Deficiencies in Continuous DRX Hypothesis as a Substitute for DRV Theory

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Keyword: dynamic recovery, continuous dynamic recrystallization

Abstract

Recent measurement of increasing density of high angle boundaries with rising hot working strain led to the proposal that the misorientations of deformation–induced boundaries march upward, leading to the continuous dynamic recrystallization (cDRX) hypothesis during straining. Dynamic recovery (DRV) theory is founded on the development of subgrains of constant size with both constant wall and internal dislocation densities that make possible steady state straining at constant temperature T, stress (creep) and strain rate (hot work). Moreover, the subgrains remain equiaxed within elongating grains, with increasing length of high angle boundary, because the sub-boundaries are ephemeral, continually rearranging, as directly observed and actually decreasing in frequency (more cells touching grain boundaries). Compared to cold working, hot worked substructures have no increased misorientations but are simply recovered; this makes the cells larger and less ragged.

1. Introduction

Continuous dynamic recrystallization (cDRX) in reference to single phase alloys [1-3] is a mistaken interpretation of microstructural evidence and a confusing terminology that is applied either to the warm working domain or to very high strains. In the warm working domain the substructure is more highly recovered than in cold working and exhibits some regions intermediate between cell and subgrain, each having around part of it a strain induced wall greater than 15°. At very high hot strains in Al, the microstructures in polarized optical microscopy (POM) and in orientation imaging microscopy (OIM) are fields of crystallites that have the size of subgrains at lower strains ε and several facets of high misorientation ψ and that camouflage the original grain boundaries (GB) [6-11]. The objective is to consider why cDRX does not meet the definitions commonly associated with recrystallization and to show how the well established and broadly based mechanism of dynamic recovery can be applied to the phenomena to provide improved understanding [10,11].

2. Discontinuous Static Recrystallization (dSRX)

Annealing of single phase cold worked metals usually leads to dSRX after some static recovery (SRV); at completion the new grains have a low dislocation density similar to the level from slow solidification [12-14]. A recrystallizing grain is a region produced by

migration of a high angle boundary through deformed matrix that eliminates the substructure from previous strain. The region of nucleation had a high ψ relative to the neighboring matrix as a result of deformation. Through local substructure rearrangements, e.g. merging of cores of closely adjacent dislocations, a high-density wall undergoes a conversion to a relaxed boundary of high mobility [15-17]. Due to differentials in strain energy, the new GB advances rapidly absorbing the substructure.

In single crystals significant sites for nucleation are transition boundaries (TB) between deformation bands; they consist of several layers of fine cells with ψ reaching 30° at $\varepsilon \approx$ 3-4 [18]. In polycrystals, there are many more nucleation sites along the original GB not because they bow out (except after low ε). Careful transmission microscopy (TEM) confirms the presence of planar boundaries or block walls (BW) that separate regions of cells with weak walls; with rising strain BW develop high misorientations some near 30° with average ψ exceeding 8° [13,19-22]. After extensive rolling ($\varepsilon >$ 4), the microstructure consists of lamellar boundaries parallel to the rolling plane separating bands, each one having an orientation that is one of the components present in the rolling texture. On annealing, larger cells in some bands grow into neighboring bands and give rise to the recrystallization texture [12-14]. In all the above cases, many high ψ boundaries are produced by strain and the materials are not considered recrystallized until nucleation and growth takes place. The dSRX boundaries are suitably relaxed (equilibrium) so that superplastic straining is possible if the final grains are small enough.

3. Discontinuous Dynamic Recrystallization (dDRX)

Classical dDRX is found in Cu, Ni and γ Fe [23-27] but only in extremely pure Al or α Fe [28,29] and is usually marked by a peak and work softening due to first wave; a steady state follows with repeated distributed nucleation. The nucleation and growth of new grains is like dSRX initiating along the original GB. Single crystals are marked by nucleation at a single site, leading to rapid growth with elimination of substructure and a drop in stress σ [30,31]. The significant difference of dDRX and dSRX is the injection of dislocations into the nucleus that initially raised the critical strain and later curtails the final grain size as determined by temperature T and strain rate $\frac{i}{\varepsilon}$ [32]. Notably, DRV plays a significant role in generation of nuclei before the peak and in steady state [24,27,33]. Although the migrating GB create trailing bands empty of dislocations DRV helps define the substructure in the steady state grains and hence controls the stress σ [33].

In the single crystal studies, DRX was not considered to have occurred until nucleation with a σ drop, although many subgrains of high ψ had developed earlier [30,31]. The new grains qualify as recrystallized because the substructure from previous straining is eliminated. The dDRX grains are about ten times the subgrain diameter both at nucleation and in the steady state regime [24,27]. On holding, they rapidly recrystallize to strain free grains more than twice the diameter.

4. Continuous cDRX, Particle Stabilized

After heavy cold working some alloys with a high density of fine particles did not undergo dSRX in prolonged annealing. However, the cells recovered and the boundaries underwent a conversion; the material had transformed into grains only slightly larger than the cells [34]. This was called cSRX, although it has also been classified as extended SRV [12]. In similarity to this, alloys such as supral (Al-Cu-Mg-Zr), Al-10Mg-Zr and Al-Li-Cu-Mg-Zr after

being given a precipitation and heavy working treatment, are resistant to dSRX when raised to 450°C, but if also strained at 10^{-3} s⁻¹ undergo fairly rapid cDRX [35-38]. They then exhibit excellent superplasticity, indicating that many pinned strain induced boundaries have undergone a conversion that allows them to slide.

The cDRX proposed for single phase [1-3,9] is very different from these phenomena: (i) the substructure developed in the initial part of the straining at high T is highly recovered compared to one produced at the much lower T of prior deformation, and (ii) the substructure is not pinned so it is able to rearrange through the DRV mechanisms. An interesting example is Al-0.65Fe-0.5Co; a substructure produced below 300°C is sufficiently pinned by small eutectic rods (0.05-0.2µm) that it is resistant to SRV at 250°C and to SRX at 500°C [40]. However, when that worked material is strained at 500°C (10^{-3} s⁻¹), it undergoes DRV developing characteristic subgrains consistent with those $\dot{\varepsilon}$ -T conditions as would alloy that was initially recrystallized [41]. In another example, when Al hot worked to a steady state at 400°C is subjected to $\dot{\varepsilon}$ reductions by factors of 10 or 100, the subgrain boundaries (SGB) rearrange into those characteristic of the new conditions [42]. If the strain rate is reduced by factors of 1000, 10,000 or to zero, either transient dDRX or dSRX takes place to same grain size. There is no trace of cDRX even with an initially dense substructure.

5. High temperature DRV

When Al is deformed above 400°C (or α Fe above 800°C), it develops subgrains that have a constant size and wall density and internal dislocation densities that are characteristic of the T- $\frac{1}{\epsilon}$ condition or of σ normalized by modulus across a strain rate range of 10⁻⁸ to 10 s⁻¹ [43-47]. Moreover as the grains elongate through strains up to over 8, the SGB rearrange to maintain those characteristics for subgrains that remain equiaxed; completion of this requires $\Delta\epsilon$ equaling the initial strain hardening transient [10,11]. The planar boundaries or block walls observed in cold working (5µm blocks containing 0.5µm cells) are generally not observed in hot deformation (subgrain size \approx 5µm) [10,11]. The SGB misorientation saturates at about 4° [7-11,48-51].

Due to the usual polycrystal constraints requiring 5 slip systems, the grains break up starting at an early strain into deformation bands separated by transition boundaries TB, each extending across a grain [10,11,18,48,49,52-57]. In accordance, with the Taylor theory of texture development (similar in hot and cold working), as the lattices in the bands rotate due to different slip systems, the TB increase in ψ up to 30° with rising ε . Such behavior accounts for all texture components developed in cold working and are not considered to be recrystallization until the metal is annealed to produce new grains. The TB are permanent so they elongate and rotate as do the GB to provide additional length of strain induced boundaries [10,11]. At high T, the TB are unified boundaries and are difficult to recognize in the TEM image although determinable by diffraction.

6. Warm DRV and gDRX or cDRX

When AI or α Fe are worked in the range 0.4 to 0.6T_M (melting point, K) (100-300°C for AI) they develop substructures that are intermediate between cold and hot working [10,11,57].



Figure 1: Development of geometric gDRX in Al-1Mg-0.3Si alloy deformation in torsion at 500°C, 1.4 s⁻¹ as viewed in tangential sections of the gage regions (a) and (b,c) that also include the shoulder at top: (a) ϵ =1.0, (b) ϵ =3.0 and (c) ϵ =9 (all at same magnification originally X80). In (c) the grains visible in (a) and (b) have been obscured by crystallites with size of subgrains in (b) [60].

The strain induced boundaries are less recovered; the SGB attain higher ψ than in hot working and are less able to completely rearrange [10,11]. This is warm DRV and is somewhat similar to stage 3 in cold working. The substructures look much more recovered than cold working; the larger clear subgrains give rise to the proposal that they are recrystallized grains [58,59]. There is no evidence that their boundaries ever become relaxed, capable of high mobility and sliding as in 2 phase cDRX above [35-38]. Although relaxed or equilibrium boundaries with ψ >15° may have high mobility [16,17]; it is not clear that an SGB so misoriented and composed of both geometrically necessary and redundant dislocations ceases to behave like an SGB. When strain is increased, the substructure remains equiaxed and constant in character as produced by DRV.

The cDRX theory proposes that all SGB are marching upward to become boundaries of new grains the size of the DRV subgrains [1-3]; yet in Cu, Ni and γ Fe with lower rates of recovery only one subgrain in a thousand attains a true boundary that leads to dDRX [24,27]. In γ Fe, cDRX has been claimed to occur before the critical strain for dDRX [58,59]; this is almost equivalent to saying all cold worked metals are in the state of cDRX until they undergo dSRX in annealing.

The field of crystallites produced at high ε (Fig. 1) in which original GB are no longer discernible [4-7,9] has been predicted accurately to occur at a strain where the grain thickness becomes equal to the subgrain size characteristic of the T- $\dot{\varepsilon}$ condition according to DRV theory [43,44]. The crystallites remain equiaxed and of this characteristic size as straining proceeds. Many facets of the crystallites are arrays of dislocations with low ψ [4,5,7,43,44]; the high ψ facets are produced by lengthening of the GB and TB that bound increasing numbers of crystallites [10,11].

The original boundaries are not clearly visible because they have become serrated in reacting to the surface energy of the intersecting SGB [5,9,43,44,60-62]; they can be picked out by diffraction. The serrations in neighboring GB may touch as grains become thin causing them to pinch off into shorter grains. This production of short refined grains by DRV and grain geometric changes, which leaves a substructure within them, has been called geometric gDRX [4-11,43-46]. The texture that develops in AI at high torsional

strains can be explained by DRV and Taylor theory [5,6,63,64] and is quite different from the texture in Cu undergoing DRX [65,66].

7. Conclusions

Dynamic recovery is able to explain the characteristic substructures that are found in steady state hot working and creep. Warm DRV is able to account for the increasing incidence of high misoriented boundaries in a substructure much more recovered than cold working. Continuous DRX in single phase AI alloys never actually produces a complete network of high angle boundaries; it has many anomalies when compared to other recrystallization mechanisms. Moreover it provides no mechanism to maintain the crystallites equiaxed and constant in size within the extending grains that are pinching off into shorter ones; for this geometric DRX is a better explanation.

Acknowledgements

Work was supported by the Natural Science and Engineering Research Council of Canada.

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