Effect of Carbon Content on Static Restoration of Hot Worked Plain Carbon Steels

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Effect of carbon content on the static softening taking place in hot deformed austenite was studied by means of interrupted tension and compression tests at a temperature of 1133 K and at a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$ for plain carbon steels. The softening curve after dynamic recovery (DRV) consists of two stages, followed by complete softening. In contrast, the softening curve after dynamic recrystallization (DRX) consists of three distinct stages accompanied with three plateaus, followed by incomplete softening. These can be controlled by metadynamic recovery (MDRV) and recrystallization (MDRX) in addition to classical static recovery (SRV) and recrystallization (SRX). The static softening taking place after DRX sensitively depends on the volume fractions of DRX nuclei, growing DRX grains and fully work hardened DRX grains. The increasing in the fractions of DRX nuclei and growing DRX grains causes the amount of rapid softening in stage I and incomplete softening in stage III to increase, respectively. The static softening rates in DRV and DRX matrices increase with carbon content because of the increased diffusivity of vacancies, which can promote the operation of static restoration mechanisms, *i.e.* SRV, SRX, MDRV and MDRX.

KEY WORDS: hot deformation; plain carbon steel; carbon content; austenite; static softening; dynamic recovery and recrystallization; metadynamic recovery and recrystallization.

1. Introduction

The clarification of static restoration processes as well as grain refinement mechanisms taking place in hot deformed austenite is very important in the thermo-mechanical processing of steel products because of the desirable mechanical properties associated with micro-structural control. Many studies of these fields have been carried out, particularly in accompaniment with the development of controlled rolling technologies.^{1–4)} They have mainly been concerned, however, with static restoration taking place after dynamic recovery (DRV) of austenite which operates in the range of initial work hardening at relatively low strains. Only a few systematic studies have been carried out on the static restoration processes operating after dynamic recrystallization (DRX) at high strains.^{5–7)} Petkovic *et al.* first investigated systematically static softening taking place after DRX and clarified the operation of metadynamic recrystallization (MDRX) in addition to classical static recovery (SRV) and recrystallization (SRX).^{5–7)} MDRX refers to the continued growth of DRX nuclei after the cessation of deformation.^{5,6)} On the other hand, the present authors recently investigated static restoration processes taking place in a DRX matrix and revealed the operation of four kinds of mechanisms, *i.e.* MDRV and metadynamic recovery (MDRV) in addition to SRV and SRX.^{8–11)} In the regions containing growing DRX

grains, static nucleation is impossible and only recovery can take place because of almost free dislocations near their boundaries. This type of recovery can occur only after DRX and is clearly different from SRV followed by SRX, so it has been termed metadynamic or post-dynamic recovery (MDRV).⁸⁾ The detailed nature and mechanisms of MDRV and MDRX still remain unclear due to limited observation.

DRX has not played an important role in the conventional controlled rolling technologies, because the pass strains as well as the accumulated ones are usually smaller than the critical one needed to initiate DRX.^{1–3,12)} However, because the austenite grains undergo considerable refinement through repeated static recrystallization at the roughing stage and strains are accumulated due to the decreasing delay time between successive passes during the finishing stage, it is considerably probable that DRX can take place at the final stages of hot strip rolling for appropriate microalloyed steels. Samuel *et al.*¹³⁾ carried out some simulation tests for hot strip rolling of Nb microalloyed steels, and found the occurrence of DRX and the evolution of fine grained austenite smaller than $5 \mu\text{m}$. They termed this processing DRX Controlled Rolling (DRCR).¹²⁾

The aim of the present work is to investigate the static softening processes taking place in hot deformed austenite by means of interrupted tension and compression tests for several plain carbon steels. The effects of hot

deformed micro-structures, *i.e.* DRV and DRX matrices, and of carbon content on the static restoration processes are investigated, and particularly the mechanisms of static restoration taking place after DRX are discussed in detail.

2. Experimental Procedure

The four kinds of plain carbon steel, prepared as ingots of 10 kg by induction melting, were hot rolled to 5 mm thickness at temperatures from 1520 to 1370 K and then cold rolled to 0.6 mm with an intermediate anneal. The samples, with gauge sections of 22 mm in length and 3 mm in width, were machined from the sheets with the tensile axis parallel to the rolling direction. The chemical compositions of the steels used are shown in Table 1. Impurity contents except for carbon atoms were prepared at almost the same level in each steel. Each sample was pre-annealed in vacuum at 1173 K for 1.2 ks for 0.05C steel, at 1273 K for 1.8 ks for 0.15C and 0.41C steels, and at 1103 K for 1.8 ks for 0.84C steel, respectively, to provide the evolution of a constant initial grain size.

The mechanical tests were carried out using a hot tensile tester, which is equipped with a hydrogen gas quenching apparatus. Details of the experimental equipment and procedure were described previously.⁸⁻¹¹⁾ The specimens were austenitized at a temperature of 1233 K for 0.9 ks in the test chamber, leading to an initial grain size of $16.5 \pm 1 \mu\text{m}$ irrespective of carbon content. The specimens with an another grain size of $90 \mu\text{m}$ were prepared only for the 0.15C steel, to investigate the effect of initial grain size. They were cooled in the furnace from 1233 K to a test temperature of 1133 K and after holding for 0.6 ks were deformed to several strains in tension at an initial strain rate of $2 \times 10^{-3} \text{ s}^{-1}$, and then unloaded. After a given time interval, the specimens were reloaded at the same strain rate and temperature. On the other hand, to examine the static softening taking place in a steady state structure, the interrupted compression tests were carried out only at a prior strain of 0.7 for 0.05C and 0.84C steels in a microcomputer aided testing machine¹⁴⁾ at the same temperature and true strain rate as in the tensile tests. The compression cylinders, 12 mm in height and 8 mm in diameter, were machined from 10 mm thick plate with the compression axis aligned along the rolling direction. They were coated with powdered glass for lubrication.

The degree of static softening, X , is defined by the following equation,^{5,6)}

$$X = (\sigma_e - \sigma_{y2}) / (\sigma_e - \sigma_{y1}) \quad \dots\dots\dots(1)$$

where σ_e is the flow stress at a strain of ϵ immediately

before unloading, and σ_{y1} and σ_{y2} are the yield stresses at prestraining and reloading, respectively. The offset yield stress used here was defined in terms of a plastic strain of 0.005.¹¹⁾ The fractional softening X in Eq. (1) should change from zero (*i.e.* as-deformed matrices) to one (*i.e.* a fully annealed matrix) with holding time at a high temperature.

3. Experimental Results

3.1. Flow Curves in Austenite

Typical stress-strain (σ - ϵ) curves at 1133 K and at $2 \times 10^{-3} \text{ s}^{-1}$ for the present steels are shown in Fig. 1. They exhibit the characteristic shape of regular oscillations in stress after the peak accompanied by DRX. Such multiple peak type of flow can be attributed to grain coarsening taking place in the initial fine grains.¹⁵⁾ It can be seen clearly in Fig. 1 that the flow stresses at low strains increase with rising in carbon content, *i.e.* solid solution hardening occurs and, in contrast, peak stresses as well as flow stresses at high strains decrease with carbon content, *i.e.* solid solution softening takes place (see Fig. 2). These results are discussed in detail elsewhere,¹⁶⁾ so the main conclusions are briefly summarized here. Flow stresses at high strains can be controlled by DRX, which brings about the evolution of new grained structures containing high dislocation densities. The diffusivity of vacancies in austenite for iron-carbon alloys increases with rising carbon content.¹⁷⁾ The operation of DRX can, therefore, be accelerated by the addition of carbon, leading to the solid solution softening for stresses at high strains.¹⁶⁾ In contrast, deformation at low strains

Fig. 1. Effect of carbon content on the flow curves for plain carbon steels having an initial grain size of $16.5 \pm 1 \mu\text{m}$ deformed at 1133 K and $2 \times 10^{-3} \text{ s}^{-1}$. Note that solid solution hardening takes place at lower strains and, in contrast, solid solution softening at higher strains.

Table 1. Chemical compositions of the plain carbon steels used. (mass%)

Designation	C	Si	Mn	P	S	Sol.Al	T.N
0.05C steel	0.054	0.26	1.46	0.004	0.0028	0.028	0.0060
0.15C steel	0.15	0.30	1.48	0.004	0.0034	0.015	0.0077
0.41C steel	0.41	0.31	1.49	0.004	0.0043	0.019	0.0090
0.84C steel	0.84	0.34	1.51	0.004	0.0061	0.027	0.0103

Fig. 2. Changes in several characteristic values of the DRX type flow curve with carbon content: yield stress σ_y , peak stress σ_p , flow stresses σ_1 and σ_2 at the interrupted strains ε_1 and ε_2 and second cycle strain hardening increment $\Delta\sigma_H$.

can be controlled mainly by the dragging stress of moving dislocations which may result from the carbon atmosphere itself or excess vacancy evolved by the addition of carbon.¹⁷⁾ The dragging stress can increase with rising carbon content, leading to the solid solution hardening in the range of low strain.

By the way, the interrupted tests were carried out at two interruption strains, ε_1 and ε_2 . The prestrain ε_1 is below half of the peak strain, so there is only DRV structure developed. In contrast, at the prestrain ε_2 which corresponds to the stress minimum after the peak, full DRX grained structure should be developed.¹⁵⁾ As can be seen in Fig. 2, ε_1 and the corresponding stress σ_1 are almost independent of carbon content but, in contrast, ε_2 and the corresponding stress σ_2 decrease with carbon content until around 0.4 mass% and then approach certain constant values at high concentration. The latter effects can be attributed to the enhanced DRX resulting from the addition of carbon described above.

3.2. Effect of Prior Strain on Fractional Softening

The effect of prestrains on the fractional softening vs. holding time ($X-t$) curves for the 0.84C steel is shown in Fig. 3. The interrupted strains ε_1 and ε_2 are 0.1 and 0.26, and the flow stresses of σ_1 and σ_2 are almost the same, 76 ± 2 MPa. Therefore the average dislocation densities evolved as well as the stored energy promoting static restoration should be almost the same under the present testing condition. The $X-t$ curve for the DRV matrix at the prestrain of ε_1 indicates a typical sigmoidal shape. The softening takes place gradually until 10^3 s, and then is followed by rapid progress to complete softening. In contrast, the $X-t$ curve for a full DRX structure at the prestrain of ε_2 is obviously different from that for DRV matrix mentioned above. It consists of three distinct stages: (i) rapid initial softening to about

Fig. 3. Effect of prior strain on the static softening-annealing time curves at 1133 K for 0.84C steel. The microstructures evolved at strains of 0.106 and 0.26 are DRV and DRX matrices, respectively.

Fig. 4. Effect of carbon content on the static softening curves for DRV matrices evolved at prior strain of around 0.1 at 1133 K.

0.23, leading to a plateau before 10 s (stage I); (ii) substantial softening from 0.23 to 0.56, followed by a second plateau at around 300 s (stage II); and (iii) some more softening to about 0.64, followed by a third plateau, thus leading to incomplete softening under the present testing condition (stage III). It is interesting to note that the softening rates for a DRX matrix are clearly higher in stage I and II, but conversely smaller in stage III than those for a DRV matrix. It is concluded, therefore, that the static restoration behaviors taking place after hot deformation depend sensitively on the type of microstructures evolved, i.e. DRV or DRX matrices.

3.3. Effect of Carbon Content on Fractional Softening

The effect of carbon content on the progress of static softening for DRV matrices at ε_1 is shown in Fig. 4. It can be seen in Fig. 4 that these sigmoidal $X-t$ curves consist of two stages. The softening takes place gradually until 10^3 s (stage I), and then is followed by rapid progress to complete softening (stage II). The former is controlled by recovery and the latter by recrystallization.⁸⁻¹¹⁾ The effect of carbon content on X is negligible small in stage I and is somewhat appreciable in the stage II of rapid softening, and so the softening rates are enhanced a little by the addition of carbon. It is concluded, therefore, that static recrystallization (SRX) operating in stage II,⁸⁻¹¹⁾ as well as DRX discussed above, can be promoted by

Fig. 5. Effect of carbon content on the static softening curves for DRX matrices evolved at strains corresponding to first stress minimum at 1133 K.

the addition of carbon.

On the other hand, the effect of carbon content on the X - t curves for DRX matrices at ϵ_2 is shown in Fig. 5. These X - t curves consist of three distinct stages, as explained in Fig. 3: rapid initial softening leading to a plateau (stage I), substantial softening followed by a second plateau (stage II), and then some softening followed by a third plateau, thus leading to incomplete softening (stage III). The amounts of static softening in stage I as well as the softening rates in stage II increase with carbon content, and the values of X at the second plateau are in the range of 0.47 to 0.57 irrespective of carbon content. It is very interesting to note, in contrast, that the softening rates and the saturation values of softening in stage III conversely decrease with increasing carbon content. Such effects of the addition of carbon on the static softening operating after DRX can result from not only the increasing of vacancy diffusion, but also from other factors, e.g. DRX matrices, which will be discussed in the next section.

4. Discussion

4.1. Static Restoration Taking Place in a DRX Matrix

The dynamically recrystallized grain structures can be illustrated schematically by the full lines in Fig. 6, which is discussed in detail elsewhere.¹⁸⁾ Here, the dislocation density ρ_0 is the initial value for the annealed state, ρ_c is the critical value for DRX nucleation, and D is the current DRX grain size. The DRX structure can be classified into the following three categories: (i) the DRX nuclei which contain few dislocations (A in Fig. 6), (ii) the growing DRX grains which contain few dislocations near the boundaries and a fairly well formed cell substructure in the grain interior (B in Fig. 6), and (iii) the critically work hardened DRX grains which contain high density dislocations for nucleation of the next cycle of recrystallization (C in Fig. 6).¹⁸⁾ It can be expected from this DRX model that the changes in such dynamic grain structures with annealing can be different in each of the three regions. On unloading, the DRX nuclei continue to grow, leading to metadynamic recrystallization (MDRX) in their localities. The growing DRX grains should contain few dislocations near their boundaries

Fig. 6. Three types of dislocation density distribution developed in the dynamically recrystallized grain structure (full lines), and the post-dynamic restoration behaviors in each of the three regions (broken lines). ρ_0 is the initial (annealed) dislocation density, ρ_c is the critical value required for dynamic nucleation and D is the current DRX grain size (after Sakai *et al.*⁸⁾).

Fig. 7. Schematic illustration showing the relationship between each of the softening stages and the main restoration processes operating after DRX.

and so classical nucleation is not possible within them, accordingly they can only soften by metadynamic recovery (MDRV) in their interiors. Finally, the full work hardened DRX grains undergo static recovery (SRV) and nucleation, leading to classical static recrystallization (SRX).⁸⁻¹¹⁾

The four mechanisms described above (MDRV, MDRX, SRV and SRX) can operate concurrently to some extent, but their effects in the DRX matrix can be distinguished in Figs. 3 and 5 and then summarized in Fig. 7. In stage I, MDRV operates initially in the regions containing dynamic nuclei and can stop when MDRV grains impinge on the growing DRX grains, because the dislocation densities across the boundaries in question are almost the same ($=\rho_0$).⁸⁾ This is the reason why the initial softening plateau appears. The substantial softening taking place in stage II is largely associated with classical SRX following SRV in the full work hardened regions. Concurrently, MDRV takes place frequently in the moderately work hardened regions. This additional softening gives rise to an Avrami exponent with a value less than one in stage II.⁹⁻¹¹⁾ The softening in stage II terminates at the second arrest, because SRX grains can

also impinge on MDRV grains.

With further annealing of such a mixed structure (*i.e.* MDRX or SRX new grains and MDRV grains), the growth rate of new recrystallized grains should become lower because of the small difference in dislocation densities across their boundaries. Recently the authors have proved much lower rates of the average grain growth in full DRX copper¹⁹⁾ and nickel²⁰⁾ compared with those in their DRV matrices, and also found that MDRV grains in stage III have many-sided irregular shapes as well as high dislocation densities. Such MDRV grains may have the potential for grain growth driven by grain boundary energy. If this driving force becomes equal to that due to the difference in the average dislocation densities between MDRV and SRX or MDRX grains (*e.g.* around 10^{13} m/m^3 ^{19,20)}), the growth of the latter grains should stop. It is concluded from the arguments mentioned above that MDRV grains can exist stably for long periods of time, leading to incomplete softening as well as to a lower rate of grain growth at stage III for the DRX matrix.

4.2. Effect of Initial Grain Size on Fractional Softening

The effect of initial grain size, D_0 , on the static softening taking place after DRX will be investigated here, because DRX behavior depends sensitively on the D_0 .^{15,18,19)} The interrupted tensile tests were carried out for the 16.5 and 90 μm specimens of the 0.15C steel at 1133 K and $2 \times 10^{-3} \text{ s}^{-1}$. The effect of D_0 on the X - t curves as well as the σ - ϵ curves are represented in Fig. 8. It can be seen clearly that the characteristic softening curves consisting of 3 stages move to the shorter periods of annealing time with increase in D_0 . This is some strange to the fact that static recrystallization is generally retarded by the increase in D_0 , because the number of nucleation sites decreases with decrease in the area of grain boundaries.^{15,22)}

By the way, it is established from the previous works^{15,21)} that multiple peak flow appears when grain coarsening occurs and single peak flow when the material is undergoing grain refinement, and so the critical condition is described approximately by the following equation.

$$D_0 = 2D_s \dots\dots\dots(2)$$

The DRX grain size at high strains, D_s , for the 0.15C steel was about 38 μm at 1133 K and $2 \times 10^{-3} \text{ s}^{-1}$.²³⁾ Accordingly, in the specimen of $D_0 = 90 \mu\text{m}$, $D_0 > 2D_s$, and a single peak type of flow and grain refinement take place during deformation. Conversely, in the 16.5 μm specimen, $D_0 < 2D_s$, and then multiple peak type of flow appears accompanying by grain coarsening.

In a full DRX structure, consisting of the three kinds of DRX grains described in Fig. 6, regions belonging to each of these three types are distributed fairly uniformly throughout and their volume fractions become almost constant, leading to steady state flow at high strains.^{15,18)} This corresponds to the dynamic grain structure evolved at a strain of 0.38 for the 90 μm specimen because of $D_0 > 2D_s$. In contrast, for $D_0 < 2D_s$ in the finer grained specimen, the excess DRX nuclei evolved at around peak strain can grow and impinge on each other at the strain of initial stress minimum, leading to the formation of metastable smaller DRX grains, D'_s , than D_s .^{15,21)} Under such a flow condition, the metastable structure can be expected to consist mainly of growing DRX grains as well as DRX nuclei, then leading to a small volume fraction of fully work hardened grains.¹⁵⁾ As discussed in Sec. 4.1, the incomplete softening in stage III can be attributed to the stable existence of MDRV grains containing high density dislocations. It is concluded, therefore, that the higher volume fraction of growing DRX grains in the finer grained specimen (16.5 μm), compared with that in the coarse one (90 μm), can give rise to the higher amount of incomplete softening in stage III.

4.3. Effect of Carbon Content on Fractional Softening

The effect of rising carbon content on the static softening taking place after DRX causes the amount of softening in stage I and II to increase and, conversely, that in stage III to decrease, leading to a higher amount of incomplete softening (see Fig. 5). The softening in stage I and II should be affected by the increase in vacancy diffusion due to the addition of carbon as described above. By the way, it can be seen in Fig. 1 that multiple peak type of flow as well as solid solution softening appear more clearly with increasing carbon content. This can be explained by using the relative grain size model for DRX¹⁵⁾ as follows.

A microstructural mechanism map,¹⁵⁾ in which the vertical coordinate indicates the testing condition Z or the developed flow stress σ and the horizontal axis shows D_0 or D_s , and the flow curves expected from this map are represented schematically in Fig. 9. The slanting line in Fig. 9(a) represents the relationship of $D_0 = 2D_s$ in Eq. (2). The relationship between σ and D_s for plain carbon steels is reported to be almost independent of carbon content.²⁴⁾ It can be derived from Figs. 9(a) and 9(b) that the D_s evolved even at the same testing conditions (*i.e.* D_0 and Z) should increase with σ decrease due to the solid solution softening in the present steels. In consequence, multiple peak type of flow appears more clearly in high carbon steels because of the increase in the difference between D_0 and D_s . The latter is supported

Fig. 8. Effect of initial grain size on the static softening curves for DRX matrices evolved at strains of 0.28 and 0.38 for the 16.5 and 90 μm specimens of 0.15C steel. The inset shows the flow curves at 1133 K and at $2 \times 10^{-3} \text{ s}^{-1}$.

Fig. 9. (a) A microstructural mechanism map for DRX. The vertical coordinate indicates the testing condition Z or the developed stress σ and the horizontal axis shows D_0 or D_s . The line of $D_0 = 2D_s$ separates the single (grain refinement) from the multiple peak (grain coarsening) region (after Sakai *et al.*¹⁵). (b) Changes in the shape of flow curve with solid solution softening expected from the microstructure mechanism map.

Fig. 10. Effect of carbon content on the static softening curves for full DRX matrices evolved at a strain of 0.7 for 0.05C and 0.84C steels. The tests were carried out by means of interrupted compression at 1133 K and at $2 \times 10^{-3} \text{ s}^{-1}$. The inset shows the flow curves.

by the experimental result that the strain hardening increment, $\Delta\sigma_H$, from the stress minimum to the second peak stress, increases with carbon content (see Fig. 2).

It is concluded from the arguments mentioned above that: (i) the difference between stable dynamic grain size D_s and metastable one D'_s evolved at the strain corresponding to stress minimum after the peak increases with rising carbon content and, therefore, (ii) the volume fraction of growing DRX grains as well as DRX nuclei in a metastable DRX structure (D'_s) is higher than in the stable one (D_s) and, consequently, (iii) the amount of incomplete softening in stage III should increase apparently with rising carbon content. It is also concluded that the $X-t$ curve consisting of three stages for full DRX matrices sensitively depends on the volume fraction for each of the three kinds of DRX grains described in Fig. 6.

To investigate the effect of carbon content on the static softening taking place in a stable or steady state DRX matrix, interrupted compression tests were carried out at a strain of 0.7 for the 0.05C and 0.84C steels at 1133 K

and $2 \times 10^{-3} \text{ s}^{-1}$. The $X-t$ curves as well as the $\sigma-\epsilon$ curves for the both steels are shown in Fig. 10. The solid solution softening appears clearly in steady state flow at high strains. It can be seen in Fig. 10 that the softening rates in stage I, II and III are enhanced by the addition of carbon and the saturation values in stage III become equal irrespective of carbon content. It should be added that, as the flow stresses and so the stored energies for the 0.05C steel are higher than those for the 0.84C steel, the enhancement of static softening due to the addition of carbon can be expected to become much larger than the results of Fig. 10. It is concluded, therefore, that the static softening taking place after DRX, as well as after DRV, is enhanced by the addition of carbon because of the increase in the diffusivity of vacancies in austenite. It is suggested that the volume fraction for each of the three regions of DRX grains in Fig. 6 can be almost the same under steady state flow irrespective of carbon content, because of the same amount of incomplete softening for the both steels.

5. Conclusions

The effect of carbon content on the static softening processes taking place in hot deformed austenite was studied by means of interrupted tension and compression tests for plain carbon steels. The results obtained can be summarized as follows.

(1) The softening curve associated with a DRV matrix has a sigmoidal shape and consists of two stages, followed by complete softening. In contrast, the softening curve for a full DRX structure consists of three distinct stages with three plateaus of softening, followed by incomplete softening.

(2) For DRX matrices evolved at a strain corresponding to the first stress minimum after peak, the softening rates in stage I and II increase and, in contrast, those in stage III decrease with increase in carbon content and also with decrease in initial grain size.

(3) The static softening taking place after DRX sensitively depends on the volume fraction of the regions containing DRX nuclei, growing DRX grains and fully work hardened DRX grains. The increase in the volume fraction of DRX nuclei and growing DRX grains causes the amount of rapid softening in stage I and of incomplete softening in stage III to increase, respectively.

(4) The static softening rates in all stages for steady state DRX matrices as well as DRV matrices increase with rising carbon content. This results from the increase in the diffusivity of vacancies due to the addition of carbon in austenite, which can promote the operation of static restoration mechanisms; *i.e.* SRV, SRX, MDRV and MDRX.

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