Note

A Speculation on Dynamic Recrystallization

1. Introduction

Moderate to low stacking fault metals deformed at high temperatures may work-harden sufficiently for recrystallization to occur simultaneously with straining in the so called "dynamic recrystallization"; this process is considered as consisting of a series of work hardening and recrystallization cycles,¹⁾ involving a stable grain size (d_s) corresponding to an "equilibrium nucleus density"¹⁾; d_s seems to depend only on Zener-Hollomon's parameter²⁾ and to decrease as Z increases.

If initial grain size (d_i) is higher than about $2d_s$, the stress-strain curve displays a single peak; as di/ds decreases below about 2, the curves show multiple peaks.¹⁾

A single peak has been attributed to desynchronization of recrystallization processes in different regions of the material, whereas multiple peaks are thought to be due to highly synchronized recrystallization processes in different regions of the material.¹⁾ The first case is considered to cause grain refinement, whereas the second to cause grain coarsening,¹⁾ although grain size evolution evidence shows possibility of multiple peaks with some grain refinement.¹⁾

In a recent study by Hatherly *et al.*³⁾ for α brass and copper, it was observed that in some deformation circumstances dislocation density within dynamically recrystallized grains was low, and an unusually "flat" rolling crystallographic texture was associated with these grains. This led the authors to postulate that grain boundary sliding should be a prominent deformation mechanism during hot deformation of α brass and copper; this deformation would thus be similar to that found in the superplastic behaviour of metals.

Superplastic behaviour has been associated⁴⁾ with non-crystallographic viscous flow (either at grain boundaries or intragranularly), grain boundary shear and grain shear (usually as some form of dislocation creep). Viscous flow has been associated with a high strain rate sensitivity parameter (m), whereas the other mechanisms lead to lower values of this parameter.

If Hatherly's postulate is true, the phenomena of single peak and grain refinement, multiple peak and grain coarsening as well as a final stable grain size could be explained by a transition from deformation involving excessive dislocation shear to deformation where there would be an equilibrium between non-

crystallographic flow (particularly at grain boundaries) and dislocation shear. This transition would involve work hardening and recrystallization cycles, where nucleus density should be very important. The following sections discuss such a possibility.

2. Grain Refinement

For this situation, initial grain size would be too big, and grain boundaries too scarce. The imposed strain rate would force intragranular dislocation movement. In the case of moderate to low stacking fault metals, this will probably lead to dislocation accumulation at grain boundaries. It is noteworthy that in the case of creep, spacing of coarse slip band goes down as stress (or, in our case, Z)⁵⁾ goes up, and that these bands are not present when the spacing is of the order of the grain diameter.

Recovery mechanisms at grain boundaries would be insufficient to suppress dislocation accumulation, and recrystallization would start at grain boundaries. For very coarse grain size, nucleation could also be expected in the grains, as the recovery at grain boundaries would be even lower.

New, smaller grains would appear at grain boundaries, forming a "necklace" around old grains.¹⁾ For the new grains the boundary areas are higher and non-crystallographic flow would occur at stresses lower than that associated to intragranular shear (otherwise, the initial larger grains would deform preferentially in non-crystallographic way).

As the volume fraction of the smaller grains increases, stress would go down, till only new grains exist under a steady state strain.

Grain refinement would proceed by thickening of the "necklace" fine grain area. It is noteworthy that the grain size of such "dynamically recrystallized" grains remains remarkably constant as their volume fraction (and strain) increases.²⁾

If recrystallized grain size is still too big, the above situation would be repeated. If recrystallized grain size is below an equilibrium value for crystallographic and non-crystallographic strain (where generated dislocations would be annihilated by recovery mechanisms, particularly at grain boundaries, establishing a stable accommodation process), the situation is as will be discussed in the next section.

Changes in the Z parameter would modify the intensity of non-crystallographic flow, and thus lead to different values of stable grain size. Decreasing initial grain size (but still keeping it above $2d_s$) increases the amount of non-crystallographic initial flow, and should decrease initial overall work hardening; transition to steady state should be faster, as initial grain

size is closer to d_s and bringing peak strain down. On the other hand, less work hardening at grain boundaries caused by decreases in d_i should delay dynamic recrystallization onset, and thus lead to higher peak strain. The balance between faster transition to steady state and delayed dynamic recrystallization onset will determine the magnitude of peak strain and thus of peak stress, which may even go down.

An analysis of Fig. 1(a) in Sah *et al.*'s paper²⁾ shows that as d_i goes down, the predicted faster transition to steady state takes over and there is a decrease in both peak stress and strain. There is, however, one example where a transition from 0.47 to 0.29 mm in grain size was able to lead to an increase in peak strain (for 0.5 rev/min). Sakai and Jonas¹⁾ results (in their Fig. 17) show a decrease in peak stress without decreasing peak strain, for high d_i , single peak curves. The same figure clearly confirms the prediction of lower work-hardening as d_i goes down (compare their curves for 350~400 and 270 μm). Fig. 1(a) of Sah *et al.*'s paper²⁾ is not very clear, but in the great majority of cases initial work hardening goes down as d_i decreases. However, these authors have worked with torsion, which dampens curve oscillations.¹⁾ The few cases of higher initial work hardening rate should be analysed taking into consideration grain size dispersion (see next sections).

3. Grain Coarsening

For this situation, initial grain size would be too small, and one would initially have excessive non-crystallographic grain boundary deformation and low intragranular dislocation work hardening. However, accommodation between excessive grain boundary and deficient intragranular deformation⁴⁾ may lead to localized shear near certain grain boundary regions, eventually causing local work hardening and nucleation of new grains.

The smaller the initial grains, the higher should be the initial work hardening rate, due to increased accommodation needs. This would lead to earlier nucleation of new grains, and the nucleation rate should be higher. This would account for experimental results concerning the increase of initial work hardening rate and decrease of peak strain and stress as grain size is decreased.^{1,2)}

Transition from grain refinement to grain coarsening behaviour should involve an increase in initial work hardening rate; in grain refinement, lowering grain size increases non-crystallographic deformation, and work hardening goes down; as grain size becomes lower than the stable size, work hardening should increase, due to increasing accommodation needs. Once again this is observed in the literature.^{1,2)}

A growing nucleus should suffer small grain boundary non-crystallographic deformation, due to the movement of its boundaries. On the other hand, if Rhines' ideas⁶⁾ are valid for hot working, the growing, softer nucleus will deform less than the surrounding harder grains as long as it is somewhat smaller than

them (due to work hardening differences). As the growing nucleus size goes beyond this point, its growth rate should decrease, as the difference between its work hardening and that of its neighbourhood decreases. As growth rate decreases, on the other hand, grain boundary deformation should increase and help annihilate intragranularly generated dislocations. Growth will eventually stop, conceivably at a grain size higher than the original one. As bigger grains take over the deformation process, there will be a softening due to their lower accommodation and work hardening needs, and the stress-strain curve will display a peak.

4. The Number of Peaks in the Stress-Strain Curves

Case 1: No Dispersion in Initial Grain Size

In this case, all initial grains would be of the same size, and deformation would be approximately the same in all grains.⁶⁾

If the final grain size is controlled by impingement, and if nucleation is reasonably homogeneous, there should be a small dispersion in final grain sizes; the following situations are possible:

(1) Grain Coarsening

If the final grain size is still smaller than the stable grain size, a new work hardening and softening cycle will happen. However, accommodation needs will be lower in the second cycle and work hardening will be lower. Nucleation rate and thus softening rate should go down. If the final grain size in the second cycle is still smaller than the stable grain size, there would be a third peak, with even lower work hardening and softening rates. This would account for the dampened oscillations experimentally observed during multiple peak behaviour. The bigger the difference in initial and stable grain size, the higher the number of cycles.

(2) Grain Refinement

If the final grain size is still bigger than the equilibrium one, a new work hardening cycle will happen, with lower work hardening (due to higher initial non-crystallographic flow) and softening (due to lower nucleation rate). One may thus have a multiple peak curve, exactly as in the case of grain coarsening. Fig. 2 in Sakai and Jonas's paper¹⁾ shows some grain refinement with two peaks. However, multiple peaks have never been observed for grain refinement.

For both cases above it is obvious that multiple peaks are a consequence of the synchronization of work hardening with softening processes in different regions of the material, as pointed out by Sakai and Jonas.¹⁾

Multiple peaks could also come from alternating grain refinement and coarsening (or *vice versa*). Initial grain refinement could lead to a grain size below the equilibrium size, and coarsening would bring it back above the equilibrium one.

If the first recrystallization cycle leads to the stable final grain size, only one peak would be observed. If

the initial grain size is very similar to the final one, no peak should be observed, and the material should go directly into steady state. For this case, however, Fig. 2 in Sakai and Jonas's paper indicates two peaks, contrary to our predictions.

Case 2: Dispersion in Initial Grain Size

Considering first the case where one has basically grain refinement, the situation should be as shown in Fig. 1. Grain sizes of non-deformed metals obey a log-normal distribution,^{7,8)} and for the case of aluminum, Rhines⁶⁾ has shown that plastic deformation is extremely heterogeneous during cold working, and particularly for low strains, big grains deform much more than smaller ones.

As grain size becomes uniform, deformation becomes more homogeneous, and strength and ductility go up.⁷⁾ If Rhines' ideas are valid for all metals, then dynamic recrystallization should be very heterogeneous for the case of grain refinement, where initial deformation would involve dislocation shear (as discussed previously). As the bigger grains deform first, the necklace mechanism¹⁾ will decrease their size, and slowly more and more grains will be involved in the deformation, which will lead to more uniformity. Recrystallization will be very heterogeneous and unsynchronized in different regions of the material, and this will lead to a single peak.¹⁾

Average grain sizes will be refined from d_i to d_s (stable final grain size). Final dispersion should be such that grains between d_s and $d_{\max}$ will not be refined and grains between d_s and $d_{\min}$ will not be coarsened during dynamic recrystallization (Fig. 1). It is probable that a drastic decrease in grain size dispersion accompanies grain refinement. As initial grain size becomes uniform, peaks in stress-strain curve should sharpen as deformation and recrystallization are more homogeneous and synchronized; there could even be a possibility of multiple peaks in grain refinement, in case several recrystallization cycles were needed for grain refinement.

Fig. 2 would apply to grain coarsening; the presence of multiple peaks indicates the following possibilities:

(1) Postulated initial excessive grain boundary deformation would not depend on grain size, and

Fig. 1. Grain size distribution evolution during grain refinement.

would occur more or less homogeneously in the material, leading to synchronized recrystallization processes in different regions of the material.

(2) If deformation at grain boundaries occurs first where grains are smaller (in a way similar to Rhines' findings), one would have to accept that usual methods of grain refinement to bring d_i below d_s also decrease grain size dispersion, making this deformation and recrystallization more uniform and synchronized in different regions of the material.

The possibility of a high number of peaks²⁾ indicates that coarsening mechanisms should act slowly, leading to a small degree of coarsening for each cycle. As the difference between d_i and d_s increases, the number of peaks should increase.

Fig. 3 shows the situation where $d_i \approx d_s$, but initial grain size dispersion is higher than the final one. Initial grains with size above $d_{\max}$ will be refined, generating a single peak behaviour, and initial grains with size below $d_{\min}$ will be coarsened generating multiple peaks. If one of the mechanisms operates before the other, even though $d_i \approx d_s$, one would have at least two peaks. This clarifies the thinking that no peak should be observed for $d_i \approx d_s$; however, if initial grain size dispersion is low, no peak would be observed, as in superplastic behaviour.

If one goes from the situation in Fig. 1 to that in Fig. 3 by decreasing d_i , at first practically only grain refinement and single peak behaviour will be observed; as d_i goes down, initial small grains will go

Fig. 2. Grain size distribution evolution during grain coarsening.

Fig. 3. Grain size distribution evolution for similar initial and final average grain size.

below $d_{\min}$ and a second, small peak (grain coarsening) will be generated. As d_i goes even lower, the fraction of small initial grains below $d_{\min}$ will increase, and grain coarsening and multiple peak behaviour will take over. For usual initial grain size distributions this seems to happen at $d_i \approx 2d_s$.¹⁾ There would also be a change from decreasing to increasing initial work hardening rate. Fig. 17 of Sakai and Jonas's paper¹⁾ corresponds exactly to the predicted behaviour: a decrease of grain size from (350~400) to 270 μm decreases initial work hardening, but brings in a small, second peak; for 150 μm , there is an increase in initial work hardening, which goes up as d_i goes down to 90 and 60 μm ; there is also the onset of multiple peak behaviour. For a range of initial grain sizes around $2d_s$, initial work hardening rate should be insensitive to grain size.

5. Necking and Dynamic Recrystallization

Dynamic recrystallization leads to work softening, and this should involve early necking in tensile testing. The absence of this necking and even the possibility of multiple peaks suggests an enhanced strain rate sensitivity in the softened regions, which would be coherent with the present model, where the material tends to superplastic type behaviour. It is interesting that Wray⁹⁾ shows tensile stress-strain curves typical of delayed necking.

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