# Strain Rate Effect on Fine-Grain Development in 7475 Al Alloy during Hot Multidirectional Forging

Alexandre Goloborodko[1,2,a], Oleg Sitdikov[2,3,b], Rustam Kaibyshev[2,c],
Hiromi Miura[1,d] and Taku Sakai[1,e]

[1] Department of Mechanical Engineering and Intelligent Systems, **UEC, Tokyo** (The University of Electro-Communications), Chofu, Tokyo 182-8585, Japan
[2] Institute for Metals Superplasticity Problems, Khalturina 39, Ufa 450001, Russia
[3] Steel Research Center, National Institute for Materials Science, Tsukuba 305-0047, Japan

[a] sasha@sakai.mce.uec.ac.jp ; [b] SITIDIKOV.Oleg@nims.go.jp ; [c] rustam@anrb.ru
[d] miura@mce.uec.ac.jp ; [e] sakai@mce.uec.ac.jp

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**Abstract.** Effect of strain rate on grain refinement was studied in multidirectional forging (MDF) of a coarse-grained 7475 Al alloy at 490°C under strain rates of $3 \times 10^{-4}$ $s^{-1}$ and $3 \times 10^{-2}$ $s^{-1}$. At a strain rate of $3 \times 10^{-4}$ $s^{-1}$, the stress – strain ($\sigma$ -$\varepsilon$) behavior shows significant work softening just after yielding and a steady-state flow at higher strains. The structural changes are characterized by development of deformation bands at early stages of deformation, followed by formation of a fine-grain structure in high strain in the whole material. The volume fraction of new grains increases with strain and approaches a value of about 0.85 over a strain of 3. At a higher strain rate of $3 \times 10^{-2}$ $s^{-1}$, in contrast, a steady-state flow following small flow softening appears at a relatively low strain. New grains are formed during steady state flow along original grain boundaries and the volume fraction reaches below 0.2 even at a strain of 6.3. The occurrence conditions and the mechanisms of grain refinement are discussed in detail.

## Introduction

Metallic materials with fine-grained microstructures have many advantages of the chemical, physical and mechanical properties [1]. At present time, several methods available for producing of bulk materials composed of a fine-grained structure are based mostly on severely large plastic deformation [1,2]. One of them is multidirectional forging (MDF), which is the easiest method without any specific device and has a great potentiality for producing of relatively large workpiece that can be used in mass production. The principle of MDF is compression process repeated with change in the direction of the applied strain (*i.e.* $x \rightarrow y \rightarrow z \rightarrow x$ ...) at each step. Since a workpiece does not change its shape under MDF conditions, large plastic strain can be introduced into material during repeated compression at ambient to elevated temperatures. It has been shown recently [3-7] that such strain accumulation accompanied with various strain paths is very important for development of equiaxial fine grains, *i.e.* grain refinement. At the same time, grain refinement during MDF can be controlled not only by total strain accumulated and strain per each pass, but also strain rate and temperature. There are, however, a few experimental data on the latter's effect under MDF conditions.

The main aim of the present work was to study effect of applied strain rate on fine-grained structure formation in a coarse-grained 7475 Al alloy during hot MDF. The mechanisms of hot deformation, microstructural development during MDF and their interrelationship are discussed.

## Experimental Procedures

The material tested was an as-cast 0.16%Zr-modified 7475 Al alloy with the following chemical composition (in mass pct): 6.04Zn, 2.46Mg, 1.77Cu, 0.23Cr, 0.16Zr, 0.03Si, 0.04Fe, 0.03Mn and the balance Al. The initial microstructure was composed of dendritic lamellar grains lying parallel to the ingot axis. The boundaries of lamellar grains were rather straight and/or corrugated repeatedly. The average grain size was in the range from 1 to 10 mm in longitudinal direction and from 100 to 200 μm in transverse direction [8]. Rectangular samples with the starting ratio of 1.8 : 1.7 : 1 were machined from the ingot for the MDF tests for a strain pass of 0.7. MDF was carried out in vacuum at $T = 490^{\circ}$C and at true strain rates of $3 \times 10^{-4}$ $s^{-1}$ and $3 \times 10^{-2}$ $s^{-1}$ with change in 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 optical microscopy after etching by a standard Dicks-Keller etchant. Scanning electron microscope (SEM) backscattering images were obtained using a Hitachi-3500A SEM with orientation imaging microscopy (OIM) OIM$^{TM}$ software provided by TexSem Lab., Inc. Surface observations were carried out by using a Hitachi-3500A SEM.

## Results

### Mechanical Properties

Typical true stress – true strain ($\sigma$ - $\varepsilon$) curves during MDF at 490°C are presented in Fig. 1. The $\sigma$ - $\varepsilon$ curve at $3 \times 10^{-4}$ $s^{-1}$ demonstrates a sharp stress peak ($\sigma_p$) just after yielding followed by significant work softening and then a steady-state flow at high strains, *i.e.* $\sum\Delta\varepsilon > 5$. The ratio of $\sigma_p/\sigma_{ss}$, where $\sigma_p$ is a peak stress and $\sigma_{ss}$ is a steady state flow stress is around 0.61. At a strain rate of $3 \times 10^{-2}$ $s^{-1}$, in contrast, a steady-state flow following small flow softening appeared at relatively low strains, *i.e.* $\sum\Delta\varepsilon > 2$. The ratio of $\sigma_p/\sigma_{ss}$ is around 0.14. In these interrupted flow curves, there is negligible small difference between the flow stresses immediately before unloading and at reloading. This suggests that any structural changes during MDF can be mainly affected by strain accumulation applied in each compression pass.

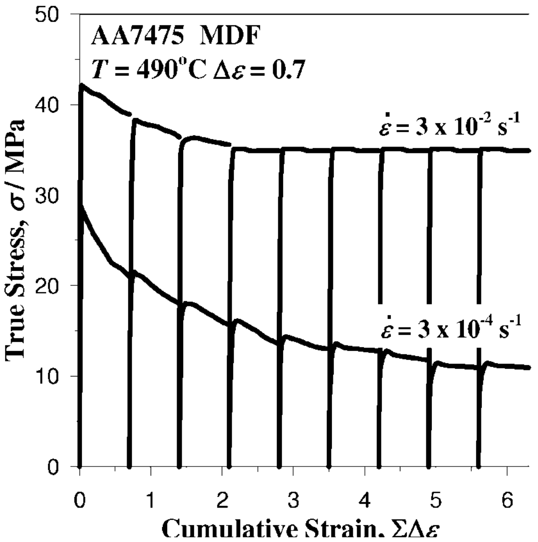

Fig. 1 Typical true stress – true strain curves obtained during MDF at 490°C and at strain rates of $3 \times 10^{-4}$ $s^{-1}$ and $3 \times 10^{-2}$ $s^{-1}$.

### Microstructural Development

Typical microstructures evolved at a cumulative strain of 6.3 are represented in Fig. 2. The regions that appear dark in color are composed of new fine grains evolved during hot MDF. It is clearly seen in Fig. 2(a) that MDF at $3 \times 10^{-4}$ $s^{-1}$ leads to a fine-grained structure formation accompanied with some remained original grains. The volume fraction of new grains with the average size of about 7.5 μm was about 0.85. During MDF at a strain rate of $3 \times 10^{-2}$ $s^{-1}$, in contrast, new grains with the average size of about 5.5 μm are formed mainly along original grain boundaries (Fig. 2(b)). The fraction of fine grains reaches a value below 0.2, which is significantly smaller than that for MDF at $3 \times 10^{-4}$ $s^{-1}$. It can be concluded from Fig. 2 that increase in strain rate leads to slow down the kinetics of new grain formation during MDF.

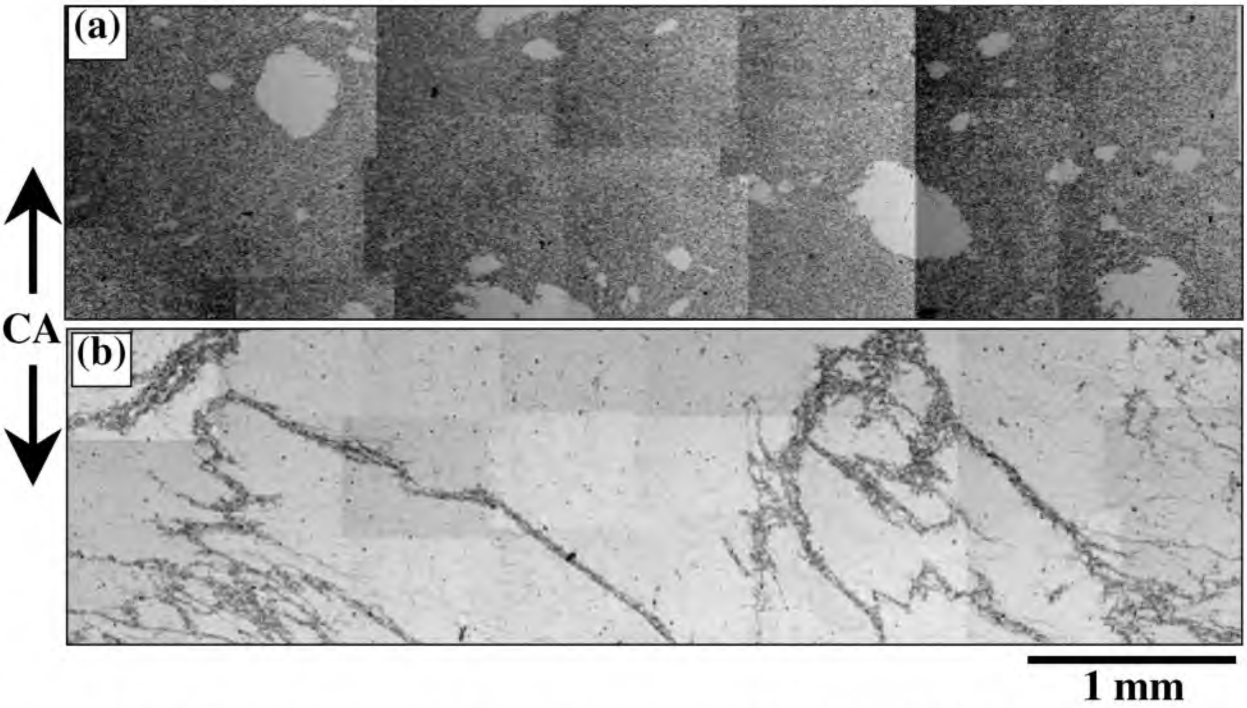

Fig. 2 Typical microstructures developed at a cumulative strain of 6.3 in 7475 Al alloy during MDF at 490°C and at strain rates of (a) $3 \times 10^{-4}$ $s^{-1}$ and (b) $3 \times 10^{-2}$ $s^{-1}$. Note the regions where new fine grains are evolved during hot MDF are those that appear dark in color.

## OIM Microstructures

Typical OIM pictures for samples processed to a cumulative strain of 2.1 at strain rates of (a) $3 \times 10^{-4}$ $s^{-1}$ and (b) $3 \times 10^{-2}$ $s^{-1}$ are presented in Fig. 3. Here the different grayscale levels indicate the different crystallographic orientations and the orientation differences ($\Theta$) between neighboring grid points, $\Theta > 2°$, $\Theta > 5°$ and $\Theta > 15°$ are marked by thin white, narrow and bold black lines, respectively. Fig. 4 represents the distributions of typical point-to-point ($\Delta\Theta$) misorientations developed in grain interiors along the lines $T_1$ and $T_2$ indicated in Fig. 3. It is seen in Figs. 3(a) and

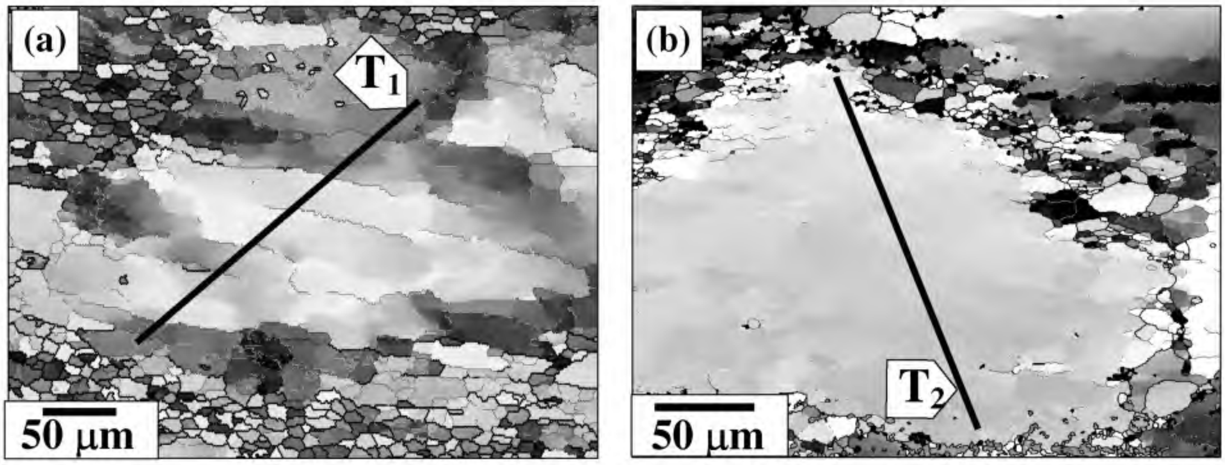

Fig. 3 Typical OIM images of 7475 Al alloy deformed to a cumulative strain of 2.1 at strain rates of (a) $3 \times 10^{-4}$ $s^{-1}$ and (b) $3 \times 10^{-2}$ $s^{-1}$. Thin white lines correspond to boundaries of misorientation > 2°, thin black lines > 5° and bold lines > 15°, respectively

4(a) that new boundaries with moderate angle misorientations, *i.e.* Θ > 8°, are developed in original grain interiors. The crystal orientation is frequently changed in the regions fragmented by such boundaries. The latters correspond to those of microshear or deformation bands, as discussed in detail elsewhere [4,7]. Development of such deformation bands can be resulted from highly heterogeneous deformation taking place in coarse grain interiors, as discussed below in more details. In contrast, development of deformation bands did not observe in original grain interiors during MDF at 3 × $10^{-2}$ $s^{-1}$ (Fig. 3(b)). It is seen in Fig. 4(b) that $\Delta\Theta$ does not exceed 4° in original grain interiors. These boundaries evolved correspond to those of conventional subgrains developed.

## Discussion

The present study shows that (i) grain refinement takes place in the as-cast 7475 Al alloy with coarse lamellar grains during hot MDF especially at lower strain rates; (ii) microstructural development depends sensitively on strain rate applied, *i.e.* an increase in strain rate tends to slow down the kinetics of new grain formation. Let us discuss the reason why the kinetics of grain formation becomes faster at lower strain rate, *i.e.* 3 × $10^{-4}$ $s^{-1}$.

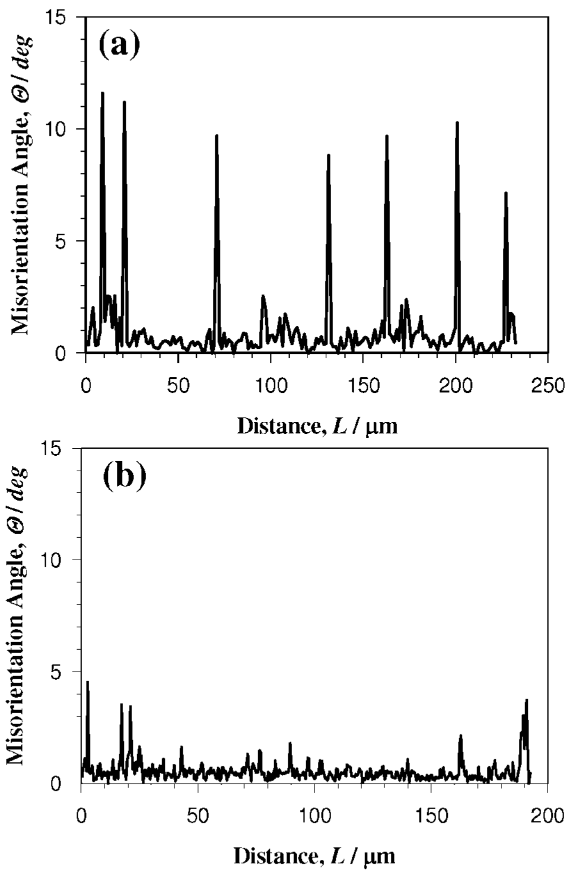

Fig. 4 Point-to-point misorientation ($\Delta\Theta$) developed in original grain interiors during MDF of 7475 Al alloy deformed to a cumulative strain of 2.1 at strain rates of (a) 3 × $10^{-4}$ $s^{-1}$ and (b) 3 × $10^{-2}$ $s^{-1}$. They were measured along the lines $T_1$ and $T_2$ indicated in Figs. 3(a) and 3(b), respectively.

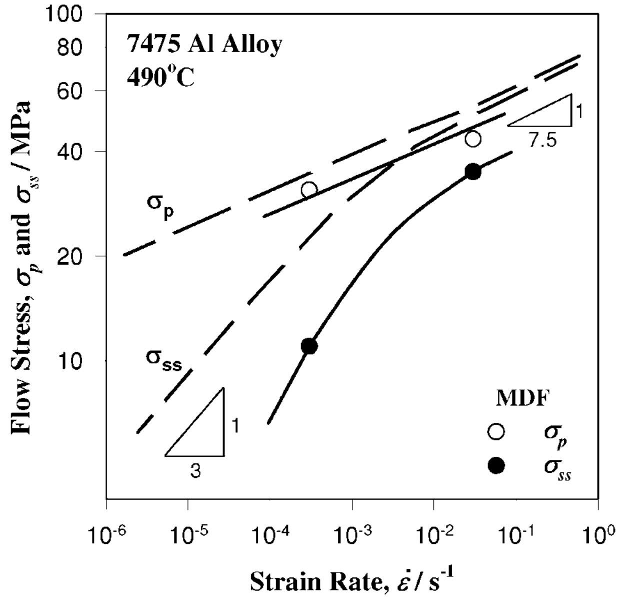

Fig. 5 The peak and steady state flow stresses, $\sigma_p$ and $\sigma_{ss}$, are plotted at strain rates tested by MDF at 490°C. The data for uniaxial compression [9] are shown by broken lines for comparison.

It has been suggested in previous work [9] that different deformation mechanisms operate during uniaxial compression of present 7475 Al alloy at 490°C. The peak and steady state flow stresses, $\sigma_p$ and $\sigma_{ss}$, are plotted at strain rates tested by MDF in Fig. 5. The data obtained by uniaxial compression [9] are also shown by solid lines. The stress exponent (n) for $\sigma_{ss}$ was found to be decreased from around 7.5 with decreasing

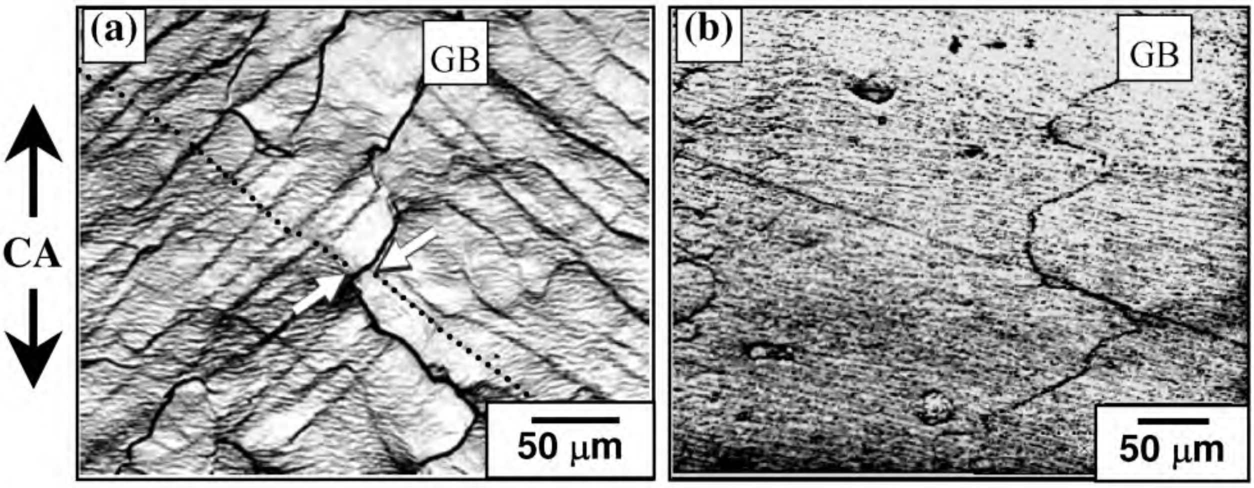

Fig. 6 Typical deformation relief developed on polished surface of 7475 Al alloy deformed to a strain of 0.16 at 490°C and at strain rates of (a) $3 \times 10^{-4}$ $s^{-1}$ and (b) $3 \times 10^{-2}$ $s^{-1}$. Note displacment of a scratched marker as well as many deformation bands developed in grain interiors in (a), but they are not in (b).

strain rate and tends to approach to around 3 in low strain rates. It is noted that such results are roughly similar to those for a coarse-grained 7075 Al alloy at the same deformation conditions [10]. In accordance with [10], such a flow behavior of $\sigma_{ss}$ allows assuming that grain boundary sliding (GBS) can frequently take place during deformation at low strain rates, *i.e.* $\dot{\varepsilon} \leq 10^{-2}$ $s^{-1}$, and, in contrast, hardly occurs in the region of $\dot{\varepsilon} \geq 10^{-2}$ $s^{-1}$. It should be noted in Fig. 5 that the values of $\sigma_{ss}$ for MDF are lower than those for uniaxial compression. It may be resulted from the difference in value of volume fraction of new fine grains developed, *e.g.* the volume fraction of new grains developed during uniaxial compression and MDF at $3 \times 10^{-4}$ $s^{-1}$ is 20 and 85%, respectively [7].

Figs. 6 (a) and (b) represents typical surface morphology of the samples deformed to a strain of 0.16 at strain rates of $3 \times 10^{-4}$ $s^{-1}$ and $3 \times 10^{-2}$ $s^{-1}$, respectively. It is clearly seen in Fig. 6(a) that GBS takes place along original grain boundaries (GB) and deformation bands are frequently developed in grain interiors even at such a low strain. It has been shown in the previous study [8] that heterogeneous strains are frequently introduced in the present Al alloy during hot deformation as GBS occurs at different rates along straight and corrugated segments of the grain boundaries. This introduces high strain gradients and stress concentrations in original grain interiors, followed by development of microshear bands [4-7]. MDF promotes the development of microshear bands in various directions, followed by their intersection in grain interiors due to changes in loading direction between subsequent passes. This can result in continuous subdivision of coarse grains into misoriented fine domains, finally leading to the evolution of new grains in high strain [4-7]. It can be concluded that GBS takes place frequently in such fine-grained regions and so can accelerate the evolution rate of fine grains (Fig. 2) and result in significant work softening (Figs. 1 and 5) [6,8,11].

On the other hand, GBS occurs hardly along initial lamellar boundaries during deformation at higher strain rate. The distribution of slip features in original grain interiors is essentially homogeneous and so strain localization and deformation bands are scarcely developed, as can be seen in Fig. 6(b). As a result, new fine grains are evolved only along the original grain boundaries and so at very slow rate during MDF at a strain rate of $3 \times 10^{-2}$ $s^{-1}$ (Figs. 2(b) and 5). At higher strain rates, dislocation motion can be controlled mainly by dragging of solute atmosphere and so slip deformation occurs homogeneously in the 7475 Al alloy [12]. This may be because minor strain gradients can be introduced only in the regions of initial grain boundaries, leading to development of new grains.

## Summary

Development of new fine grains in a coarse-grained 7475 Al alloy was studied in multidirectional forging at $T$ = 490°C under strain rates of $3 \times 10^{-4}$ $s^{-1}$ and $3 \times 10^{-2}$ $s^{-1}$. The main results are summarized as follow.

1. Increase in strain rate leads to slow down the kinetics of new grain formation during hot MDF. The volume fraction of new grains saturated in high strain decreases from 0.85 to 0.2 with increase in strain rate from $3 \times 10^{-4}$ $s^{-1}$ to $3 \times 10^{-2}$ $s^{-1}$.
2. Grain boundary sliding (GBS) takes place heterogeneously in unsymmetric lamellar grains at a strain rate of $3 \times 10^{-4}$ $s^{-1}$, followed by the formation of deformation bands in initial grain interiors. MDF promotes the development of deformation bands in various directions and results in continuous subdivision of coarse grains into misoriented domains, finally leading to the evolution of new grains in whole area.
3. Homogeneous slip deformation takes place at a strain rate of $3 \times 10^{-2}$ $s^{-1}$, where GBS and formation of deformation bands hardly take place. So fine grains are formed only along original grain boundaries and scarcely in grain interiors.

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## References

[1] R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov: Progr.Mater.Sci. Vol. 45 (2000), p.103.
[2] F.J. Humphreys, P.B. Prannell, J.R. Bowen, A. Gholinia, C. Harris: Phil.Trans.R.Soc.Lond. Vol.A357 (1999), p.1663.
[3] A. Belyakov, T. Sakai, H. Miura, R. Kaibyshev: ISIJ International Vol. 39 (1999), p.592.
[4] O. Sitdikov, T. Sakai, A. Goloborodko, H. Miura: Scr.Mater. Vol. 51 (2004), p.175.
[5] O. Sitdikov, T. Sakai, A. Goloborodko, H. Miura, R. Kaibyshev: Mater.Trans. Vol. 45 (2004), p.2232.
[6] O. Sitdikov, T. Sakai, A. Goloborodko, H. Miura, R. Kaibyshev: Mater.Sci.Forum Vols. 467-470 (2004), p.421.
[7] O. Sitdikov, T. Sakai, A. Goloborodko, H. Miura, R. Kaibyshev: Phil.Mag. Vol. 85 (2005) in press.
[8] R. Kaibyshev, O. Sitdikov, A. Goloborodko, T. Sakai: Mater.Sci.Eng. Vol. A344 (2003), p.348.
[9] O. Sitdikov, A. Goloborod`ko, R. Kaibyshev, H. Miura and T. Sakai: Phys.Metal.Metallogr. Vol. 99 (2005), p.106.
[10] T.Sakai, C.Takahashi: Mater.Trans.JIM Vol. 32 (1991), p.375
[11] X. Yang, H. Miura, T.Sakai: Mater.Trans. Vol. 43 (2002), p.2400.
[12] O. Sitdikov, A. Goloborodko, R. Kaibyshev, T. Sakai: Hot deformation of Aluminum Alloys III (Eds. Z. Jin, A. Beaudoin, T.A. Bieler and B. Radhakrishnan) TMS (The Minerals, Metals & Materials Society) (2003), p.61.