1. Introduction

In the hot working of austenite, the point at which the softening due to dynamic recrystallization counteracts work hardening to produce a peak in the stress–strain curve has considerable industrial significance. It marks the cessation of net work hardening and provides a lower estimate of the strain at which the kinetics of recrystallization after deformation cease to be accelerated by the strain. The former is important for the prediction of rolling loads while the latter is essential for forecasting interstand softening.

In a number of previous investigations, it has been assumed that the flow stress peak corresponds more or less to a fixed volume fraction of dynamic recrystallization of the order of 10%.\(^1\)\(^2\) This has posed a challenge to understanding the nature of the correlation between the strain to the peak stress and the post-deformation softening behaviour, e.g. Ref. 3). In this communication, we report measurements of the fraction of dynamic recrystallization seen in a 304 stainless steel deformed in hot torsion. These values are then used to explain the correlation observed between the dynamic and post-deformation softening behaviours.

2. Experimental

A 304 austenitic stainless steel with a chemical composition (wt%) of Fe–0.02%C–1.6%Mn–8.2%Ni–18.5%Cr–0.8%Cu was used to produce torsion samples\(^3\) for the present study. The specimens were heated to 1200°C at 5 K s\(^{-1}\) and held for 3 min. A roughing process using an applied strain of 0.5 and a strain rate of 1 s\(^{-1}\) followed by a 2 min holding time was employed. The samples were then cooled at 1 K s\(^{-1}\) to various temperatures in the range of 850–1100°C, held for 2 min. This resulted in a homogenized microstructure (as the initial microstructure for the following deformations) with an average grain size of \(\sim 35\) μm for all temperatures. The samples containing such similar microstructures were subsequently deformed at strain rates between 0.1–1 s\(^{-1}\) to different strains.

Some samples were quenched immediately (<0.5 s) after deformation so that the DRX microstructure could be preserved and characterized. Metallographic observations were performed on tangential sections at a depth of 100 μm below the sample surface. Electron backscattered diffraction (EBSD) was employed to determine the fraction of dynamic recrystallization (based on differences in grain size and morphology). For other samples, softening was measured by reloading the specimen after different unloading times. The softening fraction (X%) was determined using the 0.2% offset strain method.\(^5\)

3. Results and Discussion

Some examples of the stress–strain curves obtained in this study are given in Fig. 1 along with the fractions of dynamic recrystallization measured using EBSD. The stress–strain curves are typical of a metal undergoing dynamic recrystallization. Inspection of the fractions of dynamic recrystallization reveals, somewhat unexpectedly, that the flow stress peak corresponds to lower and lower
fractions of dynamic recrystallization as the magnitude of the peak stress increases. This is captured in Fig. 2, where it is seen that the volume fraction of dynamic recrystallization at the peak decreases in an approximately inverse manner with the value of the peak stress.

The origin of this trend can be understood in the following manner. At the higher stresses, where the temperature is lower (or the strain rate higher), dynamic recrystallization commences at strains that are closer to the onset of steady state flow due to dynamic recovery. At these strains, the work hardening rate is low. Only a small degree of extra softening due to dynamic recrystallization is required to decrease the net work hardening rate to zero and create a peak in the flow stress curve. Thus at high stress levels a peak in the flow stress curve can be generated with quite low fractions of dynamic recrystallization. At higher temperatures and lower strain rates (i.e. at lower stress levels), dynamic recrystallization is initiated at low strains where the work hardening rate is still quite high. Under these conditions, a greater fraction of dynamic recrystallization is required to decrease the work hardening rate to zero.

Turning now to the post-deformation softening behaviour, the kinetics of this reaction observed in the present work are presented in Fig. 3. Marked on the plot are the strains corresponding to the initiation of DRX, \( \varepsilon_c \), the flow stress peak, \( \varepsilon_p \), as well as the strain, \( \varepsilon^* \), that characterizes the transition to strain independent softening. These three strains are plotted in Fig. 4, together with \( \varepsilon_f \), the strain at which the DRX structure has spread completely through the material. From this diagram, it is evident that the ratio \( \varepsilon^*/\varepsilon_p \), which characterizes the correlation between dynamic and post-deformation softening, increases from about 1 at low values of \( Z \) (e.g. \( 10^{13} \)) to about 1.5 at high values of \( Z \).

The fractions of dynamic recrystallization corresponding to the softening transition strain are given in Fig. 5. It is clear that the volume fraction of dynamic recrystallization at the transition strain is relatively constant at about 50%. Also displayed on the diagram are the fractions associated with \( \varepsilon_p \) and \( \varepsilon_c \). These observations shed light on why it has been found in a number of recent studies that the strain for the onset of strain independent static softening does not coincide with the strain to the flow stress peak. (The equivalence of the two strains would follow if the flow stress peak indeed marked the attainment of a fixed microstructural state.) The present considerations indicate instead that, for the current material at least, the onset of strain inde-
pendent softening is uniquely determined by the onset of a certain fixed volume fraction of dynamic recrystallization. By contrast, the flow stress peak is associated with varying volume fractions of dynamic recrystallization and hence there is a lack of coincidence between the two characteristic strains. These observations help explain the recent results of Cartmill et al.\(^3\) shown replotted here in a somewhat different form in Fig. 6. In this diagram, it can be seen that, for a range of materials and conditions, the ratio \(\varepsilon^*/\varepsilon_p\) increases in quite a well-behaved manner with the ratio of initial grain size to the DRX grain size \(d_0/d_{drx}\). The link between the recrystallized volume fraction at \(\varepsilon_p\) and the relative grain size ratio \(d_0/d_{drx}\) seen in the present study is displayed in Fig. 7. It is evident that the volume fraction of recrystallized material at the peak strain decreases with the relative grain size ratio from a maximum value of \(\sim 50\%\) when the DRX grain size is close to the initial grain size \(d_0/d_{drx} \approx 1\) to about 5% when \(d_0/d_{drx} \approx 10\).

Thus, the “universal” trend observed by Cartmill et al.\(^3\) can be rationalized, at least in part, in terms of the volume fractions of dynamic recrystallization at the characteristic strains. When the relative grain size ratio is large, the peak in the stress–strain curve occurs at low volume fractions of DRX. In this instance, more and more necklaces of new grains have to be formed in order to achieve the “fixed” volume fraction of recrystallized material associated with \(\varepsilon^*\) (i.e. \(\sim 50\%\)). This is accomplished by applying strains that exceed the peak strain by greater and greater ratios.

These considerations are clearly of importance in the modelling of hot rolling, where it is frequently necessary to predict the characteristic strains corresponding to important changes in behaviour. The key observation is that the microstructure achieves a constant configuration at \(\varepsilon^*\) and not at the stress peak, \(\varepsilon_p\). However, it should be noted that care must be taken in extrapolating these observations too far beyond the present conditions. At lower temperatures, strain independent post-deformation softening can arise from dynamic recovery alone.\(^6,7,11\) Clearly, under these conditions, the occurrence of strain independent softening does not correspond to a fixed fraction of dynamic recrystallization.

4. Conclusions

The dynamic and post-dynamic recrystallization behaviours of a 304 austenitic stainless steel were studied, with particular attention being paid to the relationships between the DRX volume fractions at the peak \(X_p\) and transition \(X^*\) strains and the Zener–Hollomon parameter \(Z\). Also of interest was the dependence of \(X_p\) on the relative grain size ratio \(d_0/d_{drx}\). It is shown that the correlation between the dynamic and post-deformation softening behaviours can be understood in terms of the volume fractions of dynamic recrystallization. In the present material, the flow stress peak corresponds to varying volume fractions of dynamic recrystallization, where \(X_p\) decreases with increasing \(Z\) and the relative grain size ratio, \(d_0/d_{drx}\). By contrast, the onset of strain-independent softening corresponds to a fixed fraction (\(=50\%\)) of dynamic recrystallization.

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