The Dynamic, Static and Metadynamic Recrystallization of a Nb-microalloyed Steel

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Using hot torsion tests, the dynamic (DRX), static (SRX) and metadynamic (MDRX) recrystallization characteristics of a Nb-microalloyed steel were studied. The torsion tests were carried out at temperatures in the range 850 to 1050°C with strain rates ranging from 0.5 to 5/sec. At the higher temperatures, the Nb remained in solution, while precipitation was underway in the lower temperature range. The results indicate that Nb precipitation has little influence on the value of the critical strain ($\varepsilon_c$) for dynamic recrystallization. The peak strain/Zener–Hollomon parameter equation is derived and the effect of austenite grain size on the peak strain is considered. The times for 50 % recrystallization for static and metadynamic recrystallization were established by means of interrupted torsion tests and are compared. The rate of metadynamic recrystallization increases with strain rate and temperature and is observed to be independent of the pass strain; this contrasts sharply with the observations for static recrystallization. Finally, an example is given of an industrial rolling process in which DRX/MDRX can play important roles. Here, the occurrence of dynamic/metadynamic recrystallization causes the load to drop or else to increase less rapidly than in the case of pure strain accumulation in the absence of SRX.

KEY WORDS: hot rolling; dynamic recrystallization (DRX); static recrystallization (SRX); metadynamic recrystallization (MDRX); critical strain ($\varepsilon_c$) for DRX; recrystallization; precipitation.

1. Introduction

Recently, dynamic recrystallization (DRX) has been shown to take place in hot strip and rod rolling. Such processing, which has been termed dynamic recrystallization controlled rolling, leads to finer austenite grain sizes than those produced by recrystallization controlled rolling and to loads that increase less quickly than in a controlled rolling process. As a result, both the strength and the impact transition temperature properties can be improved. Because of the complex and varying schedules employed in hot strip mills, the mechanisms responsible for the grain refinement of austenite have not yet been clearly described and identified. Nevertheless, such knowledge is necessary if hot strip mills are to be modeled accurately and for the prediction of mechanical properties.1–3) Moreover, better gauge control can be achieved.

One of the keys to microstructural change, as well as to the resistance to hot deformation during the hot rolling of steel, is the recrystallization of austenite. Thus, much effort has been devoted to various aspects of recrystallization, notably the kinetics, recrystallized grain size and effect of microalloying elements on these two phenomena. However, most of these studies have concentrated on static recrystallization (SRX), which occurs in the unloaded condition.1–7) In hot strip or rod mills, the common factor is that the interpass times are short enough to restrict the amount of SRX, so that sufficient strain can be accumulated, in a series of consecutive passes, to trigger DRX. In plain C–Mn steels,3) such strain accumulation can only occur at relatively low temperatures in the vicinity of the $\text{Ar}_3$. When microalloying elements are added, however, the presence of Nb in solution can retard SRX sufficiently to increase the temperature at which DRX appears. Furthermore, the occurrence of DRX leads to metadynamic or post-dynamic recrystallization, which occurs rapidly and differs significantly from ordinary SRX.8,9)

The objectives of this study were to clarify the softening mechanisms taking place during and after deformation in hot strip mills and to produce a suitable computer model for this type of rolling. The relationship between precipitation and DRX was studied and the effect of DRX on strip behavior was considered.

2. Experimental Procedure

A 0.045 % Nb-microalloyed steel was investigated in this work, whose detailed chemical composition is listed in Table 1. Two types of torsion tests were performed in this investigation: (i) single pass torsion tests, and (ii) interrupted torsion tests. Torsion test specimens with a gauge section of 22.2 mm length and 6.4 mm radius were machined from hot rolled transfer bars. The austenitization temperature prior to deformation was 1200°C for all samples. This
temperature was selected after calculating the solution temperature, using the equation of Irvine et al. given by:

\[
\log[\text{Nb}] \left( \frac{C + \frac{12}{14} N}{1} \right) = 2.26 - \frac{6770}{T} \\
\text{......(1)}
\]

This equation does not allow for the effects of Mn and Si on Nb(C, N) solubility, but gives a good approximation. According to Eq. (1), the solution temperature for the present Nb grade was 1,110°C.

Continuous torsion tests were carried out to determine the critical strain for DRX at each experimental temperature and strain rate. Interrupted torsion tests were then conducted over the temperature range 1,050–850°C, strain rate range \(5.0 \times 10^{-2}–5.0 \times 10^{-3}/\text{sec}\), interpass time range 0.5–500 sec, and pass strain range \(1/4–3\) times the peak strain. This was done so as to evaluate the effects of the deformation variables on static and metadynamic softening.

The measured torque \(T\) and twist \(\theta\) were converted to von Mises effective stress \(\sigma\) and strain \(\varepsilon\) using the following equations:

\[
\sigma = \frac{3.3 \sqrt{3} F}{2\pi R^3}, \quad \varepsilon = -\frac{\theta R}{\sqrt{3} L} \text{.........(2)}
\]

Here, \(R\) and \(L\) are the gauge radius and length of the specimen, respectively. In order to determine the time for 50% recrystallization, the value of the torque associated with yielding was defined using a 0.2% offset method in the multiple-twist torsion tests.

### 3. Results and Discussion

#### 3.1. Dynamic Recrystallization

The effect of strain rate on the flow curves is shown in Fig. 1(a). These were determined at 950°C. The peak stress, indicating that DRX is well under way, is clearly seen in all cases. The effect of temperature on the flow curves is shown in Fig. 1(b). These were determined at a strain rate of 1/sec. This strain rate was chosen so as to avoid the occurrence of dynamic precipitation. Note that, as the amount of Nb in solution is high under these conditions, solute drag effects are significant.

This was further confirmed by an analysis of the effect of the deformation conditions on the peak stress \(\sigma_p\) using the hyperbolic sine function;

\[
\dot{\varepsilon} = A (\sinh \alpha \sigma)^{n'} \exp \left( -\frac{Q_{\text{def}}}{RT} \right) \text{.........(3)}
\]

Here \(A\), \(\alpha\) and \(n'\) are constants, \(R\) is the gas constant, \(\dot{\varepsilon}\) is the strain rate, \(\sigma\) is the stress and \(T\) is the absolute temperature.

In this way, the activation energy for hot working was found to be 314 kJ/mol, whereas the value for a C–Mn steel tested under identical conditions was 230 kJ/mol. The parameters \(\alpha\), \(n'\) and \(Q_{\text{def}}\) were determined at the peak stress for DRX. The results of the fit are presented as a plot of \(\log(\sinh(\alpha \sigma))\) vs. \(\log(\dot{\varepsilon} \exp(Q_{\text{def}}/RT))\) in Fig. 2. The resulting values of \(\alpha=0.007\) and \(n'=5.8\) are in agreement with the observations of other workers. Higher activation energies, such as the present one, are typically observed when alloying elements are added that have strong retarding effects on DRX.

The peak strain has been reported to obey the following expression:

\[
\varepsilon_p = AD_0^{p/q}Z^n \text{.................(4)}
\]

where \(A\), \(p\) and \(q\) are constants, \(D_0\) is the initial grain size, and \(Z\) is the Zener–Hollomon parameter. The present results can be seen to follow this relation in Fig. 3.
Zener–Hollomon exponent of 0.19 was found to be in good agreement with values in the range 0.12–0.22 reported by other workers.11,13)

3.2. Effect of Precipitation on Dynamic Recrystallization

According to the results of Schmitz et al.,14) while solute microalloying elements delay DRX during continuous deformation, precipitation can delay both static and dynamic recrystallization. Under these conditions, metadynamic recrystallization is also prevented and only full pancaking structures can be observed. This applies particularly to the case of multistage deformation, such as in reversing or plate mills, where there is sufficient precipitation between passes.

However, in the present work, it was found that precipitation could not prevent DRX, as illustrated in Fig. 4. In this diagram, the flow curves determined before and after precipitation are compared for the present microalloyed steel. The flow curves were obtained at a deformation temperature of 900°C and a constant true strain rate of 0.5/sec. The solid line is the curve measured after soaking at 1 200°C for 15 min and without predeformation at 900°C; in this case, there is no precipitation prior to testing. The dotted line is the curve determined following 1 min of holding after a predeformation at 900°C to a strain of 10% at 0.5/sec.

The Dutta and Sellars model for the precipitation start time is given below15):

$$t_{ps} = A[Nb]^{-1} \varepsilon^{-1} \exp \left( \frac{170 000}{RT} \right) \exp \left( \frac{B}{T^3 \ln(K_s)} \right)$$

(5)

Here, [Nb] is the Nb content in wt%, $\varepsilon$ is the strain and $Z$ is the Zener–Hollomon parameter given by $\varepsilon \exp(350 000 \text{kJ/mol}/RT)$. The supersaturation ratio ($K_s$) that applies to Nb(CN) in austenite is specified by the relation below:

$$K_s = \frac{10^{6.770/T_{RH}+2.26}}{10^{6.770/T_{pass}+2.26}}$$

(6)

Here, $T_{RH}$ and $T_{pass}$ are the reheat and deformation temperature, respectively.

According to this model, the precipitation start time is less than 1 sec at 900°C after a predeformation of 10%. So, 1 min of holding after 10% predeformation at 900°C should be enough to bring about a reasonable amount of precipitation. The highlighted area of Fig. 4(a) is shown in magnified form in Fig. 4 (b). Here, no significant difference in peak or critical strain can be seen. Thus Fig. 4 suggests that strain-induced precipitation is unable to prevent DRX. It is also of interest that the flow curve determined after precipitation contains less serrations, perhaps because the lower solute Nb level decreases the effect of dynamic strain aging.

Experiments carried out on microalloyed steels of other compositions led to similar results regarding the lack of influence of precipitation on the peak strain and to the generally higher flow stress level. Thus seems to indicate that, while the presence of precipitates can affect the flow stress, it does not influence the nucleation and growth of dynamic nuclei.

3.3. Static Recrystallization

Interrupted torsion stress–strain curves were determined at 1 000°C, using a constant true strain rate of 0.5/sec, a pass strain of half the peak strain, and interpass times of 1–500 sec. Some of the results obtained in this way are displayed in Fig. 5. Several interrupted torsion tests with increasing unloading times are plotted together to demonstrate the effect of unloading time on the flow curves. From this figure, it can be seen that, when the unloading time is short, little softening takes place. As a consequence of the lack of softening, the second twist curve displays little further work hardening. Thus, the flow curve resulting from the second twist follows the continuous one closely. When the unloading time was increased, softening mechanisms, such as static recrystallization (SRX) or metadynamic re-
crystallization (MDRX), occurred and reduced the dislocation density. Thus, if the unloading time is large enough to allow the softening mechanism to destroy the dislocation structure established during the first deformation, then the second curve work hardens in a similar way to the first curve so as to rebuild the dislocation structure.

The effect of strain rate on softening is presented in Fig. 6. The softening curves are of sigmoidal shape. An increase in the strain rate from 0.05 to 5/sec accelerates the softening kinetics by almost an order of magnitude. Here, the strain applied was again half the peak strain, which also increased with strain rate. Thus the diagram actually displays the effect of dislocation density on softening rate, as the former is sensitive to both the strain (at constant strain rate) as well as of the strain rate (at a fixed strain).

Recrystallization processes involving nucleation and growth can be described by the Avrami equation:

\[ X_{\text{SRX}} = 1 - \exp \left( -0.693 \left( \frac{t}{t_{50\%}} \right)^n \right) \]  

\[ t_{50\%} = \frac{0.5 \exp \left( \frac{324000 \text{ mol}}{RT} \right)}{d_0^2 \epsilon^{0.41}} \]  

Here, \( t_{50\%} \) is the time for half softening and \( n \) is a constant. The effect of strain rate on softening is presented in Fig. 6. The softening curves are of sigmoidal shape. An increase in the strain rate from 0.05 to 5/sec accelerates the softening kinetics by almost an order of magnitude. The strain applied was again half the peak strain, which also increased with strain rate. Thus the diagram actually displays the effect of dislocation density on softening rate, as the former is sensitive to both the strain (at constant strain rate) as well as of the strain rate (at a fixed strain).

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where the exponent \( r \) is about \(-0.41\). The dependencies of static softening on temperature and pass strain were also obtained by the above method. This led to the following expression:

\[ t_{50\%} = \frac{0.5 \exp \left( \frac{324000 \text{ mol}}{RT} \right)}{d_0^2 \epsilon^{0.41}} \]  

The least squares fit of the above expression to the present data is illustrated in Fig. 7. A relatively good fit is observed, although it should be noted that no attempt was made here to determine the form of grain size dependence term. Thus the conventional dependence (\( t_{50\%} \approx d_0^2 \)) has been retained.

The retarding effect of Nb addition can be readily estimated from this equation by comparing \( t_{50\%} \) for this steel with those for typical C–Mn steels. At 1 000°C, a strain rate of 0.5/sec, a pass strain of 0.2 and a grain size of 100 \( \mu \text{m} \), the time for 50% softening falls in the 1.5–3.5 sec range according to Sellars, Hodgson et al., and Roberts et al. However, according to Eq. (9), the \( t_{50\%} \) for the present material is about 40 sec, i.e. more than an order of magnitude greater. Such retardation effects are entirely due to solute drag at temperatures above those applicable to the precipitation of niobium carbonitride.

3.4. Metadynamic Recrystallization

Metadynamic recrystallization occurs by continued growth of the nuclei formed by dynamic recrystallization during straining. Hence MDRX does not require an incubation time and such rapid interpass softening can affect the mechanical properties, even when the pass strains are not large and the interpass times are short.

The effect of strain rate on metadynamic softening is presented in Fig. 8. All the softening curves are of sigmoidal shape; a rapid stage, which produces 40 to 50% softening, can be identified. At a strain rate of 5/sec, softening is so fast that the beginning of the process cannot be detected, even after the shortest achievable interruption time of 0.5 s. At higher strain rates, such as in rolling mills, less time is available for static and dynamic precipitation and the dri-
The force for metadynamic recrystallization is expected to be still higher. The models for metadynamic recrystallization proposed in the literature generally follow the form of the Sellars equation: \(^\text{(10)}\)

\[
\text{t}_{50\%} = AZ^p \exp \left( \frac{Q_{\text{app}}}{RT} \right) \tag{10}
\]

Here, an approach similar to that of Sellars is taken but the \(Z\) parameter is replaced by a strain rate term. This has the consequence of combining \(Q_{\text{app}}\) from Eq. \(\text{(10)}\) with \(Q_{\text{def}}\) from \(Z\) to give a new \(Q\) (see below). The results of the present work indicate that there is a linear relationship between \(\log(t_{50\%})\) and \(\log(\text{strain rate})\) at 1 000°C, which leads to an exponent of \(-0.85\) (Fig. 9). The strain rate dependence in the case of metadynamic recrystallization is usually much higher than that of static recrystallization. This is of special importance in hot strip and rod mills, where the strain rates are 10 to 100 times higher than the ones used in laboratory tests.

The effect of temperature on \(t_{50\%}\) was also estimated from the results at constant strain rate. The logarithm of \(t_{50\%}\) was found to be proportional to the inverse temperature. This dependence is characteristic of a thermally activated process, which can be represented as follows:

\[
\text{t}_{50\%} \propto \exp \left( \frac{Q}{RT} \right) \tag{11}
\]

where \(Q\) is an appropriate activation energy. The values of \(Q_{\text{SRX}}\) and \(Q_{\text{MDRX}}\) were determined to be 324 and 157 kJ/mol, respectively. Thus the overall temperature dependence of metadynamic recrystallization is seen to be lower than that of static recrystallization. These activation energies indicate that decreasing temperature retards SRX much more than it affects MDRX. The two types of kinetics are compared in Fig. 10.

Note that, although the activation energies for dynamic, static and metadynamic recrystallization are all different, no detailed explanation for these observations is available. Nevertheless, each of these mechanisms involves a sequence of nucleation and growth steps, which are themselves affected by the amount of solute segregation to grain boundaries and dislocations and by the density of deformation-induced vacancies. The importance of such segregation and vacancy effects may well differ between the above three types of recrystallization.

The \(t_{50\%}\) expression derived in this work takes the following final form:

\[
\text{t}_{0.5\%\text{MDRX}} = 1.05 \times 10^{-7} \dot{\varepsilon}^{-0.85} \exp \left( \frac{157 000}{RT} \right) \tag{12}
\]

The least squares fit of this expression to the experimental data is illustrated in Fig. 11. It is now of interest to compare the kinetics of static and metadynamic recrystallization; these are presented in the form of time for 50% recrystallization plots in Fig. 12.
Once DRX is initiated, \( \epsilon_c \), softening by means of metadynamic recrystallization will take place during the interpass interval, as long as sufficient time is available for the mechanism to make a contribution as well. The critical strain for the onset of DRX is therefore an important parameter and information regarding the initiation of DRX is a requirement for prediction of the main softening mechanisms that are active during hot working. Unfortunately, it is not easy to establish the location of \( \epsilon_c \) along a stress–strain curve. It is therefore useful to express \( \epsilon_c \) instead as a function of the peak strain (\( \epsilon_p \)), as readily determined from stress–strain curves. The \( \epsilon_c/\epsilon_p \) ratio is often about 0.8 in plain carbon steels \(^{18}\) and drops to about 0.5 or 0.6 when elements such as Nb are present.\(^{19}\)

As can be seen from Fig. 12, for (accumulated) strains between \( \epsilon_c \) and \( \epsilon_p \), SRX is expected to be slower than MDRX. Thus, although SRX may indeed contribute to the overall softening, its contribution is expected to be less than that of MDRX.

Note that the two sets of curves are not continuous in Fig. 12. By their nature, the SRX curves end in the vicinity of the critical strain for dynamic recrystallization. At strains below this values, softening is due to static recrystallization. Thus the time for 50\% recrystallization is highly sensitive to the strain or accumulated strain. When deformation is interrupted beyond or well beyond the critical strain, metadynamic recrystallization takes place. Its kinetics are no longer dependent on strain but are strongly sensitive to the strain rate. This abrupt change in the recrystallization kinetics is of considerable importance in the modeling of hot rolling. Due to the high strain rates involved, e.g. 50 to 200/sec in hot strip mills, MDRX is expected to take place rapidly, e.g. in less than 0.5 s as estimated by extrapolating the present data to higher strain rates.

### 3.5. Hot Rolling Simulation

It is useful to distinguish here between conventional controlled rolling, where the aim is to produce pancaked, \( \text{i.e.} \) work hardened austenite, and DRX (+MDRX) controlled rolling, where the main purpose is to refine the austenite grain size. Recent publications\(^{14,20}\) by other workers indicate that DRX (+MDRX) rolling can be used to design schedules for the thermomechanical processing of steels when particular mechanical properties are desired. In the present section, the mean flow stress (MFS) developed in

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**Fig. 12.** Dependence of \( t_{50\%} \) on strain at different strain rates at 1000°C and \( \epsilon_c/\epsilon_p \) ratio = 0.6.

**Fig. 13.** (a) Multistage torsion stress–strain curves determined at decreasing temperatures in the range 950–850°C at a constant strain rate of 0.5/sec, a pass strain of 0.3 and interpass times of 20 sec, (b) Multistage torsion stress–strain curves determined at decreasing temperatures in the range 950–850°C at a constant strain rate of 0.5/sec, interpass times of 20 sec and a pass strain of 0.15 in each of the first five passes. These were followed by a large uninterrupted pass strain of 1.2, (c) Multistage torsion stress–strain curves determined at a constant pass strain of 0.2, temperatures decreasing from 950 to 850°C, interpass times decreasing from 2 to 0.8 sec, and strain rates increasing from 0.5 to 5/sec, (d) The mean flow stresses (MFS’s) calculated from the curves displayed in Figs. 13 (a), 13 (b) and 13 (c). The simulation of Fig. 13 (b) displays a load drop.
each pass is derived from Figs. 13(a) to 13(c). The flow curve illustrated in Fig. 13(a) was determined at decreasing temperatures in the range 950–850°C, at a constant strain rate of 0.5/sec, a pass strain of 0.3 and an interpass time of 20 sec. A similar flow curve is presented in Fig. 13(b) but here, the pass strain is 0.15 for the first five passes and then a large pass strain of 1.2 was applied at the sixth pass. The purpose of this high strain was to induce DRX. Fig. 13(c) was obtained under the following conditions: a constant pass strain of 0.2, temperatures decreasing from 950 to 850°C, interpass times decreasing from 2 to 0.8 sec, and the strain rate increasing from 0.5 to 5/sec. These conditions are expected to approach those of practical strip rolling.

The MFS’s were calculated from the curves displayed in Figs. 13(a), 13(b) and 13(c) and are presented in Fig. 13(d). A load drop can be seen to take place after the initiation of DRX in Fig. 13(b). Basically, there are two ways for DRX to take place during finishing: i) in the initial passes, where the high temperatures and low strain rates keep the critical strain low enough to be exceeded by the strain applied in a single pass; ii) in the later passes, as a result of strain accumulation. When there is incomplete softening between passes, the retained strain can exceed the critical strain, leading to the initiation of DRX. Here, the small amounts of precipitation that may have occurred cannot prevent DRX from taking place. The present experimental results confirm this trend (Fig. 4). Thus, even when there is some precipitation of the microalloying elements, the short interpass times do not allow for the occurrence of much static recrystallization. Instead, there is strain accumulation, followed by the initiation of dynamic recrystallization. Rapid metadynamic recrystallization then takes place during the subsequent interpass interval; this mechanism is responsible for the otherwise unexpected load drops.\(^{21}\)

4. Summary and Conclusions

The peak strain of dynamic recrystallization was modeled for a 0.085\%C–0.045\%Nb–0.95Mn microalloyed steel. The kinetics of static recrystallization were measured and the rate was found to increase rapidly with strain and temperature. In the case of metadynamic recrystallization, the strain rate dependence was determined and found to be much higher than that of static recrystallization. The activation energy was measured and observed to be distinctly lower. These dependences differ sharply from those of static recrystallization and contribute to the definition of meta-
dynamic recrystallization as being a distinct post-deformation process.

Some hot rolling simulations were carried out. Load drops were observed under one set of conditions after sufficient strain accumulation, which leads to the initiation of dynamic recrystallization. The latter is in turn followed by metadynamic recrystallization in the subsequent interpass interval. These softening mechanisms are able to operate even if some precipitation takes place during the rolling schedule because the total precipitation time is much less than under plate rolling conditions.

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