Evolution of Thermoplastic Shear Localization and Related Microstructures in Al/SiC$_p$ Composites Under Dynamic Compression

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The localized shear deformation in the 2024 and 2124 Al matrix composites reinforced with SiC particles was investigated with a split Hopkinson pressure bar (SHPB) at a strain rate of about 2.0×10^3 s^{-1}. The results showed that the occurrence of localized shear deformation is sensitive to the size of SiC particles. It was found that the critical strain, at which the shear localization occurs, strongly depends on the size and volume fraction of SiC particles. The smaller the particle size, the lower the critical strain required for the shear localization. TEM examinations revealed that Al/SiC$_p$ interfaces are the main sources of dislocations. The dislocation density near the interface was found to be high and it decreases with the distance from the particles. The Al matrix in shear bands was highly deformed and severely elongated at low angle boundaries. The Al/SiC$_p$ interfaces, particularly the sharp corners of SiC particles, provide the sites for microcrack initiation. Eventual fracture is caused by the growth and coalescence of microcracks along the shear bands. It is proposed that the distortion free equiaxed grains with low dislocation density observed in the center of shear band result from recrystallization during dynamic deformation.

KEY WORDS: Al/SiC$_p$ composites, Shear localization, Recrystallization, Dislocations

1. Introduction

In the last decade, silicon carbide particle reinforced Al alloy composites have received much attention because of their high elastic modules and high specific strengths combined with light weight and wear resistance[1,2]. The increased deformation resistance of these composites is considered to be related to the particles, fine grains, high dislocation density as well as the precipitates in the matrix. The mechanical behavior of the composites has usually been characterized in terms of their quasistatic deformation[3,4]. However, the mechanical behavior of the metal matrix SiC$_p$ reinforced composites at high strain rates, in particular, their localized shear deformation, has not been well understood. Actually, there has been little work reported on the relationship between the dynamic mechanical behavior and the microstructural evolution of the composites with different sizes and volume fractions of the particles[5~7].

The goal of this study was to elucidate a fundamental understanding of localized shear deformation. The emphasis was placed on the microstructural evolution and the effect of SiCp on the formation of shear localization in composites with different sizes and volume fractions of the particles under dynamic compression.

2. Experimental

The materials used in this investigation were the 2024 and 2124 Al composites reinforced with different sizes and volume fractions of SiC$_p$. The compositions (wt pct) of the composites are given in Table 1.

The materials were machined to cylindrical specimens with 5 mm in diameter and 5 mm in height. The specimens were solution treated at 530°C for 55 min, quenched in cold water, and then aged at 170°C for 4 h. The dynamic compression tests were performed on both materials with a split Hopkinson pressure bar (SHPB) at a strain rate of about 2.0×10^3 s^{-1}. The applied stress was parallel to the extrusion direction. The tested specimens were used to characterize the evolution of shear localization and the related microstructures with SEM and TEM.

3. Results and Discussion

3.1 Shear localization

3.1.1 Critical strain The strain and strain rate conditions required to trigger shear localization and the modeling of shear banding process have been reported theoretically[8~12]. In particular, some simulations to study the effect of material constitutive parameters, such as work hardening rate, strain rate sensitivity, and thermal softening rate, on shear localization are available. Unfortunately, only few experimental data can be directly compared with these analyses to verify the formation of shear localization.

Figure 1 is an optical micrograph, showing localized plastic shear strain in the 2024Al/SiC composite, with 10 μm in particle size and 15% in volume fraction subjected to dynamic compression. It can be seen that localized shear deformation did not appear in the specimen deformed to plastic strain of 0.39, under which the specimen was still homogeneously deformed as shown in Fig.1(a). When the plastic strain reached approximately 0.56, shear localization began to appear on the cross-section of the specimen as shown in Fig.1(b). However, when the plastic strain attained to about 0.60, a well developed band with 20 μm in width appeared in Fig.1(c). Another example of the 2024Al/SiCp with 40 μm in particle size is shown in Fig.2, indicating that shear localization started to appear at a strain of 0.6 (Fig.2(a)), and then it developed a well narrow band with 10 μm in width when the plastic strain reached 0.64 as shown in Fig.2.(b). These observations support the concept of a critical strain for shear formation, and are in good agreement with the results of our recent investigation of Al-Li[13].

3.1.2 Role of SiC$_p$ Figure 3 shows a set of SEM micrographs, taken from 2124Al-17 vol. pct SiC$_p$ composites with particles of 3, 13 and 37 μm in size. It can be seen that localized shear could be significantly influenced by the size and distribution

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Table 1 Compositions of the 2024 and 2124 Al composites (wt pct)

Materials	Cu	Mn	Mg	Fe	Zn	Si	Cr	Ti+Zr	Al
2124	4.0~4.4	1.3~1.6	0.4~0.7	0.3	0.25	0.20	0.1	0.20	Bal.
2024	3.8~4.9	0.3~0.9	1.2~1.8	0.5	0.25	0.05	0.1	0.15	Bal.

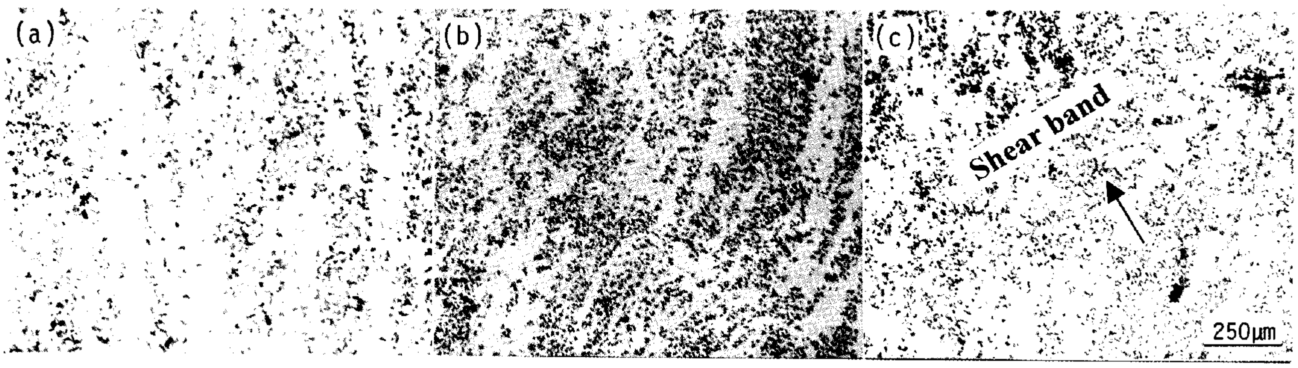

Fig.1 Optical micrographs, showing the evolution of localization with increasing plastic strain of (a) 0.39, (b) 0.56 and (c) 0.60 in 2024 Al/SiC$_p$ composite with 10 μm in particle size and 15% in volume fraction of SiC$_p$

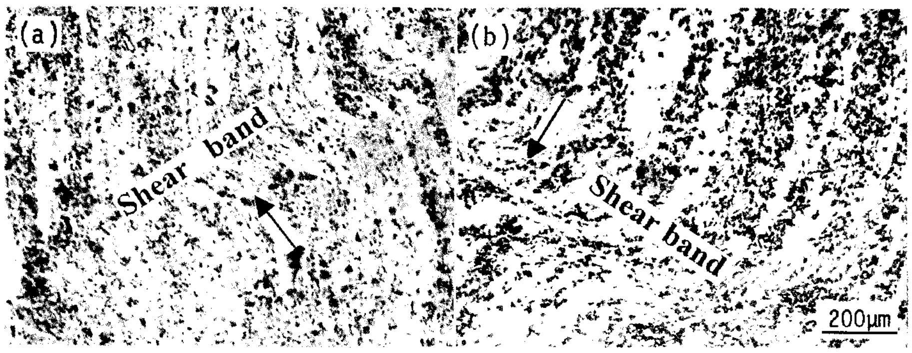

Fig.2 Optical micrographs, showing that localized shear appears at the plastic strain of 0.60 (Fig.2(a)), and well developed at a strain of 0.64 (Fig.2(b)) in 2024Al/SiC composite with SiC$_p$ of 40 μm in size

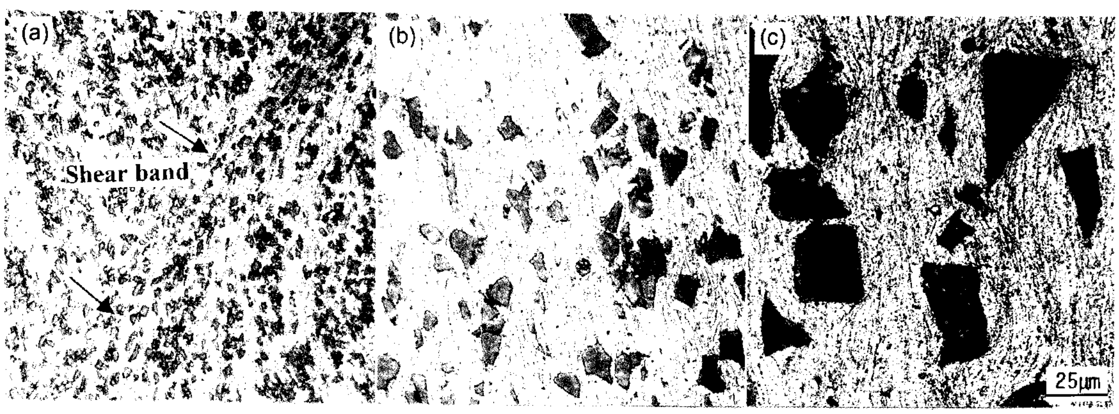

Fig.3 SEM micrographs, showing the deformation pattern in Al-17%SiC$_p$ composite with an average particle size of 3 μm (a), 17 μm (b) and 37 μm (c) subjected to dynamic loading

of the particles. In other words, the composite reinforced with smaller particles (3 μm) does develop a well defined localized band with 10 μm in width as shown in Fig.3(a). However, the formation and development of localized shear in the composites with larger SiC$_p$, 13 and 37 μm in size, tend to be blocked by the particles obviously, so the localized shear bands were not developed well as shown in Fig.3(b) and 3(c). Also, the plastic flow was changed significantly by the large particles in the band as shown in Fig.4. This implies that the larger particles may play an important role in preventing shear localization. In other words, the tendency of the composite reinforced with smaller particles to form shear is higher than that of the other two composites, when the volume fraction of SiC$_p$ in the composites remains the same. However, it is worthy noticing that smaller SiC$_p$ in the composites are always beneficial to the strength.

3.2 Deformation structure in the bands

Plastic deformation behavior of metals and alloys under quasistatic loading can be described well in terms of generation, movement and interaction of dislocations. At very high strain and strain rate, however, deformation modes of materials may be abruptly changed. The microstructures induced during this kind of deformation, especially compared to that

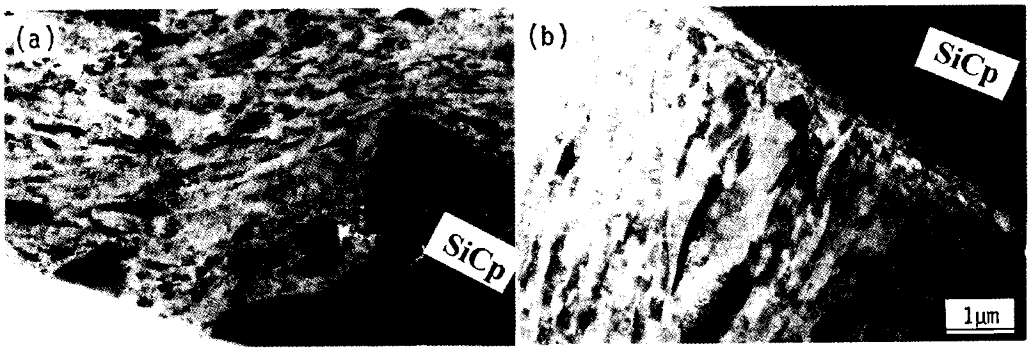

Fig.4 Plastic flow pattern is changed by large SiCp in the band

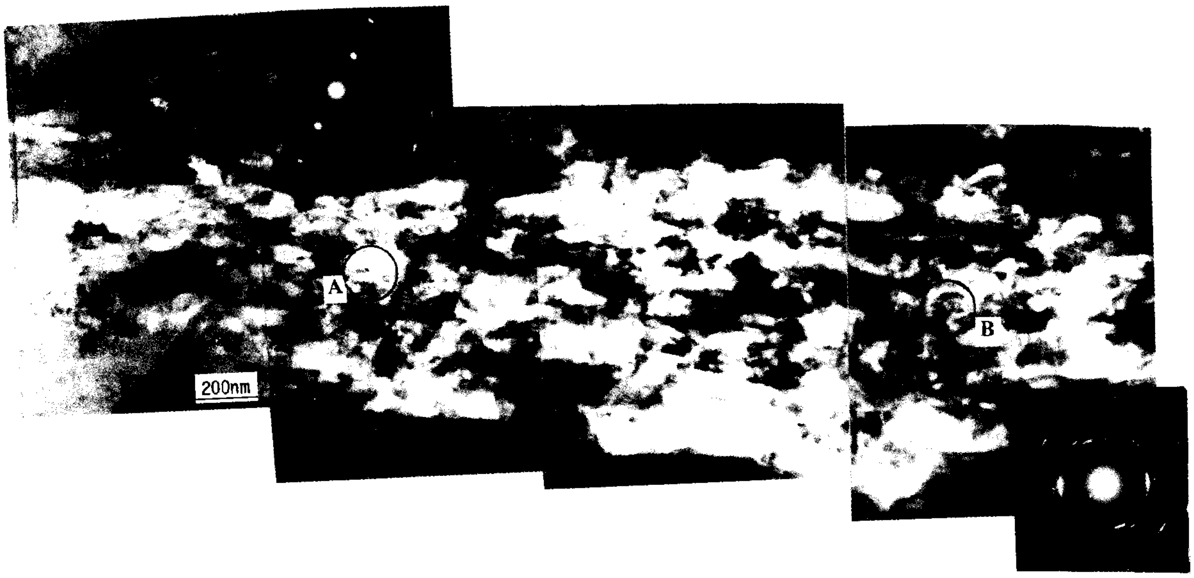

Fig.5 Microscopic shear band crossing hundreds of grains in 2024 Al/SiC_p. The elongated grains and tangled cell arrangement of dislocations tend to be aligned along the direction of the band. A and B mark two regions with entirely different deformation modes as noted in the text

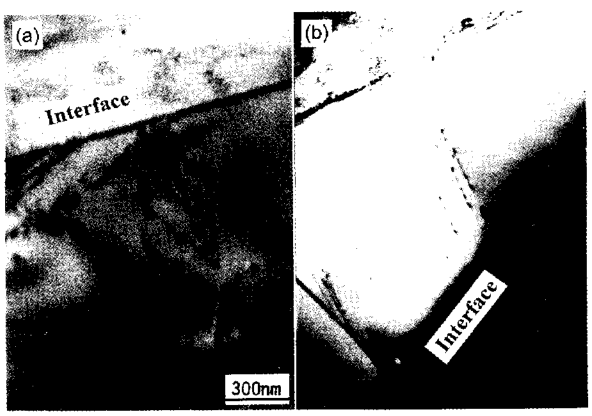

Fig.6 Dislocation emission from the interface of Al/SiC_p (a), and high density of dislocations near the interface (b)

under quasistatic conditions, become very complicated, involving a series of crystallographic and even non-crystallographic events on various structure scales. There are generation, multiplication and interaction of dislocations, refinement and rotation of the grains, sub-substructure formation, misorientation change, and even initiation, growth and coalescence of microcracks, leading to catastrophic failure of the materials.

Figure 5 shows a typical microscopic shear band, which crosses a hundred of grains in the 2024Al/SiCp composite. It can be seen that the elongated grains and tangled cell arrangement of dislocations tend to be aligned along <111> direction of the band. Electron diffraction analysis showed that this kind of substructure had low-angle boundaries of about 7~10 degree in orientation change.

Interestingly, we found distinct electron diffraction patterns from some selected areas in the band, for example, A and B marked by circles (Fig.5). A sharp and plain pattern produced from area A indicates a deformation mode, which still keeps its crystallographic nature (see the left inset in Fig.5). On the other hand, in area B, the shear band creates a well developed spotty ring (see the right inset in Fig.5), implying the operation of multislips combined with large accumulated plastic strain in the band has occurred. It is well known that this characteristic feature could only be produced by a large misorientation.

Another interesting deformation feature observed in the present study is shown in Fig.6. This figure indicates that the interfaces between the Al matrix and SiC_p may be the source releasing a great deal of dislocations (Fig.6(a)). The dislocation density was substantially higher near the interface of Al/SiC_p and decreases with the distance from the SiC_p (Fig.6(b)).

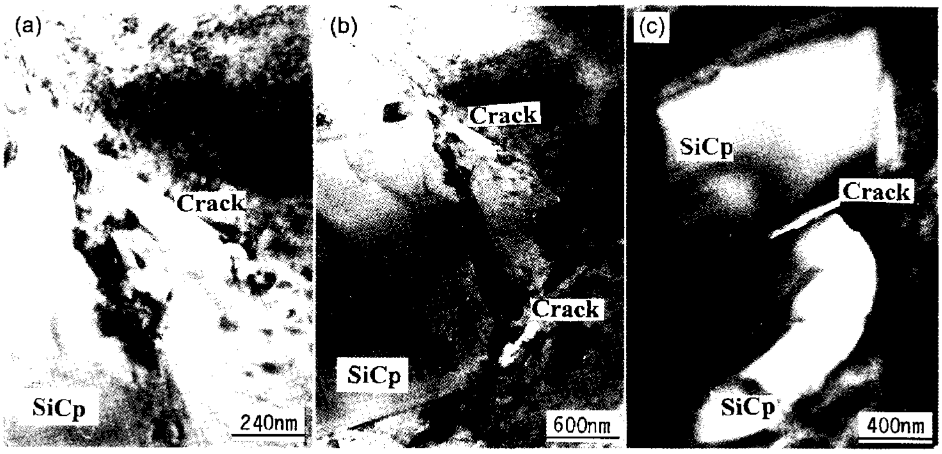

Fig.7 TEM micrographs, showing the microcrack initiation at the interface of Al/SiC_p(a), and the high density of dislocations near the interface (b), and SiC_p cracking(c) in the band

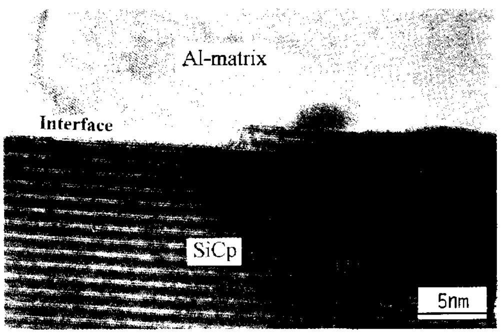

Fig.8 HREM lattice image, showing a well bonded interface of Al/SiC_p

3.3 Microcrack and fracture

The development of shear is accompanied by microstructural damage. This is particularly true for shearing in the composites reinforced with larger particles. In this case, numerous cracks linked to larger particles were visible. This may be mainly due to the deformation incompatibility between the ductile Al matrix and the hard SiC_p. These can be seen clearly from Fig.7. The microcracks initiated easily at the interfaces of Al/SiC_p, in particular on the sharp corners of the particles, although the interface were well bonded, as HREM observation shows in Fig.8. Therefore, the shear band may provide an easy path for crack propagation by the growth and coalescence of microcracks, along which eventual fracture may easily occur as shown in Fig.9.

3.4 Recrystallization in shear bands

Deformation induced recrystallized structure at high strain and strain rate has been reported[12~20]. Derby[21] classifies dynamic recrystallization mechanisms into rotational and migrational types. More recent research and calculation by Meyers *et al.*[19,22] revealed that the break-up of the elongated subgrains and diffusive rotation of the grain boundaries may occur during dynamic loading, leading to dynamic recrystallization in localized bands. This phenomenon was also observed in the present study. Figure 10(a) is a typical TEM field, taken from a local area in the band in 2024 Al/SiC_p composite subjected to dynamic loading. This picture shows distortion-free equiaxed grains with low dislocation density and well defined boundaries (by arrows). These characteristic features are quite different from those observed near (Fig.10(b)) and outside (Fig.10(c)) the band.

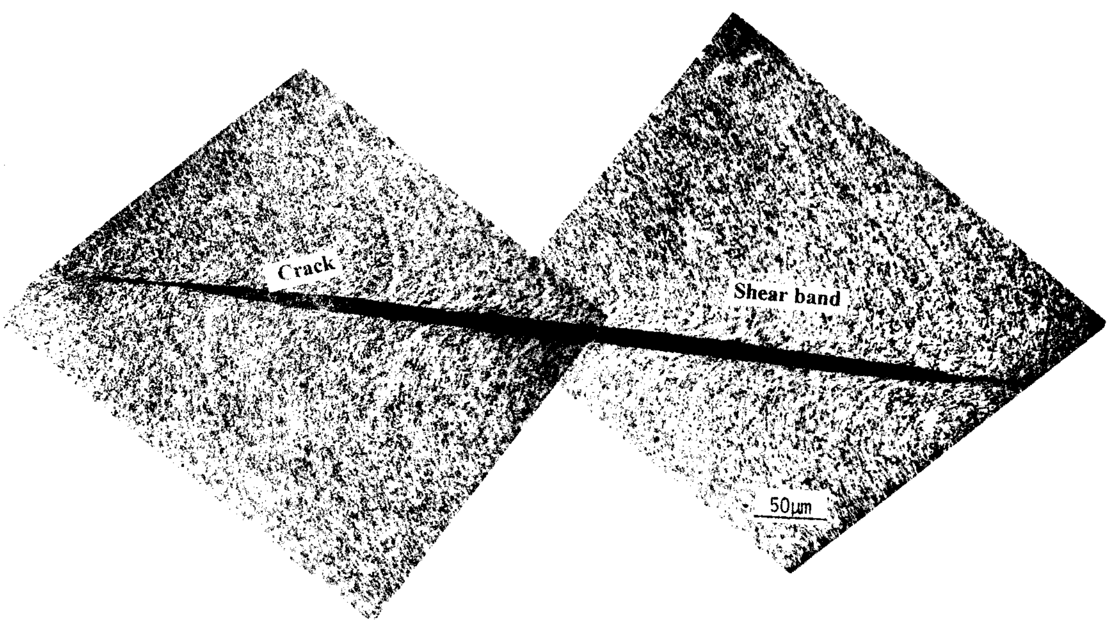

Fig.9 Crack propagation along the shear band in the 2124Al/SiC_p composite

Fig.10 Recrystallization grains (a) and elongated cell structure (b) in the shear band produced during dynamic compression in Al/SiC_p composite

These features imply that recrystallization might be the most probable mechanism. The temperature that marks the onset of thermal recovery or recrystallization in metals is generally described by:

$$T = (0.4 - 0.5)T_m$$

where, T_m, the melting point of metals, is 933 K for Al. Therefore, the onset of recrystallization in the composite may occur in the range between 373 and 466 K.

It is known that the role of temperature is of major importance for the formation of shear bands, because of its adiabatic nature. Due to the difficulty in measuring temperature within the shear band during dynamic deformation, the temperature rise within the band has to be estimated using stress strain response obtained from the same material in cylindrical compression tests[23], assuming that most of the plastic deformation work is converted to heat (90%). Thus, the temperature rise within the band can be written as:

$$T = T_o + 0.9W_p/\rho C_v$$

where, W_p the specific work of deformation, can be expressed by the following equation:

$$W_p = \int \sigma d\varepsilon$$

where T_o is the room temperature, the density of the material ρ is 2.7×10^3 kg/m^3, and C_v the heat capacity, is 903 J/kg·K for Al. Assuming linear hardening up to strain of 0.56 for the $2124Al/SiC_p$ composite, we obtained W_p=560×10^6J/m^3 according to the data in literature [23]. Thus, the temperature in the band is

$$T = T_o + 0.9W_p/C_v = 293\ K + 206\ K = 499\ K$$

which is higher than the matrix recrystallization temperature. Similarly, the temperature outside the band is estimated to be 402 K, which is lower than for recrystallization. From these calculations, it is reasonable to propose that the observed distortion-free equiaxed grains result from recrystallization during dynamic loading, although it is still not clear whether this structure develops simultaneously with deformation or subsequent to deformation.

4. Conclusions

(1) Localized shear bands were observed in both 2024 and 2124 Al/SiC_p composites with different sizes and volume fractions of the particles.

(2) A critical strain is required for shear band formation in these two composites.

(3) SiC_p plays a significant role in the formation of shear localization in the composites. The smaller the particles, the easier the band formation.

(4) The occurrence of shear localization involves a series of crystallographic and non-crystallographic deformation events in the bands, including dynamic emission, multiplication of dislocations, refinement and elongation of grains, and the formation of misorientation with low angle boundaries along the shear direction.

(5) Microcracks could easily initiate along the interfaces between Al/SiC_p, in particular, on the sharp corners of particles. Therefore the shear band may provide an easy path for crack propagation by the growth and coalescence of microcracks, leading to eventual fracture.

(6) The distortion-free equiaxed grains observed in the band are proposed to be the result of recrystallization during dynamic compression in the 2024 and 2124 Al/SiC_p composites.

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