Metadynamic recrystallization of austenitic stainless steel

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Interrupted torsion tests were performed in the temperature range of 900–1100°C, strain rate range of 5.0×10^{-2}–5.0×10^{0}/sec and interpass time range of 0.5–100 seconds to study the characteristics of metadynamic recrystallization (MDRX) for austenitic stainless steel. To compare the MDRX with static recrystallization (SRX), the pass strain was applied above the critical strain (ε_c) ($\varepsilon_c = 2.2 \times 10^{-3}\ D_0^{1/2}\ Z^{0.089}$, where Z is Zener-Hollomon parameter, $Z = \dot{\varepsilon}\exp((380000\ \text{J/mol})/RT)$ and D_0 is as-received grain size) to obtain the MDRX during interpass time. It was found that the kinetics of MDRX were dependent of the strain rate and deformation temperature but were nearly independent of the change in pass strain after the peak strain. The time for 50% metadynamic softening, t_{50}, was determined as follows: $t_{50} = 1.33 \times 10^{-11}\ \dot{\varepsilon}^{-0.41}\ D_0 \exp((230000\ \text{J/mol})/RT)$ and this calculated value was consistent with the measured value. The Zener-Hollomon parameter was impossible to evaluate the MDRX fraction, because the fractional softening values were different at the same Z values. The new parameter (MDRX parameter) considering deformation temperature, strain rate and interpass time was proposed to evaluate the MDRX fraction. The MDRX-parameter was determined as $3.25 \times 10^{-19}\dot{\varepsilon}^{0.3}\ t_i^{0.6}\ T^{12}$.

1. Introduction

The grain refinement by dynamic recrystallization (DRX) is very important during hot deformation [1–3]. DRX is generally easy to occur in some early stages like a roughing mill with a low strain rate and high deformation temperature during multipass deformation, but it is difficult to occur at the some last passes. It is also difficult for the static recrystallization (SRX) to take place between interpasses. Therefore, metadynamic recrystallization (MDRX) is nowadays interested in the hot working condition but very limited results are published until now [4, 5].

Metadynamic recrystallization occurs by the continued growth of nuclei formed as a result of the occurrence of dynamic recrystallization during prestraining [4, 6]. Hence the operation of MDRX does not require an incubation time and such a rapid interpass softening can increase the mechanical properties, even though not long pass strain and interpass time, especially for materials with relatively large deformation resistance such as austenitic stainless steel. This is also important to improve the mechanical properties and can make very fine grains during the very short interpass time. Therefore, this fast softening can reduce the interpass time and pass strain, since can accelerate the recrystallization during short interpass time.

The aim of the present study is to investigate the contribution of the metadynamic recrystallization for the softening of austenitic stainless steel. The effects of strain rate, temperature, and pass strain for metadynamic recrystallization were investigated by means of interrupted torsion testing. The mechanical data were used to derive the kinetic equation which describes the rates of softening. Finally, the new parameter, MDRX parameter, was proposed to evaluate the metadynamic recrystallization fraction.

2. Experimental procedure

The AISI 304 stainless steel of nominal composition Fe-18.25 wt% Cr-8.16 wt% Ni was produced by the vacuum induction melting and the torsion test specimens with a gauge section of 20 mm length and 5 mm radius were machined. Continuous torsion tests were carried out to calculate the critical strain at the same temperature and strain rate as the interrupted deformation. Interrupted torsion tests were conducted in the temperature range of 900–1100°C, strain rate range of 5.0×10^{-2}–5.0×10^{0}/sec, interpass time range of 0.5–100 seconds, and pass strain range of 0.25–3 times of peak strain to evaluate the effects of deformation variables on metadynamic softening.

The measured torque Γ, and twist θ were converted to Von Mises effective stress (σ) and strain (ε) using the following equations.

$$\sigma = \frac{3.3\sqrt{3}\Gamma}{2\pi R^3}, \qquad \varepsilon = \frac{\theta R}{\sqrt{3}L} \qquad (1)$$

Here, R and L are the gauge radius and length of the specimen, respectively. And 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 double twisted torsion tests.

3. Results and discussion

3.1. Decision of critical strain for dynamic recrystallization

The stress (σ)-strain (ε) curves, obtained from continuous hot torsion tests at the condition of 900–1100°C and 0.05–5.0/sec, are displayed in Fig. 1a to determine the strain hardening rate (□≡ dσ/dε) and this strain hardening rate as a function of stress (σ) at the condition of 1000□, □0.5/sec is shown in Fig. 1b. Fig. 1b consists of three stages [7]. At the first low strain stage, strain hardening rate (θ) decreases rapidly up to the strain which the subgrain formation begins. At the second stage, the strain hardening rate decreases up to the critical stress (σ_c). During this stage, subgrain formation is completed. At the third stage, strain hardening rate decreases from the critical strain, inflection point, to peak stress (σ_p), at $\theta = 0$ and this inflection point (σ_c) indicates that DRX becomes operative.

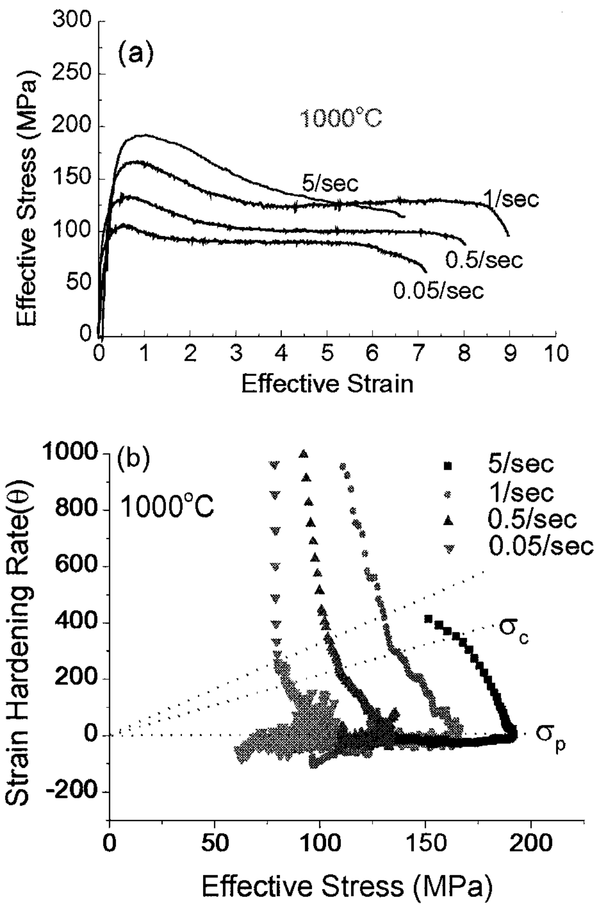

Figure 1 (a) σ-ε curve and (b) θ-σ curve used to determined the critical strain of austenitic stainless steel.

From this analysis, the relationship between the ε_c and deformation variables were determined to be $\varepsilon_c = 2.2 \times 10^{-3} D_0^{1/2} Z^{0.09}$, where D_0 is the as-received grain size and Z is the Zener-Hollomon parameter. The Z calculated from the continuous deformation is equal to $Z = \dot{\varepsilon}\exp((380000\ \text{J/mol})/RT)$, where $\dot{\varepsilon}$ is the strain rate. The pass strain can be decided by this equation. To study the metadynamic softening, the decision of critical strain for DRX is very important, because the critical strain indicates the onset of strain for DRX. If the pass strain is larger than the critical strain, the metadynamic recrystallization affects the shape of flow curve and fractional softening of successive passes in spite of short interpass time.

3.2. Fractional softening, FS

The interrupted stress-strain curves obtained at the temperature of 1000°C and strain rate of 0.05/sec with varying interpass time, are presented in Fig. 2. The flow stress of the second curve below the interrupt time of 3 seconds rises quickly up to the level of the continuous curve. However, when interruption time is longer than 10 seconds, much softening takes place and the second curve becomes similar to initial loading curves. If the time between passes 1st and 2nd is sufficiently long for full softening to occur, the stress-strain curve for the 2nd pass is essentially the same of the first curve. If there is no softening, the second pass gives rise to a curve that coincides with an extrapolation of the first curve. In order to quantify the amount of softening between two passes, two testing approaches have been used quite widely in previous work: (1) offset stress and (2) mean flow stress method. In these experiments, the first method was adopted.

In the offset stress method, the fraction softening, X is calculated according to:

$$X = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1}$$

Where σ_m is the flow stress at the end of the first curve, σ_1 is the stress at an offset of 0.2% strain in the first deformation, σ_2 is the offset stress in the second pass.

Fig. 3 is the metadynamic softening as a function of interruption time, depending on deformation

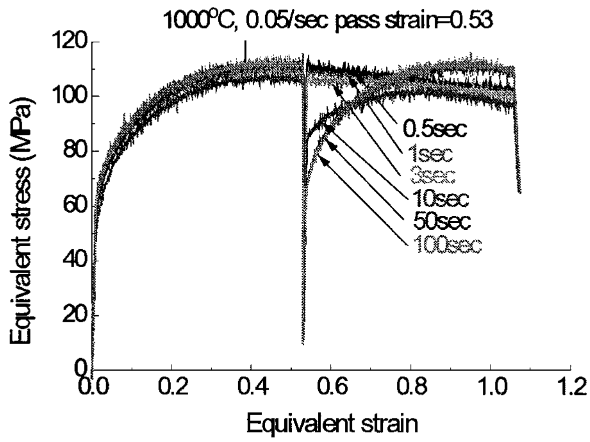

Figure 2 Double-twist flow curves obtained from interrupted torsion tests.

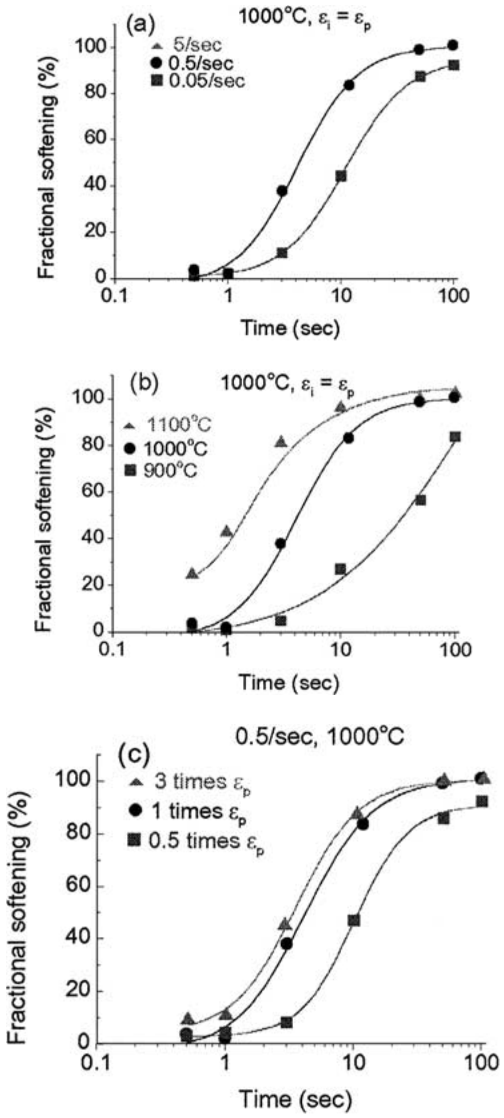

Figure 3 Effect of (a) strain rate, (b) temperature and (c) pass strain on the metadynamic softening.

temperature, strain rate and pass strain. From Fig. 3a and b, as the temperature and strain rate are increased, the kinetics of metadynamic softening are increased and these results are well accepted by the classical static recrystallization. In Fig. 3c, a very small change in the softening kinetics was observed when the pass strain was increased from 1 to 3 times of peak strain. On the other hand, a significant increase in kinetics was observed when the pass strain was raised from 0.25 to 1 times of peak strain. These softening curves indicate that the metadynamic softening was happened during the interpass time, when the pass strain was over the peak strain and also that the effect of pass strain for metadynamic softening was negligible.

3.3. Kinetics of metadynamic recrystallization

The recrystallization process involving nucleation and growth can be expressed by the Avrami equation. Although the metadynamic softening does not involve a nucleation step, it can be described by the Avrami equation:

$$X = 1 - \exp\left[-0.693(t/t_{50})^n\right] \qquad (2)$$

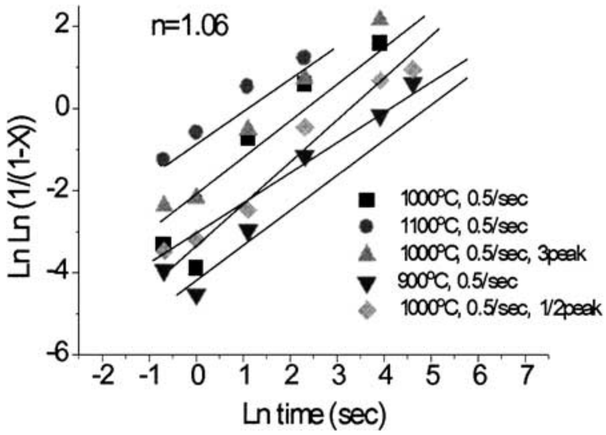

Figure 4 Dependence of ln ln $(1/(1-x))$ on ln time under different pass strains, temperatures and strain rates.

where X is the recrystallization fraction (%), t is the interrupt time, n is the Avrami constant and t_{50} is the time for 50% softening. The t_{50} can be expressed as $t_{50} = A\dot{\varepsilon}^{p} D \exp(Q/RT)$. Here, A and p are constants, Q is the activation energy (J/mol) and R is the universal gas constant.

Fig. 4 shows the ln ln$(1/(1-X))$ vs. ln time relations to determine the Avrami constant, n. The n value is determined to be 1.06. A very few information is available regarding the n value for MDRX [8, 9]. This value is closely similar to the value (1.08) for SRX on 304 stainless steel. As the pass strain does not consider in MDRX, the effects of deformation temperature and strain rate are considered to determine the t_{50}, as shown in Fig. 5. The calculated t_{50} is:

$$t_{50} = 1.33 \times 10^{-11} \dot{\varepsilon}^{-0.41} D \exp((230300\,\text{J/mol})/RT) \qquad (3)$$

This calculated value is well matched with the measured value. The relationship between the pass strain and time for softening is shown in Fig. 6. The time for 5, 20, 50 and 80% softening is presented. It was found that there's no difference in the time after 50% softening. It means the MDRX is no more sensitive after critical strain for DRX and the kinetics of static recrystallization will be different from that of MDRX. Fig. 6 also shows the change in kinetics corresponding to the

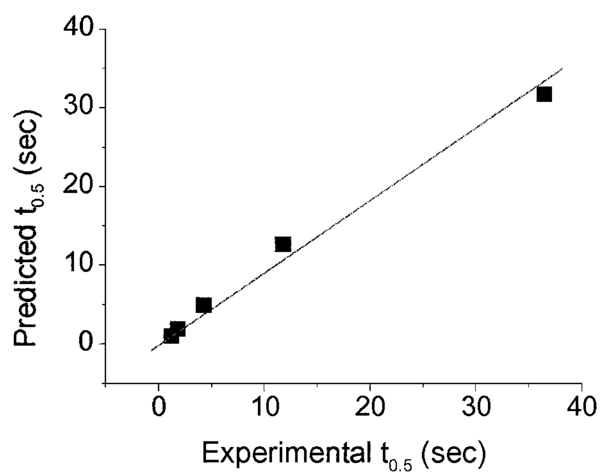

Figure 5 Comparison of experimental and calculated t_{05} values.

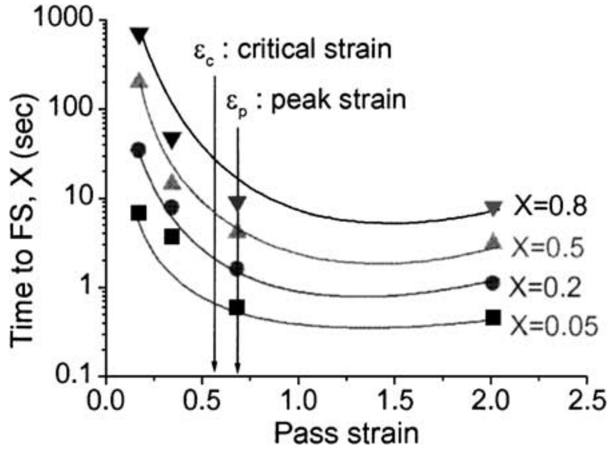

Figure 6 Pass strain dependence of the time for 5–80% softening.

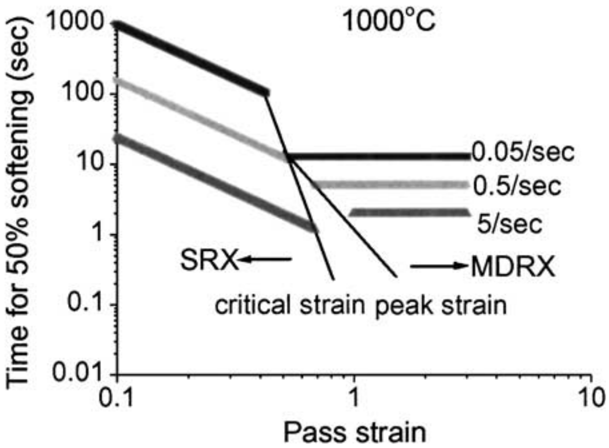

Figure 7 t_{50} as a function of the strain for strain rate of 0.05, 0.5, 5/sec. When $\varepsilon_i < \varepsilon_c$, SRX takes place and $\varepsilon_i > \varepsilon_p$, MDRX occurs.

transition from static to metadynamic softening and this pass strain dependence on the time to FS can apply to the time for 50% softening as well as the amount of fractional softening.

The time for 50% metadynamic recrystallization calculated for this steel as a function of pass strain with various strain rate is displayed in Fig. 7. There is very little sensitivity of $t_{0.5}$ to amount on pass strain.

In the case of SRX kinetics, most of investigations reveal a weak effect of strain rate but a strong effect of pass strain. Since the driving force for SRX is the reduction of strain energy, basically the annihilation of the dislocations introduced during deformation, a significant influence of strain is to be expected. In the case of MDRX, the driving force is same, but the dislocation density is that due to DRX, and changes in strain in the steady state region of DRX do not change the average dislocation density. Therefore, once the pass strain is over the critical strain for DRX, changes in pass strain do not change the MDRX kinetics any more. The MDRX kinetics, therefore associated with a steady state DRX structure are not expected to be affected by the strain changes [10–13].

3.4. The determination of MDRX parameter

The Zener-Hollomon parameter is generally accepted as a good value to explain the dynamic restoration.

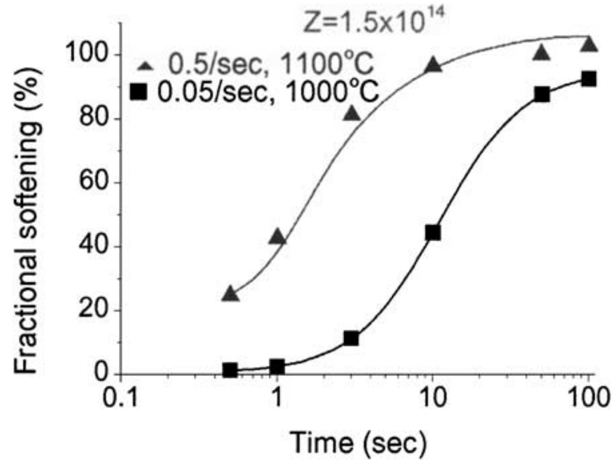

Figure 8 Comparison of softening behaviors observed after deforming to the peak strain at the similar values of Z-parameter.

This parameter can illustrate the flow stress and strain rate as a function of temperature and is associated with microstructure evolution [2]. As it is mentioned before, the nucleation of metadynamic recrystallization begins at dymaic state. Therefore, the Zener-Hollomon parameter can be expected to explain the MDRX behavior.

Fig. 8 shows the fractional softening as a function of interpass time obtained under a constant Zener-Hollomon parameter ($\sim 1.5 \times 10^{14}$). Although the driving force for recrystallization, i.e., the stored energy resulting from deformation, was constant, different degree of softening fraction was obtained under this Zener-Hollomon parameter. This indicates that a constant Z value did not lead to a similar softening fraction. This is because the Zener-Hollomon parameter includes strain rate and temperature, but not interpass time. However, MDRX fraction depends on the interpass time. Thus, since the Zener-Hollomon parameter is not an adequate value to evaluate the kinetics of metadynamic softening, it is necessary to define the new parameter considering the temperature, strain rate and interpass time. Also, since the grain size depends on the softening fraction, the new parameter can explain the MDRX fraction and grain size.

Fig. 9 shows the dependence of MDRX fraction on interpass time. The relationship between MDRX fraction and interpass time can be expressed by the following power relation: MDRX fraction $= C t_i^{0.6}$,

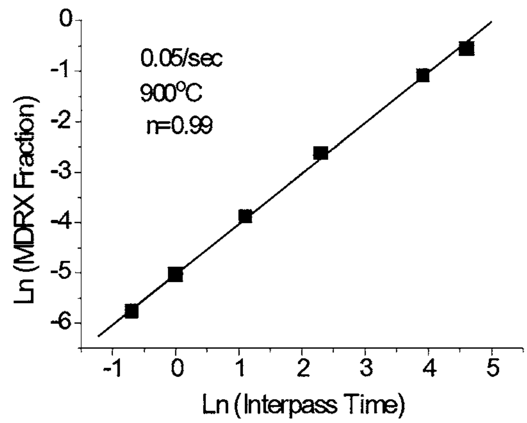

Figure 9 Dependency of interpass time on the rate of metadynamic softening.

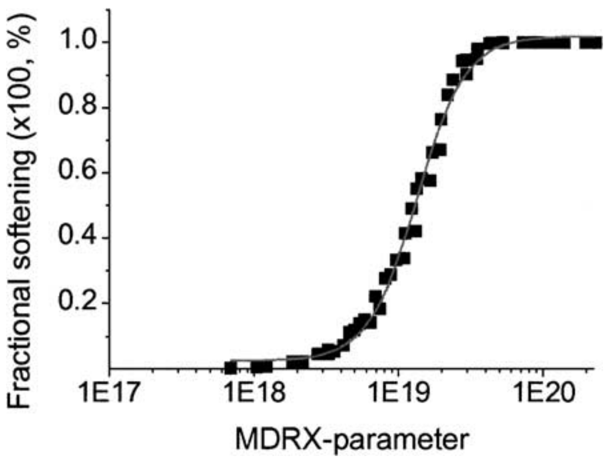

Figure 10 MDRX fraction vs. MDRX parameter for austenitic stainless steel.

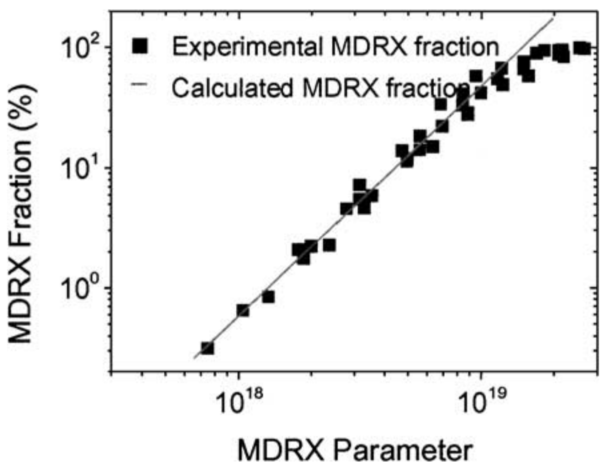

Figure 11 Experimental MDRX fraction and calculated MDRX fraction values as a function of MDRX parameter.

where C is constant. Also, the dependency of the MDRX fraction on temperature and strain rate could be obtained by the above method. Thus, the new parameter (MDRX parameter) can be determined from the analysis of dependency of MDRX softening fraction on temperature (T), strain rate ($\dot{\varepsilon}$) and interpass time (t_i) as follows:

$$\text{MDRX parameter} = 3.25 \times 10^{-19} \dot{\varepsilon}^{0.3} t_i^{0.6} T^{12} \quad (4)$$

Fig. 10 shows the MDRX fractional softening as a function of the MDRX parameter. MDRX fractional softening includes the effects of all the deformation variables, such as strain rate, temperature and interpass time. This figure shows the sigmoid shape with a very small error range. Once the MDRX parameter is decided, the MDRX fraction can be determined. One example is represented at the Table I. Table I shows the dependency of MDRX fraction, Zener-Hollomon parameter and MDRX parameter on deformation variables. For example, for ∼50% MDRX fraction (underlined conditions), the values of Zener-Hollomon parameter are significantly different (1.38×10^{13}–3.99×10^{15}), but the values of MDRX parameter are closely similar ($\sim 1.3 \times 10^{19}$). Thus the MDRX parameter can lead to the prediction of the metadynamic softening fraction.

TABLE I Dependency of MDRX fraction, Zener-Hollomon parameter and MDRX parameter with deformation variables

Deformation variables			MDRX	Zener-Hollomon	MDRX
$\dot{\varepsilon}$(/sec)	T (°C)	t_i (sec)	fraction	parameter	parameter
0.05	900	0.5	0.003	3.99×10^{15}	6.89×10^{17}
0.05	900	1	0.006	3.99×10^{15}	1.04×10^{18}
0.05	900	3	0.021	3.99×10^{15}	2.02×10^{18}
0.05	900	10	0.07	3.99×10^{15}	4.14×10^{18}
0.05	900	50	0.34	3.99×10^{15}	1.13×10^{19}
0.05	900	100	0.57	3.99×10^{15}	1.62×10^{19}
0.05	1100	0.5	0.11	1.38×10^{13}	4.55×10^{18}
0.05	1100	1	0.22	1.38×10^{13}	6.89×10^{18}
0.05	1100	3	0.55	1.38×10^{13}	1.33×10^{19}
0.05	1100	10	0.94	1.38×10^{13}	2.74×10^{19}
0.05	1100	50	1	1.38×10^{13}	7.21×10^{19}
0.05	1100	100	1	1.38×10^{13}	1.09×10^{20}
0.5	1100	0.5	0.27	1.37×10^{14}	8.09×10^{18}
0.5	1100	1	0.49	1.37×10^{14}	1.22×10^{19}
0.5	1100	3	0.88	1.37×10^{14}	2.37×10^{19}
0.5	1100	10	0.99	1.37×10^{14}	4.88×10^{19}
0.5	1100	50	1	1.37×10^{14}	1.28×10^{20}
0.5	1100	100	1	1.37×10^{14}	1.94×10^{20}

The relationship between the MDRX parameter and MDRX fraction can be expressed as the following equation:

$$\text{MDRX fraction} = \exp[1.66 \ln(\text{MDRX parameter}) - 73.67] \quad (5)$$

Fig. 11 shows the experimental MDRX fraction and the MDRX fraction value calculated from Equation 5 as a function of MDRX parameter. The calculated MDRX fraction values are well matched with the experimental values. However, some discrepancies in these two MDRX fraction values were found above 100% MDRX fraction.

In conclusion, we proposed the new parameter (MDRX parameter) considering temperature, strain rate and interpass time, to evaluate the MDRX fraction. This new parameter can be determined easily from the relationship between the MDRX fraction and deformation variables and can predict the MDRX fraction precisely.

4. Conclusions

The important changes in kinetics and softening occurred during the holding intervals after the initiation of dynamic recrystallization were investigated. From the analysis of high temperature continuous and interrupted deformation behavior, the following conclusions can be drawn:

1. The critical strain (ε_c) was decided by the Zenner-Hollomon parameter to obtain DRX effects during interpass time.

$$\varepsilon_c = 2.2 \times 10^{-3} D_0^{1/2} Z^{0.089},$$

where $$Z = \dot{\varepsilon} \exp((380000\,\text{J/mol})RT)$$

2. It was found that the softening kinetics depended on the strain rate and deformation temperature but not the pass strain.

3. The time for 50% softening (t_{50}) is determined as follow: $t_{50} = 1.33 \times 10^{-11}\ \dot{\varepsilon}^{-0.41} D \exp((230300\ \text{J/mol})/RT)$. This value is well matched with the experimental value.

4. We proposed the new parameter (MDRX parameter) considering temperature, strain rate and interpass time, to evaluate the MDRX fraction. This new parameter can be determined easily from the relationship between the MDRX fraction and deformation variables and also can predict the MDRX fraction precisely.

$$\text{MDRX parameter} = 3.25 \times 10^{-19} \dot{\varepsilon}^{0.3} t_i^{0.6} T^{12}$$

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