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The Effect of SiC and MgO Ceramic Reinforcements on the Mechanical Behavior and Electrical Properties of the Composite Structure in Al7075/SiC/MgO Hybrid Composites

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Abstract

In this study, certain technical properties of new generation aluminum-based composites, obtained by combining the Al7075 alloy were investigated. For this purpose, SiC and MgO ceramics were reinforced into the Al7075 matrix material using powder metallurgy technique and composite structures were produced in three different reinforcement ratios. Measurements to determine electrical resistance and conductivity and bending and compression strength tests were performed on the obtained composite structures. The density and porosity amounts of the composite structures were also determined, and their microstructures were examined. With the increase of SiC/MgO amount in the aluminum composite structure, the electrical resistance increased, and the electrical conductivity decreased With the effect of SiC and MgO reinforcement materials, the amount of pores increased, therefore the density decreased.The hardness values increased due to the effect of SiC and MgO ceramics in the structure. The bending and compression strength values initially increased and then started to decrease with the increase of reinforcement ratios. It has been determined that the formation of porosity in the composite structure negatively affects the mechanical behavior. The second important factor was evaluated to be the amount and shape of ceramic-based reinforcement particles in the structure. Due to the effect of SiC, which has very high electrical resistance, and MgO, which has dielectric properties, the electrical conductivity values of the composite structures decreased. The decrease in electrical conductivity were directly proportional to the amount of ceramic-based reinforcement particles in the composite structure.

Key Words

"Al7075 Composite, SiC, MgO, Mechanical strength, Electrical behavior"

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1. Introduction

Composite materials play an important and influential role in many engineering industry applications due to the physical properties (Almadhoni and Khan, 2015). In recent years, particle-reinforced metal matrix composites (MMCs) have been gaining popularity for advanced applications. Generally, a soft metal with high ductility and toughness is reinforced with a hard ceramic material with high strength and modulus in the production of a MMCs. Aluminum-based metal matrix composites for structural applications have significant potential thanks to properties like their high hardness, modulus, specific strength, corrosion and wear resistance (Nuruzzaman et al., 2016; Ma et al., 2017). In these days, aluminum alloys are the most widely used metallic engineering materials after steel. Properties such as low density, high corrosion resistance, high electrical conductivity and high specific strength are the reasons for the interest in aluminum alloys (Gökçe et al., 2017). When aluminum is chosen as the low density matrix, it has high strength. SiC and Al_2O_3 are commonly used particulate reinforcements for Aluminum Matrix Composites (AMC). In addition, some of the main reinforcements used to improve the mechanical properties of AMCs are ceramics such as TiC, B_4C, BN, TiB_2 (Nazık et al., 2017; Nuruzzaman et al., 2016).

There are developments of two main directions in metal matrix composite material production technology. These are powder metallurgy and casting methods of liquid metal alloys and ceramic preforms (Włodarczyk-Fligier et al., 2008). The addition of the reinforcement in a relatively high volume fraction, the production of composites with matrix alloy and reinforcement materials that do not mix with liquid casting are among the advantages of the powder metallurgy method (Rana et al 2012). When the literature is examined, it is seen that there are studies on composites produced by adding different reinforcement ceramics to different aluminum alloys. In these studies, different properties of composites were investigated (Kamrani et al., 2015; Butola et al., 2017; Shankar and Raghwendra, 2017; Bodukuri 2012). When the literature is examined, it is seen that there are limited number of studies on MgO reinforced composites in aluminum matrix and ceramic particle reinforced composite studies. In addition, any study in which SiC and MgO were reinforced together into the Al7075 matrix could not be found in the literature.

Unlike the literature, composite structures with Al7075 matrix were produced by reinforcing MgO and SiC ceramic particles together in this study. In the study, in which powder metallurgy was applied as the production method, measurements and tests were carried out to determine the mechanical properties and electrical behaviors on the composite structures with different reinforcement ratios. The obtained results were evaluated together with microstructure images.

2. Experimental Study

The properties of the matrix material Al7075 and the reinforcement element SiC and MgO ceramics used in the production of composite materials are shown in Table 1. The matrix-reinforcement ratios determined for production are given in Table 2.

Table 1. Technical properties of matrix and reinforcement materials used in the production of composites

Al 7075 chemical content		**Al 7075 physical properties**	
Zn%	5,1-6,1	Intensity	2,81 g/cm^3
Fe%	0,50	Melting point	635 °C
Si%	0,40	Hardness	58 HB
Cu%	1,21-2,0	Particle Shape	Cornered
Mn%	0,30	Thermal Conductivity	130 W/mK
Mg%	2,1-2,9	Electrical Resistivity	10^{-8} Ω·m
SiC chemical content		**SiC physical properties**	
Si%	61-66	Intensity	3,21 g/cm^3
Al2O3%	0,7-1,2	Melting point	2730 °C
Fe2O3%	0,6-1,1	Hardness	2480 knoop
C%	22-26	Particle Shape	Sharp Corners
		Thermal Conductivity	90 W/mK
		Electrical Resistivity	10^{7} Ω·m
MgO chemical content		**MgO physical properties**	
% MgO	98	Intensity	3,58 g/cm^3
% FeO	0,6	Melting point	2852 °C
% SiO2	1,0	Hardness	690 Knoop
% CaO	0,4	Particle Shape	Cornered
		Thermal Conductivity	42 W/mK
		Electrical Resistivity	Dielectric

Table 2. Matrix reinforcement ratios of composite samples (wt.)

Sample	Al 7075 %	SiC %	MgO %
1	90	5	5
2	85	7.5	7.5
3	80	10	10

Powder metallurgy technique was used in the production of composite materials. The materials in the determined weight ratios were mixed with a drum mixer for 2 hours. After that, It was compressed in a hydraulic press with 500 MPa pressure. Finally, the production process was completed by sintering at 580 °C for 90 minutes and rectangular prism composite specimens with the dimensions of 50*13*10 mm were obtained. Fracture strength values were found by using Equation 1, according to the bending forces obtained from the bending tests performed according to the 10*13 mm sample section.

$$\sigma = F/A \tag{1}$$

Here; F is the fracture force (N), A is the area forced to fracture mm^2, σ is the fracturestrength (N/mm^2). The second phase of the experimental study has been started by making density measurements on the composite samples whose production process was completed. Then, the porosity ratios were determined. Hardness values were determined by Brinell method. Finally, three point flexural and compression strength tests were performed and mechanical tests were completed. In the second part of the measurements, electrical resistance measurements were made on the composite structures and electrical conductivity values were determined according to the obtained data. All results were evaluated together with microstructure images taken with a digital microscope.

3. Results And Discussion

3.1. Microstructure and porosity

After the Al7075+MgO+SiC powder mixture and powder metallurgy application, the digital microscope images of the composite structure are shown in Figure 1.

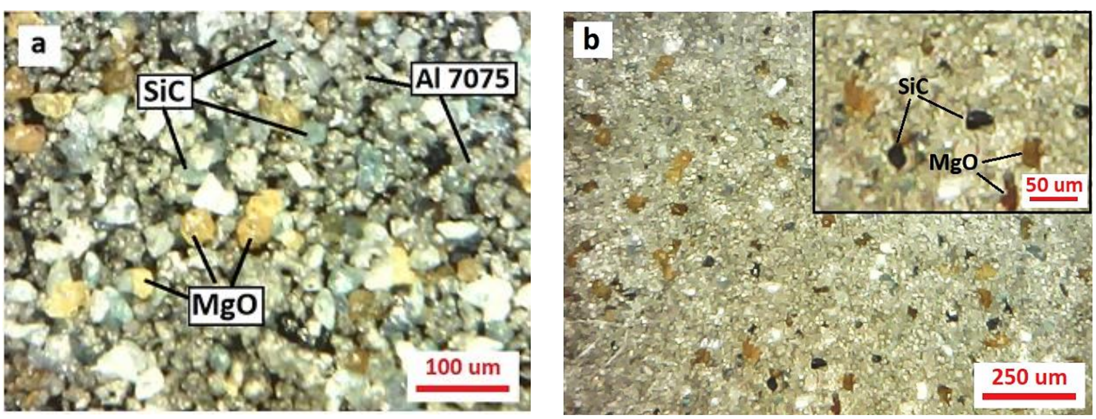

Figure 1. (**a**) Digital microscope images of the composite powder mixture; (**b**) Digital microscope images of the composite structure

When the digital microscope images in Figure 1 are examined, it can be said that SiC and MgO reinforcement particles in the Al7075 matrix structure are clearly visible. It is seen that a relatively homogeneous distribution of reinforcement is achieved and the powder metallurgy production process is carried out successfully. It is understood that the matrix material Al7075 forms a sufficient level of bond with the sintering process. However, it can be said that MgO and SiC particles, which are in the aluminum matrix and have very low thermal conductivity, affect the sintering process (Balaji et al., 2015). In addition, the porous structure, which is frequently encountered in such particle-reinforced composites, is also considered to be effective. In a study, it was reported that fine SiC particles agglomerated and a porous structure formed in the areas adjacent to these particles (Szewczyk-Nykiel, 2017). It is understood that the pore ratios increase in direct proportion with the increase in the ratio of SiC and MgO in the composite structure. It is seen that the proportional increase in the porosity values is also a result that supports the homogeneous distribution of SiC and MgO particles in the composite structure. Results close to the porosity ratios in Figure 2 were obtained in a similar study in the literature (Pul et al., 2023).

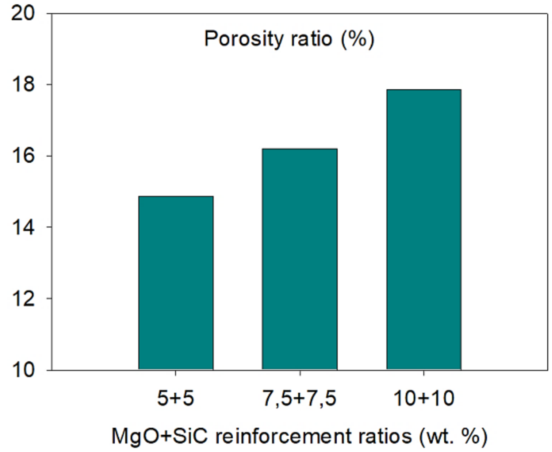

Figure 2. Porosity amounts of Al7075/MgO+SiC composites

3.2. Hardness

The hardness values of Al7075 based MgO and SiC reinforced composite structures determined by Brinell method are given in Figure 3.

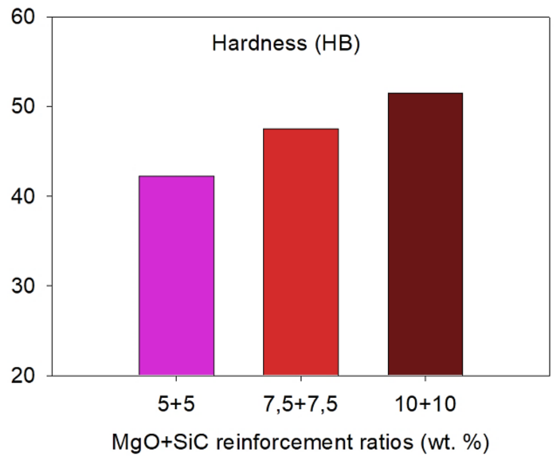

Figure 3. Hardness values of Al7075/MgO+SiC composites

When the hardness values in Figure 3 are examined, it is seen that the hardness values increase depending on the increase in the MgO+SiC reinforcement ratio in Al7075. With the effect of SiC and MgO particles in the very hard phase in the composite structure, an increase in hardness occurred throughout the structure. Similar results were found in different studies in the literature (Pul, 2019; Joshua et al., 2017). However, there was no increase in hardness at the rate of the increase in the reinforcement ratio in the composite structure. Although there was a 100% increase between the lowest reinforcement rate and the highest reinforcement, the increase in hardness value was approximately 15%.

3.3. Flexural and compressive strength

The graphs created according to the data obtained from the three-point flexural and compression strength tests of Al7075 based MgO and SiC reinforced composite structures are given in Figure 4. When the graphs in Figure 4 are examined, it is seen that there is a relationship between the flexural and compressive strength values of composite structures. In both mechanical tests, the highest strength value was obtained from 7% MgO+7% SiC reinforced aluminum composite. While the second highest value in flexural strength was obtained from 5% MgO+5% SiC reinforced Al7075 composite sample, 10% MgO+10% SiC reinforced Al7075 composite took the second place in compressive strength. It is thought that the most effective factor on these strength values is the structural feature of the composite. It is known that the properties of the reinforcement and the process parameters play an important role on the microstructure and mechanical properties in such particle-reinforced metallic composites (Caoa et al., 2016). One of the most important issues affecting the fracture in flexural tests performed with the three-point principle is the geometry of the reinforcement particles in the matrix and whether the wetting between the matrix reinforcement is at a sufficient level. In addition, it is known that the fracture strength of MgO and SiC reinforcement particles in the form of sharp corners in the aluminum matrix decreases due to the notch effect in flexural tests. A similar study in the literature is emphasized that the selection of factors such as the interface reactions in such composites, the volume ratio of SiC, the shape of the reinforcement material and its distribution in the matrix should be considered in the production processes (Suryanarayanan et al., 2013).

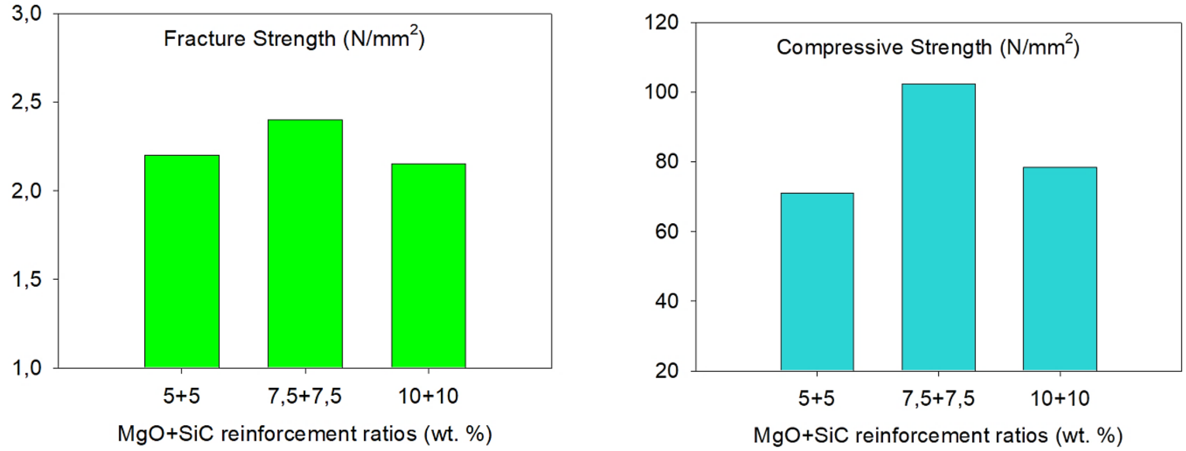

Figure 4. Flexural and compressive strengths of Al7075/MgO+SiC composites

other studies in the literature was determined that as the reinforcement ratio increased, the tensile strength, hardness and density of the AMC material increased, but the impact toughness decreased. Factors affecting the impact behavior of SiC-reinforced AMCs are reported to be particle aggregation, particle cracking, and weak matrix-reinforced bond (Iqbal and Nuruzzaman, 2016; Hashim et al., 2001). When the shape of the reinforcement particles in the powder mixture is examined in Figure 1, it is seen that they are in a rather irregular structure and in the form of sharp corners. In this case, it can be easily said that one of the factors affecting the fracture is present. The digital microscope images taken from the fractured surfaces of the composite samples after the flexural test is shown in Figure 5.

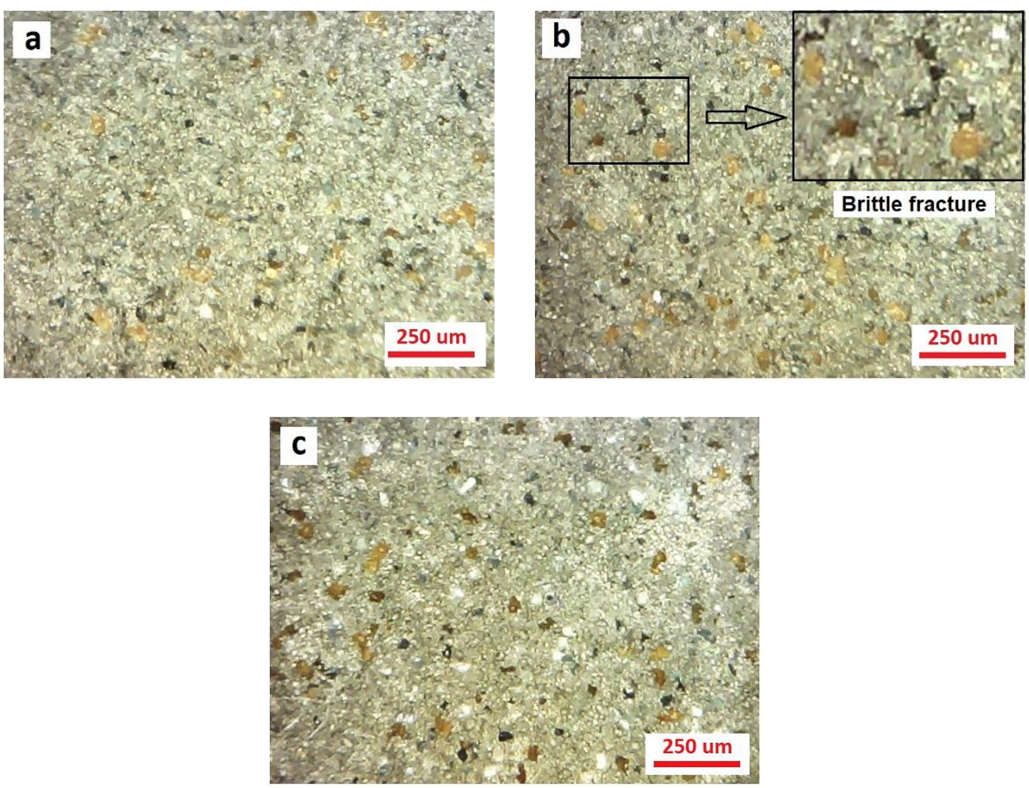

Figure 5. (a) Fractured surface images of 5% MgO+5% SiC reinforced composites; (b) Fractured surface images of %7,5 MgO+%7,5 SiC reinforced composites; c) Fractured surface images of %10 MgO+%10 SiC reinforced composites;

When the surface images in Figure 5 are examined, it is understood that the brittle fracture mechanism is effective (Figure 5b). It can also be said that there are areas with spaces in the composite structures. However, it cannot be said that there is a direct relationship between the pore ratios in the composite structure and the flexural strength values. If this were the case, the highest flexural strength value should have been obtained from the 5% MgO+5% SiC reinforced sample. In this case, it can be said that homogeneity of composite structures is more effective on flexural strength. The accumulation of reinforcement particles at a higher rate than the other sections increased the notch effect more in the composite structure in the section that is forced to flexural. This situation reduced the strength of the composite structure. When the compressive strength values in Figure 4 are examined, it is seen that the highest strength value is obtained from the composite structure reinforced with 7.5% MgO+7.5% SiC as in the bending strength. Tensile tests are generally used to determine the mechanical strength of such composite structures. Differently from the literature, compressive strength tests were carried out in this article. The digital microscope images taken from two different regions of the deformed surfaces of the composites after the compression tests are given in Figure 6.

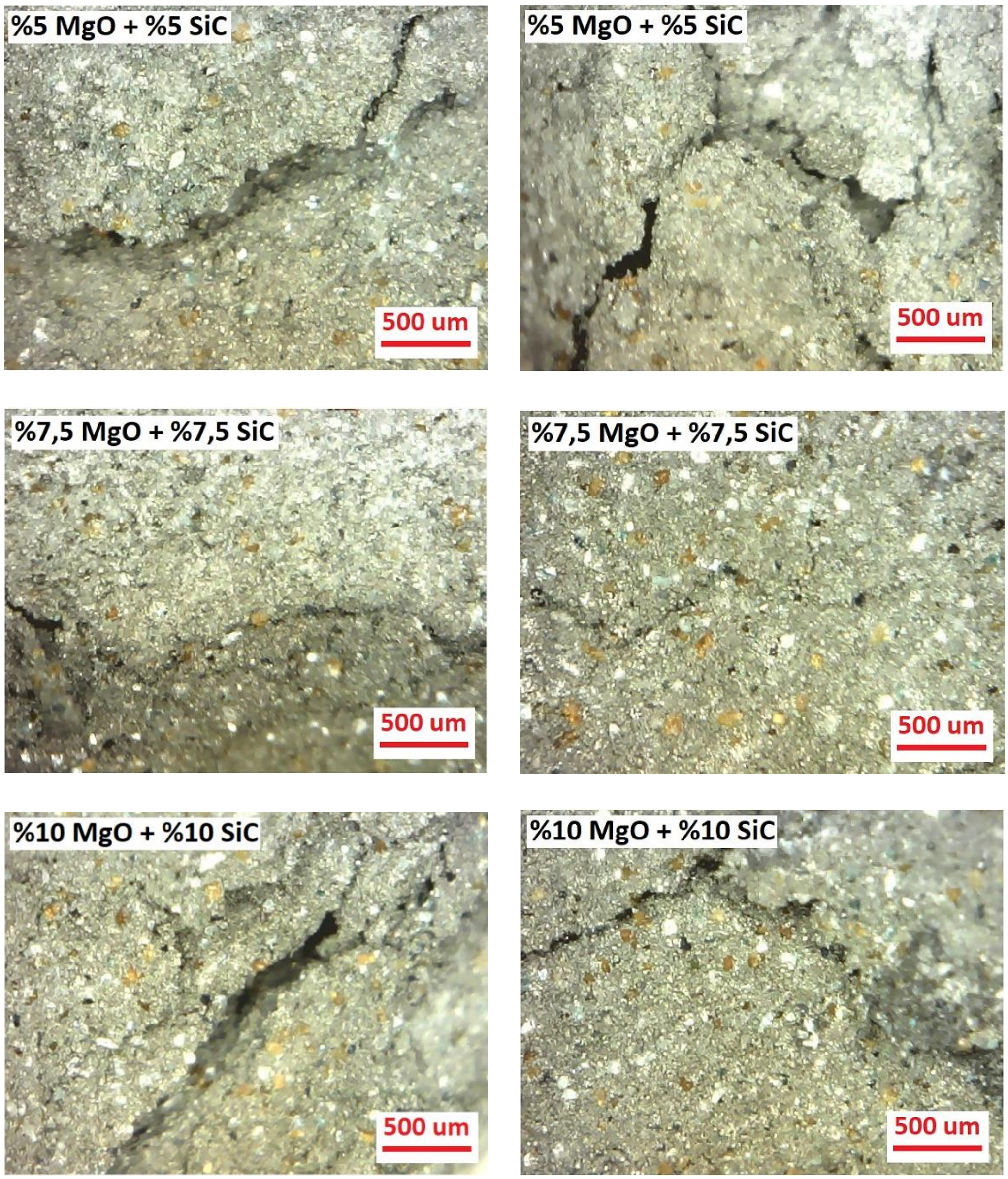

Figure 6. Microstructures of Al7075/MgO+SiC composites after compression test

When the microstructure images in Figure 6 are examined, the deformations in the composite structure are clearly seen as a result of the compression tests. It is understood that the cracks and crevices on the 5% MgO+5% SiC reinforced sample, which exhibits the lowest compressive strength, are wider and deeper than the other samples. It can be seen that the cracks and crevices formed in the 7.5% MgO+7.5% SiC reinforced sample, which has the highest compressive strength value, are narrower and less deep. As can be seen from the microstructure images taken on the composite samples after the compression test, the 7.5% MgO+7.5% SiC reinforced composite structure, which exhibits the highest compression stress value, has undergone the least deformation. In this case, it is considered that the composite structure images given in Figure 6 and the compressive strength values in the graph in Figure 4 support each other.

It can be said that ceramic particles in a certain amount in the aluminum matrix increase the compressive strength. There is a close relationship between the elasticity properties of materials and their deformation behavior. The elastic constants of SiC and MgO particles in the composite structure are much higher than the matrix material aluminum. In this case, it became difficult for Al7075 to undergo plastic deformation during the experiments. At the same time, a higher hardening occurred and the compressive strength of the composite structure increased (Abdizadeh et al., 2014; Saif et al., 2020). As the amount of MgO and SiC in the aluminum matrix increases, the distance between the particles decreases. Thus, higher stresses were needed to move the dislocations. This situation has created the effect of increasing the strength of the material (Saif et al., 2020). This effect is shown by Equation 2.

$$\tau = GB/L \tag{3}$$

Here; (τ) is the shear stress for a single crystal, (G) is the shear modulus, (B) is the Burger vector for the crystal, (L) is the distance between the reinforcement particles. According to Equation 1, the distance between the reinforcement particles must be reduced and the stress must be increased for the dislocations to slip. However, it is understood that as the reinforcement ratio increases, other factors that decrease the mechanical strength are effective in this article. Because, in the compression tests, it is seen from the graphs in Figure 5 that both the compressive and flexural strengths decrease when the reinforcement ratio of 7.5% MgO + 7.5% SiC is exceeded. The most important reason for this decrease in mechanical strength is the difficulty of particle distribution with the increasing amount of reinforcement and the formation of agglomerations. As a result of agglomeration, the bonding of the composite is adversely affected and the mechanical strength decreases. Similar results are reported in the study (Abdizadeh et al., 2014). Another study in the literature has reported that a compressive strength of 82 MPa was obtained from the undoped aluminum sample and 138 MPa from the aluminum composite with 30% SiC (Şenel et al., 2017). In this study, a compression strength value of 101.3 MPa was found with a total reinforcement content of 15%, 7.5% MgO and 7.5% SiC. The results of this study with the literature results support each other.

3.4. Electrical characteristics

The values obtained from the electrical measurements of Al7075 based MgO and SiC reinforced composite structures are given in Table 3, and the graphs created according to these values are given in Figure 7.

Table 3. Electrical measurement values of hybrid composites

Composite samples	Conductivity	Resistivity	% Change
Al7075/MgO+SiC (5+5)	$13.0025*10^{6}$	$7.6908*10^{-8}$	-
Al7075/MgO+SiC (7,5+7,5)	$10.7434*10^{6}$	$9.3080*10^{-8}$	17,37
Al7075/MgO+SiC (10+10)	$7.2432*10^{6}$	$13.8060*10^{-8}$	32,58

Figure 7. Electrical resistivity and conductivity values of Al7075/MgO+SiC composites

When the graphs in Figure 7 are examined, it is clearly seen that the electrical conductivity decreases with the increase in the SiC/MgO reinforcement ratio in the composite structure. It was observed that the electrical conductivity in the 7.5% reinforced SiC/MgO composite material was 17,37% lower than the electrical conductivity in the 5% reinforced SiC/MgO added composite. It was observed that the electrical conductivity in 10% reinforced SiC/MgO composite material was 32,58% lower than the electrical conductivity in 7.5% reinforced SiC/MgO composite material. When these results are compared with the results in similar articles, it is seen that they are quite consistent (Mohammed et al., 2021; Aydın, 2021). The fact that the electrical conductivity of the SiC/MgO reinforcement is lower than the conductivity of the Al matrix reveals these results. Therefore, as the SiC/MgO ratio added to the Al matrix increased, the conductivity of the composites decreased (Zawrah et al., 2019; Taha and Zawrah, 2017; Malliaris and Turner, 1971). The interaction of the electron with the nucleus in Al metal is very low. This gives electrons the ability to move freely. The free movement of electrons has led to an increase in the electrical conductivity of Al metal. However, with the addition of SiC/MgO particles to Al metal, the interaction between electron and nucleus increased. Thus, a stable bond structure was formed between them. There has been a noticeable decrease in electrical conductivity, as the mobility of electrons is reduced with this bond structure.

MgO/SiC reinforcement creates non-conductive particles inside the Al7075/SiC/MgO composite structure. It has been observed that the electrical conductivity varies depending on the volume state of the MgO/SiC doped particles, the percentage of the additive and the structure of the geometric shape of my material. Therefore, electrical conductivity is expected to increase as the volume and percentage of metal matrix increase in a composite. In other words, a decrease in electrical conductivity is expected as the volume fraction of the non-conductive additive increases. MgO/SiC is a semiconductor compound. In addition, as the MgO/SiC contents increase, the gaps between the Al alloy and MgO/SiC particles increase. This creates electron movement barriers that provide electrical conductivity. Therefore, it is very normal for its electrical conductivity to decrease when combined with a conductive structure such as aluminum (Srivastave and Ojha, 2005; Islak et al., 2014).

4. Conclusion

The general results obtained from the experimental study titled The Effect of SiC and MgO Ceramic Reinforcements on the Mechanical Behavior and Electrical Properties of the Composite Structure in Al7075/SiC/MgO Hybrid Composites are summarized below:

- Al7075/SiC/MgO composite structures were successfully produced by powder metallurgy method at determined matrix-reinforcement ratios.
- In the microstructural examinations of the composites, it was determined that there was a relatively homogeneous distribution, but porous regions were formed with SiC and MgO reinforcement agglomerations in some regions.
- Depending on the increase in the SiC/MgO reinforcement ratio in the composite structure, it was understood that both the hardness values increased and also the porosity amounts increased in the same way.
- The highest flexural and compressive strength values in composite structures were obtained from 7.5% MgO + 7.5% SiC reinforced sample. When the amount of reinforcement increased to 10% MgO + 10% SiC, both flexural and compression strength values decreased.
- It has been evaluated that the most effective factors on the mechanical strength values are the porosity in the composite structure, the reinforcement ratios and the geometric shape of the reinforcement particles. In particular, the porosity in the structure and the sharp-edged form of the reinforcement particles had a negative effect on the flexural and compression strength values.
- Due to the semiconductor SiC and dielectric MgO particles in the composite materials, the electrical resistance of the composite structures increased while the conductivity properties decreased. This situation changed depending on the amount of SiC and MgO reinforcement in the composite.
- It is known that the conductivity of a substance is directly related to the free movement of electrons. In this study, it has been evaluated that the most important reason for the decrease in the electrical conductivity of the composite structure is the decrease in free circulation of electrons of MgO and SiC due to their proximity to the nucleus.

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