METALLURGICALLY CONSISTENT DETERMINATION OF STEEL HOT STRENGTH USING PROCESS DATA FROM HOT STRIP MILL ROLLING[1]

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ABSTRACT

It is not rare to observe an inverse relationship between hot strength determined from rolling load of the finishing stands of the hot strip mill and strain. This situation was already described in the literature and is explained by the use of inverse rolling load models that assumes sticking friction in the determination of hot strength. The aim of this work was to show that this "work softening" effect is fictitious, disappearing when hot strength is calculated with an inverse rolling load model that properly takes account of the tribological conditions that prevail in the roll gap.

Keywords: Hot Strength; Hot Strip Mill; Rolling Load Model; Tribology

DETERMINAÇÃO METALURGICAMENTE COERENTE DA RESISTÊNCIA À DEFORMAÇÃO DO AÇO A PARTIR DOS DADOS DA LAMINAÇÃO DE TIRAS A QUENTE

RESUMO

Freqüentemente se observa uma relação inversa entre a resistência à deformação a quente determinada a partir dos dados de carga de laminação do Trem Acabador do Laminador de Tiras a Quente e o grau de deformação. Este fenômeno já foi devidamente caracterizado na literatura e está ligado à determinação da resistência à deformação usando modelos inversos de carga de laminação que assumem atrito por agarramento. O objetivo deste trabalho foi mostrar que esse efeito de "encruamento negativo" é fictício, desaparecendo ao se calcular a resistência à deformação a quente através de um modelo inverso de carga que leve em conta as reais condições tribológicas no arco de contato.

Palavras-Chave: Resistência à Deformação; Laminação de Tiras a Quente; Modelo de Carga de Laminação; Tribologia

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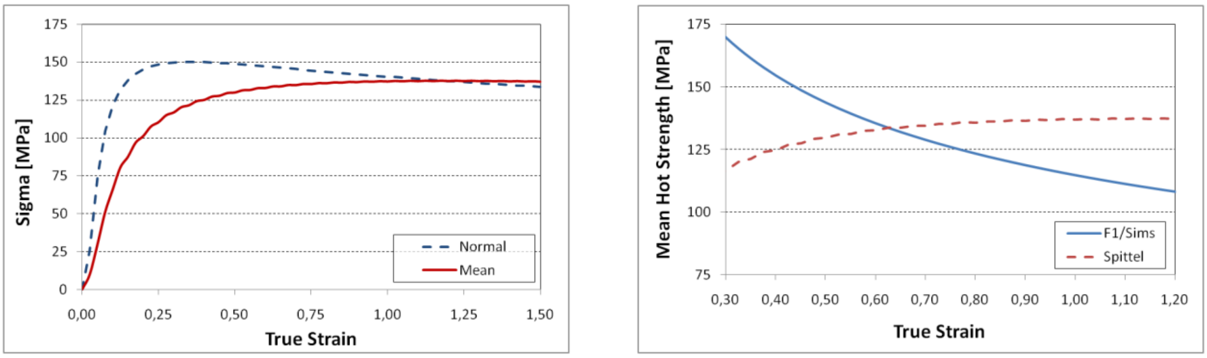
1. INTRODUCTION

The material strength σ_m associated to a rolling pass is a mean value defined by the following equation:

$$\sigma_m = \frac{\int_0^{\varepsilon} \sigma(\varepsilon)\, d\varepsilon}{\varepsilon} \qquad (1)$$

where ε is strain. Figure 1a shows the evolution of the normal and mean hot strength of AISI 1213 steel in function of strain determined from laboratory tests(1) considering typical process conditions of a F1 rolling stand of a hot strip mill. It can be seen that the strength peak value and its subsequent fall due to austenite dynamic recrystallization in the normal hot strength curve virtually disappear in the mean hot strength curve, which can be considered as a monotonically increasing function.

However, steady analysis of hot strength data got at the hot strip mill in the Cubatão works of Usiminas frequently showed an opposite and consistent tendency(2), that is, a continuous fall of the mean hot strength as strain increases. This can be seen in figure 1b, which shows a comparison between the evolution of mean hot strength along strain calculated using Spittel model(1) or from hot rolling loads of the F1 finishing stand using the inverse Sims model.



(a) (b)

Figure 1: a) Normal and mean hot strength values for AISI 1213 steel calculated according to Spittel(1); b) Comparison between mean hot strength values for AISI 1213 steel calculated by Spittel(1) and from hot rolling roads of the F1 finishing stand using the inverse version of the Sims model(2). All cases were calculated considering F1 typical process conditions, that is, temperature of 974°C and strain rate of 14 s^{-1}.

This unexpected behavior could not be associated to other potential causes of softening, like austenite transformation or adiabatic heating due to strain. So it was decided to look more carefully to the calculation of hot strength values from rolling loads. Generally this calculation uses the inverse Sims model, which assumes sticking friction – that is, it always assume a maximum value of friction coefficient in the calculations, no matter the dimensions of the rolling stock or process conditions. However, experimental determination of the friction coefficient values in Cubatão hot strip mill rolling showed that the value of friction coefficient is not fixed, but rather dependent, in an inverse way, on roll peripheral speed(3), as it was already found by other investigators(4,5), showing at least a partial slipping character. So, as strain per pass increases, roll speed also increases, in order to compensate the higher cooling rate of a thinner strip. Of course, on such cases, friction coefficient decreases, as well the contribution of friction to the rolling road value. However, as Sims model does not consider the real friction coefficient value in the roll gap, this minor contribution of friction to rolling load is erroneously and totally transferred to the hot strength value, which is artificially lowered. In other words, in such a way hot strength values are contaminated with the tribological conditions of the roll gap, losing some of its metallurgical character. So, to overcome this problem, it is necessary to use another inverse hot rolling load model to calculate hot strength, which must consider the real value of friction coefficient.

The general formula for calculation of hot rolling load **P** is

$$P = w \sqrt{R\ \Delta h}\ \sigma_m\ Q \qquad (2)$$

where **w** is the rolling stock width, **R** is the work roll radius, **Δh** is the difference between entry (**h_i**) and exit (**h_f**) thickness and **Q** is a geometrical factor.

The particular definition of this geometrical factor according to Sims, **Q_S**, is[6]:

$$Q_s = \left[\frac{\pi}{2}\sqrt{\frac{1-r}{r}}\ tan^{-1}\left(\sqrt{\frac{1-r}{r}}\right) - \frac{\pi}{4} - \sqrt{\frac{1-r}{r}}\sqrt{\frac{R}{h_f}}\ ln\left(\frac{h_n}{h_f}\right) + \frac{1}{2}\sqrt{\frac{1-r}{r}}\sqrt{\frac{R}{h_f}}\ ln\left(\frac{1-r}{r}\right)\right] \quad (3)$$

where **r** is conventional strain,

$$r = \frac{h_i - h_f}{h_i} \qquad (4)$$

and **h_n** is rolling stock thickness in the neutral point, i.e., the point in the roll gap where the speeds of work roll and rolling stock are equal. The angle in the roll gap corresponding to neutral point, **Φ_n**, can be calculated using:

$$\emptyset_n = \sqrt{\frac{h_f}{R}}\ \left\{\tan\left[\frac{\pi}{8}\sqrt{\frac{h_f}{R}}\ \ln(1-r) + \frac{1}{2}\ tan^{-1}\sqrt{\frac{1-r}{r}}\right]\right\} \qquad (5)$$

and **h_n** is determined with the equation below:

$$h_n = 2\ R\ (1 - \cos\emptyset_n) \qquad (6)$$

As can be seen, no mention is made to friction coefficient in the determination of **Q_S**.

On the other hand, according to the approach suggested by Simon et al.[7], the geometrical parameter **Q** can be expressed as a function of an adimensional parameter, **m**,

$$m = \frac{2\sqrt{R\ \Delta h}}{(h_i + h_f)} \qquad (7)$$

and the roll gap friction coefficient **μ**. Data establishing the relationship **Q** in function of **m** and **μ** for the Cubatão finishing mill were got as follows[8]. Firstly, a set of rolling load values covering all the range of typical operational conditions of this equipment were calculated using the Orowan model[9] and assuming slipping friction[3]. Then the corresponding value of the geometrical factor for each case was calculated using this formula:

$$Q = \frac{P}{w\,\sqrt{R\,\Delta h}\;\sigma_m} \qquad (8)$$

In this specific case, the geometrical factor was designated as $\mathbf{Q_{OS}}$ (from Orowan model/slipping friction). Then these values of $\mathbf{Q_{OS}}$ were used to train a neural network, which will be used to calculate this parameter from the values of **m** and **μ** when necessary. This procedure was repeated assuming sticking friction in the calculation of the rolling loads using the Orowan model[9]; in this case, the geometrical factor $\mathbf{Q_{OT}}$ (from Orowan model/sticking friction) can be calculated through a polynomial function using **m**.

The aim of this work was to verify the effect of the inclusion of the friction coefficient **μ** in the calculation of hot strength from rolling mill load data and to make a comparison with the previously adopted approach.

2. MATERIALS AND METHODS

Process data from 47.531 hot coils were collected for this analysis. Only data from the F1 finishing stand were considered, as there is no strain hardening effects from previous passes over hot strength in this case. The ranges of the collected data were: 0.001 ~ 0.23% C; 0.06 ~ 0.95% Mn; 924 ~ 1046°C; true strain **ε**: 0.31 ~ 1.15; strain rate $\dot{\varepsilon}$: 6 ~ 23 s^{-1}.

The value of mean hot strength was calculated for each coil from F1 rolling load and other process data, applying the following equation:

$$\sigma_m = \frac{P}{w\,\sqrt{R\,\Delta h}\;Q} \qquad (9)$$

The three different approaches for the calculation of the geometrical factor **Q** described before were used, that is: the one proposed by Sims ($\mathbf{Q_S}$) and those ones specifically fitted for the finishing stand at Cubatão works according to the procedure proposed by Simon et al.[7], using data generated by the Orowan model under slipping friction ($\mathbf{Q_{OS}}$) or sticking friction ($\mathbf{Q_{OT}}$). So, three different sets of hot strength values were got, corresponding to these methods for calculation of the geometrical factor **Q**: $\boldsymbol{\sigma_{m\_Sims}}$, $\boldsymbol{\sigma_{m\_OS}}$ and $\boldsymbol{\sigma_{m\_OT}}$, respectively.

3. RESULTS AND DISCUSSION

First of all, a comparison was performed between the hot strength values got in this work with those calculated using the same data, but applying traditional models: Misaka, Misaka with Dynamic Recrystallization and Shida[6]. Table I show the differences between hot strength values calculated according to these approaches. It can be seen that hot strength values calculated from rolling load data assuming slipping friction (**Q_{OS}**) showed minimum deviation in relation to the traditional models, which were fitted using hot strength laboratory data determined without action of friction between tool and steel sample. This indicates that the assumption of slipping friction lead to hot strength values nearer to those got without friction influence, as previously stated[10]. It is also interesting to note that hot strength data calculated with the Misaka with Dynamic Recrystallization model showed minimum deviation in relation to the values got from the industrial process, a fact already observed in a previous work[9].

Table I: Difference between hot strength values determined from F1 stand loads according to equation (8) using different approaches for the determination of the geometrical factor **Q** and those calculated using traditional literature models.

$\Delta\sigma_m$	σ_{m_Sims} [MPa]	σ_{m_QOT} [MPa]	σ_{m_QOS} [MPa]
Misaka	39 (29%)	36 (27%)	35 (26%)
Misaka+DRX	37 (28%)	35 (26%)	33 (24%)
Shida	83 (63%)	81 (60%)	79 (58%)

Hot strength data got from F1 hot rolling loads also were fitted to a general Hajduk equation[1]:

$$\sigma_m = k_1 \, e^{\frac{k_2 \, \%C}{T}} \, \varepsilon^{k_3} \, \dot{\varepsilon}^{k_4} \qquad (10)$$

where **%C** is steel carbon amount [wt%], **T** is temperature [°C], **ε** is true strain, **$\dot{\varepsilon}$** is strain rate [s^{-1}] and **k_i** are fitting constants, which values are showed in Table II. It can be seen that only the hot strength equation fitted using data calculated considering slipping friction (**Q_{OS}**) had a positive strain exponent equal to 0.028, although it was much lower than expected. For example, such exponent in Misaka's equation is equal to 0.21. However, it must be considered that data used to fit these equations was got from a industrial mill, where there is a strong correlation between the values of strain and strain rate, so they can not be considered as true independent variables. For this reason, it can be expected an interplay between the values of their exponents in equation (10). On another hand, the precision level of the three versions of this equation were identical, as the standard error of estimate was equal to 9.0 MPa and the fraction of residuals equal or below to 10% reaches around 88%.

This indicates that experimental error is greater than the effect of the friction coefficient over hot strength values.

Table II: Value of the fitting constants **k** of equation (4) according to the approach used to calculate hot strength from the F1 rolling load. SEE stands for standard error of estimate; **$\Delta\sigma_m$** is the residual between real and forecast values.

Model	**k_1**	**k_2**	**k_3**	**k_4**	**SEE [MPa]**	**$\lvert\Delta\sigma_m\rvert \leq 10\%$ [%]**
σ_{m_Sims}	105	351	-0.109	0.066	9.0	88
σ_{m_QOT}	105	362	-0.095	0.069	9.0	88
σ_{m_QOS}	107	351	0.028	0.084	9.0	88

The suppression of friction effects during the calculation of hot strength makes clearer the effect of alloy elements over this steel property. The influence of carbon over hot strength will be considered here as an example. An analysis of data used in this work revealed some correlations between F1 strain and strain rate with steel carbon amount, with Pearson correlation coefficient **r** equal to -0.190 and -0.272, respectively. This suggests that steels with higher carbon contents show tendency to be produced in the form of thicker coils, which requires the application of lower levels of strain per pass. This conclusion makes sense, as thicker structural material requires higher carbon amount to increase mechanical strength; for its turn, sheets for subsequent cold rolling must have lower carbon content in order to have better cold formability. Lower strain per pass lead to lower work roll peripheral speeds and, consequently, higher friction coefficients. So, when only industrial rolling mill data is available, the precise determination of the effect of carbon over hot strength requires that this parameter is not influenced by the tribological conditions in the roll gap.

As stated before(2,11), higher carbon amounts have a softening effect over austenite under the specific process conditions of the F1 stand of the finishing mill, that is, higher temperatures and lower strain rates. Table III show the results of the analysis performed in this work. It can be seen there that the effect of carbon over hot strength is lower when this parameter is calculated using the inverse load model by Sims as, in this case, friction is considered maximum and constant. But, as shown previously, friction indirectly increases with steel carbon content, promoting a hot rolling load increase. So, when hot strength is calculated by Sims, this increase is incorrectly transferred to the final result. This explain why the carbon softening effect is relatively low when it is determined from hot strength data determined using rolling load inverse models which consider sticking friction. However, when a rolling load inverse model considering slipping friction is considered, then load increase due to higher friction coefficients is correctly isolated from hot strength. So, carbon softening effect is higher – as a matter of fact, it doubled -, as can be seen in table III, reflecting more perfectly the metallurgical phenomena occurring in austenite during hot forming.

Table III: Effect of carbon over austenite hot strength determined from F1 rolling load data according to several approaches for the calculation mean hot strength.

	$\Delta\sigma_m$ / C [MPa.wt%]
σ_{m_Sims}	-30
σ_{m_QOT}	-34
σ_{m_QOS}	-61

4. CONCLUSIONS

The unexpected "strain softening" frequently observed during the analysis of low carbon austenite hot strength determined from rolling load data of industrial finishing mills can be attributed to the Sims inverse model normally used to convert rolling load data into hot strength values. This model does not take account of the variations in friction conditions prevailing in the roll gap that result from the processing of products with different dimensions. Thinner coils are processed under higher speeds, lowering friction coefficient and rolling load. As Sims model always assumes a maximum and constant friction coefficient in all instances, this rolling load decrease artificially lowers hot strength. This work showed that an approach that considers the real tribological conditions in the roll gap during the conversion from rolling mill load to hot strength avoids this problem, generating results more consistent from a metallurgical point of view.

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