The hot strip mill as an experimental tool

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INTRODUCTION

The interpass times in rolling mills vary over more than three orders of magnitude, from over 10 s in reversing mills, to times as short as 10 ms in rod mills. As a result, the softening mechanisms that operate during such interpass intervals also vary widely. When the interpass times are long, as in plate and other reversing mills, there is generally sufficient time for softening by static recrystallisation. Alternatively, in microalloyed steels, there is enough time for carbonitride precipitation, which then prevents the occurrence of any static recrystallisation at all.

At the finishing end of rod mills, the opposite situation prevails. Here, the times (10–20 ms) are too short for either conventional static recrystallisation or for the occurrence of any appreciable degree of carbonitride precipitation. Hot strip mills, with interpass times of about 1 s, fall into an intermediate category. That is, they can follow the plate mill paradigm under some conditions and the rod mill pattern of behaviour under others. It is precisely because it is difficult to characterise the mechanisms that are acting during hot strip rolling with any accuracy that mill models are not yet available that will handle a wide range of steel chemistries.

In the present paper, a method is described for the use of mill logs to improve mill models. In this approach, some basic information is required regarding the work hardening and softening behaviour of the steel. More particularly, algebraic relations are required that describe the kinetics of softening by static, dynamic, and post-dynamic (metadynamic) recrystallisation and that indicate how these kinetics are affected by grain size and steel chemistry. Similar expressions are needed to specify the precipitation start time in microalloyed steels. This information is then used to construct a mill model and to predict the separating force in each stand. The predictions are compared in turn with the load cell measurements available from mill logs. Finally, discrepancies between the predictions and measurements are used to improve the kinetic equations employed in the model.

INTERACTION BETWEEN RECRYSTALLISATION AND PRECIPITATION

In microalloyed steels, carbonitride precipitation can precede recrystallisation or, inversely, recrystallisation can precede precipitation. Once precipitation takes place, static recrystallisation is impeded or prevented. By contrast, the small amounts of carbonitride precipitation occurring in the interpass intervals can retard, but not prevent, the initiation of dynamic recrystallisation. This is generally followed by metadynamic recrystallisation, as long as the temperature is high enough and the interpass time long enough. The grain refinement produced by this mechanism then affects the critical strain for the next cycle of dynamic recrystallisation, if there is one.

By means of suitable models for the kinetics of strain induced precipitation, the rolling pass after which precipitation begins can be readily predicted. The various classes of interaction between recrystallisation and precipitation under hot rolling conditions are discussed in Ref. 4. When a strip mill behaves like a plate mill, the occurrence of precipitation precludes any further static or dynamic softening and only strain accumulation is possible. Conversely, when a strip mill follows the rod mill paradigm, neither precipitation nor static recrystallisation is possible, so that strain accumulation inevitably leads to dynamic, followed by metadynamic, recrystallisation.

Unfortunately, it is not known at the moment exactly when precipitation begins in the interpass intervals. In a similar manner, it is difficult to establish with precision whether dynamic and metadynamic recrystallisation have been initiated during the rolling sequence and to what extent the grain refinement they produce affects the subsequent nucleation of these softening mechanisms. Nevertheless, the existing relations can be employed in a generalised mill model; then predictions of the model can be compared with measurements taken from the mill logs. In this way, pass situations where discrepancies occur can be identified. Finally, the approximate relations can be modified in physically acceptable ways until there is good agreement between the predictions and observations. Comparison of the simulations and measurements in this way and reduction of the differences permits the hot strip mill to be employed as ‘an experimental tool’.

SEPARATION FORCE AND MEAN FLOW STRESS

The principal ‘measurement’ that is employed in the present approach is the mill separation force \(F_s\), which is obtained from the load cell installed in a particular stand. However, separation force is not used directly, as it must be corrected for strip width, as well as for other features of the mill and pass geometry (roll diameter, incoming and outgoing strip thickness, friction, etc.). According to this approach, the mean flow stress \(\text{MFS} = \varepsilon^{-1} \int \sigma \, \varepsilon \, d\varepsilon\), where \(\varepsilon\) is the pass true strain and \(\sigma\) is the instantaneous flow stress that applies during passage through the roll bite) is deduced from \(F_s\) using an appropriate analysis, such as that of Sims. Finally, in a further ‘normalisation’ step, the MFS can be
corrected to apply to a fixed strain rate \( \dot{\varepsilon} \) and a fixed reduction strain \( \varepsilon \). This type of normalisation simplifies the interpretation of the MFS–\( T^{-1} \) curves introduced below, where \( T \) is the absolute pass temperature.\(^3\)

The MFS values pertaining to the hot rolling of a niobium microalloyed steel (composition\(^4\) Fe–0.10C–0.35Si–0.45Mn–0.50Cr–0.40Mo–0.40Ni–0.32Cu–0.04Nb–0.08Ti–0.06V) are illustrated in Fig. 1. The values are plotted against \( T^{-1} \), and four separate temperature intervals can be distinguished:

(i) within range I, characterised by a low slope, recrystallisation is complete or nearly complete
(ii) within range II, which falls below \( T_{\text{Ar}} \), the ‘no recrystallisation’ temperature, strain accumulation occurs as described above
(iii) range III, located between the upper \( (A_r) \) and lower \( (A_f) \) critical temperatures, involves intercritical \( (\gamma + \alpha) \) rolling
(iv) range IV applies to warm, i.e. ferrite, rolling.

Of particular note here is the slope change involved in passing from range I to range II.

Figure 1 is specifically applicable to the plate rolling of microalloyed steels because the occurrence or absence of recrystallisation correlates directly with the absence or presence of precipitation respectively. Under rod as well as hot strip mill rolling conditions, the relative absence of precipitation means that strain accumulation can lead to the initiation of dynamic recrystallisation, a mechanism that is not observed under plate mill rolling conditions. Once new grains have formed during a roll pass, recrystallisation can continue without requiring an incubation time during the subsequent interpass interval. Such post-dynamic recrystallisation, referred to as metadynamic recrystallisation, is therefore very rapid.

A schematic MFS–\( T^{-1} \) diagram\(^5\) that applies to rod and strip mills is presented in Fig. 2. Here, three different slopes can be distinguished:

(i) that of the ‘low’ slope static recrystallisation region
(ii) that of the ‘high’ slope or strain accumulation region (this and (I) were present in Fig. 1)
(iii) the negative slope region that signifies that unexpected softening attributable to post-dynamic recrystallisation is taking place.

In this case, dynamic and metadynamic recrystallisation become possible because the amounts of strain induced precipitation that can occur during the relatively short interpass intervals (compared with those of plate rolling or reversing mills) are insufficient to prevent the initiation of these softening mechanisms. Such precipitation as can occur is also subject to accelerated coarsening during subsequent passes, rendering it less effective.

Although the softening illustrated in Fig. 2 could be considered as resulting from static recrystallisation, it will be shown below that the temperatures are too low and the times are too short for this mechanism to play a significant role.

### STATIC, DYNAMIC, AND METADYNAMIC RECRYSTALLISATION

From flow curves such as those presented in Ref. 8, it is evident that work hardening takes place, even at temperatures as high as 900, 1000, 1100, or 1200°C. For accurate mill modelling, equations are required that describe the work hardening, as well as the effects of steel chemistry on the level of the flow stress or, more specifically, on that of the mean flow stress. The use of such equations is described in Ref. 3.

Once work hardening has taken place, the amount of softening that is produced during the interpass interval must be calculated. This is done using equations of the form

\[
X = 1 - \exp[-0.693(t/t_{0.5})]
\]

where \( X \) is the fractional softening, \( t \) is the time, and \( t_{0.5} \) is the time of half-softening. The form of the relation for \( t_{0.5} \) depends on the operative mechanism as well as the steel grade.\(^3\)

In order for the computer model to decide whether to use the static or metadynamic recrystallisation kinetics, two further calculations are required.\(^3\) The first involves estimation of the accumulated strain \( \varepsilon_a \), which can be assessed from

\[
\varepsilon_a = \varepsilon_n + (1 - X)\varepsilon_{n-1}
\]

where \( \varepsilon_a \) is the strain applied in a specific pass, \( X \) is the fractional softening defined above, and \( \varepsilon_{n-1} \) is the accumulated strain applicable to the prior pass. With the aid of the above equations, a test can now be carried out to determine whether or not the critical strain \( \varepsilon_c \) required to initiate dynamic recrystallisation has been attained. This relation has the form\(^6\) \( \varepsilon_c \propto d_a^{0.5}Z^{0.17} \), where \( d_a \) is the grain size produced by the last cycle of recrystallisation and \( Z = \dot{\varepsilon} \exp(Q/RT) \). Here, \( Q \) is the activation energy
As indicated above, the method involves comparing the interval. The grain size calculations, which include allow-
3, 5
Three examples will now be described, selected from the (after roughing) must be provided as it determines the
An example of the set of inputs required for the mill
Hitchcock Forward slip Nominal Total Strain rate, Interpass time, Measured
Pass Roll dia., mm Roll speed, rev min⁻¹ Width, mm Gauge, mm Temp., °C Roll force, t
F1 787 32.9 1264 17.33 987 2157
F2 782 54.5 1264 10.79 951 2223
F3 761 79.2 1264 7.42 915 2116
F4 729 119.0 1264 5.10 907 1691
F5 728 147.1 1264 3.90 896 1387
F6 751 167.2 1264 3.14 884 1264
F7 755 172.0 1264 2.61 872 1627

We begin with analysis of the mill logs, from which the ‘measured’ MFS values are obtained. The first case involves
the Dofasco seven-stand strip mill (located in Hamilton, Canada), the important parameters of which are specified
in Table 1. Here the temperature applicable to each pass is taken from the Dofasco mill model and a C–Mn steel was
being rolled. The upper seven columns of Table 1 are the ‘inputs’ to the MFS calculation; the ‘outputs’ are presented
in the lower part of the table in the form of an Excel spreadsheet. Here, the effect of roll flattening can be readily
gauged by comparing the roll diameter with 2R. In a similar manner, the forward slip ratio (output column 3) is
seen to take values as high as 1.10, i.e. 10% forward slip. Comparison of the nominal (output column 4) and total (output column 5) strains permits assessment of the amount of redundant strain; for the schedule under consideration,
the latter ranges from 0.02 to 0.10. Finally, the derived (‘measured’) MFS values are given in output column 9.
As an example of the set of inputs required for the mill model is given in Table 2. Here, the starting grain size d₀
(after roughing) must be provided as it determines the recrystallised grain size present after the first interpass interval. (The grain size calculations, which include allowances for grain growth, are not described here, but the equations employed are provided in Ref. 3.)

| Pass | d₀, μm | T, °C | c, s⁻¹ | tᵢ, s | cᵢ |
|------|-------|-------|--------|-------|-----|
| F1   | 100   | 596   | 8.9    | 4.09  | 0.68 |
| F2   | ...   | 920   | 15.3   | 2.71  | 0.52 |
| F3   | ...   | 916   | 29.2   | 1.79  | 0.52 |
| F4   | ...   | 902   | 57.4   | 1.16  | 0.55 |
| F5   | ...   | 894   | 77.4   | 0.87  | 0.36 |
| F6   | ...   | 884   | 117.2  | 0.64  | 0.36 |
| F7   | ...   | 871   | 131.7  | ...   | 0.24 |

| Pass | d₀, μm | cᵢ | cᵢ | cᵢ > c₁ | t₀s | X | 1000/T, K⁻¹ | Predicted MFS, MPa |
|------|-------|----|----|---------|-----|---|--------------|--------------------|
| F1   | 100   | 0.68 | 0.47 | Yes     | 0.73 | 0.18 | 0.01 | 1.00 | 0.81 | 136 |
| F2   | 21.5  | 0.52 | 0.38 | Yes     | 0.60 | 0.15 | 0.01 | 1.00 | 0.84 | 150 |
| F3   | 18.2  | 0.52 | 0.41 | Yes     | 0.60 | 0.12 | 0.01 | 1.00 | 0.84 | 164 |
| F4   | 16.3  | 0.55 | 0.48 | Yes     | 0.65 | 0.08 | 0.01 | 1.00 | 0.85 | 186 |
| F5   | 14.4  | 0.36 | 0.50 | No      | ...  | ...  | 0.10 | 1.00 | 0.86 | 179 |
| F6   | 18.3  | 0.36 | 0.60 | No      | ...  | ...  | 0.30 | 0.90 | 0.86 | 193 |
| F7   | 14.6  | 0.24 | 0.61 | No      | ...  | ...  | 0.40 | 0.87 | ...  | 192 |

* Includes redundant strain.
The outputs obtained from the model are illustrated in the lower part of the table. It can be seen that dynamic recrystallisation is initiated in the first four passes. This is followed by rapid metadynamic recrystallisation, leading to full softening and to a change in grain size. In the fifth pass, the critical strain required to initiate dynamic recrystallisation is no longer attained, so that softening takes place by static recrystallisation instead. Once again, it produces full softening, although this is no longer possible at the somewhat lower temperature pertaining to the sixth pass. The most important column in the spreadsheet is the eleventh (far right), which lists the predicted MFS values. These are to be compared with the measured ones.

**BEHAVIOUR OF SELECTED MICROALLOYED STEELS**

The model described above is applicable to the rolling of plain C–Mn steels, but not to microalloyed steels. For the latter class of materials, some extra columns must be added to the spreadsheet. These include the supersaturation ratio $K_s$, the precipitation start time $t_{ps}$, the sum of the fractional times $t_{ip}/t_{ps}$, where $t_{ip}$ is the relevant interpass time, and a column specifying when the sum of the $t_{ip}/t_{ps}$ values exceeds unity, indicating that precipitation has begun. Several examples of such spreadsheets are given in Ref. 3. The important difference with respect to plate mill models is that, while static recrystallisation is generally impeded in both types of model (by both solute and precipitation effects), dynamic recrystallisation followed by very rapid metadynamic recrystallisation is permissible in the strip mill case. In fact, it is the rapid metadynamic recrystallisation that is responsible for the otherwise inexplicable load drops it produces full softening, although this is no longer possible observed at temperatures just above or just below 900°C.

Two simple examples will now be considered in which precipitation is either absent or present. These two cases are illustrated in Figs. 3 and 4 respectively. It can be seen from Fig. 3a that the accumulated interpass time only attains the precipitation start time $P_s$ in the last pass of this six-pass schedule, indicating that there is no precipitation during passage through the mill. Instead, there is strain accumulation leading to dynamic recrystallisation in passes 1 and 2, as well as in passes 3 and 4 (see Fig. 3a). The initiation of dynamic recrystallisation is followed by rapid metadynamic recrystallisation, leading to the load drops that are evident in passes 3 and 5 in Fig. 3a.

Such load drops are not normally predicted by mill models based solely on static recrystallisation, that is, that

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3 A comparison of MFS measurements derived from mill log with model predictions for the 0.01Si–1.1Mn–0.03Nb steel rolled at Port Kembla works of BHP Steel, Australia: observed load drops can be ascribed to metadynamic recrystallisation and overprediction of rolling load in passes 3–6 to model in which no allowance is made for dynamic and metadynamic recrystallisation; b comparison of mill cooling curve with precipitation start curve for rolling schedule of a: note that there is no precipitation during interstand intervals

4 A comparison of MFS measurements derived from mill log with model predictions for the 0.01Si–1.5Mn–0.04Nb–0.1Ti–0.04V microalloyed steel rolled at POSCO Pohang works: observed load drop in pass 7 can be ascribed to strain accumulation in prior passes, followed by initiation of dynamic recrystallisation in pass 6, and then by metadynamic recrystallisation in interpass interval; b comparison of mill cooling curve with precipitation start curve for rolling schedule of a: note that precipitation occurs (in computer model) after pass 4 (Ref. 9)
do not allow for the occurrence of dynamic and metadynamic recrystallisation. This is because the value of \( t_{0.5} \)
for static recrystallisation is substantially higher than that for metadynamic recrystallisation and generally greater
than the interpass time (except for very low niobium levels). The MFS values predicted by a mill model that
does not allow for the occurrence of dynamic and metadynamic recrystallisation are also illustrated in Fig. 3. These
are always consistently higher than the measured ones because the pass temperatures are too low in niobium steels
to produce interpass softening by static recrystallisation during the interpass times that apply to hot strip mills.

In the example cited above, and in the 30 steel grades that have been studied to date,\textsuperscript{3,5-7} the predictions of
the mill model were not always in good agreement with the mill measurements. Acceptable consistency was eventually
obtained by allowing for the occurrence of dynamic and metadynamic recrystallisation and by adjusting the values
of the coefficients and parameters in the equations describing the softening kinetics. Some of these adjustments were
based on the results of laboratory tests. In other cases, the required 'fine tuning' was carried out directly on the basis
of the mill observations. The best example of the need to make such modifications is the unexpected occurrence of
load drops.

The second example selected for description here is a 0.07C-0.2Si-1.5Mn-0.04Nb-0.04V steel that was rolled
on the seven-stand hot strip mill at the Pohang plant of POSCO in Korea. It is under current investigation as the
previous version of the model did not call for the load drop illustrated in Fig. 4 (Ref. 9). It can be seen from
Fig. 4a that the load drop occurs in the last stand, i.e. at the lowest rolling temperature (about 875°C), where the
value of \( t_{0.5} \) is the highest and the conventional recrystallisation kinetics the slowest. Detailed analysis of the rolling
schedule indicates\textsuperscript{3} that strain induced precipitation begins after pass 4 and that dynamic recrystallisation is initiated in
pass 6. Here, the occurrence of precipitation after the fourth pass clearly does not prevent dynamic recrystallisation
(followed by metadynamic recrystallisation) from taking place. The latter is responsible for the load drop. This conclusion
is drawn directly from the mill logs, i.e. by using the strip mill as an experimental tool. In the earlier version of the
present model,\textsuperscript{3} the occurrence of precipitation prevents both static and dynamic recrystallisation from taking place.
According to the present evidence, however, carbonyl niobium precipitation during strip mill rolling is unable to impede
either dynamic or rapid post-dynamic recrystallisation.

CONCLUSIONS

1. Strip mills are characterised by interpass times of about 1 s, which fall between the long interpass times of plate or reversing mills and the short ones associated with rod mills. Thus their behaviour can follow either the 'plate mill' (pancaking) or the 'rod mill' (strain accumulation leading to dynamic followed by metadynamic recrystallisation)
paradigms.

2. When there is little or no precipitation of niobium the short interpass times do not allow for the occurrence of
static recrystallisation. Instead, there is strain accumulation followed by the initiation of dynamic recrystallisation. Rapid
metadynamic recrystallisation then takes place during the subsequent interpass interval; this mechanism is responsible
for the otherwise 'unexpected' load drops.

3. When there is Nb(C,N) precipitation, static, dynamic, and metadynamic recrystallisation are all impeded. There is
some evidence that continued straining leads to precipitate coarsening, which then modifies the kinetics of softening,
permitting dynamic followed by rapid metadynamic recrystallisation to take place. The latter mechanism is again
responsible for the unexpected load drops.

4. The accurate modelling and control of strip mills necessitates taking both dynamic and metadynamic recrystallisation
into account. The kinetics of these important softening mechanisms can often be derived directly from mill logs by using the hot strip mill as an 'experimental tool'.

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