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Microstructure and Mechanical Properties of Spray Deposition Al/SiC$_p$ Composite After Hot Extrusion

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Investigations of composite based on a spray deposition Al-Zn-Mg-Cu alloy reinforced with SiC particles with the volume fraction of 15% and various extrusion ratios of 11-39 are presented. Bars with a diameter of 8-15 mm were obtained as the end product. Based on the microstructural examinations of the composite, we can find that SiC particles adhered mainly to the surface of the alloy droplets during deposition, leading to more SiC particles at the surface of the droplets and less in the inner. Thus, the distribution of SiC particles in the billet was characteristic of the layered feature. This layered feature of SiC particles was not completely removed by the following hot extrusion. The SiC particles were distributed like the streamline in the longitudinal direction. A higher extrusion ratio resulted in an more uniform distribution of SiC particles. Ambient tensile tests made it possible to demonstrate that the mechanical properties improve with the increasing of extrusion ratio. The ultimate tensile strength and elongation achieve 475 MPa and 16.5% at an extrusion ratio of 39.

Keywords composite, hot extrusion, mechanical properties, microstructure, SiC, spray deposition

1. Introduction

Particulate-reinforced metal-matrix composite (MMC) has received an increasing interest in the last few years, for they offer higher stiffness and strength (Ref 1). The MMC can be reinforced with particles, dispersoids, or fibers. However, one of the biggest interest in composite materials is observed for those reinforced with hard ceramic particles due to the possibility of controlling their mechanical properties by selection of the volume fractions, size, and distribution of the reinforcing particles in the matrix.

Aluminum-based composite materials are leading ones in this area, they are fabricated using many methods, including powder metallurgy processes, and then formed, e.g., by hot extrusion. Powder metallurgy makes materials properties relatively easy to control by mixing materials with different properties in various proportions. They are used more often, compared with the composite materials of other metals, due to the broad range of their properties and also due to the possibility of replacing the costly and heavy elements made from the traditionally used materials (Ref 2-5).

Deformation behavior at extrusion temperature is dependent on many metallurgical and technological factors, for example, temperature, flow rate, and extrusion ratio (Ref 6). The advantage of extrusion process is possibility of making extruded products with high-dimensional accuracy. Using the extrusion process, it is possible to fabricate products with different geometries like solid and hollow profiles, with a fixed or varying transverse section. There are also some shortcomings of the extrusion process, and thus shortcomings of the extruded products, which are characteristic of the significant variations of their properties along their axis, and especially in their transverse section, which are connected with the various degree of deformation during the extrusion process. Fabrication of the composite materials is focused on obtaining materials with improved properties compared to the matrix material.

The goal of the work is to investigate the microstructure evolution and ambient mechanical properties of the composite of spray deposition Al-Zn-Mg-Cu alloy reinforced with the SiC particles with the volume fraction of 15% and various extrusion ratios.

2. Experimental Material and Procedures

The chemical composition of matrix alloy is Al-11.5%Zn-3.6%Mg-1.8%Cu-0.15%Ni-0.3%Zr, and was reinforced with 10 μm α-SiC particles at a volume fraction of 15%. The composite is produced using a multilayer spray deposition technique, and Fig. 1 is the principle of it. The composite preform was first chipped into a billet of Ø48 mm in diameter and about 50 mm in length, then hot extruded to bars of Ø8 mm, Ø10 mm, Ø12 mm, and Ø15 mm in diameter, respectively, correspondingly, the extrusion ratio (λ) is 39, 25, 17, and 11, respectively, and the extruded temperature is 450 °C.

After hot extrusion, the samples were cut along the longitudinal sections in respect to the extrusion direction to investigate the evolution of microstructures and mechanical properties without any heat treatments. The distribution and morphologies of SiC particles in aluminum matrix during hot extrusion were examined using a MM-6 optical microscope. To test the mechanical properties of the Al/SiC$_p$ composite, specimens with a diameter of 5 mm and a gage length of 25 mm were tested in an Instron universal tensile testing unit and the tension experiments are conducted parallel to the

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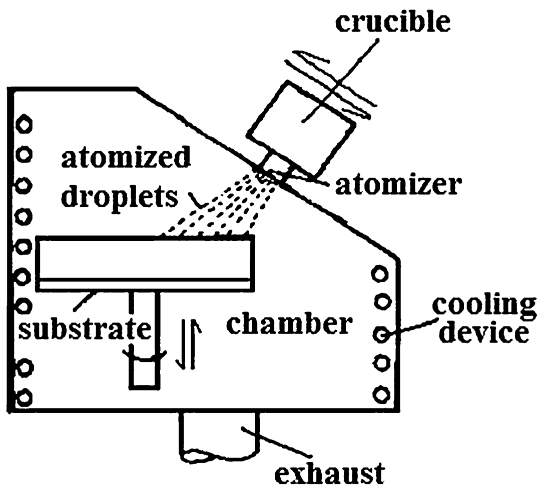

Fig. 1 Principle of multilayer spray deposition

extrusion direction. The cross head speed was set to be 2 mm/min. The fractures of the samples were examined with JSM-6700F SEM.

3. Results and Discussion

3.1 Distribution of SiC in As-Deposited Al/SiC$_p$ Composite

The microstructure of the as-deposited preform is shown in Fig. 2. There are many pores with various size and shape, which was caused by the entrapped gas, solidification shrinkage, and internal pores during spray deposition processing (Ref 7, 8). During being captured, only a few SiC particles can enter into the inner of the droplet of aluminum alloy, while most of SiC particles distribute on the face of droplet. We can see that SiC particles distributing irregularly in the spray deposited alloy matrix.

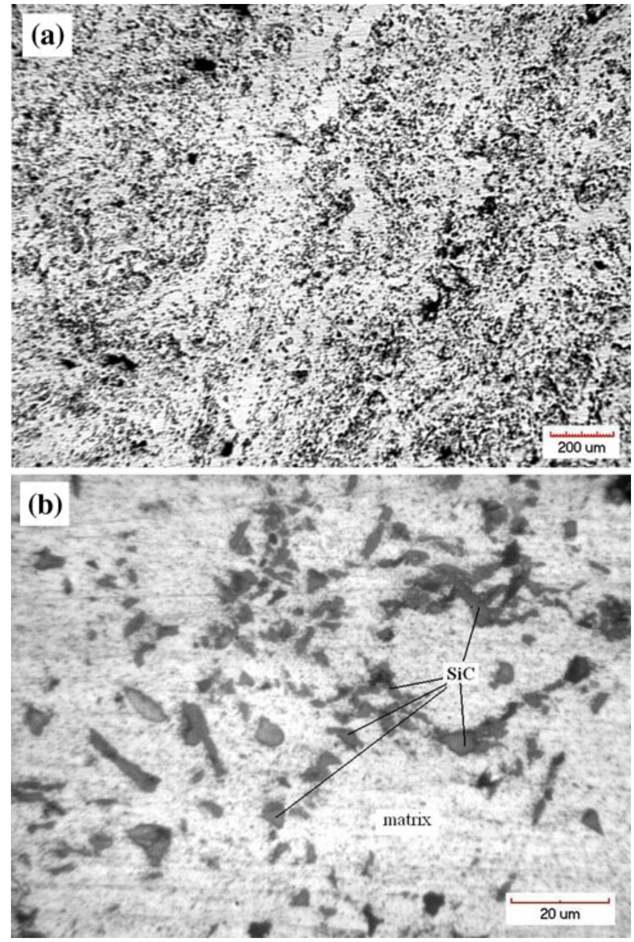

Fig. 2 Microstructure of as-deposited Al/SiC$_p$ composite

3.2 Distribution of SiC in As-Extruded Al/SiC$_p$ Composite

Figure 3(a), (b), and (c) illustrates the distribution feature of SiC particles in the extrusion bars along the axial direction, and the extrusion ratios are 11, 17, and 25, respectively. We can see from these figures that there are many dark bands and bright belts, which is caused by the un-uniformly distribution of SiC particles in the composite, parallel to the extrusion direction, and there are more SiC particles within the dark bands and less in the bright belts. With the increasing of extrusion ratio, the boundaries between bright and dark bands gradually become diluted and the distribution of SiC particles demonstrates more and more uniformly.

3.3 Moving Law of SiC Particles During Hot Extrusion

To analyze and summarize the moving law of SiC particles in as-deposited Al/SiC$_p$ composite during hot extrusion, we investigated the distribution of SiC in residual region of the preform, as shown in Fig. 4. The extrusion ratio of Fig. 4(a) and (b) is 11 and 25, respectively. As can be seen that it has shown a marked layered feature in the residual region. There are more SiC particles in zone a than zone b. Figure 4(c) and (d) shows the microstructures of zone c and zone d in Fig. 4(b), from which we can see that its distribution is oriented, and the long axis of all SiC particles is parallel to the direction of streamline.

On the basis of the above results, we can summarize that the appearance of layered feature of SiC particles within extruded bars is due to the formation of streamline distribution of SiC at the filling stage of extrusion. Figure 5(a) shows the macrophotograph of the composite along axial profile, in which region L (Fig. 5b), M (Fig. 5c), and N (Fig. 5d) represent the compressing zone, extruding region, and the extruded region. From Fig. 5(b), (c), and (d), we can see that the long axis of all SiC particles is in the same direction with streamline, while the direction of long axis of SiC begins to change gradually and be parallel to extruding direction in region N.

The movement and rotation of SiC particles are determined by the plastic deformation of aluminum alloy. Figure 6 shows the model of stress during hot extrusion, and we can see that it belongs to three-axial compression stress (Ref 9), while the radial compressive stress are much larger than the axial ones. SiC particles would move along with the deformation of the matrix during hot extrusion.

Cao et al. (Ref 10) has investigated the rotation of SiC particles in Al/SiC$_p$ composite during tensile behavior. The results show that a certain torque will act on SiC particles thus result in the rotation of SiC particles. He gives two equations about rotation during elastic and plastic deformation stage, respectively, as shown in the following:

$$\varepsilon = \sigma \sin(2\alpha)/4G \quad \text{(Eq 1)}$$

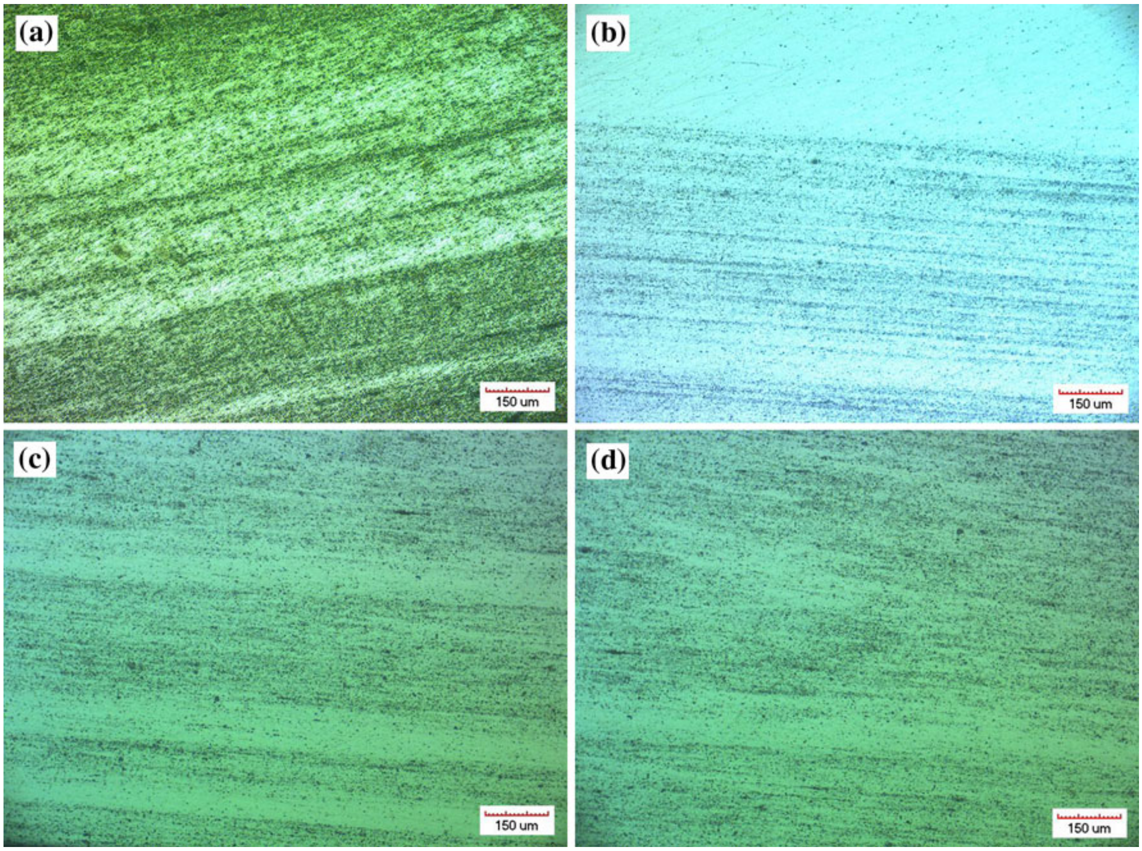

Fig. 3 Distribution of SiC particles along longitudinal direction: (a) $\lambda = 11$, (b) $\lambda = 17$, (c) $\lambda = 25$, and (d) $\lambda = 39$

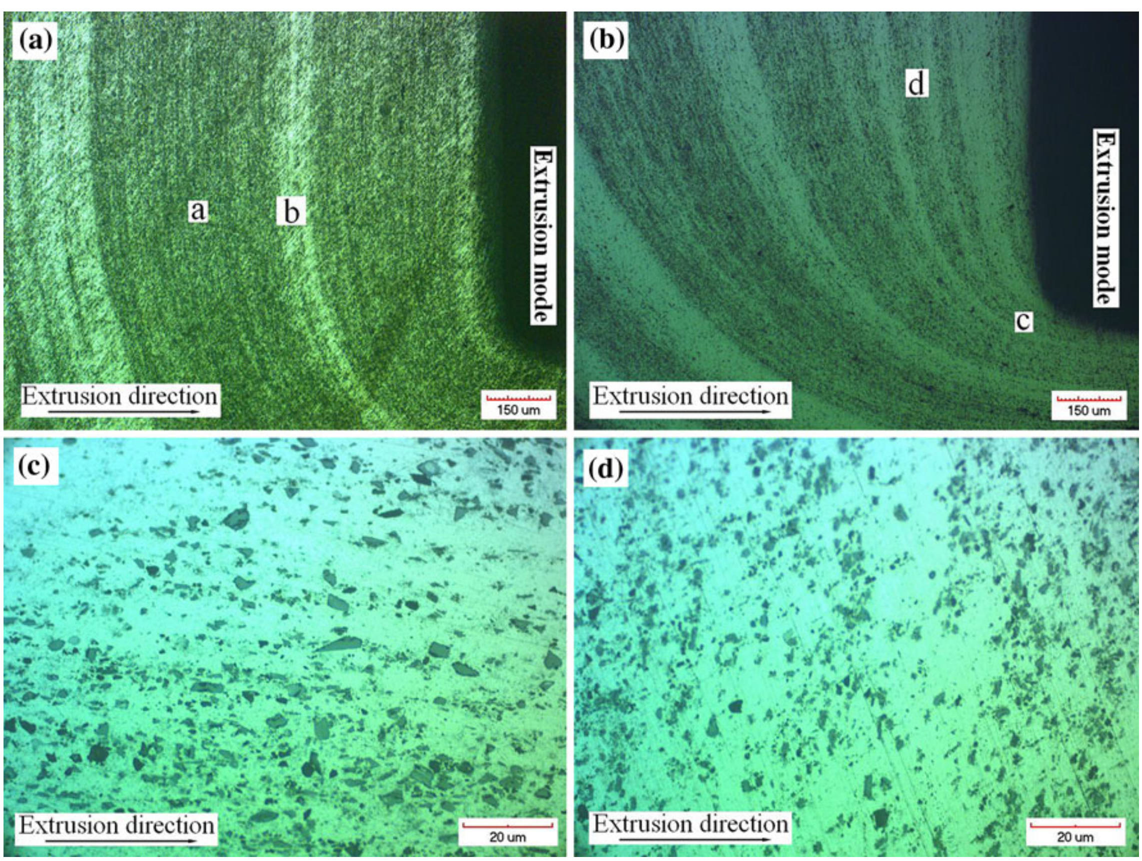

Fig. 4 Distribution of SiC in un-extruded region: (a) $\lambda = 11$, (b) $\lambda = 25$, (c) microstructure of c zone, and (d) microstructure of d zone

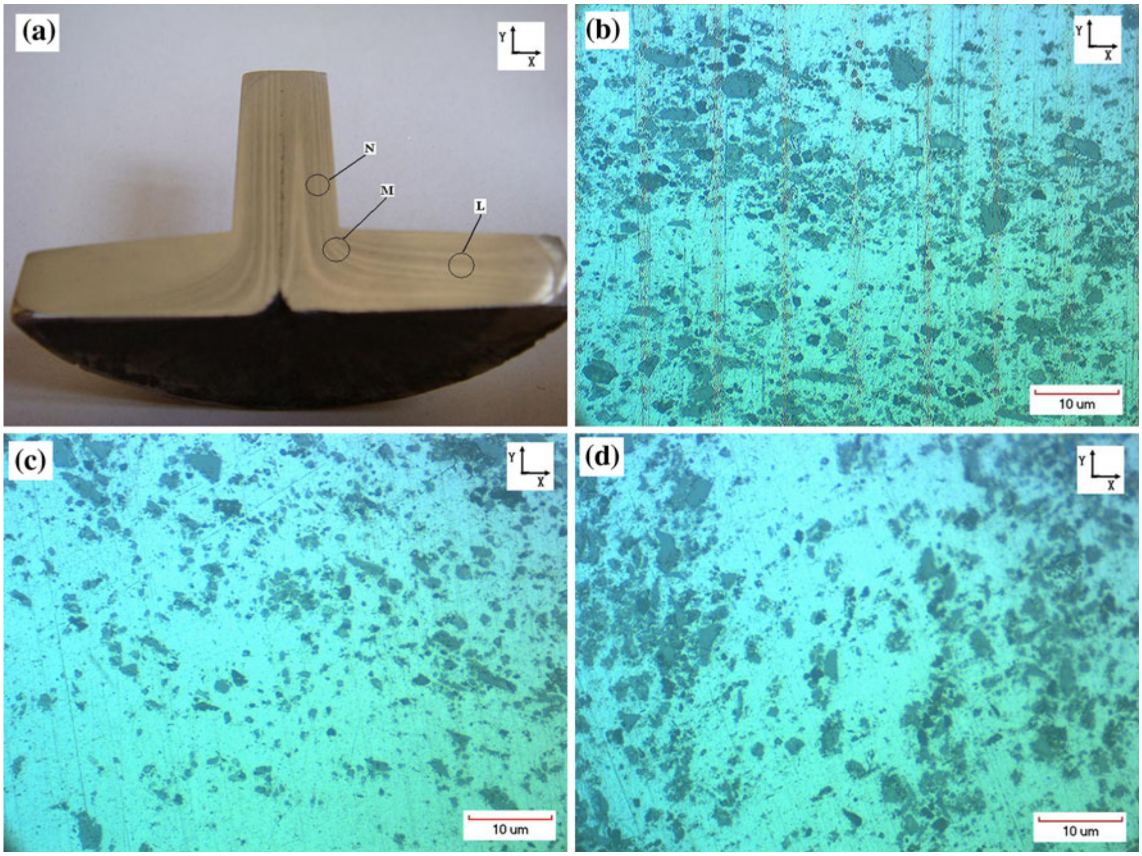

Fig. 5 Changing of the orientation for SiC during extrusion: (a) macrophotograph along axial profile, (b) region L, (c) region M, and (d) region N

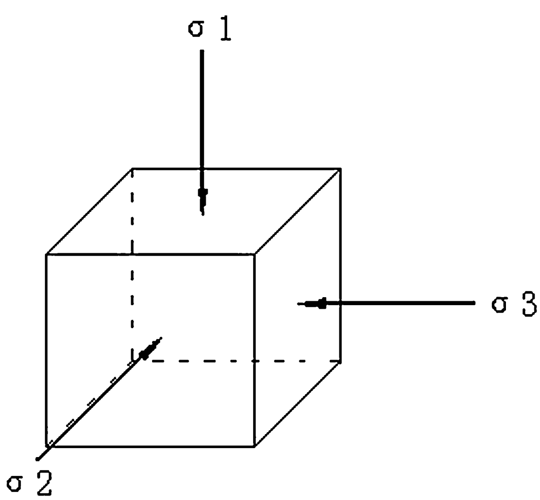

Fig. 6 Stress during hot extrusion

$$\varepsilon = 0.75\delta \sin(2\alpha), \quad \text{(Eq 2)}$$

where ε is the rotating angel of SiC particles, σ represents tensile stress acting on the composite, α represents the angle between the long axis of SiC and tensile direction, and δ represents tensile strain of the composite.

Figure 7 illustrates the rotating model caused by un-uniform flow of the matrix alloy (Ref 11). During the process of hot extrusion, we assume that there is a gradient of velocity: $V_1 > V_2 > V_3$, and SiC particles will rotate circling the mid-point

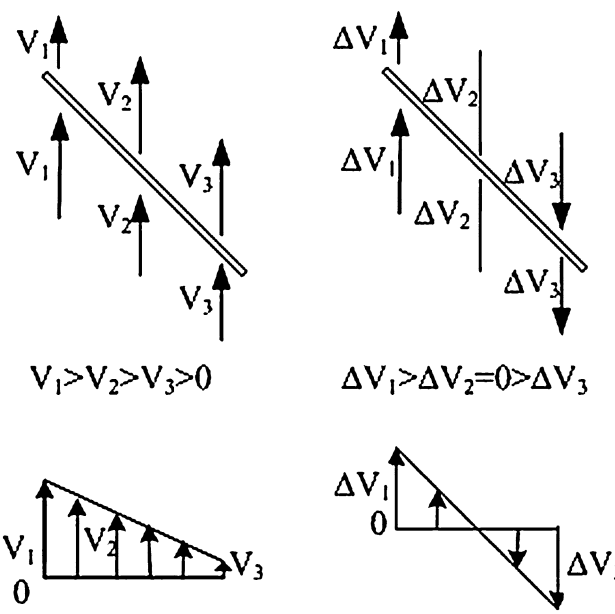

Fig. 7 Rotation model of the reinforcement particle

of the long axis of itself, and therefore resulting in an rotational torque. Hence, we can obtain the following conclusions:

- The rotating torque will be more larger with the increasing of un-uniform flow, and SiC particle will be more easier to rotate;

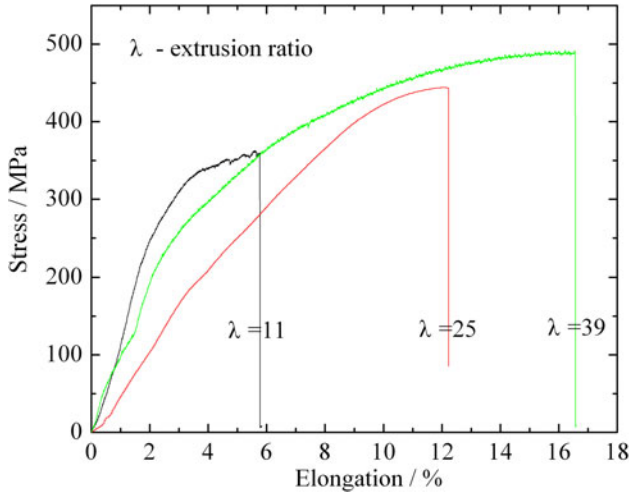

Fig. 8 Tensile properties of the composite for different extrusion ratios

- The rotating torque will be more larger with the increasing of angle between the long axis of SiC particles and the flowing direction of alloy, and SiC particle will be much more easier to rotate.

Hence, the greater the degree of nonuniform flowing of the matrix, the easier rotation of SiC particles. If there is the same velocity for extrusion rod, the flowing velocity of the matrix alloy will be faster with the increase of extrusion ratio, and the degree of rotation will be more greater. Therefore, excellent microstructure and mechanical properties can be achieved by increasing extrusion ratio appropriately. And from above results, we can see that the distribution of SiC is oriented, and the long axis of all SiC particles is parallel to the direction of streamline at an extrusion of about 25.

3.4 Mechanical Properties

Mechanical properties of the Al/SiC_p composite are also substantially improved by increasing the extrusion ratio. Effects of the extrusion ratio on tensile properties during hot extrusion is shown in Fig. 8. The microstructural evolution of the alloys during the pressing can be used to rationalize the obtained mechanical properties. The hot extrusion process applied to the as-deposited porous preforms can eliminate the porosity and increase the interface bonding strength of the as-deposited particles. Furthermore, the distribution of SiC becomes more and more uniform with the increasing of extrusion ratio, for a higher extrusion ratio can increase the relative movement between aluminum and SiC. Which all in all can improve the mechanical properties.

Figure 9 shows the fracture morphologies of the tensile samples with the extrusion ratio of 39, and which exhibits clearly ductile fracture. There are a great number of dimples (Fig. 9a) on the fracture surface. Many holes appear due to SiC particles which are pulled out (Fig. 9b). Due to the effect of shear stress on the interface of Al/SiC particle, cracks will appear at the weak interface and will extend when the stress increases (Fig. 9c).

This is consistent with the large elongation and can be ascribed to the improved microstructure during the extrusion in which the pores were minimized or eliminated. Furthermore, the extruding stress and the high temperature help to obtain sound metallurgical bonding between the as-deposited particles so as to achieve high-mechanical properties.

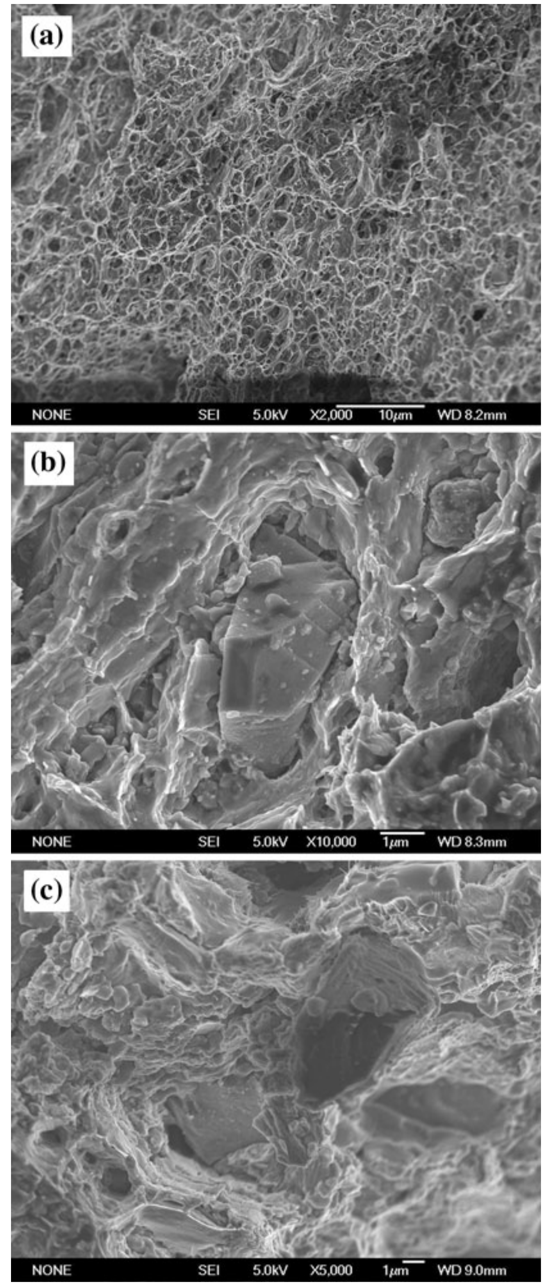

Fig. 9 Morphologies of fracture surface when λ is 39

4. Conclusions

(1) SiC particles adhered mainly to the surface of the alloy droplets during deposition, leading to more SiC particles at the surface of the droplet and less in the inner. Thus, the distribution of SiC particles in the as-deposited composite was characteristic of the layered feature. This layered feature of SiC particles was not removed by the following hot extrusion. The SiC particles were distributed like the streamline in the longitudinal direction.

A higher extrusion ratio resulted in an more uniform distribution of SiC particles.

(2) During hot extrusion, the long axis of all SiC particles is in the same direction with streamline from beginning to end, which begins to change gradually and being parallel to extruding stress. Therefore, an oriented distribution of SiC appears in the extruded bar.

(3) After extrusion, the tensile strength and elongation of the Al/SiC_p composite were improved greatly, which achieved 475 MPa and 16.5%, respectively, at an extrusion ratio of 39. Correspondingly, the fracture mode exhibits ductile fracture due to the improved microstructure.

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