Modeling of Flow Stress and Rolling Load of a Hot Strip Mill by Torsion Testing

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In order to characterize the Lake Erie Works hot strip mill, Stelco Steel, two grades of steel (C-Mn and Nb) were subjected to torsional simulation. The flow stresses and rolling loads are considered in this report. The microstructural behaviours of the two grades are compared in a separate publication. As anticipated, for long interpass times, the T_{nr} temperature (temperature of no-recrystallization) can be clearly established only for the Nb steel, the other grade undergoing nearly full softening, *i.e.* recrystallization, at all temperatures. By contrast, for short interpass times of the order of 2 s, typical of the strip mill, there is little pass-to-pass strain accumulation in either steel. In the temperature range 1 020 to 920°C, static recrystallization is largely responsible for the high degree of interpass softening in the C-Mn steel. In the case of the Nb steel, because of solute effects, the short interpass times do not permit much conventional recrystallization. Instead, softening is brought about mostly by dynamic and post-dynamic recrystallization. This is possible because there is considerably less Nb(CN) precipitation during the short interpass times than under reversing (plate) mill conditions. The decreased level of precipitation in the Nb steel, followed by the initiation of dynamic recrystallization, leads to lower rolling loads in the strip mill for this grade than in the plate mill at the same rolling temperatures.

KEY WORDS: strip rolling; plate rolling; dynamic recrystallization; rolling forces; torsional simulation.

1. Introduction

In the Lake Erie hot strip mill, the steel passes through five stands (with average roll diameters of 700 mm) at speeds ranging from 130 to 630 m/min. On passing from stand to stand, there is a period of unloading during which the steel may undergo complete, partial, or no recrystallization.¹⁻³⁾ Thus the flow resistance of the steel at each stand depends on the extent of recrystallization prior to pass execution. It also depends, of course, on temperature, reduction, strain rate, the progress of the ferrite transformation, *etc.*

A rolling schedule typical of those used at the Lake Erie Works of Stelco Steel, Canada is presented in Table 1. The delay times of 40 to 140 s after roughing listed in the table refer to the roughing-to-finishing intervals associated with the coil head and coil tail imposed by the presence of a coilbox in this mill. Because of the relatively short finishing interpass times displayed in this table, it is evident that the recrystallization behaviour during these intervals will differ markedly from that observed in plate mills, or in other forms of reversing mill, such as the Steckel mill.⁴⁾ The principal aim of the present work was to clarify the differences between the plate rolling (reversing mill) and strip rolling behaviour of microalloyed steels, with particular reference to rolling load and microstructure. Other aspects of the study concerned:

(1) Determination of the critical temperatures T_{nr} and A_{r3} (the temperatures of no-recrystallization and

the start of the austenite-to-ferrite transformation, respectively) involved in plate rolling;

(2) The generation of equations describing the dependence of the mean flow stress on rolling temperature during strip finishing; and

(3) Identification of the softening mechanisms (*i.e.*, of the types of austenite recrystallization) taking place during strip rolling.

By comparing the findings from two types of steel, *viz.*, 1) a C-Mn and 2) a Nb microalloyed grade, the metallurgical consequences of processing through the strip mill are described and discussed.

2. Experimental Procedure

2.1. Materials and Techniques

The C-Mn and Nb steels used in this work were received as 25 mm thick pieces, sectioned from transfer bars. Their chemical compositions are shown in Table 2. The carbon and manganese levels in the Nb steel (0.07 and 0.57 wt%, respectively) are slightly higher than in the C-Mn steel (0.05 and 0.3 wt%). Note also that the niobium content in the microalloyed steel (<0.03 wt%) is relatively low.

Standard torsion specimens with a 25.4 mm gauge length and 6.2 mm in diameter (Fig. 1) were machined from the steels supplied and were tested using the McGill computerized torsion apparatus equipped with a radiant furnace. The latter was programmed to simulate the pass temperatures. All torsion tests were performed in a high purity argon atmosphere to

Table 1. Average schedule for the Lake Erie strip mill.

Pass #	Temperature (°C)	Strain	Strain rate (s ⁻¹)	Delay (s)
R1	1 280	0.18	3	3.7
R2	1 268	0.25	3.8	11
R3	1 255	0.22	5.6	10
R4	1 238	0.28	6.5	12
R5	1 213	0.39	9.5	13
R6	1 185	0.67	14.5	18
R7	1 130	0.55	21	40-140
F1	1 025-990	0.50	11	3.7
F2	992-970	0.53	40	2.6
F3	973-961	0.37	60	1.9
F4	950-951	0.29	85	1.1
F5	926-932	0.21	100	Coiling

Table 2. Chemical compositions of the two steels used in the present work.

Element (wt%)	C-Mn steel	Nb steel
C	0.05	0.07
Mn	0.29	0.57
P	0.006	0.006
S	0.006	0.008
Si	0.15	0.18
Cu	0.025	0.031
Ni	0.01	0.017
Cr	0.057	0.024
Mo	0.006	0.004
ASA	0.03	0.062
Nb	N/A	0.027

Fig. 1. Torsion specimen.

minimize oxidation. Stress-strain curves were determined from the torque-twist behaviour in the usual manner.⁵⁾ Two types of schedules were carried out; these were interrupted and the samples were quenched at various points during pass execution to examine the development of the austenite microstructure. Duplicate samples were air cooled at 6°C/s to reveal the ferrite microstructure. Then, carbon extraction replicas were prepared; these were examined by electron microscopy and the characteristics of the precipitate

size distribution were determined in this way. The austenite and final ferrite microstructures were investigated by means of optical microscopy.

In order to study the progress of static recrystallization during rolling, several sets of two-hit hot compression tests were performed on both steels. The specimens were austenitized at 1 260°C for 15 min and then cooled to the testing temperature (1 000, 950, or 900°C), at a rate of 2°C/s. Once the required temperature was attained, the specimens were held for 1 min to allow for temperature homogenization. Thereafter, the specimens were hot compressed to a true strain of 0.6 at a strain rate of 2 s⁻¹. After increasing unloading times (these were varied from 0.1 to 2 000 s), the specimens were reloaded at the same strain rate. The degree of softening that took place during this period was calculated from the expression:

$$X = (\sigma_m - \sigma_r) / (\sigma_m - \sigma_0)$$

where, σ_m : the stress before unloading

σ_0 , σ_r : the yield stresses during prestraining and reloading, respectively.

2.2. Laboratory Test Schedules

The simplified plate mill schedule (schedule A) consisted of 22 passes, each of 0.3 strain, executed at a strain rate of 2 s⁻¹, with a 30 s delay time between successive passes. The purpose of these tests was to define some of the main characteristics of the steels with respect to hot deformation, i.e., the T_{nr} and Ar_3 temperatures.⁶⁾ At the same time, the dependence of flow stress on temperature under conditions of long interpass time was also determined.

A simplified strip rolling schedule (schedule B) was also employed. The first seven passes in this schedule involved a simulation of roughing using industrial strains and delay times (passes R1 to R7 in Table 1), but with a strain rate of 2 s⁻¹ throughout. Following the last roughing pass, i.e., R7, which was executed at ~1 130°C, the specimens were subjected to a special type of finishing schedule consisting of 10 to 15 passes, each of 0.3 strain, with an interpass time of 2 s and carried out at a strain rate of ~2 s⁻¹. This finishing schedule, which was used to explore the recrystallization behaviour during short interpass times over the entire finishing temperature range, was initiated at three temperatures, viz., 1 015, 960, and 920°C. For all finishing schedule variants, the temperature was lowered from 1 015 to 840°C in 28 s, i.e., at ~6.5°C/s. Under these cooling conditions, seven finishing passes were required to cover the finish rolling temperature range instead of the five usually employed at the mill. The additional passes (beyond seven) were utilized to further investigate austenite recrystallization at temperatures below 900°C. The time interval between the end of roughing and start of finishing was varied from 40 to 200 s by varying the cooling rate during this period. The shorter period corresponds to the time spent in the coilbox for the coil head. The coil tail takes about 140 s to reach the finishing stands. Nevertheless, an interval of 200 s was selected for the

simulations concerning this part of each coil so as to emphasize the effect of longer holding times. At the end of deformation, the specimens were cooled at a rate of 6°C/s.

3. Results

3.1. Static Softening (Interrupted Compression Test Results)

The static recrystallization behaviours of the two steels are compared in Fig. 2. From this figure, it is evident that the onset of recrystallization in the Nb steel is slower at 1 000°C than in the plain carbon steel at 900°C. The prestrain, 0.6, used to establish the data for Fig. 2 was greater than the strain required to initiate dynamic recrystallization in the C-Mn steel in the temperature range 1 000 to 900°C. In the case of the Nb steel, only work hardening (*i.e.*, a positive slope) was observed in the same temperature range. The recrystallization start (R_s ~20 % softening) and finish (R_f ~90 % softening) times pertaining to the two steels are shown in Table 3. (20 % softening is produced by static recovery, and does not involve the nucleation of new grains (Petkovic *et al.*,⁷ Ouchi *et al.*⁸)) The results listed in this table indicate that static recrystallization is completed in the C-Mn steel after holding times of less than 10 s, even at temperatures as low as 900°C. These times are less than the interpass times employed in reversing mills. Even under strip rolling conditions, a significant amount of softening is expected to take place during the interpass times, which range from 1 to 3.6 s, see Table 1.

By contrast, recrystallization is essentially arrested in the Nb steel at 950 and 900°C. At these tempera-

tures, static recrystallization begins after ~2.5 and 100 s, respectively. Thus it is not expected to occur under strip rolling conditions.

3.2. Characterization of Steel Behaviour under Reversing Mill Conditions (Schedule A)

Typical stress-strain curves produced from the C-Mn and Nb steels are displayed in Figs. 3(a) and 3(b), respectively. In the austenite temperature range, the C-Mn steel exhibited almost full recrystallization during the unloading intervals. (The microstructural aspects of this work are discussed in Ref. 9.) Thus, the pass-to-pass increase in flow stress is caused mainly by the decrease in the temperature. For the Nb steel, at temperatures higher than 955°C, the flow curves are similar to those obtained from the C-Mn steel. However, at temperatures below 955°C, the rapid accumulation of work hardening takes place, resulting in a sharp increase in flow stress. This can be attributed to the copious precipitation that occurs during the 30 s interpass times, which prevents both static and dynamic recrystallization.

The above observations are clarified in Fig. 4, where the mean flow stresses obtained during schedule A are plotted as a function of the inverse absolute temperature for both steels. At high temperatures, both steels behave in a similar fashion, but at 1 000/°K ~0.81 (~955°C), the Nb steel exhibits a sharp increase in the slope of the curve. This is the T_{nr} (temperature of no-recrystallization) under plate rolling (reversing mill) conditions.

The start of the austenite-to-ferrite transition is characterized by an appreciable decrease in mean flow stress for the C-Mn and Nb grades. The temperatures at which this transition takes place, *i.e.*, the A_{r3} temperatures, are 865 and 830°C for the C-Mn and Nb grades, respectively. These values are in good agreement ($\pm 5^\circ\text{C}$) with those predicted from the correlations proposed by Boratto *et al.*⁶ and Ouchi *et al.*¹⁰ for C-Mn and microalloyed steels. Deformation in the ferrite range is accompanied by a rapid increase in flow stress for both grades, with no noticeable recrystallization during the 30 s interpass time intervals.

Table 3. Recrystallization start (R_s) and finish (R_f) times for the two steels investigated.

Steel	1 000°C		950°C		900°C	
	R_s (s)	R_f (s)	R_s (s)	R_f (s)	R_s (s)	R_f (s)
C-Mn	$\ll 0.1$	6	—	—	~ 0.1	10
Nb	0.7	25	2.5	400	95	$\gg 2\,000$

Fig. 2. Comparison of the softening curves of the C-Mn and Nb steels in the temperature range 1 000–900°C. Fractional softening was determined by the offset method.

Fig. 3. Stress-strain curves for the steels rolled with schedule A.

3.3. Characterization of Steel Behaviour under Strip Mill Conditions (Schedule B)

3.3.1. Roughing

An example of the stress-strain curves that simulate the Lake Erie seven pass roughing schedule (but for a strain rate of 2 s^{-1}) is shown in Fig. 5. For passes 5, 6, and 7 and for strains ≥ 0.3 , all steels exhibit marked softening after reaching the maximum stress. This softening is brought about by the occurrence of dynamic recrystallization during these passes. The mean flow stress behaviours of these steels are compared *vs.* roughing pass number in Table 4. As can be seen, in the absence of significant precipitation, both grades fall in a narrow band of stresses.

3.3.2. Finishing

Typical stress-strain curves representing finish rolling of the C-Mn and Nb steels with the reduced interpass time (2 s) are displayed in Figs. 6(a) and 6(b), respectively. It is evident from the expanded flow curves that the C-Mn steel exhibits less strain accumulation, indicating a higher degree of recrystallization during the unloading intervals, than the Nb steel.

The mean flow stresses obtained from Fig. 6 are plotted against the inverse absolute temperature in Fig. 7. Here, the time between the end of roughing and start of finishing was varied from 40 to 200 s (to enable the coilbox to be simulated). As mentioned previously, these times are representative of the coil

Fig. 4. Mean flow stress- $1000/T$ relationships for the C-Mn and Nb steels rolled according to schedule A.

Fig. 5. Stress-strain curves for the seven roughing passes carried out at 2 s^{-1} (C-Mn steel).

Table 4. Mean flow stresses (MPa) for the seven roughing passes.

Pass #	Strain	Temperature (°C)	C-Mn	Nb
R1	0.20	1 260	52	54
R2	0.23	1 255	55	57
R3	0.23	1 243	56	61
R4	0.28	1 225	58	63
R5	0.37	1 197	62	67
R6	0.65	1 167	65	70
R7	0.54	1 125	69	72

head and coil tail. In the rest of the paper, the terms 'coil head' and 'coil tail' will be used to refer to these respective roughing-to-finishing time intervals.

Fig. 6. Stress-strain curves for steels finish rolled according to schedule B.

Fig. 7. Dependence of mean flow stress on inverse absolute temperature for the 2 s interpass time.

The data obtained using short interpass times are superimposed on those obtained for the steels rolled with the 30 s interpass time. Two main observations can be made from the figures for the two steels:

(1) The short interpass time, 2 s, leads to little pass-to-pass strain accumulation in the two steels, unlike the behaviour of the Nb steel in the 30 s interpass time tests. This can be attributed to the relative absence of precipitation in the Nb steel during the short interpass times.

(2) Increasing the time spent in the coilbox (*i.e.*, to 200 s) results in a slight hardening effect in the Nb steel. As demonstrated in Ref. 9), this hardening results from the precipitation of Nb(CN).

The mean stress data of Figs. 7(a) and 7(b) are compared in Fig. 8. These results pertain to a roughing-to-finishing delay time of 200 s and a finishing start temperature of $\sim 1015^\circ\text{C}$. As can be seen, the mean flow stress is higher in the Nb than in the C-Mn steel. The higher flow stresses are explicable in terms of the effects of Nb in solution, with perhaps a contribution from the much finer ($< 5\ \mu\text{m}$) austenite grain size. Increasing the cooling rate during the finishing passes from 1 to 6.5°C/s (*i.e.*, corresponding to the 30 and 2 s interpass times, respectively) was found to be effective in lowering the A_{r3} temperature by $\sim 15^\circ\text{C}$ for the two steels studied.

3.4. Effect of Decreasing the Finishing Start Temperature (F1 Temperature)

In Table 1, the first finishing pass (F1) temperature is around 1025°C . In practice, however, the F1 temperature can be as low as 960°C . In order to

Fig. 8. Dependence of the mean flow stress during finishing on pass temperature for schedule B (200 s in the coilbox, 2 s interpass time).

Fig. 9. Influence of temperature of the first finishing pass on mean flow stress vs. $1000/T$ for the Nb steel (tail, 200 s).

test the effect of lowering the F1 temperature on the mean flow stress behaviour, several series of tests were executed with F1 temperatures of 960 or 920°C as opposed to 1 015°C.

Lowering the F1 temperature by 40°C did not result in much change in the mean flow stress behaviour of the C-Mn steel, as shown in Fig. 7. The effect of lowering the F1 temperature for the Nb steel is displayed in Fig. 9. The results in this diagram were generated using a roughing-to-finishing time interval of 200 s and a cooling rate during finishing of 6.5°C/s. Lowering the F1 temperature to 960°C leads to a strength behaviour that is characterized by an initially sharp increase in mean flow stress (during finishing) from pass #1 to #2, followed by an increase in mean flow stress with decreasing temperature that is more or less parallel to, but at a slightly higher level than, that for the schedule where F1=1 015°C. This sort of behaviour is accentuated when the F1 temperature is lowered still further to 920°C. Here, the initial sharp increase in flow stress takes place from pass #1 to #3. Thereafter, the rate of change of flow stress with temperature is again parallel to that of the F1=1 015°C case, but the general level of the curve is much higher. One final point of interest is that, apart from the first finishing pass, the flow stresses of the two schedules with low F1 temperatures fall within the limits of the range described by the 30 s interpass (plate) schedule on the one hand and the F1=1 015°C schedule (2 s interpass time) on the other.

4. Discussion

4.1. Effect of Decreasing Interpass Time

One of the major differences between strip and plate mill schedules lies in the interpass times, which are much shorter in strip mills. The influence of interpass time depends, at the outset, on steel composition. In the case of the present Nb steel, there is a strong effect of interpass time on the resistance to hot deformation. When it was subjected to the plate mill schedule, where the interpass time was 30 s, an abrupt increase in the rate of change of mean flow stress with decreasing temperature was seen at about 960°C (see Fig. 4). As confirmed by the interrupted compression tests, supported by electron microscopy, this is due to the retardation of recrystallization via the precipitation of Nb(C,N). Such interpass precipitation is responsible for the strain accumulation that takes place during all subsequent passes. It is of considerable interest that the strain accumulation does not lead to the initiation of dynamic recrystallization, which is why the flow stress is able to increase continuously to relatively high levels.

The accumulation of strain in the finishing mill, if present at all, depends on the finishing entry (F1) temperature. For F1 temperatures somewhat higher than the plate mill recrystallization retardation temperature (the T_{nr}), there is no sign of an abrupt change in the dependence of mean flow stress on temperature during the later passes. Thus, from the F1 temperature down to the austenite-to-ferrite transformation temperature, the strip mill schedule does not exhibit a break in the flow stress, indicating the ab-

sence of appreciable amounts of strain accumulation. However, for F1 temperatures close to and below the plate mill T_{nr} , there is a rapid increase in the mean flow stress in the first 2 or 3 passes. Thereafter, the rate of change of mean flow stress falls back to that of the high F1 temperature schedules. The difference can be attributed to the precipitation that has occurred during the interval between roughing and finishing in the second case (low F1 temperature), which was absent in the first case (high F1 temperature). The roughing-to-finishing precipitation leads to the retardation of recrystallization in the first few passes. Significant strain is therefore accumulated during each of the initial passes, but, in contrast to the plate mill schedule, there is no time for further extensive precipitation. Therefore, the critical strain for dynamic recrystallization is attained and both dynamic and post-dynamic softening occur in the subsequent passes.

The strip mill behaviour of the Nb steel is compared to that of the C-Mn steel in Fig. 10. Here it can be seen that the relatively rapid rate of static recrystallization in the C-Mn steel (Fig. 2) prevents it from accumulating any significant strain during subsequent passes, see Fig. 10. Thus, it is difficult to initiate dynamic recrystallization in this material. Conversely, the almost complete absence of static recrystallization in the Nb steel leads to appreciable strain accumulation during further rolling. In this way, the Nb steel is strained into the dynamic recrystallization range of behaviour (see Fig. 10), as a result of which post-dynamic recrystallization also occurs during the unloading intervals.⁽¹⁾

This is why the rolling loads for the Nb steel in the strip mill, at temperatures below the plate mill T_{nr} , are lower than those in the plate mill. It is also why entering the finisher at F1 temperatures higher than the plate mill T_{nr} (and thereby avoiding roughing-to-finishing precipitation) will facilitate gauge control by eliminating the period of rapid flow stress increase. Finally, since it is clear that the difference between the plate and strip mill behaviours depends on the

occurrence of precipitation, it is not surprising that interpass time has no effect on the mean flow stresses of the C-Mn steel.

4.2. Mean Flow Stress/Temperature Relations

The dependence of mean flow stress on inverse absolute temperature can be expressed by a linear relation of the type:

$$\bar{\sigma} = a + b(1000/T)$$

where, a, b : constants

T : the absolute temperature

$\bar{\sigma}$: the mean flow stress.

The $\bar{\sigma}$ vs. $1000/T$ relationships obtained by applying schedules A and B to the two steels are summarized in Table 5. The main points to be noted are:

(1) For the C-Mn steel, the slope obtained on applying schedule B is somewhat higher than for schedule A. This increase in slope is associated with incomplete recrystallization during the short interpass times.

(2) For the reduced interpass time and for the same rolling parameters, the slope for the Nb steel is higher than the slope for the C-Mn steel. This is because decreasing the temperature leads to a greater increase in the amount of retained work hardening in the Nb than in the C-Mn steel.

(3) Among all the conditions studied, the slope representing the flow behaviour of the Nb steel under the no-recrystallization (reversing mill) condition is the highest. This is, of course, associated with the

Table 5. $\bar{\sigma}$ (MPa) vs. $a + b(1000/T)$ relationships for the 2 s delay time.

The first finishing pass was executed at $\sim 1015^\circ\text{C}$.

Steel	30 s delay	2 s delay
C-Mn	$-210 + 396(1000/T)$	$-261 + 460(1000/T)$
Nb	$T > T_{nr}$	Coil head
	$-213 + 405(1000/T)$	$-299 + 507(1000/T)$
	$T < T_{nr}$	Coil tail
	$-736 + 1049(1000/T)$	$-357 + 588(1000/T)$

Fig. 10.

Flow curves for the present steels tested in torsion at 900°C and a strain rate of 2 s^{-1} .

copious precipitation (see Ref. 9)) occurring during the 30 s delay periods.

4.3. Mean Flow Stresses and Rolling Loads

4.3.1. Roughing

The mean flow stresses listed in Table 4 for the seven simulated roughing passes (carried out at a strain rate of 2 s^{-1}) were corrected for the actual strain rate using a strain rate sensitivity coefficient $m=0.114$.⁵⁾ The rolling forces predicted from the present stresses (by applying the Sims equation¹²⁾) are compared with those measured in the mill in Fig. 11. Several batches rolled with the 7 pass schedule were selected for each grade from mill data. The slab width varied from batch to batch.

The correspondence between predicted and measured rolling forces is quite close, as is clear from Figs. 11(a) and 11(b) for the C-Mn and Nb grades, respectively. For some coils, discrepancies are observed for passes #1 and #7. The pass #1 discrepancy can be attributed to initial slack in the torsion apparatus; with respect to pass #7, the difference seems to be related to variations in temperature ($1\,130$ – $1\,170^\circ\text{C}$) from one coil to another.

4.3.2. Finishing

Forces during strip rolling for the C-Mn steel were predicted from the regression equations listed in Table 5. These forces are plotted against those measured

in the mill in Fig. 12 (for $F_1 \sim 1\,015^\circ\text{C}$). Note that the mean flow stress *vs.* $1\,000/T$ curve is linear only after dynamic recrystallization is initiated in the case of the Nb steel. Thus the regression equations listed in Table 5 were used to allow for the effect of temperature in this region only. For the first two passes, during which strain accumulation is taking place, the mean flow stresses utilized for predicting the forces were taken from the stress-strain diagrams of Fig. 6(b). Here, the predicted forces have been averaged over the two end-of-roughing to start-of-finishing delay times (*i.e.*, 40 and 200 s).

The correspondence between the predicted and measured forces for the C-Mn and Nb steels, Figs. 12(a) and 12(b), respectively, is good for all passes, with less than 10 % scatter around the 1:1 line. This scatter probably represents the error limit of the Sims equation and the present experimental method. Similar results were obtained for the simulation and measurements relating to rolling the Nb steel at $F_1 \sim 960^\circ\text{C}$.

5. Conclusions

- (1) The C-Mn steel does not exhibit a T_{nr} (temperature of no-recrystallization) under plate rolling

Fig. 11. Predicted *vs.* measured forces for roughing.

The first finishing pass temp.: $\sim 1\,015^\circ\text{C}$
Interpass time: 2 s
(a) C-Mn steel, (b) Nb steel

Fig. 12. Predicted *vs.* measured forces for finishing.

conditions. By contrast, the Nb steel exhibits a clear T_{nr} of 955°C for an interpass delay time of 30 s.

(2) Short interpass times of the order of 2 s lead to little pass-to-pass strain accumulation in the two steels.

(3) Increasing the cooling rate during the finishing passes lowers the A_{r3} temperature by ~15°C for the two steels (from 865 to 850°C and from 830 to 815°C for the C-Mn and Nb steels, respectively).

(4) In the temperature range 1 020 to 920°C, static recrystallization is largely responsible for the high degree of interpass softening in the C-Mn steel. In the case of the Nb steel, as indicated by interrupted compression tests, the short interpass times do not permit much conventional recrystallization.

(5) For the Nb steel, the amount of precipitation in the roughing-to-finishing time interval increases with increasing time and decreasing F1 temperature. Such precipitation retards recrystallization in the initial stages of finishing, resulting in strain accumulation and a rapid build up of stress. The absence of further precipitation leads to dynamic recrystallization and the rate of increase in flow stress with decreasing temperature is again controlled by the interpass time (and is therefore independent of the initial pass execution temperature).

(6) The rolling loads of the roughing as well as finishing passes can be satisfactorily predicted from the mean flow stress values generated in torsion simulations.

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REFERENCES

- 1) I. Kozasu, C. Ouchi, T. Sampei and T. Okita: Proc. Int. Symp. on Microalloying 75, Union Carbide Corp., New York, (1977), 120.
- 2) I. Tamura, H. Sekine, T. Tanaka and C. Ouchi: Thermo-mechanical Processing of High-Strength Low-Alloy Steels, Butterworths, London, (1988), 49-79.
- 3) T. Tanaka, N. Tabata, T. Hatomura and C. Shiga: Proc. Int. Symp. on Microalloying 75, Union Carbide Corp., New York, (1977), 107.
- 4) F. H. Samuel, R. Barbosa, F. Boratto, S. Yue and J. J. Jonas: Proc. Int. Conf. on Physical Metallurgy of Thermo-mechanical Processing of Steels and Other Metals, ISIJ, Tokyo, (1988), 721.
- 5) S. L. Semiatin, G. Lahoti and J. J. Jonas: "Application of Torsion Testing to Determine Workability", ASM Metals Handbook, Vol. 8 (Mechanical Testing), 9th Ed., Am. Soc. Met., Metals Park, OH, (1985), 154-184.
- 6) F. Boratto, R. Barbosa, S. Yue and J. J. Jonas: Proc. Int. Conf. on Physical Metallurgy of Thermomechanical Processing of Steels and Other Metals, ISIJ, Tokyo, (1988), 383.
- 7) R. A. Petkovic, M. J. Luton and J. J. Jonas: Can. Met. Quart., **14** (1975), 145.
- 8) C. Ouchi, T. Okita, M. Okado and Y. Nowa: Proc. Int. Conf. on Steel Rolling, Vol. 2, ISIJ, Tokyo, (1980), 1237.
- 9) F. H. Samuel, S. Yue, J. J. Jonas and K. R. Barnes: submitted to ISIJ Int., 1989.
- 10) C. Ouchi, T. Sampei and I. Kozasu: Trans. Iron Steel Inst. Jpn., **22** (1982), 214.
- 11) T. Sakai and M. Ohashi: Tetsu-to-Hagané, **70** (1984), 2160.
- 12) R. B. Sims: Proc. Inst. Mech. Eng., **168** (1954), 191.