Analysis of Microstructure Evolution during Steckel Mill Rolling of AISI304 Stainless Steel

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(Received on August 29, 2007; accepted on November 30, 2007)

The microstructural evolution in AISI304 austenitic stainless steel during Steckel mill rolling has been investigated. Particular emphasis is placed on the microstructural behaviour of the strip ends relative to the strip bulk. Good correlation between the development of hard ends that arise in the final strip and strip temperature and mean flow stress has been found by analysing mill log data. Measurement of the recrystallization kinetics under conditions that simulate Steckel mill rolling have shown that deformation temperatures below 950°C can lead to incomplete recrystallisation during the Steckel mill inter-pass. Predictions of the time to 50% recrystallisation ($t_{0.5}$) are used to quantify the recrystallisation kinetics of the strip ends.

KEY WORDS: austenitic stainless steel; Steckel mill; recrystallization.

1. Introduction

Steckel mill rolling presents opportunities to produce high quality strip on an economic scale, particularly where flexibility is required for smaller production quantities coupled to the need to produce a wide range in strip widths. Several new installations have occurred over the past decade or so, and particular advantages have been gained by the use of these mills for stainless steel production.1,2) The feature of the Steckel mill that distinguishes it from other hot strip reversing mills is the two coiling furnaces on either side of the work rolls and this setup is illustrated in Fig. 1. The temperature in these coiling furnaces is set at approximately 1 000°C for hot rolling AISI304 austenitic stainless steel.3) The transfer bar, which typically measures about 30 mm in thickness, approaches the entry-side of the Steckel mill after the final pass on the roughing stand and is threaded into the roll gap where after it is threaded onto the mandrel in the delivery-side cooling furnace at a speed of approximately 2–3 m s$^{-1}$. Acceleration of the mandrel and mill follows until the tail end of the strip approaches the work roll, at which time braking occurs to allow the tail end to come to a stop just outside the work roll. In this position, the roll gap is reset for the next pass. The reset time is minimized to conserve heat in the ends, but can take up to 5–7 s for 1 300 mm wide AISI304 stainless steel strip. The process is now reversed as the tail end passes through the roll gap and into the entry-side cooling furnace. The strip goes through this process an odd number of times, usually 5, 7 or 9 times depending on the final gauge required after Steckel mill rolling. On the last pass the strip passes under the delivery-side hot coil furnace to the laminar coolers and down-coiler.

Notwithstanding the immense benefits derived from Steckel mill rolling, the development of cold ends during the later roll passes can lead to microstructure, and hence mechanical property, differentiation along the length of the strip after completion of the hot rolling schedule. Cold ends arise due to the extended intervals that the tail and head ends experience outside the coil-box at the conclusion of a roll pass and the start of a new roll pass. Consequently, the temperature of the strip ends drops significantly below the nominal roll pass temperature. In the case of austenitic stainless steels, the drop in temperature can retard recrystallisation sufficiently to inhibit complete softening of the head/tail ends between roll passes. If the head/tail end differences are carried through to cold rolling, then product differentiation will occur and ends will generally be off-specification relative to the bulk strip. There are two possible ways of eliminating the head/tail end problems: (1) Anneal entire strip after completion of the Steckel mill roll

![Fig. 1. Schematic of Steckel mill illustrating coiler drums on either side of the work rolls.](image-url)
schedule (batch or continuous line-anneal), or (2) perform direct annealing in the coil drum after the final Steckel mill roll pass. Although both these processes are easily executed but costly, the level of annealing required depends on the extent of retained deformation in the head/tail ends. The present work reports on a study that was undertaken to analyse the microstructure evolution during Steckel mill rolling of AISI304 austenitic stainless steel, with particular emphasis on the head/tail ends. Metal strip has been sampled at the end of the Steckel mill process to establish the extent of property and microstructure variation along the length of the strip. Correlation of the latter with the rolling parameters has been attempted by examining the actual mill conditions (mill logs) for specific Steckel mill rolling schedules. Since emphasis is placed on eliminating hard ends, the kinetics of recrystallization under conditions that closely resemble the rolling conditions have been studied by performing controlled laboratory compression tests and static annealing heat treatments. Finally, consideration is given to the necessary remedial action that may assist in producing more homogeneous strip after Steckel mill rolling.

2. Experimental Procedure

The nominal composition of the AISI 304 stainless steel that was studied in this investigation is given by: Fe–18.0wt%Cr–0.04wt%C–8.0wt%Ni–1.4wt%Mn–0.4wt%Si–0.08wt%Mo. The study included samples extracted from two sources. In the first instance, samples were extracted along the length of the metal strip after the conclusion of the Steckel mill rolling process. These samples were used to investigate the hardness and microstructure, with particular emphasis on the comparison of the strip ends versus the bulk of the strip. Analysis of the Steckel mill log data was used to reinforce the microstructure and hardness observations and, in addition, the mill log data was used to inform the parameter choice for simulating rolling deformation in the laboratory. The material that was used for the laboratory simulations was extracted from the transfer billet at the end of the rougher mill hot rolling process. Cylindrical compression slugs (13 mm diameter×21 mm long) were machined such that the compression axis coincided with the original rolling direction. In order to establish a known reference condition, the test specimens were annealed at 1 050°C for 1 800 s to promote a homogeneous recrystallized microstructure that generated an average grain size of 35 μm. Compression testing was performed using a Cam plastometer which is able to ensure constant strain rate at levels representative of the actual rolling process (20–60 s⁻¹). Barrelling was minimized to acceptable level by the use of boron nitride lubricant. Test temperatures ranged between 850°C and 1 050°C and strain was limited to 0.2–0.3 per compression in order to simulate typical roll passes during Steckel mill rolling. In the case of single-step deformation, the specimen was rapidly heated in situ and held for 60 s prior to compression. For simulating a two-pass schedule, the specimen was held at the deformation temperature for 60 s between the two compression events. In all cases the specimens were quenched in water within 2–5 s after the last deformation event.

Post-deformation recrystallization behaviour was studied by subjecting the as-deformed compression specimens to isothermal annealing in a salt bath. Recrystallization progress was monitored by metallography and by hardness measurement. The microstructures were observed using light microscopy, but in some instances electron backscattered diffraction imaging was employed to confirm the extent of recrystallization. Two different etchants were used to reveal the microstructures. Specimens were electrolytically etched (10 V for 25–60 s) in 10% oxalic acid to reveal annealing twins. An etchant of 60% nitric acid and 40% water was used to reveal grain boundaries and grain shape. The voltage was set at 1.6 V and the current density was approximately 10 mA cm⁻².

3. Results

3.1. Steckel Mill Analysis

The measured hardness of the head, tail and middle sections of the hot rolled strip (5 mm gauge) after cooling on the down-coiler is shown in Fig. 2. The measurements in Fig. 2 represent the average from two heats which were rolled in similar 5-pass schedules. The trend is very convincing in that the head and tail ends are significantly harder than the bulk of the strip which is represented by the middle section hardness. It is interesting to note that the variation in hardness through the strip thickness is relatively low and suggests quite uniform deformation conditions through the strip thickness compared to the variations that appear to occur along the length of the strip. Comparison of the microstructures of the head and tail versus the middle section reinforces the hardness trends in that the head/tail ends always demonstrate deformed grains (flattened grain boundaries) whereas the middle section displays annealing twins as a consequence of recrystallization.

Detailed analysis of the data recorded on the Steckel mill logs has revealed the extent of variation of the deformation conditions along the length of the strip, with particular emphasis on the differences between the head/tail ends and the middle section. Since the roll gap is fixed for a particular roll pass, the variables of interest include temperature and strain rate. The roll speed accelerates and decelerates at the start and end of the roll pass, whereas the bulk of the strip experiences more or less constant roll speed conditions. Consequently, the strain rate is more or less fixed for the bulk of the strip (middle section), but is lower for the head

Fig. 2. Hardness of strip showing the contrast in the head, middle and tail sections.
and tail ends. Observations during the laboratory simulations have shown that strain rate variation has much less of an impact on microstructure evolution compared to the effects of temperature within the ranges experienced during the hot rolling process. The minimum and maximum temperatures recorded during 7-pass rolling schedules are presented in Fig. 3 for eight different heats. In each case the minima and maxima are determined from the average of the entry and exit temperature recorded for each roll pass. Understandably the maximum temperature represents the bulk strip, whereas the minimum temperature indicates the average condition of the head and tail ends. Figure 3 shows that the trend is consistent for all eight heats in that the maximum temperature changes only slightly in contrast to the significant decrease in minimum temperature as the strip reduction increases. The head/tail ends not only suffer temperature drop due to the accumulated time spent outside the coil-box, but the decreasing strip thickness assists in more rapid heat loss as reduction increases. Although the scenario depicted in Fig. 3 clearly illustrates the widening gap between maximum and minimum temperatures as rolling progresses, it does not indicate the temperature distribution along the length of the strip. Specific temperature measurements at fixed positions of equal spacing along the length of the strip for a 5-pass roll schedule are presented in Fig. 4. The hyperbolic shape of the temperature distribution along the length of the strip becomes more enhanced as reduction increases and notably after pass 5 a large portion of the metal strip is affected by significant temperature reduction, although the irregular shape of the temperature distribution curve does suggest that some of the readings may have been slightly erroneous. Nevertheless, the trend is important. A typical cast slab measures approximately 12 m long which means that the hot rolled strip after the last pass on the Steckel mill (5 mm gauge) can be up to 500 m long. Thus the distance between the 14 measurement points in Fig. 4 can be as much as 36 m for pass 5 thereby implying that the affected head/tail ends can be up to 100 m in length.

Several additional rolling parameters were also recorded for the 14 reference points in Fig. 4, which allowed the determination of the mean flow stress (MFS) for each reference point for the successive roll passes (Fig. 5). The MFS (\(\bar{\sigma}\)) was calculated from the recorded data using the equations given below \(^1\):

\[
\bar{\sigma} = \sqrt{\frac{3}{2}} \left( \frac{P}{wQ\sqrt{R'(\Delta h)}} \right)
\]

(1)

Where:  
- \(w\): width of strip (mm)  
- \(R'\): flattened work roll radius (mm)  
- \(\Delta h\): draft=\((h_i-h_o)\) (mm)  
- \(h_i\): input gauge or thickness (mm)  
- \(h_o\): output gauge or thickness (mm)  
- \(P\): roll force (N)  
- \(Q\): geometric factor in flow stress calculations (dimensionless)

\[
Q = \frac{1}{2} \left( \frac{1-r}{r} \right) \left( \pi \tan^{-1} \left( \frac{r}{1-r} \right) - \sqrt{\frac{R}{h_o}} \ln \left[ \frac{h_o}{h_i} \right] (1-r) \right) - \frac{\pi}{4}
\]

(2)

Where:  
- \(r\): reduction \(\Delta h/h_o\) (dimensionless)  
- \(h_o\): neutral height (mm)

There is reasonable correspondence between the temperature distribution depicted in Fig. 4 and the MFS trends shown in Fig. 5. At first glance it is not surprising that the cooler ends should present higher MFS values since when all else is more or less equal, temperature has a strong influence on flow stress. However, it has already been indicated that the strain rate is much lower for the strip ends compared to the bulk and thus this should compensate for the lower temperature by displaying less variance in the MFS...
value. To illustrate this, the flow stress has been simulated for pass 5 based on the measured temperature, strain and strain rate information. The simulated flow stress values were derived from a comprehensive study of the deformation behaviour of the same alloy under temperature, strain and strain rate conditions that span the full range experienced during Steckel mill rolling. In this study, the measured stress curves were fitted to a function of strain, strain rate and temperature of the form:

\[ \sigma_s(e, \dot{e}, T) = \left[ A_1 e^{0.38} + A_2 e^{0.50} + A_3 e^{0.83} \right] \cdot \left[ B_1 (\ln(\dot{e}) + 7) + B_2 (\ln(\dot{e}) + 7)^2 \right] \cdot \left[ C_1 (T - 1500) + C_2 (T - 1500)^2 \right] \]

The coefficients in the equation were solved using linear regression and gave a correlation of over 98% to the original data. This equation was used to determine the flow stress values indicated for the simulated curve (pass 5) in Fig. 5. It is necessary to emphasise for the sake of comparison that the simulated flow stress values assume a fully recovered starting strain and not calculated MFS, the flatness of the curve does suggest that the temperature drop is quite well compensated for by the reduction in strain rate experienced by the head/tail ends. Therefore the exaggerated hyperbolic shape of the actual MFS curve for pass 5 (emphasised by the dashed trendline in Fig. 5) must indicate significant accumulated deformation for the head/tail ends from previous passes.

### 3.2. Laboratory-scale Deformation Tests

Two-step (or double-hit) compression tests were performed on cylindrical specimens at temperatures in the range 850 to 1050°C to assess the extent of softening that could occur between roll passes. For each test temperature, the specimen was compressed to a nominal plastic strain of 0.2 on the first hit followed by a 60 s relaxation period, and finally compressed (second hit) by a nominal plastic strain of 0.25. The constant strain rate for both hits was 60 s⁻¹ and the specimen was quenched to room temperature immediately after the final compression event. The flow curves for the double-hit compression tests performed at 850°C, 950°C and 1050°C are exhibited in Fig. 6. Understandably, if complete softening occurs between deformation hits, then the flow curves for the successive compression events will be nearly identical. This behaviour is well represented for the double-hit test at 1050°C and to a slightly lesser extent for the test at 950°C. On the other hand, the test at 850°C demonstrates much greater resistance to plastic flow in the second hit compared to the first hit and thus suggests a high level of plastic strain retention in the microstructure even after the 60 s annealing interval. Although the data is not shown in Fig. 6, the test at 900°C also demonstrated significant plastic strain retention, yet to a slightly lesser extent than that displayed for the test at 850°C. The quenched-in microstructures were examined for each test condition and are displayed in Fig. 7. The microstructures after the double-hit tests at 850°C and 900°C are similar and indicate flattened grains with wavy boundaries. As the test temperature increases from 950°C, the microstructures demonstrate progressive increase in the extent of recrystallization, which is typified by the appearance of straight annealing twin boundaries.

A more quantitative judgment of the inter-pass annealing behaviour for the tests described in Figs. 6 and 7 can be obtained by calculating the fractional softening that has occurred between the two successive deformation episodes. The restoration of yield stress is used to determine the fractional softening in the following way:

\[ FS = \frac{\sigma_{f1} - \sigma_{y2}}{\sigma_{f1} - \sigma_{y1}} \] ..........................(4)

Where: \( \sigma_{f1} \): flow stress after the first hit (MPa) 
\( \sigma_{y1} \): original yield stress for the first hit (MPa) 
\( \sigma_{y2} \): yield stress for the second hit (MPa)

The results of this analysis are presented in Fig. 8, which agree very well with the qualitative assessment of the microstructures shown in Fig. 7.

### 3.3. Assessment of Recrystallization Kinetics

The foregoing analysis demonstrates quite clearly that the recrystallization kinetics experienced at the strip ends is much slower than that for the strip bulk, and consequently, higher accumulated strain occurs and the MFS rises for the strip ends. Despite the slow cool cycle experienced by the coil after the last pass on the Steckel mill, the hardness trends depicted in Fig. 2 indicate that complete recrystallization has not occurred in the strip ends. Remedial steps to ensure that recrystallization does occur requires some appreciation of the recrystallization kinetics under condi-

![Fig. 6. Double-hit compression tests: Hit 1 indicates the flow stress during the first deformation event and Hit 2 during the second deformation event. The temperature (°C) is given in the legend.](image)

![Fig. 7. Quenched-in microstructures after double-hit compression tests at: (a) 850°C; (b) 900°C; (c) 950°C; (d) 1000°C; (e) 1050°C. CD=compression direction.](image)
tions relevant to those experienced by the strip ends during rolling and during the slow cool after the last pass. The most common way to achieve this is to determine the time to 50% recrystallization ($t_{0.5}$) using the Johnson–Mehl–Avrami–Kolmogorov (JMAK) approach whereby the fraction recrystallized is related to the $t_{0.5}$ value as follows:\textsuperscript{9–13):} 

$$X_{SRX} = 1 - \exp\left(-\ln 2\left(\frac{t}{t_{0.5}}\right)^k\right) \quad \text{(5)}$$

Where:

- $X_{SRX}$: volume fraction of statically recrystallized grains
- $t$: annealing time (s)
- $k$: Avrami constant
- $t_{0.5}$: time to 50% recrystallization (s)

Calculation of $X_{SRX}$ requires knowledge of the Avrami constant and the $t_{0.5}$ value. The latter value is commonly described as:

$$t_{0.5} = A \hat{\varepsilon}^n e^{\frac{Q_{SRX}}{RT}} \quad \text{(6)}$$

Where:

- $D_0$: grain size ($\mu$m) before deformation
- $\hat{\varepsilon}$: strain rate ($s^{-1}$) during deformation
- $\varepsilon$: strain after deformation
- $Q_{SRX}$: activation energy of static recrystallization (J·mol$^{-1}$)
- $T$: annealing temperature (K)

The Zener–Hollomon parameter ($Z$) embraces the control variables $\hat{\varepsilon}$ and $T$ in the hot working process:\textsuperscript{14):} 

$$Z = \hat{\varepsilon} \exp\left(\frac{Q_{def}}{RT_{def}}\right) \quad \text{(7)}$$

Where:

- $T_{def}$: temperature of deformation (K)
- $R$: gas constant (8.31 J·mol$^{-1}$·K$^{-1}$)
- $Q_{def}$: activation energy for deformation (J·mol$^{-1}$)

Equations (5) and (6) indicate that if the Avrami constant is known, and if $t_{0.5}$ is able to be calculated from the relevant deformation and material parameters, then the fraction recrystallized ($X_{SRX}$) can be determined as function of time for the relevant annealing condition. Many studies of this nature have been performed on AISI304 austenitic stainless steel, but subtle variations on the form of Eq. (6) and the value of the relevant exponents have arisen.\textsuperscript{9,15–20) Furthermore, all the relevant constants for Eq. (6) are not always available. Consequently, the need has arisen in this study to refine certain parameters by measuring the recrystallization kinetics under conditions that more closely approximate Steckel mill rolling practice.

The recrystallization kinetics of the steel were determined by performing isothermal annealing treatments on specimens that were initially deformed by single hit compression and quenched to room temperature. Strain and strain rate were fixed at 0.3 and 60 s$^{-1}$ respectively and annealing was performed at a temperature equal to the deformation temperature in each case. The first step in characterizing the recrystallization kinetics was the measurement of hardness decay as function of annealing time. The results for tests performed at 900°C, 950°C and 1 000°C are indicated in Fig. 9. Included in Fig. 9 is the annealing behaviour after deformation at 850°C. In the latter case the strain rate was lowered to 20 s$^{-1}$ to more closely imitate the conditions experienced by the strip ends.

Comparison of Fig. 9 and Fig. 10 illustrates close correlation between the measured softening behaviour and the observed progression in recrystallization for each stage during the isothermal annealing treatments. Consequently, it is possible to extract the fraction recrystallized from the fraction softened, where the latter is calculated as follows\textsuperscript{18,19,21):} 

$$X_h = \frac{h - h_i}{h_i - h} \quad \text{(8)}$$
Where: $h$: instantaneous measured hardness (HV)
$h_0$: initial hardness (HV)
$h_r$: fully recrystallized hardness (HV)

The conversion of the fraction softened to the fraction recrystallized is then simply the inverse shape of Fig. 9 where the fraction recrystallized is seen to increase with time. Although the trends in Fig. 9 do not emphasise the expected incubation periods for recrystallization, it is believed that the incubation period could be so short as to be undetectable by this type of analysis. The minimum detectable time in this study is conservatively estimated at 10 s which allowed some compensation for the uncertainty associated with the quench period after the deformation event. Thus it is quite possible that incubation occurred during this short interval, or in fact it may be that metadynamic recrystallization occurred. Manipulation of the fraction recrystallized versus time data to suit the form of Eq. (5) yielded an Avrami constant of 1.1 and enabled the calculation of $t_{0.5}$ for each specific deformation/annealing condition. The expression proposed by Baraclough and Sellsars\(^{22}\) was employed since it was determined using AISI304 stainless steel from the same mill ($Q_{\text{rec}} = 434 \text{kJ} \cdot \text{mol}^{-1}$). The calculation of the constant $A$ and the activation energy for recrystallization ($Q_{\text{rec}}$) followed to give the following expression:

$$t_{0.5} = 6 \times 10^{-6} e^{2 D_0 Z^{-0.375}} \exp \left[ \frac{478 000}{RT} \right] \quad \ldots \ldots (9)$$

Equation (9) can now be used to predict the recrystallization kinetics for the strip ends after each roll pass. The relevant parameters required by Eq. (8) were extracted from the mill log data for the 5-pass roll schedules that were used to create Fig. 2. The effective strain, time to 50% recrystallization ($t_{0.5}$) and fraction recrystallized are indicated in Fig. 11 for the head end after each roll pass. The prediction only takes into account static restoration and in each case the microstructural condition is estimated at the end of the inter-pass period. Effective strain is accounted for by accumulating residual strain from the previous deformation event in proportion to the amount of recrystallization that occurs during the relevant roll pass interval. Figure 11 demonstrates that complete restoration does not occur after every inter-pass period, but that there is sufficient strain accumulation to promote complete recrystallization after the third roll pass. Strain starts to accumulate again after the fourth roll pass. The predicted $t_{0.5}$ value after pass 5 suggests that complete restoration should occur since the static annealing interval associated with down-coiling is substantially longer than the preceding inter-pass periods. However, the hardness trends in Fig. 2 indicate that this cannot be the case since the head/tail ends are consistently harder than the bulk of the strip after cooling following the final roll-pass. This disparity is discussed further in the next section.

4. Discussion

The steady decrease in the temperature of the strip ends as Steckel mill hot rolling proceeds is in most instances unavoidable due to the very nature of the rolling process design. Furthermore, the roll-speed acceleration and deceleration at the start and end of a roll pass imply non-uniform strain rate along the strip length. As a consequence, the strip ends experience different thermo-mechanical process conditions compared to the bulk of the strip. The present study has emphasised the influence of the differential thermo-mechanical process conditions on the microstructural and hardness property development in AISI304 austenitic stainless steel by way of examination of microstructure and hardness of the final strip after cooling to room temperature. Although the argument to support differential thermo-mechanical process conditions is obvious from the hardness and microstructure results, interrogation of the rolling mill logs has provided more detailed insight into the differential rolling history experienced by strip ends and bulk strip. Monitoring of the minimum and maximum temperatures demonstrates consistent lowering of the strip end temperatures as rolling progresses, whilst systematic temperature measurement at fixed intervals along the length of the strip indicates the extent to which the relative length of the affected ends increases with increasing number of roll passes. Identification of the development of the hard ends is made possible by examination of the mean flow stress (MFS) as function of pass number and strip position as depicted in Fig. 5. A rise in MFS towards the strip ends is particularly noticeable in the ultimate and final pass. Comparison of these MFS values with the predicted flow stress values if complete softening is assumed during the inter-pass period suggests that the actual MFS rise is due to strain retention between roll passes, particularly between the ultimate and final roll passes. Apart from the manifestation of differential hardness and microstructure, the increased MFS also leads to much greater demand on rolling force requirement and therefore impacts on the rolling process design.
Comparison of the strip temperature and MFS trends as function of roll pass number and strip position in Figs. 4 and 5 implies that strain retention starts to become significant when the strip temperature drops below about 900°C. The laboratory double-hit compression curves in Fig. 6 support this observation by demonstrating very little evidence of microstructure recovery during the inter-pass at 850°C as opposed to significant softening during the corresponding inter-pass at 950°C. Although the micrographs in Fig. 7 represent the quenched-in microstructures after the second compression hit, the distinction in microstructure between the tests performed at 900°C and 950°C is quite obvious. The fact that recrystallization can be identified in the quenched-in microstructure after the 950°C test suggests that either dynamic recrystallization has occurred or the incubation period for recrystallization is very short under these conditions at 950°C. The occurrence of dynamic recrystallization is often contentious, although it is quite convincingly described in the work by Belyakov et al.21) Research by Cho and Yoo23) has emphasized the critical role of dynamic and metadynamic recrystallization during hot rolling of austenitic stainless steel, although it may be deduced from their work that the critical strain for dynamic recrystallization under Steckel mill rolling conditions is generally greater than 0.4. Since the individual roll pass reductions are less than 0.4, significant strain retention between passes would have to occur in order to give rise to dynamic recrystallization. The simulation tests reported in Fig. 6 illustrate very low strain retention levels for deformation at 950°C and above and consequently the idea of dynamic recrystallization having given rise to the microstructures observed in the quenched specimens (Fig. 7) does not concur with the findings of Cho and Yoo.23) Nevertheless, it might still be possible that metadynamic recrystallization has been responsible for accelerating the onset of recrystallization during the very short static interval between the end of the deformation step and the quench to room temperature. Consequently, it is not surprising that softening has been almost complete during the inter-pass for compression simulations performed at 950°C and above. This result also supports the observation that the MFS for the bulk strip remains more or less constant during the entire Steckel mill process, which can be explained by the more or less constant strip temperature (approximately 950°C) over the bulk length (Fig. 4).

The qualitative assessment of the recrystallization kinetics, as deduced from the analysis of the mill log data and the laboratory double-hit compression tests, has been further extended by investigating the static recrystallization kinetics after single-hit compression tests in the temperature range 850 to 1000°C. There have been many comprehensive attempts at deriving expressions to quantify recrystallization in austenitic stainless steels during hot working, although in most instances the experimental deformation conditions have not closely simulated the actual hot working conditions. As a consequence, there is considerable variability in the predictive outcome of the proposed expressions. Furthermore, it has been demonstrated that static recrystallization kinetics should not be considered in isolation to dynamic and metadynamic recrystallization21) and hence the possibility of generalized expressions being able to reliably predict recrystallization kinetics under a broad range of deformation kinetics is unlikely. In our case we have limited the study to the conditions that approximate Steckel mill hot rolling and we have drawn on previously reported expressions where appropriate. The result is Eq. (9) which describes the time to 50% recrystallization. It is worth highlighting at least some similarities and differences between this expression and others. The Avrami constant (1.1) is close to the value of 1.02 reported in Ref. 9). The activation energy for recrystallization (Q_rex = 478 kJ·mol⁻¹), however, is quite different to the value of 197 kJ·mol⁻¹ reported in the same study. The value reported by Barraclough and Sellars19) is 425 kJ·mol⁻¹. The application of Eq. (9) is demonstrated in Fig. 11 for the head end of a typical 5-pass roll schedule. As already mentioned in Sec. 3.3, complete recrystallization is not expected during each roll inter-pass, but rather strain accumulation occurs which leads to significant recrystallization on a subsequent pass. Figure 11 indicates that the effective strain after pass 5 is greater than 0.6 due to strain accumulation from pass 4. Under these conditions, the predicted t_0.5 value is only 37 s after pass 5. However, the measured hardness after down-coiling and cooling to room temperature shows that very minor, if any, recrystallization occurs in the head end (Fig. 2). A similar scenario is depicted for the strip tail end. The temperatures employed in the t_0.5 prediction are measured as the strip exits the roll gap. Given that the anticipated heat loss is high at this stage of rolling due to the high surface area to volume ratio, it is quite possible that the further heat loss after the last pass drops the temperature below the critical point that would permit recrystallization. Although the metal is cooled after the last pass, the heat conduction from the hotter parts of the coil is slowed by the surface oxide build-up that has formed during rolling and therefore insufficient heat transfer occurs to raise the temperature enough to cause recrystallization. In this way, full softening of the strip ends after the last pass is only possible if the temperature of the ends can be raised after the last pass, or if the drop in strip temperature is avoided during rolling. The latter is unlikely in the present Steckel mill design. Retention of the strip in the furnace after the last pass could provide sufficient heating to cause complete recrystallization throughout the strip length.

5. Conclusions
The combination of the analysis of the rolling mill logs and metallurgical examination of the final hot rolled strip has highlighted the microstructure and hardness differences that occur along the length of the rolled strip, with particular emphasis on the distinction between the strip ends and the bulk strip. Laboratory investigation of the recrystallization kinetics under conditions that closely simulate the actual Steckel mill rolling process has demonstrated the limitations in recrystallization that are incurred at strip temperatures below 950°C. The following specific conclusions are made:

- The hardness of the strip ends is consistently greater than the strip bulk following direct cooling of the final strip to room temperature.
- Higher hardness of the strip ends can be accounted for by
the continuous drop in temperature and the resultant retardation of the recrystallization kinetics.

- Complete recrystallization of the final hot strip requires the strip temperature to be raised after the last pass in order to increase the recrystallization kinetics.

Acknowledgements
The compression testing undertaken at CANMET in Ottawa, Canada is deeply appreciated along with the technical support provided by Dr. Elachmi Essadiqi, Dr. Don Barager and Mr. Claude Marchand. The financial support provided by the National Research Foundation and the technical and financial support provided by Columbus Stainless (South Africa) are gratefully acknowledged.

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