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Low-velocity and ballistic impact resistances of particle reinforced metal–matrix composites: An experimental study

Ertan Kosedag[1] and Recep Ekici[2]

Abstract

This study investigates the low-velocity and ballistic impact responses of SiC-reinforced Al6061 metal–matrix composites in different reinforcement volume fractions. Low-velocity impact (LVI) tests were performed with samples having SiC particle volume fractions of 0, 5, 10, 15, 20, 30, and 40%, while ballistic tests were carried out with samples having volume fractions of 0, 10, 20, and 30%. The weight-drop test method was used for LVI by applying 50 J (4.45 m/s) energy to all samples. Ballistic tests were carried out under the same conditions on all samples with the projectile launched at an average velocity of 500 m/s. For the determination of the ballistic resistance of the samples, the projectile penetrations in the witness structures were taken into consideration. The damage and deformations caused by both the LVI and the ballistic test in composites were examined. By the LVI test results, composite samples have absorbed less impact energy by increasing the reinforcement volume fraction, as well as demonstrated superior performance compared to unreinforced samples. In addition, the crack formation was mainly observed in the samples containing 30% reinforcement, while the composite material with a 40% volume fraction was completely broken. With the increase in the reinforcement volume fraction, the ballistic resistance of the samples increased significantly.

Keywords

Metal–matrix composites, powder metallurgy, low-velocity impact, ballistic impact, mechanical properties

Introduction

Metal materials are used in many engineering applications due to their good toughness and high strength. However, conventional metal materials often are not characterized by good mobility and protection alone. For this reason, many studies have stated that it needs to be developed to be more efficient.[1] Ceramics such as SiC,[2,3] B_4C,[4,5] and Al_2O_3[6–8] stand out for their high strength, high hardness, and low density. But, having a brittle structure limits its use alone.

Ceramic particle reinforced metal–matrix composites are excellent feature materials that show the properties of metals and ceramics together in proportion to its mixtures. Al6061 (2.7 g/cm^3), which is about three times lighter than steel (7.5–8 g/cm^3), is a matrix material that is frequently used because it is relatively inexpensive than magnesium, titanium, etc. When it is considered in terms of cheapness, high hardness, low density, high melting point, and thermal stability, it is obvious that SiC particles will contribute to metal–matrix material in terms of impact resistance.

In numerous studies, the mechanical properties of metal–matrix composites have been determined by tensile, compression, creep, and fatigue tests.[9,10] However, in many engineering applications, metal–matrix composites are exposed to low- and high-velocity impacts. Therefore, it is important to know the impact behavior of the material used in advance.[11,12] Besides, it is an indisputable fact that lightness is important for mobility in the defense industry. Metal–matrix composite materials are also very strong candidates in the field of defense with their lightness and increased mechanical properties. Thus, the investigation of both the low-velocity and ballistic impact behavior of SiC particle reinforced Al6061 metal–matrix composites, which

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have a common share in the applications of metal–matrix composites, will be an important gain for the literature.

Some studies investigating the behavior of the low velocity of metal–matrix composites are presented. The impact behavior of SiC particle–reinforced Al6061-based metal–matrix composites was studied by Prewo[13] using the Charpy impact test. It was observed that impact resistance was reduced with reinforcement particles in metal–matrix and notch effect. Kim et al.[14] showed that increasing volume fraction decreased the fracture toughness of Al6061-T6/SiC composites. Surappa and Sivakumar[15] studied the impact behavior at temperatures varying from −196 to 100°C of particle-reinforced metal–matrix composites. They concluded that the impact strength was reduced due to brittle alumina particles in the matrix, and the fracture energies of the composites decreased, whereas the fracture energy of the unreinforced alloy increased with an increase in temperature. Ahlatci et al.[16] investigated the effect of particle size on the impact and mechanical behaviors of SiC/Al matrix composites. They found that the impact and compression strength decreased as the particle size increased because of the possibility of increasing particle cracking. Ozden et al.[17] examined the effect of temperature, artificial aging, and extrusion ratios on the impact behaviors of SiC particle–reinforced Al alloy metal–matrix composites. They found that the impact toughness of composites decreased due to both hard SiC particle reinforcements and artificial aging of Al alloys, but increasing the particle size and the extrusion ratio slightly improved the impact toughness. Ekici and Kaburcuk[18] showed that the impact energy absorbing capacity was improved by decreasing the particle volume fraction and increasing the particle size in particle-reinforced metal–matrix composite structures. Ekici and Kosedag[19] concluded that metal–matrix composites subjected to low-velocity impact tests increased the impact time and peak contact force with the increase in the impact velocity. In addition, SiC powder–reinforced composites often behaved more rigidly compared to pumice powder–reinforced composites. In another experimental study, Kosedag and Ekici[20] investigated the effects of particle volume fraction on the low-velocity impact behavior of metal–matrix composites. For this purpose, they produced metal–matrix composite (5, 10, and 15% B_4C/Al6061) materials by powder metallurgy. The samples were subjected to impact using a drop-weight test device at a velocity of 4.55 m/s with a 5.045-kg impactor. According to results, the authors reported that metal–matrix composites showed excellent impact energy-absorbing capacities compared to unreinforced material under low-velocity impact conditions. Also, it was emphasized that the reinforcement volume fraction up to 15% gradually increases the impact absorption capacity, but since the increased reinforcement volume fraction increases the brittleness in metal–matrix composites, it was underlined that new studies should be performed by adding reinforcement volume fraction more than 15%.

In a study by Chao et al.,[21] the ballistic behavior of metal–matrix composites was carried out using a 7.62-mm armor-piercing incendiary. According to the authors' report, the results showed that the metal–matrix composites have excellent ballistic performance and protection. Also, it was concluded that the impact energy was consumed through plastic deformation and damage. In another study, Kurzawa et al.[22] conducted a study on the impact behavior of metal-ceramic composites with aluminum matrix on firing with 5.56 × 45 mm caliber intermediate ammunition. For this purpose, the ballistic resistance of composites containing 0, 20, and 40% ceramic reinforcements was compared. It has been reported that 20 and 40% particulate reinforcement reduces the projectile velocity by 30 and 50%, respectively, compared to unreinforced material. Karamis[23] researched the bullet surface by a scanning electron microscope (SEM) after the impact test of Al_2O_3/Al composites and reported that the reinforcement particles can increase the friction between the bullet and composite target which would increase penetration resistance. Gangwar et al.[24] reported that the impact strength, compressive strength, and hardness of metal–matrix composites changed with the reinforcement ratio. In addition, according to a study by Bandil et al.,[25] the tribological and corrosion properties of metal–matrix composites are significantly affected by the reinforcement ratio. It is possible to come across studies similar to these studies[26,27] in the literature. Ekici et al.[28] conducted a study examining the effect of reinforcement ratio on low-velocity impact. According to the results of this study, it has been proven that the reinforcement ratio and the number of impacts have a significant effect on both impact resistance and post-impact hardness.

As can be seen from the literature, the low-velocity and ballistic impact behaviors of Al/SiC composites were mostly examined separately. To the best of the authors' knowledge, there is no other study that compares these two different loading types, which differ in deformation rate and cause different damage mechanisms on metal–matrix composites. Based on this motivation, this study aims to experimentally investigate both the low-velocity and ballistic impact behavior of SiC/Al6061 metal–matrix composites. The powder metallurgy method was used in the production of composite samples with different volume fractions. The low-velocity impact tests were carried out for 50 J (4.45 m/s) of impact energy, while ballistic tests were performed with the projectile average velocity of 500 m/s. The low-velocity impact behaviors were examined by using contact force histories, contact force–displacement curves, and deformed sample damage views. Ballistic impact behaviors were determined from the penetration amount of the bullet into the witness structure and the front and back views of the bullet hole shape.

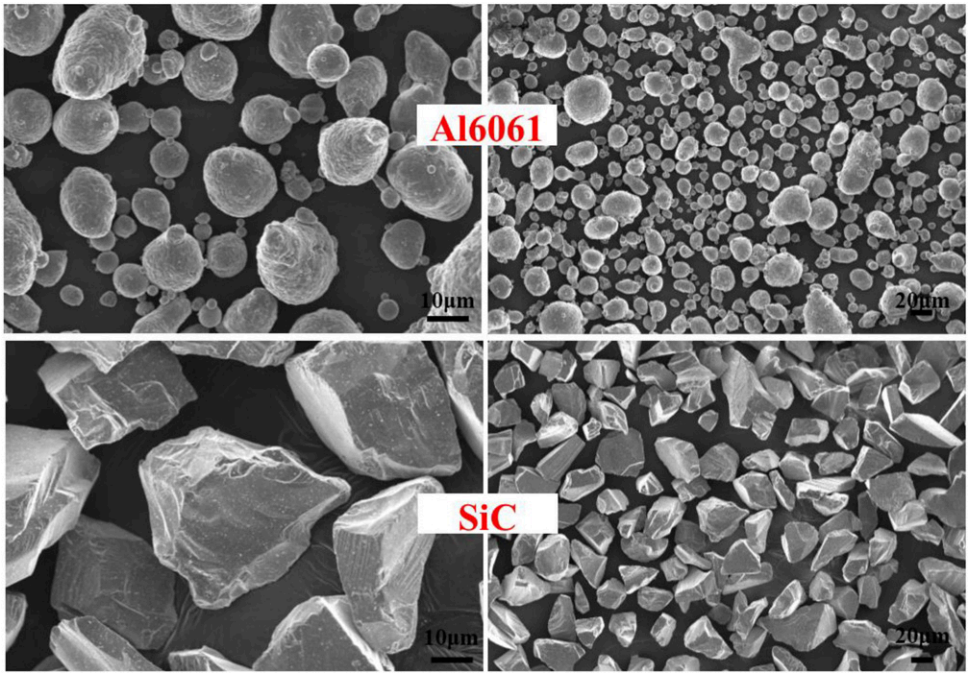

Figure 1. SEM images of Al6061 and SiC at different upsizing.

This study was carried out to find answers to the following questions to investigate the impact resistance of metal–matrix composites.

i) In metal–matrix composites, (a) what is the effect of reinforcement ratio on low-velocity impact behavior? (b) What is the upper limit for the use of reinforcement material?
ii) What is the effect of reinforcement amount on ballistic resistance in metal–matrix composites?
iii) Does the reinforcement ratio in metal–matrix composites have a similar effect in low-velocity impact and ballistic tests?

To answer these questions, various reinforced metal matrix composites were produced by the powder metallurgy method. The production is explained in detail in the experimental method section. Then, low-velocity impact tests and ballistic tests are explained in detail, and the results obtained from these tests are discussed. Finally, the results obtained are summarized in the *Conclusion* section, and suggestions for future studies are presented.

Material and method

Manufacturing process

Al6061 alloy was used as the matrix for the production of metal–matrix composites, while SiC was used as the reinforcing material. The microstructures of the powders were revealed by a Zeiss Sigma 300 field emission SEM. SEM images of the powders used are presented in Figure 1. Images are presented at 10 and 20 micron scales for both powders. The chemical content of Al6061 alloy, which is a matrix material, is given in Table 1. The matrix and reinforcing powders used are both about 30–40 microns. The mesh size of the matrix and the reinforcement element SiC material is 325–400. In addition, the purity levels were reported by the manufacturer as 99.9 and 98.7%. As seen in Figure 1, Al6061 powders are spherical, while SiC powders are sharp-edged. Metal–matrix composites are produced by hot press, which is one of the methods of powder metallurgy production. One of the advantages of using hot presses is the simultaneous application of pressure and heat; therefore, the ability of the matrix and reinforcing powders to diffuse to each other further improves. First, the powders weighed according to volume fractions were mixed in the Turbula T2F device for 4 h. This device performs the shaking and mixing process at the same time, thereby ensuring that the powders are mixed as much as possible. Next, heat and pressure are applied to the powders poured into the mold as shown schematically in Figure 2. During production, 75 MPa pressure was applied. Simultaneously, it was heated to 620°C, which is a sintering temperature, with a heating rate of 10°C/min for 62 min and sintered at this temperature for 60 min. It was then allowed to cool for 22 h in the hot press. With this method, samples with a diameter of 50 mm and a thickness of 7 mm were produced for low-velocity

Table 1. Chemical composition of aluminum 6061 alloy (by weight %).

Materials	Al	Cu	Fe	Mg	Cr	Si	Mn	Ti	Zn
Al6061	Balance	Max. 0.4%	Max. 0.7%	Max. 1.2%	Max. 0.35%	Max. 0.8%	Max. 0.15%	Max. 0.15%	Max. 0.25%

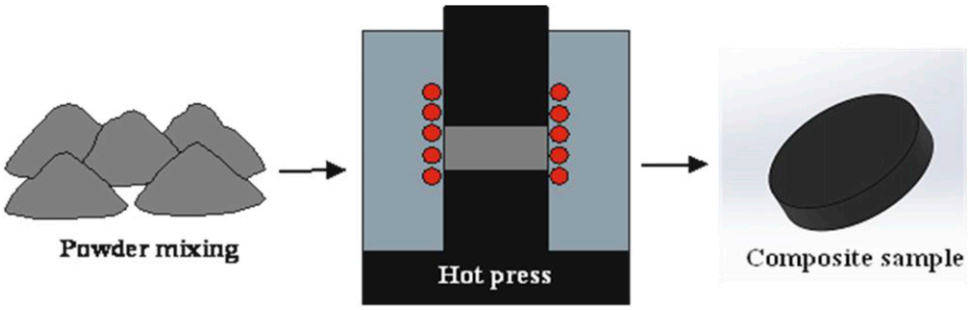

Figure 2. Hot press production stages.

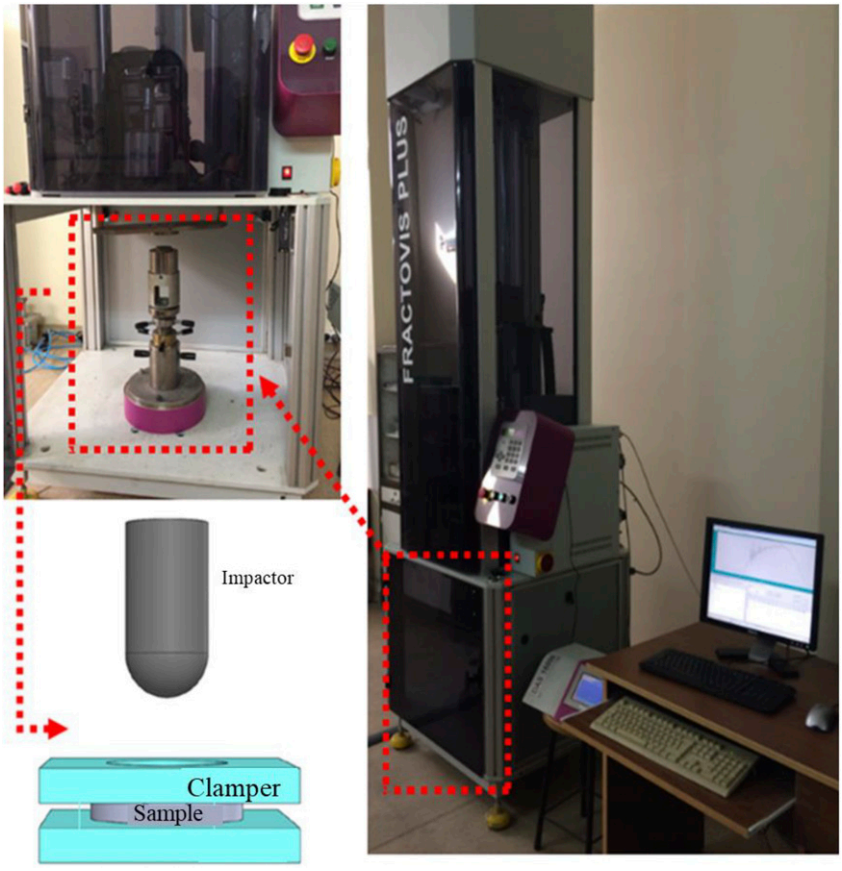

Figure 3. Low-velocity impact test device.

impact tests, while samples with a diameter of 90 mm and a thickness of 7 mm were produced for ballistic tests. Al6061–based metal–matrix composite samples for low-velocity impact tests were produced with SiC reinforcing particles in 0, 5, 10, 15, 20, 30, and 40% volume fractions. By contrast, Al6061–based metal–matrix composite samples for ballistic tests were produced with SiC reinforcing particles in 0, 10, 20, and 30% volume fractions.

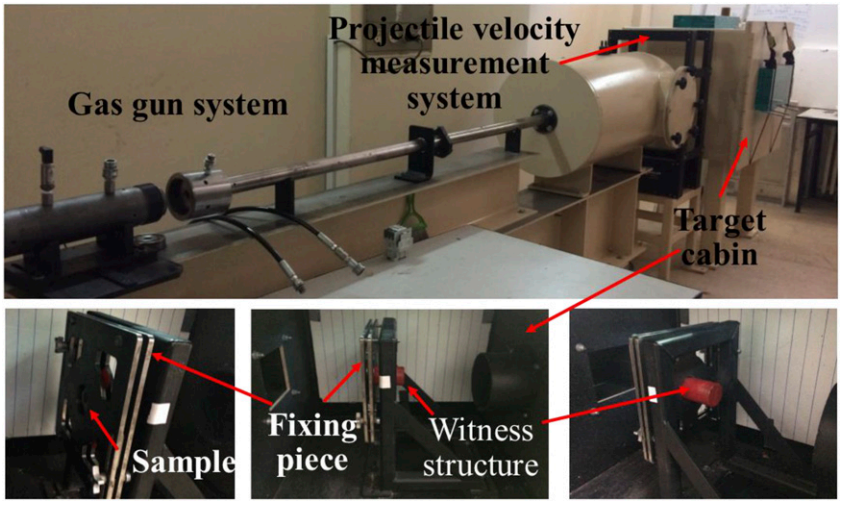

Figure 4. Gas gun system for ballistic tests.

Low-velocity impact tests

The drop-weight impact test method was used for low-velocity impact tests of the produced composite materials. As can be seen in Figure 3, the drop weight impact setup consists of a tower and a cabinet, where the sample is fixed. The scope of the impact damage is mainly controlled by the capacity of the impact energies; therefore, the mass is kept constant, and the heights vary for the specified energy values. The change in height of the impactor provides the velocity and energy required for the tests. The tests were carried out with the impactor, which weighs 5.045 kg and uses a hemispherical tip with a radius of 10 mm. The impact test was performed with a velocity of 4.45 m/s providing the energy value of 50 joules (J) to the samples. The CEAST Fractovis Plus device was used for low-velocity impact tests (Figure 3). The brake system of the device prevents the striker tip from falling on the sample after it hits. The low-velocity impact behavior of composite samples is determined by the contact force-time and contact force-displacement curves taken from this device. From these data, information about the peak contact force, the amount of displacement, and the absorbed energy is taken to compare samples. The low-velocity tests were performed on the particle-reinforced metal–matrix composites at least twice for each of all material configurations ($V_f = 0,\ 5,\ 10,\ 15,\ 20,\ 30,$ and 40%). At least 14 samples were tested for all composite material configurations. In the case of the contact force histories of the first and second impact test for a sample, the configuration was discordant; the tests were repeated for that specimen configuration until the contact force history was compatible.

Ballistic impact tests

A single-stage gas gun shown in Figure 4 was used for ballistic tests of composite samples. The single-stage gas gun system had a 12.7-mm diameter barrel and was 1.8 m long. It works on the idea of releasing helium gas from the launcher onto the projectile at a pressure that allows the projectile to accelerate to the desired speed. An integrated, optical velocity measurement device was used to measure the velocities of projectiles. Ballistic tests were taken with 0.30-caliber fragment simulating projectile (FSP), which is defined by MIL-DTL-46593B (MR)[29] and STANAG 2920[30] standards. The FSP was fixed with sabot which is shown in Figure 4. The projectiles used were made of AISI 4340 and increased to 30 ± 2 Rockwell C hardness by heat treatment. Projectile sizes and geometrical details are presented in Figure 5. A fixing piece was used to hold the samples. A witness structure made of epoxy and hardener was used to compare the output energies of the projectiles coming out of the samples. The ballistic impact resistance of composite specimens was compared according to the penetration amount in the witness structures after the shot. The sample fixing piece and the witness structure can be seen in Figure 4.

Projectile velocities were measured with an optical barrier system placed in front of the sample. Each ballistic test was carried out under the same conditions with minimal difference in impact velocities. Ballistic tests were performed on all composites which had 0, 10, 20, and 30% SiC reinforced Al6061 matrix at an average velocity of 500 ± 5 m/s.

Results and discussion

Determination of the impact behavior was carried out in two sections consisting of low-velocity impact and ballistic tests of Al6061 metal–matrix composites containing various volume fractions of SiC reinforcement. First, low-velocity impact tests were performed on Al6061 metal–matrix composites with a diameter of 50 mm and a thickness of

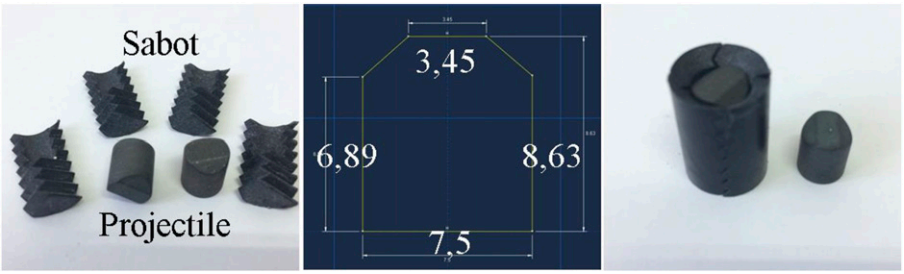

Figure 5. Sabot, the 30-caliber FSP and its geometrical details.

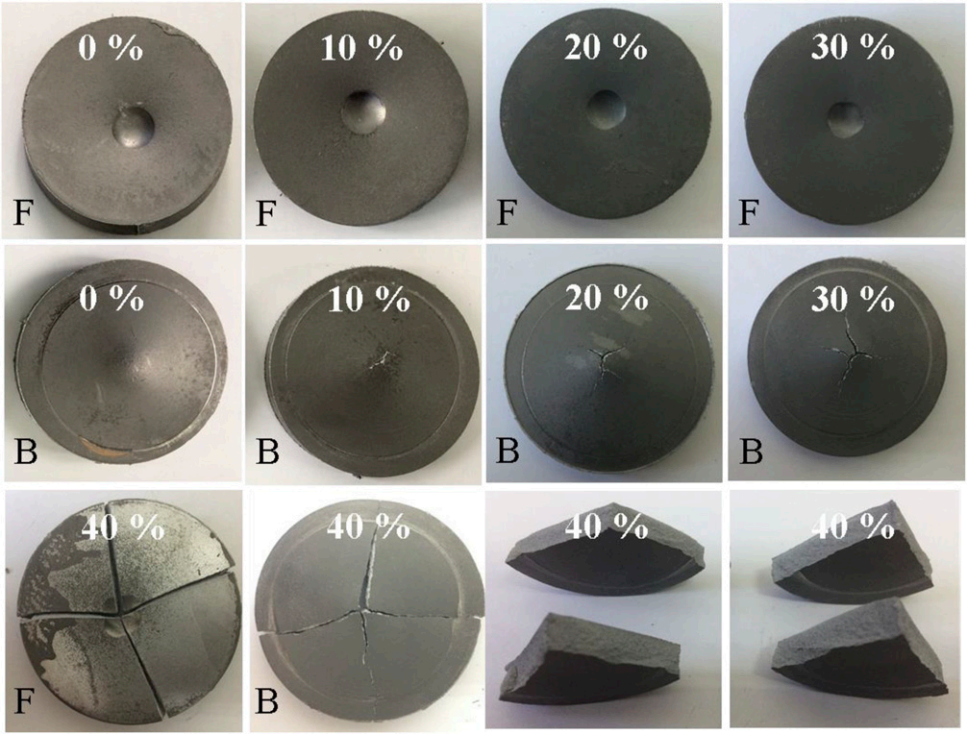

Figure 6. Front (F) and back (B) views of low-velocity impact test specimens.

7 mm, containing 0, 5, 10, 15, 20, 30, and 40% SiC, with a velocity of 4.45 m/s and energy of 50 J. Then, ballistic tests were performed on Al6061 metal–matrix composites with a diameter of 90 mm and a thickness of 7 mm and containing 0, 10, 20, and 30% SiC by using a gas gun at 500 ± 5 m/s velocities. In this section of the study, first the results of the low-velocity impact tests and then the ballistic tests will be examined.

Low-velocity impact test results

Front and back views of the samples exposed to the low-velocity impact are presented in Figure 6 (The images of the samples with 5 and 15% in the volume are not included in Figure 6 due to similarity and similar deformations). When deformed samples are examined, the formation of dents on the deformed sample front surfaces gradually becomes smaller as the volume fraction increases, but this change occurs in very small amounts. Although there were slight differences on the front surfaces of the samples with the increase in the reinforcement volume fraction, significant changes were observed in the type of deformation on the back surfaces. However, it can be seen that there is no crack back surface of the unreinforced sample due to its ductile structure, but the severe plastic deformation that occurs is more than that of the other samples. It is clear that as the

reinforcement volume fraction increases from 10 to 30%, the cracks on the back surfaces of the samples gradually increase, and a decrease in plastic deformation occurs. In addition, fracture occurred in the composite sample containing 40% reinforcement, which was impact-tested under the same conditions as the other samples. From the broken sample surfaces, it can be understood that the metal–matrix composite structure is subjected to brittle fracture. This is considered to be due to the effect of hard reinforcement (SiC) particles that increase the brittleness in the metal–matrix composite structure.

Figure 7(a) shows the effect of particle volume fractions ($V_f = 0, 5, 10, 15, 20, 30$, and 40%) on the contact force histories obtained from the low-speed impact tests. Fluctuations in force values until reaching the maximum contact force indicate matrix fractures. It has been determined that although the matrix cracking locally creates a fluctuation in contact forces, it does not cause a change in the stiffness of the entire sample. Contact force history reaches a peak level at 17.10 kN in 1.41 ms (milliseconds), 17.21 kN in 1.38 ms, 17.56 kN in 1.31 ms, 17.63 kN in 1.12 ms, 17.75 kN in 0.94 ms, 18.37 kN in 0.42 ms, and 19.08 kN in 0.41 ms for particle volume fractions of $V_f = 0, 5, 10, 15, 20, 30$, and 40%, respectively. Also, the impactor tip leaves the sample surface in 2.55, 2.48, 2.46, 2.40, 2.37, and 2.31 ms for $V_f = 0, 5, 10, 15, 20$, and 30%, respectively. However, the sample with a volume fraction of $V_f = 40\%$ broke at 1.88 ms. It is seen that as the volume fraction (V_f) is increased from 0 to 40%, the peak contact force increases, whereas the impact duration generally decreases. This change proportionally means that the peak contact force increases by 11.58% and impact durations are shortened by 2.40% as the volume fraction increases from 0 to 30% (for the samples that can be measured data). With increasing particle fraction, metal–matrix composites behave more brittle and undergo less plastic deformation.

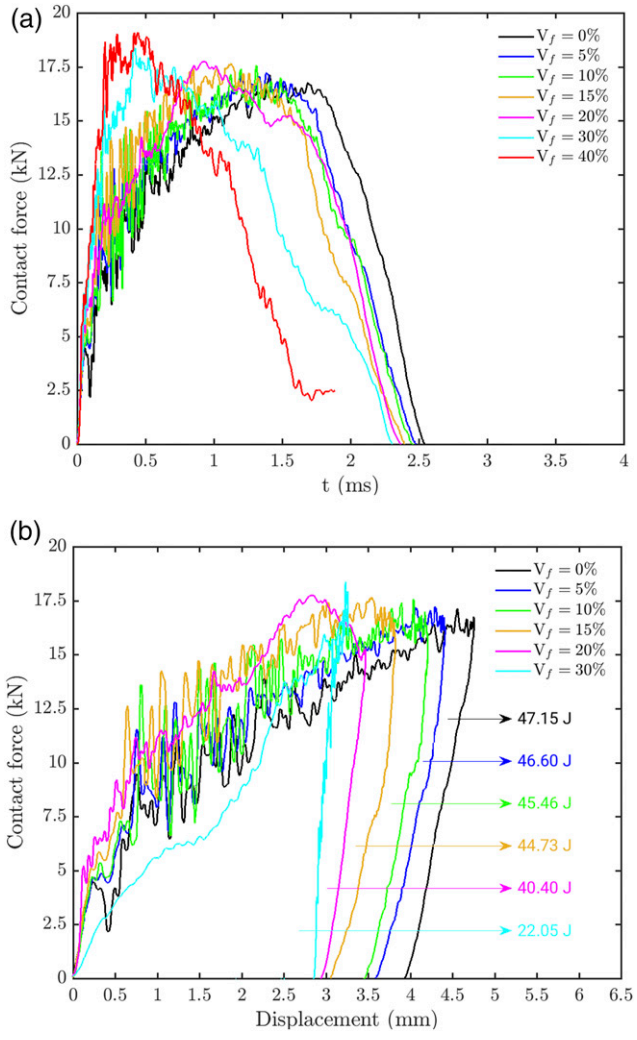

Figure 7. The effect of particle volume fractions ($V_f = 0, 5, 10, 15, 20, 30$ and 40%) on the (a) contact force histories and (b) contact force–permanent central deflection variations for the low-velocity impact tests.

Figure 7(b) presents the effect of particle volume fractions on the contact force–permanent central displacement curves. Also, the absorbed impact energies were determined by calculation from the closed area under the contact force versus displacement curves (Figure 7(b)). Permanent central deflections were measured as 3.93, 3.59, 3.45, 3.06, 2.94, and 2.85 mm for $V_f = 0, 5, 10, 15, 20$, and 30%, respectively. The absorbed energy was calculated as 47.15, 46.60, 45.46, 44.73, 40.40, and 22.05 J for $V_f = 0, 5, 10, 15, 20$, and 30%, respectively. Data could not be obtained from the sample having a 40% volume fraction because it was broken. As can be seen, with the increase in the volume fraction from 0 to 30%, the permanent central deflection decreased by 27.48%, while the absorbed energy decrease reduced by 52.68%. Increasing the volume fraction has increased the stiffness of the composite material against the impact. However, increasing the volume fraction continuously causes the composite to decrease the impact resistance and the structure to be damaged after a certain point. This is mostly due to increased brittleness of the metal–matrix structure. Also, this is thought to be due to the discontinuity created by the increasing reinforcement phase in the matrix. In this case, SiC particle–reinforced metal–matrix composites above 30% volume fraction do not provide safe strength in these impact conditions.

In the studies[31] and[32], it is stated that energy balances are generally used in determining the level of damage development during the impact event. Belingardi et al.[33] have determined when the sample will undergo full penetration with the degree of damage found from the ratio between impact energy and absorbed (plastic) energy during the low-velocity impact loading. As the damage degree approaches

1, that is, the value of the absorbed energy approaches the applied impact energy level, the sample undergoes full penetration. After low-velocity impact, impact energy is stored in two ways in samples. First of these, the rebound energy represents the energy value that causes the impact tip to return, while the remaining energy, the second one, is the plastic energy absorbed by the sample and will damage the sample. As the reinforcement volume fraction increases, it can be seen from the results that the damage level approaches 1 and that the sample containing 30% reinforcement has formed large cracks, and finally, the sample containing 40% reinforced volume fraction was broken.

Ballistic impact test results

Ballistic tests were performed on metal–matrix composites including SiC reinforcement volume fractions of 0, 10, 20, and 30% under the same conditions. Metal–matrix composite samples were 7 mm thick and 90 mm in diameter. All shots in the tests were fired at 500 ± 5 m/s. As the sample thicknesses were quite small, the samples were fully pierced, and the impact resistance demonstrated by the composites was measured by the amount of penetration in the witness structures placed behind the sample. The variation of the penetration results according to the reinforcement volume fraction is presented in Table 2. Also, the witness structure and penetration measurements are given in Figure 8. By mixing epoxy resin and hardener in various proportions and optimizing it for shooting, a witness structure with a special mixing fraction was obtained. Considering the results in Table 2, it is seen that the ballistic resistance of the composites increases as the reinforcement volume fraction increases. By taking into account the penetration amounts, it was determined that the ballistic resistance of the samples with 10, 20, and 30% reinforcement volume fraction, compared to the unreinforced

Table 2. Ballistic results of metal–matrix composites.

Materials	The velocity of the projectile (m/s)	Penetration of witness structure (mm)	Area of the projectile hole (front) (mm^2)	Area of the projectile hole (back) (mm^2)
Al6061	503	27	84.9	56.7
10% SiC/ Al6061	505	22	66.8	127.2
20% SiC/ Al6061	495	18	64.4	139.1
30% SiC/ Al6061	502	12	54.9	162.2

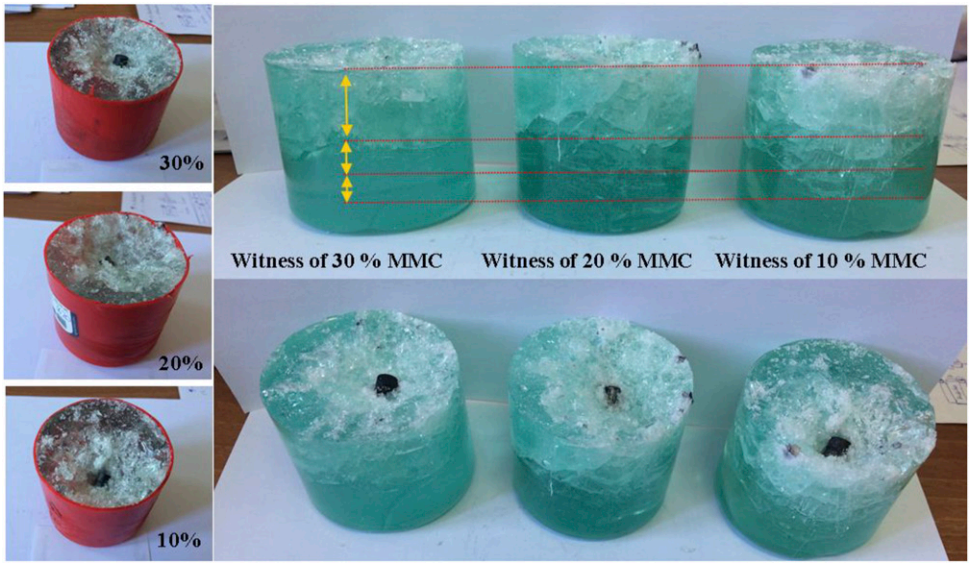

Figure 8. Witness structures after ballistic tests.

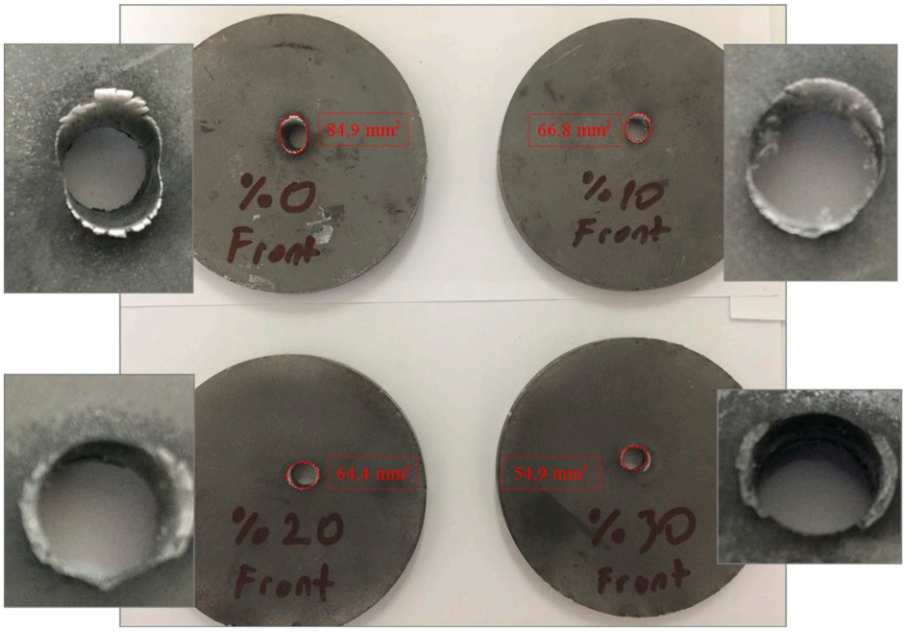

Figure 9. Front views and hole areas of ballistic test specimens.



Figure 10. Back views and hole areas of ballistic test specimens.

sample, increased by 18, 33, and 55%, respectively. It was also concluded that the composite samples containing 30% SiC particle volume fraction had 45 and 33% more ballistic resistance than 10 and 20% particle volume fraction, respectively. In addition, the composite sample containing 20% SiC particle volume fraction was calculated to be 18% more resistant than the one containing 10% particle volume fraction. It is considered that this obtained result is due to the

increased friction in the projectile with increased SiC particle volume fraction in the composite structure. Similar results were obtained in the literature.[15,16]

Figures 9 and 10 show the front and back views of the composite samples after the ballistic tests. When the front and back views are examined carefully, it can be easily seen that the reinforcement volume fraction has a significant effect on the bullet hole shape. According to the results of the area measurements with the help of the ImageJ,[34] an open-source https://imagej.net/Open_source image processing program, as the reinforcement volume fraction increases, the hole areas on the front side decrease, whereas the hole areas on the backside increase. In addition, it can be observed on the front side views that with an increase in the particle volume fraction, the petal formation gradually decreases, and spalling occurs. With the addition of hard SiC ceramic particles to the metal–matrix structure in a certain fraction, the composite structure becomes already somewhat brittle, and it is clear that the increase in volume fraction also makes the composites more brittle. A funnel shaped formation can be noticed on the back surface of the unreinforced sample, in the region where the bullet exits.

However, with the increase in the reinforcement fraction, there were outward ruptures around the hole opened by the projectile. Contrary to some studies[21,22,35] in the literature on composite samples, cracks and fractures were not observed throughout the sample. This is estimated to be due to the low fraction of the reinforcement particles. Therefore, the focus should be on the ballistic behavior of metal–matrix composites containing relatively low proportions of reinforcement elements.

Conclusions

In this study, composite materials with SiC reinforced and Al6061 matrix was produced by the powder metallurgy method to determine low-velocity impact and ballistic behavior. For low-velocity tests, samples of 40 mm diameter and 7 mm thickness with 0, 5, 10, 15, 20, 30, and 40% reinforced samples are used, whereas 90 mm diameter, 7 mm thickness, and 0, 10, 20, and 30% reinforced samples were used for ballistic tests. Low-velocity impacts and ballistic tests were carried out under the same conditions. Energy of 50 J was used in low-velocity impact tests, while the projectile with an average velocity of 500 m/s was used for ballistic tests. In general, it has been observed from low-velocity impact tests that as the SiC particle volume fraction increases, the contact force increases, but the contact time is shortened. However, the absorbed impact energy and the permanent central deflection decreased with increasing reinforcement volume fraction. This behavior persisted up to 30% volume fraction, and composites have shown superior performance compared to unreinforced samples. However, in the sample containing 30% reinforcement, mostly cracks were observed; then, 40% reinforced metal–matrix composite material was completely broken. From these results, it was concluded that the reinforcement amount of the metal–matrix composites improved the impact resistance of the samples up to a certain extent (30%), but poor results were obtained due to the embrittlement occurring after certain fractions. Ballistic test results were evaluated according to the damage types of composite specimens and their ballistic resistance. With the increase in the reinforcement volume fraction, the ballistic resistance of the samples increased significantly. In addition, due to the increasing fraction of reinforcement, the samples became brittle, and changes in damage patterns were observed. According to the results obtained from this study, the impact behavior of the material can be characterized by using different reinforcement elements and matrix materials without exceeding 30% reinforcement in terms of low-speed impact resistance. In addition, for ballistic tests, sample thickness can be increased and the ballistic limit can be determined with new tests, and sandwich structures can be obtained by using metal–matrix composites alone or in combination with polymer matrix composites for the defense industry, and the ballistic resistance of these new materials can be revealed.

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