Note

Analysis of the Occurrence of Dynamic Recrystallization in Hot Rolling by Modeling of the Stress–Strain Curve

1. Introduction

In 1989 a paper on modeling of flow stress in a hot strip mill was published in this journal.¹⁾ The paper aimed at clarifying the differences in behavior of microalloyed steel deformed in a plate (reversing mill) and strip rolling schedules. Particular emphasis was given to rolling loads and microstructure evolution. The effect of dynamic recrystallization on the microstructure evolution in strip rolling was also investigated in a companion paper.²⁾ This work is mostly experimental and the authors have shown how dynamic recrystallization once it has been initiated in strip rolling could influence the final ferrite grain size. Ferrite grains as fine as 3 μm could be then achieved when such structures were cooled down at rates of 30°C/s. Similar sizes were also obtained in plane strain experiments when dynamic recrystallization occurred in the austenite just before transformation.³⁾ It seems now clear that dynamic recrystallization is the softening mechanism happening in the finishing passes of a strip mill. However, hard microstructural evidence is difficult to be obtained since Low Carbon microalloyed steels are very difficult to be quenched.

Additional evidence of the occurrence of dynamic recrystallization can be derived from modeling of flow stresses during multi-pass deformation. This reasoning has been somewhat overlooked in the literature although isothermal simulation of flow curves has been carried out in the past using different models.^{4,5)} Furthermore, it is also recognized that simulation of non-isothermal multi-pass stress–strain curves is not quite clearly understood⁶⁾ thus far. However, if stress–strain curves are modeled in the strip rolling schedule, then the residual strain in each pass must be known. Therefore, dynamic recrystallization would occur in the event of $\varepsilon > \varepsilon_c$ (the strain accumulated immediately after a certain pass being larger than the critical deformation for the initiation of dynamic recrystallization). ε_c is a function of ε_p , the strain to peak stress, which is easily determined from isothermal experiments.⁷⁾

In this paper, the flow curves of experiments published in the literature²⁾ are modeled. The residual strain immediately after each pass is assessed by matching experimental and theoretical curves. It is then shown that dynamic recrystallization occurs in passes where ε_c is exceeded.

2. Modeling of Flow Curves above T_{nr}

Static recrystallization occurs between passes when

they are given above T_{nr} . There is full softening between deformations, that is, no residual strain is left from one pass to the other. Therefore, each pass is applied in a material with no deformation history, if grain size effects are neglected. In this case, each curve in a multi-pass deformation process can be treated as being obtained from isothermal tests. A model for isothermal flow curves can be summarized as follows⁴⁾:

$$\sigma = \sigma_e \quad \text{if } \varepsilon \leq a\varepsilon_p \quad \dots\dots\dots(1)$$

$$\sigma = \sigma_e - \Delta\sigma \quad \text{if } \varepsilon > a\varepsilon_p \quad \dots\dots\dots(2)$$

where,

$$\sigma_e = \sigma_o + B(1 - \exp(-C\varepsilon))^m \quad \dots\dots\dots(3)$$

and

$$\Delta\sigma = B'\{1 - [\exp(-k(\varepsilon - a\varepsilon_p)/\varepsilon_p)]^{m'}\} \quad \dots\dots\dots(4)$$

Here σ_o is the stress for $\varepsilon=0$, 2% and a , k , m and m' are constants. B , B' and C are functions of the Zener–Hollomon parameter $Z = \dot{\varepsilon} \exp(Q_{HW}/RT)$ given by the expressions

$$B = \sigma_{ss(e)} - \sigma_o \quad \dots\dots\dots(5)$$

$$B' = \sigma_{ss(e)} - \sigma_{ss} \quad \dots\dots\dots(6)$$

$$C = -10 \ln \left[1 - \left[\frac{\sigma_{0.1} - \sigma_o}{B} \right]^{1/m} \right] \quad \dots\dots\dots(7)$$

$$\sigma_{ss(e)} = b\sigma_p \quad \dots\dots\dots(8)$$

Q_{HW} in the Z equation is an apparent activation energy for the main mechanism of softening during deformation (the value used here was 450 kJ/mol). $\sigma_{0.1}$

Fig. 1. Comparison between measured and predicted stress–strain curves for a Nb microalloyed steel deformed in hot torsion. The experimental data were taken from Ref. 2). All passes were given above T_{nr} (955°C) simulating the roughing part of a hot rolling schedule.

and σ_{ss} are the stresses at $\varepsilon=0.1$ and at the steady state, respectively. Additionally, σ_p is the peak stress and b is a constant taken as 1.05 in this work. Equations (1)–(8) have been successfully used to simulate isothermal stress–strain curves of C–Mn steels.⁴⁾ More recently, a similar model has also been employed to simulate curves of microalloyed steels.⁸⁾

Figure 1 shows a comparison between theoretical and experimental flow curves from a torsion simulation of the roughing passes of a Steckel mill.²⁾ The shape of the curves is typically round showing no strain accumulation between passes. The level of the stresses is not significantly increased with a drop in the pass temperature from 1110 to 1010°C. There is good agreement between experimental and predicted curves. Equations (1)–(8) were used in the simulations together with the ones below

$$\sigma_o = 0 \quad (\text{assumed in the simulations}) \quad \dots\dots\dots(9)$$

$$\sigma_{0.1} = -231 + 17.2 \log_{10} Z \quad \dots\dots\dots(10)$$

$$\sigma_p = -410 + 29.9 \log_{10} Z \quad \dots\dots\dots(11)$$

$$\sigma_{ss} = -286 + 20.8 \log_{10} Z \quad \dots\dots\dots(12)$$

$$\varepsilon_p^{Nb} = 3\varepsilon_p^{C-Mn} \quad \dots\dots\dots(13)$$

$$\varepsilon_p^{C-Mn} = 4.9 \times 10^{-4} d_o^{0.5} Z^{0.15} \quad \dots\dots\dots(14)$$

The value of ε_p for Nb steels was taken as three times the one calculated for C–Mn grades as suggested in the literature.⁷⁾ Note that in order to calculate ε_p^{C-Mn} a Q_{HW} of 312 kJ/mol appropriate for C–Mn steels must be used.

3. Modeling of Flow Curves below T_{nr} (Strip Mill Schedule)

In a strip mill the interpass times are usually of the order of a few seconds or even of a fraction of a second. Strain induced precipitation may not occur in sufficient

volume to prevent dynamic recrystallization to initiate. Clearly, precipitation of very fine particles on the dislocations produced by rolling takes about 10–30 sec to occur.⁹⁾ By this time, all the process of strip rolling may have already be finished. Therefore, precipitation in microalloyed steels may play here a different role of that known for plate mill schedules.

Figure 2(a) shows a comparison between measured and predicted curves for a strip mill schedule. The first passes given below T_{nr} present rapid accumulation of work hardening. The shape of the curves suggests the occurrence of dynamic recrystallization. Softening in the short interpass times occurs by metadynamic recrystallization since, as reported in the literature²⁾ static recrystallization is suppressed at holding times of 2 sec at 900°C, and requires about 2000 sec for completion.

Agreement between measured and predicted curves is reasonable and that was obtained by matching values of residual strains as detailed in **Fig. 2(b)**. The experimental data were extracted from the stress–strain curves shown in Fig. 2(b) of Ref. 2). **Table 1** of this work gives details of the strains involved in each pass. Note that best match of measured to predicted curves produced a

Table 1. Details of the equivalent strain in each pass of the finishing schedule of a strip mill.

Pass	Temp. (°C)	Equivalent strain		d_o (μm)	ε_c
		Nominal	Residual after pass		
1	915	0.35	0.3	0.00–0.35	30
2	895	0.60	0.1	0.30–0.90	30
3	877	0.30	0.1	0.10–0.40	3.1
4	860	0.35	0.1	0.10–0.45	2.8
5	855	0.30	—	0.10–0.40	2.7

$$\varepsilon_c = 0.7\varepsilon_p$$

$$d_o = 30 \mu\text{m} \text{ (ref. 2)) (used to obtain } \varepsilon_c \text{ for passes 1 and 2)}$$

$$d_o = 3.981 Z^{-0.15} \text{ (used to obtain } \varepsilon_c \text{ for passes 3 to 5)}$$

Fig. 2. (a) Comparison between measured and predicted stress–strain curves for a Nb microalloyed steel deformed in hot torsion. The experimental data were taken from Ref. 2). All passes were given below T_{nr} (955°C) simulating the finishing part of a strip mill schedule. (b) Schematic representation of the method used in this work to evaluate the residual strain after a given pass.

Fig. 3. (a) Dependence of the dynamically recrystallized grain size on the Zener-Hollomon parameter. (b) Evolution of the strain in a given pass at the finisher of a strip mill as a function of the pass temperature. Dynamic recrystallization occurs initially during pass 2 causing severe grain refinement of austenite (from 30 to $\approx 3 \mu\text{m}$) and decreasing ϵ_c to around 0.28. In passes 3 to 5 ϵ_c will be exceeded and dynamic recrystallization will then repeatedly occur.

residual strain of 0.1 even after dynamic recrystallization had happened. This can be attributed to the fact that dynamic recrystallization may not have been completed in a single pass. Therefore, part of the microstructure was still dynamically recovered only when the following deformation was given.

Pass 2 already shows a total strain of 0.90 which exceeds ϵ_c causing the initiation of dynamic recrystallization. This refines grain size from 30 to approximately $3 \mu\text{m}$ as pointed out elsewhere.³⁾ Using data from Ref. 3) an equation for the dynamically recrystallized grain size of Nb microalloyed steels can be obtained (see Fig. 3(a)).

$$d_0 = 3981 Z^{-0.15} \dots\dots\dots (15)$$

The refinement of the austenite grain after dynamic recrystallization decreases ϵ_c to approximately 0.2–0.3. The total strain in passes 3 to 5 becomes then larger than ϵ_c producing more dynamic recrystallization. Therefore, once dynamic recrystallization is initiated during pass 2 it will repeatedly occur in every subsequent deformation as illustrated in Fig. 3(b).

4. Summary

A simple mathematical model has been used to simulate stress-strain curves of non-isothermal multi-pass torsion experiments published in the literature. The values of residual strains after each pass was assessed by sliding the experimental stress-strain curves along the strain axis so that they could match the predicted ones. The strip mill schedule examined here shows clear evidence for the occurrence of dynamic recrystallization during pass number 2. Once initiated, dynamic

recrystallization repeatedly occurs during all subsequent passes because of the considerable decrease in ϵ_c (from around 0.7 to approximately 0.28). This decrease was caused by the severe austenite grain refinement (from 30 to around $3 \mu\text{m}$) achieved through dynamic recrystallization.

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