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# Investigation of Flow Stress Behavior of AISI 4340 Steel in Thermomechanical Process

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ABSTRACT

*In this study, flow stress behavior of AISI 4340 steel in thermomechanical process was investigated under temperature and strain rate ranges of 1173 to 1373 K and 0.01 to 1 $s^{-1}$, respectively. In flow curves, mechanisms such as work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) occurred. It was also discovered that the flow stress decreases with the increase of deformation temperature and the decrease of strain rate. Flow stress curves declared that in low-strain rate and high temperature, dynamic recrystallization overcome work hardening. Also, decreasing temperature led to dynamic recovery and incomplete dynamic recrystallization. Work hardening rate-stress curves depicted that the presence of a turning point expresses dynamic recrystallization mechanism and sub-boundaries are formed at the beginning of where a turning point occurs. In partial dynamic recrystallization, the microstructure was consisted of long grains reshaped because of deformation and some recrystallized grains that nucleated around those reshaped long grains. The results also indicated that at temperature of 1373 K, stress value of $\sigma_{sf}$, for strain rate of 0.01 $s^{-1}$ was increased from 27.8 MPa to 96.5 MPa and also for strain rate of 1 $s^{-1}$ and stress of $\sigma_c$ was increased from 32.3 MPa to 105 MPa. The significance of the approach used in this work was any increase in strain rate leads to accelerating dislocation movements. Therefore, dislocations will hit the barriers sooner and will be stopped and also, as a result of delayed dynamic recovery due to dislocations movements, dynamic recrystallization is also delayed.*

*Keywords: Flow stress; thermomechanical process; AISI 4340 steel, restoration mechanism, work hardening*

## INTRODUCTION

AISI 4340 alloy steel is largely employed in production of some crucial components such as power transmission gears and shafts, aircraft landing gear, and so forth. This steel is used in components with a lot of stress such as axles, engineering nut, fasteners and others.It is a sort of alloy enjoying heat treatable feature and thus, heat treatment processes like quenching and tempering are applied to this alloy so as to attain the desired hardness, strength, and ductility (Natasha et al. 2018).

Thermomechanical process (TMP) is an established and strategic method meant for strengthening the mechanical properties of steels via engineering their microstructures and currently, it is considered one of the most important industrial technologies which leads to making fine-quality steels featuring the required mechanical properties. The very first time that the TMP method was introduced dated back to the 1950s where controlled rolling was used for commercial production of C-Mn steel plates (Gong et al. 2016). Since then, this technique has gradually turned into an indispensable part of the controlled rolling, cooling and direct quenching of countless steel products, such as beams, plates, wires, pipes, sheets, bars, and rails (Cao et al. 2015; Gong et al. 2015; Nezakat et al. 2014; Kim et al. 2013; Kong et al. 2015). The sophisticated combination of precise deformation operations and precise heat treatment in a single stage to control the microstructure of materials is known as the main feature of this method (Zhao & Jiang 2018).

It is crucial to control main parameters such as strain rate and temperature as the hot deformation is ongoing. In fact, it guarantees a successful thermomechanical process in steels. As parts of this process, mechanisms such as work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) will occur simultaneously (Kim et al. 2001; Yang et al. 2017). Other than afore-mentioned parameters, there exist some other parameters like deformation temperature, inter pass times, strain rate and strain which must be carefully monitored in order to get desired results having required shape, microstructure, and mechanical properties.

Since the stacking fault energy of austenite is low, DRV kinetic is slow and as a result, the DRX process usually happens through hot forming of steels, which is triggered by reaching critical strain ($\varepsilon_c$). Generally, three kinds of curves for DRX flow have been introduced: single peak (Luton & Sellars 1969), multiple transient steady state (MTSS) (Mirzadeh et al. 2009; Mirzadeh & Najafizadeh, 2013) and cyclic (Sakai & Jonas, 1984; Dehghan-Manshadi

& Hodgson, 2007) behaviors, that are pertinent to the level of flow stress (strain rate and deformation temperature) and initial grain size (Mirzadeh et al. 2011; Saadatkia et al. 2015).

TABLE 1. Chemical compositions of 40NICRMO8-4 alloy steel

| %C | %Si | %Mn | %P | %S | %Cr | %Mo | %Ni | %V | %Al | %W |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.39 | 0.295 | 0.73 | 0.005 | 0.004 | 0.82 | 0.26 | 1.85 | 0.01 | 0.015 | 0.02 |

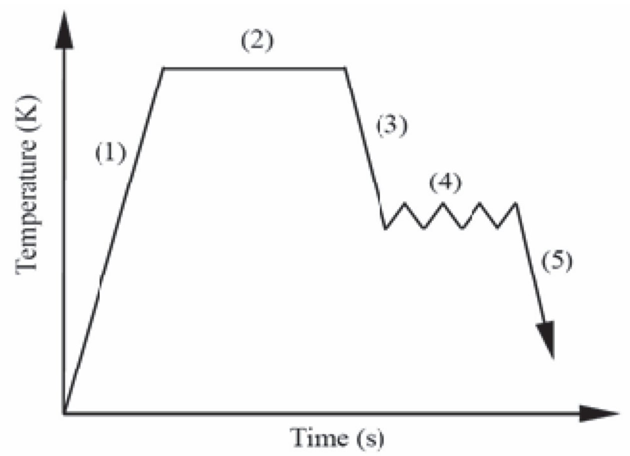



FIGURE 1. Schematic of hot compression procedure on the AISI 4340 alloy steel

This study aims to examine the thermomechanical process characteristics of AISI 4340 steel using hot compression test and the effects of deformation strain rates and temperatures. Flow stress data also is analyzed in terms of work hardening rate – stress plots.

## METHODOLOGY

The chemical compositions of AISI 4340 steel, produced in alloy steel Esfahan complex, are shown in Table 1. In this study, the thermomechanical process tests of 40NICRMO8-4 alloy steel were carried out at the temperature range of 1173-1373 K and strain rates varied from 0.01 to 1 $s^{-1}$ and a maximum strain of 0.9 on a dilatometer simulation machine.

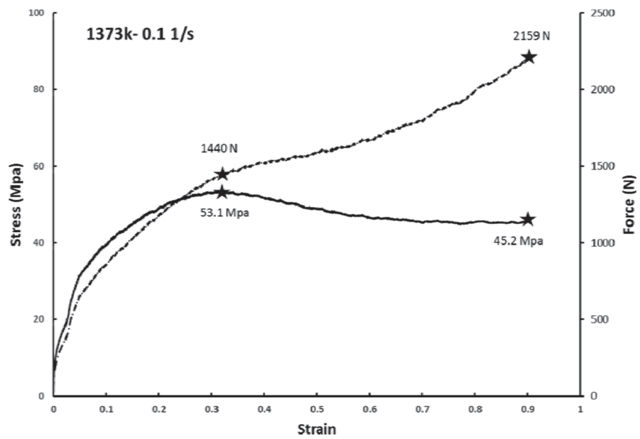
As can be seen in Figure 1, the following points are deducted: (1) Applied thermomechanical cycles to the samples comprise austenite treatment lasted 7.5 minutes at temperature point of 1423 k (2) cooling down to deformation temperatures of 1373, 1273, 1173 k and also, applying strain value of 0.9 while their strain rates were 0.01, 0. 1, 0.5, 1 $s^{-1}$ respectively. As final step, all specimens were cooled down from deformation temperature to ambient temperature with constant rate and in a specific period of time (5 minutes).

To observe the microstructure, the modified formations in the direction of the longitudinal and parallel with the axis of application of pressure were cut in the middle. Then they were subjected to sand blasting, polishing and etching.

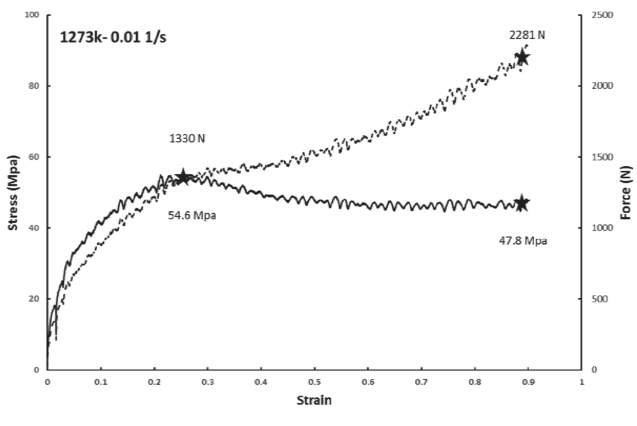
## RESULTS AND DISCUSSION

The dilatometer machine provides the results of the hot pressure tests in the form of true stress-strain curves and the true force-strain curves. The results of this experiment given by the dilatometer machine are illustrated in Figure 2.

By investigation of the curves shown in Figure 2, it can be observed that dynamic recrystallization occurs in a complete and classical manner under three conditions: at temperature of 1373K and strain rates of 0.01 and 0. 1 $s^{-1}$, as well as temperature of 1273K and strain rate of 0.01 $s^{-1}$. In fact, when the dilatometer applies force to the sample, work hardening occurs when stress value grows by increasing strain, and as a result, the density of dislocations increases continuously. For example, at temperature of 1273K and




(a)




(b)

FIGURE 2. True stress-strain curve of AISI 4340 steel on the:
a) temperature of 1373 K and strain rate of 0. 1 s-1
b) temperature of 1273 K and strain rate of 0.01 s-1

strain rate of 0.01 $s^{-1}$ (Figure 2(b)), in strain of about 0.24, tension is about 54.6 MPa, also, a force equal to 1330 N is applied.

During hot deformation, various mechanisms are carried out such as hardening (like work hardening) and restoration (including dynamic recovery and recrystallization). Work hardening mechanism usually occurs where temperature is low and strain rate is high.

This mechanism also occurs in the initial stages of strain even though the temperature is high and strain rate is low. During work hardening mechanism, as the strain grows, the density of dislocations increases and the flow stress in the true stress-strain curves increases with the continuation of the ascending trend of strain value. In this critical condition, the required motive force is provided for recrystallization during the deformation process. Therefore, the flow stress is reduced, and in a stable state with a constant amount of stress, work hardening mechanism is balanced with constant occurrence of dynamic recrystallization. In fact, the dynamic recrystallization process can be considered as continuation of the dynamic recovery process (Mcqueen & Ryan 2002).

In Figure 2 (b), the stress decreases due to activation of the softening mechanism while the strain increases because of applying more force. At this moment, the rate of dynamic recovery mechanism rate dominates the work hardening mechanism rate and stress reaches a value of 47.8 MPa in the strain of about 0.6, although the force is increasing to 2281 N. Since with the activation of the softening mechanism, the amount of deformation gets higher and easier to happen, thus, even with increasing force, stress does not follow this pattern and decreases. Also, it can be seen in figure 2 (a) that in temperature of 1373K and strain rate of 0.1, maximum stress is about 53.1 MPa and the steady-state stress is 45.2 MPa at maximum force of 2159 N while the maximum stress and steady-state stress at 1273K and the strain rate 0.01 $s^{-1}$ are 54.6 MPa and 47.8 MPa respectively.

In some other curves, as in Figure 3, the steady state for stress does not occur after decreasing from maximum point of 98 MPa, and the stress reaches 87.4 MPa at the end of the applied strain of 0.9. This can be attributed to the small amount of the applied strain, which leads to not seeing a complete and classic dynamic recrystallization. In this condition, the force is at its maximum value of 4201 N. Hence, it can be stated that dynamic recrystallization has been activated, but partially, which ultimately does not show a steady state for stress in such curves. That is the same for true stress-strain curves such as temperature of 1373K and strain rate of 1 $s^{-1}$, temperature of 1273K and strain rate of 0.1 $s^{-1}$ and temperature of 1373K and strain rate of 0.5 $s^{-1}$.

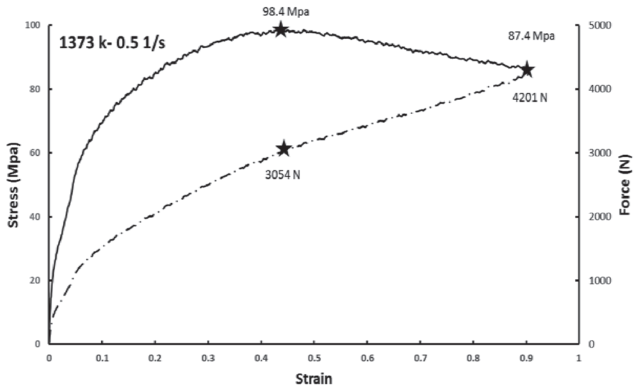



FIGURE 3. True stress-strain curve of AISI 4340 steel at the temperature of 1373 K and strain rate of 0.5 S-1.

Another type of stress-strain curves can be seen in Figure 4. For example, in the temperature of 1273 K and the strain rate 1 $s^{-1}$, after increasing stress in the strain initial state, when strain value becomes about 0.62, stress reaches its maximum value of 148.9 MPa and remains constant at this stress level until the end of the applied strain (0.9). According to the presented information at the beginning of this section, it can be said that the restoration process which led to fix stress and achieving balance with the work hardening rate is a dynamic recovery mechanism.

In another discussion on the amount of the applied force, it can be observed that the lower the temperature and higher the strain rate, the higher force is required for the strain of about 0.9, which indicates that at low temperatures and high strain rates, material resistance against deformation is larger and more force is required to reach desired strains. After thoroughly investigating true stress-strain curves given in this section, the results of this investigation has been tabulated clearly in Table 2.

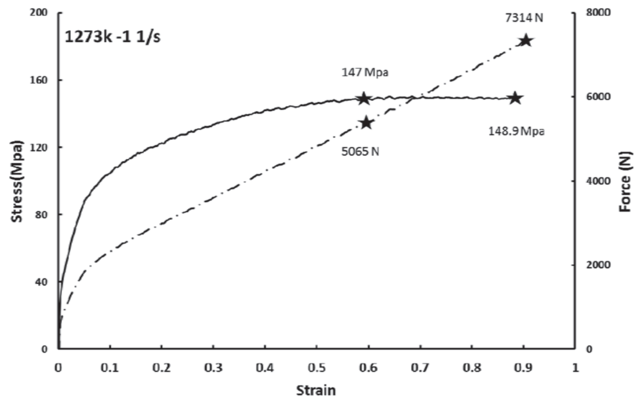



FIGURE 4. True stress-strain curve of AISI 4340 steel on the temperature of 1273 K and strain rate of 1 s-1.

TABLE 2. Experimental results

| $\varepsilon°(s^{-1})$ | T(K) | Softening Mechanism | $F_{Max}(N)$ | $\sigma_{Max}(N/mm^2)$ |
|---|---|---|---|---|
| 0.01 | 1373 | Dynamic recrystallization (steady state) | 1448 | 35.7 |
| | 1273 | Dynamic recrystallization (steady state) | 2281 | 54.6 |
| | 1173 | Dynamic recrystallization (non-steady state) | 4361 | 92.5 |
| 0.1 | 1373 | Dynamic recrystallization (steady state) | 2159 | 53.1 |
| | 1273 | Dynamic recrystallization (non-steady state) | 4611 | 107 |
| | 1173 | Dynamic Recovery | 8217 | 167.9 |
| 0.5 | 1373 | Dynamic recrystallization (non-steady state) | 4201 | 98.4 |
| | 1273 | Dynamic Recovery | 6618 | 136.7 |
| | 1173 | Dynamic Recovery | 9661 | 195.4 |
| 1 | 1373 | Dynamic recrystallization (non-steady state) | 4764 | 106.1 |
| | 1273 | Dynamic Recovery | 7314 | 148.9 |
| | 1173 | Dynamic Recovery | 9801 | 199.8 |

### WORK HARDENING RATE-STRESS CURVES

For calculating the values of work hardening rate Equation 1 was used (Mirzadeh & Najafizadeh 2010):

$$\text{work hardening rate} = \left.\frac{d\sigma}{d\varepsilon}\right|_i = \frac{\sigma|_{i+1} - \sigma|_{i-1}}{\varepsilon_{i+1} - \varepsilon_{i-1}} \quad (1)$$

Work hardening rate parameter after being calculated based on stress is shown in Figure 5. According to this figure, it can be said that the dominant mechanism in all different conditions of deformation is dynamic recrystallization mechanism. In these curves, the presence of a turning point expresses dynamic recrystallization mechanism (Rajabi 2018). And also, the scope of this change in curve trajectory at turning points must be considered after the dominant mechanism has been determined. Sub-boundaries are being formed at the beginning of a turning point, which represents the start of dynamic recovery. Likewise, the end of this zone shows the end of dynamic recovery and the start of activation of dynamic recrystallization process.

Therefore, we can conclude that at 1173 K and strain rate of 0.1, 0.5 and 1 $s^{-1}$, the dynamic recovery mechanism is not the dominant mechanism, but the mechanism of dynamic recrystallization is. To back-up this statement, we can refer to microstructure studies.

As can be seen in Figure 6, in all conditions of the afore-mentioned deformations, the process of dynamic recrystallization has been occurred, but partially and not complete and classical. Under these conditions, the microstructure consists of long grains reshaped because of deformation and some recrystallized grains that nucleated around those reshaped long grains. But, there was not enough strain to make these nucleated grains grow or producing fresh nucleated grains (Mohammed et al. 2014).

In such curves, as stress increases, the lower will become work hardening rate until it reaches the turning point. At this moment, dislocations density has reached to a peak level resulting in activation of the recovery mechanism with creating sub-boundaries to cancel out positive and negative dislocations. However, since the recovery rate is not enough, dislocations density continues growing until reaching its critical point to be able to trigger recovery mechanism of dynamic recrystallization.

As an example, in Figure 5 which illustrates the outcome for temperature of 1173K and strain rate of 0.1 $s^{-1}$, turning point region starts from stress of 140.7 MPa and ends at 156 MPa. Hence, 156 MPa of stress is considered as the start point of dynamic recrystallization at strain of 0.43.

In Figures 7, work hardening rate fluctuations have been drawn as a series of strain rates for a specific temperature and a series of deformation temperatures at a fixed strain rate. As can be seen in Figure 7, increasing temperature leads to shift the work hardening rate curve to the left and as a result, turning points appear in lower stress values.

An increase in temperature as well as reduction of stress and strain values lead to early formation of sub-boundaries and beginning of dynamic recrystallization. As the dynamic recrystallization is made with convexity of grain boundaries procedure mechanism and nucleation and growth, and also, since the temperature controls both of these mechanisms, with any increase in temperature, it is noticed that these mechanisms speed up. In fact, with temperature growth, atoms' activities get stronger and therefore, the main centers

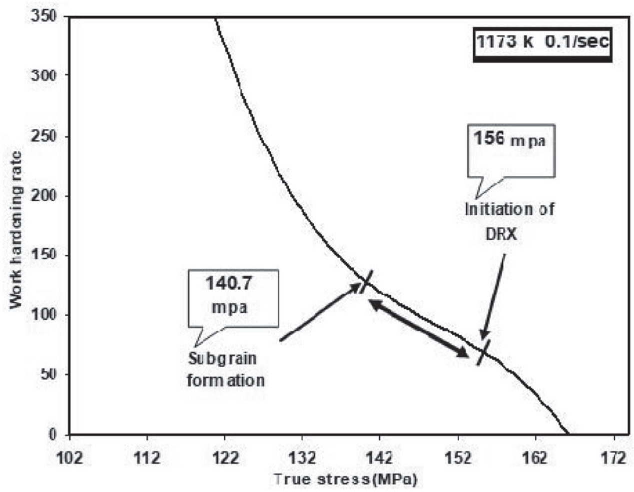



FIGURE 5. Work hardening rate- stress curve of AISI 4340 steel in temperature of 1173K and strain rate of 0.1 $s^{-1}$

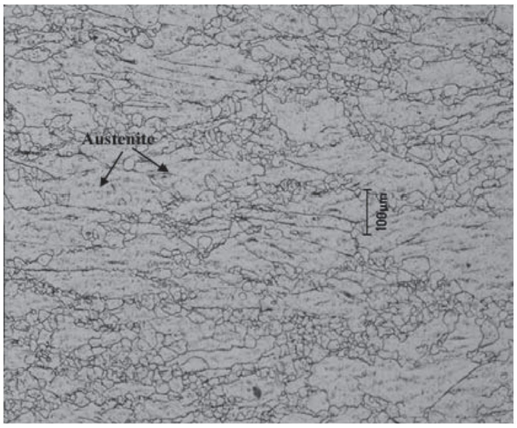



FIGURE 6. Grain austenite microstructure of AISI 4340 in temperature of 1173 K and strain rate of 0.1 $s^{-1}$ at magnification 100x

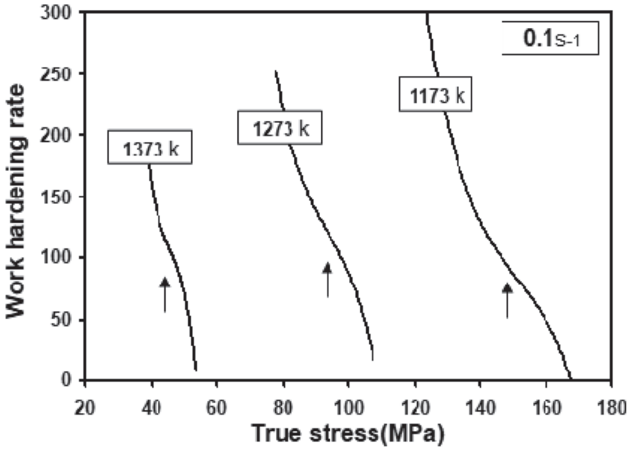



FIGURE 7. Work hardening rate-stress curves of AISI 4340 steel in temperature of 1173 K to 1373 K and strain rate of 0.1 $s^{-1}$

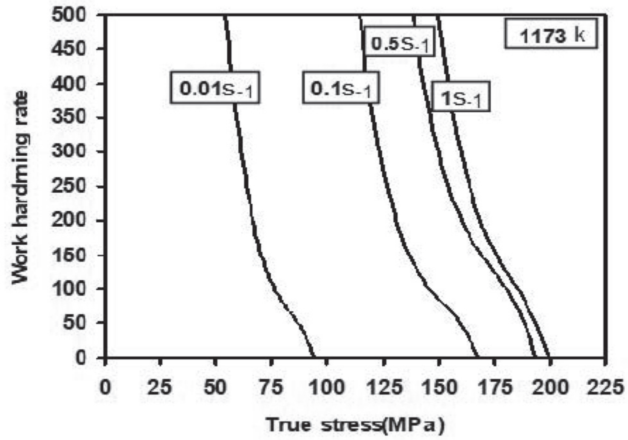



FIGURE 8. Work hardening rate-stress curves of AISI 4340 steel in temperature of 1173 K and strain rate of 0.1-1 $s^{-1}$.

of the nucleation recrystallization and sub-boundaries are formed quicker.

From another point of view, increment of strain rate leads to accelerating dislocation movements and therefore, dislocations will hit the barriers sooner and will be stopped. On the other hand, strain rate increase causes a decrease in cross-slipping screw dislocations which plays significant role in recovery process. Since dynamic recrystallization follows dynamic recovery process and during dynamic recrystallization, new grains are made at formed sub-boundaries due to the dynamic recovery process, and also, as a result of delayed dynamic recovery because of dislocations movements, dynamic recrystallization is also delayed. As an example, at temperature of 1373 K, stress value of $\sigma_{sf}$, for strain rate of 0.01 $s^{-1}$ increases from 27.8 MPa to 96.5 MPa and also for strain rate of 1 $s^{-1}$, strain of $\sigma_c$, increases from 32.3 MPa to 105 MPa.

Sandrom and Lagenberg introduced a model to explain the strain rate effect on the afore-mentioned changes (Mirzadeh & Najafizadeh, 2010; Saadatkia et al. 2015). This model states that the critical condition for triggering the dynamic recrystallization at a fixed temperature is that presents the dislocations density inside a grain) reaches to an specific value ($\varepsilon = \varepsilon_c$). So, it can be claimed that with increment of strain rate, required critical density for starting dynamic recrystallization also increases and consequently, required strain for this phenomenon to occur will also rise.

## CONCLUSION

The thermomechanical process characteristics of AISI 4340 steel have been investigated by using hot compression test under the temperature range of 1173-1373 K and strain rate range of 1- 0.01 $s^{-1}$. The results revealed that the flow stress of AISI 4340 steel increases when the strain rate increases whilst deformation temperature decreases. Although work hardening mechanism typically occurs at high strain rates and low temperatures, this mechanism also occurs in the initial stages of strain even when the temperature is high and strain rate is low. Flow stress curves also showed that in low strain rate and at high temperature, dynamic recrystallization overcome work hardening. Also any decrease in temperature leads to dynamic recovery and incomplete dynamic recrystallization. An increase in temperature as well as reduction of stress and strain values leads to early formation of sub-boundaries and beginning of dynamic recrystallization. The information provided by work hardening rate plots was used to discover the critical conditions for the onset of DRX and also, other characteristic points of flow curves. For example, in temperature of 1173 K and strain rate of 0.1 $s^{-1}$, 156 MPa of stress is considered as the start point of dynamic recrystallization at strain of 0.43. Any increase in strain rate leads to accelerating dislocation movements and therefore, dislocations will hit the barriers sooner and will be stopped. In addition, as a result of delayed dynamic recovery because of dislocations movements, a dynamic recrystallization is also delayed.

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