The characteristics of aluminum AC4B composites reinforced by the fraction volume variations of Boron Carbide through the stir casting process

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Abstract. Aluminum AC4B composite reinforced with Boron Carbide (B4C) was made by stir casting. The characteristics such as toughness, impact strength, and tensile strength were determined. Aluminum AC4B acts as a matrix in the composite given the fraction volume variation of B4C reinforcing particulate of 1; 3; 5; 7; 10 %Vf followed by the addition of 5 %wt magnesium as a wetting agent, 0.04 wt-% of Strontium as modifier agent, and 0.15 %wt Al-5 Ti-1 B as a grain refinement agent through the stir casting process. The composites produced was characterised both microstructure by Optical Microscope (OM), Scanning Electron Microscope (SEM), link to Energy Dispersive Spectroscopy (EDS), and mechanical properties such as characterize each composite material such as tensile, hardness, and impact tests. The phases formed in the composite were α-Al, Eutectic Silicon, primary Mg2Si, binary Mg2Si, ternary Mg2Si, β-Al5FeSi, Al2Cu, Al3BC, dan AlB2. There is an increase in mechanical properties of AC4B/B4C compared to Aluminum AC4B base material, such as its tensile strength which reaches 149.032 MPa and its hardness reaches 49.3 HRB.

1. Introduction
Technological developments in producing equipment used by humans and industries in Indonesia are increasingly developing and advancing. The benefits of these equipment are also very significant to help and facilitate human activities in carrying out daily activities. Due to its great benefits, the need to support human life is also increasing. Therefore, at this time, the equipment was being developed from materials that have superior and efficient mechanical properties in each application. Over time, a material that not only consist of only one constituent material, such as metals, ceramics or polymers, will be needed. To fulfil its superior and efficient, a material consisting of two or more constituent materials, namely composites, is produced.

2. Theoretical Review
Aluminum AC4B was selected as a matrix in composite materials because of its good mechanical properties, such as high strength, low melting temperature, and corrosion resistance. Meanwhile, B4C was chosen as a reinforcing particulate in composite materials due to its good mechanical properties, such as high tensile strength, high hardness, good wear resistance, and good thermal stability. In this
study, particulate reinforcement B₄C was used with variations in fraction volume of 1; 3; 5; 7; 10 %Vf to see the microstructural differences and mechanical properties of each fabricated composite material. Thus, B₄C will improve the mechanical properties of fabricated composite materials, such as tensile strength and hardness.

On the other hand, Magnesium (Mg) is added to the composite material as a wetting agent because of its ability to form strong bonds between matrix and reinforcing particulates by producing layers (Al, Mg)B₂ [4-5]. Al-Sr is also added to the composite material as a modifier agent to modify the microstructure of composite materials that are fabricated and form a dendritic structure toward the eutectic Silicon phase which is strong and not brittle. Finally, Al-5 Ti-1 B is used as a grain refining agent in composite materials to form smaller, finer, and more uniform grain structures. The fabrication process carried out in this study is stir casting method. This process was chosen because it is more economical and the process is not complicated.

3. Research Methods
The cutting of Aluminum AC4B is carried out using a chainsaw. It is followed by weighing based on mass calculations using digital scales, and it is melted in the tilting furnace at temperatures of 850°C. On the other hand, pre-heating to particulate B₄C is carried out in the muffle furnace for 1 hour at temperature of 950°C, followed by the addition of the B₄C particulate into melting Aluminum AC4B in the tilting furnace, stirred using SKD 61 rod for 40 to 60 seconds, and done degassing using Argon gas for 2 minutes. Meanwhile, metal moulds to be used were coated with a mixture of Zirconium sand and 70% alcohol. Then, it was heated in the muffle furnace for 7 minutes at 850°C. Melting composite was poured into a metal mould that has been heated to fill the mould, followed by the air cooling at room temperature. The mass calculations used in this study are shown in Table 1 and Table 2 for each composite material to be fabricated.

| Notes       | % Vf | % wt | Mass (g) | Density (g/cm³) | Volume (cm³) | Volume Fraction |
|-------------|------|------|----------|-----------------|--------------|----------------|
| AC4B        | 94.81| 568.86| 2.74     | 207.6131387     | 0.922132674  |
| Mg          | 5    | 30   | 1.74     | 17.24137931     | 0.076579157  |
| Sr          | 0.04 | 0.24 | 2.64     | 0.090909091     | 0.000403781  |
| Al-5Ti-1B   | 0.15 | 0.9  | 4.52     | 0.199115044     | 0.000884388  |
| B₄C         |      |      |          |                 |              |
| 1           |      | 5.67 | 2.52     | 2.25            |
| 3           |      | 17.02| 2.52     | 6.75            |
| 7           |      | 28.36| 2.52     | 11.26           |
| 10          |      | 39.72| 2.52     | 15.76           |

To characterize the composition of elements and compounds for each composite material, a test was carried out using Optical Emission Spectroscopy (OES) and X-Ray Diffraction (XRD). To determine the differences in microstructure produced by each composite material, Optical Microscope (OM) and Scanning Electron Microscope (SEM) were used. Both tests using Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS), were carried out to determine the microstructure and prediction of formed phases that cannot be observed with an Optical Microscope (OM). Meanwhile, to determine the actual density and porosity value of each composite material, density and porosity testing using a digital machine based on ASTM 378-88. Tensile testing was carried out using the UTM GOTECH AL-700 LA 10-machine based on ASTM B557M-02A to determine ultimate tensile strength. Hardness testing was carried out using a ROCKY engine based on ASTM E18-11 through the Rockwell B method. Finally, impact testing was carried out using GOTECH Testing Machine Inc. based on ASTM E23-01 to determine the toughness of each composite material.
4. Result and Discussion

4.1 Analysis on the Result of Chemical Composition Test

Based on the results of the OES test shown in Table 3, it can be observed that there is a mismatch of the elemental content in some composite materials toward Si, Fe, Cu, and Mg. The incompatibility of Si elements in all Aluminum AC4B/B4C composite materials is caused by the addition of modifier agents Sr resulted microstructure of eutectic Silicon in the form of dendritic with strong and not brittle properties.

Incompatibility of Fe elements in Aluminum AC4B/B4C composite material is caused by the use of scrap as the matrix material and the tendency of the element Fe to bind to the Si element easily and produce the $\beta$-Al$_5$FeSi phase which is hard and very brittle.

Whereas, the incompatibility of Cu and Mg elements in all Aluminum AC4B/B4C composite materials are interrelated. Addition of 5 %wt of the Mg element as a wetting agent shifts the main alloying element from the Aluminum matrix AC4B material which was originally a metal with the main alloy element Al-Si-Cu to Al-Si-Mg.

| Element | AC4B (JIS) | Scrap AC4B | AC4B / 1% | AC4B / 3% | AC4B / 5% | AC4B / 7% | AC4B / 10% |
|---------|------------|------------|-----------|-----------|-----------|-----------|------------|
| Al      | ≥ 80       | 86.5       | 84.2      | 82.6      | 81.367    | 81.133    | 81.133     |
| Si      | 7 - 10     | 7.65       | 5.887     | 10.143    | 6.617     | 6.413     | 6.88       |
| Fe      | ≤ 1        | 1.01       | 4.307     | 0.801     | 5.953     | 4.673     | 3.98       |
| Cu      | 2 - 4      | 2.51       | 1.827     | 1.587     | 2.107     | 2.063     | 2.113      |
| Mg      | ≤ 0.5      | 1.05       | > 2.4     | > 2.4     | > 2.4     | 4.370     | 4.63       |
| Ti      | ≤ 0.2      | 0.0364     | 0.023     | 0.09      | 0.006     | 0.013     | 0.003      |
| Sr      | < 0.0001   | < 0.0001   | 0.0080    | 0.0196    | 0.011     | 0.00114   | 0.00251    |

Meanwhile, XRD testing is only done on composite materials with the most optimal tensile strength, namely Aluminum AC4B/3 %Vf of B4C and the result can be seen in Figure 1. The compounds formed include B4C, Mg2Si, $\beta$-Al$_5$FeSi, AlB2, Al, and (Al, Mg)B2.

![Figure 1. XRD testing results on AC4B/3 %Vf B4C.](image)
4.2 Analysis on Result of Metallographic Test

Microstructure observation was carried out at 500X magnification by cutting, sanding, mounting, polishing, and adding HF etching for 10 seconds before the observation was carried out. In Figure 2 (a), it can be observed that there is an α-Al phase. Then, the eutectic Silicon phase is characterized by the presence of the Al₃Cu phase that is characterized by a dendritic form resembling a eutectic Silicon[6-7]. There ia also β-Al₅FeSi phase. In Figures 2 (b), (c), (d), (e), (f), it can be observed that there are several additional phases such as primary Mg₂Si, binary Mg₂Si, and ternary Mg₂Si[4-11]. In addition, it is seen that there is an irregularly shaped AlB₂.

Figure 2. Microstructure of (a) AC4B as cast magnification of 500X and microstructure of composite AC4B/B₄C at fraction volume (b) 1 %Vf, (c) 3 %Vf, (d) 5 %Vf, (e) 7 %Vf, (f) 10 %Vf.
4.3 Analysis on Result of Scanning Electron Microscope (SEM) and Dispersive X-Ray Spectroscopy (EDS)

SEM-EDS testing is only performed on composite materials with the most optimal tensile strength, namely Aluminum AC4B/3 %Vf of B₄C. Based on Figure 3 and Table 4, it can be observed that the results of SEM-EDS testing on Aluminum AC4B/3 %Vf of B₄C composite material at 500X magnification.

![Figure 3. SEM observation on AC4B/3 %Vf B₄C.](image)

**Table 3. EDS testing result on AC4B/3 %Vf B₄C.**

| No | B  | C  | O   | Mg | Al | Si | Ti | Fe | Ni | Cu | Sr |
|----|----|----|-----|----|----|----|----|----|----|----|----|
| 1  | 14.79 | 1.17 | 56.81 | 10.33 | 8.12 | 8.73 | 0.01 | 0.03 |  |  |  |
| 2  | 8.87  | 1.07 | 52.45 | 4.21  | 31.75 | 1.48 | 0.04 |  | 0.13 |  |  |
| 3  | 8.62  | 1.61 | 42.94 | 18.08 | 0.25 | 13.33 | 15.17 |  |  |  |  |
| 4  | 6.77  | 1.79 | 50.66 | 39.46 | 0.29 | 0.02 | 0.08 | 0.93 |  |  |  |
| 5  | 12.63 | 2   | 56.26 | 18.83 | 10.02 |  |  |  | 0.26 |  |  |

The phase prediction that is formed in arrow number 1 is primary Mg₂Si, arrows number 2 is α-Al and binary Mg₂Si, arrows number 3 is Al₂Cu, arrows number 4 is α-Al and β-Al₅FeSi, and arrows numbered 5 is Al₃BC and AlB₂.

Meanwhile, the fracture that occurs based on Figure 4 (a) is mixed fracture, because cleavage and dimple are seen as signs of brittle and tough fractures. In addition, it can also be observed casting defects in the form of porosity and shrinkage which can be observed in Figure 4 (b).
Figure 4. SEM observation in fracture surface of AC4B/3 %Vf B4C on (a) 250X and (b) 500X magnification.

4.4 Analysis on Result of Mechanical Test

Figure 5. Results of mechanical test of Aluminum AC4B/B4C composite (a) Density, (b) Porosity, (c) Tensile Test, (d) Hardness Test, (e) Impact Test.
Based on Figure 5 (a), the actual density value of the six AC4B composite variables is below the theoretical density value, this is caused by the addition of B₄C reinforcing particulates, wetting agents Mg and modifier agents Sr which have a lower density value of 2.52 ; 1.7 ; 2.69 g/cm³ if it is compared with Aluminum AC4B density value, which is equal to g/cm³ and the presence of porosity in AC4B/B₄C composite material.

Based on Figure 5 (b), the value of %porosity of the sixth material is experienced test randomly, in which the composite material AC4B up to AC4B/B₄C with a percentage of the fraction volume of 0 ; 1 ; 3 ; 5 ; 7 ; 10% Vf, respectively 3.79 ; 3.81 ; 6.56 ; 3.19 ; 5.36 ; 6.75 %. Porosity itself can be formed from an unfavourable casting process, such as the stirring and degassing process which is less than optimal and the B₄C particulate reinforcing properties that are easy to agglomerate.

Based on Figure 5 (c), the random value of Ultimate Tensile Strength (UTS) can be caused by an increase in the number of B₄C particulate reinforcement. B₄C particulate reinforcement in the matrix provide softer protection against the matrix when the matrix is still molten metal. B₄C which is a hard ceramic material capable of improving the mechanical properties of composites to be produced by the stress transfer from the matrix to B₄C particulate reinforcement through the Orowan Strengthening mechanism, the presence of modifier agent Sre, and grain refiner agent Al-5 Ti-1 B makes the grain size of the composite material to be smaller, finer and more uniform, so that it can withstand dislocations well. However, this decrease in ultimate tensile strength can be caused by the presence of porosity and the uneven distribution of B₄C particulate reinforcement.

Based on Figure 5 (d), the value of hardness in AC4B/B₄C composite material is increasing and will continue to increase with the addition of B₄C particulate reinforcement. Meanwhile, the decrease in hardness occurred because the refiner agent Al-5 Ti-1 B and the modifier agent Sr are not functioning optimally, so the intermetallic phase of β Al₃FeSi, eutectic silicon, and α-Al had less structure smooth and caused the decrease of hardness.

Based on Figure 5 (e), the highest impact value of AC4B/B₄C composite material is owned by pure Aluminum AC4B metal material. This is caused by the absence of B₄C and enhancer agent such as Mg, Sr, and Al-5 Ti-1 B.

5. Conclusion

Aluminum AC4B/B₄C composite material with the addition of the wetting agent Mg, modifier agent Sr, and grain refiner agent Al-5 Ti-1 B can be fabricated using a stir casting method. The phase formed in the AC4B/B₄C composite material namely α-Al, Eutectic Silicon, primary Mg₃Si, binary Mg₂Si, ternary Mg₅Si, β-Al₃FeSi, Al₂Cu, Al₃BC, dan AlB₂. The density value of AC4B/B₄C composite material is strongly influenced by the percentage of porosity and shrinkage formed within each material. B₄C particulate reinforcement in AC4B matrix composite material is able to increase tensile strength optimally until the addition of 3 % Vf of B₄C. Besides, it can increase the hardness optimally until the addition of 5 % Vf of B₄C. On the other hand, it is unable to increase impact strength. Thus, the most optimal impact strength is achieved by pure AC4B alloy metals.

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