larger is better)

Figure 4 (a) Main effects plot for means-ductility

Figure 4 (b) Main effects plot for means-yield strength

3.1 Optimization of wt.% of B₄C, ageing duration and mesh size parameters on yield strength.

$\text{Table 3: (b)}$
Table 4 (a): Response table for means for ductility

| Level | wt.% of boron carbide | Ageing Duration | Mesh Size |
|-------|-----------------------|-----------------|-----------|
| 1     | 10.083                | 9.317           | 7.757     |
| 2     | 8.88                  | 9.153           | 8.973     |
| 3     | 7.53                  | 8.023           | 9.763     |
| Delta | 2.553                 | 1.293           | 2.007     |
| Rank  | 1                     | 3               | 2         |

(b): Response table for means for yield strength

| Level | wt.% of boron carbide | Ageing Duration | Mesh Size |
|-------|-----------------------|-----------------|-----------|
| 1     | 185.8                 | 172             | 206.6     |
| 2     | 195.3                 | 197             | 192.9     |
| 3     | 198.2                 | 210.3           | 179.7     |
| Delta | 12.3                  | 38.3            | 26.9      |
| Rank  | 3                     | 1               | 2         |

3.2. ANOVA for ductility and yield strength

Table 5 (a) and (b) shows the result of analysis of variance on ductility and yield strength for Al2024/B4C composite material. Percentage contribution of individual parameter on ductility and yield strength is tabulated in last column by conducting ANOVA at 95% confidence level and 5% level of significance.

From Table 5 (a), it is revealed that wt.% of boron carbide has a major contribution on the ductility (Pr. = 50.27%). Hence the wt.% of boron carbide plays an important parameter which has to be controlled and taken into account for ductility property. Wt.% of boron carbide is further followed by mesh size (Pr = 31.48%), ageing duration (Pr = 15.28%) on the ductility of the metal matrix composites.

From Table 5 (b), one can easily identify that the ageing duration factor has a major contribution on yield strength (Pr. = 60.63%). Hence the ageing duration factor plays a vital role on yield strength of the Al2024/B4C composite materials. Ageing duration is further followed by mesh size (Pr = 28.87%), wt.% of boron carbide (Pr = 6.64%) on the yield strength of the metal matrix composites.

Table 5: (a) ANOVA for ductility (%)

| Factors             | Adj SS | Seq SS | Adj MS | P-Value | F-Value | DF | Pr % |
|---------------------|--------|--------|--------|---------|---------|----|------|
| wt% of Boron Carbide| 9.79   | 9.79   | 4.895  | 0.055   | 17.02   | 2  | 50.27|
| Ageing Duration     | 2.9763 | 2.9763 | 1.4881 | 0.162   | 5.18    | 2  | 15.28|
| Mesh Size           | 6.1311 | 6.1311 | 3.02655| 0.086   | 10.66   | 2  | 31.48|
| Error               | 0.5751 | 0.5751 | 0.2875 |         |         | 2  | 2.97 |
| Total               | 19.4725| 8      |        |         |         |    | 100  |
ANOVA for yield strength (N/mm²)

| Factors                  | Adj SS | SeqSS | Adj MS | P-Value | F-Value | DF | Pr % |
|--------------------------|-------|-------|--------|---------|---------|----|------|
| wt% of Boron Carbide     | 249.87| 249.87| 124.94 | 0.382   | 1.62    | 2  | 6.64 |
| Ageing Duration          | 2269.47| 2269.47| 1134.73| 0.064   | 14.69   | 2  | 60.36|
| Mesh Size                | 1085.5| 1085.5| 542.75 | 0.125   | 7.03    | 2  | 28.87|
| Error                    | 154.52| 154.52| 77.26  |         |         | 2  | 4.13 |
| Total                    | 3759.36|       |        |         |         |    | 100  |

3.3 Regression equation for ductility and yield strength

Commercially available Minitab 16 software is used for developing the General Linear (GL) regression equation. This equation gives the relationship between various factors/variable (wt.% of B₄C, ageing duration and mesh size) and a response variable (Ductility and yield strength) to the experimental data.

General Linear Regression equation for ductility and yield strength are:

(i) \[ \text{Ductility} = 9.70944 \times 0.638333 \times \text{wt.}% \text{ of } B₄C \times 0.323333 \times \text{ageing duration} + 0.0100333 \times \text{mesh size} \]

R-Sq = 77.89%  

(ii) \[ \text{Yield Strength} = 181.996 + 3.08667 \times \text{wt.}% \text{ of } B₄C + 9.57667 \times \text{ageing duration} - 0.1345 \times \text{mesh size} \]

R-Sq = 74.63%

Figure 5 (a) and (b) shows the plot of experimental values v/s forecast values for all the 3 levels of their factor. It is clearly showing that the experimental values are very close to the forecast values and hence ductility and yield strength of the formed composites are validated.

![Figure 5: (a) Comparison plot experimental values v/s Forecast values for ductility](image)

![Figure 5: (b) Comparison plot experimental values v/s Forecast values for yield strength](image)
Table 7: Comparison results of experimental values and their regression model values.

| Sl. No. | Ductility (Exp.) (%) | Ductility (%) from Reg. model (1) | Error (%) | Yield strength (Exp.) (N/mm²) | Yields strength (N/mm²) from Reg. model (2) | Error (%) |
|---------|----------------------|----------------------------------|-----------|--------------------------------|---------------------------------------------|-----------|
| 1       | 9.17                 | 9.75                             | 5.94      | 178.82                         | 181.20                                      | 1.33      |
| 2       | 10.84                | 10.10                            | 6.82      | 184.25                         | 186.91                                      | 1.44      |
| 3       | 10.24                | 10.46                            | 2.14      | 194.41                         | 192.61                                      | 0.92      |

Figure 6 (a) Interaction plot for Ductility

Figure 6 (b) Interaction plot for yield strength

Figure 6 (a) represents the data for the interaction effect of the factor ageing duration for various levels of boron carbide on ductility. It is noticed that the mean value of ductility has increased with the ageing duration particularly with the lower wt% of boron carbide in Al2024 alloy up to 3 hrs. of ageing duration and there is a decreasing trend in the ductility, particularly with higher ageing duration. This is due to precipitate formation between matrix and reinforcement material.

Figure 6 (b) represents the data for the interaction effect of the factor ageing duration for various levels of boron carbide on yield strength. It is noticed that the mean value of yield strength has increased with the ageing duration particularly with 3 wt% of boron carbide in Al2024 alloy which is maybe due to the more bonding and uniform mixture of reinforcement in the matrix material.
4. SEM Examination

Figure 7 (a) indicates the SEM image of Al2024 cast alloy. From the image, it is evident that it is a pure Al2024 alloy consist of smooth dimple structure indicating a ductile tearing.

Figure 7(b) reveals that boron carbide particles are embedded in the matrix material but not that extent. The structure looks like a spherical shape, it consists of rough dimple structure. The precipitation formation is less and results in ductile tearing.

Figure 7 (c) shows the rough hard dimple structure is found due to increase in ageing duration. Precipitation was found to be increased which increases in strength of base material.

Figure 7(d) shows that the structure looks like almost rough dimple structure are formed with the small crack generation. Uniform dimple structure varies and there is a small breakage in the dimple structure and tearing will become more ductile. This small gap in the rough dimple structure will lead to ductile tearing, further dislocation of the rough dimple structure from one region to another region may lead to a decrease in strength of the base material.

5. Conclusion

Based on the investigation, the Al2024/B4C composite material are fabricated by stir casting route. The mechanical properties were evaluated and following outcomes are drawn:

- In this research work it has been discussed the important of the Taguchi technique to know the effect and percentage contribution of each factors on Al2024/B4C composites.
- Formed composites exhibits increasing yield strength with an increase in the amount of B4C particles, which is attribute due to the more bonding between the reinforcement and the matrix.
- Ductility of the formed composite decrease with an increasing amount of reinforcement which is owed may be due to the presence of B4C in the Al2024 matrix.
- Factors which mostly affect the ductility of the formed composites are wt.% of B4C, mesh size and ageing duration, in reducing order of the influence.
- For ductility the highest percentage contribution is found that wt.% of B4C (50.27%), whereas ageing duration (15.28%) was found to be lowest percentage contribution.
- Factors which mostly affect the yield strength of the formed composites are ageing duration, mesh size and wt.% of B4C, in reducing order of influence.
- For yield strength the highest contribution is found that ageing duration (60.36%), whereas wt.% of
B$_4$C (6.64%) was found to be lowest percentage contribution.

- General linear regression equations reveal that experimental values are close with the regression model equations for both ductility and yield strength. Hence the experimental result is validated.
- Fracture studies of tensile specimens show the B$_4$C particles distributed in the matrix material. Precipitation of reinforcement particles was observed with dimple structure leading to ductile fracture.

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