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Effect of the SiC Particle Orientation Anisotropy on the Tensile Properties of a Spray-Formed SiC_p/Al-Si Composite

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Влияние анизотропии, определяемой ориентацией SiC частиц, на механические свойства при растяжении SiC_p/Al-Si композита, полученного методом напыления

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Исследовано влияние анизотропии, определяемой ориентацией SiC частиц, на механические свойства при растяжении SiC_p/Al-Si композита, полученного методом напыления. Результаты исследования SiC_p/Al-Si композита сопоставлены с таковыми сплава с неупрочненной матрицей. При растяжении Al-Si сплава в условиях максимального старения благодаря введению SiC частиц модуль упругости увеличивается, а предел прочности и удлинение уменьшаются. При определении характеристик микроструктуры было установлено, что упрочняющие частицы преимущественно ориентированы в направлении, параллельном оси экструзии. При значительном упрочнении степень анизотропии, определяемой ориентацией частиц, более высокая. Значения модуля упругости, предела прочности и удлинения при растяжении в продольном направлении (параллельно оси экструзии) оказываются выше, чем в поперечном (перпендикулярно оси экструзии). Признаком механизма разрушения композита с частицами размером 4,5 мкм полагают граничное разделение между SiC частицами и матрицей в двух направлениях. В случае упрочненного алюминия с частицами размером 20 мкм растрескивание SiC частиц в продольном направлении и граничное разделение в поперечном направлении играют важную роль в процессе разрушения.

Ключевые слова: SiC_p/Al композит, направление, размер частиц, нанесение методом распыления, механические свойства при растяжении.

Introduction. Possessing good properties including low thermal expansion coefficient, high wear resistance and high strength-to-weight ratio, Al–Si alloy composites have extensive applications as structural components in automotive and aerospace industries [1].

Usually these composites can be produced by several processing methods, such as stir casting, squeeze casting [2], powder metallurgy [3], spray forming, etc. Amongst them, spray forming technique [4] has drawn considerable interest due to its capability of forming the near-net shape product with a reduced number of process steps compared with the powder metallurgy. Moreover, the process also offers advantages of rapid solidification, forming refined equiaxed structure with negligible segregation, extension of the solid solubility limit [4], and wide compositional flexibility.

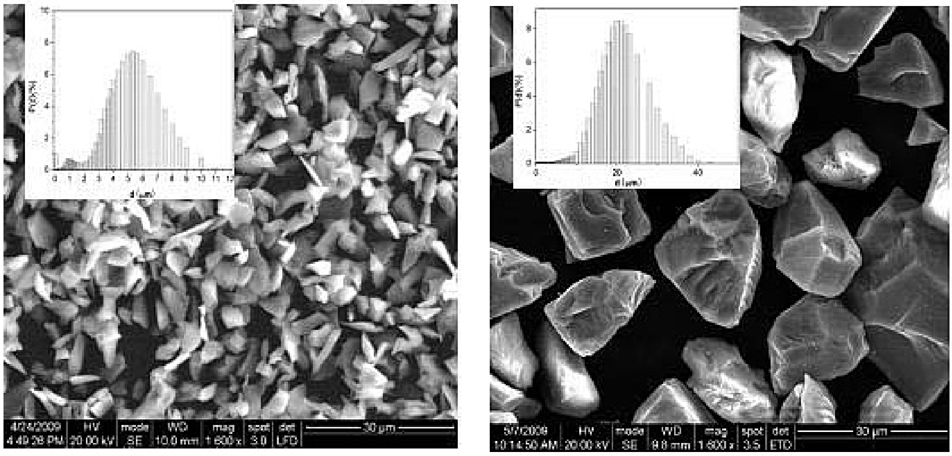
Tensile properties of composites are influenced by volume fraction of particles, nature of the interface between the matrix and the reinforcement, particle size, shape, and distribution of reinforcement particles, etc. With a given volume fraction and matrix property, the particle size of reinforcement is considered to be a key factor on tensile properties. So far only a few studies on the effect of particle size on tensile properties have been reported [2–4]. Srivastava et al. [5] investigated the microstructure and tensile properties of spray-formed SiC_p/2014Al composites containing SiC particulate with the size of 6 to 30 μm [5]. They found that the composite with intermediate-sized (17 μm) SiC particulate exhibited the increased elastic modulus as compared with the unreinforced alloy. Li et al. [6] pointed out that 8 μm SiC_p reinforced composite processed by powder metallurgy had the highest yield and tensile strength among all composites with SiC_p sized from 3 to 48 μm. However, most studies report only tensile properties measured parallel to the processing direction, while the effect of anisotropy on tensile behavior of these composites has not been well understood.

The orientation of reinforcement particles plays an important role in deformation processing, and it can also affect tensile properties significantly. Ganesh and Chawla [7] reported that the degree of orientation anisotropy decreased with increasing reinforcement volume fraction. The elastic modulus and tensile strength in the longitudinal orientation were higher than those in the transverse orientation. Thus, the orientation anisotropy of the reinforcement would strongly influence the mechanical behavior of the composite. However, the effect of particle size on the degree of orientation anisotropy has not been examined in detail [8]. It would be necessary to understand the influence of both particle size and orientation anisotropy of the reinforcement on the mechanical properties of the composite.

In this study, we conducted a systematic investigation on the effects of orientation anisotropy of SiC particles, with two different particle sizes, on SiC particle-reinforced Al–Si composites prepared by spray deposition and subsequent extrusion. The influence of preferred orientation of reinforcement particles on tensile behavior was examined for two directions: parallel (longitudinal) and perpendicular (transverse) to the extrusion axis.

Experimental Methods. The Al–Si alloy with a nominal composition of Al–7Si–0.3Mg–0.01Mn–0.01Cu (wt.%) and the composite reinforced with 15 vol.% SiC particles were prepared by multilayer spray deposition technology, the details of which were described elsewhere [4]. SiC particles of two sizes (4.5 and 20 μm) were used to prepare the reinforced composites, hereafter denoted in this paper as 4.5 μm SiC_p/Al-Si and 20 μm SiC_p/Al-Si, respectively. Characterized by scanning electron microscopy, the SiC particles of an average of 4.5 μm displayed a limited size distribution with irregular shapes, as shown in Fig. 1a. As comparison, the larger SiC particles of an average size 20 μm had a normal distribution with predominantly polygonal shape (see Fig. 1b).

All the samples were machined from the center of platform with the diameter of 160 mm and the height of 300~400 mm. They were then subjected to hot extrusion at 723 K in a 1250 ton horizontal extrusion press. The ingots were extruded into 120 mm wide and 10 mm thick plates at an extrusion ratio of 17.3:1. Optical microscopy was used to analyze the microstructure of the composites. Tensile tests were carried out on an Instron Machine (Instron model 8871) using a gauge length of 25 mm and diameter of 5 mm corresponding to the ASTM standard (E-8). Specimens were machined parallel and perpendicular to the extrusion axis. All tests were carried out on a precisely aligned servo-hydraulic load frame,



a b

Fig. 1. SEM of basic materials: (a) 4.5 μm SiC powder; (b) 20 μm SiC powder. (Insets show the corresponding particle size distributions.)

at ambient temperature, with strain control at a strain rate of 10^{-4}– $0.5 \cdot 10^{-2}$ s^{-1}. The fractured surfaces were also characterized by scanning electron microscopy (SEM) to visualize the orientation anisotropy of reinforcement particles.

Results and Discussion. ***Microstructure Characterization***. Figure 2 shows typical micrographs of the cross sections parallel and perpendicular to the extrusion direction respectively, for the unreinforced Al–Si alloy, as well as two SiC reinforced composites. The microstructure of the alloy consists of Si particles, α-Al matrix, and porosity, etc. (Fig. 2a). A reasonably uniform distribution of SiC reinforcement in the aluminum matrix was observed in the composite materials (Fig. 2b and 2c). Some clustering tendency may be observed in the 4.5 μm SiC_p/Al-Si composite, while it is less obvious in the 20 μm SiC_p/Al-Si composite.

In both reinforced composites, the SiC particles were partially aligned along the extrusion direction. This has also been confirmed by three dimensional visualization of the microstructure obtained by serial sectioning technique [9]. A quantitative analysis of the particle orientation distribution was applied by fitting the particles to ellipses, and measuring the angle between the major axis of the ellipse and the longitudinal and transversal axes. As can be seen in Fig. 3, in both SiC reinforced composites, a higher fraction of SiC particles were oriented along the extrusion axis (longitudinal) than in the perpendicular orientation (transverse). It is noteworthy that with the larger size of reinforcement particles, the degree of orientation anisotropy was considerably higher. This can be explained by observance how rotation and alignment of the reinforcement particles take place along the extrusion axis. With a constant reinforcement volume fraction, as compared to the composite with fine (4.5 μm) particles, the composite containing coarse (20 μm) SiC particles has more interparticle spacing, therefore a larger mean free path for the particles to align themselves during extrusion. Similar results were also observed in the work of Chawla et al. [9], where the degree of orientation on 2080 Al matrix composite decreased with increasing reinforcement volume fraction, due to the smaller mean free path for the particles to align themselves during extrusion.

Tensile Properties. Various tensile properties of the Al–Si alloy and two SiC reinforced composites were tested in both longitudinal and transverse directions, and the results were listed in Table 1. Compared with the Al–Si alloy, the addition of SiC particles resulted in an increase of elastic modulus, which was even higher in 4.5 μm SiC_p/Al-Si

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Tensile Properties of the Al–Si Alloy and the SiC Reinforced Composites

Composite and orientation	Elastic modulus E, GPa	Yield stress $\sigma_{0.2}$, MPa	Ultimate tensile strength σ_u, MPa	Elongation A, %
Al–Si alloy, longitudinal	72.3	242.6	336.3	11.2
Al–Si alloy, transverse	69.0	221.9	269.7	3.6
4.5 μm SiC_p/Al-Si, longitudinal	86.1	240.5	328.9	9.0
4.5 μm SiC_p/Al-Si, transverse	83.0	232.0	315.8	4.6
20 μm SiC_p/Al-Si, longitudinal	83.7	270.9	321.4	8.6
20 μm SiC_p/Al-Si, transverse	76.8	242.2	291.9	3.9

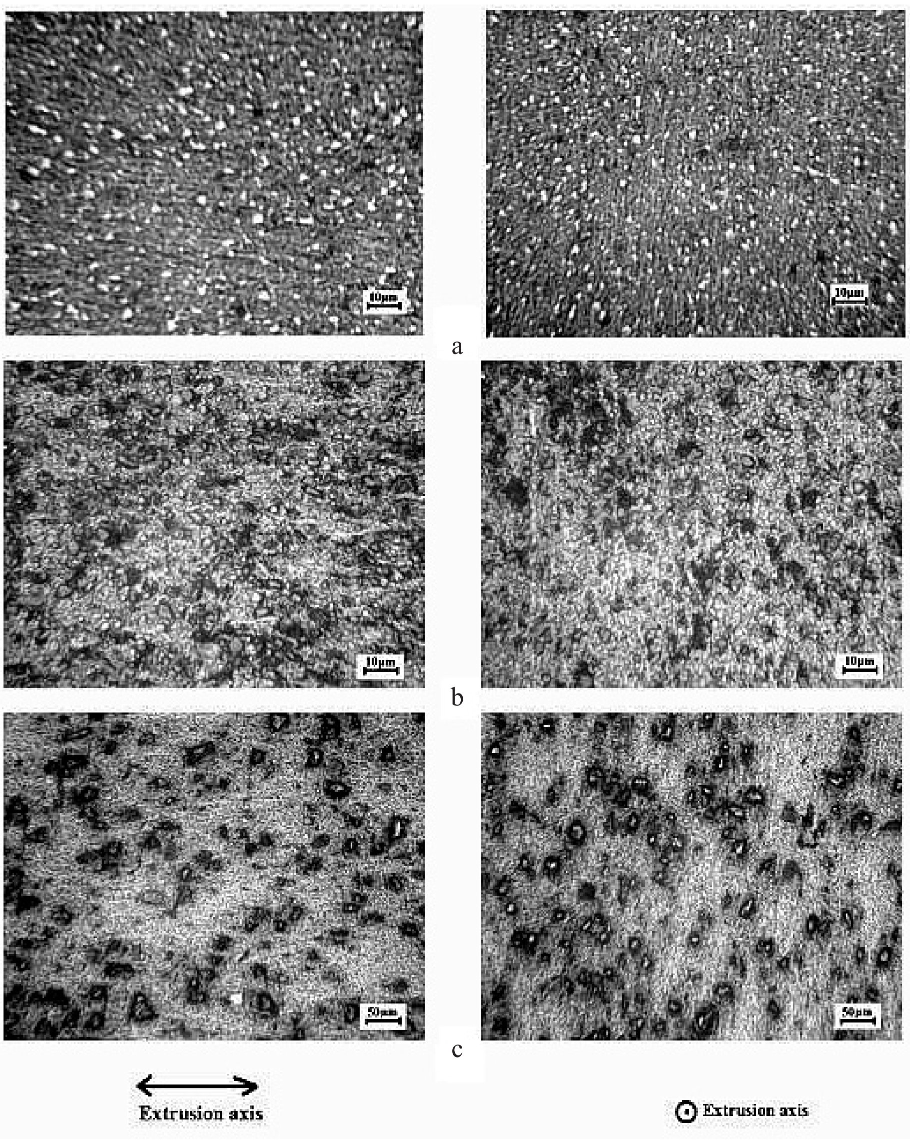

Fig. 2. Microstructure of samples: (a) Al–Si alloy; (b) 4.5 μm SiC_p/Al-Si composite; (c) 20 μm SiC_p/Al-Si composite.

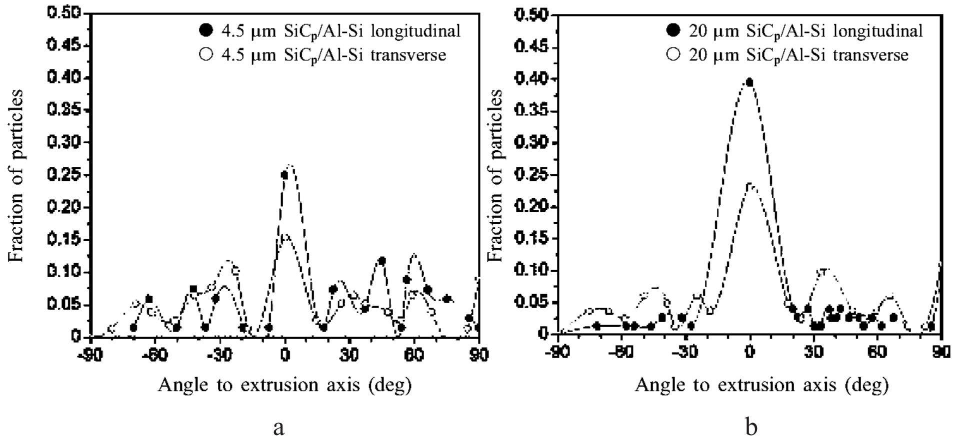

Fig. 3. Orientation of reinforcement particles relative to the extrusion axis: (a) 4.5 μm SiC_p/Al-Si composite; (b) 20 μm SiC_p/Al-Si composite.

composite than that in 20 μm SiC_p/Al-Si composite. It is reasonable that a composite reinforced with certain size of particles has the optimized mechanical properties. For a given volume fraction, the fine particle reinforced composite has less inter-particle spacing as compared to the composite with large particles. In other words, the composite with fine particles has less volume of the aluminum matrix around the reinforcement which therefore shares more portion of loading, giving rise to higher monotonic tensile strength and yield strength. In our study, the tensile strength of 4.5 μm SiC_p/Al-Si composite was higher than that of 20 μm SiC_p/Al-Si composite. These results are consistent with the work of Han et al. [10], for the powder metallurgy processed Al alloy containing 10 μm particles. Moreover, Table 1 shows that the composite reinforced with 20 μm SiC has the largest yield strength. It is reasonable to speculate that more stress concentrations are generated around the clustered particles in the 4.5 μm SiC_p/Al-Si composite, leading to earlier local yielding at relatively low loads. This may also explain why it is difficult to determine the yield strength of particle reinforced materials.

In addition to the effect of reinforcement particle size, distinct anisotropy of elastic modulus and elongation was also observed. Figure 4 depicts a plot of elastic modulus versus particle size, in both the longitudinal and transverse orientations. Apparently, the elastic modulus was higher along the extrusion axes, which can be attributed to better alignment of SiC particles in this direction. For a given reinforcement volume fraction, particle size, and aspect ratio, the elastic modulus of the composite can be controlled by the degree of particle alignment. Since the contribution of the particles to the overall modulus of the composite increases with the incorporation of reinforcement, the contribution of particle alignment will also be more significant. Results of the particles orientation analysis in Fig. 3 shows that the composite reinforced with 20 μm SiC particles exhibited the highest degree of microstructural anisotropy. Accordingly, the 20 μm SiC_p/Al-Si composite had the elastic modulus manifesting the highest anisotropy in longitudinal and transversal directions. It is noted that the anisotropy in composite properties may be a function of particle alignment degree. Ledbetter et al. [11] examined the anisotropy of the elastic modulus in a SiC/Al composite, where the particles were highly clustered. The system was described as large, elongated matrix-rich regions decorated by randomly distributed SiC particles. In this case, the observed anisotropy in elastic modulus was attributed to the alignment of the aluminum matrix-rich regions.

The elongation of the SiC reinforced composites decreased slightly with increasing particle size both in the longitudinal and transverse orientations, as shown in Fig. 5.

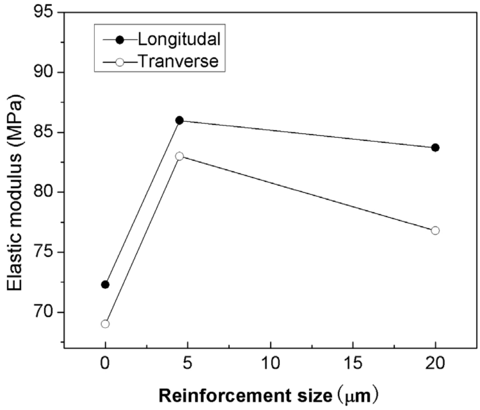

Fig. 4

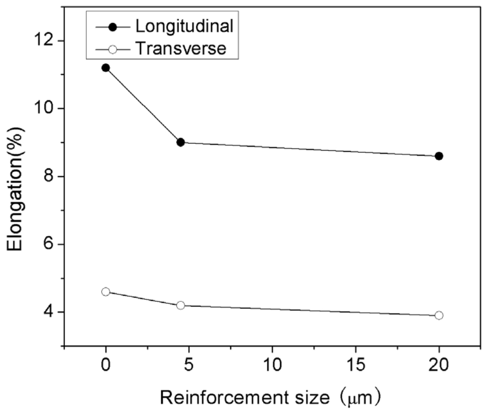

Fig. 5

Fig. 4. Elastic modulus vs. reinforcement size along the longitudinal and transverse axes, showing anisotropic behavior.

Fig. 5. Elongation vs. reinforcement size along the longitudinal and transverse axes, showing anisotropic behavior.

According to the research by Song et al. [12] the spherical Al_2O_3 particle-reinforced composite exhibited considerably higher ductility than the angular particle reinforced composite. The difference of the particle geometry caused led to a different distribution of the residual stress which is generated by the mismatch of thermal expansion coefficients between the matrix and particles. Also, the particle geometry turns to alter fracture behavior, especially near the matrix-particle interface. In our study, the 4.5 and 20 μm SiC particles exhibited a similar shape (Fig. 1) with the aspect ratio of 1.38 and 1.94, respectively.

Thus, the influence of reinforcement particle size in elongation is negligible. Since the orientation of SiC is preferred in the extrusion direction, the loading carrying area of the material reduces and the stress concentrations are generated around the particles leading to an earlier local yielding at relatively low loads. This is the reason why there is anisotropy in elongation.

Fracture Analysis. Figure 6 demonstrates the SEM micrographs of the fracture surface of the Al–Si alloy and SiC reinforced composites after tensile tests. In the Al–Si alloy (Fig. 6a), fracture surfaces were mainly composed of ductile fracture, and cleavage fracture regions were hardly observed. Small dimples with the size of about 3~4 μm can be attributed to the decohesion of Si particles in the Al–Si alloy during tensile loading. It can be seen that the eutectic Si particles were homogeneously distributed with the size similar to that of SiC particles. In Fig. 6b, it is indicated that the incorporation of the 4.5 μm SiC reinforcement had a tendency of segregation in the process of spray deposition, where cracks always occurred under tension as observed. The separation of the SiC/matrix interface is indicated by arrows in Fig. 6b, which is one of the major fracture mechanisms in the 4.5 μm SiC_p/Al-Si composite. The weak interfacial bonding between the particles and matrix in the 4.5 μm SiC_p/Al-Si composite results in poor tensile properties compared to that of the Al–Si alloy. In the 20 μm SiC_p/Al-Si composite, many cracked SiC particles were observed in the longitudinal direction which were marked by arrows in Fig. 6c.

Based on detailed examination and analysis of the fracture surface micrographs, the predominant fracture mechanisms are summarized in Table 2 for all three materials. In both the longitudinal and transverse directions, the Al-7Si alloy showed Si decohesion, while the 4.5 μm SiC_p/Al-Si composite showed Si decohesion as well as interfacial debonding between SiC particles and matrix. As comparison, SiC fracture has been observed in the

T a b l e 2

Predominant Fracture Mechanism Dependence on Particle Size in the Longitudinal and Transverse Axes

Orientation	Al–Si alloy	4.5 μm SiC_p/Al-Si	20 μm SiC_p/Al-Si
Longitudinal	Si decohesion	Si decohesion, interfacial debonding	Si decohesion, SiC_p fracture (most) or interfacial debonding (little)
Transverse	Si decohesion	Si decohesion, interfacial debonding	Si decohesion, SiC_p fracture (little) or interfacial debonding (most)

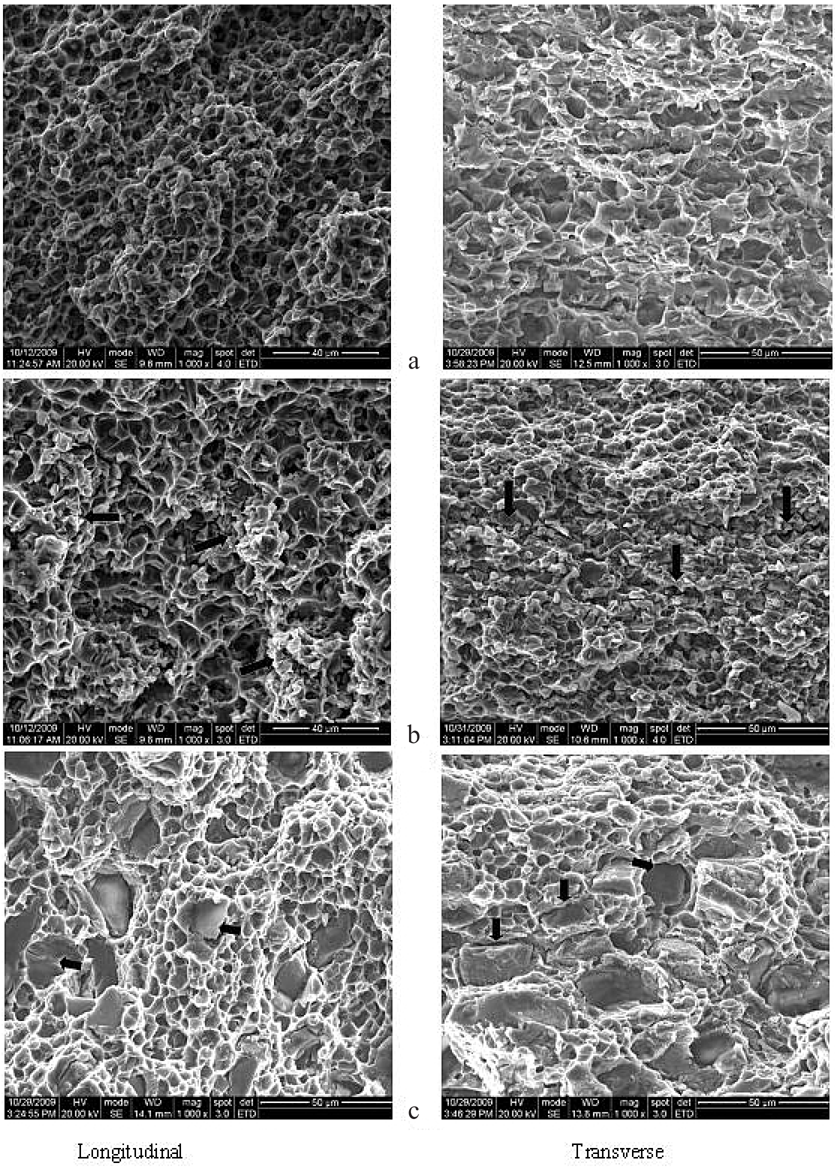

Fig. 6. SEM of tensile fracture surfaces: (a) Al–Si alloy; (b) 4.5 μm SiC_p/Al-Si composite; (c) 20 μm SiC_p/Al-Si composite.

longitudinal direction in 20 μm SiC_p/Al-Si composite, whereas the interfacial debonding between reinforcement and matrix happened mainly in the transverse direction. It implies that in the 20 μm SiC_p/Al-Si composite, the cracks nucleated at the particle/ matrix interface in the transverse direction and then propagated through the matrix by inter void coalescence. This can be related with the inclination angle between the load direction and particle orientation. In the longitudinal direction of 20 μm SiC_p/Al-Si composite, most SiC particles displayed an inclination angle to the load direction < 45 or $> 135°$. As a result, the SiC particles had high resistance to debonding due to large interface areas parallel to the loading direction, and therefore they were more likely to fracture. On the other hand, in the transverse direction of 20 μm SiC_p/Al-Si composite, it was observed that high aspect ratio SiC particles with an inclination angle to the load direction > 45 or $< 135°$ had a strong tendency to debond.

Conclusions. The influence of SiC particles with different sizes and orientation anisotropy on the tensile properties of spray-formed SiC_p/Al-Si composite was investigated and compared with that of the Al–Si alloy.

1. Microstructure characterizations manifested a preferred orientation of the reinforcement particles paralleled to the extrusion axis, and the degree of orientations anisotropy increased with increasing reinforcement size, due to an increase in mean free path between particles. In the direction perpendicular to the extrusion axis, less particle alignment was observed.

2. The SiC reinforced composites exhibited higher elastic modulus, tensile strength and elongation along the longitudinal direction (parallel to the extrusion axis) than those in the transverse direction. Moreover, the sample with larger particles displayed more anisotropic behavior because of the increasing influence of SiC reinforcement on the tensile properties, which is consistent with the microstructural anisotropy.

3. The fracture mechanism in the 4.5 μm SiC_p/ Al-Si composite was attributed to the interfacial debonding between SiC and matrix in two orientations. In the case of 20 μm SiC_p/Al-Si composite, it was SiC particles cracking predominant in the longitudinal direction and interfacial debonding in the transverse direction, respectively.

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Резюме

Досліджено вплив анізотропії, що визначається орієнтацією SiC частинок, на механічні властивості при розтязі SiC_p/Al-Si композита, отриманого методом напилення. Результати дослідження SiC_p/Al-Si композита зіставляли з такими сплава, що має незміцнювану матрицю. При розтязі Al-Si сплаву в умовах максимального старіння завдяки введенно SiC частинок модуль пружності збільшується, а границя міцності і подовження зменшуються. Визначення характеристик мікроструктури показало, що зміцнювані частинки переважно орієнтовані у напрямку, паралельному осі екструзії. При значному зміцненні ступінь анізотропії, що визначається орієнтацією частинок, значно вища. Значення модуля пружності, границі міцності і подовження при розтязі в поздовжньому напрямку (паралельно осі екструзії) більші, аніж у поперечному (перпендикулярно до осі екструзії). Ознакою механізму руйнування композита з частинками розміром 4,5 мкм вважають граничний розподіл між SiC частинками і матрицею у двох напрямках. У випадку зміцненого алюмінію з частинками розміром 20 мкм розтріскування SiC частинок у поздовжньому напрямку і граничний розподіл у поперечному напрямку відіграють важливу роль у процесі руйнування.

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