Work hardening and kinetics of dynamic recrystallization in hot deformed austenite

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Abstract. The work hardening behaviors of 4 steels deformed under dynamic recrystallization (DRX) conditions were analysed. The $h$ and $r$ parameters necessary to describe the work hardening or dynamic recovery (DRV) curves in the absence of DRX were determined from the experimental flow curves. The fractional softening $X$ attributable to DRX, defined as the difference between the calculated DRV and experimental DRX curves, was used to derive the Avrami kinetics of DRX. Some conclusions are drawn about the effects of deformation temperature, strain rate and steel composition on the kinetics of DRX.

1. Introduction
The fractional softening $X$ produced by dynamic recrystallization is of considerable importance for modeling the rolling load in steel mills. Most studies concerned with this topic have represented the DRX kinetics in terms of the recrystallized volume fraction [1] or the peak stress $\sigma_p$ of the stress-strain curve [2]. In the present work, the net softening due to DRX is defined as the difference between the work hardening curve pertaining to the as-yet unrecrystallized grains and the experimental flow curve. A method for calculating the former is described and the differences are employed to derive the Avrami kinetics of DRX according to a method described earlier [3]. The DRX kinetics under industrial conditions can then be predicted and used to model the flow stress in rolling mills.

2. Experimental data
The stress-strain curves pertaining to 4 different steels deformed in compression under the conditions shown in Table 1 [4-6] were analyzed. The curves were sampled using a higher density of points before the peak stress. The 17 stress-strain curves are depicted in Figures 1 and 2. The yield stresses were defined in terms of a 2% offset and then the curves were fitted using the MATLAB™ software to an 8th order polynomial. The latter was required for the numerical calculations that followed.

Table 1. The compositions of the 4 steels and the associated deformation conditions of $\dot{\varepsilon}$ and $T$.

| Steel          | Composition (wt%)                                                                 | Ref. | $\dot{\varepsilon}$ ($s^{-1}$) | $T$ (°C) |
|---------------|---------------------------------------------------------------------------------|------|-------------------------------|----------|
| A : SiMn low carbon steel | 0.18C; 0.71Si; 1.11Mn; 0.018S; 0.007P                                         | [4]   | 0.005                         | 900, 950, 1000 |
| B : Nb low carbon steel   | 0.11C; 0.17Si; 1.23Mn; 0.038Nb; 0.006P; 0.005S; 0.004N                         | [5]   | 1                             | 1050, 1000 |
| C : Ti low carbon steel   | 0.12C; 0.18Si; 1.23Mn; 0.015Ti; 0.006P; 0.005S; 0.004N                         | [5]   | 0.1                           | 1000, 950, 1000 |
| D : Mo-Cr high carbon steel| 0.99C; 0.24Si; 0.31Mn; 1.44Cr; 0.12Cu; 0.02Mo; 0.05Ni; 0.01P; 0.003S         | [6]   | 0.1                           | 1150, 1100, 1050, 1000, 950 |
3. Analysis procedure

The work hardening behavior of the unrecrystallized regions was considered to be described by:

$$\frac{d\rho}{d\varepsilon} = h - r \times \rho$$ \hspace{1cm} (1)

In this relationship [7], \(\rho\) is the current value of the dislocation density, \(\varepsilon\) the strain, \(h\) the athermal work hardening rate, and \(r\) the rate of dynamic recovery. Both are strain independent [3]. As shown earlier [3], the integration of equation (1) leads to the following description of the flow curve:

$$\sigma = \left(\sigma_{sat}^2 - \left(\sigma_{sat}^2 - \sigma_0^2\right) \times \exp\left(-r \times \varepsilon\right)\right)^{\frac{1}{2}}$$ \hspace{1cm} (2)

Here, \(\sigma_0\) is the yield stress and \(\sigma_{sat}\) represents the saturation stress, which is attained at high strains. The latter depends on \(h\) and \(r\) according to \(\sigma_{sat} = M \times \alpha \times \mu \times b \times \sqrt{h/r}\), where \(M\) is the Taylor factor, \(\alpha\) a material constant, \(\mu\) the shear modulus and \(b\) the Burgers vector. On the basis that the flow stress \(\sigma\) is given by:

$$\sigma = M \times \alpha \times \mu \times b \times \sqrt{\rho}$$ \hspace{1cm} (3)

Equation (1) can be expressed in terms of the flow stress, for which purpose we specify that:

$$\frac{d\rho}{d\varepsilon} = (M \times \alpha \times \mu \times b)^{-2} \times d\sigma^2 / d\varepsilon = 2 \times (M \times \alpha \times \mu \times b)^{-2} \times \sigma \times d\sigma / d\varepsilon$$ \hspace{1cm} (4)

By employing equations (3) and (4), equation (1) can be rewritten as follows:

$$2 \times \sigma \times \theta = r \times \sigma_{sat}^2 - r \times \sigma^2$$ \hspace{1cm} (5)

where \(\theta = d\sigma/d\varepsilon\) is the current value of the work hardening rate. The coefficient \(r\) is then obtained from the slopes (-\(r\)) of the \(2 \times \theta \times \sigma\) vs. \(\sigma^2\) plots of the experimental data and \(h\) from the vertical intercepts \(r \times \sigma_{sat}^2 = (M \times \alpha \times \mu \times b)^2 \times h\). This formalism indicates that the rate of storage energy (i.e. \(d\rho/d\varepsilon\)) depends on the current value of the stored energy \(\rho\).

4. Work hardening parameters

Some selected \(2 \times \theta \times \sigma\) vs. \(\sigma^2\) plots are presented in Figure 3. The critical stresses \(\sigma_c\) for the initiation of DRX were determined by the double differentiation method [8]. It can be seen that the trend line for
passes through the origin, whereas those for $\sigma_c$ and $\sigma_p$ do not. This indicates that DRX cannot take place until a minimum driving force, that is, a minimum dislocation density, has been provided.

![Figure 3](image3.png)  

**Figure 3.** Some $2 \times \theta \times \sigma^2$ vs. $\sigma^2$ plots pertaining to steels A and D (black lines). The linear behaviors of the work hardening regime have been extrapolated to provide both horizontal and vertical intercepts.

![Figure 4](image4.png)  

**Figure 4.** Dependences of $r$ (open symbols) and $h$ (closed symbols) on $Z/A$ as calculated from the 17 experimental $2 \times \theta \times \sigma^2$ vs. $\sigma$ curves.

The dependences of $r$ and $h$ on $Z$ are illustrated in Figure 4. Here, allowances have been made for the temperature dependences of $b$ [9] and $\mu$ [10] and $M$ and $\alpha$ have been set equal to 3 and 0.5, respectively. The other material constants employed are listed in Table 2. The latter were used to calculate the $Z/A$ scale employed in the preparation of Figure 4.

![Table 2](image2.png)  

**Table 2.** Values of $\alpha'$, n, A and Q as provided in Refs. 4-6 for the 4 steels. The starred values of n and $\alpha'$ were not specified and were estimated here.

The $r$ and $h$ trend line equations are given by $r = 8.225 \times \exp(-0.176 Z)$ and $h = 3.10^{14} \times \exp(0.283 Z)$. As $h = M/(L \times b)$ is inversely proportional to the dislocation mean free path $L$ [11], the present values of $h$ (15 to 35 $\mu$m) can be interpreted as indicating that, at the initiation of flow, $L$ is approximately equal to the grain size (25 $\mu$m) specified in reference [4]. Thus the rate of hardening appears to be determined by rate of dislocation accumulation at grain boundaries.

5. DRX kinetic

Three stress-strain curves reconstituted using equation (2) are depicted in Figure 5 together with their respective experimental curves. The Avrami kinetics of DRX were then derived, where the net softening $X$ was defined as the difference between the work hardening and experimental curves. Here the Avrami kinetics are represented by the relation: $\log[\ln(1/(1-X))] = \log(k) + n \times \log(t)$, where $k$ is the Avrami constant, $n$ the time exponent, and $t$ is the time elapsed since the initiation of DRX. Seven selected Avrami plots are represented in Figure 6, where the kinetics are seen to be approximately linear in the range $X = 0.1$ to $X = 0.9$. 
For the present 17 Avrami plots (10 are not displayed in Figure 6), $n$ is about 3 (it ranged from 2.2 to 3.5). It is of interest that an increase of 100°C in the deformation temperature (steel A) only led to an acceleration in the kinetics by a factor of about 1.37. A decrease of 2 orders of magnitude in strain rate, on the other hand, slowed the kinetics down by about the same factor, suggesting that the rate of dynamic softening is approximately proportional to strain rate. From the softening behaviors of steels B, C and D under the same deformation conditions ($T = 1000°C$, strain rate $= 0.1s^{-1}$), it can be seen that Nb (steel B) is the most effective retarder of DRX, followed by the combination of Mo and Cr (steel D), and then by Ti (steel C).

6. Conclusions

The work hardening behavior of the unrecrystallized regions of hot deformed austenite can be determined from $2 \times \theta \times \sigma$ vs. $\sigma^2$ plots derived from flow curves depicting the dynamic recovery behavior prior to $\varepsilon_c$, the critical strain for the initiation of DRX. Here $\theta = d\sigma/d\varepsilon$. The work hardening coefficient $h$ increases with $Z$; values of the former can be interpreted to indicate that the mean free path of the dislocations $L$ at the initiation of plastic flow depends on the grain size. Conversely, the dynamic recovery coefficient $r$ decreases with $Z$. The net fractional softening attributable to DRX was calculated from the work hardening curves and the Avrami plots were derived in each case. It is evident that strain rate has a strong influence on the DRX kinetics, as the rate of softening is approximately proportional to the strain rate. Among the common alloying elements, Nb has the strongest influence in retarding the rate of DRX.

References

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