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2 authors:

Rustam Kaibyshev
Belgorod State University

S. S. Malopheyev
Belgorod State University

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Mechanisms of dynamic recrystallization in aluminum alloys

Rustam Kaibyshev[1,a,*], Sergey Malopheyev[1,b]

[1]Laboratory of Mechanical Properties of Nanostructural Materials and Superalloys, Belgorod State University, Pobeda 85, Belgorod 308015, Russia

[a]rustam_kaibyshev@bsu.edu.ru, [b]malofeev@bsu.edu.ru

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Abstract. Mechanisms of dynamic recrystallization operating at severe plastic deformation in a wide temperature range are reviewed for aluminum alloys. The main mechanism of grain refinement in all aluminum alloys is continuous dynamic recrystallization (CDRX). Temperature, deformation process and distribution of secondary phases strongly affect the CDRX mechanism. Initial formation of geometrically necessary boundaries (GNBs) and a dispersion of nanoscale particles accelerate CDRX facilitating the formation of a 3D network of low-angle boundaries (LAB) followed by their gradual transformation to high-angle boundaries (HAB). At high and intermediate temperatures, 3D networks of LABs may evolve due to rearrangement of lattice dislocations by climb, and mutual intersection of GNB, respectively. At high temperatures, in aluminum alloys containing no nanoscale dispersoids the CDRX occurs through the impingement of initial boundaries forced by deformation-induced LABs. This recrystallization process is termed as geometric dynamic recrystallization (GDRX). At low temperatures, the extensive grain refinement occurs through a continuous reaction which is distinguished from CDRX by restricted rearrangement of lattice dislocation. Introduction of large misorientation may occur through the formation of 3D networks of GNBs, only.

Introduction

Aluminum alloys with ultra-fine grain (UFG) structure produced by intense plastic straining are advanced materials for structural and functional applications [1]. Grain refinement provides increase in strength at room temperature and makes the material superplastic at elevated temperatures [1]. Increased strength in materials with UFG structure is attributed through the grain boundary strengthening in accordance with the well-known Hall–Petch relationship [2,3]:

$$\sigma_y = \sigma_0 + k_y\, d^{-1/2} \tag{1}$$

where σ_0 and k_y are material constants. Hall-Petch strengthening in aluminum alloys is not so efficient as in steels [3] due to a low value of k_y ranging from 0.06 to 0.26 MPa×√m [4,5]. Therefore, extensive grain refinement up to sub-micrometer level is required to attain significant grain size strengthening. In addition, the utilization of superplastic blow forming technology may be significantly promoted by making a substantial reduction in the grain size to the sub-micrometer or even the nanometer level in aluminum alloys [2].

Processing aluminum alloys through conventional thermomechanical processing provides the formation of a uniform granular structure with an average size ranging from 6 to 15 μm [6]. Extensive grain refinement in aluminum alloys to levels from 100 nm to 1 μm could be attained only through dynamic recrystallization [7]. Aluminum alloys exhibit high stacking fault energy (SFE) and continuous dynamic recrystallization (CDRX) is the main mechanism of dynamic grain refinement in a wide temperature range [6,7]. However, the fully recrystallized structure evolves only at sufficiently large strain [6-14]. Any decrease in the critical strain imposed into an aluminum alloy to produce sub-micrometer scale or nanoscale structure is extremely important. The rate of the dynamic grain refinement is controlled by CDRX mechanism that, in turn, is strongly affected by the phase composition of aluminum alloys and the deformation temperature [7,10,14]. The aim of the present work is to give an outlook of CDRX mechanisms operating in different aluminum alloys in a wide temperature range.

CDRX includes the formation of stable three-dimensional arrays of deformation-induced (LABs) followed by their gradual transformation to high-angle grain boundaries (HABs) upon straining [7-9]. The new grains form as a result of the increase in sub-boundary misorientation brought about by the continuous accumulation of the dislocations introduced by the deformation [7-9]. Three conditions have to be fulfilled for a high rate of this process [6,7]:

(i) The migration ability for deformation-induced LABs has to be low;
(ii) 3D arrays of LABs have to form;
(iii) LABs should be capable of transformation to HABs by trapping mobile dislocations.

In aluminum alloys the formation of deformation-induced subgrains is the slowest process controlling the overall rate of the CDRX. The occurrence of CDRX could be highly facilitated through initial deformation banding [7,11,13,14]. At cold-to-warm working, geometrically necessary boundaries (GNBs) with initial low-angle misorientation [7,15] begin to appear at moderate strains, introducing large misorientations. Subdivision of the original grains into 3D arrays bounded by dislocation boundaries with low-angle misorientation takes place. It is apparent that this process plays a vital role in initiating CDRX at low and intermediate temperatures [7,11,13,14].

CDRX in dilute aluminum alloys at high temperatures

At high temperatures, plastic deformation becomes more homogeneous. No formation of GNBs takes place in dilute aluminum alloys at high temperatures even under equal channel angular pressure (ECAP) that provides simple shear and, therefore, extensive slip localization in the ECAP shearing plane [7,11,13,14]. High value of the SFE provides a high ability of lattice dislocations to rearrange at elevated temperatures in aluminum and its alloys [6] that hinders the formation of 3D arrays of (LAB) with moderate-to-high misorientation [7]. The deformation-induced LABs are mobile and consist of statistically stored dislocations [15]. An extensive collision of these boundaries of opposite sign may lead to their complete dissolution [8]. As a result, no increase in average misorientation of deformation-induced boundaries may occur with strain [14,16] and a partially recrystallized structure retains even after very high strains [7,11,13].

The main process of the microstructural evolution, which is often termed geometric dynamic recrystallization (GDRX) [6], consists of severe elongation of initial grains along the direction of the plastic flow (Fig.1). Transverse sub-boundaries force initial boundaries to become serrated, and then the HABs impinge. The lamellar structure with transverse LABs evolves (Fig.1a). The tension force of sub-boundaries arisen from their energies is not high [6]. As a result, the initial grain boundaries aligned along the direction of plastic flow are pushed towards each other with a low rate (Fig.1b) [13,14]. Transverse deformation-induced sub-boundaries are not capable to be transformed to HABs [14,16], but these boundaries provide impingement of mutual opposite initial boundaries during deformation that leads to the formation of relatively coarse recrystallized grains [6,13,14]. The size of new grain is essentially equal to the size of subgrains and/or thickness of elongated initial grains and even higher than that obtained by conventional cold working followed by recrystallization annealing [6]. GDRX could be considered as abnormal or apparent CDRX.

CDRX at high temperatures in aluminum alloys containing nanoscale dispersoids

Introducing nanoscale dispersoids into aluminum alloys increases the stability of LABs and enables the formation of 3D arrays of these boundaries (Fig.2a) followed by their gradual transformation to HABs by trapping mobile dislocations (Fig.2b) [8,9,13,17]. This process occurs heterogeneously and leads to the formation of a partially recrystallized structure [8,9,13,14]. There are two ways to promote the occurrence of CDRX at these conditions. First, the introduction of coherent dispersoids of $Al_3(Sc,Zr)$ phase with size less than 15 nm highly increases the Zener drag force and ceases migration of boundaries with low-angle misorientation [17,18]. The high efficiency of these particles in pinning mobile dislocations and migrating boundaries sustains the (ii) and (iii) processes of CDRX by completely ceasing mutual annihilation of LABs consisting of dislocations of opposite sign. Annihilation of separate dislocations occurs only when most of the lattice dislocations emitted by sources are accumulated in LABs increasing their misorientation that eventually leads to their transformation to HABs with strain. An almost fully recrystallized structure may evolve at very high strain [17,18].

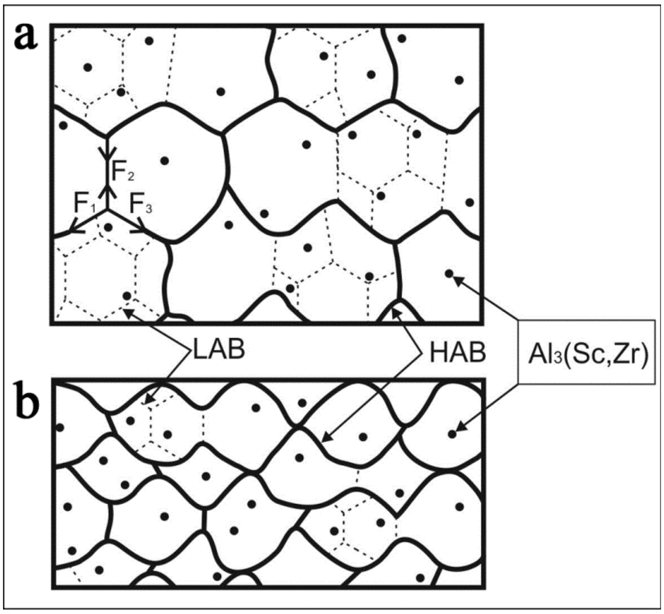

Fig. 1. Schematic presentation of the GDRX mechanism: (a) impingement of initial boundaries by deformation-induced LABs; (b) the formation of UFG structure.

Second, deformation techniques may provide intense localization of plastic deformation on the macroscale level within a narrow area of the localized plastic flow, in which a fully recrystallized structure evolves [9]. In the last case, deformation banding plays an important role in introducing initial moderate-to-high misorientation that highly facilitates the formation of 3D arrays of LABs. The pinning efficiency of incoherent or semi-coherent Al_3Zr dispersoids is sufficient to stabilize 3D arrays of deformation-induced LABs within zones of severe plastic deformation providing their gradual transformation to HABs [9]. However, no formation of recrystallized structure takes place outside of areas of severe localization of the plastic flow due to the fact that a material with UFG structure becomes superplastic. Upon further deformation the plastic flow localizes in areas of UFG structure owing to decreased flow stress. As a result, only billets with highly heterogeneous structure could be produced [9].

Thus, the formation of a fully recrystallized structure at high temperature may be attained by Sc additives [17,18] or localization of plastic deformation that highly promotes the occurrence of CDRX through local initial deformation banding [7]. However, the average grain size of the recrystallized grains is 2 μm or higher and achieving a fully recrystallized structure requires severe plastic deformation [13,17,18].

CDRX in aluminum alloys at intermediate temperatures

At intermediate temperatures, the formation of GNBs gives a major contribution to the evolution of 3D arrays of LABs. The appearance of deformation-induced HABs is attributed solely to the formation of GNBs, and, therefore, the formation of 3D arrays of GNBs having initially low-angle misorientation plays a vital role in CDRX. The GNBs evolve at the most stressed {111} planes owing to high strain gradients within narrow zones of plastic deformation (Fig.3a) [20]. Simple shear providing a very high-slip concentration in one {111} plane, and therefore, the deformation technique providing simple shear is highly capable of producing UFG structure in aluminum alloys [8,11-14]. The subdivision of initial grains by GNBs to 3D crystallites requires a continuous strain path change to make none-coplanar GNBs (Fig.3b). This change yields the subsequent activation of dislocation glide in different {111} planes in consecutive deformation passes, due to the change in the shearing patterns from pass to pass, occurring in such a way that it provides the highest stress concentration in a new {111} plane in each consecutive pass. If no strain path change takes place during deformation, the lamellar-type structure evolves [6]. It is worth noting that in this case the transverse deformation-induced boundaries, which subdivide deformation bands outlined by GNBs, may evolve due to rearrangement of lattice dislocation by climb or through the formation of GNBs along minor stressed {111} planes. However, these processes require elevated temperatures and higher strains. The introduction of nanoscale dispersoids of $Al_3(Sc,Zr)$ leads to 50K increase in the optimal temperature for extensive grain refinement [8,11-14]. As a result, the deformation-induced boundary may originate partially from GNBs and partially evolve by rearrangement of lattice dislocations by climb [8]. These dispersoids effectively suppress the migration of deformation-induced boundaries, and therefore, transformation of LABs to HABs occurs with a high rate [8]. Intense plastic straining at elevated temperatures is highly effective in producing UFG structure in aluminum alloys with average grain size of about 1 μm or less.

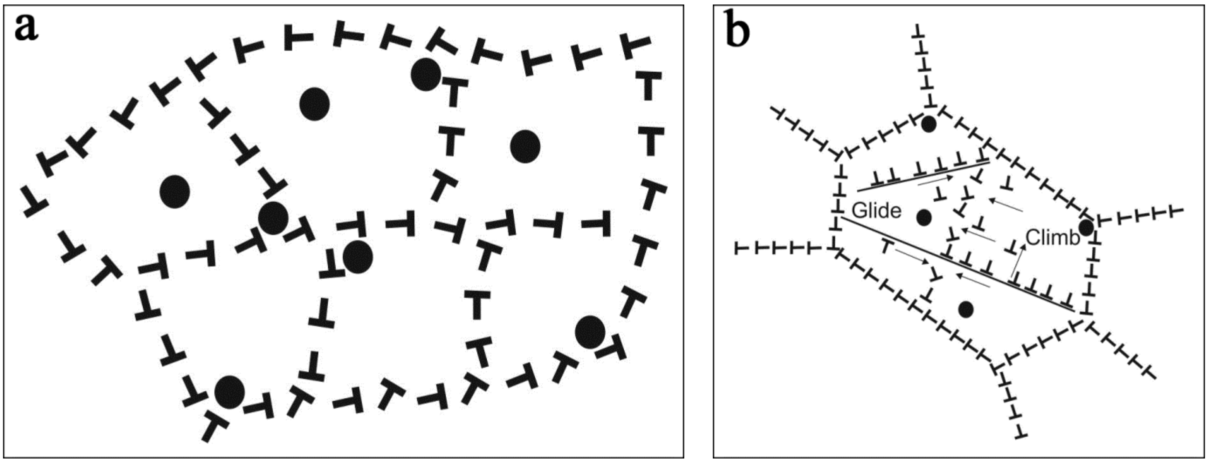

Fig. 2. Schematic presentation of the CDRX mechanism: (a) the formation of array of LABs; (b) interaction of LABs with lattice dislocations resulting in progressive increase in their misorientation.

The rearrangement of lattice dislocations by low temperature climb controlled by slow pipe-diffusion [19] occurs on short distances and hinders annihilation of lattice dislocations. This process provides the transformation of GNBs to sub-boundaries (Fig.3c) and is a prerequisite condition for a high rate of the (iii) process of CDRX. The combination of extensive deformation banding, which provides initial grain subdivision and introduce high misorientation, high stability of 3D arrays of sub-boundaries due to a high Zener drag pressure and a low portion of the lattice dislocations annihilated, allows producing UFG after relatively moderate strain [7-14]. Therefore, intermediate temperatures are optimal for the production of UFG structure in aluminum alloys.

Continuous reaction at ambient temperature

At room temperature, the ability of lattice dislocations to rearrange by climb or cross-slip is very limited and may occur only in the vicinity of deformation-induced boundaries [7]. As a result, the evolution of deformation-induced HABs may originate only from the formation of deformation bands [21,22]. The rate of continuous reaction is controlled by the rate of transformation of GNBs having initially low-angle misorientation, to HABs. This process is shown in Fig.3c. The effect of chemical composition of aluminum alloys on this process is attributed to its effect on diffusion, and therefore, on the ability of the dislocations composing GNBs to rearrange. The rate of grain refinement is dependent on the rate of dislocation rearrangement in accordance with the scheme (Fig.3c). The aforementioned role of strain path changes is extremely important for producing UFG structure with average grain size close to 100 nm [23]. If the deformation technique is not capable of the formation of GNBs along three non-coplanar {111} planes, the lamellar structure evolves. Therefore, under cold working the deformation technique is the main factor providing the formation of a granular structure instead of a lamellar one.

Summary

Continuous dynamic recrystallization is an effective mechanism for extensive grain refinement in aluminum alloys subjected to intense plastic straining. Microstructures with average grain size ranging from 100 nm to 2 μm can be produced in aluminum alloys. The chosen deformation technique, deformation conditions and the chemical composition of aluminum alloys highly affect the process of grain refinement through their influence on the mechanism of CDRX.

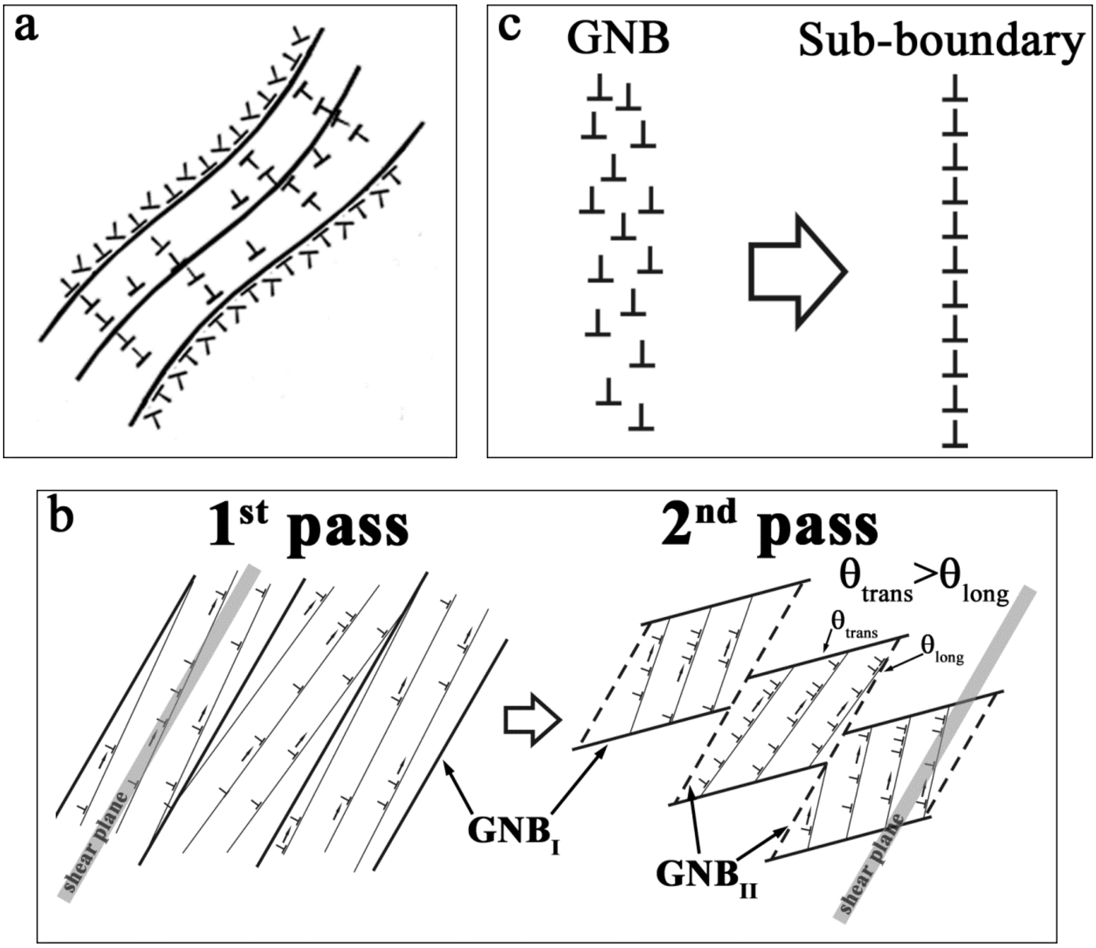

Fig. 3. Schematic presentation of the GDRX mechanism: (a) formation of GNBs; (b) the formation of 3D arrays of GNBs; (c) transformation of a GNB to a sub-boundary.

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