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Hot Deformation and Recrystallization of Austenitic Stainless Steel: Part II. Post-deformation Recrystallization

A. DEGHAN-MANSHADI, M.R. BARNETT, and P.D. HODGSON

The postdeformation recrystallization behavior of a hot-deformed austenitic stainless steel was investigated based on the first part of this study, in which the microstructure development during hot deformation and, in particular, the evolution of dynamic recrystallization (DRX), was studied. The effect of different parameters such as strain, strain rate, and temperature were examined. The dependency of the time for 50 pct softening, t_{50} , changed from “strain dependent” to “strain independent” at a transition strain (ϵ^*) that was in the steady-state area of the hot deformation flow curve. The fully recrystallized microstructure showed a similar transition in strain sensitivity. However, this occurred at strains greater than ϵ^* . A mathematical model was developed to predict the transition strain under different deformation conditions. Microstructural measurements show that the transition strain corresponds to approximately 50 pct DRX in the deformed structure at the point of unloading.

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I. INTRODUCTION

RECRYSTALLIZATION during the interpass times and after hot deformation plays a major role in microstructure evolution during hot rolling. Three different mechanisms are believed to be responsible for restoration after deformation, or during intervals between deformations. These are static recovery (SRV), static recrystallization (SRX), and postdynamic recrystallization (post-DRX).^{*} Also, after complete

^{*}This is often termed metadynamic recrystallization (MDRX), a term that here will be taken to represent recrystallization by the static growth of nuclei formed during DRX.

recrystallization, grain coarsening will take place in the recrystallized structure. However, in austenite, recovery plays a significant role only in slightly deformed structures or during the early stages (*i.e.*, short times of annealing) of restoration for heavily deformed microstructures. In the latter case, between 10 and 20 pct of the softening of the microstructure is by recovery. The recrystallization following deformation is usually termed SRX or post-DRX, for the nucleation and growth of new grains or the growth of DRX nuclei, respectively. A combination of any two or more of these mechanisms is possible under different conditions.

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The hot deformation conditions (*i.e.*, strain, strain rate, and temperature) have different effects on each recrystallization process. Strain has been shown to have little effect on the rate of post-DRX,^[1–3] such that the kinetics of post-DRX are considered to be strain independent. In contrast, the SRX kinetics are often expressed as a power-law function of strain.^[1–6] The strain to the peak stress (ϵ_p) has usually been used to separate between SRX and post-DRX. Once the applied strain is larger than the peak strain, post-DRX takes place during the softening and it does not vary by strain. It has been proposed^[2] that all the nuclei are presented at the end of deformation to the peak strain, and further deformation does not lead to any additional nuclei. Therefore, at strains beyond the peak, softening is strain independent. At strains lower than the peak, a complex combination of static and post-DRX occurs, and the softening is a power-law function of strain.

It has been shown that post-DRX is largely dependent on strain rate^[2,7–10] and weakly dependent on temperature^[2,7] and composition, whereas SRX is a strong function of both temperature and grain size and depends only weakly on strain rate.^[1,11,12] However, the strain rate did not appear to affect the general shape of the softening curve.

Due to the difficulty in discriminating between these two types of recrystallization (*i.e.*, SRX and post-DRX), the nature of softening as a function of strain can be used to explain the different types of recrystallization. Usually, the terms “strain-dependent” and “strain-independent” softening behavior are used to follow different types of recrystallization (or softening). The strain at which the softening behavior (*i.e.*, the time for 50 pct softening, t_{50}) changes from strain dependent to strain independent has been called the “transition strain” (ϵ^*).

In this work, the postdeformation softening behavior of austenite, using a 304 austenitic stainless steel, has been examined as a function of its deformed state

(from Part I). The effect of deformation parameters, including temperature, strain, and strain rate, as well as annealing time, on both the softening behavior and the microstructure development have been studied. A kinetic model has also been developed to predict the softening behavior of the material in both the strain-dependent and strain-independent regions.

II. EXPERIMENTS

The postdeformation behavior of AISI 304 austenitic stainless steel, with a chemical composition of Fe-0.02 pct C-1.6 pct Mn-8.2 pct Ni-18.5 pct Cr-0.8 pct Cu, was investigated using double twist tests on the hot torsion machine under different conditions of prestrain (ε), temperature (T), strain rate ($\dot{\varepsilon}$), and annealing time (t). Torsion samples with a gage length of 20 mm and a diameter of 6.7 mm were machined from the rolled bars. The details of the hot torsion equipments and experimental methods have been described elsewhere.^[7] After the same roughening process as described in Part I, the samples were cooled at $1\text{ }^{\circ}\text{C s}^{-1}$ to various temperatures in the range $900\text{ }^{\circ}\text{C}$ to $1100\text{ }^{\circ}\text{C}$, held for 2 minutes, and deformed to different strains at different strain rates. The samples were then unloaded and maintained for different times** at their deformation temperature.

**In the rest of this work, the delay time between two deformation passes or between deformation and quench is termed the “unloading time.”

Thereafter, two series of tests were performed. In the first series, the samples were directly (in less than 0.5 seconds) quenched for microstructural investigations (using electron backscattered diffraction (EBSD)); in the second series, they were deformed to a small strain of 0.2 (or more), to measure the softening fraction.

The relative softening during unloading was determined using the offset flow stress method and the following equation:

$$X(\text{pct}) = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \times 100 \quad [1]$$

where σ_m is the stress at the end of the first deformation, and σ_1 and σ_2 are the 0.2 pct offset yield stress for the first and the second deformation, respectively.

To investigate the post-DRX microstructure, the quenched samples were analyzed by EBSD. The EBSD studies were performed under an accelerating voltage of 20 kV, a working distance of 25 mm from the gun, and an aperture size of $60\text{ }\mu\text{m}$. The EBSD maps were analyzed using HKL technology Channel 5 software (HKL TECHNOLOGY INC., Denmark).

III. RESULTS

A. Flow Curves

The data deduced from single twist tests in Part I were used to select the appropriate strains in the range of

Fig. 1—Double twist flow curves of samples deformed at $900\text{ }^{\circ}\text{C}$ and a strain rate of 0.01 s^{-1} for strains of (a) 0.6, (b) 1.0, and (c) 2.0.

$\varepsilon < \varepsilon_c$ (critical strain) to $\varepsilon > \varepsilon_{ss}$ (steady-state strain), so that static or post-DRX occurs during the unloading times.

Examples of double twist curves at a deformation temperature of $900\text{ }^{\circ}\text{C}$ and a strain rate of 0.01 s^{-1} for different unloading times after a given strain are

presented in Figure 1. For a prestrain smaller than the peak (Figure 1(a)), little softening happened during short unloading times (*i.e.*, 20 seconds), and the second twist curve continued the trend of the first curve with a small drop in the stress. In this case, the peak strain (the sum strain of the first and second twists) was very close to the peak strain of a sample deformed continuously (*i.e.*, $\varepsilon_p \sim 0.8$). By increasing the unloading time to 90 seconds, more softening occurred in the deformed structure, and the second curve dropped further compared to the previous test. However, the difference between the second twist flow curves in the two conditions (*i.e.*, 20- and 90-second unloadings) was small. This indicates that the softening rate in this condition (prestrain of 0.6) is very low. As the DRX fraction after deformation to a strain of 0.6 is very limited (Figure 7(b) in Part I), the number of DRX nuclei growing during the unloading period is low. Therefore, the dominant recrystallization mechanism in this condition will be a classical nucleation and growth process, which needs an incubation time to start and is also very strain dependent. Increasing the unloading time to 300 seconds caused a large softening of the deformed structure by recrystallization. As a result, the second twist curve dropped significantly and a large amount of work hardening occurred during the second twist, where a peak is also visible.

By increasing the prestrain to a strain of 1.0 (Figure 1(b)), which is greater than the peak strain, softening after 20 seconds of unloading was still limited and the flow curve continued to the steady state. However, by increasing the unloading time to 90 seconds, the flow stress of the deformed microstructure was significantly decreased through recovery or recrystallization, and the second twist curve showed a higher work hardening with a faint peak. Both a higher work-hardening rate and peak are more visible when the unloading time was increased to 300 seconds.

After a prestrain of 2.0 (Figure 1(c)), which is in the steady-state region of the flow curve, the work hardening and presence of a peak in the second twist curve are more obvious, especially for longer unloading times of 90 and 300 seconds. In these cases, the peak strain and stress of the second twist are considerably smaller than the first twist. These reductions in σ_p and ε_p can be ascribed to grain refinement during postdeformation recrystallization (unloading) and its effect on DRX during the second twist.^[13,14] As shown later in this work, the postdeformation recrystallized grain size under the current deformation condition is much smaller than the initial grain size. Therefore, the DRX of the former structure (*i.e.*, second twist) starts at a strain lower than that of the initial structure (*i.e.*, first twist).

B. Softening Curves

The softening fraction was measured using the offset flow stress method and the results for a deformation at 900 °C and a strain rate of 0.01 s⁻¹ are presented in Figure 2. The time to attain 50 pct softening (t_{50}) is widely used to characterize the softening behavior (Figure 3). The time for 20 and 90 pct softening are

Fig. 2—The softening fraction as a function of time for different strains ($T = 900\text{ }^{\circ}\text{C}$ and $\dot{\varepsilon} = 0.01\text{ s}^{-1}$).

Fig. 3—Dependency of time for 20, 50, and 90 pct softening to strain at 900 °C and a strain rate of 0.01 s⁻¹.

also added to this plot, as this provides information regarding the practical start and finish of recrystallization, respectively (20 pct is the typical level of recovery, while the layering effect in torsion can make it difficult to determine the exact end of softening in the outer layers of the specimen). As expected, the time to 50 pct softening decreases with increasing strain (strain-dependent behavior), until the transition strain (ε^*), at which softening becomes strain independent. The transition strain for this deformation condition is far beyond the peak strain. This is somewhat in contrast to the results of other workers, in which it has been proposed that strain-independent softening starts at strains near the peak or the critical strain for the initiation of DRX.^[1,2,4-6]

The deformation parameters (*i.e.*, strain rate and temperature) showed different effects on each region. For a given strain, the t_{50} increased with decreasing strain rate (Figure 4). However, the effect of the strain rate at very low prestrains was low, and increased with increasing strain. The effect of the strain rate was very pronounced in the strain-independent region (at strains higher than the

Fig. 4—Effect of strain rate on time for 50 pct softening at a constant temperature of 900 °C.

Fig. 5—Effect of temperature on time for 50 pct softening at a constant strain rate of 0.01 s⁻¹.

ε^*). However, temperature showed an opposite effect, in both the strain-dependent and strain-independent regions (Figure 5). As expected, an increase in temperature decreased the time to attain 50 pct softening for both strain-dependent and strain-independent regions. Here, the temperature effect on the strain-dependent region is much greater than for the strain-independent region, where there is only a small effect of temperature. This is in agreement with other workers, who found that the temperature sensitivity of SRX is strong^[4] but is negligible for the MDRX kinetics.^[1,2]

C. Post-DRX Microstructure

Microstructural investigations were performed to gain more insight into softening and recrystallization phenomena after hot deformation. For this purpose, different unloading times were selected to obtain 20, 50, and 90 pct softening after different strains. The microstructures were analyzed by EBSD and compared with the deformed and quenched microstructures from Part I of this work.

For a prestrain lower than the critical strain of DRX (*i.e.*, $\varepsilon = 0.4$), at which the initial microstructure consisted of some slightly elongated grains with finely serrated boundaries (Figure 6(a)), a very limited number of small grains formed on the serrated boundaries after a short time (Figure 6(b)). As this strain is lower than the critical strain for the initiation of DRX ($\varepsilon < \varepsilon_c$), it can be expected that these new grains formed through a classical nucleation and growth process (*i.e.*, SRX phenomenon). As the stored energy in this slightly deformed material was not high enough (low dislocation density), the formation of new small grains (*i.e.*, fresh nucleation) did not continue with longer unloading times. Rather, the small recrystallized grains started to grow and, after 50 pct softening, most disappeared from the microstructure (Figure 6(c)). With an increase in the unloading time to 1200 seconds (90 pct softening), the deformed structure was replaced by an equiaxed and large-grained microstructure (Figure 6(d)).

After deformation to a strain just beyond the ε_c , at which a small fraction of DRX grains were formed during deformation (Figure 6(e)), short unloading times led to an increased number of small grains (Figure 6(f)) through postdeformation recrystallization. This was especially obvious around the serrated pre-existing grain boundaries. With increasing holding time, more new grains were formed inside the initial deformed grains, possibly by classical nucleation and growth phenomenon (*i.e.*, SRX). On the other hand, it seems that the small grains, which formed during DRX or earlier stages of unloading, also started to grow (Figure 6(g)). Finally, a nearly equiaxed microstructure was obtained after 90 pct softening (Figure 6(h)). However, this microstructure was finer than the previous condition.

At a prestrain just beyond the peak (*i.e.*, $\varepsilon = 1.0$), where a relatively high fraction of new DRX grains are formed on the serrated pre-existing grain boundaries during the hot deformation (Figure 6(i)), the microstructure after a short unloading time (20 pct softening) consisted of elongated work hardened initial grains and a large number of small grains (Figure 6(j)). It seems that the number of these small grains is considerably higher than the DRX grains in the deformed structure. These small grains in the 20 pct softened microstructure consisted of both DRX and newly (postdeformation) recrystallized grains. The latter grains may have grown from the DRX nuclei available at the end of deformation (*i.e.*, post-DRX phenomenon), or formed during a classical nucleation and growth process (*i.e.*, SRX phenomenon). With increasing unloading time (50 pct softening), it seems that the number of small grains slightly decreased and a small amount of growth was also observed in these grains (Figure 6(k)). On the other hand, the initial elongated grains started to change to equiaxed grains, through the formation of new grains by SRX. After holding for longer times (90 pct softening) the microstructure was replaced by larger grains and a more homogeneous microstructure was obtained (Figure 6(l)).

By increasing the prestrain to the strain-independent region (*i.e.*, $\varepsilon = 2.0 > \varepsilon^*$), where most of the initial microstructure was replaced by new small DRX grains

Fig. 6—EBSD maps of samples deformed at 900 °C to different strains and held for different times after deformation ($\dot{\epsilon} = 0.01 \text{ s}^{-1}$), to produce softening levels of 20, 50, and 90 pct.

formed during the hot deformation (Figure 6(m)), postdeformation softening proceeded rapidly and 20 pct softening occurred after a very short unloading time (25 seconds). The number of small grains in this

microstructure (Figure 6(n)) had slightly increased compared with the deformed microstructure and had replaced nearly all of the initial microstructure that had not been recrystallized during deformation. As is

Table I. Softening Mechanisms of Material Deformed to Different Strain Regions

Strain Range	Softening < 20 pct	Softening 20 to 50 pct	Softening > 50 pct
$\varepsilon < \varepsilon_c$	recovery, SRX	SRX, grain growth	grain growth
$\varepsilon_c < \varepsilon < \varepsilon^*$	recovery, post-DRX	post-DRX, SRX, low grain growth	grain growth
$\varepsilon > \varepsilon^*$	post-DRX, low recovery	post-DRX, low recovery, low grain growth	grain growth

clear from Figure 6(n), the fraction of nonrecrystallized grains in this microstructure is negligible. The microstructure at 50 pct softening (Figure 6(o)) shows evidence of limited grain growth for some of the small grains. However, the difference between this microstructure and the 20 pct softened microstructure is negligible. This is one of the interesting features of this work, in which there is a large amount of softening but with relatively little microstructural change. While one possibility is that recovery could be responsible for this, another possibility is that there is recrystallization occurring, but the difference between the static, dynamic, or even the postdynamic grain sizes is small. Considerable grain growth occurred when the holding time was increased to achieve a 90 pct softened sample in which the grain size was much greater than the DRX average grain size (Figure 6(p)).

A comparison between these observations shows that the microstructural development during the unloading of a deformed structure strongly depends on the strain (at a constant temperature and strain rate). After any strain smaller than the critical strain of DRX, ε_c , a low level of recrystallization nucleation (*i.e.*, formation of new grains) was observed. These new grains were probably formed through the classical nucleation and growth (*i.e.*, SRX). When the strain increased to the strain-independent region, softening may start by post-DRX and then continue by grain growth (*i.e.*, migration of recrystallized grain boundaries). However, the low level of general microstructural change during softening from 20 to 50 pct indicates either that there are some internal changes in the microstructure (such as recovery) or that it is not possible to distinguish between the various events taking place. For any strain in between (*i.e.*, $\varepsilon_c < \varepsilon < \varepsilon^*$), softening has occurred by post-DRX, SRX, and the subsequent grain growth. It seems that softening was started by the growth of DRX nuclei (*i.e.*, post-DRX), which were mostly located on the serrated pre-existing grain boundaries. It then continued (after an incubation time) through the nucleation and growth of new grains (*i.e.*, SRX) inside the deformed initial grains. Finally, the recrystallized grain boundaries started to grow (grain growth). However, an overlap area between the different softening mechanisms is expected. The softening mechanisms after hot deformation of the present material can be summarized as shown in Table I.

IV. DISCUSSION

The results of the present work showed the major effect of the deformation conditions, including temperature,

strain rate, strain, and unloading time, on the postdeformation softening behavior; implicit in this is the state of the initial microstructure at the point of unloading. The time for 50 pct softening, t_{50} , has often been used to characterize the softening behavior under different deformation conditions. As the distinction between the postdeformation recrystallization mechanisms (*i.e.*, static and MDRX), which have usually been used in the literature to explain the softening behaviors of a deformed material, is not simple and accurate (there is always an overlap area between those two phenomena), the postdeformation softening has been characterized based on the dependency of the rate of recrystallization on the strain. For all deformation conditions, the t_{50} curves (*i.e.*, t_{50} vs strain) showed two very different regions. In the first region, the softening behavior is strain dependent and t_{50} decreased with increasing strain. However, in the second region (*i.e.*, strain-independent), which starts at a transition strain, ε^* , the softening behavior no longer depended on the strain and, hence, the time for 50 pct softening remained constant with increasing strain. The effect of deformation parameters in each region is different. While the strain rate showed a pronounced effect on the strain-independent area, its effect on the strain-dependent region was much lower (Figure 4). However, the effect of temperature on the strain-independent region was more significant than in the other region (Figure 5).

The reason for the transition from strain-dependent to strain-independent behavior has been the subject of several investigations over the past decade.^[14–16] Although the essential required conditions for this transition are not well understood, it seems that the strain-independent behavior is available only when the deformed microstructure consists of an adequate fraction of DRX grains.

The mechanism of postdeformation recrystallization can also play an important role in this transition. Three different mechanisms of SRV, SRX, and metadynamic (or postdynamic) recrystallization are proposed as possible mechanisms for restoration of a deformed structure. The extent of the contribution of each mechanism changes according to the strain (or microstructure). Recovery will be the dominant restoration for a lightly deformed structure, but this is likely to be negligible in the present material which has very low stacking fault energy (SFE).

It has been proposed that for a material deformed to any strain lower than the critical strain for initiation of DRX (*i.e.*, ε_c), SRX is the sole restoration mechanism (with the exception of recovery) during annealing (or unloading).^[17,18] On the other hand, when the strain exceeds ε_c , post-DRX can also contribute in the

softening of the deformed material.^[1,19] In many studies, it has been proposed that when the post-DRX is the softening mechanism, the softening behavior changes from strain dependent to strain independent.^[1,15] However, the softening measurements (Figures 2 through 5) and microstructural observations (Figure 6) in this study indicate that the traditional classifications for postdeformation softening behavior are not sufficiently accurate and other factors such as the fraction of DRX grains formed during deformation (and probably the dislocation density of the deformed structure) can influence the softening mechanisms and the transition behavior. This means that there is always an overlap between the regions of SRX and post-DRX.

To study the role of SRX and post-DRX in softening of a deformed material, three different regions can be labeled in the softening curves (Figure 3). During the initial stages of hot deformation in stage I (*i.e.*, at $\varepsilon < \varepsilon_c$), in which no DRX nuclei are available, softening can proceed through the classic nucleation and growth of new grains on serrated pre-existing grain boundaries or on the deformation features inside the grains (*i.e.*, the SRX mechanism). Since the driving force is the stored energy of deformation and, as this stored energy increases with increasing strain, the significant influence of strain on softening kinetics in this area ($\varepsilon \leq \varepsilon_c$) is expected.

As the applied strain exceeds ε_c , some DRX nuclei are formed in the deformed structure. The density of these nuclei increases with increasing strain. As the serrated initial grain boundaries are the most important sites for the initiation of those DRX nuclei, it can be concluded that the density of the nuclei can increase, while some noncovered (by DRX grains) initial grain boundaries are still present in the microstructure. It has been proposed that increasing the density of DRX nuclei will stop at a specific strain,^[2,16] at which the density of DRX nuclei reaches a saturation point. The results in Part I of this work showed that, under current deformation conditions (*i.e.*, $T = 900^\circ\text{C}$ and $\dot{\varepsilon} = 0.01\text{ s}^{-1}$), almost all the initial grain boundaries are covered by DRX grains when the strain increases to 1.5. As the serration of DRX grain boundaries was not commonly observed during deformation, the formation of new DRX nuclei on the existing DRX grain boundaries is less likely. However, the formation of new DRX nuclei inside the deformed grains (grain interior) can continue by further deformation, the frequency of which is very low compared to grain boundaries. Therefore, it can be concluded that the density of DRX nuclei, and probably the dislocation density, has reached a saturation value at $\varepsilon = 1.5$, which is the start of the strain-independent region. These DRX nuclei can grow during the unloading and, therefore, the post-DRX mechanism can be considered as the most important restoration mechanism in the strain-independent area (region III). However, the contribution of both SRX and post-DRX mechanisms in the softening process of a material deformed to any strain in the range of $\varepsilon_c < \varepsilon < \varepsilon^*$ (*i.e.*, region II) is likely.

Figures 2 and 3 showed that the transition strain strongly depends on temperature and weakly on strain

Fig. 7—DRX fraction at transition strain as a function of Z .

rate. Most researchers^[2,3,5] have previously shown that the transition strain is very close to the peak strain (ε_p), although some studies suggest a transition strain of 1.3 to 1.7 times the peak strain.^[10,19,20] Other recent work for an high strength low alloy (HSLA) steel showed that the ratio of transition to peak strain can vary widely as the ratio of the DRX to the initial grain size changed.^[21] However, the current study showed a tight relationship between the transition strain and DRX fraction. Figure 7 shows that ~50 pct DRX corresponded with the transition from strain-dependent to strain-independent behavior. As discussed previously, this 50 pct volume fraction of DRX also corresponds to the decoration of all the pre-existing grain boundaries by the new DRX grains.

The results of the softening measurements under different deformation conditions showed a strong relationship between the transition strain and the Zener–Hollomon parameter (Figure 8), as previously suggested by Hodgson *et al.*^[15] However, this dependency with Z was very complex.

It can be concluded from this discussion that the volume fraction of DRX in the deformed structure has the strongest influence on the transition from strain-dependent to strain-independent behavior. This means that the SRX and MDRX mechanisms, which were proposed for strain-dependent and strain-independent regions, respectively, are not the sole factors determining the softening behavior, as the conditions for both mechanisms will be available during deformation for any strain in the range of $\varepsilon_c \leq \varepsilon \leq \varepsilon^*$, in the strain-dependent area. Further, the transition from strain-dependent to strain-independent behavior has a complicated relationship with strain rate and temperature.

A. Recrystallization Kinetics

As seen in Figure 2, the softening fraction as a function of unloading time at different applied strains has an S-type curve. This means that an Avrami equation can be developed for postdeformation softening. The kinetics of postdeformation softening (both strain-dependent and strain-independent behaviors) can be described by an Avrami equation:^[12,22]

Fig. 8—Transition strain from strain-dependent to strain-independent behavior as a function of Z .

Fig. 9—Dependency of $\ln \ln (1/(1-X))$ to $\ln (\text{time})$ for different strains (at 900 °C and a strain rate of 0.01 s⁻¹).

$$X = 1 - \exp \left[-B \left(\frac{t}{t_f} \right)^n \right] \quad [2]$$

where X is the recrystallization (softening) fraction, t is the unloading time, t_f is the time for a given level of softening, $B = \ln (1 - F)$, and n is the Avrami exponent.

Normally, f is taken as 0.5 (*i.e.*, 50 pct softening), so that $t_f = t_{50}$ and $B = 0.693$, and the following expression can be used to predict the recrystallization fraction:

$$X = 1 - \exp \left[-0.693 \left(\frac{t}{t_{50}} \right)^n \right] \quad [3]$$

To determine the Avrami exponent, n , the softening results in the form of $\ln \ln \left(\frac{1}{1-X} \right)$ were plotted as a function of $\ln (\text{time})$ for both strain-dependent and strain-independent regions in Figure 9. In all cases tested here, most of the measured values fell in straight near parallel lines and a mean value of 1.1 was found for the Avrami exponent. Hence, there was no difference in

recrystallization behavior for the strain-dependent and strain-independent regions. However, a deviation is obvious for long holding times (dashed lines). This generally corresponded with the softening fraction reaching a maximum value with further holding, leading to grain coarsening of the recrystallized microstructure. In some earlier work^[2,23] a similar deviation was observed for very short times, where it was attributed to the recovery of the deformed material before initiation of recrystallization. In the current case, in which the SFE of the material is very low and recrystallization can easily start, this deviation is not obvious. This supports the observation of significant microstructural change, even at 20 pct softening.

It has been reported^[17,23-27] that the deformation parameters (strain, strain rate, and temperature), deformation mode, initial grain size, and composition may affect the Avrami exponent. However, in the current study, the results did not show any noticeable effect of strain, strain rate, and temperature on the n value. Nonetheless, the value of 1.1 for Avrami exponent is in agreement with the n values reported in other studies on static or MDRX kinetics.^[1,25,28-31]

Determining the trend for time to 50 pct recrystallization is the next step in modeling the recrystallization kinetics in Eq. [3]. For a given initial grain size, the time for 50 pct recrystallization, t_{50} , is usually described by a power-law equation:^[4]

$$t_{50} = A \varepsilon^{-p} Z^{-q} \exp \left(\frac{Q_{\text{rex}}}{RT} \right) \quad [4]$$

where A , p (zero for the strain-independent region), and q are constants, Q_{rex} is the activation energy for recrystallization (J/mol), T is the absolute deformation temperature (K), and R is the gas constant (*i.e.*, 8.314 J/mol/K).

The Q_{rex} for the strain-independent region is the activation energy for post-DRX. The apparent activation energy of post-DRX, which is a function of the activation energy of recrystallization, may be estimated from the Q_{rex} and the deformation activation energy:^[4]

$$Q_{\text{app}} = Q_{\text{rex}} - 0.6Q_{\text{def}} \quad [5]$$

However, the value of 0.6 in Eq. [5] is suggested for C-Mn steels and the material composition may have an effect on this value.

To determine the different constants in Eq. [4], the effect of each deformation parameter was examined individually, while the other parameters were kept constant. The results are summarized in Table II.

The equations in Table II can also be used to model the transition strain, ε^* , for which the experimental values are presented in Figure 8. As t_{50} at the transition point has equal values for strain-dependent and strain-independent behaviors, the following equation can be derived by equating Eqs. [6] and [7]:

$$\varepsilon^* = 3.88 \times 10^{-5} Z^{0.13} \exp \left(\frac{56000}{RT} \right) \quad [8]$$

Table II. Softening Equations for Strain-Dependent and Strain-Independent Regions

Area	n	p	q	Q_{rex} (kJ/mol)	t_{50} (s)
Strain dependent	1.1	1.48	0.42	375	$t_{50} = 8 \times 10^{-9} \varepsilon^{-1.48} Z^{-0.42} \exp\left(\frac{375,000}{RT}\right)$ Eq. [6]
Strain independent	1.1	0	0.61	292	$t_{50} = 2.7 \times 10^{-2} Z^{-0.61} \exp\left(\frac{292,000}{RT}\right)$ Eq. [7]

This equation implies that the transition strain is a function of both temperature and Z , rather than a simple function of Z . However, Figure 8 shows that in a log-scale, Eq. [8] is very close to the linear (at least under the deformation conditions tested here) and, therefore, the transition strain can be presented by a simpler form:

$$\varepsilon^* = 0.228 \ln Z - 7.06 \quad [9]$$

The initial grain size should also have a strong effect on this equation. The predicted values of transition strain showed a good agreement with the measured values in Figure 8. However, there is a deviation at very high Z values.

B. Recrystallized Grain Size

The evolution of grain size during recrystallization has always been an important area of interest, due to its essential role in defining the properties of a deformed material. Several attempts have been made to correlate the average grain size with the fraction recrystallized,^[4,7,17,32–37] but it seems that it is impossible to make such a correlation. However, the evaluation of average grain size can show the progress of grain refinement during recrystallization. The change in the average grain size, $\bar{d}$, with unloading time is presented in Figure 10, for a constant temperature of 900 °C and a strain rate of 0.01 s⁻¹. Here, the average grain size decreased with increasing unloading time to a minimum value, and then increased with further annealing. At low prestrains, at which some new grains were formed through SRX or MDRX processes, the linear intercept decreased with increasing unloading time, indicating the progress of postdeformation recrystallization. However,

Fig. 10—Dependency of average grain size to time for different strains (at 900 °C and a strain rate of 0.01 s⁻¹).

Fig. 11—Dependency of fully recrystallized grain size to strain (at 900 °C and a strain rate of 0.01 s⁻¹).

after a minimum, the linear intercepts increased by further deformation, and, at the end of the softening process, there was no change in the linear intercept with holding for longer times.

At strains higher than 1.5 ($\varepsilon \geq \varepsilon^*$), the decrease in the linear intercept at short times was negligible, and it increased continuously with increasing the time. As most of the deformed structure is replaced by DRX grains for a deformation to a strain larger than the ε^* (Figure 6(m)), the dominant recrystallization process during unloading is the growth of DRX nuclei (strain-independent recrystallization), which starts immediately after the unloading.^[1] In this case, most of the unrecrystallized microstructure is replaced by new small grains just after short unloading times (*i.e.*, 20 pct softening) and more time causes the growth of these newly formed and DRX grains (grain coarsening). The similar grain size after full softening in the strain-independent region ($\varepsilon \geq 1.5$), demonstrates the small effect of strain on strain-independent recrystallization, as observed in Figure 2.

The dependency of the fully recrystallized grain size (measured from 90 pct softened samples) on the applied strain was very similar to the dependency of softening fraction on the strain (Figure 11). In fact, the fully recrystallized grain size decreased with increasing strain, and reached a steady-state condition (strain independent) at a strain apparently beyond the transition strain of softening behavior, ε^* , although the data are limited. The strain-independent grain size, usually referred as the MDRX grain size, is proposed as a power-law relationship to the Zener–Hollomon parameter (as for the DRX grain size). Hodgson^[7] has

Fig. 12—Dependency of dynamic and postdynamic recrystallized grain size to Z .

shown that the strain-independent grain size is almost 1.6 times the DRX grain size. This is close to the ratio of about 1.8 in the present work (Figure 12).

V. CONCLUSIONS

The postdeformation restoration behaviors were examined using both microstructural observations and mechanical measurements. The effect of different deformation conditions, including temperature, strain rate, strain, and unloading time, were studied. The results of investigations during hot deformation in Part I of this study (*i.e.*, DRX) were used to examine the effect of the deformed structure (including the frequency of DRX grains) on postdeformation softening mechanism and kinetics. The most important results can be summarized as follows.

1. The postdeformation softening showed two different regions of strain-dependent and strain-independent behavior, with a transition strain, ϵ^* , which was far beyond the strain to the peak stress.
2. The microstructural observations showed a tight relationship between the transition strain and the DRX volume fraction. In all deformation conditions, an average DRX volume fraction of 50 pct corresponded to the transition from strain-dependent to strain-independent behavior.
3. A strong relationship between the transition strain and the Zener–Hollomon parameter was found from both experimental measurements and the modeling data.
4. The linear intercept measurements showed a decrease to a minimum value, followed by a continuous increase with increasing unloading time. However, in the strain-independent region, the decrease to the minimum value was negligible and a continuous increase was observed during the unloading.
5. Similar to the softening fraction, the postdeformation fully recrystallized grain size showed a strain-dependent

and a strain-independent region separated at a transition strain, ϵ_t , between them.

6. The post-DRX grain size was almost 1.8 times that of the DRX grain size.

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