Influence of Accumulated Stress in Austenite on Transformed Ferrite Grain Size by Hot Rolling for a V-microalloyed Steel

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Torsion test rolling simulations have been performed in different conditions (pass strain, interpass time) for a V-microalloyed steel (C=0.165; V=0.170 wt%). The accumulated stress (Δσ) in austenite at temperatures below the no-recrystallisation temperature (Tnr) has been measured. The accumulated stress is directly related to the dislocation density. The ferrite grain size (Da) obtained after hot rolling simulations for different conditions and a cooling rate of 3.5 K/s has been measured. Da is found to be dependent on Δσ and on the austenite grain size prior to the austenite–ferrite transformation during cooling. On the other hand, a higher strain accelerates recrystallisation between passes, lowers the Tnr value, and consequently leads to a smaller accumulated stress. It is seen that a minimum value of 15 MPa must be reached in order for Da refinement to begin.

KEY WORDS: simulation; hot rolling; interpass time; accumulated stress.

1. Introduction

Microalloying elements dissolved in austenite have a considerable effect on grain growth, the progress of recrystallisation, and on phase transformation. However, the main reason for the presence of these elements in microalloyed steels lies in their precipitation, and particularly in the interaction between particles of these elements (Ti, Nb, V) and interstitials (C, N) with austenite grain boundaries in motion.

Whereas solutes hinder the advance of grain boundaries by means of a friction effect originated by the difference in their atomic radius compared to iron, precipitates cause a decrease in the effective grain boundary area and thus in the associated surface energy. The latter leads to an obstruction of grain boundary motion or a pinning effect which is much stronger than the solute drag.1,2)

The no-recrystallisation temperature (Tnr) represents the start of inhibition of the static recrystallisation of austenite during hot rolling. The most common method for determining Tnr consists of simulating successive rolling passes and then graphically representing the Mean Flow Stress (MFS) versus the inverse of the absolute temperature for each of the simulated passes. The inhibition of recrystallisation indicated by Tnr appears as a rise in the slope of the MFS curve and in the studied steel is mainly caused by the strain-induced precipitation of vanadium carbonitrides3–8).

This method also offers the possibility of obtaining the Aγ phase transformation temperatures when austenite is being deformed in conditions similar to rolling and the stress accumulated (Δσ) in the austenite between Tnr and Aγ.9,10) The accumulated stress in austenite is a direct and precise measurement of the state of austenite as a function of the temperature and can be directly measured without the need to measure the size and lengthening of the austenite grain.11)

There are basically three types of heterogeneous nucleation sites for ferrite in austenite, namely grain and subgrain boundaries, the latter as stacks of dislocations or polygonisation, and precipitates or inclusions. VC or VN have a low interfacial energy in relation to ferrite but a relatively high interfacial energy in relation to austenite for the (001)V(C, N) boundary compared to MnS. MnS type inclusions produce a local Mn impoverishment that increases the Aγ value, favouring the nucleation of ferrite. However, the advantages of VC and VN over MnS in the balance of interphase boundary energy presumably promote the intragranular ferrite transformation for complex precipitates.12)

In the hot working of microalloyed steels, all three of the aforementioned nucleation sites can coexist and act simultaneously on ferrite grain refinement.13) The present work studies the influence of different rolling conditions on the final ferrite grain size, varying the interpass time and the strain in each pass. This influence has also been established by determining the accumulated stress in austenite prior to the ferrite transformation.

2. Experimental Procedure

Table 1 shows the chemical composition of the steel used. The material was received from the steelmaker in the form of 13 mm rolled plate. Rolling simulation tests were carried out in a computer-controlled hot torsion machine.

Torsion specimens were prepared to a gauge length of
50 mm and a diameter of 6 mm. The reheating temperature before torsion deformation was above the solubility temperature of vanadium nitrides and the holding time was 10 min. The solubility temperatures were calculated according to Turkdogan’s solubility product (Table 2). In the hot deformation of microalloyed steels the reheating temperature must always be higher than the solubility temperature, in order for the precipitate-forming elements to be placed in solution and for strain-induced precipitation to take place.

Prior to the simulation tests the specimens were reheated at a temperature of 1230°C for 10 min. The temperature was then lowered to that corresponding to the first pass, which was 1150°C. The simulations consisted of the performance of 21 passes, with a temperature step of 25°C between passes, the last pass being carried out at 650°C. The strain applied in each pass was 0.20 and 0.35, respectively, and the strain rate was equal to 3.63 s⁻¹. Several different interpass times (Δt) from 20 to 200 s were used. The study of precipitates (VN) was carried out using a scanning electron microscope with a field emission gun (SEM-FEG).

### 3. Results and Discussion

#### 3.1. Equivalent Magnitudes

The torsion magnitudes (torque, number of turns) and the equivalent magnitudes (stress, strain) have been related in accordance with Von Mises criterion: \( \varepsilon = \frac{2\pi R_1 N}{L \sqrt{3}} \) \( \sigma = \frac{C \sqrt{3}}{2\pi R_1} (3 + r + s) \)

where, \( R_1 = \) torsion specimen radius
\( N = \) number of turns
\( C = \) torque
\( L = \) gauge length of specimen
\( r = \) strain rate sensitive
\( s = \) strain hardening exponent
\( \dot{N} = \) rotation rate (turns/s).

Equations (1) and (2) refer to magnitudes reached on the cylindrical specimen surface. For this reason the microstructures are observed on a flat longitudinal machined plane, at a small depth from the surface (normally 0.35 mm, i.e. 2.65 mm from the axis).

The equivalent strain in a rolling pass is given by: \( \varepsilon = \frac{2}{\sqrt{3}} \ln \frac{h_1}{h_2} \)

Where \( h_1 \) is the incoming plate thickness and \( h_2 \) is the outgoing thickness in each rolling pass.

Equalling Eqs. (1) and (3) yields an expression that relates torsion parameters with rolling parameters:

\[ \ln \frac{h_1}{h_2} = \frac{\pi R_1 N}{L} \]

On the other hand, the conventional reduction (\( \delta_c \)) in each rolling pass is given by:

\[ \delta_c = \frac{h_1 - h_2}{h_2} \]

Comparing Eqs. (3) and (5), we finally reach the following relationship,

\[ \ln \left( \frac{1}{1 - \delta_c} \right) = \frac{\sqrt{3}}{2} \varepsilon \]

In this way, the equivalent strains of 0.20 and 0.35 correspond to reductions \( \delta_c \) of 0.16 and 0.26, respectively.

The equivalent strains of 0.20 and 0.35 have been chosen because the strain is an important variable in static recrystallisation kinetics. Furthermore, the value of 0.35 is not yet sufficient to produce dynamic recrystallisation in the austenite phase, even at high temperatures, in most microalloyed steels.

The maximum turning rate in the torsion machine used was 2 400 turns/min = 40 turns/s. Thus the maximum equivalent strain rate would be 8.7 s⁻¹, which is easily calculated simply by deriving Eq. (1). The strain rate is the magnitude that least influences the static recrystallisation of austenite. Accordingly, the tests have been performed at a set rate of 3.63 s⁻¹, which is equivalent to a torsion rate of 1 000 turns/min. On the other hand, working at higher strain rates may imply some additional heating of the specimen due to the deformation work performed, and although the strains are relatively low (0.20 and 0.35) they may give rise to slight heating of the specimen during deformation.

#### 3.2. Hot Rolling Simulation and Accumulated Stress

The torsion test gives the applied torque versus the number of turns made on the specimen, which are transformed respectively into the equivalent stress and strain. The simulation consisted of 21 passes, with first pass temperature of 1150°C, a temperature drop of 25°C between each pass, and so the temperature of the final pass was 650°C. Several interpass times (Δt) were tested. The effect of the strain (\( \varepsilon \)) was also tested by applying values of 0.20 and 0.35 in two simulation series, respectively. The strain rate (\( \dot{\varepsilon} \)) of 3.63 s⁻¹ was applied in all the simulation series. The different deformation conditions are shown in Table 3.

**Figure 1** shows the simulation of 21 rolling passes for the studied steel with an interpass time of 20 s. The stress rises as the temperature decreases, and there is a change in the slope with a growth in the stress, which means a greater tendency to strengthening. Later, the stress drops and then grows again during the final passes.

The meaning of these zones is better explained by ob-

<table>
<thead>
<tr>
<th>Precipitate</th>
<th>( T_n ), °C</th>
<th>( X_p ) (800°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VN</td>
<td>1146</td>
<td>9.35x10⁻⁴</td>
</tr>
<tr>
<td>VC²⁷</td>
<td>857</td>
<td>4.38x10⁻⁴</td>
</tr>
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</table>

**Table 1.** Chemical composition of steel used (wt%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>V</th>
<th>N</th>
</tr>
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<tr>
<td>0.165</td>
<td>0.532</td>
<td>1.560</td>
<td>0.170</td>
<td>0.016</td>
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</tbody>
</table>

**Table 2.** Solubility temperatures (\( T_n \)) and precipitated volume fraction (\( X_p \)) at 800°C.
serving Fig. 2, which shows the graphic representation of Mean Flow Stress (MFS) versus the inverse of the absolute temperature for an interpass time of 20 s and strain of 0.35. MFS is determined in each step by dividing the area below the stress–strain curve by the strain applied. In Fig. 2 it is possible to see three different zones. In the first zone (I), which corresponds to deformations at the highest temperatures, MFS grows as the temperature decreases. Austenite recrystallises completely between passes and there is no accumulated stress. The increase in stress is only due to the decrease in temperature. In the second zone of the curve (II) there is a change in the slope, which indicates a greater tendency towards hardening. Here the stress accumulates in the austenite, whose recrystallisation between passes is partially inhibited. The third phase (III), characterised by a drop in MFS as the temperature decreases, corresponds to the austenite to ferrite and pearlite transformation.

The intersection of the straight regression lines of phases I and II defines the value of $T_{nr}$ and the intersection of the regression lines of phases II and III determines the value of $A_3$. The method applied considers that if the austenite were to recrystallise completely between passes until reaching $A_3$, the slope of the zone II straight regression line would be the same as that of the zone I straight line, and in this case the accumulated stress ($\Delta \sigma$) would be nil.

The value of $\Delta \sigma$ can be measured from the graph of MFS versus the inverse of the temperature and will be given by the length of the vertical segment limited by the phase I and phase II regression lines, as is illustrated in Fig. 2. When the temperature is $A_3$, $\Delta \sigma$ reaches its maximum value in austenite. In this way it has been possible to measure accumulated stress for all the thermomechanical simulations in a quick and precise way, since this magnitude represents better than any other the degree of strengthening of the austenite in the temperature interval $T_{nr}/H11002$.

### 3.3. Determination of Critical Parameters ($T_{nr}$, $A_3$, $\Delta \sigma$)

Figure 3 shows another example of a thermomechanical simulation where the value of MFS is represented versus reciprocal pass temperature ($1/T$) for a strain of 0.20.

The values of $T_{nr}$, $\Delta \sigma$ and $A_3$ were measured on the graphs of MFS versus reciprocal pass temperature $1/T$ for all the tested deformation conditions. Figures 4 and 5 illustrate the influence of $\Delta \sigma$ and the strain on $T_{nr}$ and $A_3$, respectively. $T_{nr}$ decreases considerably with $\Delta \sigma$ and is always lower for the strain of 0.35. An increase in $\Delta \sigma$ obviously means improving the possibility of the recrystallised fraction increasing between passes with temperatures below $T_{nr}$.

In the same way, $\Delta \sigma$ decreases with $\Delta \sigma$ and is also lower when the applied strain was 0.35. These results indicate that in order to achieve good strengthening of the austenite dur-

### Table 3. Hot rolling simulation conditions.

<table>
<thead>
<tr>
<th>RT, °C</th>
<th>Pass strain (ε)</th>
<th>Pass strain rate ($L_e$, s⁻¹)</th>
<th>First pass temp., °C</th>
<th>Last pass temp., °C</th>
<th>$\Delta T$, °C</th>
<th>$\Delta \sigma$, s</th>
<th>Cool., rate, K/s</th>
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<tbody>
<tr>
<td>1200</td>
<td>0.20</td>
<td>3.63</td>
<td>1150</td>
<td>650</td>
<td>25</td>
<td>20</td>
<td>1.250</td>
</tr>
<tr>
<td>1200</td>
<td>0.20</td>
<td>3.63</td>
<td>1150</td>
<td>650</td>
<td>25</td>
<td>30</td>
<td>0.833</td>
</tr>
<tr>
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<td>1150</td>
<td>650</td>
<td>25</td>
<td>60</td>
<td>0.417</td>
</tr>
<tr>
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<td>3.63</td>
<td>1150</td>
<td>650</td>
<td>25</td>
<td>100</td>
<td>0.250</td>
</tr>
<tr>
<td>1200</td>
<td>0.20</td>
<td>3.63</td>
<td>1150</td>
<td>650</td>
<td>25</td>
<td>200</td>
<td>0.125</td>
</tr>
<tr>
<td>1200</td>
<td>0.35</td>
<td>3.63</td>
<td>1150</td>
<td>650</td>
<td>25</td>
<td>20</td>
<td>1.250</td>
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<td>1200</td>
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<td>25</td>
<td>200</td>
<td>0.125</td>
</tr>
</tbody>
</table>

Fig. 1. Strain–stress curves in hot rolling simulation.
ing hot rolling, close to pancaking, it is necessary to apply low strains and to reduce the interpass time, as would be the case in the finishing strip mill. In plate hot rolling it is more difficult to achieve pancaking, but a reduction in the interpass times and low strains in the final passes would help to achieve this objective.

Following the geometric procedure noted above for determining $\Delta \sigma$, the accumulated stress can easily be measured at any temperature above $A_{\text{r}3}$ and below $T_{\text{nr}}$, thus making it possible to know the gradual grade of strengthening as a function of the temperature. For this purpose it is sufficient to subtract from the zone I regression plot the zone II regression plot for temperatures between $T_{\text{nr}}$ and $A_{\text{r}3}$. The results calculated in this way are shown in Figs. 6 and 7 for strains of 0.20 and 0.35, respectively. The graphs clearly show the evolution of accumulated stress versus temperature and make it possible to find, either directly or by interpolation, the accumulated stress that the austenite would have at the end of hot rolling, whatever the temperature at which it finishes.

When the values of $A_{\text{r}3}$ corresponding to the two strains are compared (Fig. 8) it is seen that those corresponding to the strain of 0.20 are slightly higher than those corresponding to the strain of 0.35. The explanation for this must lie in the evolution of the austenite. The combination of the $\Delta \sigma$ value and the austenite grain size gave rise to more nucleation sites for ferrite when the applied strain was 0.20 than when it was 0.35.

Given that the hardening of austenite takes place between $T_{\text{nr}}$ and $A_{\text{r}3}$, the difference between these two temperatures ($\Delta T$) marks the interval where hardening is possible. Figure 9 shows this interval as a function of the interpass time ($\Delta t$) for each of the strains applied in each pass. The influence of strain was not important and only a regression was done. The logarithmic regression, whose curve have been plotted, yielded a higher correlation index compared to
other possible regressions, such as potential or exponential, whose expression is as follows:

\[ \Delta T(\degree C) = 184.5 - 26.8 \ln(\Delta t) \]

The above expressions clearly indicate that a cut in the interpass time reduces the temperature interval where austenite can be strengthened, due especially to the decrease in the parameter \( T_{nr} \). Comparison of these results with Nb microalloyed steels indicates that this interval is much smaller for V microalloyed steels, even with much greater V than Nb contents.\(^{11,18}\) However, the interval for V microalloyed steels is greater than that for Ti microalloyed steels, where the \( T_{nr} \) temperature is often inexistent when the rolling conditions imply a relatively high pass strain and even when interpass times are short.\(^{19}\)

### 3.4. Ferrite Grain Size

Microalloyed steels are normally rolled at temperatures above \( A_3 \) and the final pass, e.g. in the hot strip mill, is performed at a temperature close to \( A_3 \). In view of this fact, new simulations were carried out in the same conditions as the previous simulations but performing the last pass at 800°C and cooling the specimen in an argon stream at a rate of approximately \((3.5 \text{ K/s})_{800-500} \degree\text{C}\) to room temperature. Figures 10 and 11 show microstructures obtained in the conditions noted in the respective captions with regard to pass strain and interpass time. The ferritic grain sizes measured \( (D_a) \) for all the conditions are shown in Fig. 12 versus the accumulated stress \( (\Delta \sigma) \) in austenite at 800°C. On the other hand, the accumulated stress at 800°C interprets the stress state of austenite at that temperature and is closely related with the dislocation density.\(^{19}\)

Although larger values of \( \Delta \sigma \) were reached when the strain was 0.20, \( D_a \) was lower for the strain of 0.35. The increase in strain originates a greater recrystallised fraction between passes and thus a lower \( \Delta \sigma \) value. At the same time, the average austenite grain size will be somewhat smaller when the strain is greater, because a higher recrystallised fraction percentage reduces the average austenite grain size.\(^{20}\) In the case of the strain of 0.20, \( D_a \) starts to drop slightly when \( \Delta \sigma \) exceeds a value of 17 MPa. For the strain of 0.35, \( D_a \) shows a slight tendency to decrease with the accumulated stress, although not so clearly as in the previous case.

On the other hand, it is very well known that in order for the nucleation of ferrite to take place to an important extent

![Fig. 10. Microstructures obtained by hot rolling simulation and cooling from 800°C. Pass strain=0.20; interpass time: (a) 20 s; (b) 100 s.](image1)

![Fig. 11. Microstructures obtained by hot rolling simulation and cooling from 800°C. Pass strain=0.35; interpass time: (a) 20 s; (b) 100 s.](image2)

![Fig. 12. Ferrite grain size versus accumulated stress.](chart1)
on arrangements of dislocations (subgrains) it is necessary to reach an accumulated stress of more than 40 MPa. Consequently, the nucleation of ferrite has happened preponderantly on grain boundaries, as can be deduced by comparison of the graphs corresponding to the two strain values, and possibly also on VN precipitates. Nevertheless, it is difficult to quantitatively distinguish these two contributions from the tests performed.

3.5. Relation between Austenite and Ferrite Grain Sizes

The influence of the austenite grain size prior to the ferrite transformation is known, but in the present case of a V microalloyed steel with relatively high V and N contents it is useful to know, albeit approximately, the quantitative relation between the two magnitudes. For this purpose simulations were performed at a pass strain of 0.20, an interpass time of 30 s, and final rolling temperatures of 1 100, 1 000, 900 and 800°C, respectively. In the first series of simulations each specimen was quenched in water after being deformed at the final rolling temperature and held for a time of 30 s at this temperature. In this way the accumulated stress reached in the austenite after holding may be deduced from Fig. 4. In the second series the specimens were cooled by means of an argon stream at a cooling rate of approximately 3.5 K/s.

The measured grain sizes are shown in Fig. 13. The final temperature of 800°C is lower than \( T_{nr} \), which according to Fig. 6 corresponds to a \( \Delta \sigma \) value of approximately 19 MPa. However, the accumulated stress corresponding to the final temperatures of 900, 1 000 and 1 100°C is zero, because these temperatures are higher than \( T_{nr} \). Therefore, in Fig. 13 the point referring to the final temperature of 800°C, represented by an asterisk, is outside the logarithmic tendency of the other points which are related to completely recrystallised austenites, i.e. austenites without deformation. It should be noted that the average austenite grain size was approximately the same at 900°C as at 800°C. If it is accepted that strain induced precipitation in microalloyed steels starts at a temperature close to \( T_{nr} \), it is highly likely that the ferrite grain refinement obtained by cooling from 800°C compared to that obtained in cooling from 900°C is not only due to the accumulated stress but also to the possible intragranular nucleation of ferrite on VN precipitates. The latter conclusion is also confirmed by other studies of intragranular nucleation of ferrite in high V and N content steels.\(^{13}\)

3.6. Analysis of Precipitates by SEM-FEG

With the aim of revealing possible intragranular ferrite nucleation on V-precipitates, a further microscopy study, using a Jeol JSM 6500F scanning electron microscope equipped with a field emission gun (SEM-FEG), was carried out on several samples for different hot deformation conditions.

Figure 14 shows a SEM image where a relatively large VN precipitate can be seen inside a ferrite grain well below the average size, it being highly likely that this precipitate may have served as a source for the nucleation of this grain. In the same image a large number of VN-precipitates can also be seen. The observation of several images allowed the verification of the presence of many small ferritic grains on this specimen and on others tested in different conditions and for longer precipitation times, corresponding to higher precipitated volumes and coarser precipitate sizes. Vanadium and nitrogen peaks can be found in the spectrum performed for the largest precipitate (Fig. 15). Finally, the precipitated volume fractions for nitrides and carbides were calculated at 800°C, in accordance with Manohar et al. (Table 2), respectively.\(^{21}\) In the calculation of the precipitated volume fraction of carbides, consideration has been made of the V precipitated at this temperature as VN and this has been deducted from the total content. The calculation performed is an approximation to the true nature of the precipitates, since a large part could be present as carbo-nitrides. The total precipitated volume fraction, adding to-
gether nitrides and carbides (Table 2), is $1.37 \times 10^{-3}$, which is higher than the precipitated volume fraction of other V microalloyed steels which presented intragranular ferrite nucleation on VN type precipitates.\(^ {13}\)

4. Conclusions

(1) Thermomechanical simulation makes it possible to know the apparent $A_{\text{r3}}$ transformation temperature at the same time as determining the no-recrystallisation temperature ($T_{\text{nr}}$) and residual stress ($\Delta \sigma$).

(2) The accumulated stresses between $T_{\text{nr}}$ and $A_{\text{r3}}$ were relatively small as a consequence of the low $T_{\text{nr}}$ values obtained, implying an insufficient temperature interval to reach high $\Delta \sigma$ values that favour ferrite grain refinement by intragranular nucleation on dislocations.

(3) The accumulated stress is a direct and precise measurement of the state of austenite as a function of the temperature, and is greater the lower the strain applied in each pass.

(4) In order to obtain strongly deformed austenite microstructures before the $\gamma \rightarrow \alpha$ transformation it is advisable to reduce the interpass time and the magnitude of the strain applied in the final passes.

(5) The $A_{\text{r3}}$ values found by thermomechanical simulation were slightly higher when the strain was slightly smaller (0.20), as a consequence of the higher $\Delta \sigma$ values.

(6) Induced precipitation improves ferrite grain refinement. In the present case the intragranular nucleation of ferrite on VN precipitates has played a notable role.

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