Grain refinement in coarse-grained 7475 Al alloy during severe hot forging

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Grain refinement taking place in a coarse-grained 7475 Al alloy was studied in multidirectional compression at 490°C and at a strain rate of $3 \times 10^{-4}\,s^{-1}$. The integrated flow curve displays significant work softening just after yielding and an apparent steady-state plastic flow at high strains. The structural changes are characterized by the development of deformation or microshear bands in coarse-grain interiors, followed by homogeneous evolution of new grains at high strains. The new grains are considered to be developed by a kind of continuous reaction through grain fragmentation that is similar to continuous dynamic recrystallization (cDRX). The mechanism of fine grain production and the factors controlling grain refinement during hot multidirectional deformation are discussed in detail.

1. Introduction

In recent years, fabrication of ultrafine-grained materials by means of severe plastic deformation (SPD) has been in the limelight of material engineers because ultrafine-grained structures have great potential for improvement of mechanical, chemical and physical properties [1–3]. Several SPD techniques such as equal channel angular extrusion [1, 3–9], torsion under high pressure [1, 3, 6, 9, 10] and multidirectional forging (MDF) [1, 2, 11–13] are now available for attaining of fine grain structures in numerous metals and alloys. These SPD techniques can also be a very valuable scientific tool for studying the microstructure development in large strain deformation [1, 4–9, 11–13]. Many studies concerned with the processing and the properties of fine-grained Al alloys have been reported [1, 3–9]. It has been discussed that fine grain formation during SPD may result from a kind of continuous dynamic recrystallization (cDRX), i.e. the formation of deformation-induced dislocation

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boundaries followed by a gradual increase in their misorientation, finally leading to their transformation into usual large-angle grain boundaries during cold to hot deformation [5–9, 11–14]. Another possible mechanism operating during hot deformation is geometric dynamic recrystallization (gDRX); original grains are extremely pancaked accompanied with boundary serration and parts of the serrated grain portion are pinched off during hot SPD, leaving an equiaxed grain structure at high strains [e.g. 9, 14–16]. A detailed understanding of the grain refinement mechanisms, however, has been complicated by various deformation modes in SPD techniques and also a scarcity of the related experimental data.

The aim of the present work is to reveal the process of the fine grain evolution in a coarse grained Al alloy during MDF. Specific attention is paid to elucidate the main factors controlling the grain refinement in the Al alloy and to study any effect of strain paths, i.e. MDF, on it. The structural mechanisms operating at high temperature are discussed in detail.

2. Experimental

The material tested was an as-cast 7475 Al alloy with the following chemical composition: Al–6% Zn–2.5% Mg–1.8% Cu–0.23% Cr–0.16% Zr–0.04% Fe–0.03 %Si–0.03% Mn (in mass per cent). The ingot was homogenized at 490°C for 20 h. The initial structure was composed of coarse dendritic lamellar grains. Parts of the grain boundaries were rather straight and the others were corrugated, as shown in figure 1. The average spacing of the lamellas was in a range from 1 to 10 mm in longitudinal direction and from 50 to 200 μm in transverse direction. Two types of dispersoids distributed in the alloy were identified by TEM analysis as Al_3Zr and Al_3Cr, which were equiaxed having an average size of 20 nm and 100 nm, respectively [17, 18].

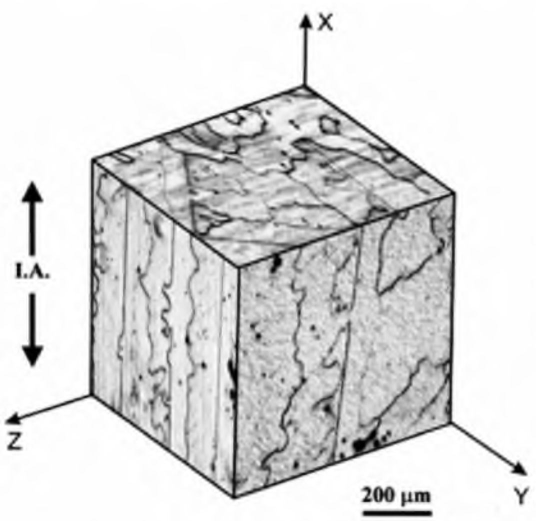

Figure 1. Initial structure of as-cast 7475 Al alloy. I.A. is the ingot axis. The axes of X, Y and Z indicate the sequence of loading directions during multidirectional compression.

Rectangular samples of $10 \times 8 \times 6.5$ mm (1.5:1.25:1) were machined from the ingot supplied. Three-directional multipass compression was carried out while changing the load direction by 90° from pass to pass at $T = 490°C$ under a strain rate of $3 \times 10^{-4}\,s^{-1}$. The dimension ratio of the sample did not change during repeated deformation in a pass strain ($\Delta\varepsilon$) of 0.4. A boron nitride powder was used as a lubricant. Metallographic analysis was carried out on a section parallel to the last compression axis by using optical microscopy after etching by a standard Dicks–Keller etchant. The fraction recrystallized was evaluated by the point–count technique in the area of around 3×5 mm in central parts of deformed specimens. The misorientation distributions of the developed dislocation boundaries were measured by orientation imaging microscopy (OIM). Marker lines were scribed on some sample surfaces polished before deformation using a diamond paste. The surface relief changes and the occurrence of grain boundary sliding (GBS) were observed by using a Hitachi S4300FE-SEM.

3. Experimental results

3.1. *Stress-strain behaviour*

Figure 2 represents a series of true stress–true strain (σ–ε) curves plotted for 15 consecutive compression passes. A σ–ε curve in single pass compression is also represented by a broken line. The integrated flow curve obtained by MDF demonstrates a sharp stress peak just after yielding followed by significant work softening. Strain softening takes place continuously up to strain over 4 and then the cumulative flow curve shows a steady-state-like flow behaviour. The ratio of the flow softening ($\Delta\sigma$) and the stress peak (σ_p), $\Delta\sigma/\sigma_p$, is around 0.5 in MDF and, in contrast, 0.2 in a single pass compression. It should be also noted in figure 2 that there is a

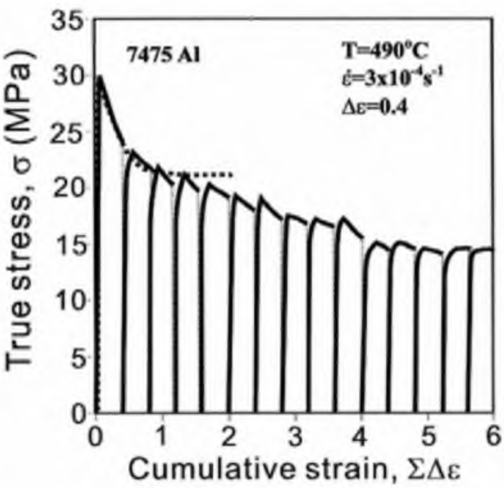

Figure 2. True stress vs. cumulative strain (σ–$\Sigma\Delta\varepsilon$) curves for coarse-grained 7475 Al alloy plotted over 15 compressions at $T = 490°C$ and at a strain rate of $3 \times 10^{-4}\,s^{-1}$ with changing in loading direction 90° for each pass. The broken line shows a σ–ε curve in single pass compression.

small difference between the flow stresses immediately before unloading and at reloading. This suggests that some static restoration and/or aging processes may occur during interrupted deformation. However, this difference appears to be quite small compared with the applied stress level; that is, any structural changes in the deformed samples can be mainly affected by accumulation of strains applied in each compression pass [11].

3.2. *Surface observations*

Typical surface morphologies evolved after first compression to $\varepsilon = 0.16$ are represented in figure 3. It can be seen in figure 3a that plastic deformation occurs heterogeneously accompanied with deformation bands developed in grain interiors even at such low strain. Most of the deformation bands are developed roughly parallel to each other within a grain, while two sets of the bands were also developed in some grains. Displacement of the scratched marker line in figure 3a indicates that the grain-boundary sliding (GBS) took place along the corrugated grain boundaries. Figure 3b, an enlarged portion of figure 3a, shows that such deformation banding leads to rigid rotations of the scratched markers and so a process akin to kinking or folding can cause a reorientation of the material within these bands. These are considered to be similar to microshear bands [19, 20]. The development of such microshear bands and their intersection take place more frequently by further straining (as shown in figures 4 and 5). This is rather strange because such

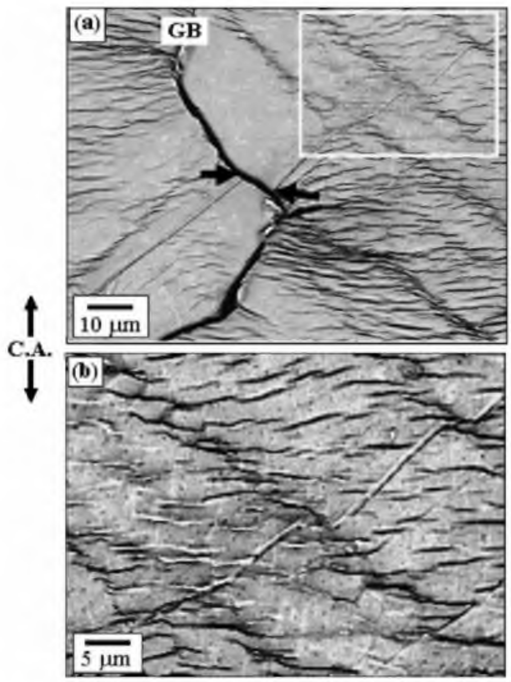

Figure 3. (a) Typical deformation relief in coarse-grained 7475 Al alloy deformed to a strain of 0.16 at 490°C and at a strain rate of $3 \times 10^{-4}\,s^{-1}$. Arrows indicate a displacement of scratched marker line along grain boundary (GB). (b) The enlarged morphology in the portion outlined in (a). C.A. is the compression axis.

microshear bands were reported to develop in Al alloys at relatively large strains during cold deformation [19, 20], but not during an early stage of hot deformation [14, 15]. The development of such bands may be the result of heterogeneous strains developed in the present unsymmetric and layered coarse-grained structure, as described in detail in [17]. This will be discussed later in more detail.

3.3. *Microstructural changes*

A series of typical microstructures evolved at $\Sigma\Delta\varepsilon = 1.2$ to 6.0 is represented in figure 4. It is seen in figures 4a and 4b that the initial lamellar grains are bent and rotated by MDF, and concurrently new fine grains are frequently developed along the regions of original grain boundaries (see figure 11) and high-density deformation bands in the remaining grain interiors, as described below. It is interesting to note that the deformation bands developed are clearly visible in a polarized optical microscopy [18] and several sets of deformation bands are developed in various directions depending on each grain. With further multiple deformations, the volume fraction of the regions with high-density deformation bands progressively decreases and that of new fine grains conversely increases, as can be seen in figures 4a–4c. At a strain of 6,

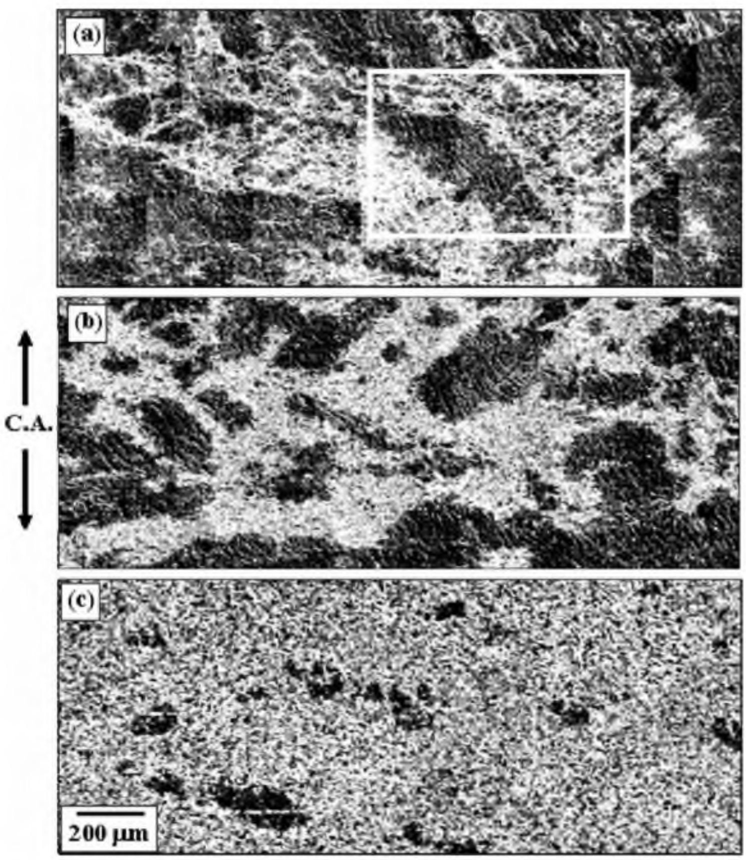

Figure 4. Typical microstructures evolved during MDF to various strains (polarized light). C.A. is the last compression axis. (a) $\Sigma\Delta\varepsilon = 1.2$, (b) $\Sigma\Delta\varepsilon = 2.4$, (c) $\Sigma\Delta\varepsilon = 6.0$.

the initial coarse-grained microstructure is almost fully replaced by a new fine-grained one, although relatively coarse grains still remain. The regions of such fine grains and remnant original grains are distributed homogeneously in high strain.

Figure 5a, an enlarged micrograph of the region outlined in figure 4a, shows the microstructures developed at a strain of 1.2, which are composed of the following three typical components: (i) fully developed fine grains (lower left); (ii) parts of remnant original grain with several sets of deformation bands (centre) and (iii) their mixed structures (upper right). Figure 5b shows a typical surface relief observed by SEM for the sample initially deformed to $\Sigma\Delta\varepsilon = 1.2$, unloaded and then further deformed an additional 0.16 parallel to the last compression axis after the surface was polished. Figure 5 suggests that new grains may be evolved in close connection with deformation bands, namely formation of deformation bands as well as their mutual crossing can result in grain fragmentation followed by development of new fine grains during hot MDF.

3.4. *OIM microstructures*

A typical orientation imaging microstructure developed at $\Sigma\Delta\varepsilon = 1.2$ is represented in figure 6a. Here the different greyscale levels indicate the different crystallographic

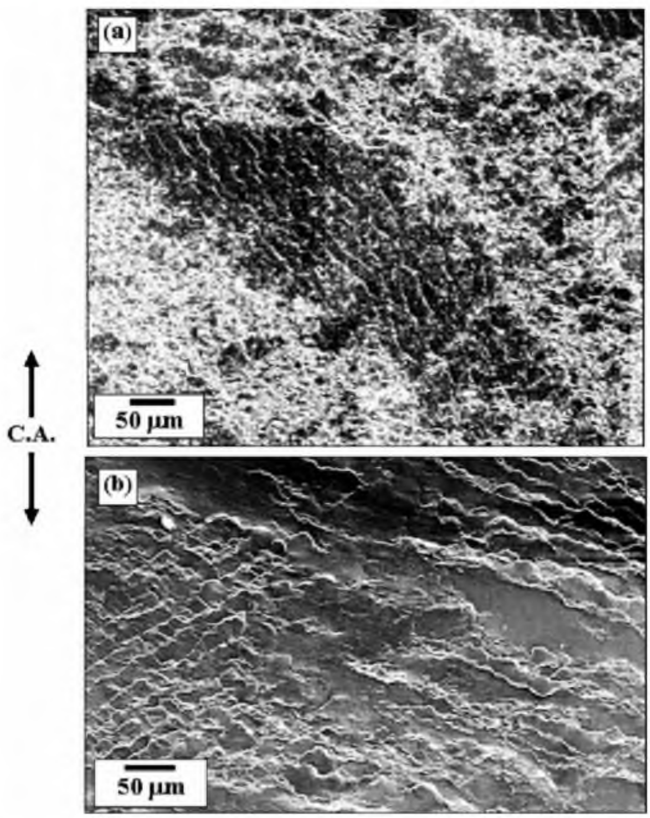

Figure 5. (a) A microstructure enlarged in the portion in figure 4 (a) (polarized light). (b) A SEM micrograph for a mixed region corresponding to that in upper right in (a). C.A. is the last compression axis.

orientations and the misorientation angles (Θ) between neighbouring grid points, $\Theta > 2^\circ$ and $\Theta > 15^\circ$ are marked by the thin and bold black lines, respectively. New fine grains are frequently but inhomogeneously evolved along the original layered grain boundaries and also newly formed dislocation sub-boundaries with moderate to high angle misorientation. Such mutual crossing boundaries subdivide original grains into small separate misoriented domains, some of which are transformed into new fine grains.

Figure 6b shows changes in point-to-point ($\Delta\Theta$) and cumulative ($\Sigma\Delta\Theta$) misorientations along the line T in figure 6a. The values of $\Delta\Theta$ and $\Sigma\Delta\Theta$ define the misorientations evolved by 1 μm step relative to the previous point and to the first point, respectively. The sub-boundaries with $\Delta\Theta \geq 5^\circ$ to 20° developed in grain interiors may correspond to the boundaries of microshear bands mentioned in sections 3.1 and 3.2. The cumulative misorientation, $\Sigma\Delta\Theta$, is changed

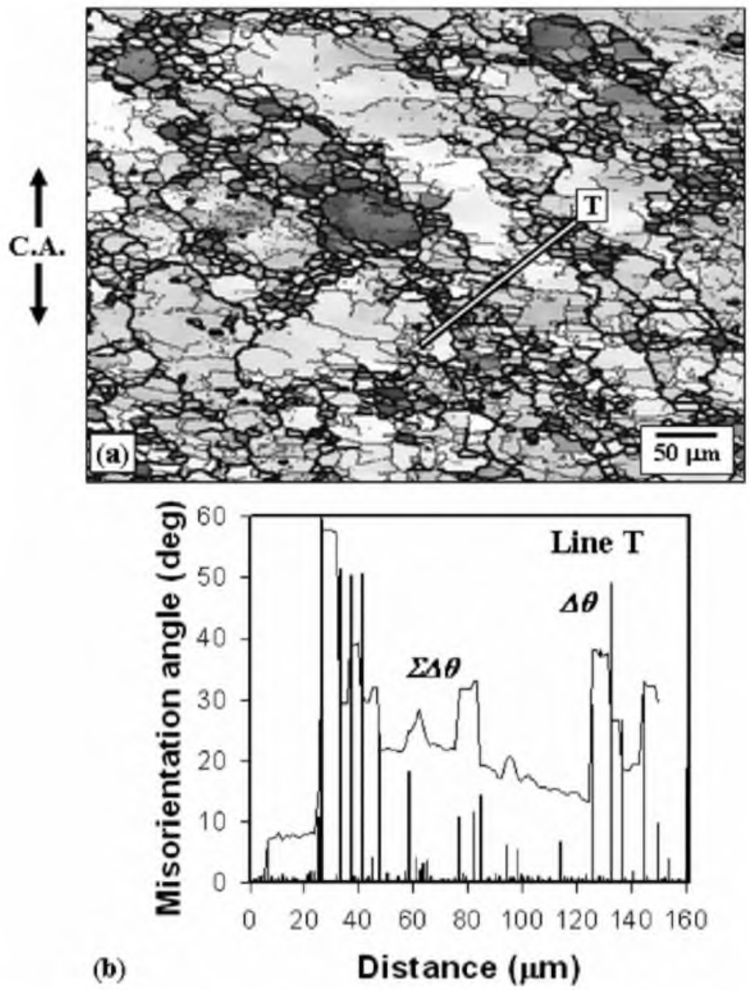

Figure 6. (a) OIM micrographs of coarse-grained 7475 Al alloy deformed to $\Sigma\Delta\varepsilon = 1.2$. Thin and bold lines correspond to boundaries of misorientattion $>2^\circ$ and $>15^\circ$, respectively. C.A. is the last compression axis. (b) Typical point-to-point ($\Delta\Theta$) and cumulative ($\Sigma\Delta\Theta$) misorientations developed were measured along the line T indicated in (a).

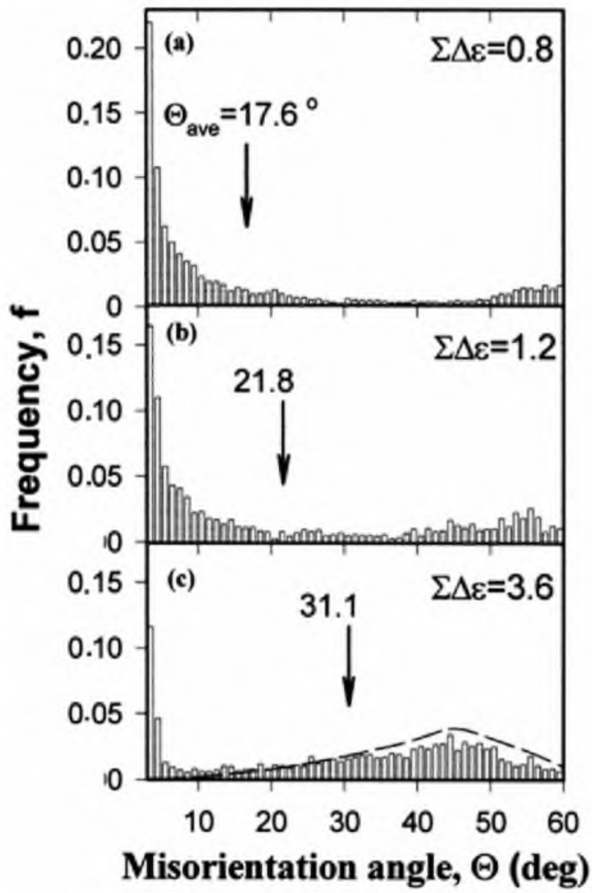

Figure 7. Changes in misorientation distributions of dislocation and (sub)grain boundaries developed with straining by MDF. The broken line indicates the random misorientation distribution evaluated by Mackenzie [21]. (a) $\Sigma\Delta\varepsilon = 0.8$; (b) $\Sigma\Delta\varepsilon = 1.2$; (c) $\Sigma\Delta\varepsilon = 3.6$.

discontinuously and crystal orientation is frequently alternated at the same places. Note also that some high angle boundaries with $\Delta\Theta \geq 30^\circ$ to 50° are evolved frequently near the grain boundary regions.

Figure 7 represents changes in the misorientation distributions derived from OIM analysis. It is seen in figures 7a and 7b that most boundaries developed at $\Sigma\Delta\varepsilon \leq 1.2$ exhibit low-to-medium angle misorientations below 20°, although a small fraction of high angle boundaries with over 40° is also detected. The fraction of low angle boundaries rapidly decreases and that of high-angle ones conversely increases with further deformation. Note here that the average misorientation of 31.1° at $\varepsilon = 3.6$ (figure 7c) is less than that for a random misorientation of polycrystalline aggregates of cubic metals, 40.7°, predicted by Mackenzie [21]. This difference would be the result of strain-induced microstructure evolved through grain fragmentation by MDF.

Figure 8 shows changes in some summarized microstructural parameters with repeated MDF, i.e. the strain dependence of (a) the average new grain size, d_{rex}, (b) the average misorientation, Θ_{ave}, in the fine grained regions and (c) the volume

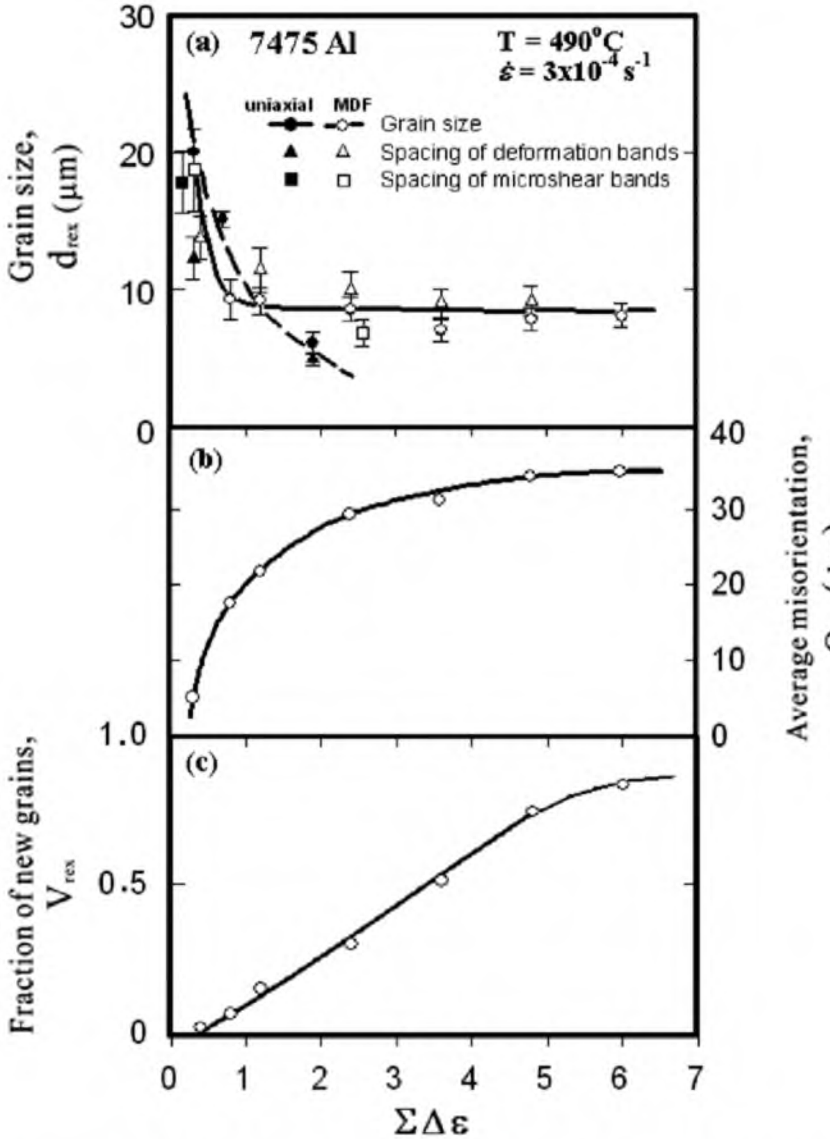

Figure 8. Effect of hot multidirectional deformation on (a) the average grain size, d_{rex} and the minimal spacing of deformation and microshear bands in remained original grains, (b) the average misorientation of dislocation/(sub)grain boundaries, Θ_{ave}, in the fine-grained regions and (c) the fraction of fine grains evolved, V_{rex}. The open and closed symbols in (a) indicate the data obtained from MDF and uniaxial compression, respectively.

fraction of the new grains, V_{rex}. The grain size developed during uniaxial compression is also represented by a dashed line in figure 8a. The minimal spacing of deformation bands derived from polarized microscopy and microshear bands measured from surface relief are also plotted in figure 8a. d_{rex} rapidly drops to around 9 μm at $\varepsilon \approx 0.8$ and then shows a roughly constant value of about 7.5 μm at higher strains. It is important to note in figure 8a that the new grain size is similar to the minimal spacing of deformation and microshear bands within an experimental scatter. The Θ_{ave} increases rapidly at low strains and gradually at moderate strains, and finally approaches a saturation value of around 35° at high strains (figure 8b). On the other hand, V_{rex} increases gradually with deformation in the strain range investigated and is saturated at the value of about 0.85 (figure 8c).

4. Discussion

It has been shown in the present work on a coarse-grained 7475 Al alloy that new fine grains are developed by grain fragmentation of the original coarse grains during hot multidirectional forging (MDF). Some characteristics of this process can be summarized as follows:

(i) New grain formation is accompanied with significant flow softening followed by an apparent steady state in flow stress and also in grain structure.
(ii) Deformation occurs heterogeneously in a mesoscopic level, resulting in frequent development of deformation or microshear bands in grain interiors even at early stages of hot compression.
(iii) The misorientation and the number of boundaries attributing to deformation and/or microshear bands rapidly rise with repeated deformation. Concurrently new grains are evolved first along the regions of initial grain boundaries and also in grain interiors through formation of deformation or microshear bands.

Let us discuss the development of microshear bands followed by grain refinement, and then the interrelationship between evolution of new grains and work softening during repeated hot compression.

4.1. *Heterogeneous deformation accompanied by GBS*

It is known that microshear bands or so-called 'S-bands' [19] can frequently appear to be the persistent features of the microstructure that develops usually during cold deformation of fcc metals and alloys at moderate to high strains [19, 20]. These bands are considered to be caused by strain gradients resulting from heterogeneous strains introduced by cold deformation. In the present unsymmetrical, columnar and coarse-grained Al alloy, however, heterogeneous strains were easily introduced even under hot deformation conditions. The previous structural results in single pass hot compression are described in [17, 18] and briefly summarized here. At early stages of deformation, GBS operating in the layered dendritic structure can occur with different rates along straight and corrugated grain boundary segments, as represented in figure 9. GBS may also be frequently accompanied by grain boundary shearing in corrugated segments and result in significant stress concentration at the grain boundary irregularities. As a result, high strain gradients should be introduced in the columnar grains, followed by development of microscopic shear bands even at early stages of hot deformation.

On the other hand, it has been shown [18] that GBS took place scarcely in the current Al alloy during hot compression at higher strain rates above $10^{-2}\,s^{-1}$, where deformation bands as well as new grains were scarcely developed in the strain range below $\varepsilon = 1.4$. This is in clear contrast with the results shown in figures 4–6. It is concluded, therefore, that during hot deformation of the present alloy, microscopic

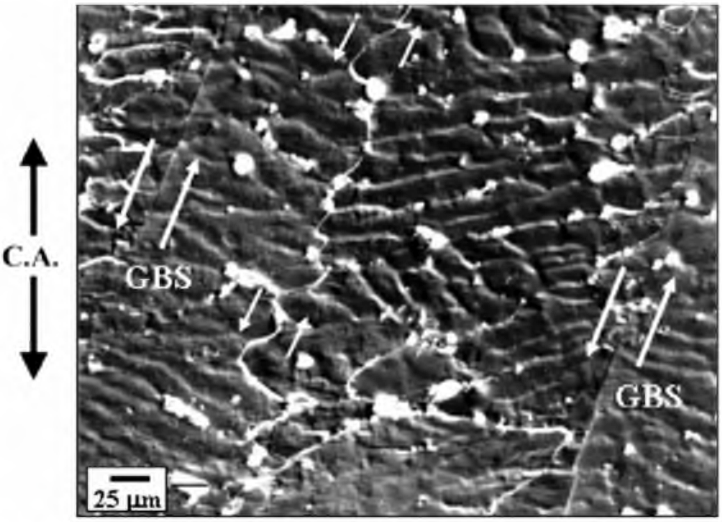

Figure 9. Polarized microstructure evolved after compression to $\varepsilon = 0.3$. This suggests that GBS can take place at different rates along straight and corrugated lamellar grain boundaries, leading to development of heterogeneous local strains and then deformation and/or micro-shear bands. C.A. is the compression axis.

shear bands may originate from a geometric instability of layered dendritic structure that results from heterogeneous operation of GBS. Note also that the 7475 Al alloy contains many insoluble dispersoid particles, which can serve as very effective pinning agents and so retard or prevent any relaxation of strain gradients [17]. This is considered to be another factor promoting the evolution of microshear bands under high temperature deformation conditions.

4.2. *Grain refinement processes during MDF*

It has been shown in figure 8 that the average grain size developed is similar to the minimal spacing of deformation or microshear bands evolved in grain interiors. This suggests that the main mechanism of the grain refinement during MDF of the present Al alloy is directly associated with the grain splitting by formation of microshear bands. Namely, microshear bands can be continuously formed by strain accumulation and microstructural heterogeneities evolved in each compression pass, accompanying with their intersection in grain interiors. This results in subdivision of original grains into separate misoriented domains (figures 5–6). Concurrently misorientation of such domain boundaries rises with repeated deformation followed by their progressive change to large-angle ones. It is noteworthy that the present observations of microshear bands (figure 3) can provide a much-improved understanding of such a grain refinement process. It has been clarified [20] that the boundary misorientations in microshear bands developed in cold-rolled Al alloys grow continuously with increase in reduction and, on the other hand, those of other deformation-induced boundaries, such as microbands and cell boundaries, scarcely increase during rolling. This suggests that microshear bands developed can be a very significant structural factor making an outstanding contribution to grain refinement, irrespective of deformation temperature.

A rapid rise in boundary misorientation can be promoted by GBS operating more frequently in new fine-grained regions [17, 22]. GBS takes place first near the initial grain boundaries and subsequently along deformation bands with high-angle boundaries, leading to development of new fine grains in high strains. This new grain formation may be comparable with an *in situ* dynamic recrystallization by progressive lattice rotation [14]. It should also be noted in figures 7 and 8 that strain dependencies of the microstructural parameters developed during such grain refinement process can be considered to be a specific feature of strain-induced grain structures, which is typical of continuous dynamic recrystallization (cDRX) [e.g. 13, 14, 17, 22–24]. It is concluded, therefore, that new grains evolved during hot MDF of the 7475 Al alloy can result from a series of strain induced continuous reactions; that is essentially similar to cDRX.

Figure 10 shows typical crystallographic textures for (a) a region of remnant original grains with microshear bands and (b) a fine-grained region developed in the sample deformed to $\Sigma\Delta\varepsilon = 2.4$ (see figure 4b). This indicates that near $\langle 111 \rangle$ strong texture developed in the original grains is changed to a roughly random one in new grained regions. This is in contrast with cDRX texture developed by cold and warm SPD, i.e. the textures developed are usually the same as those of deformed matrix [25]. Grain rotation can take place frequently accompanied by GBS in the present Al alloy, as mentioned above. This should lead to randomization of the crystal orientation of each new grain evolved [22]. It is remarkable to note that this microstructural development is roughly the same as that taking place during conventional hot deformation of unrecrystallized Al alloys [e.g. 22, 23].

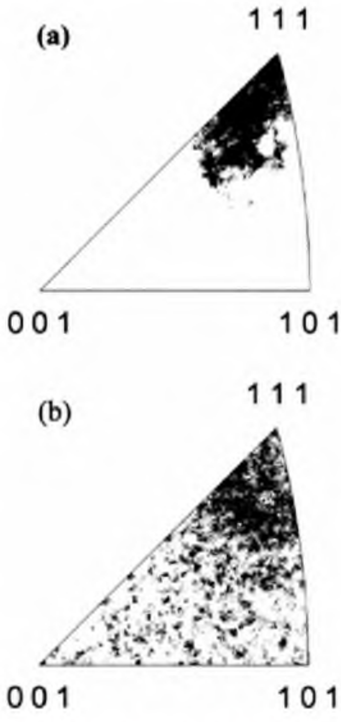

Figure 10. Typical inverse pole figures showing the deformation texture of (a) the remnant original grain fragmented and (b) a fine-grained region developed at $\Sigma\Delta\varepsilon = 2.4$.

Finally, it is interesting to note that the formation of granular structure was first detected in the grain boundary regions in the current alloy (figures 4–6). This is because the highest strain gradients can be introduced by GBS (and/or grain boundary shearing) near original grain boundaries, as compared with those in grain interiors [11]. As a result, microshear bands with large misorientation are readily developed in grain boundary regions in the earlier stages of deformation (figures 3 and 6b), leading to more rapid evolution of new grains. Such structural behaviour of cDRX looks similar to that of the necklace dynamic recrystallization, which takes place in low- to medium stacking fault energy materials during hot working [12, 14, 26], although their structural mechanisms are completely different.

4.3. *Comparison with uniaxial compression*

The evolution process of new grains during early MDF is roughly the same as that operating during conventional single pass compression. A detailed comparison of the microstructures evolved during MDF and single pass compression indicates, however, different development processes occurring in the both cases. The volume fraction of new grains evolved, V_{rex}, rapidly approaches a saturation value of around 0.2 [27] in uniaxial compression, while it is about 0.85 in MDF as mentioned above. It is also interesting to note that the new grain size after uniaxial compression is around 5.5 μm in high strain, which is smaller than 7.5 μm evolved after MDF (figure 8a). Such effects of multidirectional deformation on fine grain evolution will be discussed here.

If one set of microshear bands could be evolved parallel to each other within a grain during uniaxial deformation (figure 3), two-dimensional planar microstructures, e.g. layered boundary structures, should be developed in high strain. There spacing would be significantly reduced with strain increasing eventually leading to formation of high-density two-dimensional planar microstructure, i.e. layered lamellar structure, as proved by cold to warm rolling [19, 20] and high-pressure torsion [10]. Under a constant strain path condition at high temperature, new grains may be evolved only along grain boundaries, but scarcely in grain interiors, as shown in figure 11. This is the reason why new grain formation may be saturated at $V_{rex} \approx 0.2$. The change in strain path under MDF conditions, in contrast, can introduce microshear bands in various directions [28] followed by much more homogeneous formation of equiaxed grains not only along grain boundaries, but also in grain interiors (figures 4–6). On the other hand, finer grains are evolved in uniaxial compression at moderate to high strains, because the density of dislocation sub-boundaries is smaller, compared with that in MDF. Such a strong strain path effect on microstructural development during SPD has also been observed by using other deformation techniques [e.g. 8].

4.4. *Flow softening during new grain evolution*

It was concluded in section 4.2 that new grain formation in the present Al alloy can result from cDRX, which is considered to be controlled mainly by dynamic recovery [14]. The σ–ε curves under dynamic recovery conditions show, in general, a steady-state flow in high strain. This is in conflict with the present integrated flow curve accompanied with a sharp stress peak followed by work softening. This will be discussed here on the basis of GBS operating in developed fine-grained regions.

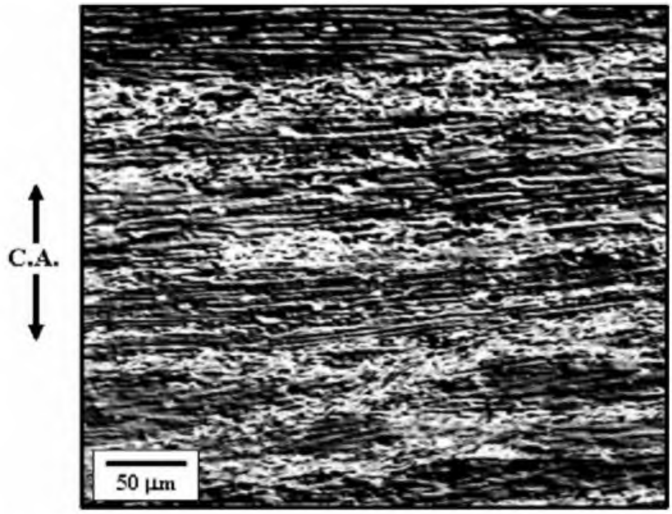

Figure 11. Typical microstructure of coarse-grained 7475 Al alloy deformed to $\varepsilon = 1.9$ in uniaxial compression. Polarized light. C.A. is the compression axis.

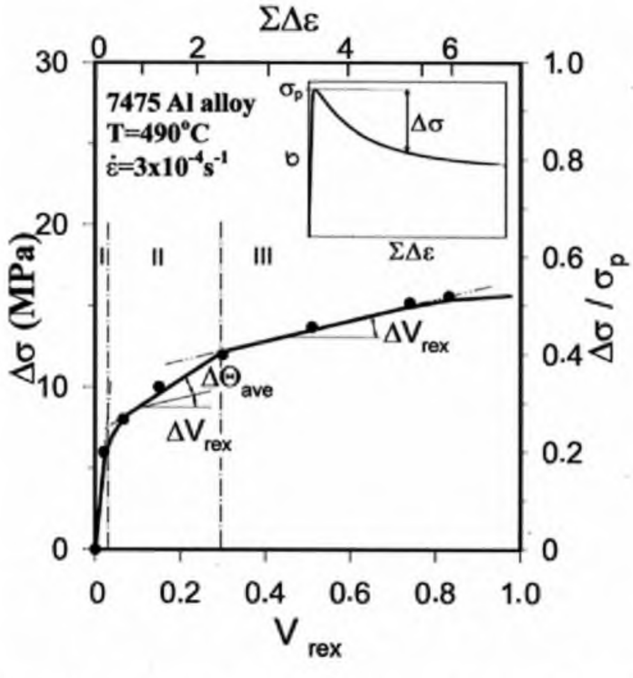

Figure 12. Relationship between flow softening, $\Delta\sigma$ or $\Delta\sigma/\sigma_{\mathrm{p}}$, and the volume fraction of new fine grains, V_{rex}, developed during hot MDF.

Figure 12 represents the relationship between the value of flow softening, $\Delta\sigma$ or $\Delta\sigma/\sigma_p$ and V_{rex}. Here σ_p is the peak stress and σ is the instantaneous flow stress in integrated flow curve and $\Delta\sigma = \sigma_p - \sigma$. Three different regions can be roughly categorized during flow softening and designated hereafter as the regions I, II and III: (I) $\Delta\sigma$ increases first rapidly and (II) then at a medium rate and (III) finally at a gradual rate with V_{rex}. An initial rapid flow softening in region I can originate mainly from GBS along original grain boundaries, which are declined and bended during early compression [17]. Subsequent strain softening in the regions II and III can be caused by new grain development accompanied with increase in the boundary misorientation (figure 8) and frequent operation of GBS in these regions.

When hot deformation of fine-grained materials is mainly controlled by GBS, the deformation equation is approximated by [29]

$$\dot{\varepsilon} = C_1 d^{-p} \sigma^n \exp(-Q/RT), \tag{1}$$

where C_1, $p > 0$, $n > 0$ are experimental constants, d is the grain size, Q is the activation energy for deformation and the others have usual meanings. When T, $\dot{\varepsilon}$, C_1 and Q are constant, σ vs d can be expressed by

$$\sigma = C_2 d^{p/n}, \tag{2}$$

where C_2 is a constant. In region II, microstructural evolution is accompanied with rapid increase in Θ_{ave} and also gradual increase in V_{rex}. This corresponds to rapid decrease in the average grain size in the whole area, leading to rapid decrease in σ in accordance with equation (2). In region III, where the misorientation distribution approaches that expected by Mackenzie [21], flow softening can result mainly from gradual increase in V_{rex} (figure 8). It is concluded, therefore, that significant flow softening can result from GBS taking place in the fine grained regions developed through increase in both Θ_{ave} and V_{rex} in region II and mainly in V_{rex} in region III. A remarkable effect of multidirectional deformation on flow softening can cause V_{rex} to increase from around 0.2 in single pass compression, to around 0.85 and so $\Delta\sigma/\sigma_p$ to increase from 0.2 to around 0.5 (figure 2). The reason why the volume fraction of new grains does not approach 1 within the strains investigated can be explained as follows. The shape of remnant original grains becomes more equiaxed and their average size decreases in high strain. Then heterogeneous strains can be hardly developed in these grain interiors because of frequent operation of GBS in surrounding fine-grained regions. As a result, parts of original grains remain stable in high strain.

5. Conclusions

Strain-induced grain refinement in a coarse-grained 7475 Al alloy was studied by means of multidirectional forging (MDF) carried out at a temperature of 490°C under a strain rate of $3 \times 10^{-4}\,s^{-1}$ with a pass strain of 0.4. The main results are summarized as follows:

1. The integrated flow curve plotted over 15 compression passes exhibits a significant work softening just after yielding, followed by steady-state-like behaviour at high strains. Flow softening can result from dynamic evolution of new fine grains and operation of grain-boundary sliding (GBS) in fine-grained regions.
2. GBS occurs inhomogeneously in corrugated and straight lamellar grain boundaries, resulting in frequent formation of heterogeneous strains and subsequently deformation or microshear bands in grain interiors. GBS can also promote an increase in the new grain boundary misorientations and cause the new grain orientations to randomise.

3. Deformation or microshear bands are developed in various directions by sequential changing of deformation direction and so intersect with each other, followed by subdivision of original grains into misoriented small domains. The average grain size evolved is similar to the minimum spacing of deformation or microshear bands.
4. A strain-induced new fine grain structure develops due to gradual increase in the number and the misorientation angle of deformation or microshear bands, finally followed by their transformation into high-angle boundaries. It is concluded that grain refinement under hot MDF occurs by a series of deformation-induced continuous reactions; that is essentially similar to continuous dynamic recrystallization.

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