THE EFFECT OF CHEMICAL COMPOSITION ON THE HOT-DEFORMATION RESISTANCE DURING HOT STRIP ROLLING OF MICROALLOYED STEELS PROCESSED AT THE SIDOR HOT STRIP MILL

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ABSTRACT

Most of the ultra high strength steel grades use the benefits of grain refinement in order to raise both strength and toughness as well as to keep the carbon content to a minimum, improving weldability and ductility. Processing data from the Sidor hot strip mill (HSM) were collected and analyzed. The analysis of rolling loads is a powerful tool to study the deformation resistance during hot strip rolling. The present study shows the effects of the most common alloying/microalloying additions and their effects on the rolling loads during the hot strip rolling of microalloyed steels. The hot strip mill data were analyzed using Sims' equations and the mean-flow-stresses pertaining to each pass were calculated. Six grades were tested and a MFS equation was derived which takes into account the effects of the elements C, Mn, Nb and Mo. At typical microalloying additions, the stronger effect was found to be of Nb but the additions do not cause drastic increases in the hot deformation resistance due to the typical low concentration of microalloying elements.

Keywords: hot rolling, microalloyed steels, recrystallization, rolling load, deformation resistance

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INTRODUCTION

Industrial mill logs from the Sidor 6-stand hot strip mill were collected and analyzed in order to calculate the mean flow stress (MFS) developed in each stand. Three families of steels were analyzed: Nb-Ti-V-Mo, Nb-V-Ti and C-Mn. It is known that the load behaviour during hot strip rolling is one of the key factors to obtain stable processing conditions and good dimensional tolerance, as well as to help understanding the effects of alloying elements on the recrystallization behaviour. Models which predict the MFS behaviour during hot rolling are of fundamental importance for hot strip mill operation. The two most popular models are the ones due to Misaka and Yoshimoto[1] and Shida[2]. Both use process variables and chemical compositions to predict the hot deformation resistance during hot rolling of carbon steels. Several tentatives to derive multiplying factors to be applied to the Misaka equation were performed in recent years [3-9] including Misaka himself together with co-workers [10]. In the present work, a Misaka-type equation is proposed, in stead of the derivation of a multiplying factor. Later, it is briefly shown the thermomechanical processing (TMCP) of high strength Nb-microalloyed steel grades processed at Sidor HSM. TMCP is widely used to produce sheet steels for several applications including automotive, construction and linepipe.

The MFS equation was derived from the high temperature side of HSM schedules, where full softening is taking place as shown in Figure 1. Strain accumulation may take place during the final final passes causing the MFS to increase.

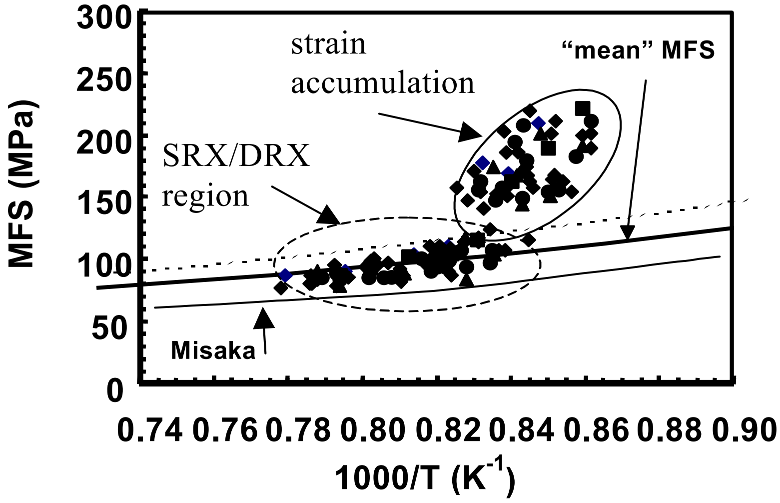


Figure 1 Mean MFS on the high temperature side of strip rolling processing. Sims MFS was calculated from mill logs plotted vs. 1000/T for several Nb containing grades, corrected to a constant strain of 0.4 and to a constant strain rate of $5s^{-1}$ [9]. (SRX = static recrystallization; DRX = dynamic recrystallization)

Misaka's equation [1] has often been employed to specify the MFS for C-Mn steels during hot strip rolling and is displayed below; here, the MFS is a function of the strain, strain rate, temperature and carbon content (C) in wt %.

$$\sigma_{(kgf/mm^2)} = \exp\left(0.126 - 1.75[C] + 0.594[C]^2 + \frac{2851 + 2968[C] - 1120[C]^2}{T(K)}\right)\varepsilon^{0.21}\,\dot{\varepsilon}^{0.13} \quad \ldots(1)$$

The new equation derived will be in the form shown below:

$$\sigma_{(MPa)} = 9.81 \cdot \exp\left(\frac{a + b[C] + c[Nb] + d[Mn] + \ldots}{T(K)}\right)\varepsilon^{0.21}\,\dot{\varepsilon}^{0.13} \quad \ldots(2)$$

Basically, it is the same concept of the original Misaka equation, however, some less powerful terms were eliminated and the effects of other elements were allowed together with carbon. In addition, the multiplier 9.81 is used to convert Misaka´s equation from kgf/mm^2 to MPa.

EXPERIMENTAL PROCEDURE

The set of steel chemistries listed below in Table I is the basic set, from where the equation was derived. The above compositional range was selected due to the typical chemistries found in UHSS, where strengthening elements (including C) are used together with grain refining elements such as Nb and Ti. A fine-grained microstructure will result in good toughness and ductility. For each strip, the following data were used: chemical composition, strip width, thicknesses before and after all passes, work roll speeds, roll forces and mean temperatures for each pass (given by the mill data log). The above parameters were then employed to calculate the true strains and strain rates, interpass times and MFS's according to the Sims formulation [11,12]. The corrections for roll flattening, redundant strain and forward slip between roll and strip were taken into account [3].

Table I Chemical compositions of the steels investigated.

Steel	C	Mn	Si	Cr	Cu	Nb	Ti	V	Mo
Nb-Ti-V-Mo	0.084	1.49	0.31	0.17	0.007	0.062	0.018	0.055	0.193
Nb-V-Ti	0.120	1.54	0.28	0.01	0.010	0.056	0.017	0.037	0.001
Nb-V	0.129	1.29	0.27	0.01	0.013	0.052	0.014	0.044	0.002
C-Mn 1	0.271	0.71	0.17	0.01	0.009	0.002	0.002	0.001	0.001
C-Mn 2	0.145	0.84	0.19	0.01	0.012	0.002	0.002	0.001	0.003

In the present method, the Sims formulation is employed to calculate and plot the MFS versus 1000/T for several bars such as in Figure 1. For modern steels (including microalloyed grades) Misaka's equation sometimes underpredicts the calculated (Sims) MFS obtained from the mill logs. Considering that in the initial stands (high temperature side) the elements Nb, Mo and V are in solid solution, the MFS equation may take solution hardening elements into account. The following composition ranges are applicable: Mn:[0.71-1.54%], Nb:[0-0.062%], C:[0.084-0.27%], Mo:[0-0.20%]. Using multiple linear regression, the resulting equation has the basic form of Equation (2).

RESULTS AND DISCUSSION

The solution strengthening effects can therefore be added in the equation to fit all grades. Considering the elements C, Mn, Nb and Mo, the result of the linear regression is the final MFS equation shown in Table II below together with the other equations in previous works.

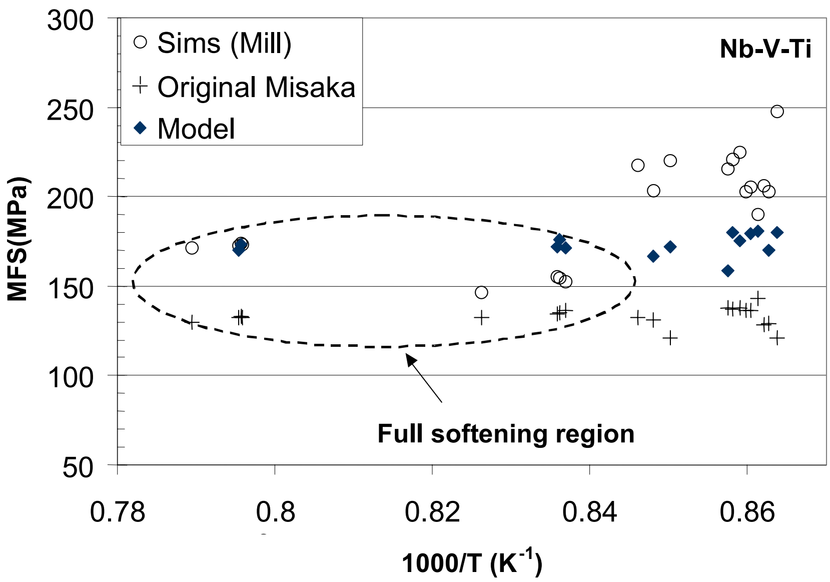
Table II- MFS equations derived in the present paper and in previous works.

Author	Mill	Equation	#
This work	Sidor	$MFS(MPa) = 9.81 * \exp\left(\frac{3126 + 68[C] + 2117[Nb] + 54[Mn] + 152[Mo]}{T(K)}\right) \cdot \varepsilon^{0.21} \cdot \dot{\varepsilon}^{0.13}$	(3)
"Original Misaka" [1]	Mechanical Testing	$\sigma_{(MPa)} = 9.81 * \exp\left(0.126 - 1.75[C] + 0.594[C]^2 + \frac{2851 + 2968[C] - 1120[C]^2}{T(K)}\right) \varepsilon^{0.21}\ \dot{\varepsilon}^{0.13}$	(1)
Misaka et al. [10]		MFS=[Original Misaka]*(0.916+0.18·[Mn]+0.389· [V]+0.191· [Mo]+0.004· [Ni])	(4)
Minami et al. [4]*	Sumitomo-Kashima	MFS=[Original Misaka]*(0.78+0.137·[Mn]+0.51· [Nb]+4.217· [Ti])	(5)
Kirihata et al. [5]*	Sumitomo-Wakayama	MFS=[Original Misaka]*(0.835+0.098·[Mn]+ 0.51· [Nb]+0.175· [V]+0.144· [Mo]+0.01· [Ni] +0.128· [Cr])	(6)
Kang et al. [6]*	POSCO	MFS=[Original Misaka]*(0.68+0.161·[Mn]+ 2.74· [Nb]+ 4.03· [Ti] +0.86· [V]+0.29· [Mo] +0.128· [Cr])	(7)
Bruna et al. [7]	Siderar	MFS=[Original Misaka]*(1.02+0.097·[Mn]+ 2.13· [Nb]+0.53· [V]+ 1.01· [Ti] +0.30· [Cu])	(8)
Poliak et al. [8]	Mittal-Inland	MFS=[Original Misaka]*(1.09+0.056·[Mn]+ 4.54· [Nb]+ 1.21· [Ti] +0.056· [Al]+0.10· [Mo]	(9)

*note that in the equations from references [4-6] it was omitted the term which takes into account the occurrence of dynamic recrystallization for the sake of simplicity.

Since the equation (3) has a different form, only equations (1) and (4-6) can be compared in terms of coefficients. The multiplying factors in equations (4) to (9) are very close to each other. Figures

2a and 2b show the fitting of the present equation in two different grades: one microalloyed (Nb-V-Ti) and one C-Mn (C-Mn 1). It can be seen that the equation fits the mill data closer than the original Misaka equation.



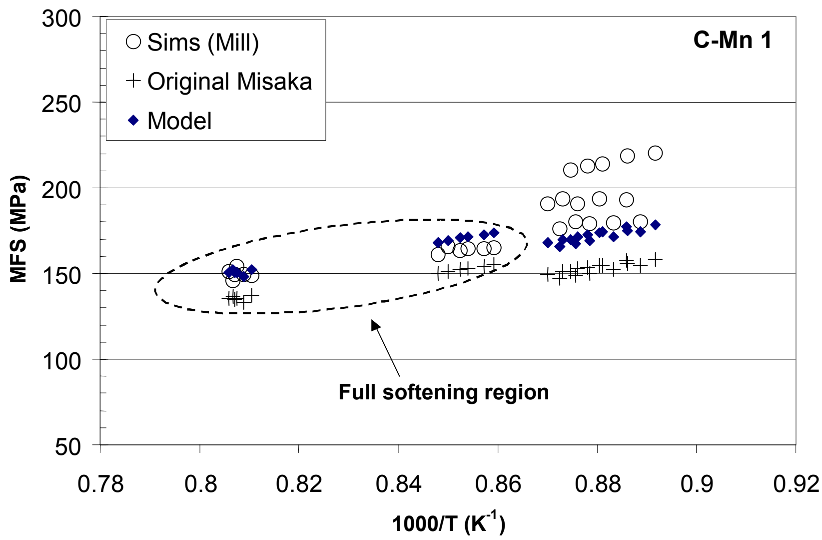


Figure 2. MFS *vs.* 1000/T (K^{-1}) charts. (a) microalloyed Nb-V-Ti and (b) C-Mn 1 grades.

It can be noted that the Misaka equation underpredicts the MFS in both cases. According to the previous works, the original Misaka equation was derived using experimental data from the drop hammer test where high strain rates are applied as compared to hot strip rolling. This difference may result in underprediction. On the other hand, it was reported that, for low C grades, the Misaka equation can also overpredict the MFS under industrial conditions [9]. Note that the proposed equation is valid for the full softening region. During latter passes, it is clear from Figure 2 that the effects of strain accumulation and possibly dynamic recrystallization will result in deviations from the proposed equation. After pass 3, some high MFS variations are observed in most of the bars, especially the ones from grades Nb-V-Ti-Mo. Figure 3 shows the typical MFS behaviour of one bar of steel Nb-V-Ti-Mo. In the 5-pass schedule, it seems that after pass 3, intense strain accumulation took place, and a MFS drop was observed in pass 4. The MFS drop can be explained by strain

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accumulation followed by dynamic recrystallization, or simply due to the small strain applied in the pass, which caused the MFS to be apparently lower.

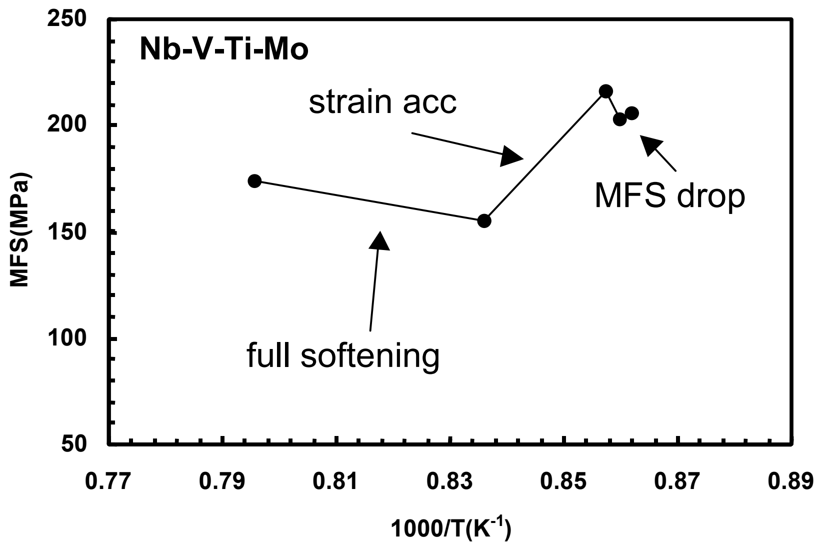

Figure 3: Typical MFS behavior of steel Nb-V-Ti-Mo during strip rolling.

In order to have more clues about the mentioned mechanisms, several simulations should be performed. Simulations of softening and grain size evolution would be of great help in answering these questions. These mechanisms, however, are not analyzed here.

In order to compare MFS values calculated with equations 1-9 displayed in Table III with values pertaining to the mean MFS value (indicated by "Sims") of the first pass of the schedules of the grade Nb-V-Ti. Although the calculations are made with industrial data, it is shown that most of the correction factors applied to the original Misaka equation are effective in improving accuracy. The equation developed in this work and the one derived by Kang et al. display the smallest error, followed by "Misaka 1981" and the one derived by Poliak. In analyzing the accuracy performance of these equations, it seems that they work very well in the particular HSM which the data were used for derivation, suggesting that each machine "reacts" differently. For example, Bruna´s equation, when applied to the Siderar mill, shows a mean deviation of about 5%. This implies that the differences shown in Table III are not undoubtedly determinant on the accuracy of the calculation for the present rolling schedules.

Table III-Accuracy of the equations listed in Table II for the mean MFS value of the first pass of bars of steel Nb-V-Ti.

	Sims	**New equation**	Misaka [1]	Misaka [10]	Minami [4]	Kirihata [5]	**Kang [6]**	Bruna [7]	Poliak [8]
MFS (MPa)	**172.7**	**169.6**	131.8	163.7	143.8	141.2	**169.6**	216.7	185.4
Difference (%)	**--**	**-1.8**	-23.7	-5.2	-16.7	-18.2	**-1.8**	+25.5	+7.3

The interactions effect of two or more microalloying elements was shown in previous work [13]. If these interactions are considered, the analysis and the equation form/multipliers may become more complex. This topic turns to be a suggestion for future work, with a larger range of data.

Finally, it should be pointed out that the knowledge of the rolling load behavior during hot rolling is of fundamental importance to design steel chemistries and processing conditions.

Considering the high amounts of industrial processing data available at the plants, it is an endless source of data. These data can be used to derive models which are directly applied to the plant.

SUMMARY

A new equation was proposed to predict the MFS in the high temperature side of hot strip rolling schedules. The analysis of the Sidor HSM processing data considered the effects of alloying/microalloying additions on the hot deformation resistance. It was found the following crescent effects: C, Mn, Mo and Nb. Within the available data, a "*taylor-made"* MFS equation was derived for the Sidor HSM. Although this equation represents a preliminary study made with limited amount of mill log data, the continuous analysis of industrial processing allows to greatly improve the accuracy.

REFERENCES

1. Y. Misaka & T. Yoshimoto: J. Japan Soc. Technol. Plast., 1967-8, vol. 8, p. 414.
2. S. Shida: J. Japan Soc. Technol. Plast., 1969, vol. 10, p. 610.
3. F. Siciliano, K. Minami, T.M. Maccagno & J.J. Jonas ISIJ Int., 1996, vol. 36, p.1500.
4. K. Minami, F. Siciliano, T.M. Maccagno & J.J. Jonas ISIJ International, 1996, vol 36, p. 1507.
5. A. Kirihata, F. Siciliano, T.M. Maccagno & J. J. Jonas: ISIJ Int., 1998, vol. 38, p. 187.
6. K.B. Kang, S.H. Cho, F. Siciliano & J.J. Jonas: The Fourth International Conference on HSLA Steels, Xi´an, China, 2000, G. Liu, F. Wang, Z. Wang & H. Zhang (eds.), The Chinese Society for Metals, p. 359.
7. F. Siciliano & R. Bruna: IAS 15th Rolling Conference–November 2-5, 2004, San Nicolás, Argentina.
8. F. Siciliano & E. I. Poliak: Microalloyed Stees for New Steel Processes and Applications International Symp. CEIT, San Sebastian, September, 2005.
9. F. Siciliano & J.J. Jonas: Metall. Trans., 2000, vol. 31A, p.511.
10. Y. Misaka, T. Yokoi, R. Takahashi & H. Nagai: J. Iron and Steel Inst.Japan, 1981, vol. 67, p. A53.
11. R.B. Sims: Proc. Inst. Mech. Eng.,1954, vol. 168, p. 191.
12. T.M. Maccagno, J.J. Jonas, S. Yue, B.J. McCrady, R. Slobodian & D. Deeks: ISIJ Int., 1994,
13. F.Siciliano & M. Imagumbai: Thermec 2003, Madrid, Trans Tech Publications, 2003, p. 223.