JOURNAL OF MATERIALS SCIENCE 37 (2002) 2527–2534

Influence of SiC whisker on planar slip in Al-Li based alloys

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The tensile deformation microstructure characteristics of silicon carbide whisker (SiC_w) reinforced Al-Li and Al-Li-Cu-Mg-Zr composites prepared by squeeze casting technique were studied by means of transmission electron microscopy (TEM), in order to evaluate the influence of SiC whisker on planar slip in Al-Li based alloys. For the purpose of comparison, the microstructural features of the unreinforced matrix alloys with the identical fabrication, thermal processing and tensile deformation history were also investigated. Dislocation pairs and intense slip bands originated from cutting of δ' (Al_3Li) phases by moving dislocations, could be found in the specimens of Al-Li and Al-Li-Cu-Mg-Zr alloys, whereas absent in either SiC_w/Al-Li or SiC_w/Al-Li-Cu-Mg-Zr composites. The results demonstrate that the addition of SiC whisker to Al-Li based alloys, has a considerable effect on suppressing planar slip which is a general phenomenon in Al-Li based alloys resulting from the interaction between δ' phase and dislocations.

1. Introduction

Among the discontinuously reinforced aluminum matrix composites developed and evolved extensively in the past decades, silicon carbide particulate or whisker reinforced aluminum-lithium matrix (SiC/Al-Li) composites have gained increased attentions. In the view of composite design, the addition of Li to SiC/Al composite is projected to enhance the bonding of SiC reinforcement and Al matrix, thus resulting in the improvement of the SiC/Al composite properties [1–4]. On the other hand, from the point of modifying Al-Li based alloys, the incorporation of SiC particulate or whisker which could be regarded as the "dispersed strengthening constituent" to Al-Li based alloys, would be anticipated to have either directs or indirect effect on suppressing the planar ship inherently existed in the Al-Li based alloys [5]. Coplanar ship is a common phenomenon in the coherent or semi-coherent precipitation-hardened alloys which originates from the cutting of the coherent or semi-coherent precipitates by moving dislocations and would degrade the mechanical property with substantial decrease of ductility and fracture toughness [6, 7]. The binary Al-Li alloy is a typical coherent precipitation-hardened alloy strengthened by the metastable δ' phase. The cutting of δ' phase by moving dislocations on a single slip plane would lead to slip localization and subsequently formation of dislocation pairs and planar slip bands [8, 9]. Alloying attempts such as the addition of zirconium, copper and magnesium elements to Al-Li binary alloy, directed at retarding grain boundary migration or forming other phases to disperse ship has been made [10–14], but could not totally eliminate the coplanar ship. As non-shearable particle, silicon carbide whisker or particulate is rationally expected to be effective in partially or fully suppressing the coplanar ship in Al-Li based alloys, which would enhance uniform deformation and subsequently improve the mechanical properties, especially the ductility and toughness of the alloys. It tends to be of particular interest to certify such assumption, as is the objective of present investigation.

The deformation microstructure in a polycrystalline aluminum alloy containing small size ceramic particles has been evaluated in order to reveal the interaction of the ceramic phases with dislocations and their possible effects on slip deformation [15]. Following the similar consideration, the microstructural features of the tension deformed Al-Li and Al-Li-Cu-Mg-Zr alloys reinforced with SiC whisker are studied in present study using TEM technique, focusing on demonstrating the influence of SiC whisker on deformation behavior of Al-Li based alloys. In order to avoid interference from secondary processing such as extrusion or rolling, the experimental materials were all in the as-received (squeeze casting) condition. Further, keeping it in minds that the possible existence of non-shearable precipitates, such as S′ (Al_2CuMg) or T_1 (Al_2CuLi) phases in Al-Li-Cu-Mg-Zr alloy would also favor the dispersion of planar slip, the SiC_w/Al-Li and its counterpart matrix alloy were firstly examined, and then the SiC_w/Al-Li-Cu-Mg-Zr composite and its unreinforced matrix alloy.

2. Experimental

The SiC whisker reinforced aluminum-lithium matrix composites employed for this study were fabricated by

TABLE I Composition of the experimental composites

SiC_w (vol%)	Li (wt%)	Cu (wt%)	Mg (wt%)	Zr (wt%)	Al
17	2.01	–	–	–	Bal.
15	2.18	2.10	0.8	0.13	Bal.

a squeeze casting route [5], with the composition listed in Table I. The counterpart unreinforced matrix alloy for each composite was obtained from the same manufacturing processing. The as-cast composites and their unreinforced matrix alloys were subject to an annealing treatment of 480°C × 8 h + 520°C × 16 h, followed by a solution (530°C × 40 min, water-quenched) and immediate artificial aging at 190°C for various time. Referencing to the difference of aging time, the conditions such as under-aged, peak-aged and over-aged could be reached for SiC_w/Al-Li composite, SiC_w/Al-Li-Cu-Mg-Zr composite and their unreinforced matrix alloys, respectively, and further details have been provided elsewhere [5].

The tensile tests were carried out at ambient temperature on an Instron 1186 tensile machine using plate specimens at a constant cross head velocity of 0.5 mm/min. The tensile specimen with thickness of 2 mm and width of 4 mm, has a gage length of 14 mm.

The specimens for TEM examination were mechanically cut from the tensile fractured specimens, parallel to the specimen axis, in the region adjacent to the fracture surface. The TEM foils of composite were finally ion milled with liquid nitrogen cooling, while the foils of unreinforced matrix alloy were electrolytically thinned at −20°C. TEM examinations were preformed at 120 kV in a Philippics CM analytical transmission electron microscope.

3. Results

3.1. Deformation microstructures in Al-Li alloy and its composite

TEM observations were extensively carried out on the well-prepared thin foils of Al-Li alloy and SiC_w/Al-Li composite at different heat treatment conditions, in order to examine the main features of the deformation microstructures. The general views of the deformation microstructures observed in Al-Li alloy aged on different conditions are shown in Fig. 1. In the specimens with various aging time, it is not unusual to find the typical planar slip dislocation structures such as dislocation pairs and intense slip bands, which are also thought to result from the cutting of δ' phase by moving dislocations, the same as identified by previous studies [7–9]. Fig. 1a and b provide the discrete dislocation pairs and slip bands in the under-aged specimen, respectively, which are all locally distributed, clearly revealing that the planar slip appears to be the predominate deformation mode in the under-aged Al-Li alloy.

The representative dislocation configuration in peak-aged specimen, as shown in Fig. 1c, also exhibits distinct localized slip band characteristics. Many dislocation pairs which array along the same direction and heavily pile up could be found within the slip bands. Compared with that in the under-aged specimen, the slip band in the peak-aged specimen seems coarser and more concentrated, indicating that the slip band becomes more intense with the proceeding of aging up to peak-aging, and consequently implying the more localized deformation in the Al-Li alloy on peak-aged condition.

But in the case of over-aged condition, the slip band tends to be less intense and distribute uniformly, as seen in Fig. 1d. And some dislocation loops attributed to sweeping past δ' phase by moving dislocation can also be visibly found in the over-aged specimen, which demonstrates the transition in the deformation models in Al-Li alloy as the progress of aging to over-aged condition. Such conversion of dislocation motion is expected to be beneficial to enhancing uniform deformation and somewhat effective in suppressing the planar slip in Al-Li alloy [14].

All the above mentioned dislocation configurations which reflect the deformation microstructure features in different aged Al-Li specimens, should correlate with the interaction between δ' phase and moving dislocation and would be discussed in the following section.

Sufficient TEM examinations preformed on SiC_w/Al-Li composite showed that the introduction of SiC whisker to Al-Li alloy had a considerable influence on the dislocation configuration as well as the deformation patterns. The typical TEM micrographs showing the dislocation configurations in the specimens of SiC_w/Al-Li composite at various heat treatment conditions are provided in Fig. 2. It can obviously be seen that the dislocation density in SiC_w/Al-Li composite is fairly high compared with the unreinforced Al-Li matrix. And either in the solutionized specimen (Fig. 2a) or in the aged specimens (Fig. 2b–d), do the dislocation structures not show any planar slip characteristics, no matter whether they are in adjacent to SiC whisker (Fig. 2a–c) or far from SiC whisker (Fig. 2d). Instead, the dislocation configuration tends to show tangled structure feature, with the formation of random net arrays. The dislocation near SiC whisker is frequently found to more tangly distribute and to be higher in density, as is the case for solutionized specimen shown in Fig. 2a. Similar dislocation configuration could also be observed in the under-aged SiC_w/Al-Li composite, no dislocation pairs and slip bands are present, whereas with random distributed dislocations being seen in the matrix of the composite (Fig. 2b).

The dislocation arrangement in the specimen of peak-aged SiC_w/Al-Li composite is rather tangled, with the formation of sinuous dislocation veins, and the dislocation configuration near SiC whisker displays more tanglesome characteristics (Fig. 2c) as compared to that in the solutionized and under-aged specimens. Although the dislocations in the over-aged SiC_w/Al-Li composite still distribute as sinuous veins, the extent of dislocation tangle appears lower (Fig. 2d) than in peak-aged composite, which is thought to be due to the recovery of the matrix dislocation leading to the reduction in dislocation density in SiC_w/Al-Li after aging for long time.

Based on the TEM examination results of dislocation configurations in tensile deformed specimens of Al-Li

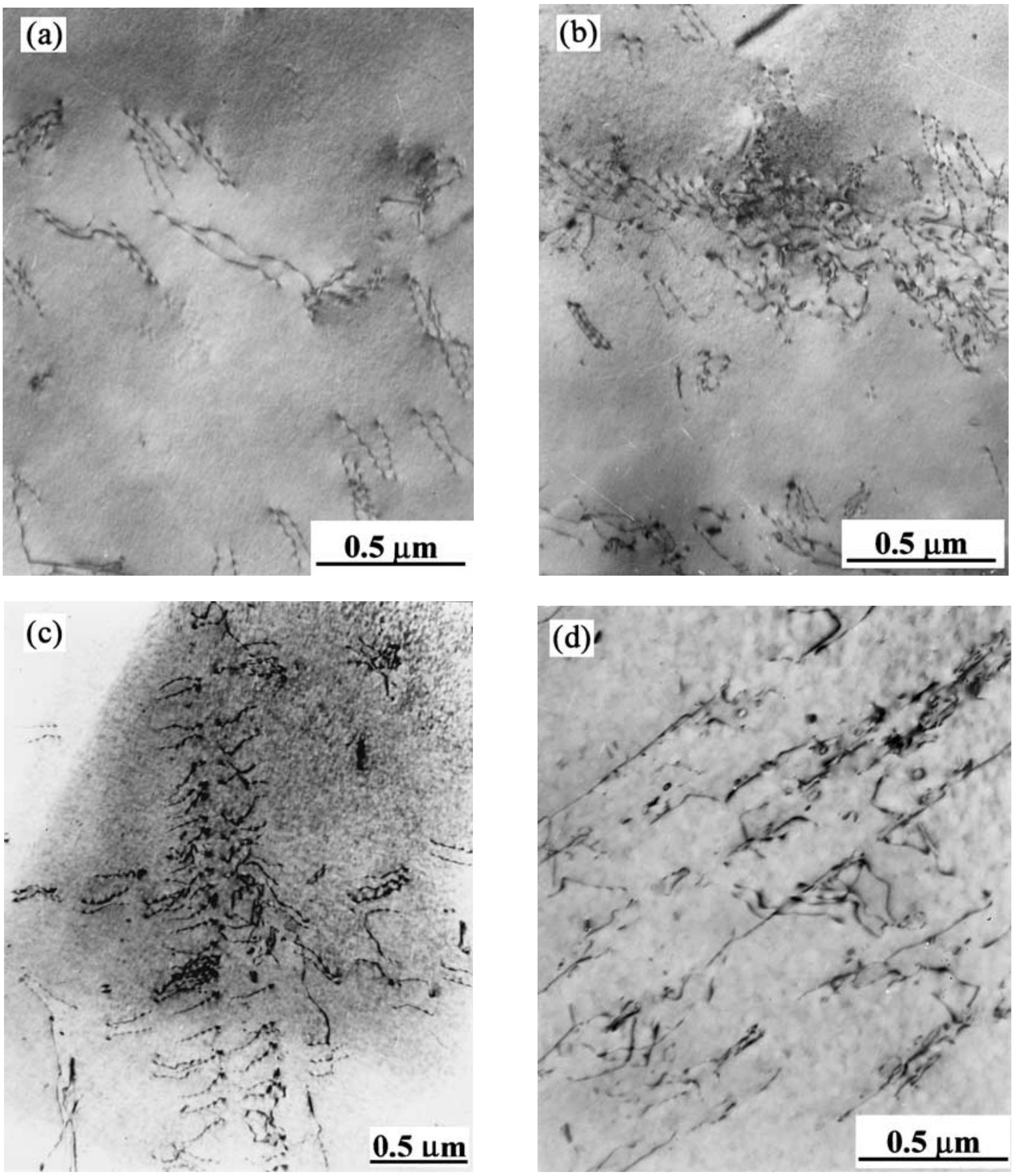


Figure 1 Dislocation configuration in the tensile deformed specimens of the Al-Li alloy aged at 190°C: (a) Paris of dislocation in the underaged specimen; (b) Coarse slip bands in the underaged specimen; (c), (d) Slip bands in the peakaged and overaged specimens, respectively.

alloy and SiC_w/Al-Li composite, it can be concluded that the dislocation motion pattern would be modified, from pronounced planar slip to relative dispersed slip in the Al-Li alloy after the incorporation of SiC whisker. The presence of SiC whisker, a kind of nondeformable phase, and the relative microstructure development are suggested to be responsible for this conversion, and to be advantageous to promoting the mechanical properties of Al-Li alloy. Further discussion on this will be given in the subsequent section.

3.2. Deformation microstructures in Al-Li-Cu-Mg-Zr alloy and its composite

On the base of deformation microstructure examinations in Al-Li alloy and SiC_w/Al-Li composite, the influence of SiC whisker on dislocation structures, thus on deformation patterns in Al-Li-Cu-Mg-Zr alloy was investigated following the same strategy. The dislocation configurations in Al-Li-Cu-Mg-Zr alloy and SiC_w/Al-Li-Cu-Mg-Zr composite are shown in Figs. 3 and 4, respectively. The presence of planar slip features could also be apparently observed in Al-Li-Cu-Mg-Zr alloy. Both in the under-aged and peak-aged specimens of Al-Li-Cu-Mg-Zr alloy, the strongly sheared δ' precipitates cut by moving dislocations could be detected using TEM dark field images, as shown in Fig. 3a which is a typical sheared δ' phase morphology in the peak-aged specimen. In TEM bright field images, the intense slip bands were also found in aged A-Li-Cu-Mg-Zr alloy, but the level of homogeneity appears to increase compared to that in Al-Li alloy, which is attributable to the combined dispersion effect on dislocation of precipitates such as S′ phase, β' (Al_3Zr) phase, refinement of grain or subgrain within the Al-Li-Cu-Mg-Zr alloy. The general TEM micrographs showing slip bands

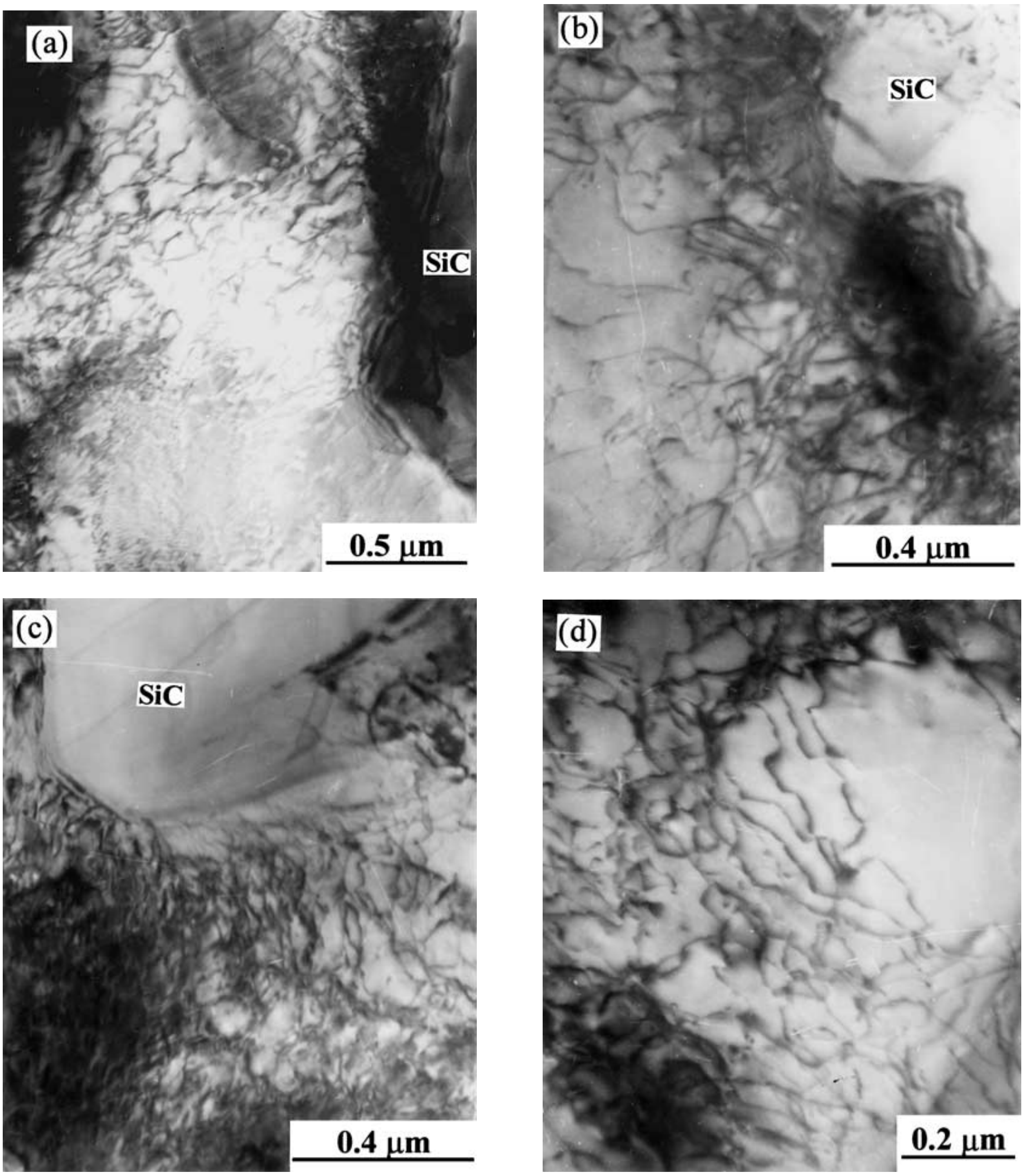


Figure 2 Dislocation configuration in the (a) as-quenched, (b) underaged, (c) peakaged and (d) overaged specimens of the SiC_w/Al-Li composite after tensile deformation.

in the under-aged and peak-aged specimens of Al-Li-Cu-Mg-Zr alloy are demonstrated in Fig. 3a and c, respectively.

Similar as the case for SiC_w/Al-Li composite, the incorporation of SiC whisker to Al-Li-Cu-Mg-Zr alloy, does also bring considerable change in deformation dislocation structures. No evidence either of dislocation pairs or of intense slip bands was found in the SiC_w/Al-Li-Cu-Mg-Zr composite. Relatively uniform dislocation tangles and nets were seen in the matrix both far from or near SiC whisker, and the dislocation density around SiC whisker tended to be higher. The typical deformation microstructures observed in the specimens of solutionized, under-aged, peak-aged and over-aged SiC_w/Al-Li-Cu-Mg-Zr composites are shown in Fig. 4a–d, respectively. The detailed TEM examinations preformed on deformed specimens of SiC_w/Al-Li-Cu-Mg-Zr composite reveal that the planar slip of dislocation in Al-Li-Cu-Mg-Zr alloy is also suppressed by the presence of SiC whisker, the same as in Al-Li binary alloy.

4. Discussion

The deformation microstructure in finely dispersed coherent or semi-coherent precipitation-hardened alloy is governed by the interaction between moving dislocations and the precipitates which act as obstacles against shearing and thus against dislocation slip. Consequently, this interaction which depends on the precipitate/matrix system features would determine the deformation patterns as well as the arrangement of dislocations in the alloy [7]. The previous studies have clearly revealed that the fine coherent precipitate, δ' phase, with an ordered structure offering the high-strength, could be cut by moving dislocations, which should be responsible for the planar slip in Al-Li based alloys

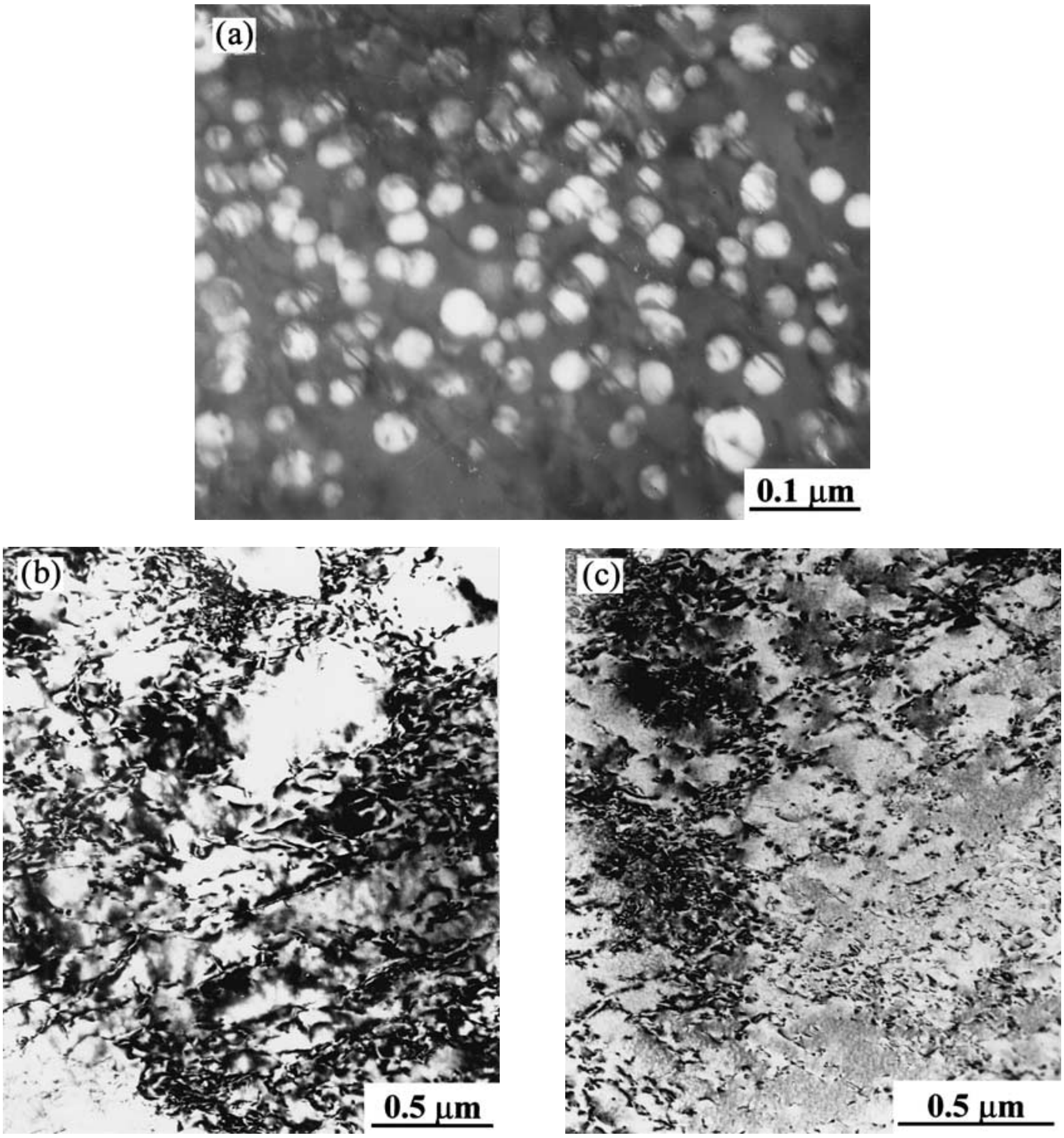


Figure 3 Dislocation configuration in the tensile deformed specimens of the Al-Li-Cu-Mg-Zr alloy aged at 190°C: (a) Dark-filed image of δ' phase cut by moving dislocations in the underaged specimen; (b), (c) Slip bands in the underaged and peakaged specimens, respectively.

[7–9]. The δ' phase precipitated during aging and even during quenching from solution temperature and finely dispersed in the matrix of Al-Li based alloys, forms a well-ordered atomic structure and undoubtedly would serve as the obstacle of dislocation motion during deformation. But once a slip plane is activated, the coherency of fine δ' precipitates and matrix would allow the occurrence of planar slip. The δ' precipitate, which has the same slip orientation as the Al matrix, would be cut through by the leading dislocation forming an antiphase boundary, and then by the following dislocations until all the δ' particles of this activated slip plane are completely cut [7]. Thus the deformation, which is strictly localized on several single slip planes, occurs via paired dislocations. That is planar slip correlating with isolated activated slip planes.

In general, locally distributed dislocation pairs and intense slip bands which are normally composed of numerous piled-up dislocation pairs, are found to be the typical microstructure characteristics for planar slip deformation [8, 9, 16]. Up to date, it has been well established that planar slip, which leads to deformation localization and subsequent stress concentration, has a detrimental effect on mechanical properties of Al-Li based alloys and is a common cause of low ductility in Al-Li based alloys, in addition to the formation of precipitation free zone (PFZ) along grain boundaries and the intergranular compound precipitation [7, 14, 16]. During the exploration and development of Al-Li based alloys in the past more than two decades, considerable attempts have been made focusing either on understanding the physical basic of planar slip or on searching appropriate approaches to reduce the unfavorable effects of slip localization.

It is now also common known that the variation of mechanical properties as well as the dislocation configuration with aging in binary Al-Li alloys after deformation should arise from the interaction between δ' precipitate and dislocation [17]. At the early stage of aging, the size of δ' precipitate is small and its volume fraction within the matrix is low. Hence the concentration of dislocation slip is not too serious, and the main

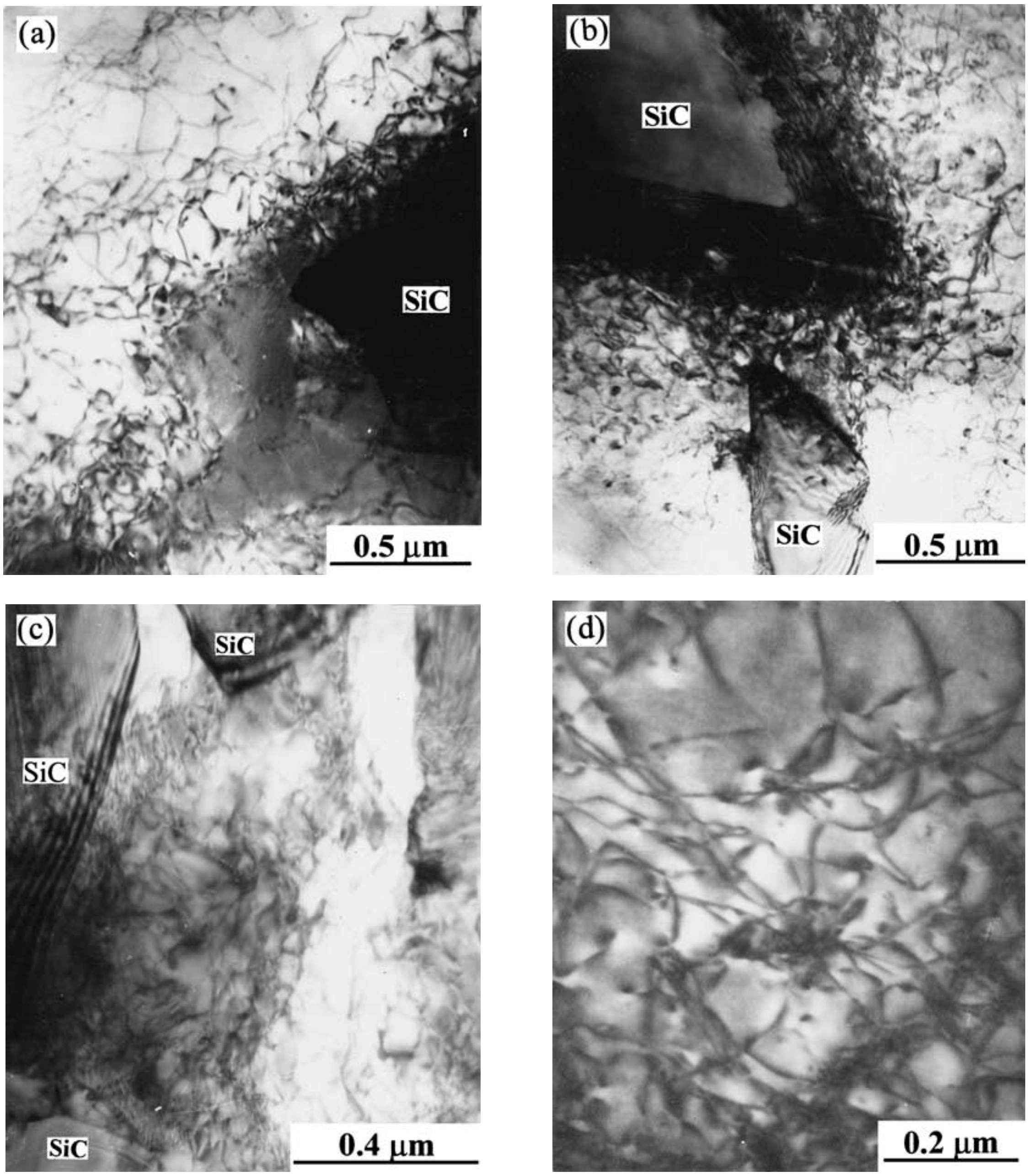
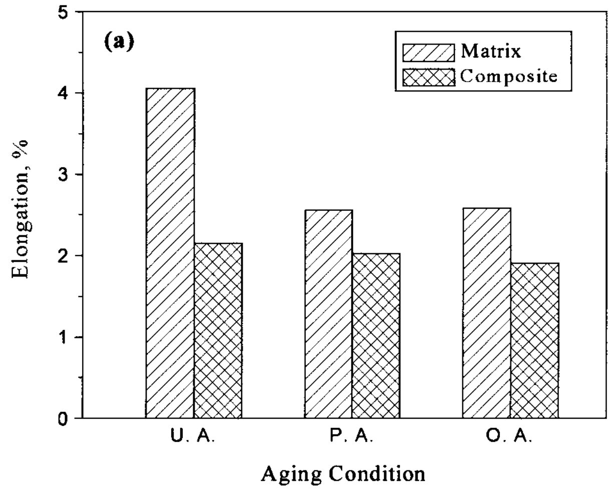


Figure 4 Dislocation configuration in the tensile deformed specimens of the SiC_w/Al-Li-Cu-Mg-Zr composite aged at 190°C: (a) as-quenched; (b) underaged; (c) peakaged; (d) overaged.

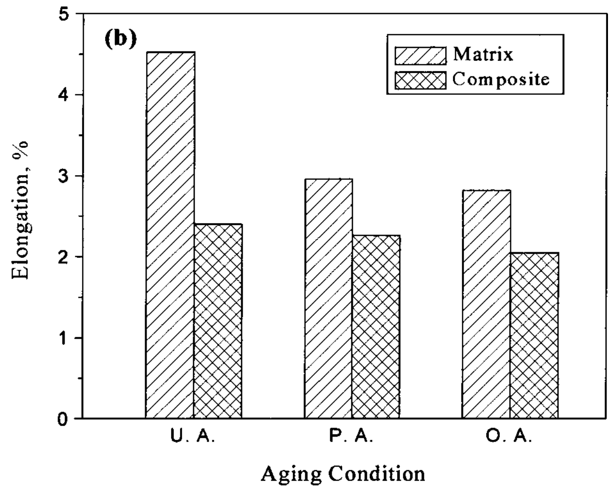
features of deformation microstructure in the underaged specimen are loose dislocation pairs and relatively less intense slip bands as described in Fig. 1a and b.

With the processing of aging, the volume fraction of δ' precipitate rises resulting from both further nucleation and growth of δ' phase within the matrix. This would cause higher slip resistance to dislocation motion and thus increase the strength and hardness of binary Al-Li alloy. Meanwhile, the slip localization becomes severe with aging, and up to peak-aging, the planar slip bands have been quite intense as shown in Fig. 1c. The pileups of a large number of dislocation pairs within the intense slip band localize the deformation and induce stress concentration, which reduce the ductility of Al-Li alloy. Under the peak-aged condition, the planar slip is mostly strict (Fig. 1c) and usually associated with the lowest value of ductility as seen in Fig. 5a.

As for the over-aged condition, the planar slip could be partially reduced mostly probably by the change in dislocation motion patterns, which in turn leads to the relatively random deformation bands as shown in Fig. 1d. Such transition is thought to originate from the further growth of δ' phases in the over-aged condition, which would continue to increase the slip resistance to dislocation motion. The tendency of localized slip on several isolated activated slip planes can be reduced to some extent with increasing of shearing resistance. As the diameter of δ' phase reaches the critical size, the δ' precipitate can no longer be cut through by moving dislocation. The deformation will occur via dislocation bypassing δ' phase, resulting in the formation of dislocation loops which can also be found in Fig. 1d. From this sense, the ductility of over-aged binary Al-Li alloy should show a slightly increase due to the reduction of slip localization. But taking into account of the coarsening effect of intergranular precipitate, on the other hand, the ductility of the over-aged Al-Li is apparently no much greater than that of the peak-aged material, as



(a)



(b)

Figure 5 Variation of tensile elongation with aging conditions for (a) the Al-Li alloy and SiC_w/Al-Li composite and (b) the Al-Li-Cu-Mg-Zr alloy and SiC_w/Al-Li-Cu-Mg-Zr alloy, respectively.

shown in Fig. 5a, which has also been pointed out by previous studies [14, 17] .

Considerable efforts have been directed towards enhancing the ductility of binary Al-Li alloy by addition of other elements such as copper, magnesium and zirconium. In fact, visible improvement in ductility has been obtained, conjunction with the remarkable increase in strength which results from the combinative effect of solute solution strengthening, precipitation hardening and grain refinement strengthening after adding these alloying elements to binary Al-Li alloy. But the nonshearable precipitates such as θ' phase, S′ phase and T_1' phase which are expected to favor dispersion of slip, have no the effect to completely eliminate the planar slip in Al-Li based alloys. This comprehension has been confirmed in Al-Li-Cu and Al-Li-Cu-Mg-Zr alloys [16, 17] as well as the present study, in the case where planar feature as intense slip band is still apparent in the specimens with different aging histories (Fig. 2). Compared with binary Al-Li alloy, the level of slip localization in Al-Li-Cu-Mg-Zr alloy is found to be less severe (see Fig. 2) and the tensile elongation is a little higher (Fig. 5b), thus it appears true that planar slip in binary Al-Li alloy could, at least, be partially reduced by alloying approaches.

The distinguished microstructural alternation in Al-Li based alloys after the incorporation of SiC whiskers is the high density dislocations produced either during squeeze casting or during quenching from the solution temperature due to the thermal mismatch between Al-Li matrix and SiC reinforcement, as the case with the other SiC_w/Al and SiCp/Al composites [18, 19]. These misfit dislocations would hinder the motion of activated matrix dislocations during deformation. As a consequence, the plastic deformation behavior and hence the dislocation configurations in the matrices of SiC_w/Al-Li or SiC_w/Al-Li-Cu-Mg-Zr composites are dominated by SiC whisker and these initial thermal mismatch dislocations, and different from that in the unreinforced Al-Li based alloys. The presence of SiC whisker would heavily limit the plastic flow of the matrix in the composite, and simultaneously alter the slip patterns of dislocations. It is supposed that the randomly distributed SiC whiskers within the matrix of composite would significantly reduce the tendency of localized slip on isolated activated slip plane mainly via the initial thermal mismatch dislocations. Numerous same events simultaneously taking place within the matrix of SiC_w/Al-Li or SiC_w/Al-Li-Cu-Mg-Zr composites are expected to prevent the occurrence of planar slip. In fact, from the TEM examinations carried out on SiC_w/Al-Li and SiC_w/Al-Li-Cu-Mg-Zr composites, it is evident that the planar slip has effectively been eliminated, which could be confirmed by the absence of dislocation pairs and intense slip bands in the deformed composite specimens (see Figs. 2 and 4). From the point view of suppressing the planar slip by the presence of SiC whiskers within the matrix of Al-Li based alloys should be the beneficial factor to promote the level of uniform deformation by reducing the slip localization, and somewhat contributes to increase the ductility of the material. Therefore, the ductility of SiC whisker reinforced Al-Li based alloys should be little sensitive to aging conditions, which has been proved by the tensile test results of SiC_w/Al-Li and SiC_w/Al-Li-Cu-Mg-Zr composites as listed in Fig. 5a and b, respectively.

On the other hand, after introduction of SiC whisker into Al-Li based alloys, the much more degradation in ductility has to be taken into account, resulting from the stress concentration within the matrix derived directly from the presence of SiC whisker, and resulting from non-uniform distribution of strain during plastic deformation as well as resulting from the increase of potential crack sources existed in the composite. This loss of ductility is too large to be balanced by the enhancement effect benefited from the suppression of planar slip by SiC whisker. Therefore, the overall level of ductility, as the tensile elongation of SiC_w/Al-Li and SiC_w/Al-Li-Cu-Mg-Zr composites shown in Fig. 5, is still very low. However, the ductility of SiC whisker reinforced Al-Li matrix composites seems comparable with that of other SiC_w/Al composites produced with the same SiC volume fraction and similar processing operation [20], while considering of the relative low original ductility level of the unreinforced Al-Li based alloys. Furthermore, with the superior specific strength and specific modulus as well as creep resistance to other AMC, the

SiC whisker reinforced Al-Li matrix composites should be more potentially competitive in structural applications, such as weight-save critical or dimension stable components.

Up to the present, the microstructural dislocation evolution after cooling from primary fabrication or thermal processing of aluminum matrix composites (AMCs) has been well preformed, but relatively few studies of dislocation microstructure were carried out for AMCs under applied loads. The current work is a general examination of the microstructural development, particularly comparison of dislocation configurations in deformed Al-Li based alloys and their composites reinforced with SiC whisker, to estimate the effect of SiC whisker on the planar slip, a specific phenomenon, inherent in Al-Li based alloys. There is undoubtedly scope for further exploration on this subject. It has long been assumed that hard particles play a role in the development of dislocation slip under applied loads, but their importance is uncertain [19]. It is evident from present observations that the planar slip seems to be prohibited with the presence of SiC whisker in the Al-Li based alloys, since no characteristics of planar slip dislocation was found in the resultant composites. Reminding of the fact that the size of SiC whisker is generally above 1 μm, one has to learn that the interaction of SiC whisker with dislocation is negligible [19]. Thus, in order to take advantage of the prohibitive effect of nonshearable particles, it is logical to pay particular attention to the more small particles with the size of sub-micrometer or nanometer. Such nondeformable small particles, homogeneously distributed throughout the Al-Li based alloys after their addition by appropriate process, are expected to be more effective in suppressing planar slip. On the other hand, the mechanical properties especially the ductility and toughness of the corresponding composite would be enhanced, as a result of the relatively less inhomogeneous deformation and strain distribution compared with the composite reinforced large size ceramic such as SiC whisker. Further systematic investigation is needed to testify this assumption.

5. Conclusions

TEM examinations of deformation microstructures of purposely-prepared Al-Li, Al-Li-Cu-Mg-Zr alloys and their composites reinforced with SiC whisker have been carried out to access the effect of nonshearable ceramic phase such as SiC whisker on planar slip inherent in Al-Li based alloys. The typical microstructural features as dislocation pairs and intense slip bands could be readily observed in Al-Li binary alloy, which is controlled by aging condition of the alloy. The alloying elements of copper, magnesium and zirconium are somewhat effective in dispersing planar slip in Al-Li binary alloy by the formation of nonshearable precipitates and refinement of grain, but unable to exclude the planar slip at all. With the addition of SiC whisker to Al-Li or Al-Li-Cu-Mg-Zr alloy, no indication of planar slip dislocation configurations could be detected, implying that the planar slip in Al-Li based alloys would be suppressed by the presence of SiC whisker. Such prohibition effect is thought to relate to the high-density primary thermal misfit dislocations in the composite induced during fabrication or thermal processing, and to the restriction of SiC whisker on deformation of matrix. It is suggested that the incorporation of nondeformable small particles with dimension in the sub-micrometer or nanometer range to Al-Li based alloys, a topic worthy of further investigation, would be beneficial to both suppressing the planar slip and improving the ductility and toughness of the resulting materials.

Acknowledgement

The financial support of the National Natural Science Foundation of China under Grant No. 58971033 is greatly appreciated.

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Received 19 April 2001
and accepted 14 February 2002