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Low-velocity impact performance of B_4C particle-reinforced Al 6061 metal matrix composites

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Keywords: low-velocity impact, metal matrix composite, B_4C particles, particle volume fraction

Abstract

This study addresses the effects of particle volume fraction on the low-velocity impact behavior of B_4C particle-reinforced Al6061 metal matrix composites. For this purpose, Al6061 matrix B_4C reinforced metal matrix composite materials were produced by powder metallurgy method. Metal matrix composite samples were produced by hot pressing in B_4C particle volume fractions of 0, 5, 10 and 15%. Composite samples were subjected to impact using a drop-weight test device in a velocity of 4.55 m s^{-1} with 5.045 kg striker. After low-velocity impact tests, samples were cut out for cross-sectional examination and measuring residual central transverse displacements. The results were examined in terms of contact force-time, contact force-displacement, impact energy-time curves as well as residual central transverse displacements. Also, microstructural characterizations before and after the impact tests were performed by the Scanning Electron Microscopy (SEM). It was found that metal matrix composite samples exhibited superior impact energy absorbing capacities than unreinforced material under low-velocity impact conditions. Particle volume fraction had a considerable effect on the impact strength, and thus, the impact energy absorbing capacity in composites improved with increasing the particle volume fraction. While the particle volume fraction increased, the composite structures behaved stiffer. As a result, the peak contact force was increased, and the impact durations were almost decreased. However, Al6061/B_4C metal matrix composite materials having 15% volume fraction exhibited best impact performance.

1. Introduction

Advanced structural materials have been increasingly needed with the development of sectors such as space, aviation, defense, marine and automotive. Conventional materials such as metals, ceramics and polymers have not been sufficient to satisfy the need in these advanced technology applications. Hence, composite materials have highly gained importance in the past thirty years, and researchers have been working intensively on the mechanical strength of these materials. Among the composites, particle reinforced aluminum metal matrix composites are attractive materials due to their excellent mechanical and tribological properties such as high specific modules, stiffness and strength, high strength/weight ratios, excellent wear resistance, low thermal expansion coefficients, good toughness, good corrosion resistance etc. In addition, they can be shaped by traditional metal working techniques such as forging, rolling, extrusion [1–6].

In many studies, the mechanical properties of metal matrix composites have been identified by tensile, compression, creep, fatigue etc tests [7, 8]. But, particle reinforced metal matrix composites are also exposed to dynamic loads like impact in many applications. Thus, determining the response of metal matrix composite materials under dynamic loads is vital importance for their safely usage by engineers and users [9, 10]. SiC, B_4C, TiC, Al_2O_3 and SiO_2 ceramics are mostly used as reinforcement in aluminum metal matrix composites [11]. Among these reinforcing materials, B_4C has a special place. B_4C has hardness of 3800 HV considered as third hardest material next to diamond and C-boron nitride also it has good impact and wear resistance, low specific density (2.52 g cm^{-3}), low thermal conductivity (35 W mK^{-1}) and high stiffness (445 GPa) [12]. Despite the

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Table1. The chemical composition (wt%) of Al 6061 matrix alloy.

Material	Al	Cu	Fe	Mg	Cr	Si	Mn	Ti	Zn
Al 6061	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

broad literature on mechanical characteristics of Al/B_4C composites, few studies have been conducted on the low-velocity impact behavior of B_4C reinforced composites. It is quite important to eliminate the lack of data deal with the impact behavior of these composites, which may limit the potential industrial applications by conducting extensive research.

Some studies on the low-velocity impact behavior of particulate reinforced metal matrix composites are presented. Prewo [13], researched the impact performance by pendulum impact testing in a charpy impact tester of 30% SiC particle-reinforced Al 6061-based metal matrix composites. It was shown a decrease in impact resistance with reinforcement, and the notch effect caused a 10-fold reduction in impact resistance. Kim *et al* [14], showed that Al 6061-T6/SiC composite fracture toughness reduced with increasing volume fraction. Surappa and Sivakumar [15] observed that the impact strength of Al 2024/Al_2O_3 composites decreased due to brittle Al_2O_3 particles. In addition, the increase in temperature reduced the fracture energies for the composites but increased for the unreinforced samples. Ahlatci *et al* [16], researched the effect of particle size on the impact and mechanical characteristics of 60% SiC strengthened Al matrix composites and found that impact resistance and compression strength decreased as the particle size increased owing to increased particle cracking. Ekici and Kaburcuk [17], investigated how particle volume, particle size and impact velocity affect the impact behavior of Al 6061 matrix SiC reinforced composites produced through powder metallurgy. Composites were produced with Al 6061 matrix reinforced SiC particles with 10, 20, 30% volume fraction and an average size of 37, 102, 356 μm. According the study, the capacity of composites to absorb impact energy was improved by reducing particle volume fraction and growing particle size. In order to investigate the effects the reinforcement particle type on the impact behavior of metal matrix composite for different particle volume fractions and impact velocities, finite element analyses were carried out by Ekici and Kosedag [18]. The authors reported that the impact time and the peak contact force increased with increasing the impact speed. In addition, SiC particle reinforced composites usually exhibited stiffer behavior when compared to pumice particle-reinforced composites. Some researchers studied to investigate the temperature effect on the impact behavior. Bonollo *et al* [19], carried out a study about the impact behavior of Al_2O_3 particle reinforced composites in a temperature range of 25 to 200 °C. They determined decreasing in the impact strength of composites because of the brittle ceramic particles. Also, the test temperature increased impact energies, and had an insignificant effect on the failure mechanisms. Ozden *et al* [20] showed that the impact strength of Al-based SiC reinforced metal matrix composites was decreased in a temperature interval −176 to 300 °C. In contrast to temperature, micro-structural defects played the most important role in this result.

In this study, Al 6061 matrix reinforced with B_4C in four different volume fractions of 0, 5, 10 and 15% were produced by powder metallurgy method, and low-velocity impact behavior was investigated experimentally. Contact force histories, contact force-displacement, impact energy-time curves, and residual central transverse displacements were examined to determine deformation characteristics of B_4C particle reinforced metal matrix composites under the low-velocity impact loading in detail. In addition, Scanning Electron Microscopy (SEM) studies were performed before and after the impact tests for observing cross-sections of metal matrix composite structures. Microstructural characterizations of the deformation mechanisms were carried out by SEM micrographs.

2. Experimental

Al 6061 alloy was used as a matrix material for the production of composite samples while B_4C was used for reinforcement. The chemical composition of Al 6061 alloy was given in table 1 [19]. The powder sizes used for Al 6061 alloy and B_4C were almost same and approximately in size of 90–100 μm. Composites were produced by using single axis hot press with powder metallurgy method. Firstly, the matrix and reinforcement phases were mixed for 6 h with the Turbula T2F brand mixer and shaker device. Then, the powders were poured into the mold made of hot work steel and placed on the hot press. 75 MPa pressure and 630 °C temperature applied simultaneously. The hot press reached sintering temperature (630 °C) in 1 h and sintering at this temperature for 1 h. All processes were carried out in an argon shielding gas environment. Samples were produced in a diameter of 50 mm and a height of 7 mm. It was produced four type composite samples listed in detail in table 2. The low-speed impact tests were repeated with at least three samples for each parameter. At least twelve samples were tested for three volume fractions (5, 10 and 15%) as well as unreinforced samples.

Table 2. Composite sample types and contents.

Composite Sample Name	B_4C Volume fraction (%)	Al 6061 Volume fraction (%)
S-1	0	100
S-2	5	95
S-3	10	90
S-4	15	100

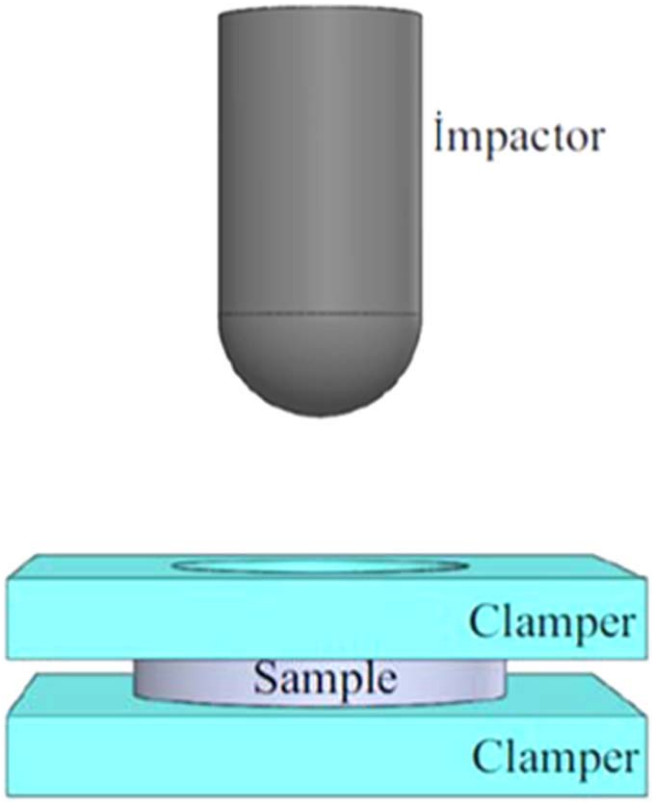

Figure 1. The schematic diagram of the impact test.

Low-velocity impact tests were performed with CEAST Fractovis Plus model impact tester. A schematic view of the impact method is shown in figure 1. A hemispherical impactor having $m = 5.045$ weight and 10 mm radius was used. The impactor velocity was set at 4.55 m/s so that the impact energy was 52.2 joule. The specimens are attached with a 40 mm diameter pneumatic stabilizer. The contact of the collision device is provided in the middle of the upper surface of the sample. Contact data during the impact event was recorded by a data acquisition system. The pneumatic rebound brake prevented the specimen from having multiple impacts. The load-time records were acquired for each experiment straight from the data acquisition system.

Energy calculations were made using $E = mgh = 0.5mv^2$ equations. Here, E, m, g, h and v are impact energy, impactor mass, gravitational acceleration, the drop height, and impactor velocity, respectively. Moreover, Scanning Electron Microscopy (SEM) was used for the microstructural observations of both deformed and undeformed specimen surfaces. Specimens were cut from the centerline, and cross-sections of specimens were hot mounted into an acrylic hot mounting resin (Bakalite) for good positioning during photographic studies. Then, standard metallography methods were applied for preparing the specimens. For this, the specimen surfaces were firstly hand-ground with SiC grinding papers up to 2500 grit and then mechanically polished with a diamond paste. Lastly, Keller solution was used to etch specimens for 35–50 s to reveal microstructures. SEM photos were taken from a ZEISS GeminiSEM 500. Figure 2 shows SEM micrographs of the metal matrix composites with B_4C particles having $V_f = 0$, 5, 10 and 15% volume fractions and a particle size of 100 μm in the Al 6061 matrix. Micrographs were taken at a magnification scale of 50× zoom (l00 μm). As shown in the figure 2, B_4C particles have a relatively good distribution in the metal matrix structure without clustering.

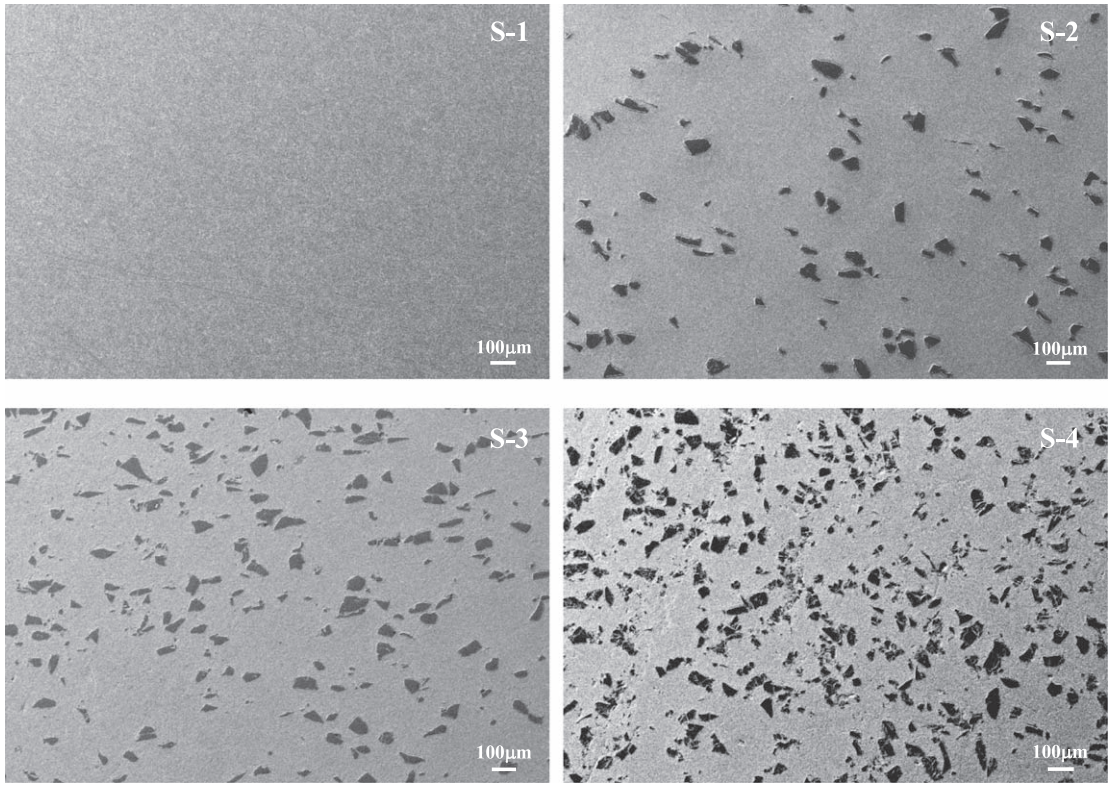

Figure 2. SEM micrographs of undeformed specimen cross-sections for $V_f = 0\%$(S-1), 5%(S-2), 10%(S-3) and 15%(S-4) volume fractions.

3. Results and discussion

The effects of different particle volume fractions ($V_f = 0$, 5, 10, and 15%) on the low-velocity impact behaviors of B_4C particle reinforced metal matrix composites were studied. Figure 3 shows the corresponding image of the composites front-back face after 4.55 m/s velocity (52.2 J) impact tests for different volume fractions. It can be clearly seen that the all composite samples are subjected to considerable plastic deformations at impact energy of 52.2 J, and some visible radial cracks are formed especially on the back surface of S-3 and S-4 samples. The sample S-2 (see table 2 for details) with B_4C reinforcing particles at $V_f = 5\%$ did not contain these cracks unlike S-3 and S-4. The front surfaces of the specimens exhibit similar behavior, whereas the cracked images on the back surfaces different. Considering the formation of cracks, it was concluded that the damage of the composite samples were from the back surface towards the front surface. In case of lower volume fraction, composites deforms more ductile. However, the increase of volume fraction caused an increase in visible radial cracks on the back surface of metal matrix composites subjected to impact load at the same speed. Thus, increasing the reinforcement volume fraction makes the metal matrix composite structure more brittle.

The specimens were placed in an epoxy mold and cut from their midpoints to prepare cross-sectional images. Figure 4 shows cross-sectional images of S-1, S-2, S-3, S-4 samples taken after impact tests. After the photographs were taken at a fixed height, the scale was added with the help of CorelDRAW Graphics [21], and the deformation amount of each sample was measured from the top surface. According to obtained results, S-1($V_f = 0$), S-2 ($V_f = 5\%$), S-3 ($V_f = 10\%$) and S-4 ($V_f = 15\%$) samples had central permanent deflections of 4.05, 3.84, 3.49 and 3.44 mm, respectively. As can be seen, the maximum deformation occurs in the unreinforced sample. Also, the permanent deflections reduce with increasing the reinforcing particle volume fraction for composites. Composite structures spend the total impact energy as elastic and plastic deformations. Metal matrix mostly increases energy absorption capability by plastic deformations, whereas elastic deformations are recovered in the composite structure. It seems that B_4C reinforcing particles reduced the ductility of the composite specimens, and composite structures behave stiffer with increasing V_f. As a result, with increasing particle volume fraction, metal matrix less deforms plastically to dissipate impact energy and reinforcing particles provide more rigidity to composite structures by increasing load bearing capacity. Meanwhile, this also makes the structure more brittle (see figure 3). Therefore, particle volume fraction affects evidently the deformation characteristics and the impact strength of particle reinforced metal matrix composites.

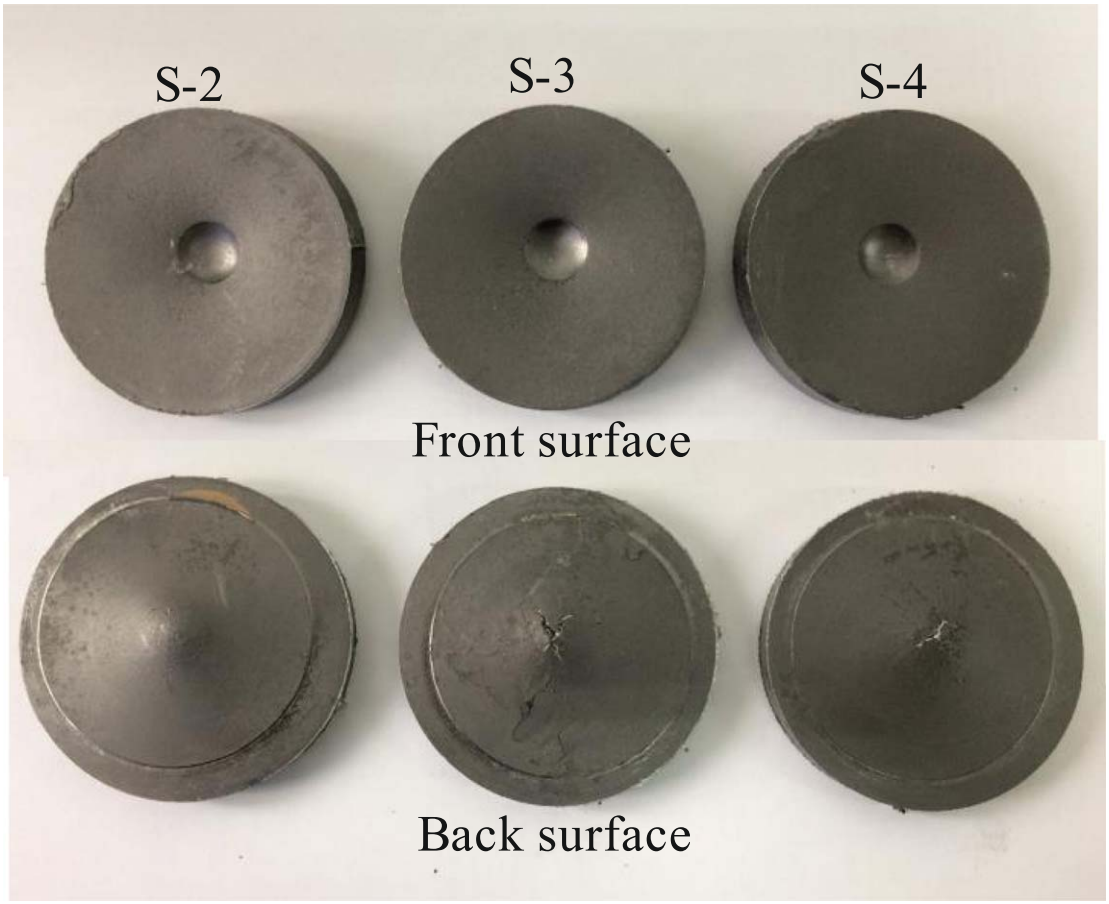

Figure 3. Front and back surface views of composite specimens after impact testing.

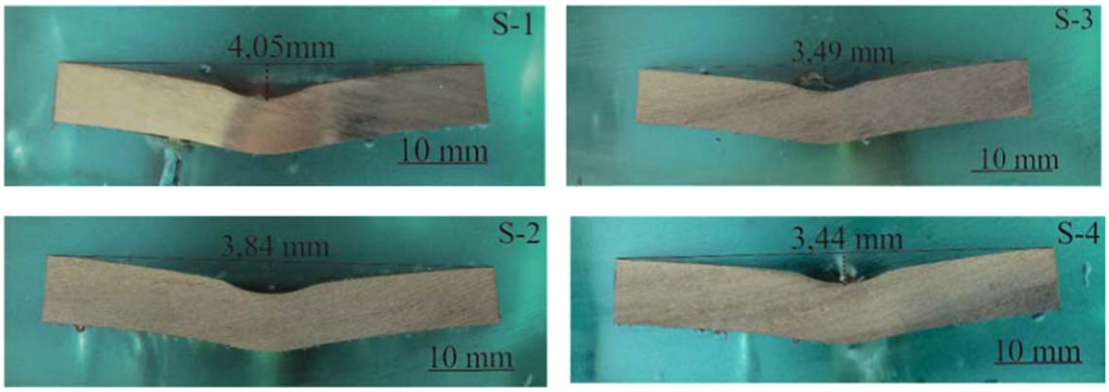

Figure 4. Cross-sectional images of S-1, S-2, S-3 and S-4 samples taken after impact tests.

Figure 5 shows the effect of particle volume fraction (V_f) on the measured contact force histories of samples. The maximum contact forces for S-1, S-2, S-3 and S-4 are 17.12, 18.10, 18.41, 19.30 KN, respectively while the contact times are found to be 3.52, 3.50, 3.46, 3.45 ms. It can be seen evidently that the sample S-4 ($V_f = 15\%$) exhibits the highest peak contact force, and the peak contact force in the sample S-4 increases 12.73% compared to the unreinforced sample S-1. Also, when compared to S-1, the peak contact forces increases 5.72 and 7.54% for S-2 and S-3 samples, respectively. However, there are very small differences in impact durations, but tend to reduce. Thus, it can be clearly observed that as the volume fraction (V_f) is increased from 0 to 15% the peak contact force increases (figure 6), whereas the impact duration almost decreases. The impact load is mainly carried by B_4C particles as the volume fraction increases, and the matrix material is experienced less plastic deformation for the same impact energy. This causes an increase in the stiffness of composites. Thus, increasing stiffness with increasing volume fraction results a notable rising at the peak contact force values and a minimal

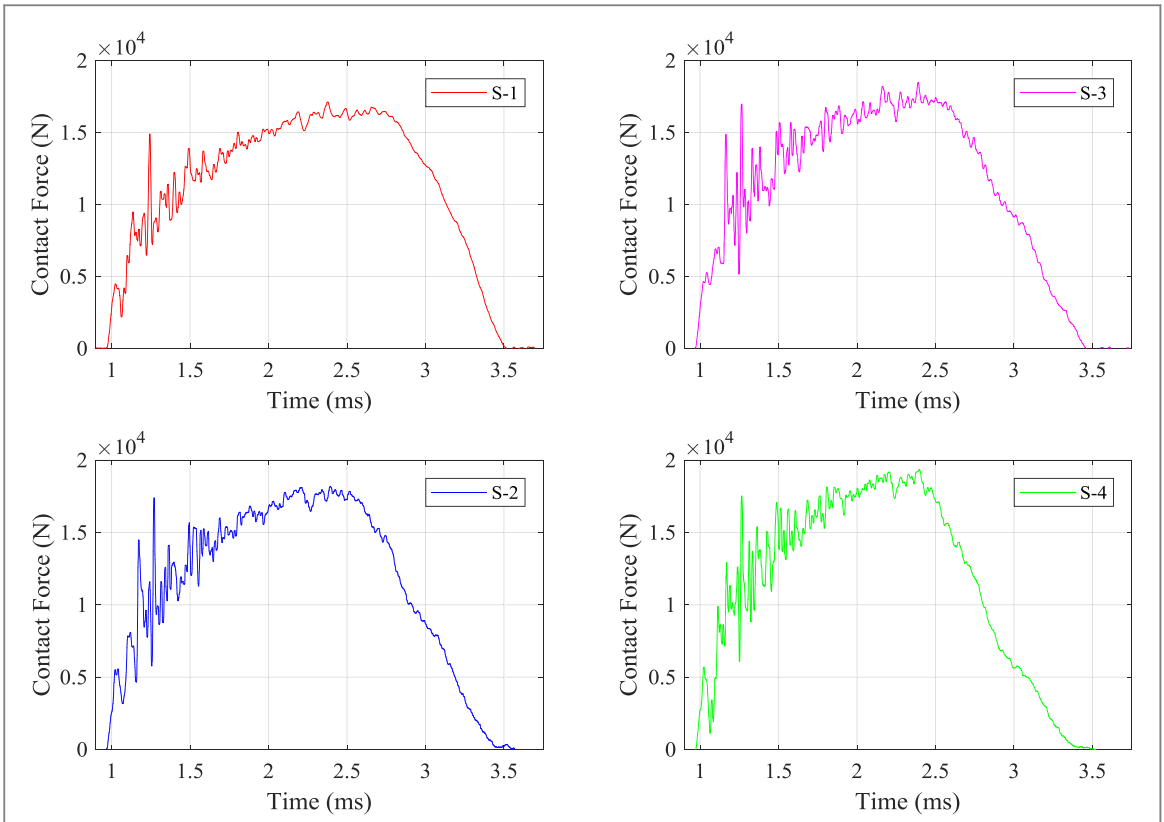

Figure 5. Contact force-time curves for different volume fractions.

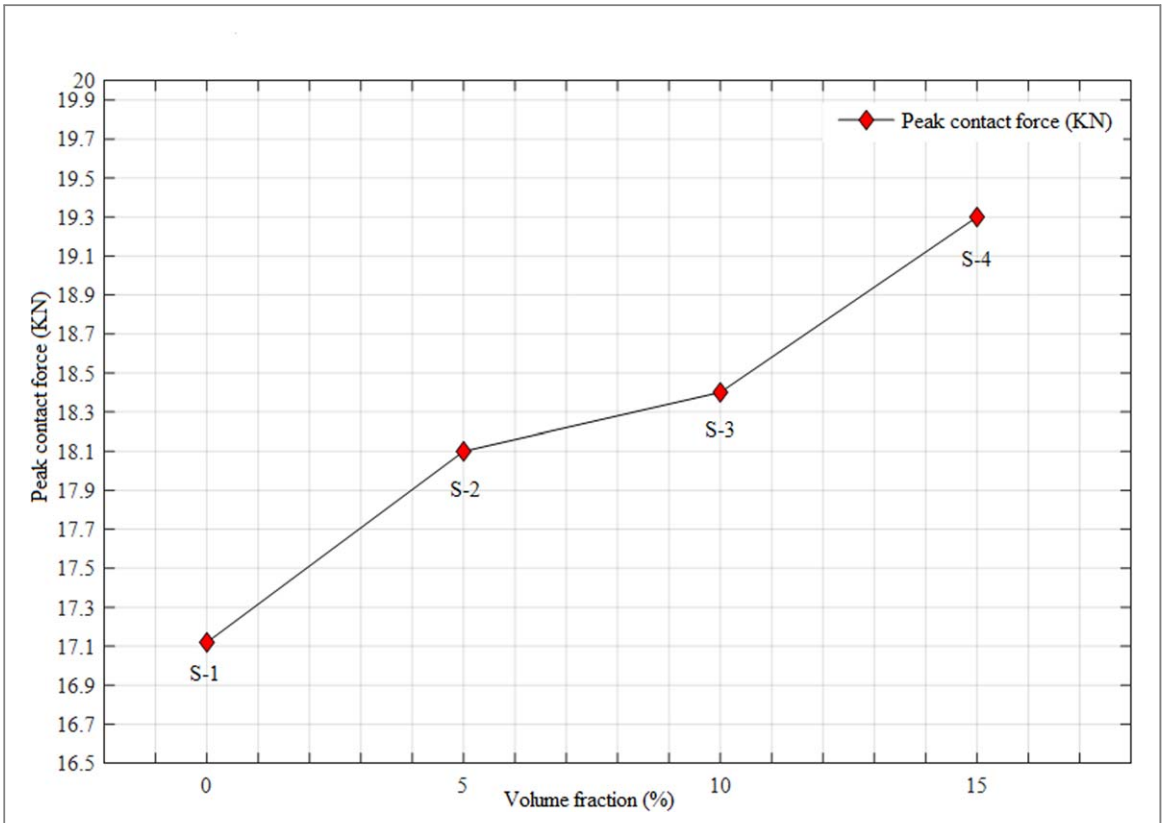

Figure 6. Variation of peak contact forces with respect to particle volume fraction (V_f).

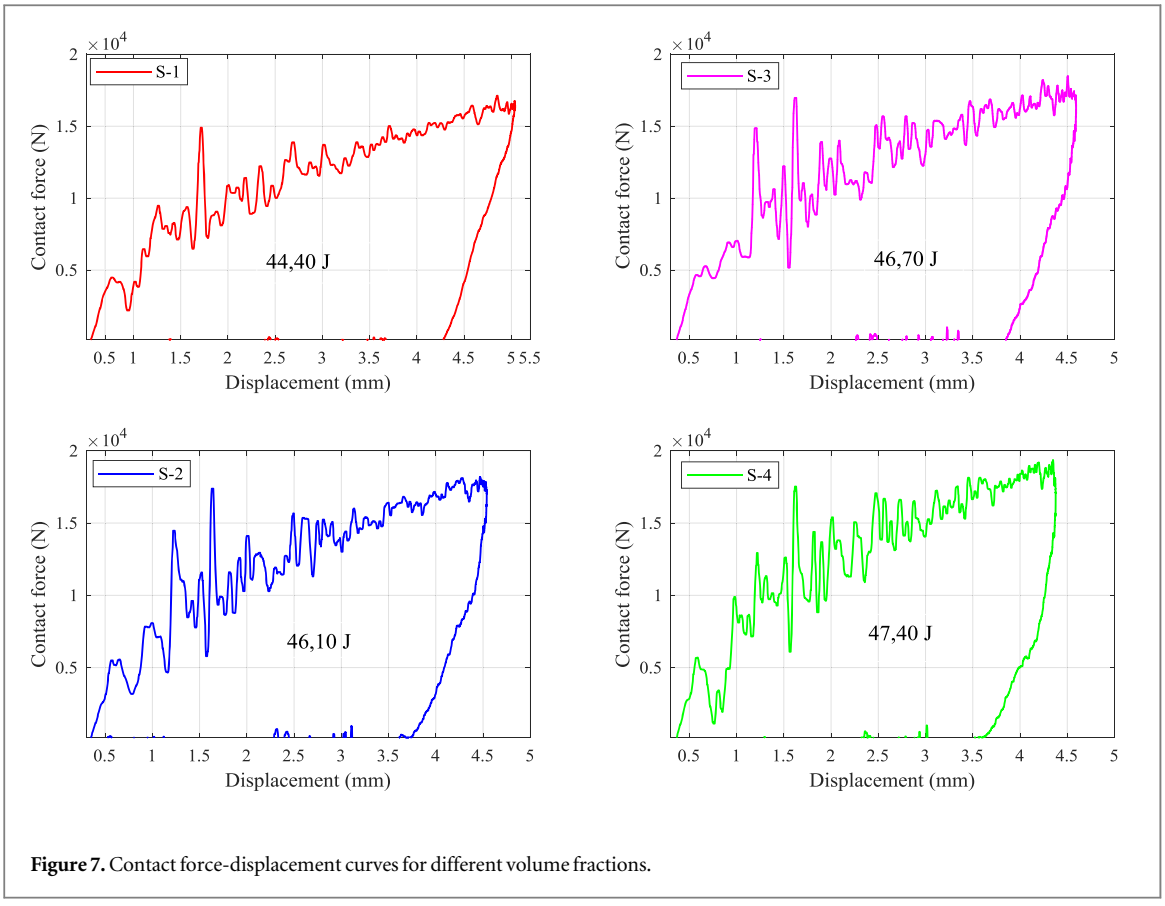

Figure 7. Contact force-displacement curves for different volume fractions.

reduction in the impact duration. This means an improvement in the impact strength of metal matrix composite structures. A similar result was reported by Ekici and Kaburcuk [17]. They observed that the impact strength of metal matrix composites improved due to rising stiffness as the particle volume fraction increased.

Figure 7 indicates the contact force-displacement variations. The contact force-displacement curves are closed for all samples, which implies that complete penetration and perforation was not observed. Also, the area under the contact force-displacement curve gives the absorbed energy. Accordingly, the contact force-displacement plots of S-1, S-2, S-3, S-4 samples were plotted and the area of the plots was calculated by integration with the help of MATLAB [22]. The results were given for variations of the contact force with respect to displacement in figure 8 and for variations of absorbed energy with respect to volume fraction (V_f) in figure 9. Absorbed energy by unreinforced sample S-1 is 44.40 J while other composite materials absorbed 46.10 (S-2), 46.70 (S-3), 47.40 (S-4) J energy when subjected to impact under the same conditions. S-1, S-2, S-3 and S-4 samples absorbed approximately 85, 88, 89 and 91% of the impact energy, respectively. Also, compared to unreinforced sample S-1, S-4 having $V_f = 15\%$ volume fraction absorbed approximately 6% more impact energy, S-4 has the highest impact absorption capacity among composite samples. This was also confirmed by the energy-time graph shown in figure 8. Here, energy absorbing capabilities can be seen very clear in detail. However, Ekici and Kaburcuk [17] reported that increasing volume fraction of metal marix composites reinforced with SiC particles showed improved stiffness with increasing contact force and reducing contact duration, but decreased energy absorption capacity. In another study, Ekici and Kosedag [18], which compared the reinforcing particle types (SiC and Pumice) of metal matrix composites at low-velocity impact conditions, reached similar results. Compared to these studies, the increased B_4C particle volume fraction in this study increased the energy absorption capacity of the metal matrix composites as well as playing the stiffness-enhancing role on the contact force history. This result is highly significant due to showing that the impact strength of metal matrix composites is improved much better by using B4C particles and also increasing volume fractions.

When the figures 5 and 7 were examined, a set of fluctuations were seen in both contact force-time and contact force-displacement curves. These fluctuations show discontinuous force responses. Metal matrix composite materials consist of powder particles and cannot react like a continuous material when exposed to external force. Many parameters such as type, durability, shape and size of powders forming metal matrix composite material during impact may cause this discontinuity. Also, fluctuations increase as the reinforcement volume fraction increases. This is mostly due to the fact that the B_4C reinforcing particles are stiffer than the Al

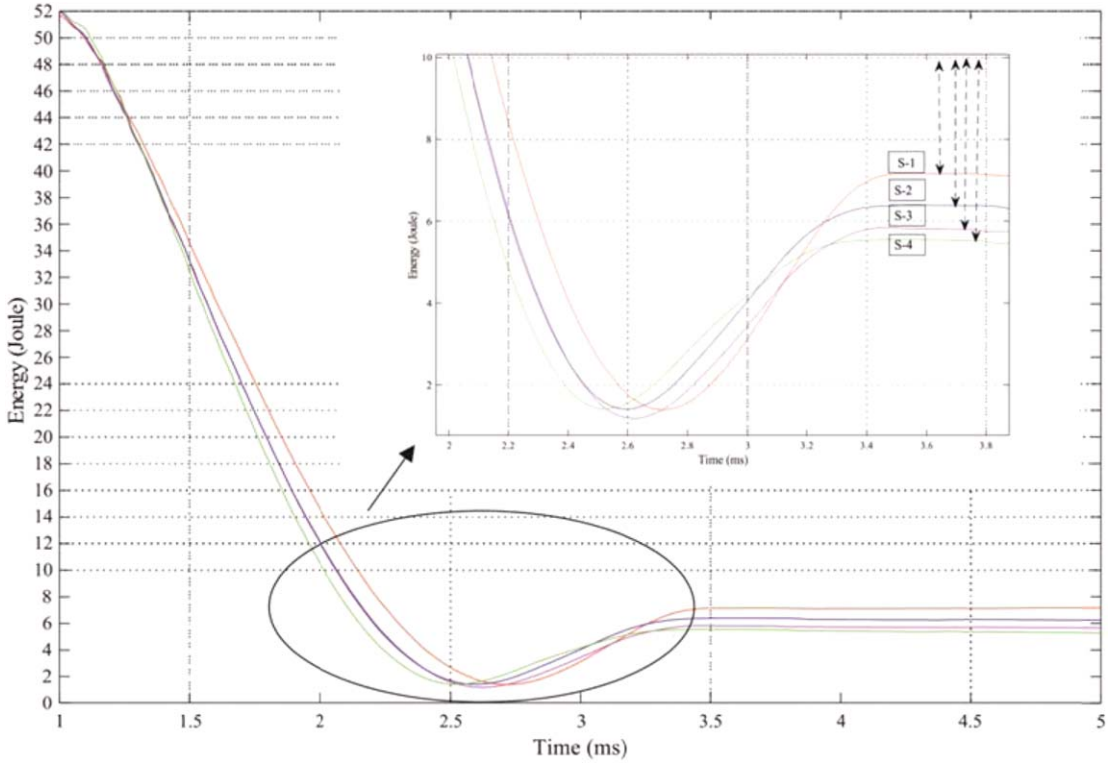

Figure 8. Energy-time curves for different volume fractions.

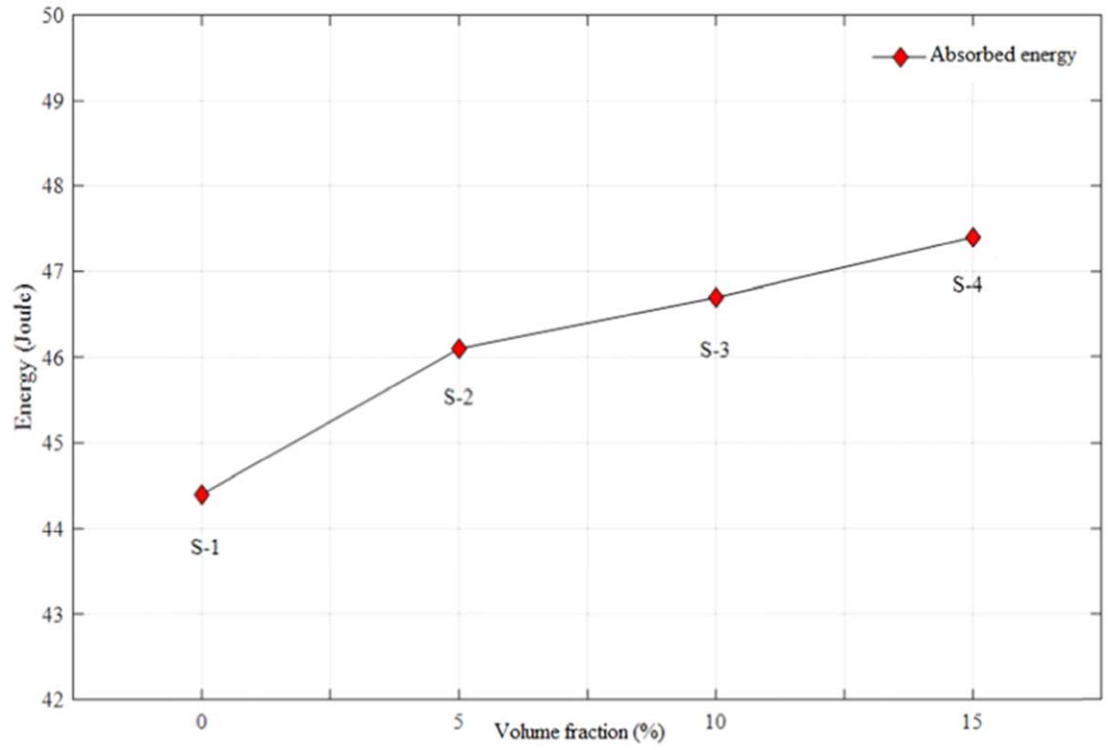

Figure 9. Variation of absorbed energy with respect to volume fraction (V_f).

6061 matrix material, and is found to be more intense as the reinforcing volume fraction increases in the composite structure. When the particle volume fraction increases, the composite structures exhibits tougher behavior. Therefore, the contact force was increased, while the impact duration slightly reduced.

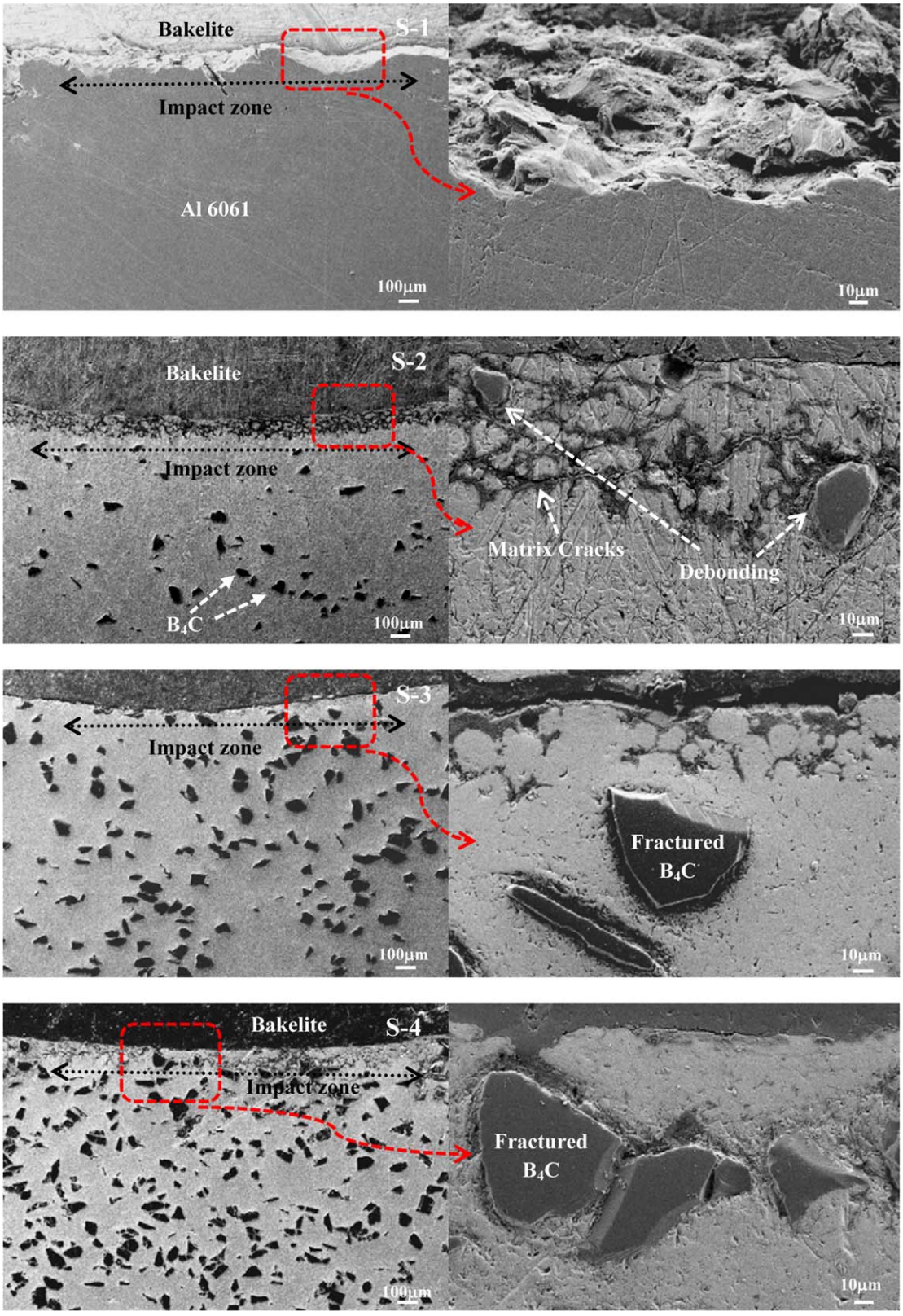

Figure 10. SEM micrographs of deformed specimen cross-sections taken underneath the impactor for $V_f = 0\%$(S-1), 5%(S-2), 10% (S-3) and 15%(S-4) volume fractions.

Figure 10 shows SEM micrographs of deformed specimen cross-sections taken underneath the impactor for $V_f = 0$, 5, 10 and 15% volume fractions after impact tests. As can be seen in figure 10, the unreinforced specimen (S-1) experienced intense plastic deformation in the absence of reinforcing particles. In case of composite specimens, for lower volume fractions, micro-cracks in matrix can be seen on the cross-sections underneath the impactor. B_4C particles cause stress concentrations in the impact region due to their higher stiffness and

irregular shape. The matrix-reinforcement interface easily weakens under impact loading and can be resulted debonding. This accelerates particle cracking and void nucleation in the surrounding matrix and hence, facilitates linkage between neighboring voids and microscopic cracks. Therefore, it results the formation of continuous micro-cracks in the matrix underneath the impactor. This mechanism is in confirmation with the literature where it is reported that fundamental failures under the dynamic loading for particle-reinforced metal matrix composites [19, 20]. The reinforcing particles play a more effective role than the matrix by carrying more load with increasing volume fraction. Matrix microcracks and debonding appears to be the dominant failure type in the microstructure under the impact for lower volume fractions. However, particle cracking and fracture can be observed mostly with increasing volume fraction.

4. Conclusions

A drop-weight impact test procedure was used to investigate the low-velocity impact behavior on the B_4C reinforced Al 6061 matrix composites. For this purpose, metal matrix composites with different particle volume fraction were produced by powder metallurgy and subjected to the low-velocity impact tests. As the particle volume fraction increases, the energy absorbing capability of B_4C/Al 6061 composites samples improves. Volume fraction significantly affected the impact behavior of B_4C/Al 6061 composites. The impact energy absorbed by metal matrix composites for highest volume fraction ($V_f = 15\%$) is more than 6% according to unreinforced sample ($V_f = 0$). This is a distinctive result in this study for B_4C particulate reinforced composites. All samples experienced intensive plastic deformations. Radial crack formation observed on the back surface of composite samples with increasing volume fraction, as well. The peak contact forces appeared in the metal matrix composites having the highest B_4C volume fraction, and the contact durations almost decreased with increasing volume fraction. The maximum permanent deflection occurred in the unreinforced sample, but the maximum peak contact force appeared in metal matrix composites having highest volume fraction ($V_f = 15\%$). From SEM examinations, matrix microcracks and debonding were the dominant failure type for lower volume fractions whereas particle cracking and fracture can be observed mostly with increasing volume fraction. According to these results, B_4C/Al 6061 metal matrix composites having 15% volume fraction showed the best impact performance in the volume fraction limit range used in the study. It is foreseen that the particle volume fraction of composite samples can be increased to over 15%, but composites can be more brittle by increasing the volume fraction. This means that the stiffness of composites is to be reduced too much after a point. Therefore, the determination of the upper limit of volume fraction will be valuable to continue research for the best low-velocity impact performance.

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