Optimization of Stir-Squeeze Casting Parameters to Analyze the Mechanical Properties of Al7475/B4C/Al2O3/TiB2 Hybrid Composites by the Taguchi Method

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Stir-squeeze casting (SSC) is the appropriate and inexpensive technique for producing aluminum hybrid matrix composites as it creates a uniform distribution of reinforcements in the composite with finer grains. Al7475 is a lightweight castable alloy that possesses enough hardness and strength with applications in automotive and aerospace. This research work examines the effect of process parameters for Al7475/Al2O3/B4C/TiB2 hybrid matrix composites produced by the stir-squeeze casting methodology. As per Taguchi design L16, four parameters with four levels were selected in the optimization process of SSC are stir speed (SD) of 300-450 rpm, melting temperature (ME) of 750–900 °C, squeeze pressure (SE) of 50-125 MPa, and reinforcement (RT) of 2-8 wt%. The mechanical properties such as tensile strength (TS) and hardness (HN) are studied by the variation of each process parameters levels. The optimization results on TS and HN are predicted by Minitab-17 Software. It is observed that maximum TS of 325 MPa and HN of 130.6 Hv are attained at experiments L1 and L7, respectively. From the SN ratio result, the TS value is improved at the parameter level of RT2-SE4-ME2-SD4. The ANOVA result exposed that reinforcement is the most significant factor for enhancing tensile strength which contributes 38.9%, followed by squeeze pressure of 28.4%, stir speed of 13.6%, and melting temperature of 12.16%.

1. Introduction

Metal matrix composites are formed by combining two or more materials, and custom qualities are created by carefully combining the constituent parts. Specific combinations of features in composites, such as fatigue strength, hardness, damping property, coefficient of friction, wear resistance, and coefficient of thermal expansion, are made possible by systematic designs and synthesis techniques. Because of their superior physical and mechanical characteristics, aluminum-matrix composites reinforced with discontinuous supports have been used more frequently in the automotive, aerospace, and electrical industries [1]. Al7000’s superior strength is by far its most significant advantage. Its tolerance of stress/strain makes it extremely valuable in aircraft applications, where it allows for weight savings over steel, even if it does not have a similar level of corrosion opposition or weldability as other alloys do. Stir-squeeze casting is a flexible method for making the composite cheaply. The components’ sizes typically vary from small to large and have elaborate designs. Melt and solidification are crucial phases in the casting processes. [2] The effect of the cast feature is based on a number of factors,
combined with the effect of limited automation [3]. Segregation, center-line cracking, and porosity are the uncontrollable process characteristics in casting that show poor mechanical characteristics. Squeeze casting could be able to solve these issues. This process combines closed die forging with gravity die casting. High squeeze pressure crystallization of liquid metal results in better microstructure and mechanical properties [5]. B4C/SiC-strengthened AA7075 composites with various compositions were effectively produced by utilizing the stir and squeeze casting methods to study mechanical properties. SEM and optical microstructure analysis revealed a uniform dispersion in the A7075 matrix strengthened with 1% wt of both B4C and SiC. The A7075 alloy’s hardness values were also raised by the addition of 1.5 wt% of boron carbide and 1% of tiny SiC particles. [6] To clarify the impact of extra additive particles on the mechanical properties of the produced composites, the hardness and elongation behaviors of AA7039 strengthened with particular particles of alumina, boron carbide, and also silicon carbide were investigated. Utilizing powder metallurgy and the hot-extrusion technique, AA7039 along with three composite specimens reinforced Al2O3, B4C, and SiC (10 wt.%) were effectively created. The findings showed that all reinforcement particles were dispersed properly in the matrix and a strong interfacial bond between reinforcements and matrix components had been achieved. The specimen with the highest hardness and elongation among the other samples was 10 wt.% Al2O3 with Al alloy. Compared to the B2C- and SiC-reinforced composites, the Al2O3-reinforced composite demonstrated improved interfacial bonding [7]. According to the study of Zheng et al., secondary phases are produced quickly in the melt as a result of the reaction between molten aluminum and B2C, which leads to the formation of the Al6B4C and AlB2 phases [8]. Rajan et al. looked into how various stir casting processes such as (i) compo casting and modified compo casting and squeeze casting routes affected the microstructure and characteristics of small fly ash/Al-7Si-0.35 Mg composites. There have been reports of MgAl2O4 being formed by the reaction of aluminum with SiO2 and Al2O3 [9]. The evaluation of mechanical and wear properties were done after stir casting a 6061 Al–Al2O3 metal matrix composite. The melt stirring process, which combines three stages of mixing with preheat reinforcement, was successfully used to create composites including 6061Al with 6–12wt% of Al2O3. The alumina particle in the 6061Al metal matrix is distributed pretty uniformly in the optical micrographs of stir-cast composites [10]. Tiwen Lu and colleagues examined into the impact of Zr/Fe particle modifications on the microstructure and mechanical performance of 7075Al-based composites reinforced with 40 wt.% SiC. The created composite has the highest UTS and fracture strain with a measurement of 564 MPa and 1.12%, respectively. It also displays a mixed ductile and brittle fracture feature, with Zr elements being infrequently found in the fracture due to strong interphase bonding. The majority of the iron particles in the broken AMC/Fe composite, however, show interfacial debonding from the Al matrix [11]. Ni/Ti particles of the same size were added to SiCp/7075Al composites using squeeze casting. Ti particle-added composites had better tensile strength and plasticity with values of 573 MPa and 0.65%, respectively. The more desirable interfacial structure that would guarantee the strengthening effects of metal particles is the interdiffusion metallurgical bonding. [12] The literature survey revealed that the AA7xxx series has received very little attention. In various industries, especially in the automotive and aerospace sectors, the improvement of reinforced 7475 composites with high strength and light weight is essential. Many researchers have attempted to produce composites using combined stir-squeeze casting. However, little effort has been put into optimizing the stir-squeeze casting process parameters (SSC). The novelty of this work is to produce AA7475/Al2O3/B4C/TiB2 hybrid composites by the stir-squeeze method and determine the mechanical properties of the prepared composites. The primary goals of this research are to identify the most appropriate SSC parameters and the contribution of reinforcements to enhance tensile strength (TS) and hardness (HN). With the help of the Taguchi method and Minitab software, we were to find the optimized parameters of stirrer speed (SD), melting temperature (ME), squeeze pressure (SE), and also reinforcement (RT).

### 2. Materials and Methodology

AA7475 is used as the main material and Al2O3/B4C/TiB2 with 50 μm powder as the reinforcement. A strong substance with excellent strength and high wear resistance at high temperatures is titanium diboride (TiB2). It has high stability and wettability in liquid metals like zinc and aluminum and is unaffected by the majority of chemical reagents. Boron carbide powder acts as an abrasive material for polishing purposes, especially in grinding and water jet cutting applications due to its high hardness. Additionally, it is employed for treating diamond tooling. Aluminum oxide (Al2O3), a commonly used ceramic reinforcing material, has shown to exhibit good compressive strength, wear resistance [13], and high machinability. The base alloy 7475 chemical elements contributions are exposed in Table 1.

| Compositions | Cr | Cu | Fe | Mg | Mn | Si | Ti | Zn | Al |
|--------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Weight in%   | 0.20 | 1.8 | 0.12 | 1.9 | 0.05 | 0.12 | 0.07 | 5.6 | Balance |

Table 1: AA7475 chemical compositions.
Taguchi methodology was employed using different orthogonal arrays to offer reduced variance and less number of experiments. The Taguchi method resulted in sixteen experimental arrangements (L1–L16) with parameters disseminated at four levels. AA7475 was melted in a heating furnace with the stirrer. Ages, melted 7475 was mixed with Al₂O₃/B₄C/TiB₂ at various weight percentages in the casting to produce a hybrid composite. 5–10 g of Na₃AlF₆ were further added to the furnace throughout the melting process in order to reduce the production of slag and increase casting effectiveness. The SSC complete setup is given in Figure 1. The lifting mechanism facilitated the travel of the stirrer into contact with the mix’s constituent elements. Al alloy was kept inside a crucible and melted at around 750°C in an electric furnace. 2wt% of Al₂O₃/B₄C/TiB₂ mixed powder burned at 280°C in another furnace. 7475 alloy and reinforcements were blended and heated. To create Al-based composites, the prepared melted particles were placed into the required mold after being continuously stirred by a stirrer connected to the motor for 5-10 min; then, the plunger was used to apply the pressure (50 MPa) from the top of the die, and holding that plunger for 1-2 minutes and then removing the solidified part from the preferred die [14–17]. This process is to be continued for the remaining parameter levels to create several specimens by adjusting the casting parameters.

3. Result and Discussion

The fabricated specimens underwent a tensile test in accordance with the ASTM B557M Standard. The entire samples were cleaned and polished using an abrasive paper to remove any slag from the surface prior to applying a load of 6 KN. Using a 1/16-inch ball indenter and a 250 kg weight, the Brinell hardness machine conducts hardness tests at room temperature. Each specimen is subjected to three different trails which are then averaged. TS and HN readings from the experiment and signal to noise ratio are displayed in Table 3. It was comprehended that the highest and lowest optimum groupings of parameters for tensile strength were acknowledged at SD1-ME1-SE1-RT1 (300 rpm, 750°C, 50 MPa, and 2wt%) and SD4-ME1-SE4-RT2 (450 rpm, 750°C, 125 MPa, and 4wt%), respectively. The best and least for the HN value were also discovered at SD2-ME3-SE4-RT1 (350 rpm, 850°C, 125 MPa & 2wt%) and SD4-ME3-SE2-RT4 (450 rpm, 850°C, 75MPa & 8wt%). S/N ratio response table and main plots help to find the suitable level of each parameter in the mechanical properties (TS and HN) (TS and HN). From Table 4 and Figure 2, it can be seen that the second level of RT was the first rank to develop tensile strength, followed by the fourth level of SE, second level of ME, and fourth level of SD parameters. The smallest is considered as a significant value. Similarly, from Table 5 and Figure 3, it was noticed that HN values were improved by SD4 as the first influencing parameter level, trailed by SE1, RT4, and ME3. Table 6 and Table 7 show the percentage contribution of SSC parameters of SD, ME, SE, and RT for HN and TS properties. F value, P value, and contribution percentage acted as controllable and probability of irrepressible to achieve the maximum TS value [18]. The highest contribution of RT is 38.9% which is the most significant factor to improve TS, followed by SE 28.4%, SD13.6%, and ME 12.16%. Similarly, in the case of hardness (HN), SE is the

| SSC parameter         | Unit | 1   | 2   | 3   | 4   |
|-----------------------|------|-----|-----|-----|-----|
| Stir speed (SD)       | Rpm  | 300 | 350 | 400 | 450 |
| Melting temperature (ME) | °C  | 750 | 800 | 850 | 900 |
| Squeeze pressure (SE) | MPa  | 50  | 75  | 100 | 125 |
| Reinforcements (RT)  | wt%  | 2   | 4   | 6   | 8   |

Figure 1: Stir-squeeze casting setup.
Table 3: Hardness and tensile strength results from experiment and Minitab.

| Experiment No | SSC parameters | Observational result | S/N ratio |
|---------------|----------------|----------------------|-----------|
|               | SD (Rpm) | ME (°C) | SE (MPa) | RT (wt%) | TS (MPa) | HN | TS (dB) | HN (dB) |
| L1            | 300      | 750    | 50      | 2       | 325.23   | 95.60 | -50.2438 | -39.6092 |
| L2            | 300      | 800    | 75      | 4       | 245.23   | 108.20| -39.6092 | -40.6845 |
| L3            | 300      | 850    | 100     | 6       | 315.26   | 107.80| -49.9734 | -40.6524 |
| L4            | 300      | 900    | 125     | 8       | 278.69   | 88.20 | -48.9024 | -38.9094 |
| L5            | 350      | 750    | 75      | 6       | 322.56   | 95.60 | -50.1722 | -39.6092 |
| L6            | 350      | 800    | 50      | 8       | 285.36   | 110.50| -47.7915 | -40.8672 |
| L7            | 350      | 850    | 125     | 2       | 258.69   | 130.60| -47.7307 | -42.3189 |
| L8            | 350      | 900    | 100     | 4       | 243.52   | 120.80| -47.7307 | -41.6413 |
| L9            | 400      | 750    | 100     | 8       | 312.60   | 95.60 | -49.8998 | -39.6092 |
| L10           | 400      | 800    | 125     | 6       | 246.87   | 105.80| -47.8494 | -40.4897 |
| L11           | 400      | 850    | 50      | 4       | 275.23   | 79.25 | -48.7939 | -37.9800 |
| L12           | 400      | 900    | 75      | 2       | 315.26   | 112.87| -49.9734 | -41.0516 |
| L13           | 450      | 750    | 125     | 4       | 215.23   | 128.50| -46.6581 | -42.1781 |
| L14           | 450      | 800    | 100     | 2       | 276.29   | 89.50 | -48.8273 | -39.0365 |
| L15           | 450      | 850    | 75      | 8       | 243.88   | 79.20 | -47.7435 | -37.9745 |
| L16           | 450      | 900    | 50      | 6       | 302.89   | 102.90| -49.6257 | -40.2483 |

Table 4: S/N ratio response for TS.

| Level | SD | ME | SE | RT |
|-------|----|----|----|----|
| 1     | -49.23 | -49.24 | -49.44 | -49.33 |
| 2     | -48.82 | -48.39 | -48.92 | -47.74 |
| 3     | -49.13 | -48.69 | -49.11 | -49.41 |
| 4     | -48.21 | -49.06 | -47.92 | -48.91 |

Delta 1.33 0.73 1.30 1.28
Rank 1 4 2 3

Figure 2: SN plot for TS.

Table 5: S/N ratio response for HN.

| Level | SD     | ME | SE | RT |
|-------|--------|----|----|----|
| 1     | -39.96 | -40.25 | -39.68 | -40.50 |
| 2     | -41.11 | -40.27 | -39.83 | -40.62 |
| 3     | -39.78 | -39.73 | -40.23 | -40.25 |
| 4     | -39.86 | -40.46 | -40.97 | -39.34 |

Delta 1.33 0.73 1.30 1.28
Rank 1 4 2 3
The most influencing factor (50.26%) to develop hardness of prepared composite, trailed by RT 38.23%, SD 5.71%, and ME 4.52%. The results of tensile tests reveal the ductility and strength of materials when subjected to uniaxial tensile stresses. A metal’s capacity to bear tensile loads without breaking is largely determined by its tensile strength. Brittle metals are more likely to rupture and are an important component in the metal forming process.

This test can determine whether potential materials meet the necessary strength and elongation standards for a certain product. Generally, tensile and hardness offer an opportunity to identify novel alloys, their characteristics, and potential applications in the metal of manufacturing industries. The applications of developed composites are bicycle frames, shell casings, aircraft components, and rock climbing equipment, etc.

3.1. Regression Equation. The relationship among process parameters was recognized with the aid of a regression equation and also calculate the value of HN and TS in (1) and (2), which were carried out by Minitab software.

\[ TS = 415 - 0.169 \text{SD} - 0.033 \text{ME} - 0.547 \text{SE} + 0.54 \text{RT}. \] (1)

\[ HN = 103.6 - 0.0315 \text{SD} + 0.0056 \text{ME} + 0.212 \text{SE} - 2.37 \text{RT}. \] (2)
3.2. Contour Plots. These plots are to illustrate the three-dimensional surface on a two-dimensional plane. It displays two parameters on the x and y axes and a response variable of TS and HN on the Z axis. Figure 4, Figure 5, and Figure 6 show the interaction between the SSC parameters on the output response of TS, and Figure 7, Figure 8 and Figure 9 show the interaction between the three parameters on HN. From graph observation, the ranges of casting factors SD(320–450Rpm), ME(800–875°C), SE (65–110MPa), and RT (4-7wt%) were suggested for achieving high tensile strength and hardness of Al7475/Al2O3/B4C/TiB2 hybrid composites.
3.3. Microstructure of the Composite. Figure 10(a) shows the microstructure of Al7475 alloys without the addition of any reinforcements. It is observed that all elements are evenly dispersed in 7475 Al. Figure 10(b) presents the microstructure of the L13 sample and exposed a tough to find out any major difference in dimple morphology in the sample due to the spreading of the reinforcing particles (B₄C/Al₂O₃/TiB₂). Figure 10(c) shows that the L7 sample and reinforcement particles are well engaged in this composite, no marked interfacial products are perceived at the boundaries between the Al7475 matrix and B₄C/Al₂O₃/TiB₂ particles. Figure 10(d) exposes the L1 sample of composites. No cracks and dimples are observed, and reinforcements are distributed uniformly.
4. Conclusion

In this research work, Al7475/Al2O3/B4C/TiB2 hybrid matrix composites were prepared by the stir-squeeze casting process. Four parameters with four levels were selected, such as stirrer speed, melt temperature, squeeze pressure, and reinforcement weight percent. The various tests were performed to analyze mechanical properties of tensile strength and hardness using L16 orthogonal array in the Taguchi methodology. From the experimental observation and optimization technique, we have made the following conclusions.

The maximum TS (325 MPa) was attained at experiment L1 with combined process parameters of a stir speed of 300 rpm, melting temperature of 750°C, squeeze pressure of 50 MPa, and reinforcements of 2wt%, whereas maximum HN (130.6 Hv) was observed by maintaining a stir speed of 350 rpm, melting temperature 850°C, squeeze pressure of 125 MPa, and reinforcements 2wt% which was in the L7 experiment.

From the S/N ratio response table, it was noticed that TS was increased at the RT2 level followed by SE4, ME2, and SD4.

ANOVA results revealed that the most important factor in enhancing tensile strength is reinforcements, which contribute 38.9%, followed by a squeeze pressure of 28.4%, stir speed 13.6%, and melting temperature of 12.16%. Similarly, when it comes to hardness (HN), SE has the greatest influence (50.26%), followed by RT (38.23%), SD (5.71%), and ME (4.52%).

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Disclosure

It was performed as a part of the Employment Bule Hora University, Ethiopia.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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