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Characteristic Points of Stress-Strain Curve at High Temperature

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Abstract

Determination of critical points on hot stress-strain curve of metals is crucial in thermo-mechanical processes design. In this investigation a mathematical modeling is given to illustrate the behavior of metal during hot deformation processes such as hot rolling. The critical strain for the onset of dynamic recrystallization has been obtained as a function of strain at the maximum stress. In addition, the transition strain from static recrystallization to full metadynamic recrystallization has been presented to form an equation as a function of peak strain, peak stress and steady-state stress. The results of this mathematical modeling are in a good agreement with the experimental data.

Keywords: Dynamic Recrystallization, Metadynamic Recrystallization, Transition Strain, Critical Strain.

Introduction

Evaluation of forces and forming energy is the most important aspect of mechanical design in metal forming processes [1,2)]. This requires a knowledge of the flow stress of metals. Predicting and controlling the microstructure during hot deformation in industrial processes such as hot rolling is of great importance. Microstructure evolution and deformation mechanisms during deformation are closely related to flow stress [3-7)]. Determination of mechanisms and microstructural evolution by methods such as optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) is possible but expensive and time consuming. Many researchers have tried to predict microstructural evolution from stress-strain curves; thus, by proper designing of thermo-mechanical processes, the suitable microstructure is formed.

Flow stress is a function of dislocation density ($\sqrt{\rho}$) [8)], and dislocation density at high temperature is a function of some parameters such as primary microstructure, temperature and strain rate. Therefore, for a given microstructure, temperature and strain rate condition, the change of stress versus strain is closely related to metal microstructural evolution. Appearance of the maximum stress on the stress-strain curve and its slow decrement to the steady-state stress are the characteristics of dynamic recrystallization (DRX). This phenomenon usually occurs in the metals with low to medium stacking fault energy (SFE) such as Iron, Copper, Austenitic Stainless Steel, etc.

Work hardening and dynamic recovery (DRV) mechanisms control the flow stress up to the maximum stress. DRX occurs before the maximum stress, but since the latter is easier to determine, it is practically used in the design of thermo-mechanical processes even though many researches have tried to locate the exact point of the on set of DRX on the stress-strain curve, i.e. the critical strain [9-12)].

After the peak of stress-strain curve is reached, the rate of softening increases to a maximum value at a particular strain. This particular strain is called "transition strain to full metadynamic recrystallization" [13,14)]. Determining this transition strain is very important in industrial processes such as hot rolling. This means that the process must be designed in such a way to allow the nucleation of new grains during deformation. Afterwards, full metadynamic recrystallization happens in the time between rolling stands. Therefore, critical points are essential in the design of thermo-mechanincal processes. The purpose of this paper is to present a mathematical model which shows the metal behaviour during hot deformation. This model can exactly determine the critical strain, ε_C, for the onset of DRX and the transition strain, ε_T, for static-metadynamic recrystallization transition into full metadynamic recrystallization after deformation.

Mathematical analysis of flow stress

Flow curves of metals having low to medium SFE show clear DRX behavior. Thus, these curves always have only one peak. McQueen et al. have modeled the stress-strain curve up to the peak by [9,15)]:

$$\frac{\sigma}{\sigma_P} = \left[\left(\frac{\varepsilon}{\varepsilon_P}\right)\exp\left(1-\frac{\varepsilon}{\varepsilon_P}\right)\right]^C \tag{1}$$

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where C is a constant and must be determined for each metal and σ_P and ε_P are the maximum stress and strain at the maximum stress, respectively.

Figure 1 is a schematic hot flow curve when DRX occurs. This curve indicates two zones. In zone I, work hardening prevails DRV, so the flow stress increases up to a maximum value. In zone II, DRV and DRX occur simultaneously, thus flow stress gradually decreases and at large strains reaches a steady-state value. The derivative of flow stress is positive in zone I and negative in zone II, and approaches zero in the steady-state zone. Equation 2 demonstrates the stress-strain relationship after the maximum stress as a complement for McQueen equation [16]:

$$\sigma = \sigma_S + (\sigma_P - \sigma_S)\exp\left[C_1\left(\varepsilon - \frac{\varepsilon_P}{2} - \frac{\varepsilon^2}{2\varepsilon_P}\right)\right] \qquad (2)$$

where σ_P is the maximum stress, ε_P is the strain at the maximum stress and σ_S is the steady-state stress. In order to determine the constant, C_1, a point, K is chosen on the curve such that $K<1$ and $\sigma_K>\sigma_S$. Then C_1 is given by equation 3:

$$C_1 = \frac{2}{(K^2 - 2K + 1)\varepsilon_P}\ln\left(\frac{\sigma_P - \sigma_S}{\sigma_K - \sigma_S}\right) \qquad (3)$$

where σ_K is calculated by Eq. 1 at $\varepsilon_K = K\varepsilon_P$.

The equations represented by this model require the values of stress and strain at the peak and stress at the steady-state zone. These parameters can be calculated by kinetic equations [16].

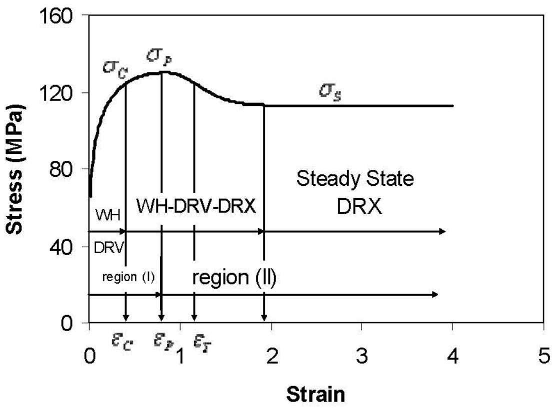

Fig. 1. Schematic flow curve at high temperature for DRX.

Critical strain for the onset of DRX

During the deformation, an increase in the work hardening increases the dislocation density leading to a critical microstructural condition at which new grains nucleate and new high-angle boundaries grow. This phenomenon is called dynamic recrystallization, DRX. Gradually, the dislocation density increases in other areas as well. Therefore, the flow stress increases up to a maximum value and the rate of softening mechanism prevails work hardening afterwards. Thus, flow stress reaches a steady-state condition at which the rate of generation and annihilation of dislocations become equal each other.

The critical strain at the onset of DRX can be determined metallorgraphically from the observation of microstructure of quenched specimens. This technique requires a large number of specimens deformed to different strains. On the other hand, the critical strain thus obtained is not precise [11]. Ryan and McQueen observed an inflection in the $\theta = \frac{\partial\sigma}{\partial\varepsilon}$ vs. σ curve [15]. Then Poliak and Jonas showed that this inflection corresponds to the initiation of DRX and occurs at $\varepsilon_C=0.55\varepsilon_P$ for Nb-microalloyed steels [11]. This is when the critical strain of the onset of DRX, formerly reported by microscopic observation, was $\varepsilon_C=0.8\varepsilon_P$ [12].

In this research, applying Ryan and McQueen theory and mathematical calculations, an equation is introduced to calculate the critical strain at the onset of DRX. The derivative of Eq. 1 gives:

$$\frac{d\sigma}{d\varepsilon} = C\sigma\left[\frac{1}{\varepsilon} - \frac{1}{\varepsilon_P}\right] \qquad (4)$$

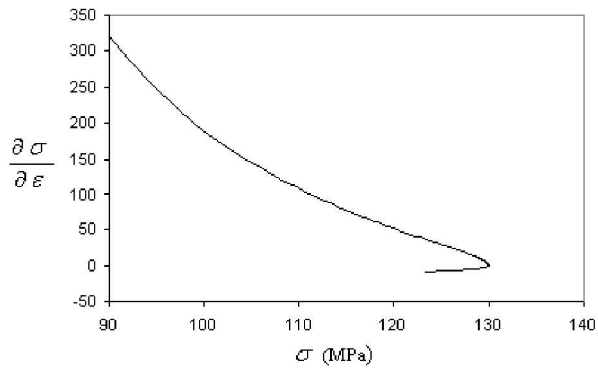

Fig. 2. Derivative of stress with respect to strain vs. stress.

Figure 2 is obtained from Eq. 4 by assuming $\varepsilon_P=0.85$ and C=0.2 just as a sample data to show the form of Eq. 4. The schematic shape of this curve is exactly like the ones reported in the references, with only one inflection [11]. As Figure 3 and Figure 4 show, the second derivative of $\theta = \frac{\partial\sigma}{\partial\varepsilon}$ with respect to σ must be zero, in order to determine the critical point.

$$\frac{d^2\left(\frac{\partial\sigma}{\partial\varepsilon}\right)}{d\sigma^2} = 0 \qquad (5)$$

by solving Eq. 5 we get the critical strain for the onset of DRX as a function of strain at the maximum stress:

$$\varepsilon_C = \left[1 - \frac{1-\sqrt{1-C}}{C}\right]\varepsilon_P \qquad (6)$$

where C is the constant of equation 1 and varies between 0.1 to 0.3 for different alloys [15]. Therefore, the critical strain values vary between $0.46\varepsilon_P$ to $0.49\varepsilon_P$ for different alloys which is in a good agreement with values ($\varepsilon_C=0.55\varepsilon_P$) reported by other researches for Nb-microalloyed steel [11]. As a result, if the flow stress equation for different alloys is available, the exact amount of the critical strain for the onset of DRX could be calculated by Eq. 6.

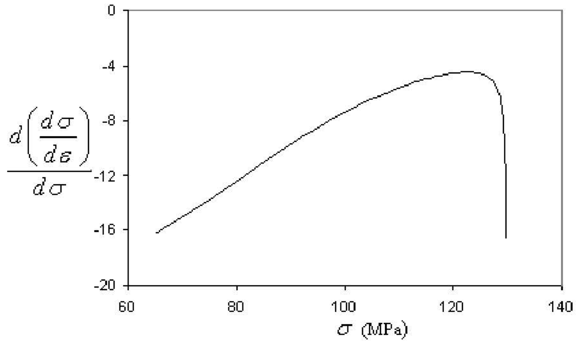

Fig.3. Derivative of work hardening rate with respect to stress vs. stress.

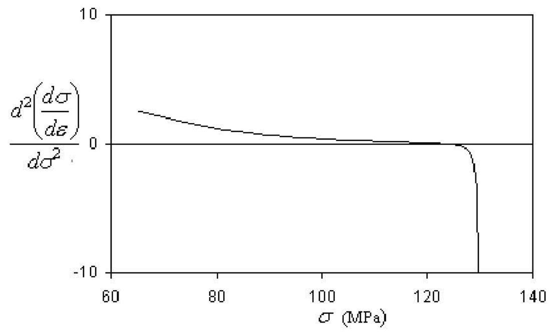

Fig. 4. Second derivative of work hardening rate with respect to stress vs. stress.

Transition strain to full metadynamic recrystallization

As Figure 5 shows [13], whenever strain during hot deformation reaches a critical value and then deformation stops, the static recrystallization phenomenon that occurs after deformation is called metadynamic recrystallization. This is because nucleation happens during deformation. After the peak, the rate of softening increases continuously and gets to its maximum value at a particular strain. If deformation continues up to this specified strain and then stops, full metadynamic recrystallization occurs. This is due to the achievement of the maximum rate of softening which guaranties that nucleus has formed throughout the specimen. Thus, this certain strain is called transition strain to full metadynamic recrystallization state. The value of this strain is reported $1.5\varepsilon_P$ for Nb-microalloyed steel [13,14]. Therefore, to estimate this transition strain, the maximum value of softening i.e. maximum slope of stress-strain curve at the zone with negative slope and softening mechanism must be determined. So the first derivative of $\theta = \dfrac{\partial\sigma}{\partial\varepsilon}$ with respect to σ must be zero.

$$\frac{d\left(\dfrac{d\sigma}{d\varepsilon}\right)}{d\sigma} = 0 \tag{7}$$

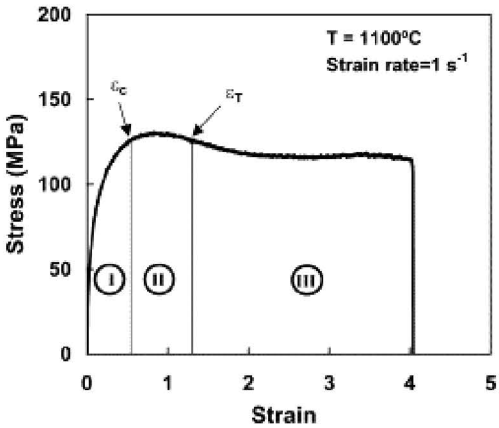

Fig. 5. Effects of strain on softening mechanisms during and after deformation:
Zone I-SRX, Zone II-SRX and MDRX, Zone III-DRX and MDRX [13].

by solving Eq. 7 we get the transition strain to full metadynamic recrystallization as a function of strain at the maximum stress:

$$\varepsilon_T = \varepsilon_P + \sqrt{\frac{\varepsilon_P}{C_1}} \tag{8}$$

where C_1 is the constant of Eq. 2 that is determined by Eq. 3. Now, in order to check Eq. 8, we determine the transition strain for Figure 5 i.e. for a Nb-microalloyed steel [13]. From this curve we found the approximate values of σ_S, σ_P and ε_P to be 113 MPa, 130 MPa and 0.85, respectively. Also by assuming K=0.7, the approximate values of σ_K and ε_K are 125 MPa and 0.6, respectively. Inserting these values into Eq. 3, C_1 is found to be 7.013. Eq. 8 gives the transition strain of 1.2. Thus the ratio of the transition strain to strain at the maximum stress equals 1.41 $\left(\dfrac{\varepsilon_T}{\varepsilon_P} = 1.41\right)$ which is comparable to the approximate value of 1.5 $\left(\dfrac{\varepsilon_T}{\varepsilon_P} \approx 1.5\right)$ reported by other researches for Nb-microalloyed steel [13,14].

Conclusions

A mathematical model was presented to directly determine the critical strain for onset of DRX and the transition strain from static-metadynamic recrystallization to full metadynamic recrystallization

after deformation. Numerical results of these equations are:
1-Critical strain, ε_C, for onset of DRX by Eq. 6 was found to be $0.46\varepsilon_P$ to $0.49\varepsilon_P$ which is in a good agreement with $0.55\varepsilon_P$, reported by other researches for Nb-microalloyed steel.
2-Transition strain, ε_T, from static-metadynamic recrystallization to full metadynamic recrystallization after deformation is given by Eq. 8 which was $1.41\varepsilon_P$ for Nb-microalloyed steel that is comparable to $1.5\varepsilon_P$, reported by other investigators.

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