Metadynamic and Static Recrystallization of Hypereutectoid Steel

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The metadynamic and static recrystallization behavior in hypereutectoid steel containing 1 % carbon was determined by hot compression testing. Compression tests were performed using double hit schedules at temperatures between 900 to 1050°C, strain rates of 0.01 to 1s⁻¹ and recrystallization times of 0.1 to 500 s. The characteristics of static and metadynamic recrystallization are distinctly different. Results show that the metadynamic kinetics was twice as fast as the static kinetics. These data were used to generate equations to predict the kinetics of static and metadynamic recrystallization, as well as the evolution of grain size, after recrystallization.

KEY WORDS: hot rolling; metadynamic and static recrystallization; hypereutectoid steel; grain size; mathematical model.

1. Introduction

A hot rolling process consists of several successive deformations incorporating interpass periods in between deformations. During the interpass time, the material softens by recovery and recrystallization. In certain hot rolling processes, two types of recrystallization can occur: static recrystallization, involving nucleation and growth of new grains, and metadynamic recrystallization which is largely due to the static growth of nuclei formed during dynamic recrystallization.1) Unlike static recrystallization, dynamic recrystallization takes place in the roll gap.

In the case of the finishing stage of steel rod hot rolling, although the nominal pass strains are individually below the critical strain for dynamic recrystallization, the interpass times are too short for full static recrystallization to occur.2) As a result, the strain can accumulate from pass to pass until the critical strain for dynamic recrystallization is reached. This is the case even for plain carbon-manganese grades.2,3) At the completion of a pass in which dynamic recrystallization has occurred, static recrystallization can take place in the interpass time. This type of static recrystallization is known as metadynamic recrystallization.4,5) Previous work6,7) indicates that metadynamic recrystallization can result in fine austenite grain sizes at high values of the Zener–Hollomon parameter, \( \dot{e} \exp(Q_{\text{act}}/RT) \), i.e., at high strain rates and relatively low temperatures.

The aim of the present work is to characterize both static and metadynamic recrystallization and to develop a mathematical expressions that can be incorporated into models for prediction of microstructural evolution in hypereutectoid steel during hot deformation.

2. Experimental Procedure

2.1. Material and Process Parameters

The chemistry of the hypereutectoid steel used in this work is given in Table 1. This material was provided by IVACO Rolling Mills (L’Orignal, Ontario, Canada). Compression test specimens, 11.4 mm in height with an aspect ratio of 1.5, were machined from a continuously cast billet. High temperature compression tests were carried out using a MTS (Materials Testing System) machine equipped with a radiant furnace. Details of the equipment are described elsewhere.8)

Table 1. Chemical composition of experimental steel.

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>0.91</td>
</tr>
<tr>
<td>Mn</td>
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<tr>
<td>Si</td>
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<tr>
<td>Cu</td>
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<td>Ni</td>
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<td>Cr</td>
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<td>P</td>
<td>0.008</td>
</tr>
<tr>
<td>S</td>
<td>0.005</td>
</tr>
<tr>
<td>Co</td>
<td>0.04</td>
</tr>
<tr>
<td>N</td>
<td>0.0031</td>
</tr>
<tr>
<td>Austenite grain size, μm</td>
<td>110</td>
</tr>
</tbody>
</table>
2.2. Thermal Cycles and Deformation Schedules

2.2.1. Single Hit Compression

As shown in Fig. 1(a), to determine the dynamic recrystallization characteristics, the specimens were heated at a constant rate of 1.5°C/s to 1200°C for 20 min. Then the temperature was decreased at a rate of 1°C/s to the test temperature (900, 950, 1000, 1050°C) and held for 5 min to homogenize the temperature within the specimen. The specimens were deformed isothermally at a strain rate of 0.01, 0.1 or 1/s and the specimens were then water quenched.

2.2.2. Double-hit Compression Tests

To study the progress of static and metadynamic recrystallization, several sets of double hit compression tests were performed (Fig. 1(b)). The tests were performed in a radiant furnace using mica sheets lubricated with boron nitride, which were positioned between the anvils the specimen, in order to reduce frictional effects. The specimens were austenitized at 1200°C for 20 min, and then slowly cooled (1°C/s) to the test temperature. After holding at the test temperature for 5 min the first deformation was applied. For the metadynamic recrystallization tests, the first strain had to be at high enough to at least initiate dynamic recrystallization. Testing was conducted using a strain rate range of between 0.01 to 1 s\(^{-1}\) and a temperature range from 900 to 1050°C to generate a number of different dynamically recrystallized conditions. At the peak strain of dynamic recrystallization, the specimen was unloaded and held at the test temperature for times between 0.1 to 50 s to allow metadynamic recrystallization to occur. Then the specimen was reloaded to measure the level of metadynamic softening that had occurred and the specimens were then water quenched.

In the case of static recrystallization, testing was first interrupted at a strain below the critical strain for nucleation of dynamic recrystallization using the same strain rate and temperature ranges that were used for the metadynamic investigations. In this case the kinetics were followed from 1 to 500 s and the specimens were then water quenched.

2.2.3. Quantifying the Softening

The interrupted deformation method is based on the principle that the yield stress at high temperatures is a sensitive measure of structural changes. In this work, the 0.2% offset yield strength was used to determine the softening due to metadynamic and static recrystallization. The fractional softening, \(X\), is measured by:

\[
X = \frac{[\sigma_m - \sigma_1]}{[\sigma_m - \sigma_2]} \times 100\%
\]

where: \(\sigma_m\) is the flow stress at the interruption, \(\sigma_1\) is the offset stress (0.2%) due to the first hit, and \(\sigma_2\) is the offset stress (0.2%) due to the second hit.

3. Results and Discussion

3.1. Austenite Grain Size

To determine the austenite grain size before deformation, the steel was held at the austenitization temperature (1200°C) for 20 min before quenching. The austenite grain size was determined by the intercept method (ASTM E112). The grain size determined in this way is shown in the Table 1. The results indicate a coarse austenite grain size for this condition.

3.2. Flow Curves

3.2.1. Single Hit

The flow curves obtained for the three steels deformed to a strain of 0.7 were plotted for the deformation temperatures (900–1050°C) for various strain rates. All flow curves displayed a rapid initial increase to a stress maximum, characterized by a peak strain and peak stress, followed by a gradual fall to a steady state stress. Examples of the flow stress/strain curves are given in Fig. 2.

3.2.2. Double Hit

For the metadynamic case, interrupted compression stress–strain curves with increasing unloading times are given in Fig. 3. As expected, when the unloading time is short, a relatively small amount of metadynamic recrystallization occurs. However, it is enough to reduce the dislocation density to below the critical strain for dynamic recrystallization, as can be seen by the return of the peak strain. When the unloading time was increased, the extent of metadynamic recrystallization increased, leading to an increase in the amount of work hardening on reloading. The peak strain increases when the unloading time is increased due to the necessity of rebuilding more of the dislocation structure.
before dynamic recrystallization can resume. After hold times greater than seven seconds, the peak stress and strain is slightly higher than the initial values. This may be due to grain coarsening during dynamic recrystallization, as indicated by the occurrence of cyclic dynamic recrystallization peaks in the second hit, at this temperature. Coarser grains require more strain for dynamic recrystallization to be initiated, since the number of potential dynamic recrystallization nucleation sites have decreased. At lower temperatures (Fig. 4), after a hold time of 85 s, the peak stress and strain are reduced after full metadynamic recrystallization because of the grain refinement that has occurred.

3.3. Influence of Deformation Conditions on the Kinetics of Metadynamic and Static Recrystallization

3.3.1. Effect of Strain

To investigate the effect of strain on the kinetics of metadynamic recrystallization of the steel studied in this work, the strain from the first deformation of the double deformation test was varied from the peak strain to the strain at steady state stress. The softening curves shown in Fig. 5 indicate that strain has little influence upon the fractional softening of metadynamic recrystallization. This observation agrees with that of Hodgson, Roucoules and Bai. For dynamic recrystallization, beyond the peak strain, changes in strain do not significantly change the substructure; hence the lack of influence of strain on the metadynamic characteristics.

The influence of strain on static recrystallization is shown in Fig. 6. In these tests, reheating temperature to 1200°C and holding time for 20 min was used to produce the initial grain size. Then, the specimens were cooled to 1050°C and deformed to different strains at constant strain rate. It can be seen that the higher the deformation strain, the faster the recrystallization rate. This can be attributed to the higher dislocation density generated by the increased deformation, which results in a greater driving force for static recrystallization.
3.3.2. Effect of Strain Rate

The effect of strain rate was investigated over the range 0.01 to 1 s\(^{-1}\) at 1 050°C. The metadynamic recrystallization softening is plotted as a function of the logarithm of the holding time as shown in Fig. 7. These plots have the beginnings of a sigmoidal appearance, and the softening increases with increasing strain rates. The effect of strain rate is significant. For example, for 50% softening, 5 s is required at a strain rate of 0.01/s and 0.7 s, is required when the strain rate is increased to 1/s. The present observations are in good agreement with those reported by Hodgson\(^9\) and Roucoules.\(^7\)

For the kinetics of static recrystallization, the influence of strain rate on static recrystallization, as shown in Fig. 8, is less than the influence of other variables (temperature, strain), agreeing with previous investigations.\(^{10,11-14}\) Again, using the kinetics for 50% softening at a strain rate of 0.01/s the required hold time is 60 s, compare to 80 s when the strain rate is increased to 1/s.

In general, the kinetics of recrystallization are accelerated as the strain rate increases for both static and metadynamic conditions. This is due to the reduced extent of dynamic recovery occurring at higher strain rates, which in turn produces a higher dislocation density and increases the driving force for recrystallization.\(^{15}\) However, static recrystallization is much less strain rate dependent compared to metadynamic recrystallization.

3.3.3. Effect of the Deformation Temperature

It is clear from Figs. 9 and 10 that the recrystallization kinetics is enhanced as the temperature is increased for both static and metadynamic recrystallization. For example, at a holding time of 10 s, the fraction of metadynamic recrystallization attained in this steel increased from about 25% at 900°C to 35% at 950°C, to 50% at 1 000°C, and to 70% at 1 050°C. This effect is due to the increasing mobility of the recrystallizing grain boundaries.\(^{16}\)

3.3.4. Effect of the Initial Grain Size

The effect of initial grain size on the fractional softening of static recrystallization is shown in Fig. 11. In this case, the strain rate and deformation temperature were held constant, while the reheated temperature was varied from 1 200–1 000°C. In general, the austenite grain size increased with increasing reheat temperature. It is clear that as the grain size decreases the rate of recrystallization increases markedly. This is because smaller grains have a large grain boundary area per unit volume, which leads to an increase in the density of potential nucleation sites for static recrystallization.
4. Modelling the Effect of Deformation Conditions on the Kinetics of Metadynamic and Static Recrystallization

The kinetics of static and metadynamic recrystallization are usually described by an Avrami type Eq. (1), which incorporates an empirical time constant for 50% recrystallization, $t_{0.5}$.

$$X = 1 - \exp \left(-0.693 \left(\frac{t}{t_{0.5}}\right)^n\right) \quad \text{(1)}$$

As the data generated in this work was for a constant prior austenite grain size, a simplified expression of the following form was derived to describe the data:

Metadynamic

$$t_{0.5} = A\dot{\varepsilon}^p \exp \left[\frac{Q_{\text{app}}}{RT}\right] \quad \text{(2)}$$

Static

$$t_{50} = B\dot{\varepsilon}^n d^q \dot{\varepsilon}^r \exp \left[\frac{Q_{\text{rex}}}{RT}\right] \quad \text{(3)}$$

where

- $t$: times (s)
- $\dot{\varepsilon}$: strain rate ($s^{-1}$)
- $\varepsilon$: strain
- $A$, $B$, $n$, $r$, $q$, and $p$: material dependent constants
- $t_{0.5}$: hold time for 50% softening to take place (s)
- $Q_{\text{app}}$: apparent activation energy of metadynamic recrystallization (kJ/mol)
- $Q_{\text{rex}}$: apparent activation energy of static recrystallization (kJ/mol)
- $T$: absolute temperature (K)
- $R$: gas constant (J/mol K)

4.1. Determination of $n$

To determine $n$, the softening results were plotted as log($\ln(1/(1-X))$) vs. log time. The results are presented for different conditions of temperature, strain and strain rate, as shown in Figs. 12 and 13. For metadynamic and static recrystallization, $n$ has been reported to increase with decreasing temperature. As well, $n$ has also been found to decrease from 2 to 1 when the grain size was increased from 140 to 530 $\mu$m. Furthermore, values of $n$ close to 1 have been also reported for smaller grain sizes. Sellars suggested that such variations in $n$ could be due to differences in the grain size distribution. In this work, values of $n$ for static and metadynamic recrystallization were found to be 1.3 and 1.2, respectively. These are similar to the values reported by Sellars and Roucoules for metadynamic recrystallization and Hodgson et al. and Laasreaoui for static recrystallization.

4.2. Effect of Strain Rate

The effect of strain rate on $t_{0.5}$ was determined at constant temperature and strain; under these conditions, $t_{0.5}$ was found to have a power law dependence on strain rate

$$t_{0.5} = \alpha \dot{\varepsilon}^p$$

Figure 14 show experimental results of the dependence of the time for 50% recrystallization, $t_{0.5}$, on strain rate. Metadynamic recrystallization displays a strain rate dependence about twice as strong as that of static recrystallization. The exponent, $p$, for static and metadynamic recrystallization was found to be $-0.34$ and $-0.61$, respectively. The present values are similar to those reported by
Hodgson and Roucoules for metadynamic recrystallization. The static recrystallization value was in good agreement with values of \( \frac{1}{H} \) to \( \frac{1}{H} \) observed by other workers. The higher values of \( p \) for metadynamic recrystallization can be attributed to the finer dynamically recrystallized grains achieved during the higher strain rate deformation, which increases the rate of metadynamic recrystallization. As peak strain and stored energy are increased with increasing strain rate, the driving force for metadynamic recrystallization is further increased.

4.3. Effect of Strain

In the case of static recrystallization, the strain stored in the material represents the main driving force for recrystallization and the strain exponent is therefore negative. The effect of strain on \( t_{0.5} \) was estimated at constant temperature and strain rate. Under these conditions, \( t_{0.5} \) was found to have a power dependence on strain, as shown in Fig. 15.

\[
t_{0.5} = \alpha e^p
\]

It is worth emphasizing that the above power function is only valid for deformation leading to static recrystallization, i.e., above the critical strain necessary for static recrystallization to proceed and below the critical strain for the onset of dynamic recrystallization. (The critical strain is usually expressed in term of the peak strain. Sellars has proposed a relationship between the peak strain \( \varepsilon_p \) and the critical strain \( \varepsilon_c \).) A strain exponent of 2 was found and is in agreement with values 2 to 4 observed by other workers.

The absence of a strain effect on the kinetics of metadynamic recrystallization is in agreement with previous work as noted earlier. Strain can thus be ignored in the mathematical expression for \( t_{0.5} \).

4.4. Activation Energy of Deformation

To determine the activation energy for metadynamic recrystallization, the parameter \( \ln(t_{0.5}/Z^{-0.61}) \) was plotted as function of the inverse absolute temperature, as shown in Fig. 16. The activation energy for metadynamic recrystallization can be determined from the slope and intercept of this plot. A value of \( Q_{mdx} = 330 \text{ kJ/mol} \) was found for the C–Mn steel used in this work. The activation energy in Eq. (4) is an apparent energy, which is a function of the activation energy of metadynamic recrystallization and, through the Zener–Hollomon parameter, also a function of the activation energy of deformation.

\[
Q_{app} = Q_{mdx} - 0.61 Q_{def} \tag{4}
\]

The activation energy for deformation and apparent activation energy, \( Q_{def} \) and \( Q_{app} \), were found to be 300 and 146 kJ/mol, respectively. The effect of temperature on metadynamic recrystallization is usually observed to be quite weak. For example, Hodgson et al. report values of \( Q_{mdx} = 230 \text{ kJ/mol} \), \( Q_{def} = 300 \text{ kJ/mol} \), and \( p = 0.8 \) for plain C grades, which result in an apparent activation energy \(-10 \text{ kJ/mol} \). In this present work, the activation energy higher than the activation energy reported by Hodgson. The reason for that is not yet clear.

The activation energy for static recrystallization was determined from the following Arrhenius relationship

\[
\ln t_{0.5} = \ln A + \left( \frac{Q_{rex}}{R} \right) \left( \frac{1}{T} \right) \tag{5}
\]

The parameter \( \ln(t_{0.5}) \) was plotted as function of the inverse absolute temperature, as shown in Fig. 17. The value of \( Q_{rex} \) was determined to be 270 kJ/mol. Usually, the activation energy for static recrystallization is considerably higher than for metadynamic recrystallization. These activation energies indicated that decreasing the temperature retards static recrystallization much more than it affects metadynamic recrystallization.
4.5. Metadynamically and Statically Recrystallized Grain Size

The recrystallized grain size also varies according to the mechanism responsible for softening. The dynamically recrystallized grain size depends sensitively on the Zener–Hollomon parameter, while the static grain size is independent of $Z$.

$$d_{mdrx} = 2.55 \times 10^4 Z^{-0.22} \quad \text{(6)}$$

The parameter $\ln(d_{mdrx})$ was plotted as function of the $\ln(Z)$, as show in Fig. 18. The Zener–Hollomon exponent for this work was found to be 0.22 (for full softening after metadynamic recrystallization), and is in good agreement with values of (0.15 to 0.27) reported in previous investigation for plain carbon steel \textsuperscript{21,22,25,28–30}.

The statically recrystallized grain size is a function of initial grain size and strain, but not temperature. Note that the final grain size increases with the initial grain size and decreases with increasing with applied strain.

$$d_{srx} = 0.3 d_0^{0.67} \varepsilon^{-0.9} \quad \text{(7)}$$

All the equations required to follow microstructural evolution during the hot rolling of high C steel are in list in Table 2.

<table>
<thead>
<tr>
<th>Event</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional softening by metadynamic and static recrystallization</td>
<td>$X = 1 - \exp\left[-0.693 \frac{1}{\ln 1.105}\right]$</td>
</tr>
<tr>
<td>Time for 50% recrystallization</td>
<td>$t_{0.5} = 1.5 \times 10^{-8} Z^{-0.41} \exp\left(\frac{330000}{RT}\right)$</td>
</tr>
<tr>
<td>Metadynamic recrystallization</td>
<td>$t_{0.5} = 1.5 \times 10^{-7} \varepsilon^{-0.44} \exp\left(\frac{146000}{RT}\right)$</td>
</tr>
<tr>
<td>Static recrystallization</td>
<td>$t_0 = 4.2 \times 10^{-16} d_0^{-2} \varepsilon^{-0.34} \exp\left(\frac{270000}{RT}\right)$</td>
</tr>
<tr>
<td>Grain size of metadynamically recrystallized</td>
<td>$d_{mdrx} = 2.55 \times 10^4 Z^{-0.22}$</td>
</tr>
<tr>
<td>Grain size of statically recrystallized</td>
<td>$d_{srx} = 0.3 d_0^{0.67} \varepsilon^{-0.9}$</td>
</tr>
</tbody>
</table>

4.6. Comparison between Dynamic, Metadynamic and Static Recrystallization

The differences between static, dynamic and metadynamic recrystallization are summarized in Table 3.

With regard to kinetics, the differences between the static and metadynamic recrystallization kinetics are presented in the plot of the time for 50% recrystallization in Fig. 19 for the present steel. It can be seen that there are two distinct regions as a function of the strain. As strains increase the time for 50% recrystallization decreases until at some point
it becomes independent of strain. Note that the two sets of curves are not continuous in Fig. 19. Once the critical strain for dynamic recrystallization is surpassed during deformation, the metadynamic recrystallization takes place. Its kinetics are no longer dependent on strain but are strongly dependent on strain rate. As noted earlier, strain rate has a strong effect on the metadynamic recrystallization kinetics. Identification of this abrupt change in the recrystallization kinetics is of considerable importance in the modeling of hot rolling.

4.7. Effect of Carbon Content on Static Restoration

The results presented above show that the overall softening rates are effect by initial grain size, strain and strain rate as well as by temperature. The static and metadynamic softening goes to completion under the conditions tested in this work and the kinetics illustrate sigmoidal behavior. These results can be compared with those of Xu et al.,\textsuperscript{31} who conducted compression and tension studies on plain carbon steels with carbon contents ranging from 0.054 to 0.84 wt% at a temperature of 860°C, a strain rate of $2 \times 10^{-3}$/s and initial grain size 16.5 μm. The metadynamic softening curve consists of an almost instantaneous degree of softening due to growth of dynamically recrystallized nuclei, followed by an incubation period leading to classic static recrystallization. This is then interrupted by grain growth, which presumably reduces the driving force for recrystallization for some period. Thereafter, static recrystallization resumes, but not to completion. The difference in behavior may be due to the lower temperature used in the work of Xu (860°C vs. 900°C). The slower kinetics of recrystallization could allow grain growth to become a significant factor, eventually stabilizing the structure against further softening.

Xu et al. also show that the static and metadynamic softening rates increase with rising carbon content. This is explained through an increase in the diffusivity of vacancies due to the addition of carbon in austenite, which will promote static restoration mechanisms. The time for 50% metadynamic recrystallization is in the range of 400–500 s for the 0.84% C steel compared to 800 to 1 000 s for the 0.054% C steel. Using the equation for metadynamic recrystallization listed in Table 2, the time for 50% metadynamic recrystallization under the test conditions of Xu et al. is 350 s, which compares favourably with their result for the higher C steel.

From Xu et al.’s work, the time for 50% static recrystallization is again faster for the higher C steel, being in the range of 1 000–2 000 for the 0.84% C compared to 4 000 to 5 000 s for the 0.054 C steel. This compares rather unfavourably with the prediction of 260 s using the equation for static recrystallization listed in Table 2. In Table 4 are listed other equations available in the literature for the time for 50% recrystallization in C–Mn steels, and the predicted times for 50% static recrystallization. There are noticeable differences between the equations, with some predicting times that are significantly lower than those observed by Xu et al. These differences may be due to differences in the experimental conditions or the specific constitutive equations used in the model.
The differences between the predictions of the models under many conditions. It can be seen that the equations by Choquet et al., Senna and Yada appear to be closer to the current work. None of these predictions are at all close to the kinetics measured by Xu et al. It is not clear why such a large discrepancy exists.

5. Conclusions

Model and laboratory simulation have been used to determine the effect the deformation parameters on the kinetics and grain size of static and metadynamic recrystallization for hypereutectoid steel. The results can be summarized as follows:

1. Equations to predict metadynamic and static recrystallization kinetics for hypereutectoid carbon have been generated.
2. Comparison of kinetics of metadynamic and static recrystallization shows that metadynamic recrystallization is the more rapid of the two.
3. The activation energies of the metadynamic and static recrystallization are about 136 and 270 kJ/mol, respectively.

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