CHARACTERIZATION OF THE FRICTION CONDITIONS IN THE FINISHING STANDS OF A HOT STRIP MILL[1]

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ABSTRACT

The decrease in hot strength or even rolling load as strain increases in some stands of the finishing hot strip mill with no metallurgical reasons is a relatively common event. Apparently this fact is associated with modification in the tribological conditions between rolling stock and work roll surfaces due to unexpected interactions with scale. The aim of this work was to determine the values of the friction coefficient in the several stands of the finishing hot strip mill at Usiminas-Cubatão, as well to determine quantitative relationships between this coefficient and relevant process parameters, like strain degree and peripherical work roll speed.

Keywords: Hot Strip Rolling, Friction Coefficient, Forward Slip

CARACTERIZAÇÃO DAS CONDIÇÕES DE FRICÇÃO NO TREM ACABADOR DE UM LAMINADOR DE TIRAS A QUENTE

RESUMO

Não é raro observar redução na resistência à deformação ou mesmo na carga sob níveis crescentes de deformação em algumas cadeiras do trem acabador do laminador de tiras a quente sem que haja razões metalúrgicas para o fato. Aparentemente esse fato está associado à modificação das condições de atrito no arco de contato decorrentes de interações inesperadas com a carepa. Este trabalho teve como objetivo determinar os valores de coeficiente de atrito no trem acabador do laminador de tiras a quente da Usiminas-Cubatão. Além disso, foram determinadas relações quantitativas entre esse coeficiente e parâmetros relevantes de processo, tais como grau de deformação e velocidade periférica dos cilindros de trabalho.

Palavras-Chave: Laminação de Tiras a Quente, Coeficiente de Atrito, Deslizamento a Vante

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[1] *Paper to be presented at the First International Brazilian Conference on Tribology – TriboBR-2010, Associação Brasileira de Metalurgia, Materiais e Mineração, Rio de Janeiro RJ, Brazil, 24th to 26th November 2010.*

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1. INTRODUCTION

During flat rolling of metals the speed of the rolling stock increases steadily as it is being deformed. At some location of the rolling gap, called neutral point, the speed of the rolling stock equals the peripherical speed of the rolling rolls. The rolling stock speed keeps growing after the neutral point, so the rolled material exits the roll gap faster than the rolls. In other words, the rolling gap is comprised of a forward and a backward region, which are separated by the neutral point. There is sliding in both directions, forward and backward, with different continuously varying relative speeds. So, there is always friction between rolls and rolled material along the rolling gap and it is generally assumed that it follows the Coulomb's model. Several processes factors, as rolling speed, strain, temperature and lubrication, among others, can significantly influence the friction conditions in the rolling gap and, indirectly, the resulting sliding intensity and rolling load.

Usiminas-Cubatão, an integrated steelworks near São Paulo, Brazil, has a hot strip mill which produces coils of carbon and microalloyed steels. This line has a six stand hot strip finishing mill which uses work rolls made of indefinite chill double poured cast iron (ICDP) in all stands. The analysis of operational data from that finishing mill frequently shows that rolling load of some stands decreases as pass strain is increased. This phenomenon can be seen more easily when the rolling load values are converted into steel hot strength using an inverse hot rolling model, like Sims[1]. As generally it is assumed that friction in hot rolling is of sticking type, at first sight this decrease in hot strength with higher strains only can be explained by some metallurgical mechanism, like dynamic recrystallization of austenite, austenite-to-ferrite transformation or temperature increase due to forming work. However, data analysis and microstructural evolution models showed that these mechanisms were not likely to occur in the rolling events associated with the data analysed[1].

But rolling load decrease with increasing values of strain during hot strip rolling is not rare, as this fact is reported in several papers[2-4]. Generally there is a given value of pass strain where rolling load stopped growing and began to decrease. And the magnitude of load or hot strength decrease is greater than the effect that could be expected exclusively from austenite dynamic recrystallization or some other softening metallurgical effect. As this hot strength decrease is accompanied by the release of red dust and intensification of work roll wear and banding, it was attributed to a reduction in the hot rolling friction coefficient due to scale crushing and powdering when strain degree is above some critical value[3]. So now it is believed that friction in hot rolling is not exclusively of the sticking type. Values of friction coefficient determined from hot strip mill data showed that this parameter decreased with increasing values of strain, confirming these previous observations[5]. More recently, new hot rolling load models including the effect of friction were developed. They yielded more precise results than the former versions that only considered sticking friction[6].

So, it was decided to develop a work to calculate the friction coefficient values for the rolling stands of the finishing stands of the hot strip mill of Usiminas-Cubatão, in order to better understand its tribological condition and its relationship with several process parameters. These models would be necessary to a future rolling mill load model that would use friction coefficients as an input parameter.

2. EXPERIMENTAL PROCEDURE

The direct measurement of friction coefficient is not feasible in industrial hot rolling. However, it can be calculated using some other approach – for instance, from the forward slip value for each stand. The calculation of forward slip requires the measurement of the work rolls peripherical speed and rolling stock speed. The first parameter is easy to measure, but the other requires laser velocimetry or some tricky analysis of rolling data.

On the other hand, forward slip is calculated by the automation system of the Usiminas-Cubatão finishing mill considering conditions of steady metal flux between the several rolling stands. The value of the angle of each looper is used to correct the calculated forward slip value for the preceding stand. The inconvenience of such approach is that the forward slip of the sixth (and last) stand is not corrected. The values of forward slip determined in such way apparently have enough accuracy, as the correct metal flux along the several stands of the finishing mill depends on very representative values of such parameter.

From the forward slip **S** value one can calculate the value of average friction coefficient μ for a rolling pass using the following equation system proposed by Tselikov[7]:

$$S = \left(\frac{2\,R}{h_2}\cos\emptyset\ -\ 1\right)\,2\,sen^2\left(\frac{\emptyset}{2}\right) \qquad (1)$$

$$\emptyset = sen^{-1}\left[\frac{sen\,\alpha}{2} - \frac{(1-\cos\alpha)}{2\,\mu} + \frac{(T_2\ -\ T_1)\,\sqrt{\Delta h}}{4\,P\,\mu\,\sqrt{R}}\right] \qquad (2)$$

$$\alpha = cos^{-1}\left(1 - \frac{\Delta h}{2\,R}\right) \qquad (3)$$

where α is the bite angle, **R** is the flattened work roll radius, h_1 is the initial and h_2 is the final thickness of the strip, ϕ is the neutral angle, T_1 is the entry and T_2 is the exit tension stress in the strip, **P** is the rolling load and Δh is the difference between h_1 and h_2. The values of all those parameters but μ and ϕ are known, so the calculation of these parameters is possible using the numerical method of bisection. However, this procedure does not guarantee that the calculated values of the friction coefficient are always between zero and the unity. So, values of μ eventually out of this range were discarded, as they are physically incoherent. The calculation of the friction coefficient values required process data got from 16,383 hot coils processed in the six stand finishing mill and available in the hot strip mill data base.

Some relevant process parameters were included in a data set used for the statistical analysis done in order to identify the main variables that affect friction coefficient: carbon, manganese and silicon contents of the steel coil, rolling temperature, strain degree, peripherical work roll speed, length of strip processed up that coil by the work rolls, forward slip, hot strength and neutral angle. Hot strength values were calculated from rolling load using an inverse Sims model[8]; friction coefficient and neutral angle were calculated using equations (1) to (3); the remainder parameters were got from the hot strip mill data base.

3. RESULTS AND DISCUSSION

Table 1 shows the average values of strain ε, forward slip **S**, friction coefficient μ and neutral angle ϕ determined for each rolling stand of the Usiminas-Cubatão finishing mill. The values of all those parameters decreased along the finishing mill. This tendency and their values are much alike similar data available in the literature[6], which confirms the adequacy of the algorithm proposed here for the calculation of the hot rolling friction coefficient. The exception is the value of friction coefficient of the F6 stand, which was slightly higher than the F5 stand.

Table 1: Average values of strain ε, forward slip **S**, friction coefficient μ and neutral angle ϕ got here for each rolling stand of the finishing mill.

Stand	ε	**S [%]**	μ	ϕ **[°]**
F1	0.68	11.6	0.43	4.58
F2	0.51	9.4	0.35	3.02
F3	0.43	8.3	0.28	2.23
F4	0.33	6.8	0.26	1.71
F5	0.25	5.3	0.24	1.27
F6	0.18	4.3	0.26	1.05

That discrepancy can be understood considering Table 2, which shows the fraction of data records that yielded consistent values of friction coefficient for each rolling stand of the finishing mill. As one can see, the fraction of good records fall slightly from F1 to F4 but, anyway, for such stands this fraction was greater than 99%. The situation of F5 was somewhat worse, with 92% of good data records, but F6 showed unsatisfactory results, as this fraction fell to only 35%. The better performance got for earlier stands can be attributed to the progressive greater number of looper angle data available to correct the calculated values of forward slip, increasing their precision in relation to the real values. That is, forward slip calculated for the **i** stand can be corrected using data from the following **i-1** loopers. There is no looper after F6, so the correction of the forward slip values calculated for such stand is most deficient. Besides that, it must be also considered that the sensitivity of μ with variations of forward slip, as defined by equations (1) to (3), became small as the value of pass strain decreases, which makes the calculation of μ less accurate as the rolling reduction became smaller[9]. So, no wonder that the precision of μ decreased for the rolling stands with decreased strain degree.

An example of the results got from the principal component analysis determined from the data set collected here is shown in figure 1. These results, corresponding to the rolling stand F2 of the finishing mill, are representative for all other stands. From that analysis it can be seen that the position in the graph corresponding to the friction coefficient is directly opposed to the positions of the parameters strain degree, work roll peripherical speed and forward slip, a condition that indicates a strong inverse relationship between friction coefficient and those other parameters. These correlations were already shown in the literature[5,7]. As there is no other parameters near the position corresponding to the friction coefficient, it can be deduced that the other variables considered have no significant influence over that parameter. This includes temperature, which sometimes is included as an relevant factor to determine the hot rolling friction coefficient[7]. These results got from the principal component analysis were confirmed in the graphs of friction coefficient versus strain degree (figure 2), roll speed (figure 3) and forward slip (figure 4).

Table 2: Fraction of data records for each rolling stand that yielded physically sound friction coefficient values.

Stand	F1	F2	F3	F4	F5	F6
OK	99.99%	99.90%	99.87%	99.14%	92.02%	35.48%

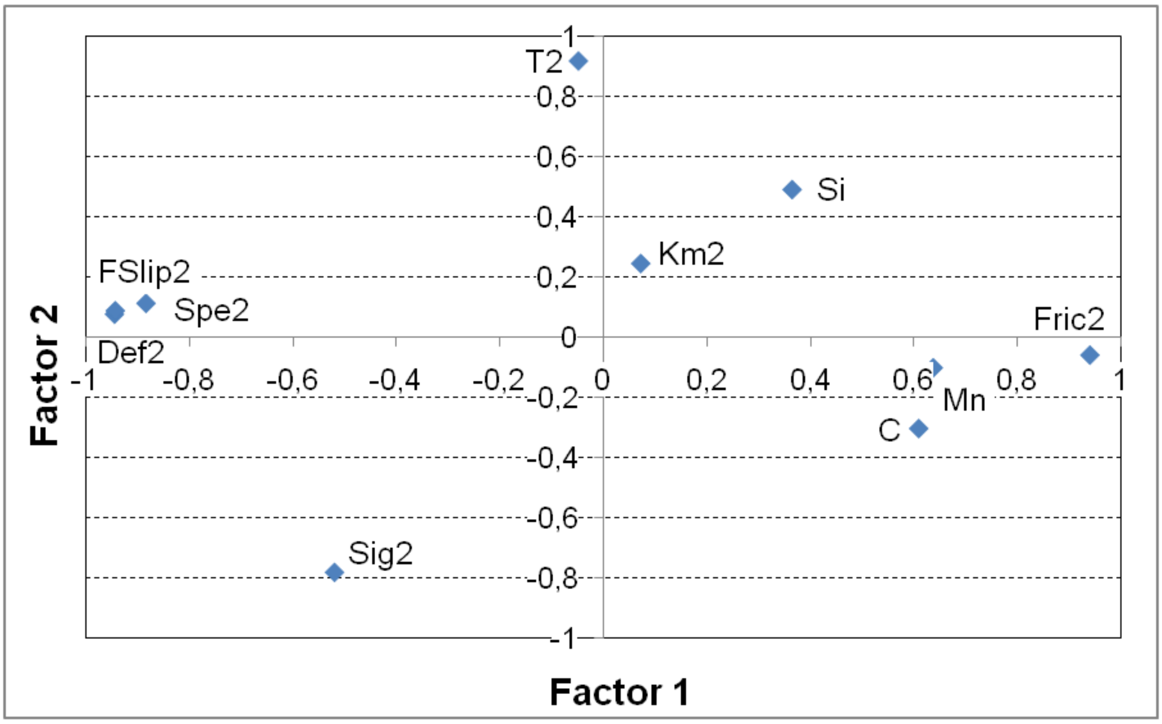

Figure 1: Results of the principal components analysis determined from F2 stand rolling data. Legend: **C**, carbon content; **Mn**, manganese content; **Si**, silicon content; **T2**, rolling temperature; **Def2**, strain degree, **Km2**, length of strip processed up to that moment by the work rolls; **FSlip2**, forward slip; **Sig2**, hot strength; and **Fric2**, friction coefficient.

The traditional equations used for the calculation of the friction coefficient does not consider the effect of strain degree[7], but industrial hot strip mill evidence, both indirect[2-4] and effectively measured[5], points that this parameter is also important in this case, eventually due to some interaction with scale – eventually its crushing and powdering under heavy strains. Apparently this was also the case here.

However, it must be noted that there is a strong correlation between work roll peripherical speed and strain degree in the hot strip mill, as it is shown in figure 5. This is a intrinsic condition of these rolling mill lines, as heavier strains generally result in longer and thinner strips, which must be moved faster along the mill in order to keep temperature decrease within safe operational intervals. So, a reliable discrimination between the effects of strain degree and work roll peripherical speed over friction coefficient is virtually impossible in this case.

According to the classical hot rolling theory, the acceleration of the rolling stock when it passes between the work rolls is directly proportional to the friction coefficient, which implies in the increase of the forward slip[10]. This is not what can be seen from figure 4, where all forward slips curves show a decreasing effect of the friction coefficient. However, this is explained by the fact that forward slip is also defined by strain degree, as shown in figure 6, as higher thickness reductions result in longer rolling stocks and in a stronger longitudinal acceleration. So, in the finishing mill, greater strain increases forward slip and work roll speed. The greater speed, for its turn, reduces the corresponding value of friction coefficient. But the effect of strain over forward slip must be greater than that of the friction coefficient, so there is a net increase of forward slip associated with decreasing values of friction coefficient. This must be the reason for the unexpected relationship between forward slip and friction coefficient when the same rolling stand is considered. This explanation is confirmed by the fact that, for constant values of strain degree, forward slip values determined in this work were proportional to friction coefficient, as originally expected. Besides that, the average values of forward slip and friction coefficient for each rolling stand, as seen in table 2, show the expected trend, except for the F6 stand. However, as it was stated later, forward slip values for this stand have significant errors, as can be seen in figure 6. The curve forward slip versus strain degree for the F6 stand has a strong deviation which is not observed in all remaining curves.

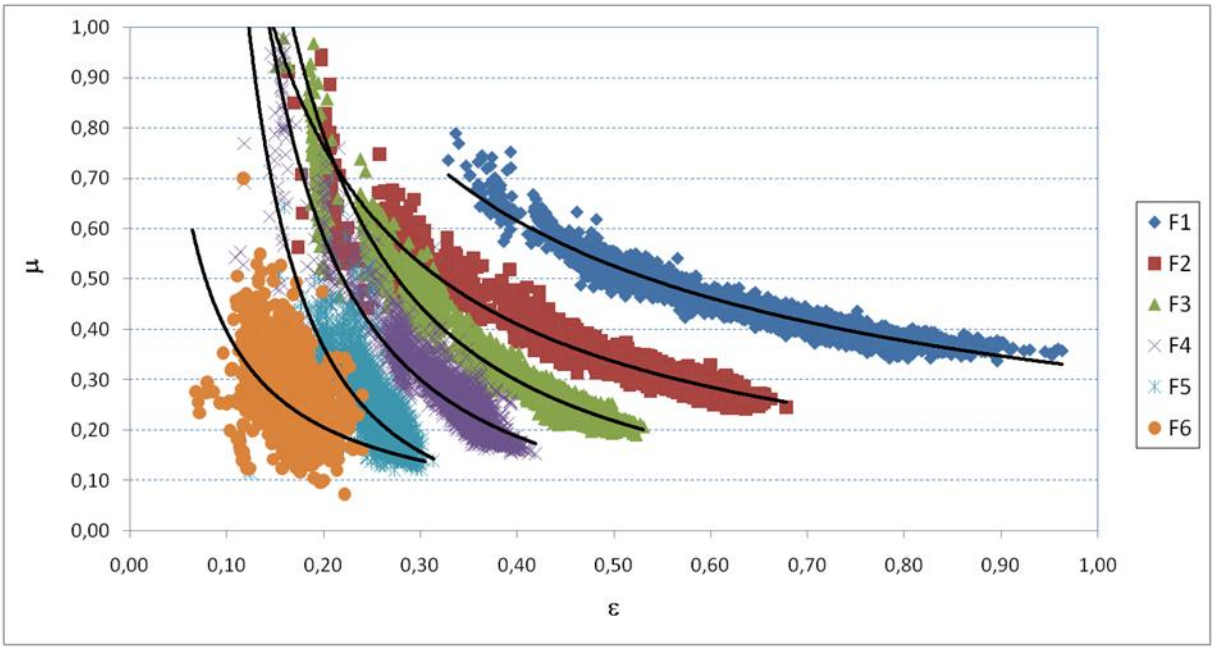

Figure 2: Friction coefficient μ in function of strain degree ε for the six rolling stands of the finishing mill.

A multiple stepwise correlation analysis involving the parameters considered in this study revealed that strain degree **ε** and work roll peripherical speed **v** were the most relevant independent parameters for the calculation of forward slip **S**. The best predicting equation has the form

$$S = a\,\varepsilon^{b} + c\,v^{d} \qquad (4)$$

where **a**, **b**, **c** and **d** are fitting constants. On the other hand, the analysis considering Pearson's correlation coefficient **r** and standard error of the estimate **SEE** of this equation, shown in table 3, indicates that, for all rolling stands, the predicting performance of the equation virtually had no improvement with the incorporation of the work roll peripherical speed. This can be justified by the strong relationship between this parameter and strain degree, as shown in figure 5.

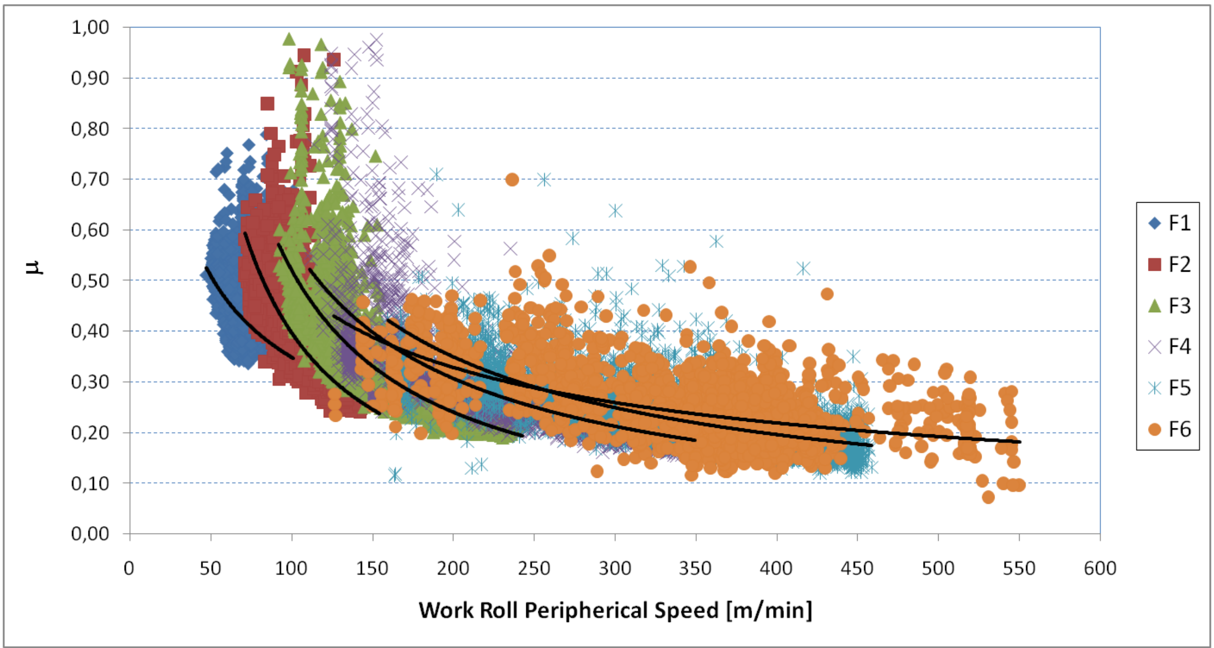

Figure 3: Friction coefficient μ in function of work roll peripherical speed for the six rolling stands of the finishing mill.

A similar result was got for the friction coefficient μ. This is not surprising, as friction coefficient was calculated from forward slip values. The best predicting equation is identical to that used for forward slip:

$$\mu = a\,\varepsilon^{b} + c\,v^{d} \qquad (5)$$

where **a**, **b**, **c** and **d** are fitting constants. The analysis considering Pearson's correlation coefficient **r** and the standard error of the estimate **SEE** of this equation, shown in table 4, yielded results similar to those got for the forward slip equation. The inclusion of the work roll peripherical speed led to some improvement of the predicting performance of the equation, especially for the last stands and only regarding the Pearson's correlation coefficient **r**. The standard error of estimate was not improved so much.

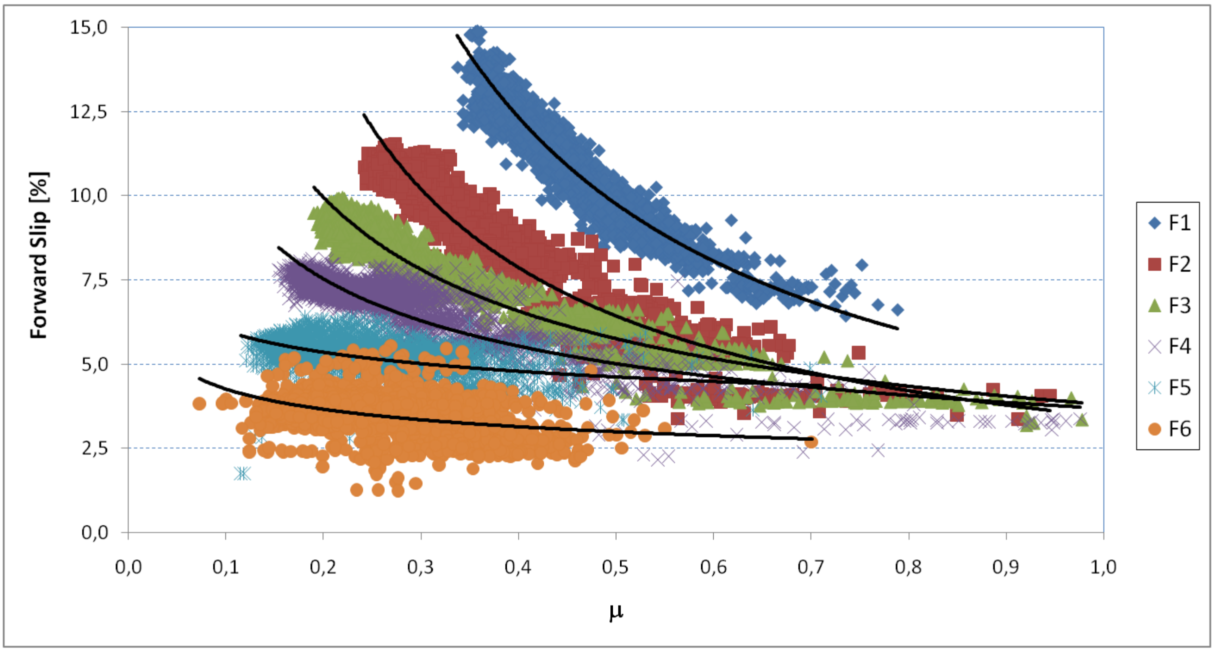

Figure 4: Forward slip in function of friction coefficient μ for the six rolling stands of the finishing mill.

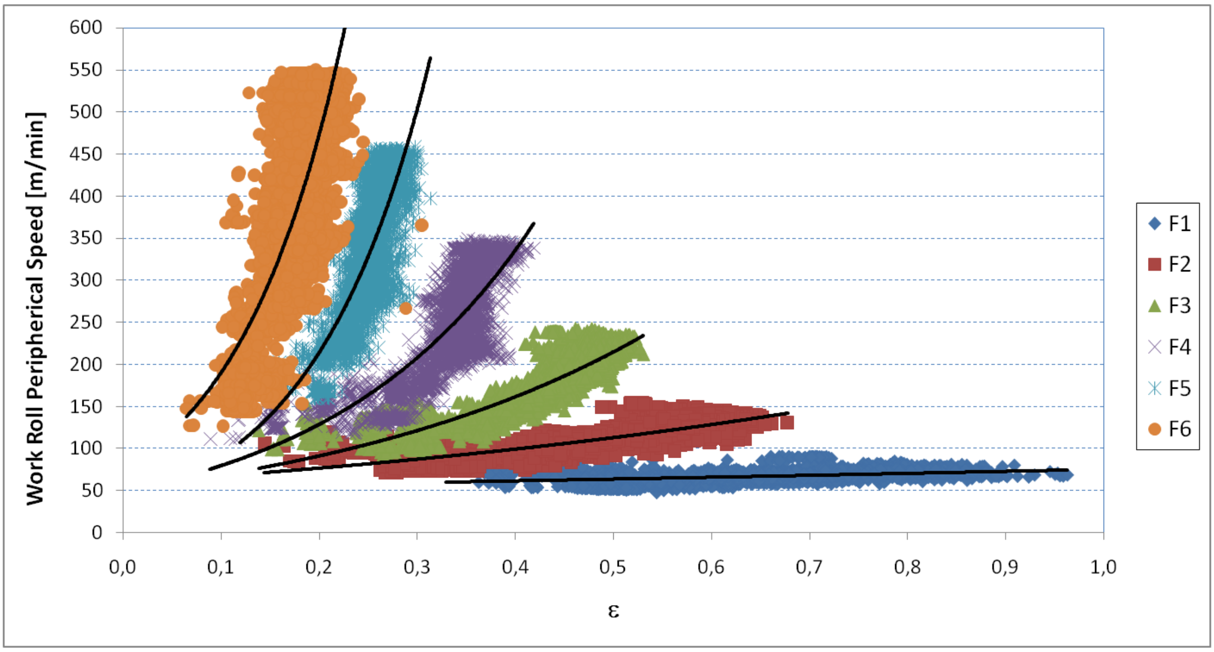

Figure 5: Work roll peripherical speed in function of strain degree ε for the six rolling stands of the finishing mill.

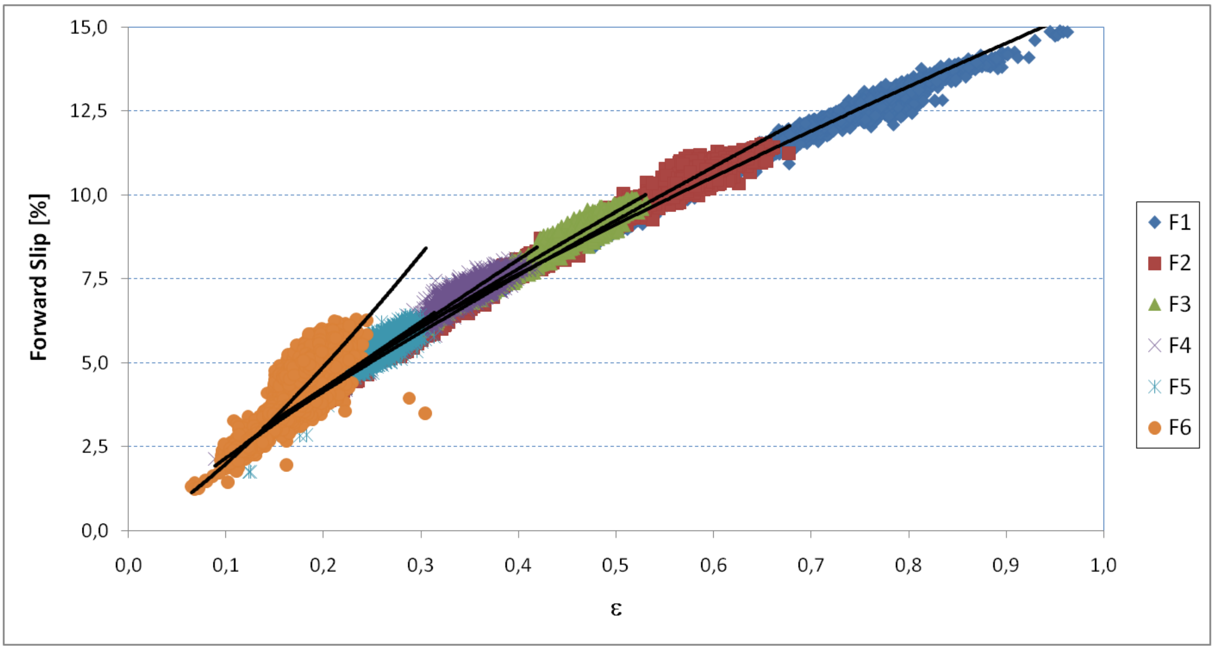

Figure 6: Forward slip in function of strain degree ε for the six rolling stands of the finishing mill.

Table 3: Values of Pearson's correlation coefficient **r** and standard error of estimative **SEE** for equations used to calculate forward slip **S** from strain degree ε or strain degree ε and work roll peripheral speed **v**.

ROLLING STAND	$S = a\,\varepsilon^b$		$S = a\,\varepsilon^b + c\,v^d$	
	r	**SEE**	**r**	**SEE**
F1	0.996	0.15	0.996	0.15
F2	0.995	0.16	0.997	0.14
F3	0.992	0.16	0.993	0.15
F4	0.980	0.19	0.985	0.17
F5	0.903	0.19	0.920	0.18
F6	0.902	0.47	0.913	0.45

Table 4: Values of Pearson's correlation coefficient **r** and standard error of estimative **SEE** for equations used to calculate friction coefficient μ from strain degree ε or strain degree ε and work roll peripheral speed **v**.

ROLLING STAND	$\mu = a\,\varepsilon^b$		$\mu = a\,\varepsilon^b + c\,v^d$	
	r	**SEE**	**r**	**SEE**
F1	0.973	0.02	0.976	0.01
F2	0.954	0.03	0.963	0.02
F3	0.953	0.03	0.963	0.03
F4	0.885	0.05	0.914	0.04
F5	0.708	0.05	0.962	0.05
F6	0.492	0.07	0.643	0.06

4. CONCLUSIONS

The calculation of friction coefficients of a finishing hot strip mill from values of forward slip determined by its automation system yielded coherent values for all rolling stands, except the last one, where the absence of a subsequent looper prevented the adequate correction of the forward slip values. These calculated values of friction coefficients showed strong dependence with strain degree and work roll peripherical speed, but not with rolling temperature. While the decreasing effect of speed over friction coefficient is already known, the similar influence of strain degree still is to be completely explained, but apparently it can be attributed to the crushing and powdering of oxide scale under heavy thickness reductions. Both forward slip and friction coefficient can be calculated with reasonable accuracy only from strain degree, with work roll peripherical speed having an almost negligible influence. Apparently the highly correlated operational conditions of the hot strip mill converged most of the rolling effects into only one representative parameter, that is, strain degree.

5. REFERENCES

1. GORNI, A.A. & SILVEIRA, J.H.D. Caracterização da Ocorrência de Recristalização Dinâmica na Laminação de Tiras a Quente. In: 60° Congresso Anual da Associação Brasileira de Metalurgia e Materiais. **Anais…** Belo Horizonte, 2005, 192-199.

2. WIESINGER, H. et al. Das kontinuierliche Stranggießen und –walzen von Dünnbrammen. **Stahl und Eisen**, v. 110, n. 11, p. 81-88, 14 November 1990.

3. KOST, R. et al. Berechnung der Werkstoffkennwerte von Warbreitband auf Basis einer Walzspaltanalyse. **Stahl und Eisen**, v. 112, n. 11, p. 69-74, 9 November 1992.

4. REIMER, C. & HUISMAN, R.L. Geometrical Effects of Large Reductions in First Stands of Finishing Mill. **Ironmaking and Steelmaking**, v. 20, n. 4, p. 275-279, 1993.

5. MORALES, J. et al. Influence of Process Parameters on Friction Coefficient of High-Chromium Rolls. **AISE Steel Technology**, v. 76, n. 11, p. 46-48, November 1999.

6. LI, Y. et al. Roll Force Model for Online Application in hot Strip Rolling with Varying Friction Conditions. International Conference on Steel Rolling, **Proceedings**. Association Technique de la Siderurgie Française, Paris, 2006, 8 p.

7. TSELIKOV, A. **Stress and Strain in Metal Rolling.** MIR Publishers, Moscow, 1967, 475 p.

8. MACCAGNO, T.M. et al. Determination of T_{nr} from Rolling Mill Logs - Comparison with Laboratory Data. **ISIJ International**, v. 34, n. 11, p. 917-922, November 1994.

9. FLETCHER, A.J. et al. Prediction of Roll Force and Torque during Hot Flat Rolling of En2 Steel. **Metals Technology**, v. 11, n. 4, 156-166, April 1984.

10. SEREGIN, S.A. About Mechanism of Forward Flow Formation in Rolling. **Steel in Translation**, v. 23, n. 4, p. 31-33, April 1993.