

New Grain Formation in a Coarse-Grained 7475 Al Alloy during Severe Hot Forging

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Keywords: *grain refinement, multidirectional forging, shear band, grain boundary sliding*

Abstract. Strain-induced grain refinement in a coarse-grained 7475Al alloy was studied by means of multidirectional forging (MDF) carried out at $T = 490^{\circ}\text{C}$ under a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$. Integrated flow curves exhibit significant work softening just after yielding, followed by steady-state-like behavior at high strains. The evolution of new fine grain structure during deformation can be assisted by grain-boundary sliding, resulting in frequent formation of high strain gradients and subsequently microshear bands in grain interiors. Microshear bands developed in various directions are intersected with each other, subdividing original grains into misoriented small domains. The number and the misorientation angle of microshear bands progressively increase during deformation, finally followed by their transformation into high-angle boundaries. It is concluded that grain refinement under hot MDF conditions occurs by a series of deformation-induced continuous reactions; that is essentially similar to continuous dynamic recrystallization.

Introduction

Recent investigations have shown that deformation methods for intense plastic straining (IPS), such as equal-channel angular extrusion, multidirectional forging (MDF) and torsion straining under high pressure, could be applied to produce submicron- or nanocrystalline grain structures [1]. There have been number of works to data connected with the studies of evolution of such ultrafine grain microstructures in Al - based alloys at low- to moderate deformation temperatures [e.g.1-3]. It was shown in these works that new fine grain structure could be evolved in accordance with a mechanism of continuous dynamic recrystallization (cDRX) [3,4]. Namely, some low - to medium - angle boundaries, often called as *deformation bands* or *geometrically necessary boundaries*, may be created within the old grains at relatively low strains due to high strain heterogeneity. They are progressively transformed into high-angle boundaries with further deformation resulting in development of new grain structures. At the same time, only a limited number of studies were dealt with the evolution process during severe deformation of Al alloys at elevated temperatures. As a result, the mechanisms of grain refinement taking place during IPS are currently a matter of some debate and not clear, although cDRX was frequently reported as a main mechanism responsible for formation of new grains during hot deformation by conventional deformation techniques [e.g.5-7]. Main factors controlling the development of (ultra)fine grain structures remain unknown.

The aim of the present work was to study the fine grain evolution in a coarse-grained 7475 Al alloy by means of MDF. A specific attention was paid to elucidate main factors controlling grain refinement in the Al alloy under MDF conditions and to discuss the mechanisms operating in detail.

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 pct). The initial microstructure was composed of dendritic lamellar grains lying parallel to the ingot axis; the grain boundaries were rather straight and/or corrugated. 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 one. Rectangular samples with the starting ratios of 1.5 : 1.25 : 1 and 1.8 : 1.7 : 1 were machined from the current Al ingot for MDF tests with a pass strain ($\Delta\varepsilon$) of 0.4 and 0.7, respectively. MDF was carried out in vacuum at $T=490^\circ\text{C}$ under a strain rate of $3 \times 10^{-4} \text{s}^{-1}$ with changing in the loading direction of 90° from pass to pass. The metallographic analysis was carried out on a section parallel to the last compression axis by using conventional and polarized optical microscopy after etching by a standard Dicks-Keller etchant. Scanning electron microscope backscattering images were obtained using a Hitachi-3500A SEM with OIMTM software.

Results and Discussion

Mechanical properties. Fig. 1 represents typical true stress - true strain ($\sigma - \varepsilon$) curves summarized for MDF of $\Delta\varepsilon = 0.4$ and 0.7. A $\sigma - \varepsilon$ curve in single pass compression is also represented by a broken line for comparison. It is seen that both the integrated flow curves demonstrate a sharp stress peak just after yielding followed by significant work softening. The latter takes place continuously up to large strains and then the cumulative flow curves show a steady-state-like flow behavior. It is remarkable to see in Fig. 1 that work softening appears more clearly in $\Delta\varepsilon = 0.7$ and flow stress reaches rapidly a steady state flow one comparing with that during MDF of $\Delta\varepsilon = 0.4$.

Microstructural development. MDF at moderate to high strains brings about the evolution of new grain structures initially along original grain boundaries and subsequently in some grain interiors. Fig. 2 represents typical microstructures evolved at $\varepsilon = 1.2$ in MDF of $\Delta\varepsilon = 0.4$ (i.e. after a first cycle of MDF). It can be seen in polarized microscopy, Fig. 2(a), that roughly regular arrays of parallel bands are developed within remained coarse grains. This suggests that crystal orientation of the local regions inside these bands can be something different from that of matrix grain. It is remarkable to note that several sets of deformation bands are developed in various directions and intersected in grain interiors. The deformed microstructure in Fig. 2(a) can consist of the regions of fine grains with a size of $9 \mu\text{m}$ and original grains fragmented by deformation bands.

It is seen in Fig. 2(b), an enlarged portion outlined in Fig. 2(a), that elongated grains are evolved in colonies accompanied with evolution of more equiaxed grains, suggesting that the formers can be transformed into the latters by further deformation. Fig.3 represents a typical OIM picture developed at $\varepsilon = 1.2$. Here different grayscale levels indicate different crystallographic orientations and orientation differences (θ) between neighboring grid points, $\theta > 2^\circ$, $\theta > 4^\circ$ and $\theta > 15^\circ$ are marked by thin white, narrow and bold black lines, respectively. It is seen in Fig. 3 that many fine grains and dislocation boundaries with low to moderate and even high angle misorientations are developed in coarse grain interiors. These boundaries are considered to correspond to those of deformation bands revealed by polarized optical microscopy. This suggests that mutual crossing boundaries can result in grain fragmentation leading to development of new fine crystallites with a roughly equiaxed shape.

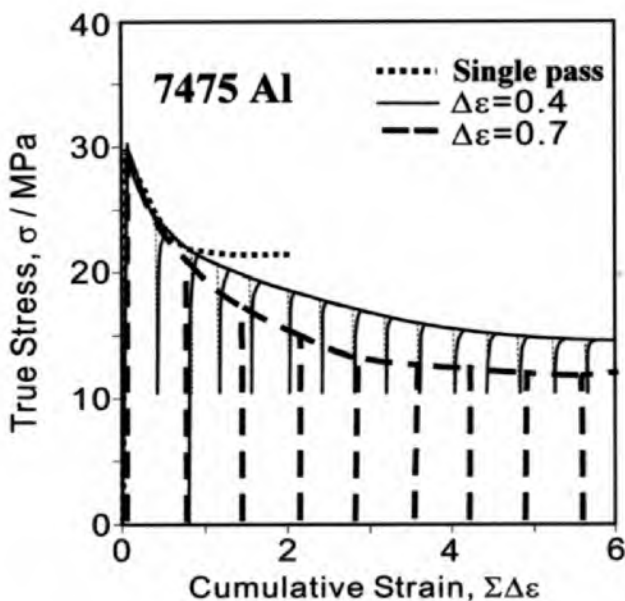


Fig. 1. Typical true stress - true strain curves obtained during MDF of $\Delta\varepsilon = 0.4$ and 0.7 at 490°C and at $3 \times 10^{-4} \text{s}^{-1}$. The $\sigma - \varepsilon$ curve in single pass compression is represented by dashed line for reference.

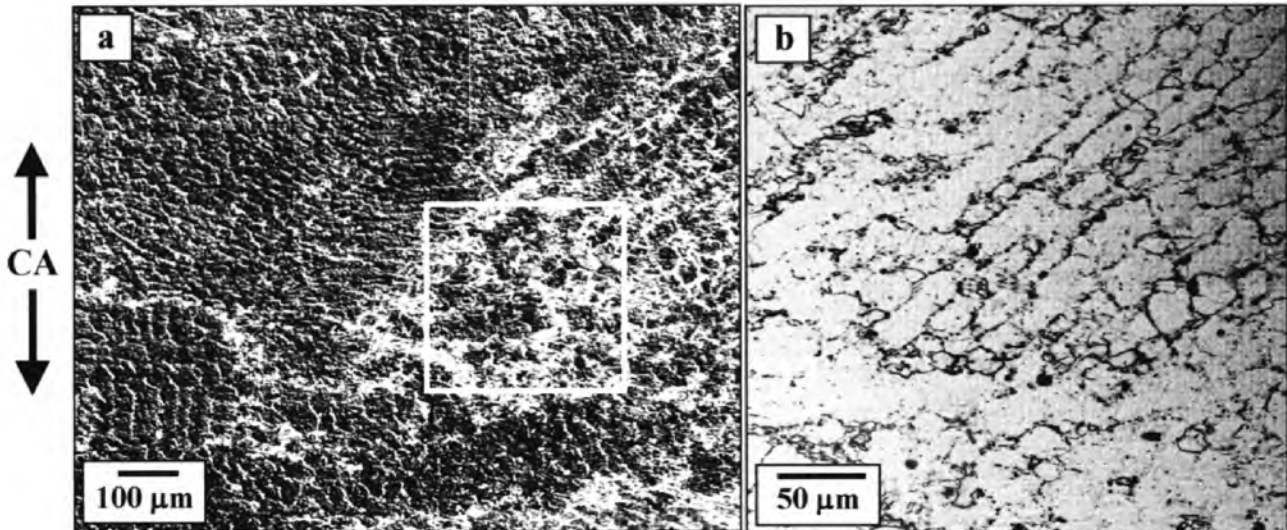


Fig. 2. Typical microstructures evolved in 7475 Al alloy during MDF with a pass strain of 0.4 to a cumulative strain of 1.2; (a) polarized light; (b) enlarged part outlined in (a) taken in conventional light. Hereafter CA is the last compression axis.

With further compression, the regions of original grains with deformation bands decrease and, in contrast, those of new fine grains progressively increase. At a strain of 6, initial coarse-grained microstructure is almost fully replaced by a new fine-grained one (see Fig. 5). Thus, new grain evolution taking place in the current 7475Al alloy can be closely related to the operation of structural mechanisms caused by grain fragmentation due to development of deformation bands, followed by evolution of new fine grains with moderate to large angle misorientation in high strain. Such a mechanism is generally believed to operate in materials strained by cold and warm IPS [4]. Let us consider the development process of deformation bands and discuss the mechanism of new grain evolution in more details.

Heterogeneous deformation and new grain formation. Fig. 4 represents a typical surface morphology developed after compression to (a) $\epsilon = 0.16$, (b) $\epsilon = 0.32$ ($= 0.16 + 0.16$) where the sample was compressed twice with rotation of 90° , and (c) $\epsilon = 2.56$, where the sample was deformed

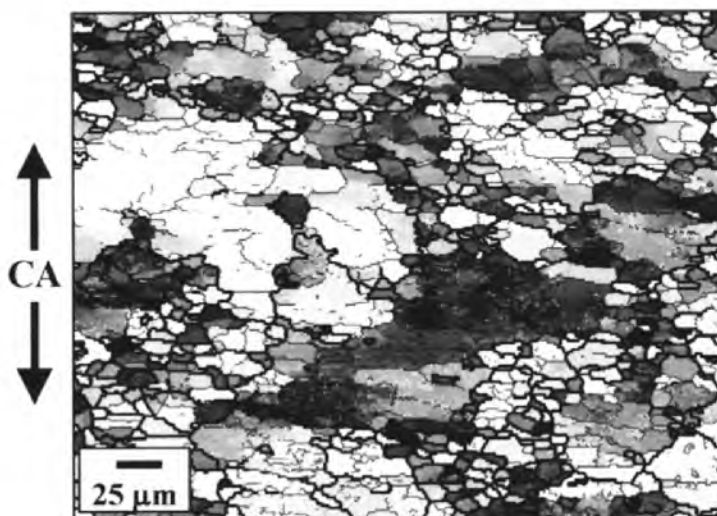


Fig. 3. OIM micrograph of 7475 Al alloy deformed to a strain of 1.2 with a pass strain of 0.4 at 490°C and at $3 \times 10^{-4} \text{ s}^{-1}$.

to $\epsilon = 2.4$ by MDF and then further deformed an additional 0.16 parallel to the last compression axis. It can be seen in Fig. 4(a) that grain boundary sliding (GBS) takes place along the initial grain boundaries (GB) and deformation bands are developed in grain interiors even at such a low strain. It is remarkable to note in Fig. 4(a) that deformation banding leads to rigid rotations of the scratched markers. This suggests that a process akin to kinking or folding can bring about a progressive reorientation of material inside these bands. Such deformation bands may be similar to *microshear bands* observed in cold-rolled Al alloys [8]. This is rather surprising because microshear

bands were reported to have a persistent feature of the microstructure developed during *cold deformation* of fcc metals at moderate to high strains [e.g.8]. In contrast, at early stages of hot deformation such strain - induced boundaries can be hardly developed in conventional Al alloys with equiaxed grain structures [6].

The authors showed in [9] that heterogeneous deformation could be sometimes introduced in the current Al alloy with an unsymmetrical, columnar structure during hot deformation due to inhomogeneous operation of GBS. Namely, GBS can occur with different rates along straight segments of the grain boundaries and corrugated ones. This introduces high strain gradients and stress concentrations in grain interiors. As a result, microscopic shear bands can be developed in these coarse grains even at early stages of hot deformation.

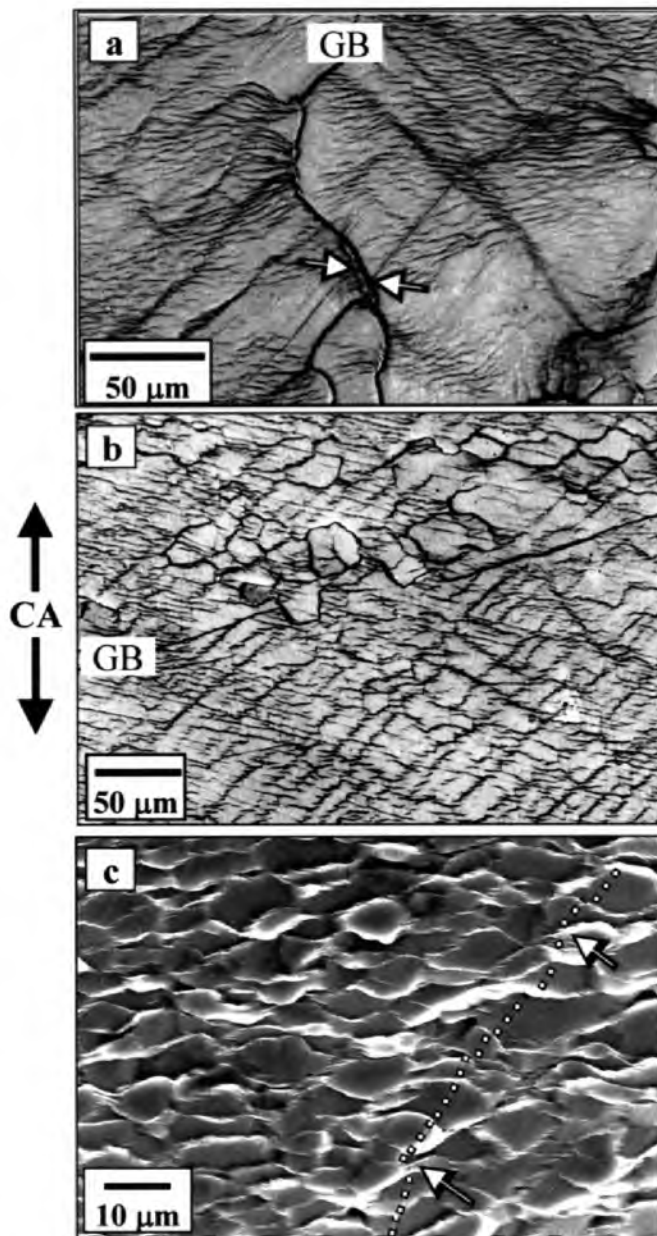


Fig. 4. Typical deformation relief developed on polished surface of 7475 Al alloy deformed to a strain of (a) 0.16, (b) 0.16 + 0.16 and (c) 2.4 + 0.16 at 490°C and at $3 \times 10^{-4} \text{ s}^{-1}$. Arrows and dashed line in (a) and (c) indicate position of scratched markers.

Multidirectional deformation can promote the development of microshear bands in various directions followed by their frequent intersection in grain interiors because of changing of deformation axes from pass to pass (Figs. 4(b) and 4(c)). This results in continuous subdivision of coarse grains into misoriented fine domains. It can be seen in Figs. 4(b) and (c) that new crystallites are evolved in the place of regions fragmented by boundaries of microshear bands. It is important to note here that at all strains investigated, the average size of such new grains was found to be similar to the minimal spacing of deformation bands derived from polarized microscopy and also that of microshear bands measured from surface relief [10]. This suggests that a main mechanism of grain refinement in the present Al alloy can be directly associated with grain splitting due to formation of *microshear bands* followed by increase in their number and misorientation.

During hot deformation, growth in the boundary misorientation of the crystallites fragmented by microshear bands may be also attributed to GBS. It can be seen in Fig. 4(c) that rotation and displacement of scratched markers can frequently take place along deformation - induced boundaries in fine-grained regions. In such regions, GBS can start to occur along layered boundaries, which have primary the high angle misorientations (see Fig. 4(b)). The rotation of these crystallites can promote progressive increase in misorientation of low angle boundaries and their rapid conversion into high angle ones [5,7].

Such model can be supported by the data of microstructure evolution taking place during hot deformation of unrecrystallized Al alloys [e.g.7].

The average size of new grains developed during MDF, d_{rex} , the volume fraction of new grains, V_{rex} , and the average misorientation, θ_{ave} , in the fine – grained regions are plotted against accumulated strain in Figs. 5(a), 5(b) and 5(c), respectively. The d_{rex} vs ε relationship obtained from uniaxial compression is also represented by dashed line in Fig. 5(a) for reference. It is seen that d_{rex} rapidly drops at earlier stages of deformation and approaches a constant value after a cycle of MDF, i.e. at $\varepsilon = 1.2$ in MDF of $\Delta\varepsilon = 0.4$ and $\varepsilon = 2.1$ in MDF of $\Delta\varepsilon = 0.7$ (Fig. 5(a)). V_{rex} increases with deformation and approaches a saturation of about 0.85 at large strains (Fig. 5(b)). θ_{ave} increases rapidly at low strains, gradually at moderate strains and then approaches a saturation value of around 34° (Fig.5(c)). Noteworthy that such strain dependencies of the microstructural parameters can be considered to be a specific feature of strain-induced grain structures, which is typical of cDRX [4-7]. It is concluded, therefore, that new grains evolved during hot MDF of the present alloy can result from strain induced continuous reactions; that is similar to cDRX.

Effect of pass strain on grain refinement. The data in Fig. 5 indicate that fine grain formation during MDF can be dependent on not only to accumulated strain, but also each pass strain, $\Delta\varepsilon$. Namely, increase in $\Delta\varepsilon$ from 0.4 to 0.7 results in evolution of smaller stable grain size and also promotes more rapid increase in the volume fraction and the average misorientation of new grains. It is also important to see in Fig. 5(a) that d_{rex} after MDF is larger than $5.5 \mu\text{m}$ after uniaxial compression in high strain. It is necessary to note that an evolution process of new grains during hot MDF can be principally the same as that operating during conventional single pass compression [9]. It is possible to consider that when uniaxial compression is continuously applied to the material, i.e. under a constant strain path condition, arrays of roughly parallel microshear bands can be evolved in one preferred direction within each grain. Their spacing is gradually reduced with compression, eventually leading to formation of high - density two - dimensional planar microstructure, i.e.

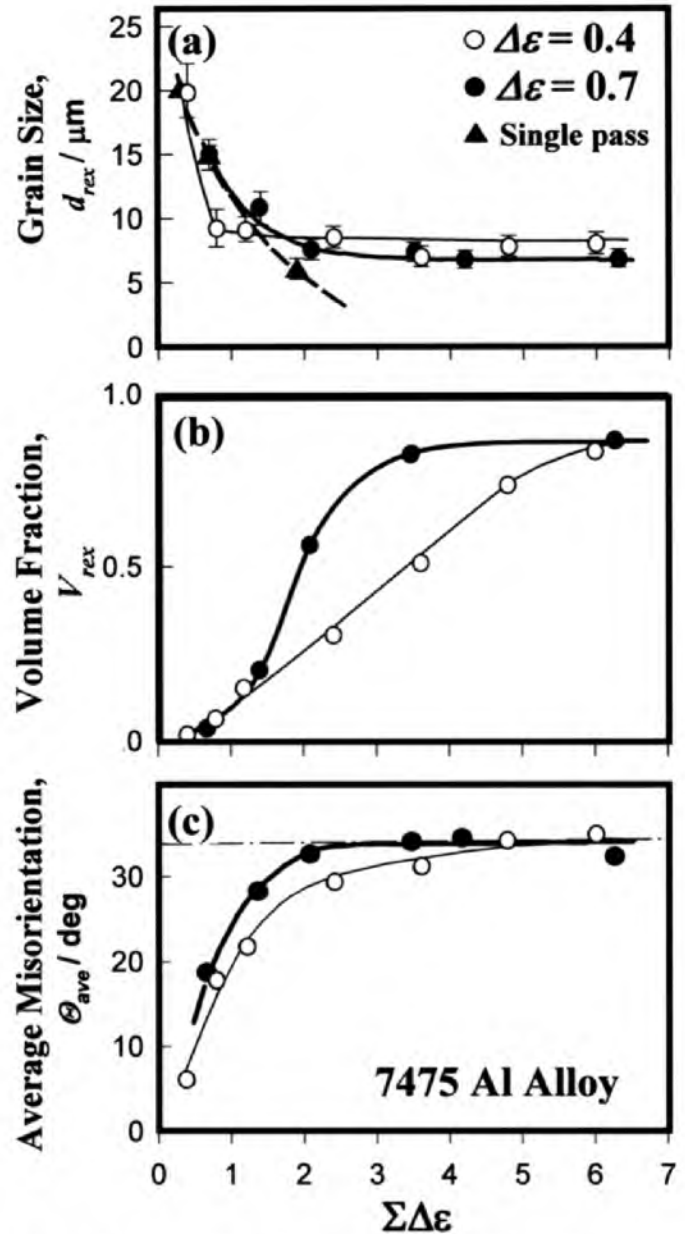


Fig. 5. Changes in the average size of new grains, d_{rex} , the volume fraction of new grains, V_{rex} , and the average misorientation angle of strain-induced boundaries, θ_{ave} , evolved during MDF with various pass strain. Dependence d_{rex} vs strain obtained from uniaxial compression is represented by dashed line for reference.

layered lamellar structure. In this case, new equiaxed grains with smaller size can be evolved only near the regions of grain boundaries, but scarcely in grain interiors. Interruption of uniaxial deformation at a strain of $\Delta\varepsilon$ and changes in strain path during repeated MDF can, in contrast, promote more homogeneous formation of equiaxed grains in grain interiors, which can be dependent on $\Delta\varepsilon$ (see Figs. 4(b) and (c)). Various shearing directions appearing during MDF and so the number of repeated compression passes can be more useful for mutual intersection of layered boundaries evolved and formation of equiaxed grains. The stable larger grain size is, therefore, developed more rapidly during MDF with smaller pass strain, i.e. $\Delta\varepsilon = 0.4$ (Fig. 5(a)). On the other hand, larger magnitude of local strains can be introduced during each pass in MDF with larger $\Delta\varepsilon$ and so the density and misorientation of microshear bands become larger, finally resulting in more rapid evolution of new finer grains. It has been discussed in [11] that strain-induced boundaries developed during MDF of $\Delta\varepsilon = 0.7$ can be more stable during reheating between passes and more readily support GBS. Accordingly, they can more rapidly increase their misorientation and faster transform into high-angle boundaries, resulting in large volume fraction of new grains. Such a strain pass effect disappears, however, with further compression and the characteristics of strain-induced grains, e.g. Θ_{ave} and V_{rex} , become roughly similar at severe large strains irrespective of $\Delta\varepsilon$ (see Figs. 5 (b) and (c)).

Summary

Strain-induced grain refinement in a coarse-grained 7475Al alloy was studied by means of multidirectional forging (MDF) carried out at a temperature of 490°C under a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$. The main results obtained by MDF of $\Delta\varepsilon = 0.4$ and 0.7 are summarized as follows.

1. The integrated flow curves exhibit a significant work softening at moderate strains, followed by steady - state like flow at large strains. With increasing in $\Delta\varepsilon$, flow stress decreases more rapidly and approaches faster a lower steady - state flow stress.
2. Deformation bands including microshear bands are developed in various directions during hot MDF and so intersect each other, resulting in continuous grain fragmentation. Further deformation leads to increase in the number and misorientation of these boundaries and finally almost full development of fine equiaxed grains in high strain. This grain refinement mechanism can be similar to continuous dynamic recrystallization.
3. Increasing $\Delta\varepsilon$ from 0.4 to 0.7 results in more rapid evolution of finer grains at moderate strains and finally faster development of a stable grain structure in high strain. The characteristics of such strain-induced grain structure, i.e. the average misorientation and the volume fraction, however, become almost similar at severe large strains irrespective of $\Delta\varepsilon$.

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