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Dynamic Recrystallization and its Effect on Microstructure and Texture Evolution in Magnesium Alloys

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Introduction

Plastic deformation of metals leads to the formation of thermodynamically unstable microstructures containing defects, dislocations and subgrains. This stored energy of the microstructure may be lowered by recovery, recrystallization and grain growth (Humphreys and Hatherly, 2004). During recovery, the stored energy of the material is lowered by the removal of point defects, and annihilation and rearrangement of dislocations into lower energy configurations by glide, climb and cross-slip mechanisms. The process of recovery may occur during deformation and is called dynamic recovery. Recovery can thus be defined as the annealing processes that usually precede recrystallization, although not necessarily a precursor, that occurs in the material without migration of grain boundaries. The recrystallization is the formation and migration of high-angle grain boundaries (HAGB) by the stored energy of deformation or temperature (Humphreys and Hatherly, 2004). Recrystallization can also be static or dynamic recrystallization. This is followed by grain growth, which is regarded as the migration of grain boundaries driven by the purpose of grain boundary area reduction (Doherty et al., 1997). The information available about annealing of magnesium and its alloys in the literature is scarce. This is due to the limited plasticity of Mg at low or ambient temperature (Biswas et al., 2010, 2015a, 2011a, 2008; Biswas and Suwas, 2012; Toth et al., 2013), and most of the plastic deformation processes take place above recrystallization temperature (Biswas et al., 2013; Beausir et al., 2009; Biswas et al., 2012, 2011b).

Static Recrystallization

Early research showed that magnesium deformed at high temperature does not show any grain growth when annealed at \( \sim 200^\circ C \). They categorized this as an incubation temperature. The deformed microstructure containing bimodal grains changed into unimodal grains with rapid grain coarsening at \( \sim 270^\circ C \), which continues as normal grain growth at higher temperatures. Researchers attributed the recrystallization mechanism as "continuous static recrystallization". The recrystallization behavior of cold deformed magnesium was studied using micro-hardness measurements. It was observed that with the increase in strain, the incubation temperature decreases. The hardness values remain constant up to an incubation temperature, and lowers down with the increase in strain. The hardness values follow a rapid decrease with the further increase in temperature and then a slight decrease at higher temperatures. It was also found that the annealing response of cold deformed Mg alloy (AZ31) is sensitive to the amount of deformation, temperature and annealing time. With the increase in strain, the annealing (both recovery and recrystallization) temperature decreases. It is also shown that recrystallization occurs in deformation bands, which leads to finer microstructure at larger strains.

Biswas et al. (2009a) investigated the annealing behavior of pure Mg after equal channel angular pressing (ECAP) and calculated the grain growth kinetics. No significant grain growth occurred up to \( 200^\circ C \). The activation energy for the grain growth was lower than that of the activation energy required for lattice and grain boundary diffusion. A detailed investigation of static recrystallization behavior in Mg could be observed in a very recent publication (Biswas et al., 2015b).

Dynamic Recrystallization

The processing of magnesium and its alloys is possible at elevated temperature, and in these conditions, dynamic recrystallization (DRX) takes place. One of the earlier studies has led to the understanding that dynamic recrystallization is a consequence of the relative difficulty of operating non-basal slip systems in the temperature range of 150–330°C leading to “continuous dynamic recrystallization” (CDRX). Later, it was shown that below \( 200^\circ C \), DRX is associated with the operation of twinning, basal slip and \( \langle c+a \rangle \) dislocation glide. In the temperature range, 200–250°C CDRX was observed with extensive cross-slip, while in the temperature range 300–450°C bulging of original grain boundaries and subgrain growth occurred and were controlled by dislocation climb. Humphreys and Hatherly (2004) attributed this to the availability of non-basal slip at 300–400°C, which eventually led to homogeneous deformation and consequently “discontinuous dynamic recrystallization” (DDRX). Another study showed the occurrence of CDRX in the temperature range 250–400°C by transmission electron microscopy (TEM). The mechanism of CDRX is

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Change History: April 2020. Somjeet Biswas made updates throughout the text. A new section on DRX, texture evolution and plastic energy was added along with Figure 4.

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based on the local shearing near grain boundaries, which occurs due to the lack of five independent slip systems required for homogeneous plasticity. Dynamic recovery of geometrically necessary dislocations occurs, resulting in the formation of new subgrains and grains. Such a process is progressive, with no clear division between nucleation and growth stages. It was also shown later that during ECAE of Mg-alloys, at and above 200°C, conventional discontinuous dynamic recrystallization did not occur.

With regard to the recrystallization texture of HCP metals, rotations of ~30° around (0001) and ~90° around (10T0) have been reported (Beausir et al., 2009). Earlier research works have shown that, for magnesium alloys, the recrystallization texture is identical to the deformation texture of the sample. If annealed at a temperature more than 400°C, some other components develop although predominant texture does not change. Similar observations were also observed in Ti₃Al and titanium, respectively, where the texture evolution was sluggish during static recrystallization. Biswas et al. (2011b) on their observation on ECAE processed pure Mg, showed that the deformation texture did not alter during static recrystallization. The nature of recrystallization texture is determined by the orientation of the new grains and the relative nucleation and growth rates of these grains. Retention of the deformation texture is said to be due to either extensive recovery and polygonization or the nucleation of newly oriented grains during deformation. Studies on annealing of magnesium alloys (Biswas et al., 2013; Beausir et al., 2009; Biswas et al., 2015b), has revealed that there is a growth preference for 30° rotation along {0002} axis from (2TT0) to (10T0). This 30° rotation could be seen in φ = 90° section, as a shift of texture component from φ₂ = 0° or 60° to 30° with no change around φ₁.

**Recent Advances**

**DRX Mechanism During Large Strain Plastic Deformation**

Biswas et al. (2010) investigated ECAP of pure Mg at various temperatures from 250 to 27°C. They showed that the microstructure of pure Mg could be tailored by initially high-temperature deformation at 250°C up to four passes. Thus, the initial average grain size reduces from 21 to ~6.3 μm. A smaller grain size after four ECAP passes allowed pure Mg to deform at 200°C in the 5th pass to obtain further grain refinement. This in turn allowed it to deform at 150°C in the 6th pass to obtain average grain size of ~0.69 μm. This allowed the Mg to deform at 100°C in the 7th pass and at 27°C in the 8th pass to obtain ~0.28 and ~0.25 μm average grain size respectively. The microstructure from 1st to 8th ECAP passes exhibited serrated grain boundaries, partial necklace structure and near bimodal grain size distribution. The mechanism of obtaining grain refinement in this technique was dynamic recrystallization.

They indicated that the mechanism of deformation was influenced by the anisotropy in stacking fault energy (SFE). The SFE of the basal plane is ~36 mJ/m², whereas the SFE of pyramidal and prismatic planes are ~344 and ~265 mJ/m², respectively (Biswas et al., 2010). In low SFE basal planes due to large distance between dislocation partials, there is a restriction in the cross-slipping activities of screw dislocation and the climb of edge dislocations, preventing recovery and thereby strain-hardening occurs. Simultaneously, the high SFE leads to cross-slipping of screw dislocation as well as climb of edge dislocations and thereby recovery occurs in pyramidal and prismatic planes. Utilizing the anisotropy in SFE they achieved room temperature plasticity in Mg (Biswas et al., 2010, 2015a), and patented the technology (Biswas et al., 2009b). It is well known that the critical resolved shear stress (CRSS) ratio of the basal, prismatic, Pyramidal <c+a>, Pyramidal <c+a>-II and Pyramidal <c+a>-II type dislocation slip is ~1:8:8:6:6 at 250°C. If the temperature of deformation is reduced to 27°C, this ratio will tend to 1:100:100:100:100 (Biswas et al., 2010, 2013; Beausir et al., 2009; Biswas et al., 2015b). It was proved that by reducing the deformation temperature in steps, this ratio could be gradually reduced to 1:8:8:6:6 for ambient temperature.

The influence of SFE on the dynamic recrystallization behavior could be observed from the quantitative micrographs taken on the plane normal to “transverse direction (TD)” and “45° to the ECAP direction (ED)” and are shown in Fig. 1, Fig. 2, respectively.
The TD plane normal exhibits mostly pyramidal and prismatic planes. Whereas, the 45° to ED plane normal shows almost all grains with near basal orientation. At 250°C, evidence of continuous dynamic recovery and recrystallization (CDRR) was mostly present in the TD plane. This is substantiated by observing the 30° rotation of the DRX grains from the parent-deformed grains (Biswas et al., 2010). However, few new recrystallized grains also had a completely different orientation that could be marked as evidence of discontinuous dynamic recrystallization (DDRX). It can be well understood that the effect of dislocation activity of the high SFE prismatic and pyramidal planes leading to CDRR could be largely observed on the TD plane. Whereas the influence of low SFE basal slip, leading to DDRX could be observed fractionally less. Contrastingly, observations on the 45° plane indicated more of DDRX and little of CDRR. This evidence suggests that the effect of basal slips were explicitly observable on the 45° plane. When the deformation was carried out at lower as well as at ambient temperature, the microstructure consisted of a mixture of elongated and equiaxed grains, giving an indication of partial DRX. As the deformation was slip dominated, the TD, as well as the 45° plane exhibited both CDRR and DDRX. ECAP imparts large strain that leads to DRX at a temperature lower than the minimum recrystallization temperature (~100°C) for Mg.

Microstructure Evolution by CDRR in a Single-Phase Mg Alloy AM30

Recently, it was investigated that single phase Mg alloys AM30 exhibits mostly CDRR during high-temperature shear deformation at 250°C (Biswas et al., 2013). It was experimentally shown that when shear is applied, the initial equiaxed grains in the microstructure elongates and new DRX grains develops at the grain boundaries. As deformation proceeds, a necklace structure develops and thickens with increasing strain. This is shown schematically in Fig. 3 and is discussed in detail in the next paragraph.

It is well known that geometrically necessary boundaries (GNB) slip and cluster together to increase the misorientation within the grains. Biswas et al. (2013) observed that as the equiaxed grains elongate, the cluster of these polar dislocations (GNB) increases in the vicinity of grain boundaries. In order to accommodate the strain, the grain boundaries tend to rotate. This rotation is not possible homogeneously, and therefore serrated boundaries form to maintain grain boundary contiguity. GNB density becomes inhomogeneous in the grain boundary vicinity (Doherty et al., 1997). When the incoming dislocation density exceeds their absorption capacity of grain boundaries or when the dislocation absorption process requires incubation time, the grain boundaries become serrated (Biswas et al., 2013). The boundary shifts towards the region where there is a high density of GNBs, creating a bulge with the increase in strain. Subsequently, GNBs near this bulged grain boundary evolves and increases its misorientation angle, and with further deformation, a new DRX grain evolve. The new DRX grain deforms consequently with strain. With further deformation, it becomes elongated with the evolution of new misorientations inside. Thereby the second stage of CDRR takes place. While necklace structure develops by this process, it is important to know that, minimum five independent slip systems are present during the deformation and the CRSS ratio of the basal, prismatic, Pyramidal $\{a\}$, Pyramidal $\{c+a\}-I$ and Pyramidal $\{c+a\}-II$ type dislocation slip was found out to be $\sim 1:7:7:4:5:4:5$ for this alloy system.

DRX, Texture Evolution, and Plastic Energy

The DRX process is controlled by the energy induced in the material during plastic deformation (Biswas et al., 2015b). The associated plastic power in the grain is defined as:

$$E(g) = \sum_{f} \sum_{t} \tau_{f}^{t}(g)\dot{\varepsilon}_{f}^{t}(g)$$
Here, $\tau^{sf}$ is the resolved shear stress for the slip system, $s$ of the family indexed by $f$ and $\dot{\gamma}^{sf}$ for a grain $g$. The plastic power can be used to interpret the shift in the texture components due to DRX (Biswas et al., 2013; Beausir et al., 2009). The plastic power can be plotted over the entire Euler space denoted by $\phi_1, \phi, \phi_2$, also denoted as orientation distribution function (ODF). It is comprehensible that the DRX grains are expected to appear in those orientation positions that have minimum $E_{\{g\}}$.

Fig. 4 shows the $\phi = 90^\circ$ ODF sections of the Magnesium alloy AM30 samples subjected to shear deformation at 250°C. The experimentally observed texture for the entire microstructure with increasing strain is shown in the left column. The map of the plastic power is plotted on the top-right corner in the same figure. Visco-plastic self-consistent (VPSC) approach is used to plot the plastic power plot (Biswas et al., 2013; Beausir et al., 2009; Biswas et al., 2015b). The $\phi = 90^\circ$ ODF section of the DRX grains is plotted in the right column as a function of strain. By comparing the plastic power map with the ODF of DRX domains, it can be verified that the $\phi_2 = 30^\circ$ section corresponds to the local minimum plastic power and therefore relates to the positions of DRX grains.

**Summary and Conclusions**

This review highlights important research works on the dynamic recrystallization phenomena of Magnesium (Mg) and its alloys. It also provides brief information on static recrystallization behavior in Mg alloys. Early researchers have reported that in Mg and its alloys, deformation in the range of 150–330°C is governed by continuous dynamic recovery and recrystallization (CDRR). Whereas in the temperature range 300–450°C discontinuous dynamic recrystallization (DDRX) takes place.

Recent developments show that the anisotropy in stacking fault energy (SFE) in pure Mg is very instrumental for defining the DRX mechanism. The low SFE basal planes prevent Mg to recover during the basal slip, and DDRX could be observed on the microstructure in the temperature range of 27–250°C. The newly formed DDRX grains had un-correlated texture with respect to the parent grains. The high SFE prismatic/pyramidal planes do not restrict climb as well as cross-slip and thereby reflects this
Fig. 4 \( \varphi = 90^\circ \) ODF sections of the measured textures (left column) and for the DRX grains only (right column) as a function of strain and the corresponding plastic power map (top right). Reproduced from Biswas, S., Beausir, B., Toth, L.S., Suwas, S., 2013. Evolution of texture and microstructure during hot torsion of a magnesium alloy. Acta Mater. 61 (14), 5263–5277.
property indirectly as CDRR in the microstructure. The CDRR grains were found to be rotation by 30° about {0002} axis from the deformed grains. This anisotropy in SFE could be used to strain-harden Basal plane and strain-soften the non-basal planes through a sequence of thermo-mechanical equal channel angular pressing (ECAP) by decreasing the temperature from 250 to 27°C in subsequent passes to obtain ultra-fine/nanostructured microstructure.

Another recent noteworthy research on single-phase Mg alloy AM30 elucidates the mechanism of microstructural evolution and development of necklace structure during CDRR. It was shown that the heterogeneous development of geometrically necessary boundaries (GNBs) in the vicinity of grain boundaries leads to grain boundary serration. This finally leads to bulging in the grain boundary in the direction of higher dislocation density. With strain, this bulge reforms itself into a new DRX grain. This new grain deforms, and the CDRR process repeats itself more than once during the deformation to produce a continuous necklace-type CDRR grains around every deformed parent grains.

It is noteworthy that the 30° rotation of the DRX grain about {0002} from the deformed grains is controlled by plastic power. The shift in the crystallographic orientation of the DRX grains to φ2 = 30° position corresponding to the minimum plastic power in the Euler space.

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