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Effect of Hot Extrusion on Interfacial Microstructure and Tensile Properties of SiC_p/2009Al Composites Fabricated at Different Hot Pressing Temperatures

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The effects of hot extrusion on the interfacial microstructures and tensile properties of 15 vol.% SiC_p/2009Al composites fabricated at different hot pressing temperatures were investigated. After hot extrusion, the relative density of the composites increased, the SiC particle distribution became more uniform, and the SiC particles tended to align along the extrusion direction. Furthermore, the interface bonding was improved after hot extrusion; however, the extrusion exerted no obvious effect on the interfacial reaction products formed during sintering process. Tensile tests indicated that the mechanical properties of the composites were improved significantly after extrusion. Fractography revealed that the fracture mechanism of the extruded composites fabricated at the hot pressing temperatures below 540°C was mainly the interfacial debonding. For the extruded composites fabricated at 560–600°C, the fracture was the matrix ductile fracture and the SiC particle fracture. When the composites were hot pressed at or above 620°C, after extrusion, the fracture mechanism of the composites was the matrix ductile fracture, the interface cracking and the SiC particle fracture.

KEY WORDS: Aluminum matrix composite; Hot extrusion; Microstructure; Mechanical properties

1. Introduction

SiC particle reinforced Al matrix (SiC_p/Al) composites offer many advantages, such as high specific strength and specific modulus, good wear resistance, high dimensional stability, enhanced damping capacity, good impact and erosion resistance, resistance to burning and high temperature exposure[1,2]. SiC_p/Al composite is an important commercial product for the aerospace due to a superior balance of good properties, modest cost and commercial availability in a range of semi-finished product forms[3,4]. Interest in the SiC_p/Al composites for aerospace applications has been increased over the last decades. Powder metallurgy (PM) technique is a widely used route to manufacture the composites for structural applications, and the composites manufactured by PM exhibit better mechanical properties than other processing routes[5].

Plastic processing techniques are not only the approach to deform the composites into the components but also the main method of improving the microstructure and properties of the composites. Among these techniques, hot extrusion is one of the most important forming technologies and has been reported to be able to enhance the mechanical properties of the composites significantly.

Hong *et al.*[6] investigated the effects of extrusion ratio and extrusion temperature on microstructures and tensile strengths of 20 vol.% SiC_w/2124Al composite. It was reported that when the extrusion ratio was 15:1, the tensile strength of the composite reached the highest value due to the optimum effective aspect ratio of the whiskers and relative density of the composite. Furthermore, with increasing the extrusion

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Table 1 Density of extruded composites fabricated at different hot pressing temperatures

Hot pressing temperature/°C	Density/(g/cm^3)	Relative density/%
540	2.805	99.52
560	2.807	99.59
580	2.816	99.91
600	2.808	99.63
620	2.806	99.56
640	2.801	99.38

temperature from 470 to 530°C, the mechanical properties of the composite increased due to the increase in the relative density and effective aspect ratio. In SiC_p/Al composites produced by compocasting route, with increasing the extrusion temperature to 550°C, severe breakage of SiC particles was reduced during extrusion, and the porosity level also decreased[7]. Cöcen *et al.*[8] found that after extrusion, SiC_p/Al-5 wt% Si-0.2 wt% Mg composite fabricated by casting exhibited a more uniform distribution of the SiC particles and the substantially reduced porosity content, thus the yield strength and the tensile strength were improved. Wang *et al.*[9] proposed that the extrusion reduced the number of the pores and improved the interfacial bonding strength between the SiC particles and the matrix.

Although the effect of hot extrusion on the porosity, the damage and distribution of reinforcing particles has been extensively studied in aluminum matrix composites[6–9], the investigations of the effect of hot extrusion on interface bonding are very limited[9]. In our previous paper[10], the effects of hot pressing temperature on the microstructures and tensile properties of 15 vol.% SiC_p/2009Al composites have been investigated. It was reported that the hot pressing temperature exerted a significant effect on the interfacial bonding and mechanical properties of the composites. The hot pressing at 580°C produced the best interface bonding and mechanical properties. Lower hot pressing temperatures below 560°C generated a weak interface bonding, whereas at higher hot pressing temperature of above 620°C, the brittle $MgAl_2O_4$ and Al_4C_3 formed at the interfaces, which resulted in the decrease of the mechanical properties[10].

Considering that the composites produced at different hot pressing temperatures exhibited quite different interfacial bonding statuses, it is of practical importance to know if the hot extrusion can improve the interface bonding to enhance mechanical properties of the composites. In this study, 15 vol.% SiC_p/2009Al composites fabricated at different hot pressing temperatures were subjected to hot extrusion, and the microstructure and mechanical properties of extruded composites were systematically analyzed. The aim is to understand the effect of second hot processing on the interfacial bonding and to improve the mechanical properties of the composites with weak interfacial bonding.

2. Experimental

2009Al powders with a nominal composition of Al-3.7Cu-1.3Mg (wt%) and a particle size of 6 μm were used as the matrix, and the SiC particles with a nominal particle size of 7 μm were used as the reinforcement. The Al and 15 vol.% SiC powders were blended for 8 h and then compacted with a single-action, uniaxial hydraulic press at a pressure of 150 MPa. The compacts were sintered at 540, 560, 580, 600, 620 and 640°C, respectively, for 1 h and then extruded at 480°C under an extrusion ratio of 10:1. The as-extruded composites were solution treated at 495°C for 1 h, water quenched, and then aged at room temperature.

The bulk densities of the extruded composites were measured by standard Archimedes method. The specimens for microstructural examinations were machined perpendicular and parallel to the extrusion direction, ground with 2000 grit abrasive paper and then mechanically polished. The specimens were observed by optical microscopy (OM, AXIOVERT 200 MAT). The interface microstructure was examined by transmission electron microscopy (TEM, TECNAI G^2). The thin films for TEM were prepared by ion-milling technique.

Tensile test was performed at a crosshead speed of 1 mm/min using an Instron 100 kN screw-driven machine. The tensile specimens with a gage diameter of 5 mm and a gage length of 25 mm were machined from the as-extruded bar with the loading axis parallel to the extrusion direction. The specimens were heat treated prior to machining to prevent specimen distortion during the heat treatment. The fracture surfaces of the tensile specimens were observed by scanning electron microscopy (SEM, HITACHI S-3400N).

3. Results and Discussion

3.1 Relative density

Table 1 summarizes the density of the composites fabricated at different hot pressing temperatures after extrusion. It is noted that the density of the extruded composites is close to the theoretical density, but still correlated with hot pressing temperature. The variation trend of relative density in the extruded composites is similar to that in the hot pressed composites[10], with the hot pressing temperature of 580°C producing

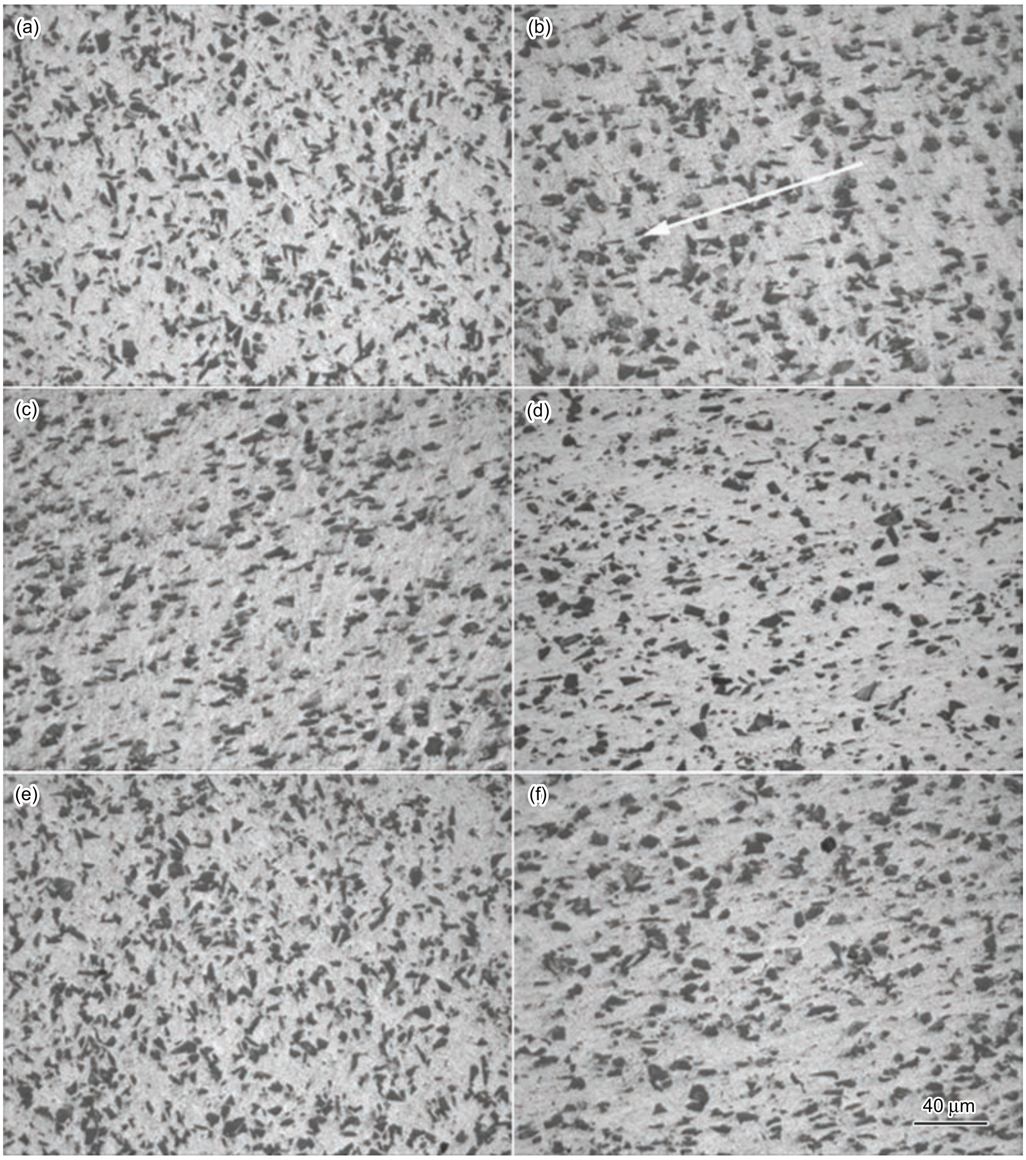

Fig. 1 Optical micrographs of SiC_p/2009Al composites at different hot pressing temperatures: (a) 540°C, (b) 580°C and (c) 640°C in the transverse direction; (d) 540°C, (e) 580°C and (f) 640°C in the longitudinal direction (the arrow indicates the extrusion direction)

the highest relative density. Tekmen *et al.*[11] suggested that with the application of the extrusion process, the porosity content of SiC_p/Al-Si-Mg composite was substantially reduced. Song *et al.*[12] reported that the extrusion improved the density of SiC_p/Al composite. Rozak *et al.*[13] revealed that hot deformation processing reduced the porosity levels in the sand cast SiC_p/A356 composite, the deformation of 90% or greater could eliminate the porosity virtually. The present density analysis indicated that most of the porosity was eliminated by the higher triaxial stresses during hot extrusion, but the relative density of the extruded composites was still affected by the initial density of the hot pressed composites.

3.2 Distribution of SiC *particles*

Figure 1 shows the microstructures of the extruded composites. The extrusion further improves the distribution homogeneity of the SiC particles in the matrix and eliminates the porosity, and the SiC aggregation is significantly improved compared with the hot pressed composites[10], especially, those fabricated at higher hot pressing temperatures. From the longitudinal section of the extruded composites, it can be seen that the SiC particle segregation is largely eliminated by extrusion, at the same time, the SiC particles tend to align along the extrusion direction. Because the extrusion ratio of 10:1 is relatively low, the alignment of the particles is not so obvious.

It is well known that extrusion generated severe plastic deformation of the matrix, leading to the rearrangement of the SiC particles[9]. Rahmani Fard *et al.*[7] thought that the applied shear stress during extrusion broke up particle clusters, resulting in a more

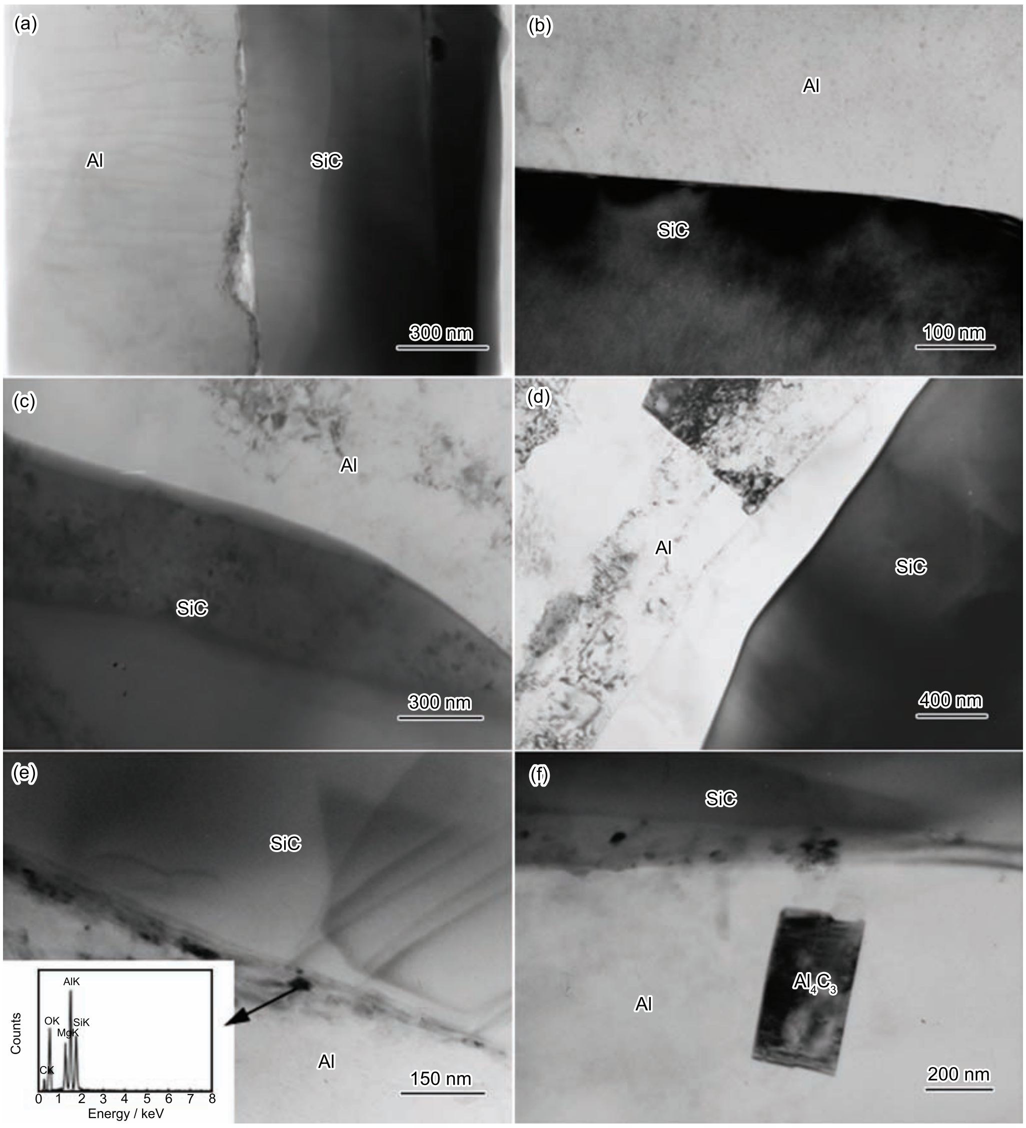

Fig. 2 TEM micrographs of the interfaces in extruded SiC_p/2009Al composites fabricated at different hot pressing temperatures: (a) 540°C, (b) 560°C, (c) 580°C, (d) 600°C, (e) 620°C, (f) 640°C

uniform particle distribution. The equiaxed particles which exerted no obvious block to the plastic deformation of the matrix flowed with the plastic flow of the matrix. However, for the particles with a large aspect ratio and the major axis of the particles departing from the flow direction of the matrix, the particles rotated towards the flow direction of the matrix and tended to align directionally under the shear stress applied on the major axis of the particles[14].

3.3 Interface

Figure 2 shows the TEM interfacial microstructure between SiC particles and matrix in the extruded composites. The holes and cracks are detected at the interface in the extruded composite fabricated at 540°C (Fig. 2(a)). This indicates that the interface is weak, and prone to separate during long time ion milling. For the extruded composites fabricated at 560–600°C, no holes and cracks are observed, and the interface is clean (Fig. 2(b)–(d)). Especially, the interface bonding of the extruded composite fabricated at 560°C is obviously improved compared with that of hot pressed composite[10]. For the composites fabricated at 620–640°C, the $MgA1_2O_4$ remains at the interface after extrusion (Fig. 2(e)), and the Al_4C_3 is also observed at the interface (Fig. 2(g)).

Figure 3 shows the X-ray diffraction (XRD) profiles of the extruded composites. For the extruded composites fabricated below 600°C, Al_2Cu, Mg_2Si and Al_7Cu_2Fe are detected (Fig. 3(a)–(d)). When the hot pressing temperatures are increased to 620 and 640°C, in addition to Al_2Cu, Mg_2Si and Al_7Cu_2Fe, the existence of the $MgAl_2O_4$ and Al_4C_3 is also identified in the extruded composites.

Compared with the interfacial microstructure and XRD analyses of the hot pressed composites[10], it could be concluded that extrusion improved the weak

Table 2 Tensile properties of extruded SiC_p/2009Al composites

Hot pressing temperature/°C	Yield strength/MPa	Tensile strength/MPa	Elongation/%
540	225	380	8.0
560	330	465	8.2
580	365	520	8.4
600	345	510	8.0
620	340	500	7.6
640	320	495	7.6

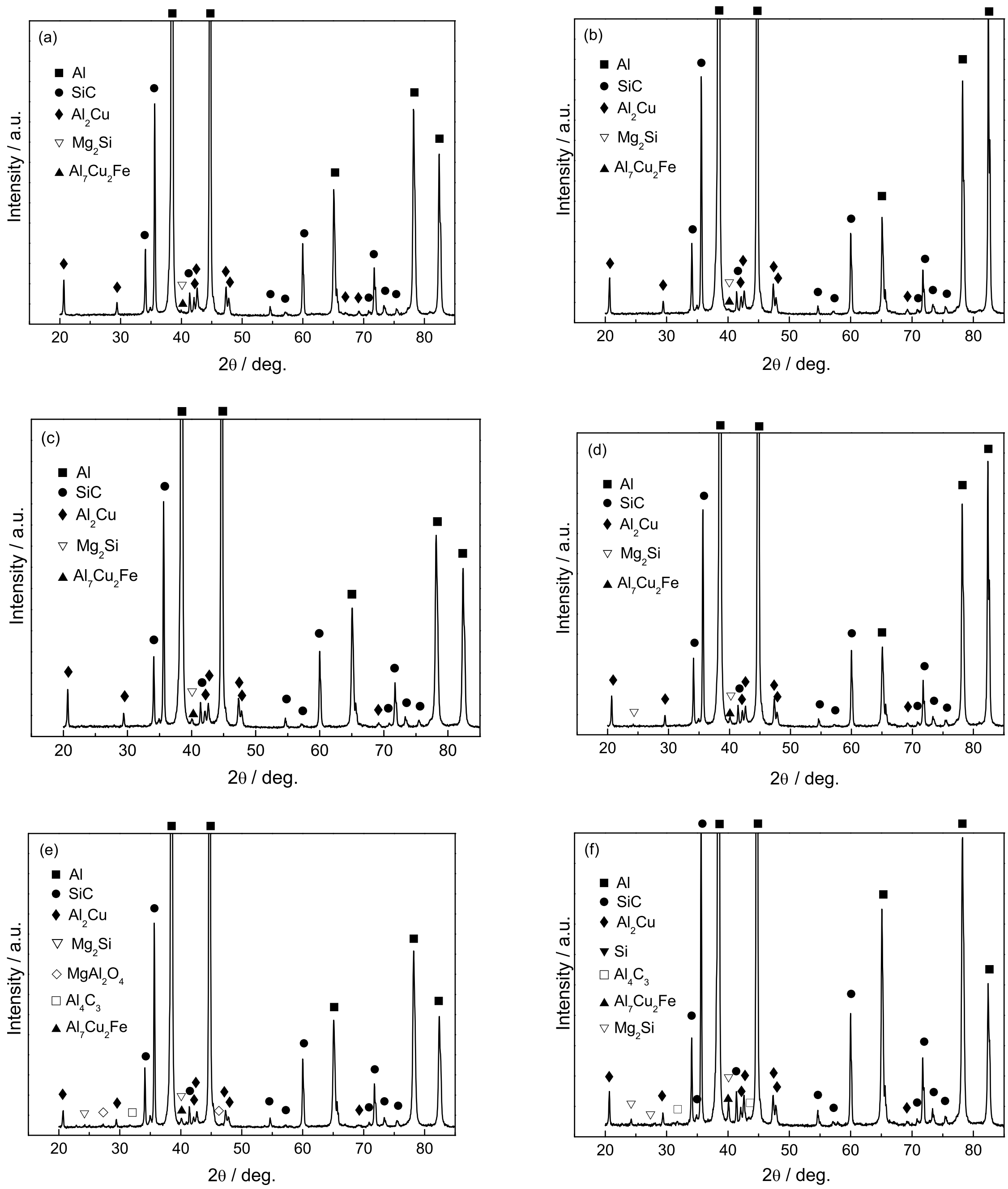

Fig. 3 XRD patterns of the composites fabricated at different hot pressing temperatures: (a) 540°C, (b) 560°C, (c) 580°C, (d) 600°C, (e) 620°C, (f) 640°C

interface bonding, but did not change the distribution of the interface reaction products, and the $MgAl_2O_4$ and Al_4C_3 remained at the interfaces. Furthermore, the extrusion neither aggravated the interface reaction, nor resulted in the formation of new phase.

3.4 Mechanical properties

The mechanical properties of the extruded composites are given in Table 2. It is noted that the strength and elongation increase with increasing hot

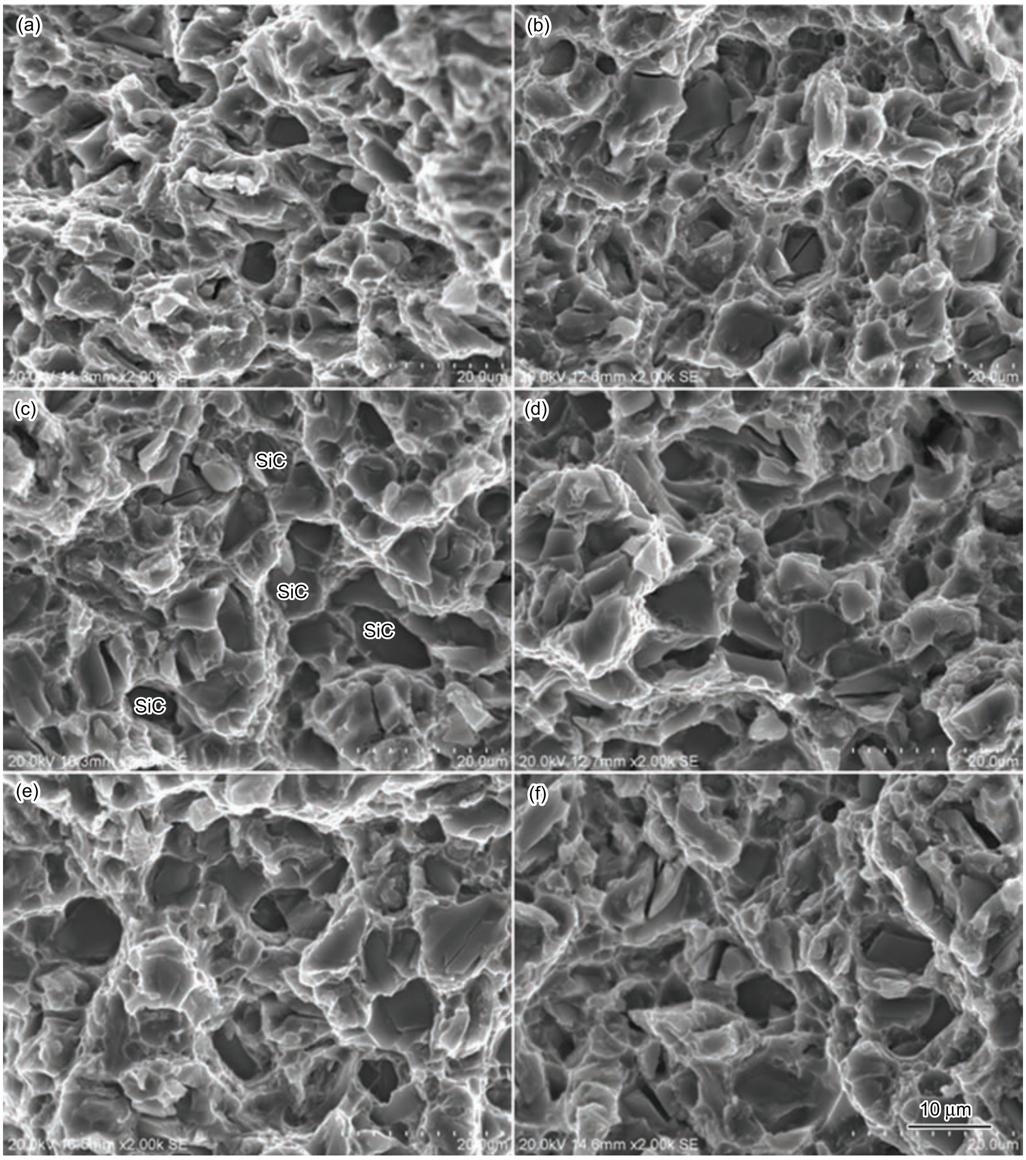

Fig. 4 Fractographs of the composites fabricated at different hot pressing temperatures: (a) 540°C, (b) 560°C, (c) 580°C, (d) 600°C, (e) 620°C, (f) 640°C

pressing temperature to 580°C, and then decrease as the hot pressing temperature increases. However, the variation in the ductility of the extruded composites with the hot pressing temperature is very slight. The mechanical properties of the extruded composites are obviously improved compared with those of the hot pressed composites[10].

Figure 4 shows the SEM fracture morphologies of the extruded composites. Generally, the six composites prepared at different hot pressing temperatures exhibited a ductile fracture mechanism after extrusion. However, the fracture modes of SiC particles and interfaces were different. For the composite prepared at a lower hot pressing temperature of 540°C, the crack along the interface and the decohesion of the SiC particles are observed due to the weak interface bonding (Fig. 4(a)). The cracks tend to initiate at the interface and propagate along the interface. The SiC particle fracture was rarely detected. For the extruded composites fabricated at 560–600°C, the number of fractured SiC particles increases (Fig. 4(b)–(d)), this indicates that the interface bonding strength is improved, enhancing the load transfer ability from the matrix to the SiC particle. With increasing hot pressing temperature to 620°C and above, the number of fractured SiC particles in the extruded composites decreases gradually, and the interface cracks appear (Fig. 4(e)–(f)).

After extrusion, the improvement in the strength and ductility of the composites was attributed to the decreased porosity level and the improved microstructure[9,15–17]. Zhang *et al.*[18] thought that the extrusion deformation increased the ultimate strength of SiC_w/6061Al composite because the strength of the composite′s matrix was increased due to the high density of dislocations generated by extrusion deformation. The increased elongation of the composite after the extrusion deformation was attributed to increased plastic deformation capacity of the matrix after extrusion deformation. The homogenous distribution of SiC particles blocked the propagating crack and deflected it. By deflecting the crack, the energy level at the crack tip which is necessary for its propagation decreased, disabling its further propagation. Therefore, more energy (larger applied force) had to be introduced to the system for continuing the crack propagation. In this case, the composites with homogenously-distributed particles exhibit better mechanical properties[19].

The properties of the composites depend strongly on the interfaces bonding. It is well documented that the function of the interface is to transfer the load from the matrix to the reinforcements, and a strong interfacial bonding is expected to produce a high strength in the composites[20–23]. A parametrical study of the influence of the interface properties on the failure micromechanisms and the macroscopic tensile properties indicated that higher interface strength increased the tensile strength remarkably, and on the contrary, the tensile ductility of the composite decreased monotonously with the brittle interfaces[24]. Gao *et al.*[25] found that the coarse $MgAl_2O_4$ with a high brittleness at the interface was easy to fracture, decreasing the mechanical properties of $Al_{18}B_4O_{33w}$/6061Al composite considerably. Ceschini *et al.*[26] observed the particle debonding in Al_2O_3/2618Al composite, which was attributed to a weak interface bonding resulting from the existence of the brittle $MgAl_2O_4$ spinel. Park *et al.*[27] found that the interfacial debonding was dominant in the composite with a great amount of interfacial Al_4C_3, which embrittled or at least weakened the interface bonding.

4. Conclusions

(1) Hot extrusion resulted in the increase in the density of hot pressed SiC_p/2009Al composites, the improvement in the distribution homogeneity of the SiC particles, and the alignment of the particles along the extrusion direction. Furthermore, the composite fabricated at 580°C had a maximum relative density.

(2) Hot extrusion improved the interface bonding, but did not change the distribution of the interfacial phases $MgA1_2O_4$ and Al_4C_3. While the composite fabricated at 540°C still exhibited a relatively weak interface bonding after extrusion, the extruded composites fabricated at 560–600°C had a clean and well-bonded interface. Furthermore, the $MgA1_2O_4$ and Al_4C_3 existed at the interface of the extruded composites fabricated at 620–640°C.

(3) The mechanical properties of the extruded composites were obviously improved compared with those of hot pressed composites. The extruded composite fabricated at 580°C exhibited the best mechanical properties due to the excellent interfacial bonding. At lower or higher hot pressing temperatures, the extruded composites exhibited reduced strength due to relatively weak interfacial bonding and the existence of brittle $MgA1_2O_4$ and Al_4C_3 phases at the interface.

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