

## METADYNAMIC RECRYSTALLIZATION OF A PRECIPITATION HARDENABLE STAINLESS STEEL

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### ABSTRACT

In this research, the metadynamic recrystallization (MDRX) behavior of a precipitation hardenable stainless steel has been investigated by conducting interrupted hot compression tests at temperatures of 950-1150 °C and under strain rates of 0.001-1 s<sup>-1</sup>. The kinetics and fractional softening of MDRX were found to increase with temperature and strain rate. It was realized from metallographic observations that the kinetics of MDRX increases with Zener-Hollomon (Z) parameter and more fine-grained structure can be achieved. The kinetics of MDRX was investigated on the basis of JMAK model and equation  $X = 1 - \exp[-0.693(t/t_{0.5})]^{0.5}$  was proposed. From the variation of  $t_{0.5}$  with deformation temperature and strain rate the equation  $t_{0.5} = 1.73 \times 10^{-7} \varepsilon^{-0.33} \exp(191000/RT)$  was proposed.

**Key words:** Metadynamic recrystallization, hot compression, precipitation hardening stainless steel

### 1. INTRODUCTION

Thermomechanical processing in the form of hot deformation is an important production process which is employed for optimization of microstructure, mechanical and metallurgical properties of precipitation hardenable (PH) stainless steels. Hot deformation processing of these steels is conducted almost in the temperature range of stability of austenite phase [1]. Because of low stacking fault energy of austenite in steels [2], the major restoration processes during and after hot deformation of PH-stainless steels are dynamic and metadynamic recrystallization (DRX and MDRX), respectively. However, deformation resistance and critical strain for initiation of DRX are higher in the case of stainless steels than those of carbon steels [3], DRX is generally occurs in early stages of multipass industrial hot working processes such as rough rolling. Hence, DRX and MDRX have been incorporated into many of actual industrial hot working processes, such as rod rolling [4].

To apply the results of laboratory studies to industrial hot working processes, many researchers have developed equations for defining the relationships between the kinetics of softening processes and the processing variants [5-7]. Indeed, there is a close relation between all the structural evolutions associated with hot working and Z parameter which is defined as follows:

$$Z = \dot{\varepsilon} \exp(Q/RT) \quad (1)$$

Where, Q, R and T are activation energy, gas constant and absolute temperature respectively. The most important parameter for prediction of microstructural changes during hot deformation is the critical strain for initiation of DRX,  $\varepsilon_c$ . Many researchers have proposed equations for modeling of DRX in different steels [8-15]. These studies have led to find relations between structural evolutions and processing parameters. It is known that  $\varepsilon_c$  depends on Z as follows:

$$\varepsilon_c = A \cdot Z^p \quad (2)$$

Where, A and p are materials constants which have been determined as  $3.01 \times 10^{-4}$  and 0.14 for this PH-stainless steel [16]. If the pass strain is higher than  $\varepsilon_c$ , the DRX and MDRX occur during and after deformation, respectively. On the other hand, if the pass strain is lower than  $\varepsilon_c$  static recrystallization (SRX) is the only restoration process which triggers after unloading and proceeds during interpass time.

The MDRX occurs by continued growth of nuclei formed by DRX during the former pass [17, 18]. Hence, this process doesn't require an incubation time and thus it proceeds more quickly than SRX. The fractional softening developed by MDRX under different hot deformation conditions can be determined by interrupted hot compression or hot torsion tests. Although, there is no nucleation, the kinetics of MDRX can be determined by the JMAK equation as follows:

$$X_{\text{MDRX}} = 1 - \exp\left[-0.639\left(\frac{t}{t_{50}}\right)^n\right] \quad (3)$$

Where, n is called Avrami exponent and  $t_{0.5}$  is the time for 50 percent recrystallization, which can be presented as follows:

$$t_{50} = A \dot{\varepsilon}^{-p} \exp\left(\frac{Q_{\text{MDRX}}}{RT}\right) \quad (4)$$

Where, A and p are material constants and  $Q_{\text{MDRX}}$  is activation energy for MDRX.

In this research, the MDRX in a precipitation hardenable stainless steel have been investigated by studying the fractional softening between two passes of hot compression tests.

## 2. EXPERIMENTAL PROCEDURES

The chemical composition of the precipitation hardenable stainless steel used in this investigation is given in Table 1. This material was produced by casting and then it was refined by ESR (electroslag remelting) process. The ESR billet was homogenized at 1220 °C for 2 hours and then quenched in water to room temperature. After the homogenization heat treatment and quenching, hot compression specimens of 9 mm diameter and 14 mm height were machined from the ESR billet. All specimens were preheated at 1200 °C for 10 minutes. Afterward, interrupted hot compression experiments were carried out in the temperature range of 950-1150 °C and strain rates of  $0.001-1 \text{ s}^{-1}$  rate with different interpass times such as 5, 25 50, 80 and 100 seconds. On

the basis of equation (2), the true strain was adopted to be 0.5 for each pass to ensure the occurrence DRX during hot deformation and thereby MDRX between passes.

Table 1 - Chemical composition of investigated PH-stainless steel

element	C	Cr	Ni	Mo	Cu	Ti	Si
Wt%	0.02	10.21	10.11	5.06	1.96	1.050	0.30

### 3. RESULTS AND DISCUSSION

Typical true stress-true strain curves obtained from interrupted hot compression tests at different deformation conditions are shown in Figs. 1 and 2.

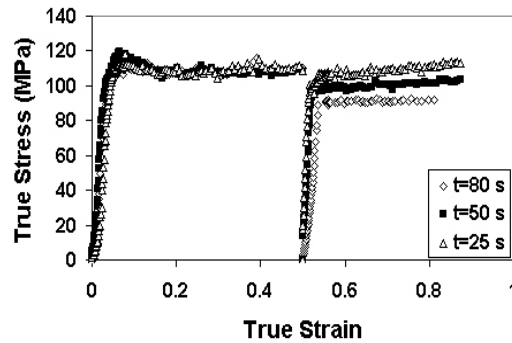


Fig.1. The true stress-true strain curves of interrupted hot compression tests at temperature of 1000 °C and strain rate of 0.001 s<sup>-1</sup>

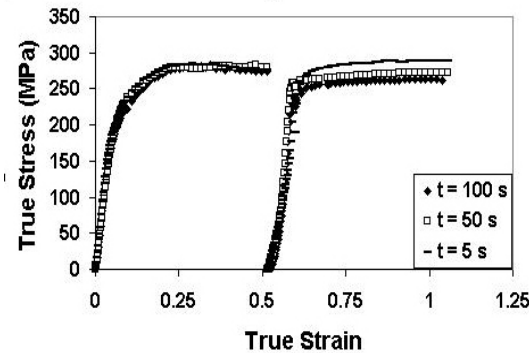


Fig.2. The true stress-true strain curves of interrupted hot compression tests at temperature of 900 °C and strain rate of 0.01 s<sup>-1</sup>

The fractional softening (X) is determined by the 0.2% proof stress method as following equation [19]:

$$X = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \tag{5}$$

Where,  $\sigma_m$  is the flow stress of interrupted point and  $\sigma_1$  and  $\sigma_2$  are the 0.2% proof stresses of the first and second passes, respectively. As it's illustrated in Figs.1 and

2, the fractional softening which is appeared by dropping of flow stress between two passes increases with interpass time. It was well known that nucleation and growth of new grains during recrystallization proceed with time. Fig.3 shows the dependency of X on interpass time at different deformation conditions. As it's illustrated by this figure, at constant values of deformation temperature and interpass time fractional softening increases with strain rate. At a given strain value, the density, interactions and tangles of dislocations increase with strain rate. The increase in density of deformation features, like dislocation tangles by increasing strain rate, augments the deformation energy stored in the structure of the material. It is well known that, this stored energy is the driving force for successive recrystallization. On the other hand, fractional softening increases with deformation temperature. Indeed, nucleation of MDRX, which occurs during the preceding DRX and the growth stage of new grains are accelerated by increasing temperature. The increase in the rate of nucleation and growth by temperature may be attributed to increase in the mobility of high angle boundaries.

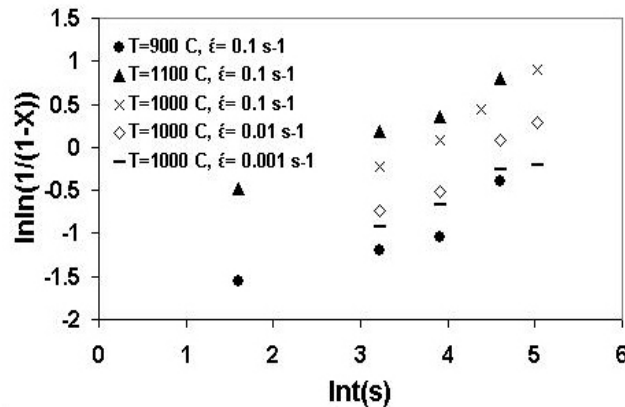


Fig. 3. The dependency of fractional softening on interpass time at different deformation conditions

On the basis of Fig.3, the exponent of the JMAK equation can be determined as 0.5. The value of n has been determined to be 1.06 for 304 austenitic stainless steels [14]. This can be attributed to discrepancy in chemical compositions. The higher contents of Ti, V, Mo and Cu in PH-stainless steel delay the occurrence of recrystallization and decrease its rate. Hence, The JMAK equation is proposed as follows:

$$X_{\text{MDRX}} = 1 - \exp[-0.693(t/t_{0.5})]^{0.5} \quad (6)$$

The microscopic observations of specimen tested at different deformation conditions (different Z) are shown in Fig. 4. As it's illustrated in this figure, the larger the Z value, the finer the grain structure of the material. Therefore, the kinetics of MDRX increases with Z value. Because of the exponential relation between temperature and Z, it's effect on the kinetics and microstructural evolution associated with MDRX is more appreciable than that of  $\dot{\epsilon}$ . Fig. 5 shows the effect of interpass time on the microstructural changes during MDRX. This figure shows that the old coarse grains produced by successive DRX and work hardening processes are replaced gradually by new fine grain structure associated with MDRX. As mentioned earlier, the fractional softening proceeds towards unity with increase in the interpass time. The impingement of new grains of MDRX in the early stage of recrystallization is the major cause of grain refinement.

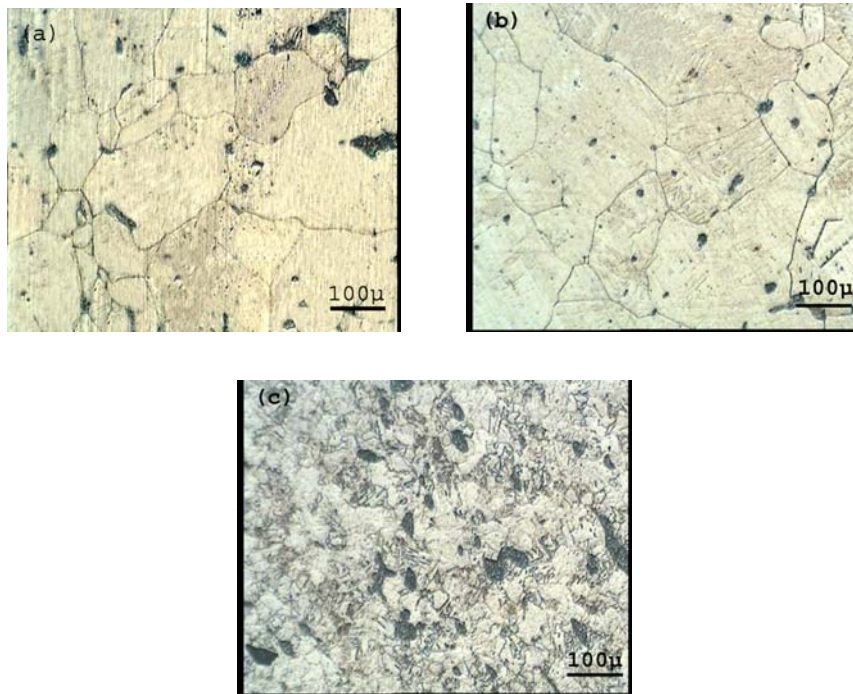


Fig.4. Micrographs of specimens tested at constant interpass time of 100 s. (a) at temperature of 1000 °C and strain rate of  $0.1 \text{ s}^{-1}$  (b) at temperature of 1000 °C and strain rate of  $1 \text{ s}^{-1}$  (c) at temperature of 1100 °C and strain rate of  $0.1 \text{ s}^{-1}$

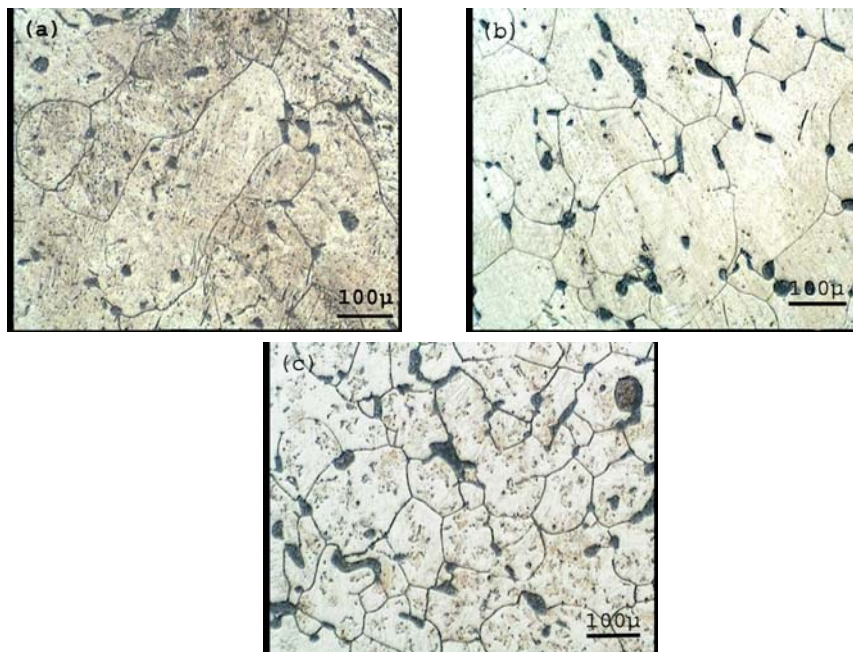


Fig.5. Micrographs of specimens tested at constant deformation condition (temperature of 1000 °C and strain rate of  $0.1 \text{ s}^{-1}$ ) and different interpass times of (a) 50 s (b) 100 s (c) 150 s

The time for 50% recrystallization is another criterion for assessing the kinetics of MDRX. The activation energy for occurrence of MDRX can be estimated by using the dependency of  $t_{0.5}$  on deformation temperature according to equation (4). Figs. 6 and 7 shows the dependencies of  $\ln t_{0.5}$  on  $1/T$  and  $\ln \dot{\epsilon}$ , respectively. As mentioned earlier and it's clear from these two figures,  $t_{0.5}$  decreases with increase in deformation temperature and strain rate. In regard to equation (4), the slope of Fig.6 is equal to  $Q_{\text{MDRX}}/R$ . Hence, the activation energy for MDRX was determined to be 191 kJ/mol. It should be noted that, the activation energy of MDRX is lower in comparison with that of DRX. Therefore, the former occurs more quickly than the latter. The power of  $\dot{\epsilon}$  in equation (4) is determined to be 0.33 by using Fig.8.

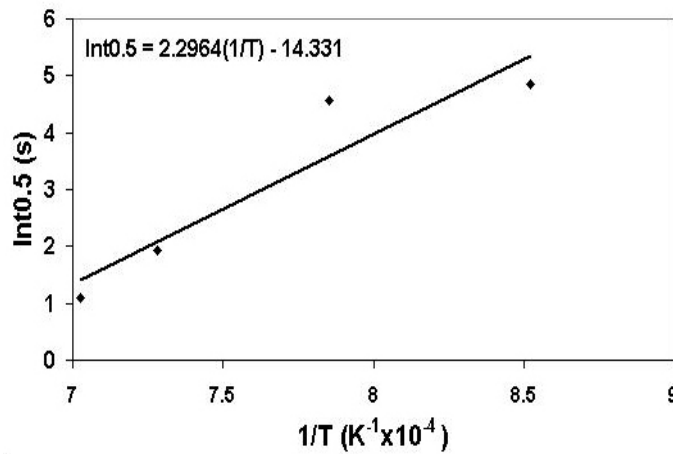


Fig.6. The dependence of  $\ln t_{0.5}$  on  $1/T$  for determination of  $Q$

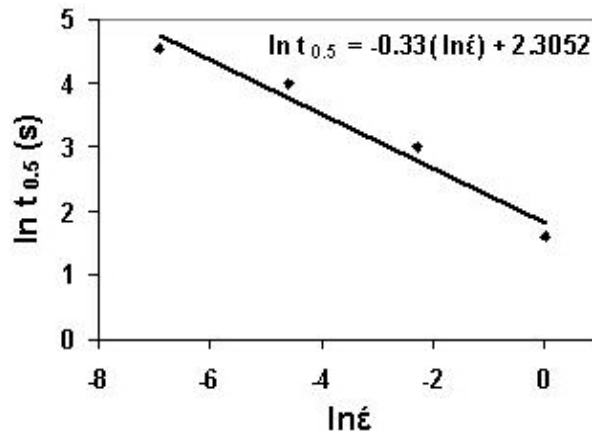


Fig.7. The dependence of  $\ln t_{0.5}$  on  $\ln \dot{\epsilon}$

On the basis of these numerical results the following equation can be proposed for  $t_{0.5}$ :

$$t_{0.5} = 1.73 \times 10^{-7} \dot{\epsilon}^{-0.33} \exp(191000/RT) \quad (7)$$

The difference between experimental values of  $t_{0.5}$  and predicted data is demonstrated in Fig. 8. As it's shown in this figure, there is a good agreement between experimental and predicted points.

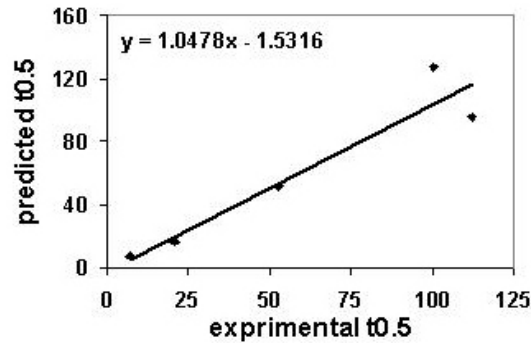


Fig.8. the accordance between predicted and experimental data

#### 4. CONCLUSION

1- It showed that fractional softening and kinetics of MDRX increases with strain rate and temperature.

2 - MDRX can be used for refining of grain structure of PH-stainless steels.

3 - For MDRX the JMAK equation was founded to be  $X_{MDRX} = 1 - \exp[-0.693(t/t_{0.5})]^{0.5}$ .

4- The Proposed equation to describe the kinetics of MDRX is  $t_{0.5} = 1.73 \times 10^{-7} \dot{\epsilon}^{-0.33} \exp(191000/RT)$ .

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