Retransformation Behavior of Dynamically Transformed Ferrite during the Simulated Plate Rolling of a Low C and an X70 Nb Steel

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Plate rolling simulations were carried out on an X70 Nb and a low C steel by means of torsion testing. A seven-pass rolling schedule was employed where the last pass was always applied above the respective A}_{3} temperature of the steel. Interpass intervals of 10 and 30 s were employed, which corresponded to cooling rates of 1.5 and 0.5 °C/s. The mean flow stresses (MFS’s) applicable to each schedule increased less rapidly than expected from the decreases in temperature due to the dynamic transformation (DT) that took place during straining. The amounts of ferrite that retransformed into austenite during holding were determined by optical metallography. These increased with length of the interpass intervals and were reduced in the X70 steel due to the presence of Nb. The holding times after rolling required to increase the amount of austenite available for microstructure control on subsequent cooling were also determined for the two steels.

KEY WORDS: plate rolling; ferrite retransformation; X70 steel; low C steel; continuous cooling.

1. Introduction

The formation of ferrite by dynamic transformation at temperatures above the A}_{3} during simulated plate rolling has been described in detail by several researchers.\textsuperscript{1–7} This has been shown to occur throughout the austenite phase field.\textsuperscript{8,9} In earlier publications, the present authors have reported that the amounts of ferrite formed per pass increase with decreasing temperature.\textsuperscript{9,10} Subsequently, the metastable ferrite tends to retransform to austenite to an extent that increases with the length of the interpass interval.\textsuperscript{10,11} Such ferrite was demonstrated to form displacively, leading to the appearance of very narrow (200 nm) plates of Widmanstätten ferrite that coalesced into polygonal grains during continued straining or holding after deformation.\textsuperscript{1,2,4} The amount of ferrite formed in a given pass was also shown to be reduced in the presence of Nb, an effect that has been attributed to a combination of solute drag and precipitate pinning effects.\textsuperscript{1,2,4,5}

The reverse transformation takes place much more slowly than the forward, displacive one as it appears to be controlled by diffusional mechanisms.\textsuperscript{1} Although some studies regarding the retransformation of ferrite into austenite during holding have already been published,\textsuperscript{1,8,10,12} these have been limited to isothermal and single pass conditions. Here this phenomenon is explored under continuous cooling and multiple pass conditions, which are closer to those applicable to industry. For this purpose, a seven-pass finishing schedule was simulated under continuous cooling conditions. The kinetics of retransformation were determined on a plain C and on a Nb-microalloyed pipeline steel using two different interpass times. Their behaviors are compared here and the effects of holding time on the amount of ferrite that undergoes retransformation are also discussed.

2. Experimental Procedures

A plain C and an X70 Nb steel were investigated in the present research. They were supplied in the form of hot rolled plates with thicknesses of 12.5 mm. The plates were machined into torsion specimens with diameters of 6.35 mm and gauge lengths of 22.2 mm with their cylinder axes parallel to the rolling direction. The chemical compositions of these steels are presented in Table 1 together with their corresponding paraequilibrium and orthoequilibrium A}_{3} temperatures. The latter were calculated using the FS\text{stel} database of the FactSage thermodynamic software.\textsuperscript{13}

2.1. Torsion Tests

The tests were conducted on a computer-controlled MTS torsion machine fitted with a Research Incorporated radiation furnace and superalloy tooling. Thermocouples were spot welded to the mid-lengths of the torsion specimens. The samples were protected by an atmosphere composed of Ar and 5% H\textsubscript{2} in order to prevent oxidation and decarburization of the samples during testing at high temperatures. The torque/twist data were converted into equivalent stress/strain form using the Fields and Backofen relations.\textsuperscript{14} The small diameter increases that took place during free-end torsion...
testing were taken into account in deriving the stress-strain curves from the torque/twist data.\textsuperscript{(5)}

The schedules and procedures employed here for the X70 steel are illustrated in Fig. 1(a). The samples were heated to 1200°C at the rate of 1°C/s and held for 20 minutes to promote full austenitization. They were then cooled at 1°C/s to 1100°C and held at this temperature for 60 seconds after which the first roughing pass was applied. After holding at this temperature for a further 120 seconds, a second roughing pass was applied. Each roughing pass involved a strain of 0.4 applied at a strain rate of 1.0 s\textsuperscript{-1}. After roughing, the samples were held at 1100°C for 60 s to allow complete recrystallization before being cooled down to 950°C.

The samples were maintained at this last temperature for 60 s before application of the first of seven finishing passes, each of 0.2 strain applied at a strain rate of 1.0 s\textsuperscript{-1}. After roughing, the samples were held at 1100°C for 60 s to allow complete recrystallization before being cooled down to 950°C.

The temperature of the last pass was 860°C (15°C above the \(A\text{e}_3\)) in both simulations. The samples were quenched before and after the 1st, 3rd, 5th and 7th passes to permit quantification of the volume fractions of the dynamically formed and retained ferrite. Additionally, for measurement of the volume fraction of retransformed ferrite after the last pass was applied at 860°C, the samples were held at temperature for increasing times and quenched. These intervals were 1, 10, 30, 60, 120 and 240 s, see Fig. 1(a).

The plain C steel, samples were heated to 1200°C at the

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Nb</th>
<th>N</th>
<th>Orthoequilibrium (A\text{e}_3)</th>
<th>Paraequilibrium (A\text{e}_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>0.047</td>
<td>1.56</td>
<td>0.25</td>
<td>0.21</td>
<td>0.092</td>
<td>0.008</td>
<td>845°C</td>
<td>810°C</td>
</tr>
<tr>
<td>Low C</td>
<td>0.06</td>
<td>0.30</td>
<td>0.11</td>
<td>––</td>
<td>––</td>
<td>––</td>
<td>877°C</td>
<td>870°C</td>
</tr>
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</table>

Fig. 1. Torsion testing schedule employed for the rolling simulations. Interpass times of a) 10 and 30 s in the X70 steel and b) 10 s in the low C steel, were employed.

Fig. 2. Stress-strain curves determined according to the schedule in Fig. 1 using pass strains of 0.4 applied at 1 s\textsuperscript{-1}. Interpass times of a) 10 s, b) 30 s for the X70 steel and c) 10 s for the low C steel.
rate of 1°C/s and held for 20 minutes for total austenitization. They were then cooled at 1°C/s to 1 100°C and held for 60 seconds, after which the first roughing pass was applied. The samples were held for a further 120 seconds at the same temperature and then the second roughing pass was applied. The two roughing passes involved strains of 0.4 applied at a strain rate of 1.0 s⁻¹. After roughing, the samples were held at 1 100°C for 60 s to allow complete recrystallization before being cooled down to 980°C. The samples were maintained at this temperature for 60 s before application of the first of seven finishing passes each of 0.2 strain applied at a strain rate of 1.0 s⁻¹. The samples were deformed while being cooled at 1.5°C/s, which led to temperature decreases of 15°C when the interpass time was 10 s. The last pass of the plain C simulation was 890°C (13°C above the Ae₃ for this material). The samples were held at 890°C for 1, 5, 10, 20, 40 and 80 s before being quenched, see Fig. 1(b).

2.2. Metallography and Ferrite Phase Quantification

The samples were cut both transversely and longitudinally to provide cross-sections for microstructure analysis. These were hot mounted and polished using silicon carbide paper grits of 400, 600, 800, 1 000 and 1 200 while being lubricated with water. Diamond paste (3 μm and 1 μm) suspensions and a 0.02 μm colloidal silica suspension were used for final polishing. Then, the samples were etched with a 2% nital solution for approximately 15–20 seconds and then treated with a 10% aqueous sodium metabisulfite (Na₂S₂O₅) solution for 10 seconds in order to improve the contrast between ferrite and martensite. The microstructural analysis was carried out using optical microscopy and both ImageJ and the MagniSci software to measure the ferrite volume fractions. For this purpose, the martensite areas (previous austenite) were subtracted from the total area of each image to provide ferrite volume fraction. For each measurement, 10 to 15 images were taken from regions near the outer radius (i.e. in the vicinity of the maximum strain). Magnifications of ×200, ×500 and ×1 000 were employed, supplemented by EBSD micrographs when more detailed information was required.

3. Results

3.1. Stress-strain Curves

The flow curves determined in the 7-pass continuous cooling simulations are displayed in Fig. 2. Here the 10 s and 30 s interpass times results for the Nb steel are displayed in Figs. 2(a) and 2(b), respectively, while only the 10 s interval data are depicted in Fig. 2(c) for the plain C steel. The temperatures at which each pass was applied are

![Fig. 3. Optical microstructures of the X70 steel subjected to holding after the seventh pass. The samples were quenched immediately after: a) 1 s, b) 10 s, c) 30 s, d) 60 s, e) 120 s and f) 240 s of holding. Light regions are ferrite while dark regions are martensite (prior austenite).](image-url)
also shown in each figure. Note that all the tests were conducted above the \( A_{e1} \) temperature for both the X70 (845°C) as well as the plain C steel (877°C), see Table 1.

The stress levels of the curves increase progressively as the temperature is decreased but not as much as expected from the amount of the temperature decrease. This low rate of increase in flow stress can be attributed to the progressive formation of DT ferrite during straining.

The shapes of the curves indicate that there is considerably more static recrystallization in the low C steel than in the Nb microalloyed grade, which undergoes “pancaking”. Such static softening reduces the amount of retained work hardening in the low C steel, which contributes to the driving force for both transformation and retransformation. By contrast, there is more retained hardening in the X70 steel, due to the retarding effect of Nb addition.

3.2. Finishing Microstructures

The effect of holding time on the finishing microstructures was determined on the transverse samples. The X70 results that correspond to the 1, 10, 30, 60, 120 and 240 s holding times are presented in Fig. 3. The 1, 5, 10, 20, 40 and 80 s interval data for the low C steel are depicted in Fig. 4. Here the ferrite is light while the martensite (prior austenite) appears dark.

It can be seen that large amounts of ferrite are present 1 s after the last finishing pass, see Fig. 3(a) for the X70 steel. These were produced and retained during the simulation. The volume fraction of ferrite can be seen to decrease progressively as the holding times increase but does not vanish even after 240 s of holding, see Figs. 3(b)–3(f). This is a topic that is examined in more detail below. The quantity of ferrite is reduced more quickly on holding in the plain C steel, as can be seen in Figs. 4(a)–4(f). Only a few traces of ferrite are visible when the holding time is increased to 80 s, Fig. 4(f). The grain size is also much larger in the latter material.

4. Discussion

4.1. Mean Flow Stress

The mean flow stresses (MFS’s) determined on the two steels are displayed in Fig. 5. These were calculated using Eq. (1) on the flow curves of Figs. 2(a) and 2(c) for the 10 s intervals.

**Fig. 3.** Optical microstructures of the low C steel subjected to holding after the seventh pass. The samples were quenched immediately after: a) 1 s, b) 5 s, c) 10 s, d) 20 s, e) 40 s and f) 80 s of holding. Light regions are ferrite while dark regions are martensite (prior austenite).

**Fig. 4.** Optical microstructures of the low C steel subjected to holding after the seventh pass. The samples were quenched immediately after: a) 1 s, b) 5 s, c) 10 s, d) 20 s, e) 40 s and f) 80 s of holding. Light regions are ferrite while dark regions are martensite (prior austenite).
In this expression, $\sigma_{eq}$ is the equivalent stress and $(\varepsilon_b - \varepsilon_a)$ is the equivalent strain applied in each pass. The temperature associated with each pass is also shown in Fig. 5. It can be seen that there is a sharp increase in MFS from the first to the second pass in both steels; this is most visible in the X70 steel in which there is about a 30% increase. For the low C steel, this increase was about 10%. From the second to the last pass, the expected effects of the decrease in temperature are shown as dotted lines. These were calculated using the procedure described in previous papers.10,17) In the later passes, the MFS’s continue to increase in both steels, but only by about 1%. The low MFS increases in the late passes indicate that appreciable ferrite (which is softer than austenite) is formed in each pass. Although the times between passes employed in the two materials are equal, the differences between the observed and expected MFS’s are greater in the X70 steel. This is because the addition of Nb is effective in retarding the retransformation of ferrite into austenite.1,4,11)

4.2. Ferrite Retransformation in the X70 Steel

The cumulative volume fractions of retained and retransformed ferrite produced using interpass times of 10 s and 30 s are displayed in Figs. 6(a) and 6(b), respectively. It is clear that the amount of ferrite produced and retained increases with pass number and with decrease in temperature. The amounts of ferrite that were retransformed were determined from the quantities present before the next pass. The volume fractions of both transformed and retransformed ferrite increase more rapidly for the 10 s as opposed to the 30 s interpass intervals. Once formed displacively, the volume fraction of DT ferrite retransforms only slowly because of the diffusional nature of this phenomenon.1,18–21)

It is important to note that there was a small amount of ferrite (7.5%) present before the first finishing pass; this was produced during roughing. With regard to the effect of holding time, the volume fractions of ferrite decreased from 11% to 10% after the second pass, from 17% to 14% after the fourth, and from 27% to 20% after the sixth for the 10 and 30 second schedules, respectively. Thus, it is clear that, despite the presence of Nb, the amount of reverse transformation increases perceptibly when the interpass interval is lengthened.

The percentage of ferrite retransformed into austenite during a given interpass interval in the X70 steel is illustrated in Fig. 7. These amounts correspond to the difference between the quantity of ferrite present after a particular pass and that remaining after the interpass interval (i.e. before the next pass). Note that amounts retransformed between the first and second, and second and third interpass times are greater for the 30 s than the 10 s intervals. This is because the length of the interval plays a larger role in the early passes than the retained strain. This trend is reversed in the later intervals when, somewhat unexpectedly, more ferrite retransforms during the 10 s holding times. This appears to be a result of the increased influence of the larger amounts of retained strain that are accumulated at the shorter intervals than for the longer interpass time. For the six intervals shown in Fig. 7, the percentages of retransformed ferrite amounted to 3.1 and 4.5%, for the 10 s schedule and 3.7 and 4.8% for the 30 s interpass times in the early passes and 6.0, 7.6, 9.0 and 12.5% as opposed to 5.6, 6.2, 7.0 and 10.0% in the
The relation between the amount of \(\alpha\) retransformed between passes and the quantity of \(\alpha\) available at the beginning of the interval is shown in Fig. 8. Here it can be seen that the amounts of retransformed ferrite increase with the length of the interpass interval, as expected.

4.3. Influence of Holding Time after the Last Pass

The effect of holding time on the retransformation of ferrite is displayed in Fig. 9 for the two steels. Here, the samples were held at the last pass temperature for the times shown. These amounts were calculated from the microstructures shown in Figs. 3 and 4.

In the X70 steel, the quantity of DT ferrite formed and retained 1 s after the seventh pass was approximately 50%. When the sample was held for 10 s, this was reduced to 43%. Then, when the holding time was increased to 30, 60 and 120 s, the volume fractions of ferrite were reduced to 35, 21 and 11.5%, respectively. Finally, when this time was increased to 240 s, this fraction was further reduced to 7.1%. If continued holding were to be employed, the amount of ferrite retained at 860°C (15°C above the \(Ae_3\)) is expected on this basis to be about 4% after 1 000 s.

In the plain C steel, the decrease in the proportion of ferrite is more rapid than in the X70. After the last pass, only 34.6% of retained ferrite was detected and this was reduced to 28% after 5 s of holding. When the time was increased to 10, 20 and 40 s, the amounts of ferrite decreased to 21.7, 9.5 and 6.5%, respectively. Finally, after 80 s of holding, only about 3% remained. The above results indicate that the amount of retransformation depends on the length of the holding time as well as on the composition of the material.

The observations summarized above have implications with respect to the plate rolling of X70-type pipeline steels and, more specifically, with regard to controlling the transformation behavior of the rolled plate during accelerated cooling after rolling. The results displayed in Fig. 9 indicate that holding at temperature for about 100 s or more after rolling is sufficient to ensure that a large volume fraction of austenite is available for conversion into bainite and other transformation products on controlled cooling.

4.4. EBSD Microstructures

The formation of ferrite during straining and its retransformation during holding were confirmed in the two materials using the EBSD technique of phase identification, as illustrated in Figs. 10 and 11 for the X70 and low C steels, respectively. Inverse pole figure (IPF) plots related to the orientations of the ferrite formed are shown on the left sides of the diagrams while the phase distributions are displayed on the right-hand sides. Here the red regions are ferrite while the black ones are unindexed martensite (prior austenite).

The images associated with the X70 samples directly quenched 1 and 60 s after the seventh pass are displayed in Figs. 10(a) and 10(c), respectively. Here it can be seen that the proportion of ferrite is higher in the 1 s sample than in the sample held for 60 s. This confirms the interpretation of Figs. 3 and 9 where the decrease in ferrite volume fraction was attributed to the reverse transformation.
Fig. 10. EBSD micrographs of transverse cross-sections of the X70 steel after holding. These were quenched immediately after being held for 1 s: (a) inverse pole figure colors and (b) phase identification. After 60 s of holding: (c) inverse pole figure colors and (d) phase identification. In (b) and (d), the ferrite phase is red while the prior austenite is black.

Fig. 11. EBSD micrographs of transverse cross-sections of the low C steel after holding. These were quenched immediately after being held for 1 s: (a) inverse pole figure colors and (b) phase identification. After 10 s of holding: (c) inverse pole figure colors and (d) phase identification. In (b) and (d), the ferrite phase is red while the prior austenite is black.
Similar analyses were performed on the low C steel. Here Figs. 11(a) and 11(c) show the phases present in the 1 s (Fig. 3(a)) and 10 s (Fig. 3(c)) samples, respectively. The presence of DT ferrite is again confirmed, although there is less retained ferrite than in the other material.

5. Conclusions

The occurrence of retransformation during the simulated plate rolling of an X70 steel and a low C steel has been examined in detail. The results obtained have led to the following conclusions.

1) The levels of the flow curves increase less rapidly than expected from the decreases in temperature due to the occurrence of dynamic transformation. The relatively large increase from the first to the second pass is a result of strain accumulation. The low rate of increase in subsequent passes is attributable to dynamic transformation.

2) The optical micrographs confirm that ferrite retransforms during holding and that the volume fractions decrease with holding time.

3) For a given interpass time, more ferrite is produced and retained in the X70 than in the low C steel. This is because the presence of Nb retards the retransformation of ferrite into the more stable austenite.

4) A hundred seconds of holding after the last finishing pass reduces the amount of retained ferrite in the X70 steel to about 10%. In the low C steel, the ferrite volume fraction is reduced to negligible levels.

5) Knowledge of the ferrite volume fraction present after finishing and holding can be used to design improved models for transformation on accelerated cooling.

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