HOT STRENGTH DURING COILING OF LOW C AND Nb-MICROALLOYED STEELS

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Abstract

The flow stress under typical hot coiling conditions has been quantified for low C and Nb-Ti (V) microalloyed steels. The equation is intended for calculating the amount of bending torque required during coiling, particularly for thick, microalloyed skelp, so as to optimally adjust the coiler tension settings. Simplified rolling, runout table (ROT), and coiling simulations, typical for 10mm strip were performed. A small plastic strain was applied during the coiling stage to study flow behaviour in the ferrite and two-phase regions. The flow stress equation developed is applicable for the following chemistry limits: 0-0.09%Nb, 0.25-1.59%Mn, 0.06-0.16%C, 0-0.25%Si, 0-0.02%Ti and 0-0.07%V. Dilatometry measurements showed that, at high coiling temperatures, a significant fraction of untransformed austenite was often present during coiling. The most significant variables contributing to flow stress in the coiling region in decreasing order are: strain, Nb content, temperature and Mn content.

Introduction

Conventional hot coiling is normally conducted between 500 and 750ºC, *i.e.* in the ferrite or austenite-ferrite two-phase temperature regions for most steels. Optimized wrapping during coiling requires the correct tension setting which is a function of the strip flow stress, *i.e.* chemistry and deformation conditions, strip thickness and strip width [1-3]. Whilst much research [4-5] has focused on the flow behaviour of steel in the austenite region, little attention has been given to understanding the flow behaviour of low C and Nb-microalloyed steels in the ferrite region. Although other authors [6-9] have studied flow behaviour during warm deformation of steels, the only equation found for instantaneous flow stress of steels in the ferrite region was that reported by Saito [6]. However, this equation is only applicable for 0.06% C-Mn steel. A general flow stress equation, formulated as a function of chemistry and coiling parameters, is required to accurately calculate the amount of bending torque required during coiling, particularly for thick microalloyed strip where skelp tension is appreciable.

Experimental

Chemistry

A selection of C-Mn and microalloyed steels were studied, Table I.

Table I. Chemistry of the studied steels

Steel	Type	C %	Mn %	Si %	Nb %	Ti %	V %	Al %	P %	N ppm	S ppm
A	C-Mn	0.06	0.25	0.01	-	0.010	-	0.043	-	88	190
B	C-Mn	0.16	1.13	0.24	-	0.002	0.001	0.047	0.008	58	40

C	0.03Nb-Ti	0.06	0.80	0.21	0.025	0.012	-	0.046	-	77	-
D	0.04Nb-Ti-V	0.07	1.51	0.25	0.040	0.020	0.070	0.037	0.021	71	12
E	0.07Nb-Ti	0.06	1.59	0.19	0.070	0.010	0.005	0.038	0.015	50	52
F	0.09Nb-Ti-low Mn	0.06	0.27	0.17	0.090	0.010	-	0.033	0.016	33	60

Deformation during coiling

Equations 1 and 2 are used to calculate the strain rate ($\dot{\varepsilon}$) during coiling and the torque required to bend the strip at the mandrel (T_b) [1], where, ε is the strain applied, v the strip speed (ms^{-1}), D the mandrel diameter (m), $\sigma_{0.2}$ is the flow stress at 0.2% strain (MPa), t the strip thickness (mm) and w is the strip width (mm).

$$\dot{\varepsilon} = 4\frac{\varepsilon v}{D} \qquad (1)$$

$$T_b = \frac{\sigma_{0.2} t^2 w}{4} \qquad (2)$$

Gleeble tests

Axisymmetric compression specimens were heated to 1200ºC at 4ºCs^{-1}and soaked for 5 minutes. After applying single roughing ($\varepsilon = 0.4$) and finishing ($\varepsilon = 0.3$) passes at strain rates of 0.5 and 1s^{-1} respectively, accelerated runout table (ROT) cooling, typical for a 10mm strip, was applied down to simulated coiling temperatures between 500 and 700ºC and held isothermally for 30s before deformation. An isothermal coiling strain of 0.2 at strain rates of 0.01, 0.1 and 1s^{-1} was applied to study the effect of flow stress. Actual coiling strain rates vary between 0.018 and 0.2 s^{-1} depending on the strip thickness, whilst the actual coiling strain is relatively small about 0.03. A flow stress equation was compiled using multiple linear regression on chemistry and process variables. The fraction transformed just before coiling was measured on duplicate tests where the deformation step was omitted.

Results and Discussion

Dilatometry

Fig. 1 shows the temperature profiles and corresponding dilation curves during ROT cooling of steel E and steel A. Steel A is fully transformed before the onset of coiling at all temperatures studied since no change in the dilation ratio is observed. Steel E is fully ferritic when coiling at or below 600^{0}C, but has increasing volume fractions of austenite at higher coiling temperatures.

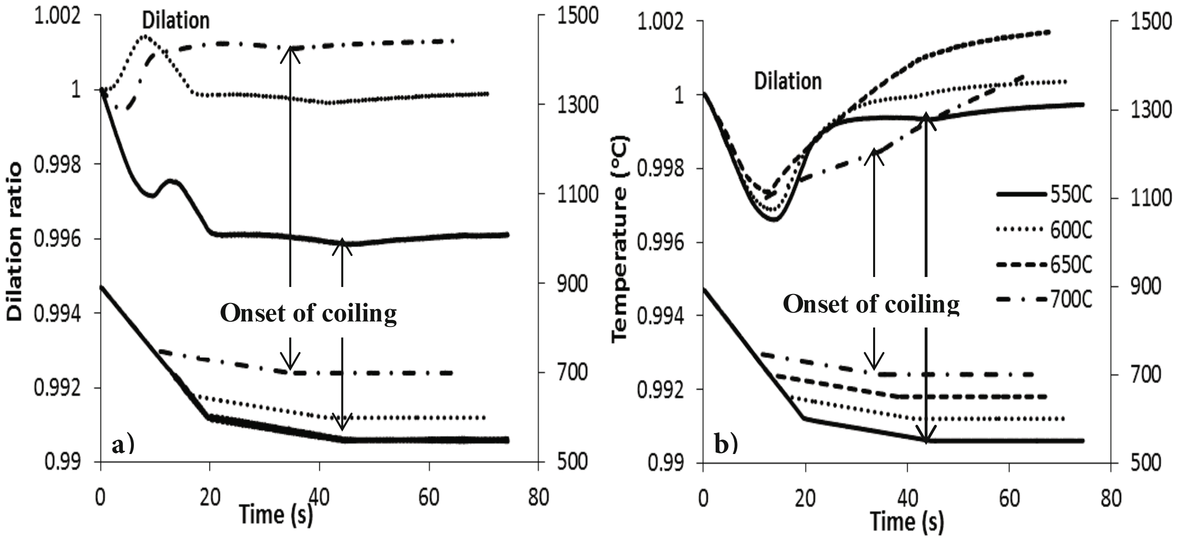

Figure 1. Temperature profiles and corresponding dilation curves during ROT cooling of 10mm skelp and a few seconds into coiling for a) steel A and b) steel E. Coiling starts on the onset of isothermal holding (see arrows).

Flow curves

Fig. 2 shows the flow curves for the six steels in the coiling region at a strain rate of $0.1s^{-1}$. As expected, the Nb-microalloyed steels experience higher flow stresses than the plain C-Mn steels due to precipitation of carbonitrides and/or solute drag effects. The difference in stress magnitude between the steel groups becomes larger at lower temperature due to increased super-saturation and carbonitride precipitation in the microalloyed steels. Comparing steels D and E, the 0.04%Nb in steel D is offset by the V addition to give similar flow curves as 0.07%Nb steel E at all coiling temperatures.

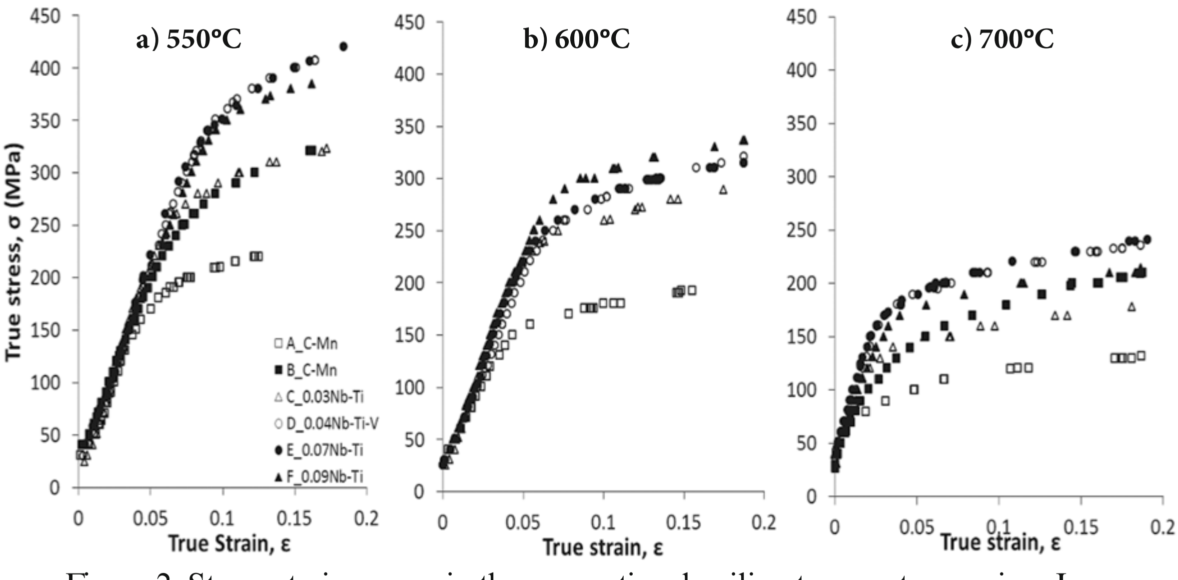

Figure 2. Stress-strain curves in the conventional coiling temperature region. Low temperatures and high Nb contents increase flow stress.

The flow stress at each investigated coil temperature (CT) can be summarized in Table II:

Table II. Flow strength categories at various coiling temperatures

CT, ºC	Very High	High	Intermediate	Low
550	D,E,F	B,C	A	
600		C,D,E,F	A	
700			B,C,D,E,F	A

Flow stress equation

The instantaneous flow stress, σ (MPa), similar in format to the Misaka equation [5] was formulated using multiple linear regression, eqn. 3. The adjusted R^2 is 0.92 and the standard error 21 MPa. Total alloy content was used and T is in K. The *t*-statistic for each variable is shown in Table III.

$$\sigma = \exp\left(2.56 + 0.43Mn + 7.81Nb - 5.4NbMn - 9.03C + \frac{(7328.8C + 2578.2)}{T}\right) \varepsilon^{0.113} \dot{\varepsilon}^{0.0435} \quad (3)$$

Table III. *t*- statistic of components in eqn. 3.

Variable	ε	Nb	1/T	Mn	έ	NbMn	C	C/T
t-stat	32	24	16	15	14	-12	-4	4

The most significant variables contributing to flow stress in the coiling region are strain (dislocation density), Nb (precipitation hardening in ferrite [10]), temperature, Mn (solid solution strengthening [11], and grain refinement through the lowering of the Ar_3 [12]). The contribution of carbon is weak, but positive. Note: eqn. 3 may overestimate flow stress at the onset of coiling due to the 30s isothermal hold before applying the coiling strain, which is sufficient time to allow precipitation of NbTi(C,N) and VN.
Fig 3a) shows a 10% error in the predicted flow stress for steel A at 700ºC and $0.1s^{-1}$ using eqn. 3 compared to 28% difference when using Saito's model [6] with T in ºC, eqn. 4. Fig. 3b) and Fig. 3c) show a good correlation between predicted and measured flow stress for steel E and steel C with 1 and 3% error respectively.

$$\sigma = 0.242\varepsilon^{0.141}\dot{\varepsilon}^{8.91\times10^{-5}T}\exp\left(\frac{4470}{T}\right) \quad (4)$$

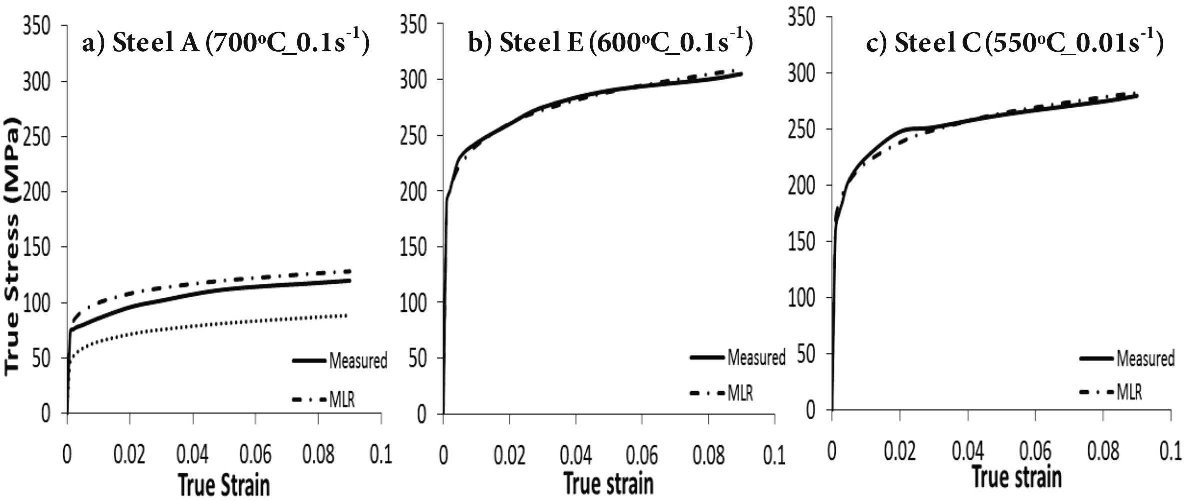

Figure 3. a) Eqn. 3 and Saito's equation compared to the measured flow curve for steel A at 700 ºC ($\dot{\varepsilon} = 0.1s^{-1}$) and accuracy of eqn. 7 for b) steel E at 600ºC ($\dot{\varepsilon} = 0.1s^{-1}$), and c) steel C at 550ºC ($0.01s^{-1}$).

Nb-Mn interaction

Fig. 4 shows the contribution of Nb and Mn to the 0.2% flow stress for 0.06%C steel at 550ºC and $0.1s^{-1}$ as predicted by eqn. 3. As the Mn content decreases, so does the flow stress decrease sharply with decreasing Nb content. The decrease in flow stress in lower Mn steels can be explained, in part, by the γ/α transformation, where both lower Mn and lower Nb contents increase the Ar_3 temperature and resulting ferrite grain size [13], which decreases strength. Low Mn decreases the solubility of Nb in austenite [4], thereby promoting NbTi(C,N) precipitation. Thus, an additional contributor to the lower flow stress during coiling of low Mn Nb-Ti steels may be a reduction in Nb solute available for very fine NbTi(C,N) precipitation in ferrite, which should weaken the material. Eqn. 3 predicts higher flow stresses in lower Mn steels at Nb contents above 0.08%, although this is within the experimental error of 21MPa.

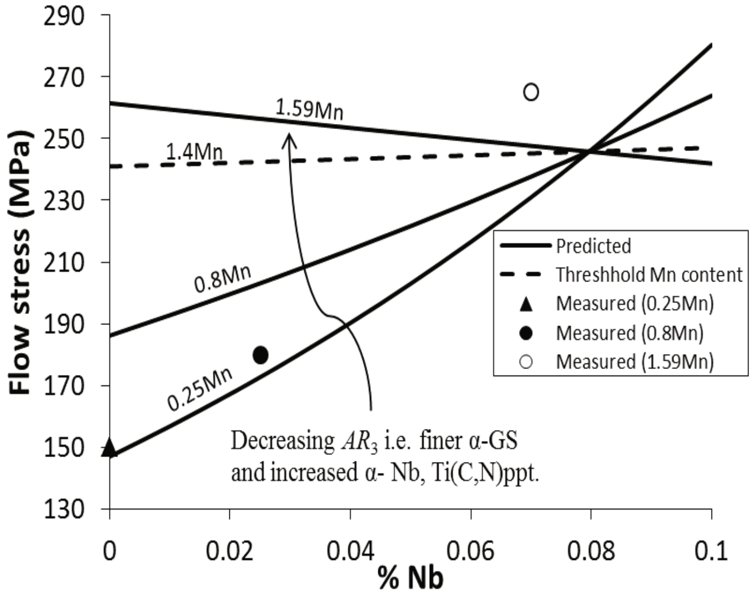

Figure 4. Predicted influence of Nb and Mn on the flow stress at 0.2% (0.002) strain for a 0.06%C steel at 550^{0}C and $0.01s^{-1}$ strain rate.

Conclusions

1) The following equation can be used to describe flow stress and bending torque within 12% error in the coiling region for C-Mn and Nb-microalloyed steels:

$$\sigma = \exp\left(2.56+0.43Mn+7.81Nb-5.4NbMn-9.03C+\frac{(7328.8C+2578.2)}{T}\right)\varepsilon^{0.113}\dot{\varepsilon}^{0.0435}$$

2) The most significant variables contributing to flow stress in the coiling region in decreasing order are: strain, Nb content, temperature and Mn content.

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