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**ON THE STRAIN-RATE DEPENDENCE OF DYNAMIC RECRYSTALLIZATION
IN COPPER POLYCRYSTALS†**

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ABSTRACT

The observed strain-rate dependence of stress strain curves with and without dynamic recrystallization is analyzed. It is found to be incompatible with models of a strictly time-dependent, "simultaneous static" recrystallization. The activation energy of dynamic recrystallization is strongly stress dependent: similar, but not identical, to that of dynamic recovery. A new criterion for the transition from single-peak to double-peak behavior is proposed.

INTRODUCTION

Dynamic recrystallization (DRX) is thought of as essentially a competition between hardening processes (dislocation accumulation) and restitution processes (recrystallization). The latter is generally treated as similar to static recrystallization, with its aspects of the generation and motion of large-angle grain boundaries. It is admitted that the local driving force for grain-boundary motion depends on the difference in dislocation densities in front of and behind the boundary (where straining is again taking place); this should presumably *slow down* the rate in "dynamic" as compared to static recrystallization. Some allowances are also made for differences in "nucleation" behavior, primarily based on metallographic observations.[1] The influence of the deformed state at the beginning of either static or dynamic recrystallization is often characterized by the "Zener parameter" which combines the temperature and strain rate conditions *in the past*. Note, however, that, while the dependence on the *current* temperature has been reflected in activation energies, no emphasis has been placed on "dynamics", in the sense of a strong influence of either the applied stress or the currently imposed strain rate: the assumed mechanism is essentially "simultaneous static recrystallization".

This cannot be the whole story. If recrystallization is described as dependent on time, by some form of Avrami expression (with constant coefficients), then,

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at any prescribed strain rate, time should be convertible to strain. This is the basis of the explanation given by Luton and Sellars [2] for the difference between single-peak and multiple-peak behavior. It is reproduced in figure 1. the assumed volume fraction recrystallized is shown in the insert; the strain-converted time for recrystallization is labeled ϵ_x . One may assume, for the present purposes, that the only difference between figure 1(a) and figure 1(b) is that the former is run about three times slower than the latter. Now imagine you were to run another test that is slower by another factor 3: you would expect a saw-tooth behavior of the stress strain curve, since complete recrystallization would happen during a very small strain increment, while renewed nucleation would have to wait for sufficient hardening. This is not observed: all curves appear to be essentially sinusoidal, damped oscillations.

Figure 2 reproduces a classic result on DRX in steel [3]. The only difference between the various curves is the strain rate. Observe the following: the strain rates span a range of three orders of magnitude; the oscillations, when they occur, are of similar shape; their period changes by only about a factor 4; and finally, the total stress change amounts to about a factor of 3 (in roughly equal absolute increments for each factor 10 in strain rate). The latter fact is reminiscent of dynamic recovery (or other dislocation) processes: the stress depends approximately on the logarithm of the strain rate.

The current paper has essentially two parallel aims: to study similarities and possible connections between dynamic recovery and dynamic recrystallization; and to assess the effects of strain rate on DRX quantitatively. These aims are helped by the fact that we have extensive new data on the deformation of copper polycrystals at high temperatures (to $T/T_m = 0.75$), both with and without DRX.

First, we will analyze the experimental stress strain curves to see whether a rule can be found that characterizes the *beginning* of DRX - the assumption being that it may be related to some property of the deformed state. Then, we will attempt to find a scaling procedure for the entire DRX behavior, single- or multiple-peak, that reduces the data to a single curve, or a simple set of curves. We will find that the asymptotic steady-state flow stress (or the mean stress in continued oscillations) is a helpful parameter. As a last step, the

Fig. 1 (above) - Model for the occurrence of single-peak versus multiple-peak behavior, based on the relative time for recrystallization compared to the strain for hardening. [2]

Fig. 2 (right) - Experimental stress strain curves for an austenitic low-carbon steel at 1370 K, for a variety of strain rates. [3]

kinetics of this DRX parameter will be analyzed: it will be found to be similar, but not identical, to that of dynamic recovery. Finally, the discussion will address conclusions and open questions.

THE BEGINNING OF DYNAMIC RECRYSTALLIZATION

From a physical point of view, it is well recognized that details of the dislocation arrangement in the deformed structure may affect what is called "nucleation" (at least in the absence of grosser heterogeneities). In general, a sharper (i.e., more recovered) subgrain structure should be more conducive to the generation of new large-angle boundaries than tangled cell walls.[4] It may also be postulated that the dislocation arrangement in the vicinity of grain boundaries might well lead to higher misorientations, so that nucleation near (or at) grain boundaries could be linked to recovery mechanisms.[5]

The first question then is whether a phenomenological link can be established between the "beginning" of DRX - or, since we do not report on metallographic observations, at least the beginning of excessive softening - and some measure of the degree of dynamic recovery. Dynamic recovery serves to lower the strain-hardening rate from that due to the statistical storage of dislocations during glide. Thus, a low strain-hardening rate should indicate a highly recovered structure.[6] We will therefore investigate whether a correlation can be established between the beginning of DRX and a critical rate of strain hardening.

Stress strain curves have been obtained in compression [7] at five strain rates, from 1 s^{-1} to 10^{-4} s^{-1} , every 100°C to 700°C . Figure 3 shows a subset: those at 400°C and at 600°C (3 rates only); they span the range of no DRX, a single peak, and oscillations. The marked points (squares indicate where DRX started. These points were determined from plots of the kind shown in figure 4 for three of the curves in figure 3. Figure 4 shows the strain hardening rate H , normalized by the initial value H_0 , versus the applied stress σ in excess of the yield stress σ_0 , normalized by the "Voce stress" σ_v , which was obtained by

Fig. 3 - Some of the measured stress strain curves in copper polycrystals. The squares indicate the beginning of dynamic recrystallization.

Fig. 4 - Differentiated and normalized hardening curves for 400°C , at 1 , 0.1 , and 0.001 s^{-1} . Observe the first departures from standard hardening behavior for two curves at large stresses.

matching the initial linear decrease of these curves for all strain rates and temperatures [7]. The curves deviate from Voce behavior, especially at high stresses; but they all do so in a very similar manner. It is therefore quite easy to establish the beginning of deviations from the strain-hardening behavior expected in the absence of DRX.

It turned out that most of these points of departure occurred at $H/H_0 \approx 0.08$; however, especially in marginal cases like the ones shown in figure 4, the ratio could be as low as 0.04. The correlation is (cf. figure 3) much better than with any constant value of the critical strain, or a constant value of the critical stress (which would roughly relate to the driving force for recrystallization). Gottstein and Kocks [8] observed a correlation between the stress at the beginning of DRX and the saturation stress in $\langle 111 \rangle$ single crystals of Cu and Ni; this is similar to the current proposal. (They also noted a change in behavior above about $3/4$ of the melting temperature; this regime is not covered in the current paper.)

Much as we cherished the correlation with a critical strain-hardening rate (even though it was not perfect), there are two observations that it cannot explain at all. First, stress strain curves at lower temperatures or higher strain rates do reach, under appropriate circumstances, very low values of H/H_0 , without recrystallizing. And second, strain-rate changes designed to occur before DRX could start, but such as to produce a low strain-hardening rate at lower strains, revealed that DRX did not start earlier, but occurred at about the same value of strain (figure 5). It remains a major question of interpretation, how a fixed value of strain, regardless of history, but severely dependent on the current conditions of strain rate and temperature, can determine any aspect of material behavior. But in any case, a critical value of H/H_0 is not able to unify the observations in general.

Fig. 5 - Strain-rate changes from 10^{-2} to 10^{-4} s^{-1} at 400°C at a stress just below and just above the expected peak stress. Note that the peak strain is about the same in all three DRX curves.

THE PROGRESS OF (PERIODIC) SOFTENING

We tried to describe the similarities between stress strain curves at different strain rates and temperatures, in the DRX regime, in some quantitative form: figure 6 is the result for one temperature, 600°C (from the stress strain curves shown in figure 3). We took advantage of the long-known fact that the periodicity is related to the "critical strain". In fact, we ascertained that it is the "peak strain" ϵ_p that is essentially equal to the spacing between successive maxima, not the strain at the beginning of DRX, as established by the above procedure (which is about 20% lower). This explains the choice of abscissa.

For the stress normalization, we found that the asymptotic steady-state stress serves best as a baseline; we labeled it $(\sigma_0 + \sigma_f)$. Calling the peak stress $(\sigma_0 + \sigma_p)$, $(\sigma_p - \sigma_f)$ serves well as a scaling factor: then, all the curves, at all temperatures and strain rates, could be made to look very similar — except for the amplitude damping. This procedure was, in turn, used to establish final best values for σ_f , corrected but little from initial guesses. (In a few cases, ϵ_p was also slightly adjusted, since the period is known with more certainty than the absolute value of strain from the beginning of the test.)

Fig. 6 — Normalized diagram for DRX oscillations: three strain rates at 600°C. These curves look similar for all cases, except for the amplitude damping.

Fig. 7 — The dependence of various stress parameters on a combination of temperature and strain rate. The abscissa is a normalized activation energy: the plot demonstrates its dependence on stress. (The temperature dependence of the shear modulus μ has normalized out.)

THE KINETICS OF DYNAMIC RECRYSTALLIZATION PARAMETERS

Figure 7 displays (as symbols) the kinetics of dynamic recovery, as quantified by the dependence of the Voce scaling stress σ_v on the combination of temperature and strain rate that signifies the activation energy. The strain-rate normalizing constant ($\dot{\epsilon}_0$) had been chosen as 10^7 s^{-1} , in order to make different temperatures and strain rates fall on a single curve. [7]

The lower one of the two continuous lines shows the value of σ_f . The first remarkable fact is that the same value of $\dot{\epsilon}_0$ produced a good coincidence for different temperatures and strain rates. The second point of note is that the plot of the DRX parameter σ_f exhibits a strong stress dependence of the activation energy, much like the plot of σ_v does: it is certainly not a constant activation energy of any kind of diffusion.

Nevertheless, the behavior of σ_f is different from that of σ_v , and it is this difference that controls the variety of behavior. First, whether by coincidence or not, the crossing of the σ_f and σ_v -lines marks the transition from single-peak to multiple-peak behavior. Second, not surprisingly, when σ_f , slightly extrapolated, reaches about $1.3 \cdot \sigma_v$, DRX ceases: the hardening curve can never get that high.

The top line in figure 7 shows the peak stress, σ_p : at the lower stresses, we find fairly consistently that σ_p is about $1.25 \cdot \sigma_f$. It is always above σ_v .

DISCUSSION AND CONCLUSIONS

- 1) The kinetics of dynamic recrystallization appears to be characterized, in general, by a strongly stress dependent activation energy: this is necessary to explain the relatively weak (i.e., much less than linear) dependence of the asymptotic steady-state flow stress, and of the oscillation period, on strain rate. (Another possibility is a strong dependence of the Avrami parameters on the current strain rate: this is phenomenologically equivalent to a dependence on stress, but may have different mechanistic interpretations.) In any case, it seems inconsistent with these findings that diffusive processes have any rate-controlling influence (even though, without doubt, they occur).
- 2) For the particular tests on copper polycrystals reported here, for temperatures up to $3/4$ of the melting point, the asymptotic steady-state flow stress seems to play a unifying role: its relation to the "Voce stress", which describes the temperature and strain-rate scaling of dynamic recovery, determines whether DRX happens at all, and whether it occurs as a single- or multiple-peak behavior. The peak stress is essentially proportional to it. It almost looks as if this ultimate behavior is what determines the *beginning*, too.
- 3) The kinetics of dynamic recovery can be described by the temperature- and rate-dependence of the "Voce stress" - even though departures from the "Voce law" are well established. It is interesting to note that this Voce stress appears to play a determinant role: DRX never begins unless the Voce stress is exceeded; and the Voce stress serves as a demarcation line for the difference between single-peak and multiple-peak behavior.
- 4) An attempt to characterize the *beginning* of DRX by a macroscopic dynamic-recovery parameter has essentially failed to provide a unique criterion. This does not negate the possibility that there is a critical *dislocation arrangement* such as very sharp cell walls or subboundaries: this structural feature may not *exactly* correlate with H/H_0 ; in fact, it is known that this correlation is by no means perfect [9].
- 5) The existence of a critical value of strain, which characterizes both the first stress peak and the subsequent periodicity, does not appear to depend on history, but is strongly dependent on the current conditions of strain rate and temperature, continues to be major mystery of dynamic recrystallization.

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