Modeling of critical strain for dynamic recrystallization of niobium microalloyed steels

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Keywords: dynamic recrystallization, critical strain, Johnson-Cook model, Jonas model

Abstract

The critical strain for dynamic recrystallization (DRX) is most important in designing rolling schedules for the refinement of grain size by boundary-induced transformation mechanisms. Modeling of the critical strain for DRX from the stress-strain curves obtained from hot compression was physically built in this paper. The stress-strain behaviour of materials during hot deformation should be a combination of work-hardening and recrystallization softening. Before DRX occurred, the stress-strain behaviours could be described by a constitutive equation in which basic strain hardening and the effect of strain rate and temperature on stress-strain behaviour are included. Once DRX was promoted, obvious deviation between the experimental and calculated stress-strain curves appeared, which denoted the critical strain for DRX. The modeling in this work could be used not only to accurately calculate the critical strain for DRX but also to analyze the dynamic softening behaviours during hot deformation. To validate the calculated results, the stress-strain database was analyzed in the H beam sample deformed at 1000 °C with a strain rate of 0.1/s, and a critical strain of 0.22 was obtained by this novel method as an example. The calculated result is in good agreement with the experimental data obtained by micrographical observations.

1. Introduction

It is well known that there is a critical strain required for the onset of dynamic recrystallization (DRX), and only when the accumulated strain reaches and then exceeds this critical strain can DRX be activated. In fact, adopting the critical stress associated with dislocation accumulation to describe DRX behaviour might be more adequate. However, the critical strain is dominantly used for discussions of DRX behaviour in most published works [1, 2], which might be because softening could be ignored before the onset of DRX and stored energy could be expressed easily by the accumulated strain. Li et al [3] demonstrated that the occurrence of DRX is conducive to the refinement of austenite grains during hot rolling. Furthermore, Ding et al [4] demonstrated that the achievement of ultra-fine austenite grains and the resulting abundant grain boundaries could promote the accelerated nucleation of ferrite phase transformation, which contributes to the achievement of ultra-fine ferrite grains and the subsequent excellent performance. Obviously, the critical strain for DRX is an important parameter to control the deformation and recrystallization behaviours of austenite. To ensure the DRX of austenite and make full use of its positive effect on grain refinement, it is necessary to obtain a relatively precise critical strain value, especially for some large-size structural steels with limited reduction.

McQueen et al [5], Sellars [6] and Elwazri et al [7] proposed a classical empirical formula, \( \varepsilon_c = 0.65 \sim 0.8\varepsilon_p \), to approximately calculate the critical strain associated with the onset of DRX, in which \( \varepsilon_c \) is the critical strain for DRX and \( \varepsilon_p \) is the peak strain in the stress-strain curve obtained from experiments. Obviously, the critical value of the strain for DRX calculated by such an empirical equation usually has a wide variable range, which makes it difficult to reasonably assign the total strain accumulation into different rolling passes with the aim of achieving the optimal scheme for grain refinement.

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Table 1. Chemical compositions of the investigated steel (wt.%).

| Element | C   | Mn  | Si  | Nb  | V   | P   | S    |
|---------|-----|-----|-----|-----|-----|-----|------|
| wt.%    | 0.18| 1.45| 0.52| 0.027| 0.021| 0.0062| 0.0019|

To obtain a relatively precise value of the critical strain for DRX, Poliak et al. [8] and Jonas et al. [9] proposed an approach to calculate the critical strain based on the stress-strain curves obtained from hot compressions, in which the determination of the critical value depended strongly on the changes in the strain hardening rate as a function of the flow stress. Deng et al. [10] applied this method to analyze the DRX behavior of 23Cr–2.2Ni–6.3Mn–0.26N duplex stainless steel and obtained an empirical equation of \( \varepsilon_c = 0.4 \varepsilon_y \). Shaban et al. [11] demonstrated that this critical strain could be calculated by \( \varepsilon_c = 0.64 \varepsilon_P \), based on the analysis of DRX in low carbon Nb-Ti microalloyed steel. It can be concluded that the critical ratio of \( \varepsilon_c/\varepsilon_P \) is not a fixed value for steels with different compositions. Although the deformation mode, such as compression or torsion, and process parameters, such as temperatures and strain rates, will also have significant effects on this value, the error resulting from three-time data fitting is another inevitable factor for the difference.

In addition, Johnson and Cook [12, 13] proposed a model, which was then widely used to predict the deformation or fracture behavior of different metallic materials subjected to deformation over a wide range of temperatures and strain rates. Recently, some modified Johnson–Cook models have also been proposed. For example, Wang et al. [14] considered the coupled effects of temperature and strain rate on this model, Shokry et al. [15] studied the coupled effects between strain, strain rate, and temperature on this model, and Couque et al. [16] confirmed the effect of high strains larger than \( 10^5 \) s\(^{-1}\), and Mareau [17] confirmed thermodynamics with internal variables on this model. Almost all of these studies can be considered as an ongoing effort to further improve the prediction accuracy of Johnson–Cook model to meet the requirements of different alloys subjected to large strains, high strain rates and high temperatures. The application of Johnson–Cook model in the prediction of critical strain for DRX has not been reported.

In this paper, the work hardening curve considering the temperature change is derived from the experimental data obtained from hot compression based on Johnson–Cook model, and then it is used to compare the actual stress-strain curve in which dynamic recrystallization softening is included. The critical strain of dynamic recrystallization is determined as the strain where continuous softening is started. The calculated result was also verified by microstructure observation. Based on this new method, not only can the critical strain for DRX be precisely calculated but also the dynamic softening kinetics associated with DRX during hot deformation can be analyzed.

### 2. Experiment

H-beam steel was used for the hot compressions with the aim of achieving the actual stress-strain curve and providing the samples for microstructure observation. The compositions of the studied steel are shown in Table 1.

The studied steel was melted in a vacuum induction furnace. The ingot was homogenized at a temperature of 1250 °C for 1 h and subsequently forged into slabs with a size of 60 mm × 120 mm × 350 mm. The cylinder sample of 10 mm × 15 mm was cut from the forged slab for hot compression. The uniaxial hot compression test was carried out at 1000 °C with an initial strain rate of 0.1 s\(^{-1}\) in a Gleeble 3500 thermal simulator.

The sample was compressed to a total strain of approximately 1.1 (66% reduction in height), and the loading force varying with increasing movement during hot compression was recorded to obtain the corresponding stress-strain curve. The samples used for the microstructure observations were compressed to different strains of 0.17, 0.21 and 0.23. After compression, all the samples were water-quenched immediately to avoid possible microstructure changes during the cooling stage. The compressed samples were cut into two pieces along the compression direction for microstructure observation. The samples were polished and then etched with a saturated solution of picric acid to observe the prior austenite grain boundaries on a Zeiss Axio Vert. A1 Inverted Microscope.

### 3. Results and discussion

#### 3.1. Calculation of critical strain for DRX based on Jonas’s model

According to the principle of material science, the flow stress is increased in the initial stage of hot deformation due to the increase of dislocation density caused by deformation. As deformation increased, the dislocation density increased, and the strain accumulated gradually to overcome the critical strain for dynamic
recrystallization, resulting in the occurrence of dynamic recrystallization. When recrystallization occurs, a large number of dislocations are eliminated by the migration of grain boundaries of the recrystallized nuclei, which macroscopically expresses that the softening effect partially offsets the work hardening effect in the stress–strain curve, and the work hardening rate is obviously decreased. Furthermore, when the softening effect caused by dynamic recrystallization becomes dominant, the flow stress begins to decrease, and the stress–strain curve reaches the peak value. Therefore, the stress–strain curve would be exhibited as two stages classified by the work hardening rate under the condition that the strain rate and deformation temperature are given. The first stage tends to have a larger work hardening rate, while in the second stage, the work hardening rate gradually decreases with increasing deformation due to softening, especially in the hot deformation process at high temperature.

The typical stress–strain curve showing a plot of stress as a function of strain during the hot compression of the studied steel is shown in figure 1 (a). It can be seen that the flow stress reached an obvious peak value when the sample was compressed to a strain of 0.3, illustrating that DRX occurred during hot compression. Generally, the flow stress will increase significantly in the initial stage of hot compression due to the appearance and rapid proliferation of dislocations caused by deformation. As deformation increased, the dislocation density increased gradually, and when the accumulated strain reached and even exceeded the critical strain, DRX will be activated. Once DRX occurs, a large number of dislocations would be consumed because of the migration of grain boundaries for recrystallization nucleation. The loss of dislocations leads to a decrease in the work hardening rate. Furthermore, when the decrease in the work hardening rate tends to be the domination factor, the flow stress begins to decrease, and the stress–strain curve reaches the peak value.

It should be noteworthy that the peak strain corresponding to the maximum stress is a strain at which the competition between work hardening and recrystallization softening reaches a dynamic balance but not the critical strain for DRX. As described above, there is an inevitable change in the work hardening rate due to the occurrence of DRX. According to the research by Poliak et al [8], the occurrence of DRX would result in an inflection point in the stress–strain curve. This strain at the inflection point is actually the critical strain for DRX, which can be obtained by mathematical calculations, including data fitting and second derivative treatment [9].

For the present H-beam steel, the data processing for the calculation of the critical strain is carried out based on Jonas’ method [8, 9]. The detailed process is illustrated in figures 1(b) and (c). The expression of the work-hardening rate \( \theta \) can be obtained from:

\[
\theta = -\frac{\partial \sigma}{\partial \varepsilon}
\]
where \( i \) represents a given data point in the stress-strain curve. The evolution of the work hardening rate as a function of the flow stress is presented in figure 1(b). The results show that several fluctuation points existed in the work-hardening curve, which results in difficulty in determining the critical strain. Then, the second derivation of stress \( \frac{d^2\theta}{d\sigma^2} \sim \sigma \) is adopted, as shown in figure 1(c). To conveniently observe and analyze \( -\frac{d\theta}{d\sigma} \sim \sigma \) curve, an enlarged curve in the stress range of 60 ~ 110 MPa is shown in figure 1(c). Unfortunately, the anticipated inflection point near the peak stress is still not unique, implying that it was still difficult to determine a relatively precise critical strain.

In this case, the experimental curve is considered to be fitted and smoothed with a seventh-order polynomial [9] with the aim of eliminating the fluctuations in the stress-strain curve. The fitted curve is illustrated in figure 2(a), together with the experimental curve. Then, this fitted curve is used as the original data for the next calculation on the critical strain. The first derivative subjected to equation (1) represents the change in the work-hardening rate with increasing stress, as shown in figure 2(b). Compared to figure 1(b), the work-hardening rate curve exhibits a monotonous decrease with increasing stress prior to peak stress \( \sigma_p \). The second derivative of the work hardening rate with respect to stress, i.e., \( -\frac{d\theta}{d\sigma} \sim \sigma \), is plotted in figure 2(c). As can be seen, the data fluctuation prior to peak stress is still obvious, which means that the difficulty of determining the critical strain has not been fundamentally solved. Therefore, a further data treatment on the \( -\frac{d\theta}{d\sigma} \sim \sigma \) curve by a percentile filter is adopted to obtain the value of critical strain, as displayed in figure 2(d). Although the value of critical strain can be achieved after a series of data processing steps, including polynomial fitting, second derivative and percentile filtering, the uncertainties associated with these processes cannot be ignored.

Based on the analysis and calculation displayed in figure 2, the critical strain for DRX of the studied steel is 0.17, which is approximately 0.57 times the peak strain, i.e., \( \varepsilon_c = 0.57 \varepsilon_p \). Obviously, this critical ratio of 0.57 is less than the range of 0.65 ~ 0.8 in empirical equations [5–7].

### 3.2. Calculation of critical strain for DRX based on Johnson-Cook constitutive model

Johnson–Cook model is usually used to predict the flow behaviour of materials deformed at different temperatures and/or strain rates, in which the relationship between stress and strain can be described as follows [12, 13, 18, 19]:

\[
\theta = \frac{(\sigma - \sigma_y)}{(\varepsilon - \varepsilon_y)}
\]

Figure 2. Analysis of the critical strain for the onset of dynamic recrystallization based on the fitted stress-strain curve.
where $\sigma_0$ is the material constant expressing the basic strength, $\varepsilon$ is the equivalent strain, $\dot{\varepsilon}$ is the equivalent strain rate, $\beta$ is the conversion coefficient between heat and temperature, $\rho$ is the material density, generally equal to $7890 \text{ kg m}^{-3}$, $H$ is the specific heat, and the others are material constants.

The effects of strain, strain rate and temperature on the flow stress of materials are fully considered in the Johnson-Cook model, as shown in equations (2) and (3). The terms $C_1 \ln \dot{\varepsilon} + T^m$ and $T^m$ represent the effect of strain rate hardening and temperature softening on the flow stress, respectively. For a given temperature and strain rate, only the first term is considered for ease of calculation. That is, the relationship between stress and strain can be simplified as follows:

$$\sigma = (\sigma_0 + B\varepsilon^n)(1 + C \ln \dot{\varepsilon})(1 - T^m)$$

(2)

$$T^m = 1 - \exp \left( -\frac{\beta(1 + C \ln \dot{\varepsilon})}{\rho H(T_m - T_0)} \sigma_0 + \frac{B\varepsilon^{n+1}}{n + 1} \right)$$

(3)

As reported in previous works [20, 21], all the parameters in Johnson-Cook’s model can be obtained according to different experimental or simulation studies. In the present paper, the parameters used for Armco iron were selected, and the corresponding values were taken as $\beta = 0.9$, $C = 0.06$, $H = 477$, $m = 0.55$, and $\rho = 7890$ [13].

The variation in stress with increasing strain described by equation (4) can be plotted in Figure 3(a), in which the logarithmic relationship of stress and strain is adopted. It is clear that except for some data fluctuation in the initial stage of hot compression, the $\ln \sigma$ vs $\ln \varepsilon$ curve can be divided into two straight lines prior to peak strain according to the different slopes in the curve. Note that these two stages exactly correspond to work hardening and recrystallization softening caused by the change in dislocations, as mentioned above. Figures 3(b) and (c) illustrate the results of linear fitting to the $\ln \sigma$ vs $\ln \varepsilon$ curve, by which the corresponding values of the hardening exponent $n$ at each stage can be obtained.

Figures 3(b) and (c) illustrate the results of linear fitting to the $\ln \sigma$ vs $\ln \varepsilon$ curve, by which the corresponding values of the hardening exponent $n$ at each stage can be obtained. The determination of the starting point and ending point for each stage has a significant impact on the fitting results related to the hardening rate exponent. To minimize the calculation error, the fitted stress is required to approach the experimental value as much as possible. Since the second stage (Figure 3(c)) is closely related to the initiation of DRX, it is selected to be approached to the experimental value. During the data fitting,
the parameters in equation (4) such as $B$, $\sigma_0$, and $n$ would be adjusted until the difference of the sum of stress between the predicted value and the experimental result at all data sets in second stage reaches a value less than 5 MPa. In this case, the uncertainties associated with the difference between them could be controlled to a small value of approximately 0.5% because the sum of stress in the second stage is larger than 1000 MPa. As a consequence of the data fitting based on the Johnson-Cook equation, the comparison of the calculated curve without consideration of DRX and the experimental curve is shown in figure 4.

As known, the strain hardening behaviour is dominantly presented in Johnson-Cook model, in which the stress is described as a function of the exponential form of the strain without considering the softening behaviour. However, for the experimental stress-strain curves, the softening phenomenon caused by DRX is inevitable. It can be found from figure 4 that as the strain increases, the difference between the flow stress predicted by the Johnson-Cook model and the experimental value tends to become more and more significant. The softening effect resulting from DRX in the actual experiment would be responsible for this result. Therefore, it is reasonable that the deviation point of the predicted stress from the experimental value is considered the critical strain for DRX. For the present work, the critical strain obtained from this approach is 0.22, which is 0.73 times the peak strain. The critical ratio of $\varepsilon_C/\varepsilon_p$ falls in the range of 0.65 ~ 0.8 described in most works [5–7].

### 3.3. Experimental verification

A comparison between the predicted critical strain using the Jonas and Johnson-Cook models shows that the critical value for DRX is different based on different models. The corresponding values are 0.17 and 0.22 obtained from Jonas and Johnson-Cook models, respectively. To determine the critical strain for DRX and verify the precision of the calculated results, the microstructures of the deformed samples were observed. The samples were hot-compressed to different strains of 0.17, 0.21 and 0.23, followed by water quenching for microstructure observations. The microstructure observations obtained from scanning electron microscopy for the sample compressed to a strain of 0.21 are shown in figure 5. Obviously, martensite is the typical microstructure of the sample after quenching. The transition from austenite to martensite usually occurs when the sample is rapidly quenched to a temperature below the Ms point. In the present study, hot compressions were carried out at a temperature of 1000 $^\circ$C. In this case, the experimental steel maintains austenite and does not undergo martensite or ferrite transition. Therefore, it can be inferred that the softening behaviour during hot compression might be dominantly induced by DRX.

Figure 6 illustrates the corresponding optical microscope images showing the prior austenite grains in the deformed samples. For the sample compressed to a strain of 0.17, most of the prior austenite grains have a size larger than 50 $\mu$m (figure 6(a)). A few grains with relatively small sizes can also be found, which is caused by static recrystallization rather than DRX. Because hot compression is a continuous deformation, once DRX occurs, the matrix will be rapidly replaced by small recrystallized grains. Due to the strain accumulation in the compressed sample being less than the critical value for DRX, a large number of dislocations would be retained, which provides a necessary driving force for the subsequent static recrystallization. It is difficult to suppress the occurrence of static recrystallization even in the condition of water quenching because the time delay from unloading to quenching is inevitable. Similarly, for the sample compressed to a strain of 0.21, some small grains
are also deduced to form as a result of static recrystallization, and the dominant microstructure in the samples is still nonrecrystallized grains (figure 6(b)).

Regarding the sample compressed to 0.23, a fully recrystallized microstructure can be observed, as shown in figure 5(c). As well known, once the accumulated strain reaches the critical value, DRX will be initiated and then proceed rapidly to completion. Even if DRX does not finish completely after hot compression, meta-dynamic recrystallization usually takes place following DRX and will greatly contribute to obtaining uniform fine recrystallized grains. Because it is actually a grain growth process without the requirement of nucleation [22], meta-dynamic recrystallization usually has a greater rate than static recrystallization. For instance, it has been reported that only approximately 0.1 ~ 3 s is needed to achieve a completely recrystallized microstructure via meta-dynamic recrystallization [23, 24]. It is therefore deduced that the completely recrystallized microstructure in figure 5(c) is just the best evidence that DRX has been triggered for the sample compressed to a strain of 0.23. Combined with figures 5(b) and (c) for comparative analysis, it can be concluded that the critical strain for DRX should be approximately 0.22 when the studied steel is compressed at 1000 °C with a strain rate of 0.1 s⁻¹. Remarkably, the result obtained from the microstructure observation is consistent with the calculated value, which means that the method present in the present work is an effective approach to calculating the critical strain for DRX.

Additionally, as shown in figure 4, the most significant difference between the calculated and actual stress-strain curves is whether the softening effect caused by DRX is reflected in the curves. That is, the deviation of the experimental curve from the calculated curve is attributed to recrystallization softening. Therefore, the change in the relative fraction of recrystallization softening during hot deformation can also be calculated as follows:

\[
X = \left( \frac{\sigma_H - \sigma_S}{\sigma_H} \right) \times 100\% \tag{5}
\]
where $\sigma_{ui}$ is the calculated value of stress corresponding to work hardening and $\sigma_f$ is the actual value associated with recrystallization softening. This provides another approach for the calculation and analysis of the kinetics of recrystallization softening.

4. Conclusion

A novel method for calculating the critical strain for DRX during hot deformation has been proposed based on Johnson–Cook model in this paper. The calculation error resulting from the polynomial fitting and smoothing processing can be effectively reduced by the continuous data approximation to the experimental values, and then a more precise critical strain can be obtained. The kinetics of recrystallization softening could also be analyzed by this novel method. The accuracy of the calculated critical strain is verified by microstructure observations. The present work can also provide strong support for the design of a hot rolling schedule with the aim of promoting the occurrence of DRX and then refining the ferrite grain size.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 52174367). The authors are thankful for the experimental support from Maanshan Iron and Steel Co., Ltd. We would also like to acknowledge the helpful discussion with Professor Q. W. Chen and Y. Q. Wang at Anhui University of Technology.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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