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COMPARISON OF THE LOW-VELOCITY IMPACT BEHAVIORS OF SIC AND PUMICE PARTICLE-REINFORCED METAL MATRIX COMPOSITES

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Abstract— This study investigates the reinforcement effect of particle-reinforced metal matrix composites on the low-velocity impact behaviors. Ceramic SiC (Silicon Carbide) and Pumice (a volcanic lava rock) were used for the reinforcing particles. Finite Element Method (FEM) was used to model and perform the low-velocity impact analyses of SiC and pumice particle-reinforced aluminum 6061 matrix composites. Reinforcing particles were distributed randomly in metal matrix. The numerical impact tests were carried out for three different particle volume fractions (10, 20 and 30%) of reinforcements at the same particle size (250 μm) under 1 and 3 m/s impact velocities. The effects of the particle type on the impact behavior were explained by comparing the contact force histories, the residual stress and plastic strain distributions, and the transverse deflections, according to the particle volume fraction and the impact velocity. Generally, SiC particle-reinforced PRMMCs usually exhibit stiffer behavior when compared to pumice particle-reinforced PRMMCs. Particle reinforcements affect the equivalent residual stress and plastic strain distributions. SiC reinforcing particles make the metal matrix composite stiffer and reduces the transverse deflections whereas pumice reinforced metal matrix composites behave more ductile. When the volume fraction (V_f) is increased, the peak contact force increases whereas the impact time decreases.

Index Terms—Finite element analysis, drop-weight test, low-velocity impact, particle-reinforced metal matrix composite.

I. INTRODUCTION

In recent years, researchers have significantly focused on metal matrix composites (MMCs) reinforced with hard particles. The most important reasons for this are improved mechanical and physical properties of these materials on conventional monolithic materials such as higher wear resistance, specific modulus, hardness, fatigue resistance and weight saving, as well as lower thermal expansion and higher thermal conductivity coefficient. In comparison with their continuous fiber reinforced counterparts, particle reinforced metal matrix composites (PRMMCs) are more attractive due to their isotropic properties, cost savings and their capability to be processed using conventional metal manufacturing processes [1–7]. However, the mechanical properties of PRMMCs are affected by some micro-structural parameters such as reinforcement particle distribution, size and volume fraction. With rapid development of technology, computational modeling efforts for researching the effects of these parameters have gained more importance. A large amount of work has been conducted in an effort to characterize the mechanical behavior of PRMMCs with various modeling approaches. Furthermore, the low-velocity impact behavior of PRMMCs has not been adequately investigated.

PRMMCs can be subjected to static and dynamic loading conditions during their service life. Unlike static loading, mechanical behavior of these materials can be quite different during dynamic loading [8]. The impact is a sudden dynamic loading and can cause damage in structures because it does not have enough time to respond in many times. Therefore, the response to the impact loading is an important design parameter for using PRMMCs reliably in operating conditions [9-11].

Aluminum MMCs are used in important advanced technology fields such as aircraft, aviation, automobile. Silicon Carbide (SiC) is one of the most popular reinforcing materials for aluminum matrix due to its good compatibility [12]. Also, it has high modulus, strengths and excellent thermal resistance. However, Pumice is a type of porous volcanic lava rock and it is composed of significant amount of silicate oxides and smaller amount of alumina (Al_2O_3) and other metallic oxides. Due to the high porous structure of pumice, it has low density, excellent thermal isolation properties, and good temperature and chemical resistance properties. Because of these reasons and low cost, it has become a desirable reinforcing material in industrial applications [13].

Turkey has important pumice reserves and is located in the fifth place in the world in terms of pumice production [14]. Hence, it is very important to investigate the effects of usage the pumice for metal matrix composites as reinforcing particles. The literature survey indicates that the studies about the pumice-reinforced metal-matrix composites are at the beginning stage [15].

This study aims to investigate the reinforcement effect on the impact behaviors of PRMMCs. For this purpose, the numerical modeling and analyses were carried out by Finite Element Method (FEM) to compare the low-velocity impact behaviors of SiC and pumice particle-reinforced Al matrix composites. The reinforcing particles (SiC and pumice) were randomly distributed in 3D metal matrix structure in accordance with the actual particulate composite structure. In

order to show the reinforcing performance under dynamic loading, the results were compared according to the particle volume fraction and the impact velocity.

II. FINITE ELEMENT METHOD

The non-linear FEM was used for numerical modeling and impact analyses of SiC and pumice particle-reinforced Al 6061 metal matrix composites. Analyses were performed by ABAQUS/Explicit [16] finite element software. Figure 1 shows the FEM model of the impactor and a PRMMC specimen clamped with top and bottom cylindrical fixtures. The geometry of the PRMMCs was a rectangular prism with dimensions of 50x50x5 mm whereas the impactor with semi-spherical tip was a diameter of 20 mm and 5.045 kg mass. PRMMC models were clamped from top and bottom with the cylindrical fixtures in 40 mm inner and 50 mm outer diameter. However, the top and bottom surfaces of the composite structure were free. The impact velocity and mass were assigned at a reference point on the center of impactor (see Fig.1). PRMMCs were modeled with eight-noded brick element (C3D8R) with reduced integration in a size of 250 μm for three basic dimensions. Also, the impactor was also modeled with four-node R3D4 rigid shell elements. Therefore, PRMMC model was meshed with 800.000 finite elements, and the impactor was meshed with 1152 un-deformable finite elements. Each of the cylindrical fixtures was modeled with 200 rigid shell elements (R3D4).

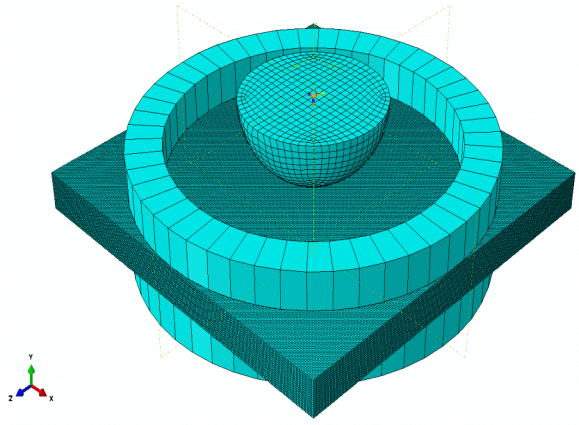


Figure 1. FEM model of the impactor and a PRMMC specimen clamped with top and bottom cylindrical fixtures.

The PRMMC composite material was modeled with a random distribution of cubic ceramic SiC particles embedded within an Al 6061 alloy metal matrix for achieving a real PRMMC structure (Fig. 2). The mechanical properties of Al 6061 alloy, pumice and ceramic SiC can be seen in Table 1. Numerical low-velocity impact analyses on FEM specimens were carried out for three different particle volume fractions (V_f = 10, 20 and 30%) and two different impact velocities (V = 1 and 3 m/s). Al 6061 matrix was assumed as an elastoplastic material, whereas SiC and pumice particles were behaved elastic, and any failure of constituents was not considered.

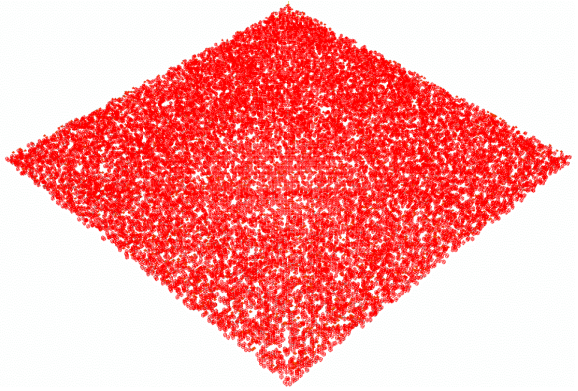


Figure 2. The random particle distribution in a metal matrix specimen for particle volume fraction of V_f = 10% .

Table 1. Mechanical properties of Al 6061, SiC and pumice.

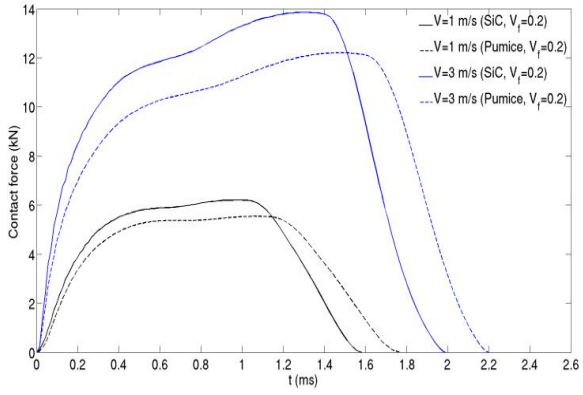
Property	Al 6061[17]	SiC[17]	Pumice[18]
Modulus of Elasticity (E), (GPa)	70	420	115
Poisson's ratio (υ)	0.33	0.17	0.22
Density (ρ), (kg/m^3)	2700	3100	2400

According to a developed algorithm in python programming language for the random particle arrangement, the volume fraction of reinforcing particles in the composite structure is adjusted as a percentage of total finite element number (800.000). Thus, a volume fraction of 10% for particles corresponds to 80.000 finite elements representing the reinforcing particles. These 80.000 elements are assigned randomly as SiC particles among the total finite elements in the meshed region. So, the reinforcing particle elements randomly changes for each new analysis.

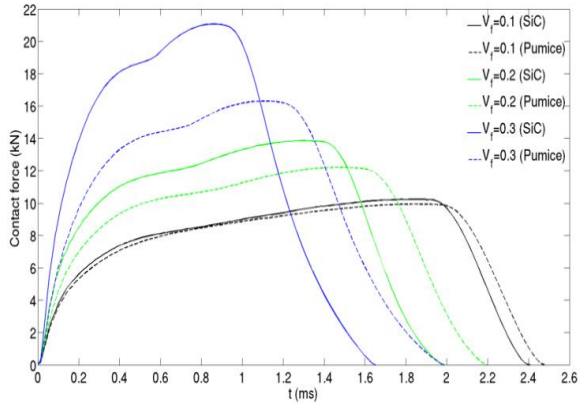
III. NUMERICAL RESULTS

The low-velocity impact analyses of both SiC and pumice particle-reinforced PRMMCs were carried out for volume fractions of V_f= 10, 20 and 30% and impact velocities of V = 1 and 3 m/s. Fig. 3 (a) and (b) present the contact force histories of PRMMCs testedto show the effects of the impact velocity (for the constant V_f = 20%) and the particle volume fraction (for the constant V = 3 m/s), respectively. It can be seen easily that both the impact time and the peak contact force increase with increasing the impact velocity for all PRMMCs. PRMMCs exhibit a highly ductile behavior due to Al 6061 matrix and can absorb more impact energy since the contact time and contact force increase with increasing the impact velocity. Hence, PRMMCs experience more plastic deformation with the increasing impact velocity. However, SiC particle-reinforced PRMMCs usually exhibit stiffer behavior when compared to pumice particle-reinforced PRMMCs. Volume fraction also

affects the contact force histories. Contact force histories reveal that increasing SiC and pumice particle volume fraction increases the peak contact force but decreases the contact time. The most important reason of this behavior is the reduction of the ductility of PRMMCs by the increasing particle volume fraction. The differences between the contact forces and durations of the SiC and pumice particle-reinforced composites are increased with the volume fraction increment, although it is not obvious at low volume fractions. With the increasing of the volume fraction, SiC particle-reinforced PRMMCs exhibit significantly more rigid behavior compared to pumice particle-reinforced PRMMCs.



a) V_f = 0.2



b) V = 3 m/s

Figure 3. The contact force histories of SiC and pumice particle-reinforced PRMMCs for a) the particle volume fraction V_f =0.2 and b) the impact velocity V= 3 m/s.

The residual equivalent (Mises) stress distributions through the cross-sections of SiC and pumice reinforced quarter PRMMCs can be seen in Fig. 4. The effect of impact velocity on the residual equivalent stress is given in Fig. 4 (a) and (b), while the effect of reinforcing particle volume fraction can be seen in Fig. 4 (b) and (c). The elastic ceramic particles in metal matrix were removed to show the pure residual stress distributions. SiC and pumice reinforced PRMMCs exhibit similar residual stress distributions. As the impact velocity increases for constant particle volume fraction(V_f =10%), the maximum residual stress through the cross-section underneath the impactor changes considerably more intensive due to increasing permanent deformation. The reinforcing particles in the metal matrix highly influence the equivalent residual stress distributions and cause the distribution to be heterogeneous. It can be seen in Fig. 4 (b) and (c) that the particle volume fraction considerably affects the maximum residual stress distribution. As the particle volume fraction increases, the composite structure behaves stiffer and the maximum stress distributions increase in the impacted region for both particles reinforced composites.

Fig. 5 (a) and (b) shows the residual equivalent plastic strain (PEEQ) distributions through the cross-sections of V_f= 10% SiC and pumice particle reinforced quarter PRMMCs for the impact velocities V = 1 and 3 m/s, respectively. Increased the impact velocity leads to increase plastic deformation since composites have to absorb more impact energy. In addition, the effect of particle volume fraction on the residual plastic strain can be seen in Fig. 5 (b) and (c) for the constant impact velocity (V = 3 m/s). The residual plastic strain distributions are also similar for both SiC and pumice reinforced PRMMCs. The particle volume fraction affects the plastic strain distributions and levels. The thin transverse strain bands disperse laterally and the level of plastic strain increases as the volume fraction increases.Moreover,after the impact completes, the metal matrix is exposed to additional elastic loads by the ceramic particles during unloading, and this maximizes the residual strain levels.The stiffness of composite structure is lower and the impact load is carried mostly by metal matrix for lower volume fractions. Thus, the metal matrix undergoes higher plastic deformations and absorbs more impact energy. But, increasing the volume fraction of particles increases the stiffness, and the impact load is carried mostly by elastic SiC and pumice particles and the metal matrix absorbs lower impact energy. Therefore, the impactor bounces back more quickly from the impact surface and the contact duration reduces.

Fig. 6 (a) shows the central transverse displacements along the top surface diameters of the PRMMCsamples for the impact velocities V = 1 and3 m/s. With the increasing impact velocity, the PRMMC structures undergo more residual deformation to be able to absorb more impact energy. Thus, the central transverse deflection of composite structure as well as the impact time and the contact force increases when the impact velocity increases. Fig. 6 (b) reveals the effect of the volume fraction on the central transverse displacements.It can be clearly seen from Fig. 6 (b) that PRMMC structures behave stiffer and the central transverse deflection reduces when the particle volume fraction is increased. Thus, the capacity of the impact energy absorption of PRMMC structures decrease and the impact strength increases.However, pumice particle-reinforced PRMMCs generally exhibit a more ductile behavior than SiC particle-reinforced PRMMCs.This behavior is made more apparent with increasing the particle volume

fraction. Therefore, it can be concluded that the impact behaviors of PRMMCs are highly affected by reinforcing particle type as well as the particle volume fraction and the impact velocity.

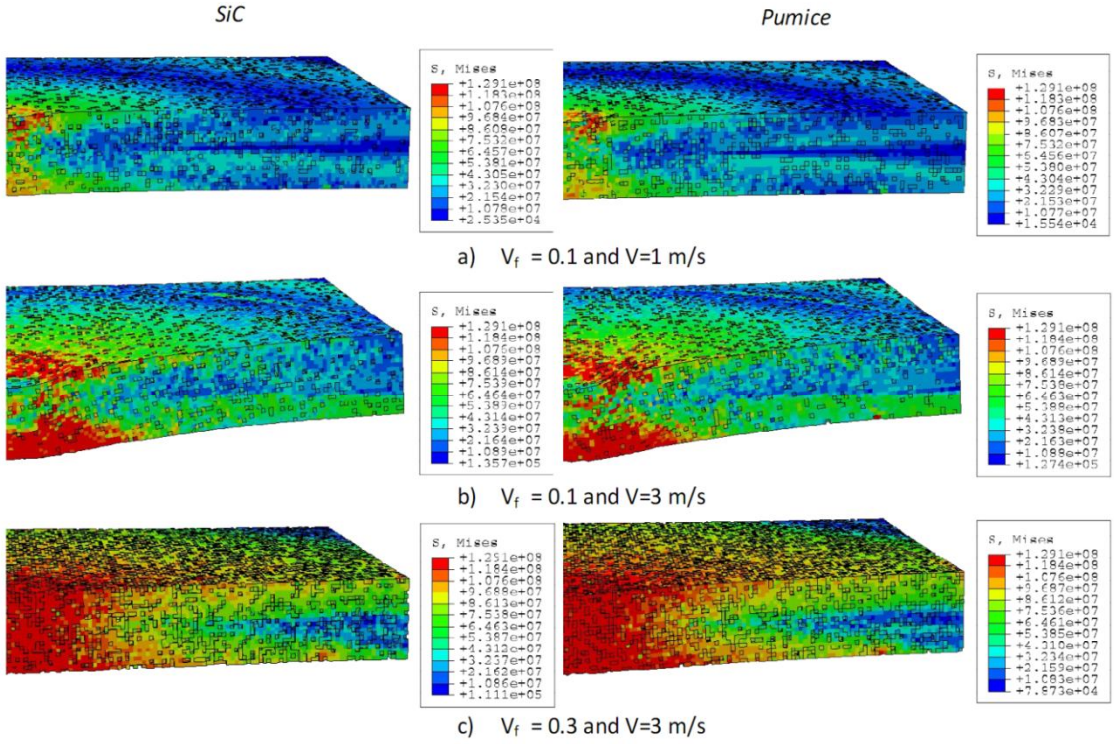


Figure 4. The residual equivalent (Mises) stress distributions through the cross-section of quarter PRMMC specimens for (a) V_f = 10% and V=1 m/s, (b) V_f = 10% and V=3 m/s and (c) V_f = 30% and V=3 m/s.

Figure 4. The residual equivalent (Mises) stress distributions through the cross-section of quarter PRMMC specimens for (a) V_f = 10% and V=1 m/s, (b) V_f = 10% and V=3 m/s and (c) V_f = 30% and V=3 m/s.

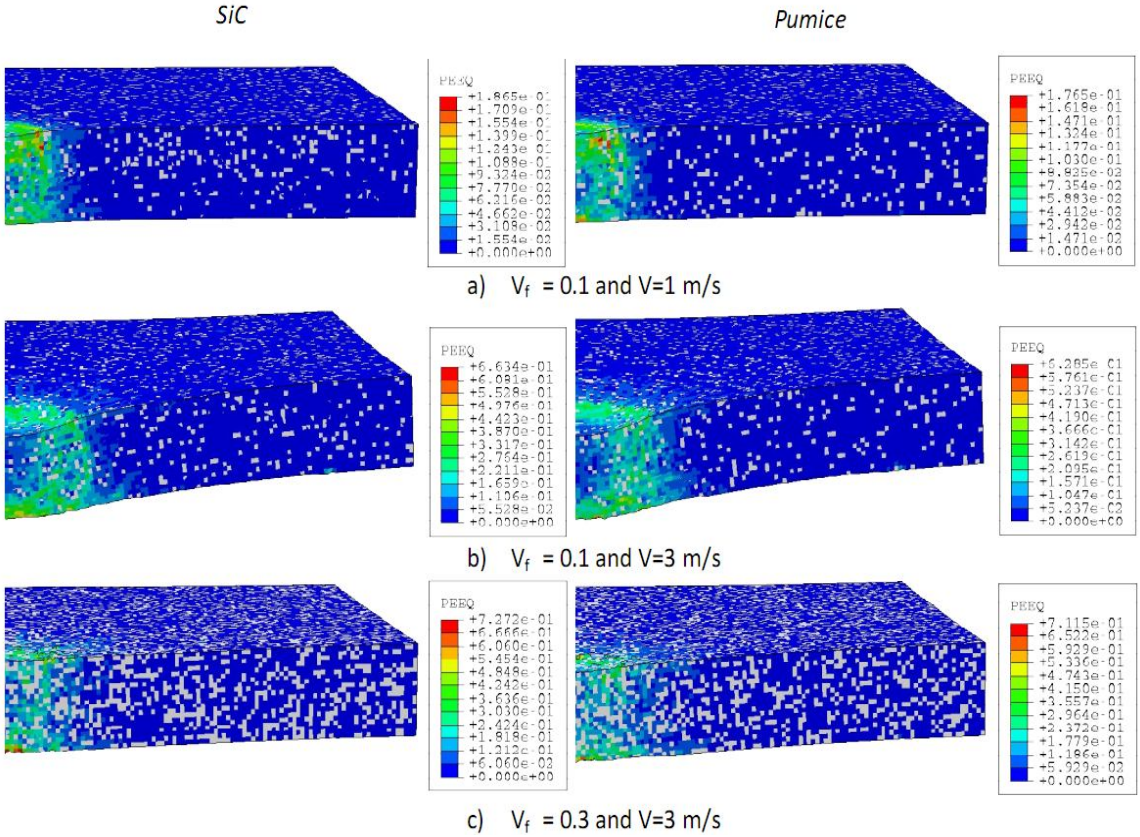
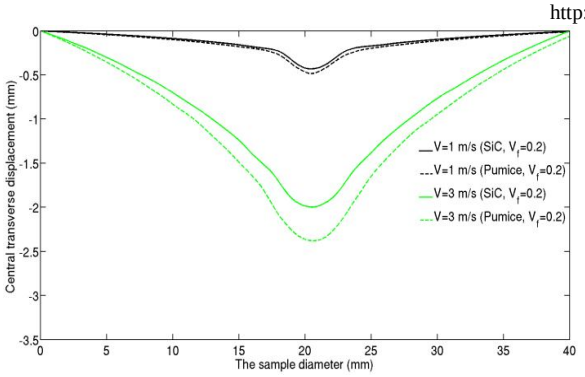
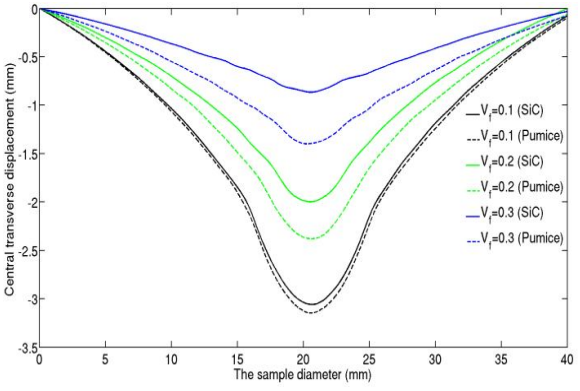


Figure 5. The residual equivalent plastic strain (PEEQ) distributions through the cross-section of quarter PRMMC specimens for (a) V_f = 10% and V=1 m/s, (b) V_f = 10% and V=3 m/s and (c) V_f = 30% and V=3 m/s.



a)



b)

Figure 6. The residual central transverse displacements along the sample diameter of PRMMCs in the impacted surfaces for (a) the impact velocities V = 1 and 3 m/s (V_f = 20%), and (b) the particle volume fractions V_f = 10, 20 and 30% (V = 3 m/s).

CONCLUSION

In this study, finite element analyses were carried out to search the effects the reinforcement particle type on the impact behavior of PRMMCs for different particle volume fractions and impact velocities. The impact time and the peak contact force increase with increasing the impact velocity. The peak contact force increasesbutthe contact timedecreases increasing both SiC and pumice particle volume fraction increase since the ductility reduces by increasing the particle volume fraction. Generally, SiC particle-reinforced PRMMCs usually exhibit stiffer behavior when compared to pumice particle-reinforced PRMMCs.SiC and pumice reinforced PRMMCs exhibit similar equivalent residual stress and plastic strain distributions, and reinforcing particles cause the distributions to be heterogeneous. While the impact velocity increases, the maximum residual stress through the cross-section changes considerably more intensive due to increasing permanent deformation. However, as the particle volume fraction increases, the maximum residual stress and strain distributions as well as the equivalent residual strain levels increase in the impacted region for both particles reinforced composites due to unloading effect of elastic reinforcing particles on the metal matrix. The residual central transverse deflections increase when the impact velocity increases and decrease with the increasing particle volume fraction.

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