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Investigation of mechanical properties of Al/Al-B_4C circular hybrid composites

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ABSTRACT

Hybrid composites are material types obtained by combining two different composite structures. This study focused on investigating the mechanical properties of a hybrid composite material produced in a circular shape with aluminum sheath and metal matrix composite core (Al-Ceramic mixture). Mechanical properties were determined by compression, bending, and hardness tests. Ceramic reinforcement improves the basic mechanical properties of metal matrix composites (MMC). However, some features such as strain ability are adversely affected. It was aimed to improve such properties by producing MMC material with sheath. Al7075 was used as the sheath material and Al2124-B_4C MMC material was used as the core material in this hybrid material. Composite rods were produced by extruding the billets prepared by the PIT (powder in tube) method. With this method, the core material in powder form was compressed into Al tube materials. In the core material, three different ratios of B_4C were used as 5, 10, and 15% by volume fraction. The extrusion process was carried out at 500°C degrees and with an extrusion rate of R=14. According to the test results, the strain ability, which decreased with the B_4C reinforcement, improved in materials produced with sheath.

1. Introduction

Composite materials are material types obtained by combining two or more materials and have the superior properties of these materials [1,2]. Today, many reasons such as developing technology, energy consumption, and material costs reveal the need for composite materials and the studies in this field are increasing day by day. Composite materials consist of the matrix phase that generates the main structure and the reinforcement phase called the secondary phase being in the matrix [3,4]. According to the situation of the reinforcement phase, composite materials can be classified as fiber and particulate reinforced or layered and hybrid composite [5,6]. Hybrid composite materials can find a wide usage area because of the their advantages [7]. Although hybrid composite materials are generally in the form of sheet, they are also produced in circular form such as bars and pipes or other special forms [8,9,10]. Materials used on the inside and outside of the circular hybrid composites vary according to the requirements. Creating a new structure by combining the properties of two different materials or achieving different properties inside and outside of the material is an example of these requirements. When the general structures of circular composites are looked;

- Copper(Cu)-aluminum(Al) material pairs to obtain conductivity, lightness, and cost properties [11-13],

- Al-Al, steel-steel material pairs because of the requirement of the different properties on inside and outside of the composite material [14-16],

- Cu-conductive powder pairs to obtain superconductive material [17],

are the most common circular metal composite materials. In the production of these materials, different methods are used such as extrusion, rolling, and explosive coating [18-20]. In this study, the circular form of Al/Al-B_4C hybrid composite was studied. In this material, while Al-B_4C forms the core of the hybrid composite material, Al forms the sheath. Aluminum has intensive use in the fields of machinery, automotive, and aerospace because of its high strength/density ratio and good machinability properties [21]. At the same time, the studies to improve the properties of composite materials are multiplying. Ceramic reinforced composite is one of these areas in which aluminum is used as the matrix phase [22]. The core of the circular hybrid composite that formed as Al-B_4C, is an MMC material and its density is reduced and some mechanical properties are increased with B_4C reinforcement. However, its toughness, namely the ability of plasticity, decreases.

In this study, materials were produced with a ceramic-free sheath on their outer surfaces in order to eliminate some of the negative results that occur with ceramic

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reinforcement in ceramic reinforced metal matrix composite materials. The decrease in surface quality and toughness values is the most important of these negative results. By producing the Al-B_4C composite material with the same or a different aluminum alloy sheath on the outside, the ceramic reinforcement will be prevented from being on the outer surface, and since the aluminum ratio in the material cross-section will be high, its deformation ability will be partially preserved. This material can be preferred in areas where surface quality is at the forefront with its high strength properties.

2. Materials and Methods

The production of circular hybrid rods was carried out by the extrusion method (Figure 1). In this method, the circular cross-section material (billet) was pushed through a die system with high forces. The first stage of production is the preparation of billets. They were prepared with the powder in tube method [23]. Al-B_4C powders mixed homogeneously were compressed into Al tubes in this method (Figure 2).

In these composite materials, the outer of the material is called "sheath" and the inner is called "core". Al7075 alloy as sheath material, Al2124-B_4C powder mixture with an average size of 30 μm Al2124 and 20 μm B_4C as core material was used in these composites. The dimensions of Al tubes (sheath of billet) were presented in Figure 2 and were obtained by drilling the rod-shaped Al7075 alloy. Al2124/B_4C powder mixture was prepared with 5%, 10%, and 15% B_4C volume fractions to be used as core material in these sheaths. The powder mixture was mixed for 2 hours with a three-dimensional mechanical mixer. The powder mixture was compressed into aluminum tubes at an average pressure of 500 kPa. The billets were extruded after the sintering process at 500°C for 1 hour. The diameter of billets was reduced from 30 mm to 8 mm with an extrusion rate of R=14. In each extrusion process, billets, extrusion sleeve and die were spray coated with graphite. In Table 1, the material structure of 9 different billets and products was given in detail. The outer and core diameters of circular hybrid composites were achieved at 8 mm and 5.33 mm respectively.

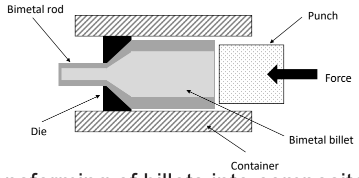

Figure 1. Transforming of billets into composite bars by extrusion method.

(a)

(b)

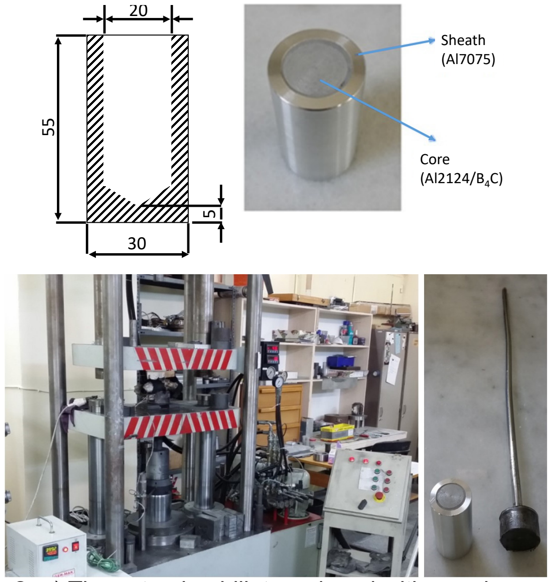

Figure 2. a) The extrusion billet produced with powder in tube method, b) Extrusion press and product (circular hybrid bar).

The samples taken from the composite materials were first mounted and then prepared for micro structural examination. Polishing process was carried out with 600, 1200 and 2000 numbered paper grinding discs and woven polishing cloth. In etching, a general purpose etchant (1,5% Hydrofluoric Acid(HF)-98,5% pure water) was used. On the other hand, bending tests were carried out according to the ISO 7438 standard, and the distance between the supports was determined as 50 mm and the sample length was determined as 80 mm. The test speed was applied as 0.02 mm/sec [24]. Compression tests were carried out according to ASTM E9-09 standard, and compression samples were

Table 1. Technical details of nine different extrusion billets and products.

Samples	Sheath	Core	D_{outlet}-Billet (mm)	D_{inlet}-Billet (mm)	Doutlet-Rod (mm)	D_{inlet}-Rod (mm)
1	Al7075		30	-	8	-
2	Al7075	Al2124	30	20	8	2,66
3	Al7075	Al2124-B_4C(5%)	30	20	8	2,66
4	Al7075	Al2124-B_4C(10%)	30	20	8	2,66
5	Al7075	Al2124-B_4C(15%)	30	20	8	2,66
6	Al2124		30	-	8	-
7	Al2124-B_4C(5%)		30	-	8	-
8	Al2124-B_4C(10%)		30	-	8	-
9	Al2124-B_4C(15%)		30	-	8	-

prepared as 16 mm length by taking L/D=2. The tests were carried out at speeds of 0.02 mm/s [25]. Also, hardness measurements were carried out separately in the sheath and core regions at the cross section perpendicular to the material axis In the tests carried out with the Vickers microhardness measurement method for 5 seconds at 100 g load, at least 3 healthy measurements were obtained at appropriate intervals and the hardness values were determined by taking the average of them. The densities of the materials were measured according to the Archimedes principle [26]. For this, Presica precision balance (with precision of 0,0001 g) and density measurement kit were used.

3. Results and Discussion

When the sheath-core boundaries of hybrid circular composites were examined with a micro-scale, it was observed that the sheath and core were very well bonded to each other, and there was no separation or gap in the boundaries (Figure 3). It was seen that B_4C distribution was homogeneous in B_4C reinforced core (Figure 3b, c, d). In addition, it was observed that the linearity disappeared at the sheath-core boundary with increasing in the B_4C ratio in the core material. The increase in the bond strength between sheath-core could be attributed to the fact that the sheath and core materials crossed each other's boundaries (Figure 3c, d).

The bending test is used to specify the mechanical properties of materials under loads that force them to bend. In this test, a bending force is applied to the middle of the material placed between two supports and the material is deformed. As a result of this experiment, values such as bending moment, bending strength, modulus of elasticity, and bending displacement can be calculated [27]. According to the bending tests, first of all, the bending strengths of the aluminum materials used in this study were compared with each other. The Al7075 rod was produced by extrusion from a rod product with a diameter of 30 mm. Al2124 rod was produced by extruding of billets obtained by compressing the Al2124 powder used in MMC production. According to the bending test graphics, Al2124 has lower bending strength and strain rate than Al7075 (Figure 4a). When the material was layered as Al7075-Al2124, although the deformation did not increase, a significant increase in bending strength was achieved.

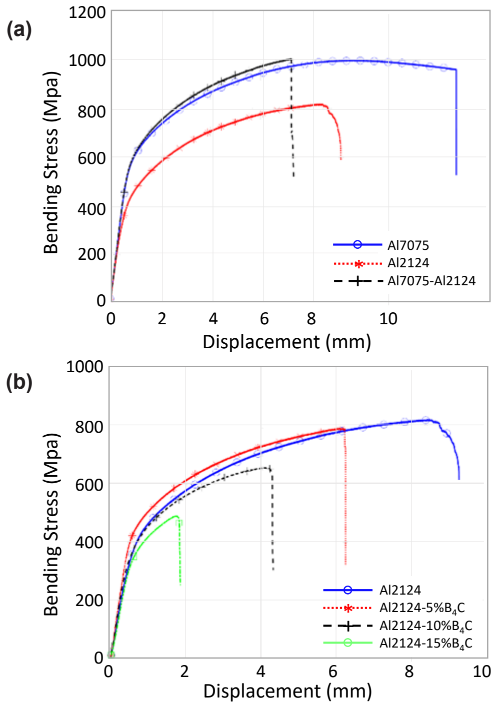

Figure 4. a) Bending stress-displacement (σ-δ) curves of Al7075 and Al2124 rods and Al7075/Al2124 circular composite, b) Changing of σ-δ curves with B_4C ratio in circular composites.

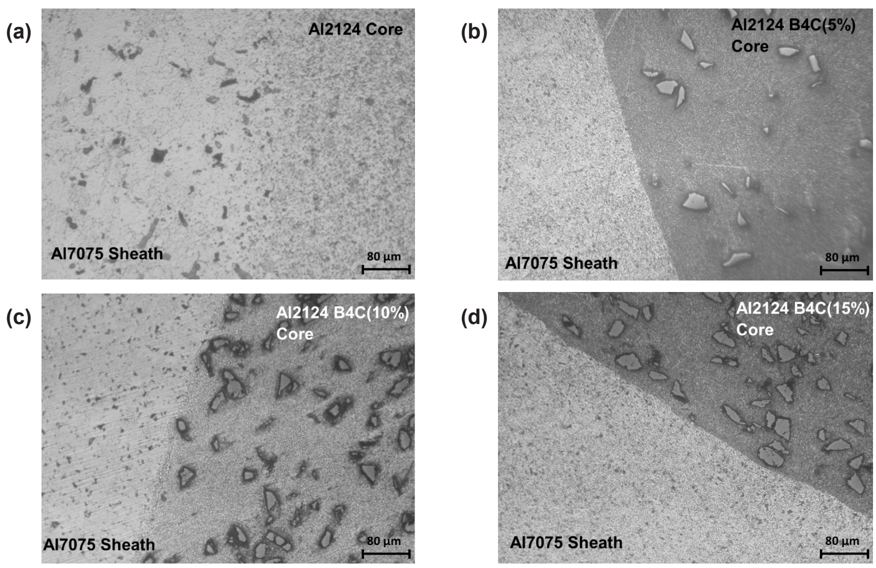

Figure 3. Optical microscope images of sheath-core boundary in hybrid composite materials, a) Al7075-Al2124 sheath-core boundary, b) Al7075-Al2124/B_4C (5%) sheath-core boundary, c) Al7075-Al2124/B_4C (10%) sheath- core boundary, d) Al7075-Al2124/B_4C (15%) sheath-core boundary.

In ceramic reinforced composites, the strength values of the materials can be improved considerably by optimum adjustment of the reinforcement ratio. However, high ceramic ratios increase the brittleness of the material as well as decrease the strength values [28]. As can be seen in Figure 4b, the material with B_4C ratio of 5% provided superiority in terms of yield strength compared to Al2124, while the material rapidly loosed its strength and deformability with an increase in this ratio to 15%. The poor wettability between Al and B_4C is also an important factor in this situation [29,30].

When the rods containing B_4C of 5%, 10%, and 15% were turned into hybrid composites with Al 7075 sheath, significant changes occurred in their mechanical properties, with an increase of approximately 25%, 45%, and 90% in yield and breaking points, respectively. In other words, the bending strengths of MMCs could be improved with the hybrid composite structure. And this improvement rate increased with increasing in B_4C ratio (Figure 5a, b, c, d).

The analysis of the bending samples reveals that the fracture cross-sections were shaped in different structures depending on the bending rate and the bending ability of the material. Al7075 was the material that have the most strain, and it showed a brittle fracture surface because of its structure (Figure 6a). On the other hand, Al2124 displayed multiple fractures with a smooth surface because of its ductility (Figure 6a). The fracture surface in Al2124-B_4C composites was quite rough and brittle because of the separation that occurred at the B_4C-Al grain interfaces (Figure 6b). The limited bending deformation observed in Al2124-B_4C composites reinforced B_4C of 5% was almost never observed in composites containing 10% and 15% B_4C, and their fracture types were quite similar to the type of brittle fracture encountered in tensile tests (Figure 6b). The fracture behavior of the materials changed with the Al7075 sheath. In Al7075-Al2124 material, the bending deformation of both layers decreased (Figure 6a). In Al7075/Al2124-B_4C sheathed composites, the Al7075 sheath increased the bending strength and the bending strain rates of the composites significantly (Figure 6c). In the bending tests, the punch forces to separate the interfaces of sheathed composites because of the application type. However, no separation was observed between the sheath and core in the tests of the Al7075/Al2124-B_4C composites.

According to the compression test results, the yield strengths of the materials increased with the increase of B_4C ratio in Al2124-B_4C composites, but the compression strength and strain rate decreased (Figure 7b). It was observed that Al7075 material was better than Al2124 in terms of strength values (Figure 7a). The yield strength of the composites, which was produced in Al7075/Al2124 form with sheath, reached the Al7075. In the circular hybrid composite materials, the yield strengths increased in each one. However, these hybrid composite materials lost some of their strain rates compared to the MMC ones. In terms of compression strength, the hybrid composite materials containing 5% B_4C was very close to the unsheathed one. However, hybrid composites containing 10% and 15% B_4C exceeded the unsheathed form of these materials in terms of compression strength. The tensile strengths of hybrid composites were above those of unsheathed ones (Figure 7c, d, e).

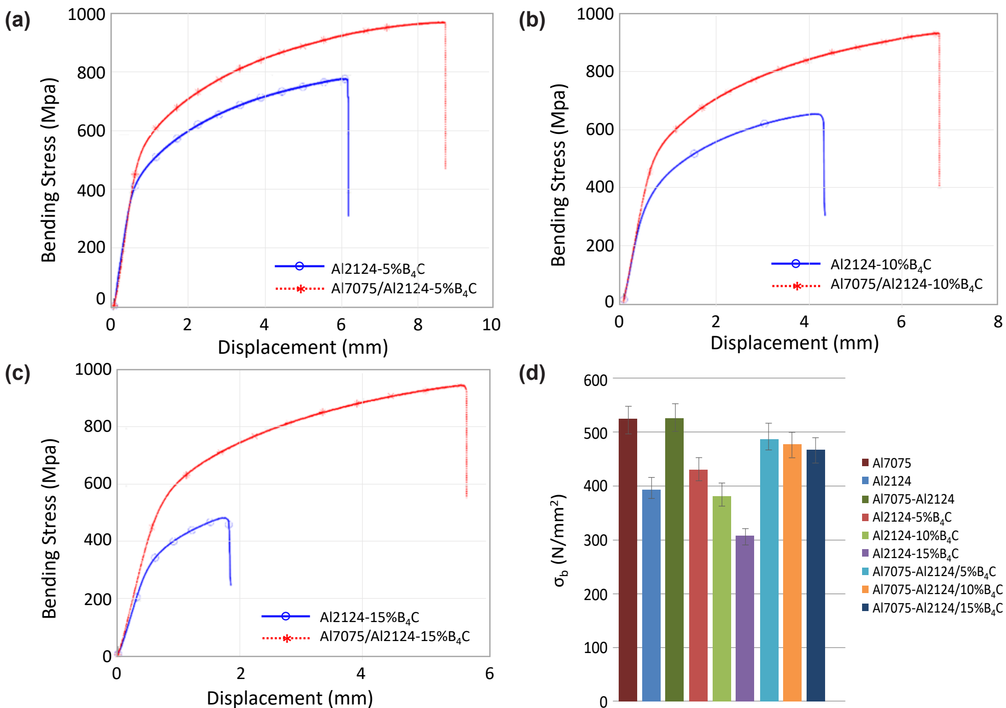

Figure 5. Changing of bending stress-displacement (σ-δ) curves in a) unsheathed and sheathed composites containing 5% B_4C, b) unsheathed and sheathed composites containing 10% B_4C, c) unsheathed and sheathed composites containing 15% B_4C, d) changing of bending strength of sheathed and unsheathed composites.

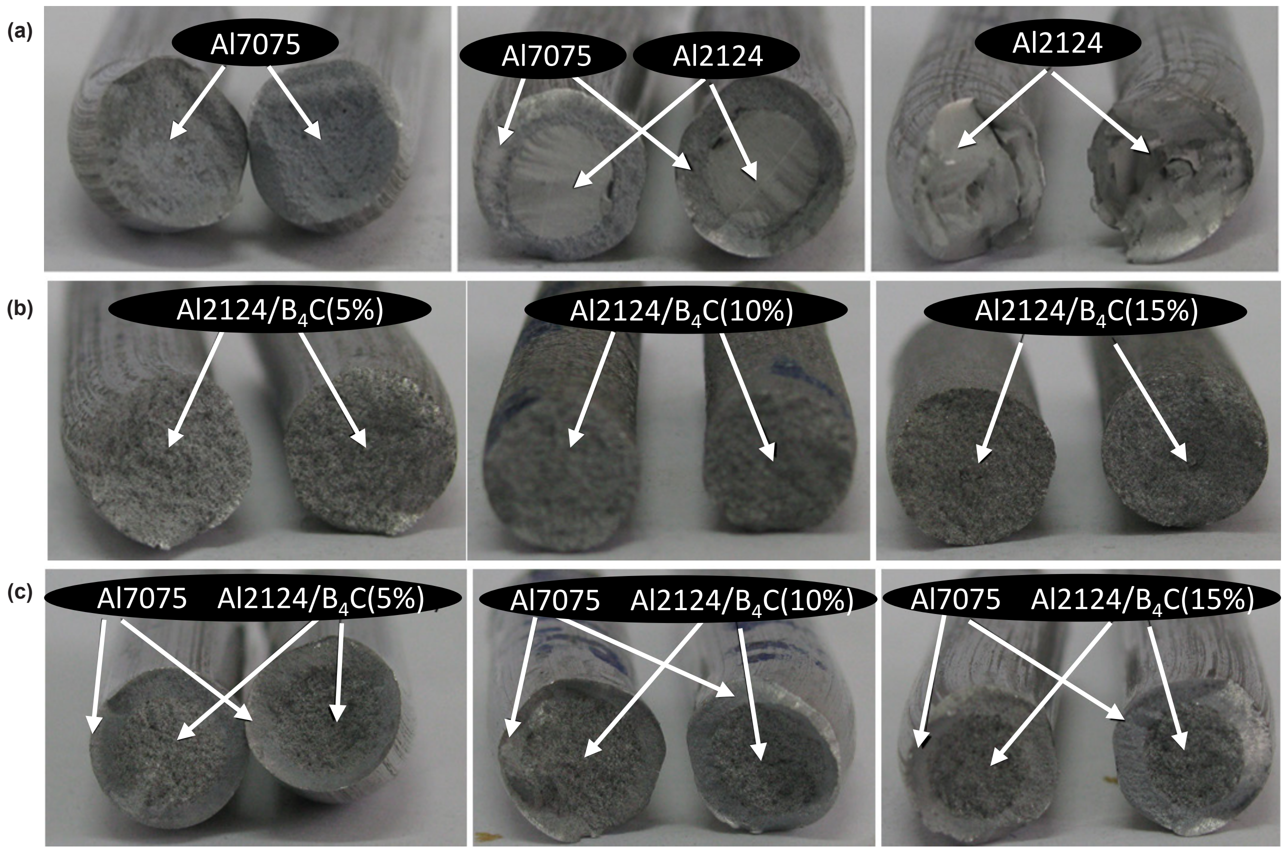

Figure 6. The fracture types of materials subjected to bending test, a) Al7075, Al7075-Al2124 and Al2124, b) Al2124-B_4C (5%), Al2124-B_4C (10%) and Al2124-B_4C (15%). c) Al7075-Al2124-B_4C (5%), Al7075-Al2124-B_4C (10%) and Al7075-Al2124 (15%).

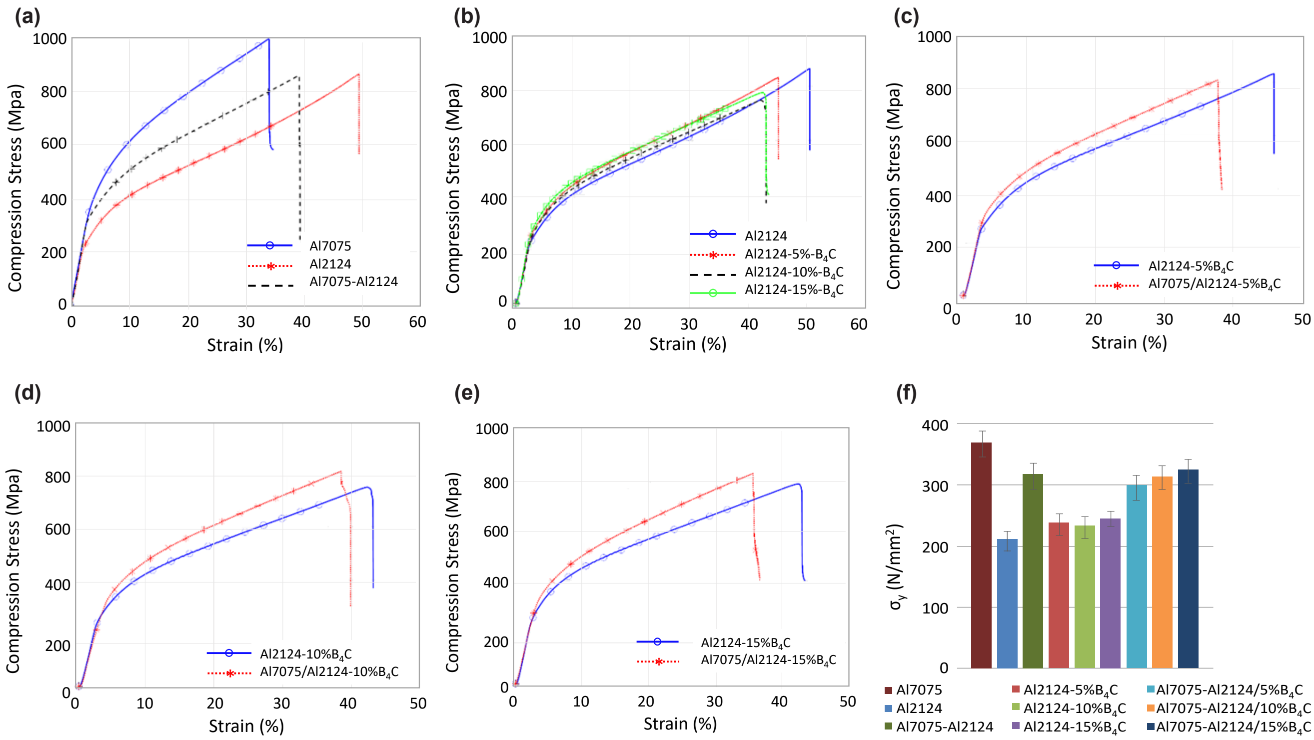

Figure 7. The changing of compression stress-strain % (σ-ε%) curves in a) Al7075, Al2124, and Al7075/Al2124 MM composites b) MM composite materials with B_4C ratio, c) Hybrid and MM composites containing 5% B_4C, d) Hybrid and MM composites containing 10% B_4C, e) Hybrid and MM composites containing 15% B_4C, f) changing of yield strength of sheathed and unsheathed composites.

According to the fracture types seen in the compression samples [31], an evaluation can be made on the deformation ability of the materials (Figure 8).

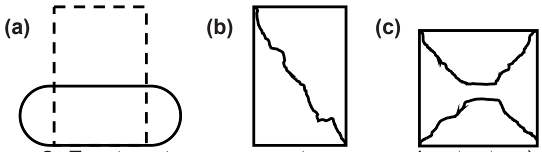

Figure 8. Fracture types seen at compression tests a) Failure by barreling, b) Brittle fracture, c) Semi-brittle fracture.

From the observation of the fracture structures of the compression test specimens, it was noticed that Al2124 and Al2124-B_4C (5%) materials showed semi-brittle fracture behavior (Figure 9a). Al7075 is a popular aluminum alloy with high strength and brittle structure. Therefore, the fracture behavior of Al7075 and Al7075 sheathed composites was in the brittle type (Figure 9b). In Al2124-B_4C composites, the semi-brittle fracture type turned into brittle fracture with increasing in B_4C ratio from 5% to 10% and 15% (Figure 9c). Also, the fracture behavior of materials and σ-ε curves were compatible with each other.

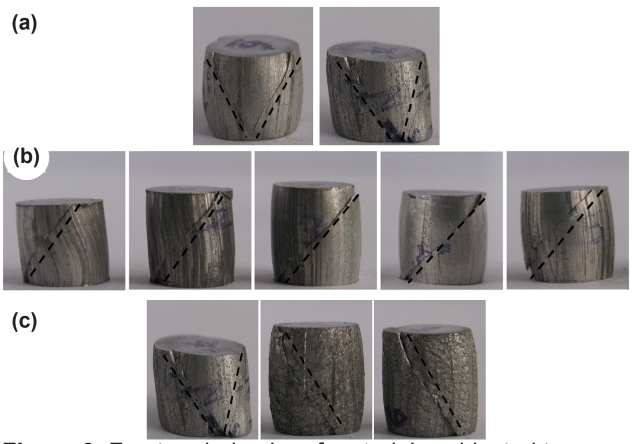

Figure 9. Fracture behavior of materials subjected to compression test, a) Semi-brittle fracture behavior of Al2124 and Al2124-B_4C (5%), b) Brittle fracture behavior of Al7075, Al7075-Al2124, Al7075-Al2124-B_4C (5%), Al7075-Al2124-B_4C (10%) and Al7075-Al2124 (15%), c) Fracture behavior of Al2124-B_4C (5%), Al2124-B_4C (10%) and Al2124-B_4C (15%).

Aluminum, MM composite, and laminated composite bars were subjected to tests after the extrusion process and any heat treatment did not apply to them after extrusion. When the hardness tests of these materials were examined, it was seen that Al7075 had a higher hardness value than Al2124 and A2124-B_4C composites because of its alloy structure (Figure 10b). In Al2124-B_4C composites, the hardness values of MM composites increased with increasing in B_4C ratio (Figure 10a) [32]. In the hardness tests performed on hybrid composite materials, the hardness values of the sheath and core material were different from unsheathed materials. The sheath and core hardness of Al7075-Al2124 material were slightly higher than other hybrid composites. In Al7075-Al2124/B_4C composites, the hardness of sheath and core increased with the increase in the B_4C ratio in the core material (Figure 10b). When the density of the materials was examined, the density decreased with B_4C reinforcement and with increasing the B_4C ratio [33]. In materials that became hybrid composite with Al7075 sheath, the densities increased slightly compared to MMC materials (Figure 10c).

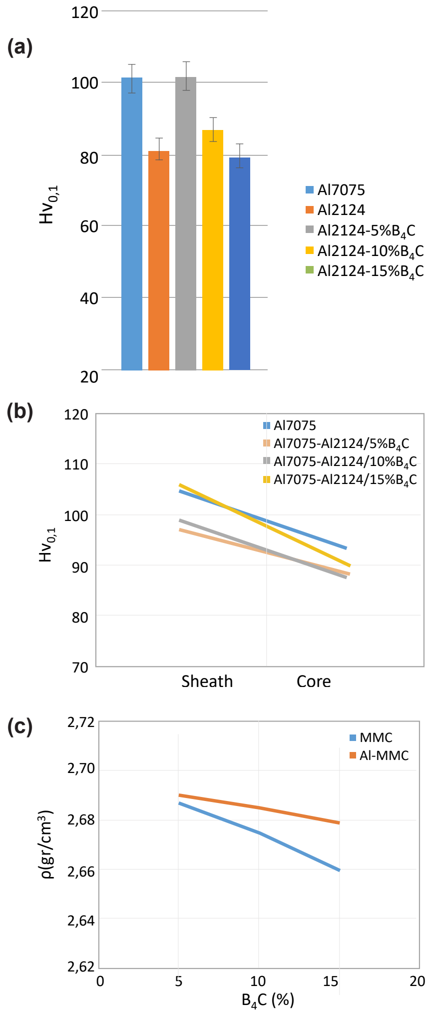

Figure 10. a) Changing of hardness values of Al7075, Al2124 and Al2124-B_4C materials, b) Sheath-core hardness changing of sheath-core materials in hybrid composites, c) Density changing in Al2124-B_4C and Al7075-Al2124/B_4C composites depending on the B_4C ratio.

4. Conclusions

According to the bending and compression tests of metal matrix composites (MMC) and hybrid composites;

- The composite materials produced in Al7075/Al2124 form had better strength values under bending loads compared to Al2124.

- While the B_4C ratio was 5% in Al2124/B_4C MMC materials, it was found that the bending strength increased and the strain rate decreased compared to Al2124. With the increase of the B_4C ratio to 10% and 15%, both strength values and strain rates decreased rapidly.

- The bending strength and strain ability of circular hybrid composites increased considerably compared to unsheathed ones, and the highest increase occurred in composite material containing 15% B_4C.

- With the increase of the B4C ratio in MM composites, the yield strength values of the materials increased, but the compression strength and strain rate decreased.

- It was observed that the Al7075 material was better than Al2124 in compression strength values. The yield strengths of the composite materials produced in Al7075/Al2124 form approached to the strength of the Al7075.

- The yield strengths of the hybrid composite materials increased in each form. Hybrid composite materials loosed some of their strain rates compared to unsheathed ones. In the compression strength, the hybrid material containing 5% B_4C was very close to the unsheathed one. However, the compression strength of hybrid composites containing 10% and 15% B_4C exceeded unsheathed ones.

- Microstructurally, the materials were examined to see the sheath-core boundary region. Microstructure images showed that Al7075 and Al2124 alloys fully bonded with each other and a gapless boundary region was formed. From these images, it was determined that the B_4C dispersion in the core region is generally homogeneous.

- Hardness tests shown that the hardness of the Al7075 sheath material is higher than the Al2124 core matrix material. In addition to this, it was observed that the hardness of the core region increased with the B_4C reinforcement and the increasing of the reinforcement ratio. The density value of the core material, whose density decreased with the B_4C reinforcement and increasing the reinforcement ratio, continued to decrease with the Al7075 sheath. However, the density decrease in these materials was more limited compared to the unsheathed material.

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