Experimental and numerical investigation on the influence of the back tension during cold rolling

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Abstract: *During the cold rolling of a steel strip on a four high mill, it has been observed that when the strip is transported between the rolls and the coiler, rolling torque peaks occur. Although these peaks happen in a relatively short time interval, measured in milliseconds, the mill mechanical components that drive the working rolls are subject to loads much higher than those observed during a regular pass. The relationship between the peak torque and the mean rolling torque is known as the Torque Amplification Factor – TAF.*

In this work, Adaptive Neural Networks (ANN) has been utilized to relate operational factors with the appearance of TAF during introduction of the steel strips in the rolling mill. For the training of the ANN, large amounts of regular process data were acquired. Based on Ford's rolling torque equation, the neural network architecture has been selected. Some operation parameters were chosen and their values changed in order to understand the influence of the back tension on the torque during the introduction stage. The results achieved with the ANN model have shown the way to reduce TAF and, in consequence, to improve mill component lives. Experiments were carried out to confirm the expected results.

Keywords Cold rolling mill, Neural Networks, Torque amplification

1. INTRODUCTION

In a reversible four high cold rolling mill, at each new coil to be rolled, there's a need for an operation called "strip introduction". The introduction of the strip means taking the tip of the coil from the uncoiler leading it down to the coiler. This operation can be divided in two phases: the first one is when the tip leaves the uncoiler and arrives at the working rolls, and the second one is when the tip is carried from the working rolls to the coiler. For the Brasmetal Waelzholz mill, during the introduction, the drive motors of the uncoiler, working rolls, coiler and uncoiler are commanded by the Jog switch. When the Jog is pressed, the motors are driven according to what is requested by the operator. In some cases, during introduction, peaks in the torque of the working rolls are observed (Fig. 1). Normally the amplitude of these peaks is larger than the mean rolling torque. These peaks are related to the so-called TAF – "Torque Amplification Factor". TAF is defined as the peak torque, divided by the mean rolling torque, as given by equation 1. [6,12].

$$TAF = \frac{T_{peak}}{T_{mean}} \qquad (1)$$

In the technical literature, the occurrence of TAF has been extensively studied for hot rolling. In this case, the working rolls are idle by the time they receive the strip that will be rolled. As a result of the impact between the strip and the working rolls, a torque peak occurs in the working rolls that lead to a wave propagation through the driving components [6,12]

H.Honjyo and H. Wataname [6] showed that TAF can be influenced by many factors and that its amplitude will be determined by the sum of these factors. According to these the authors, in hot rolling, TAF derives from two aspects:

-Pure Impact: speed of introduction, response of the driving system, impact of the rolling loads, mechanical structural stability of the driving system.

-Equipment or maintenance and operation: Imperfections in the synchronism between the working rolls and the rolled strip, looseness in the drive set, imperfections in the synchronism with the neighboring mill stand, imperfections in the lubrication and cooling systems, torque unbalance between the upper and lower working rolls.

On observing the TAF occurrence during cold rolling, some aspects were common to both rolling processes (hot and cold). Indeed, making an analogy to the factors pointed out by Honjyo and Wataname [6], it was verified that during cold rolling the following aspects are common:

- Pure impact: Breaking or strip folding, emergency stops, "introduction speed" and drive system response are all related to the frequency of Jog usage;

- Equipment, maintenance and operation: Imperfections in the tension control, imperfections in the mill stand motor control system, improper reductions and incorrect tensions.

Depending on amplitude and frequency of the occurrence of the TAF, in the studied rolling mill, the main consequence is breakage of the safety pins, installed in the transmission spindles of the working rolls. Obviously, the function of these pins is to break when some overload occurs during the process that could damage the drive set (gear box, motor, coupling, etc). Although the drive set is protected even when the safety pins brake, in many cases, damage occurs to the working roll surface, with tearing of the rolled strip and leading to the undesired stop for pin replacement. Due to the derived TAF problems on the rolling mill and on the productive process (it is evident that during either hot or cold rolling), that basic importance is put on to know and to eliminate the factors that influence their breakage.

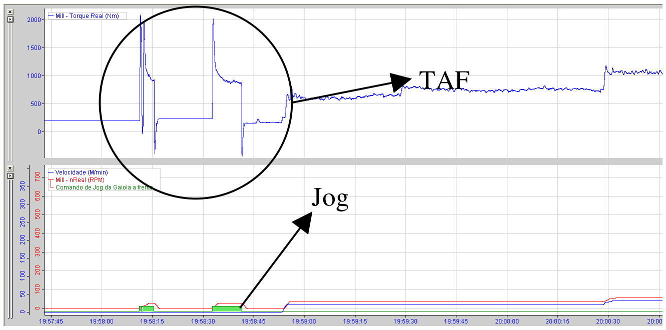


Figure 1 – TAF during the introduction stage

2. OBJECTIVES

The study of the TAF (during the introduction stage of the steel strip in the mill), was motivated due to its systematic occurrence (in contrast to other phases of the process, where its occurrence was less frequent), meaning greater frequency in the safety pin breakage. Hence, the objectives of this project are:

- Application of Adaptive Neural Network relating operational parameters (during introduction), with the TAF;
- Analyze the influence of back tension on the rolling torque, and consequently on the TAF, during the introduction of the steel strip in the rolling mill;
- Optimization of the rolling pass scheme, aiming at minimization of the TAF (during the introduction).

3. DATA COLLECTION AND ANALYSIS

Data collection and analysis were carried out in three phases [1].

In the first phase, the introduction of the strip was done with variations in back tension, with the objective of verifying the influence of back tension on the rolling torque.

In the second phase, the operational parameters were monitored during 200 hours in order to identify the main variables during the occurrence of the TAF during the introduction.

In the third phase, the amplitude of the TAF was compared in two situations. Therefore a coil was divided into two new coils. The first coil was rolled according to the standard procedure. The second coil was rolled according to the calculation methodology (available from the cold rolling theory).

In the three phases, data collection and analysis (including thickness, velocity, torque, rolling load and tension), were obtained through a supervision package, consisting of two modules: one for data collection –*ibaPDA Lite*- and one for data analysis -*ibaAnalyser*[8].

4. USES AND CONFIGURATION OF THE ADAPTIVE NEURAL NETWORK (ANN)

In an industrial environment where the main objective is the accomplishment of a production that takes care of the market demands, it becomes very difficult to perform experiments that follow definitive standards of repeatability. Therefore, the collected data are found in a variety of operational conditions, each aiming at the product specification. Hence, it was opted to use the ANN to relate the operational parameters to the occurrence of the TAF.

Adaptive Neural Networks are computer-oriented algorithms that can recognize standards in a particular data set and produce a model from this data. They are useful tools in various areas and their applications can be found in: process modeling, quality control, machine diagnosis, forecast in the financial market, etc. [15,17,19]. In the case of rolling, there are published papers in the areas of hot as well as on cold rolling of sheets [3,5,910].

The option to use the Adaptive Neural Network to relate the operational parameters in the rolling process with the TAF was mainly related to their particular characteristic. Adaptive Neural Networks are a very useful tool to obtain valid answers from unrelated data and that originally may have been used for the study. The neural network has a true learning phase and it is very important that the data collection is made in a rigorous basis in order to avoid spurious data [2,7,15].

For this objective to be met, many adaptive neural networks were elaborated with different data entry. These networks were, then, validated and tested. The selection criterion was the adherence between the produced data by the network and the input data. Next, two networks that had the best adherence will be presented. In these networks, the input and output variables were determined, based on the torque equation given by Ford (eq. 2) [14]:

$$M_d = M + \left(\frac{\sigma_r h_0 - \sigma_a h_1}{2} \right) .R.b.10^{-3} \qquad \text{or} \qquad M_d = 2.P.a + \left(\frac{\sigma_r h_0 - \sigma_a h_1}{2} \right) .R.b.10^{-3} \tag{2}$$

Where,

h_0	entry thickness	a	lever arm
h_1	exit thickness	σ_r	back tension
M_d	rolling torque with tension	σ_a	forward tension
M	rolling torque without tension	P	rolling load – without tension
R	roll radius	b	strip width

In equation 2, the variable *P* stands for rolling force without tension. However, the rolling force obtained during data collection was under tension's influence. Literature shows that strip tension influences rolling force. To verify the magnitude of this influence on the rolling force the Hessenberg and Sims relationship (eq. 4) has been employed for the collected data [13,14].

$$F = P.\left[1 - \frac{1}{3.\overline{\sigma}} (2.\sigma_r + \sigma_a) \right] \tag{3}$$

Where:

σ	plain strain flow stress
F	rolling load (with tension)

Once corrected the rolling force (for the influence of the tension), the flattened radius of the roll was evaluated according to equation 4 [13, 14]:

$$\frac{R'_n}{R'_{n-1}} \cong 1{,}05 \tag{4}$$

Where:

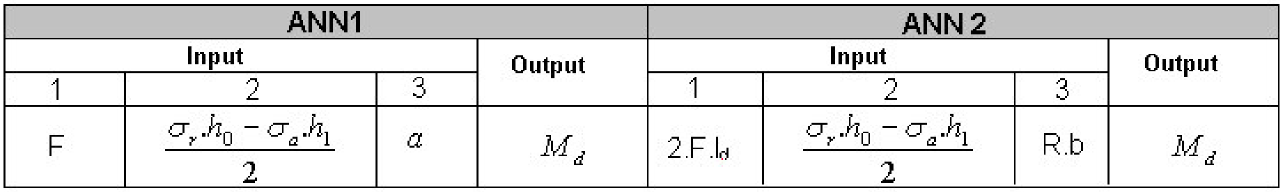
R'_n and R'_{n-1} flattened roll radius iteration relationship.

Figure 2 shows that majority of the results satisfy equation 5. The rolling loads with tension have been compared to those of the Hessenberg and Sims equation. From Figure 3 it may be observed that the rolling load is systematically larger without tension, however it may be observed that, in the present case, this difference was relatively small. Majority of the points in the graph were below 4% and, only in some cases, over 8%.

$$M_{do} = 2.F.a + \left(\frac{\sigma_r h_0 - \sigma_a h_1}{2} \right) .R.b.10^{-3} \tag{5}$$

Table 1, presents the input/ output variables that have been used for the two networks. In network1, input data was based upon variables of equation 5 to calculate the torque. In this case, the first column takes into consideration the rolling force, the second column the applied strip tension and the third column the lever arm, calculated through equation 5.

Table 1 – Input / output variables for the ANN



ANN1				ANN 2			
Input			Output	Input			Output
1	2	3		1	2	3	
F	$\frac{\sigma_r.h_0 - \sigma_a.h_1}{2}$	a	M_d	$2.F.l_d$	$\frac{\sigma_r.h_0 - \sigma_a.h_1}{2}$	R.b	M_d

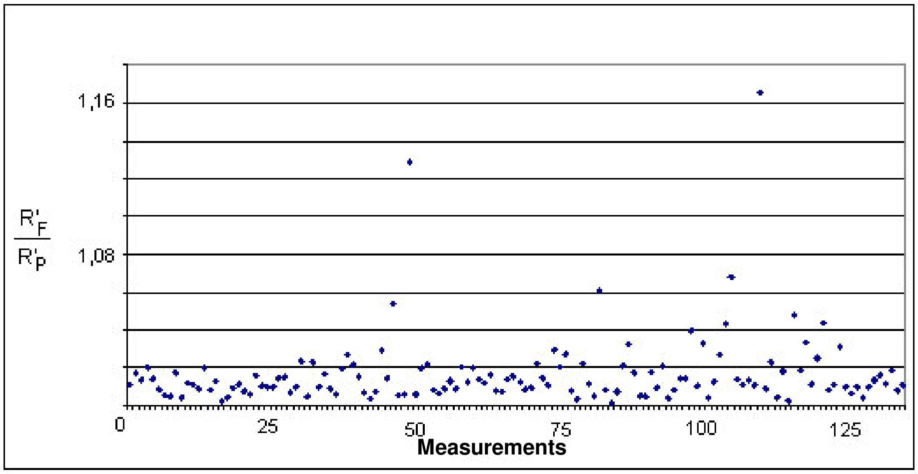


Figure 2-Ratio between flattened roll radius (without and with applied tension).

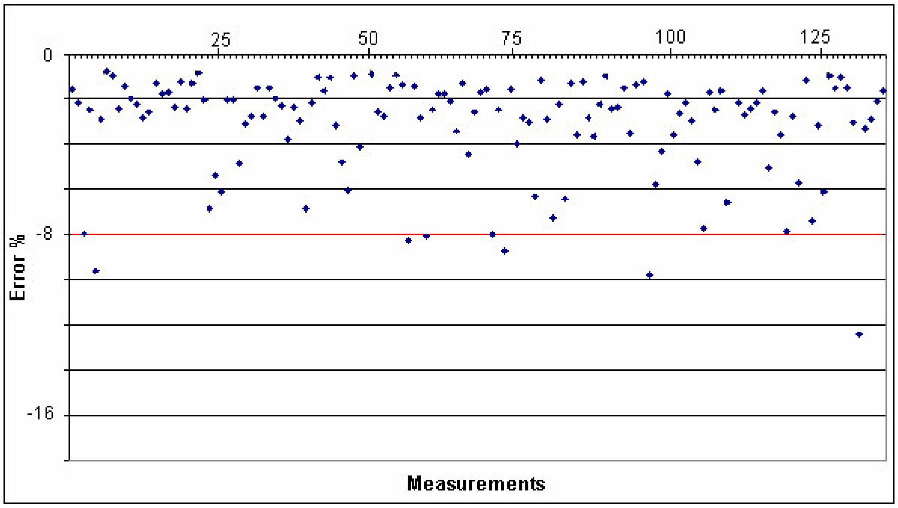


Figure3- Rolling load variation (without and with applied tension)

As for Network 1, Network 2 was also based on equation 5. In this configuration, the second and third columns, input data reproduced the variables of the equation, leaving the variables in the first column of table 1 as outstanding. This was due to the direct relation between the rolling torque and the fraction, *w*, of the lever arm, knowing that:

$$a = w.l_d^{'} = \frac{M_d}{2F} \Rightarrow 2.F.l_d^{'} = \frac{M_d}{w} \tag{8}$$

Where $l_d^{'}$ is the flattened arc of contact.

Once defined the input/output variables, the next step was the configuration of the networks. For this paper the Neurosolution for Excel software was employed [11]. The adopted network was a multilayer perceptron[7]. This type of network is designed in layers where data is inserted in the input layer and then processed by the hidden layers and the results obtained in the output layer. Three hidden layers have been used with the Biasaxon transfer function. The training method was through trials, evaluating the network learning capacity. The networks were elaborated with 380 data, and, as previously explained, the learning capacity will determine the quality of its performance. Therefore, the learning phase must be made rigorous, to provide consistent results. In this paper, the distribution of data was: 75% for network training, 12. 5 % for validation and 12. 5 % for testing [15].

5. INFLUENCE OF TENSION

In the practice of sheet metal rolling, frequently the deformation is performed only through the action of both driven rolls, having identical diameters and speed. Additional control is gained through the back and front tension provided by the uncoiler and coiler, respectively. Applying tension on the sheet has a direct effect on the load and torque. Hence, changes in the lever arm are expected (Fig 4). For similar back tension, σ_r, and forward tension, σ_a, the applied load *P* should be in line with the rolling vertical central axis , while if $\sigma_r < \sigma_a$, or $\sigma_r > \sigma_a$ the resulting load axis will be inclined [16, 18, 20].

Analysis of the influence of the tension on the starting torque was performed for two projects. One of them was based on Pawelski and Lindemann [13] approach relating the influence of tension on the rolling torque and the lever arm. The other project was based on the traditional Ford, Ellis, and Bland [4] equations. Calculated rolling loads were based on Hill´s diagrams [4] where λ_1 e λ_2 are non-dimensional numbers (eq. 10 and 11).

$$\lambda_1 = \frac{M_d / b}{(F/b)R} \tag{10}$$

$$\lambda_2 = \frac{\sigma_a . h_1 - \sigma_r h_0}{F/b} \tag{11}$$

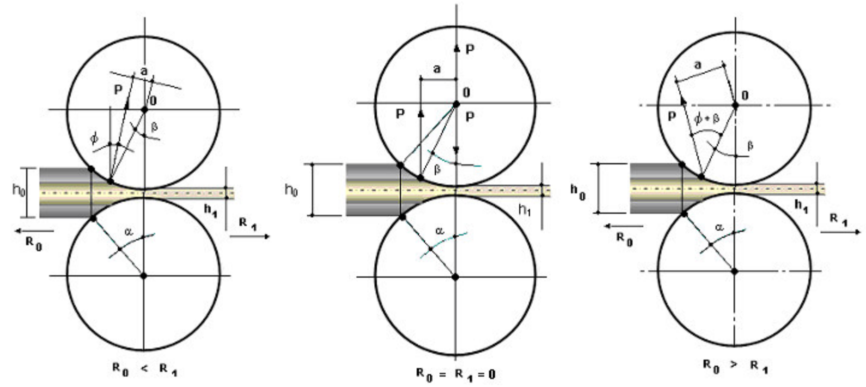


Figure 4 – Lever arm position and tension [18]

6. RESULTS

6.1. Adaptive Neural Networks

Both neural networks, ANN 1 and ANN 2, presented good convergence indicating that the learning process was quickly assimilated. Both networks presented good adherence, as presented in the Figure 5 (Graphic 1), where ANN 1 produced $r \cong 0{,}98$ while ANN 2 produced a value of $r \cong 0{,}94$.

As pointed out previously, the main goal of the ANN was to evaluate the relationship between input and output data. Figure 5 (Graphic 2) presents the results for ANN1 and ANN2, where the first one is related to the lever arm while the second one to the applied tension. Results are consistent since applied tension, lever arm and torque are all closely related [16, 18, 20].

Comparing the results from the ANN with the experimental results obtained by O. Pawelski and F. Lindemann [13] and Bland, Ellis and Ford [4], the influence between the following relationships should be pointed out:

- Back tension, applied reduction and rolling torque;
- Lever arm, rolling torque and back tension;
- Rolling pressure and back tension.

Initially, the experimental results of O. Pawelski and F. Lindemann [13] were reproduced for the rolling of steel strips SAE 1006. The results of this experiment are presented in Figure 6. It can be observed that there is an increase in the rolling torque with an increase in applied reduction during the rolling process. There is also an increase in torque with the increase of the applied reduction and back tension. Comparing present results with those obtained by Pawelski e Lindemann, we may observe that both follow the same trend for increasing torque, however at different levels. This occurs because there is a major difference in the operational parameters between both experiments. The applied tension in the researcher's experiments was much larger than the one used in the present processing of the SAE 1006 steel strips. For safety reasons it was decided to perform our experiments with relatively lower tension, otherwise there could be some irreparable damages.

An alternative method that was employed to assess the influence of the applied tension in the rolled strip on the rolling torque was the diagram proposed by Hill, and utilized by Bland Ellis and Ford in the method of evaluating rolling force calculation [4]. To reproduce the diagram proposed by Hill (Fig. 7), the same steel strip was rolled under two distinct tensions, having rolling load as a variable for a constant entry and exit thickness. The forward tension and back tension varied as following:

-Applying back tension (by lowering the uncoiler load) during the introduction of the steel. No forward tension was applied.

- Applying increasing back tension during the introduction of the steel strip. No forward tension.

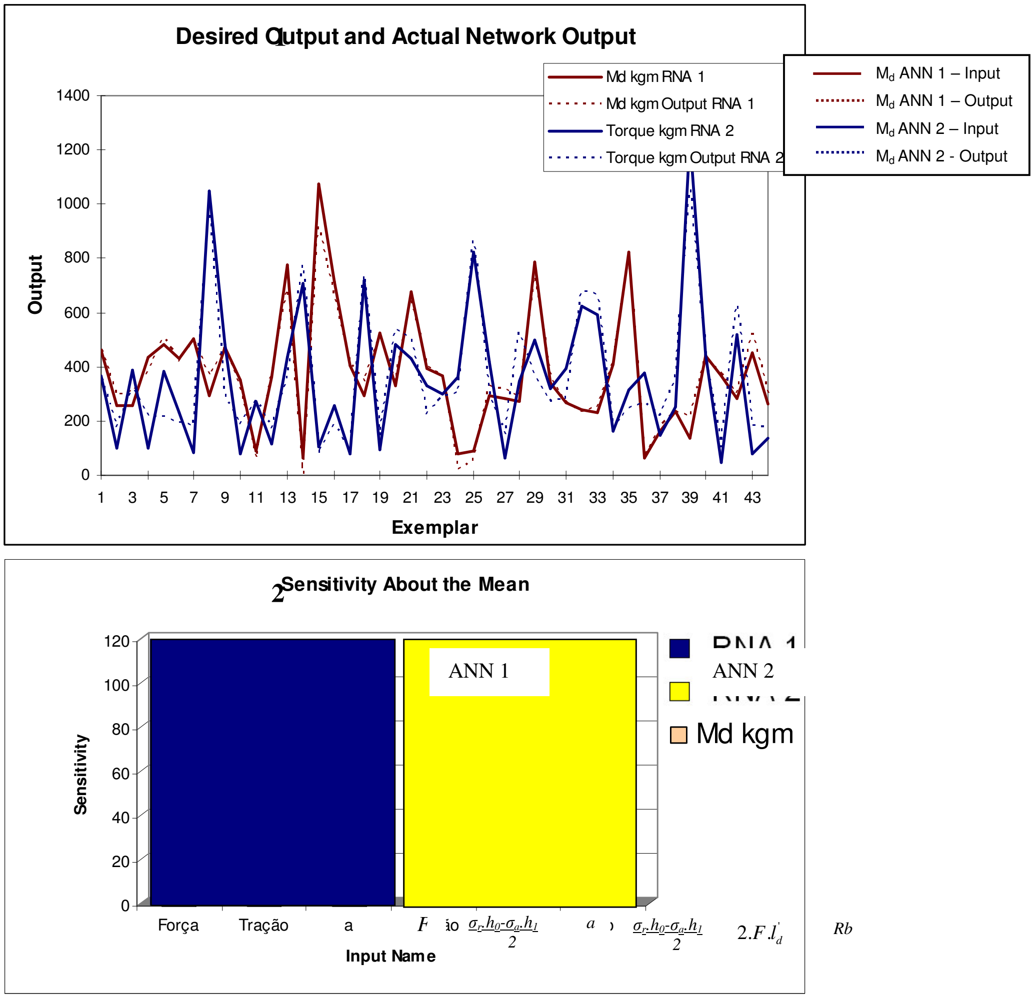


Figure 5 – ANN output results

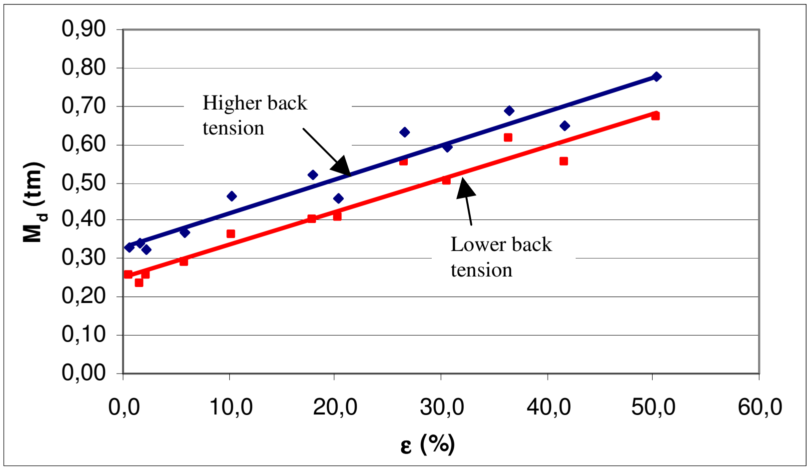


Figure 6 - Influence of tension on torque, according to Pawelski and Lindemann [13]

Data collected during the "sheet introduction" and using equations 10 and 11 resulted in the non-dimensional λ_1 and λ_2, as plotted in Figure 7. To compare results the value of λ_1 was further corrected, obtaining equation 10.

$$\lambda_1 = \frac{\frac{M_d}{b}}{\frac{F}{b}R} \cdot \frac{D}{D_{Hill}} \tag{12}$$

The slope of the lines in Figure 7 relating λ_1 and λ_2, is similar and is verified by keeping constant the rolling load, entry and exit thickness and forward tension. Increasing back tension increases the value of λ_1. This occurs as a consequence of the increased rolling torque.

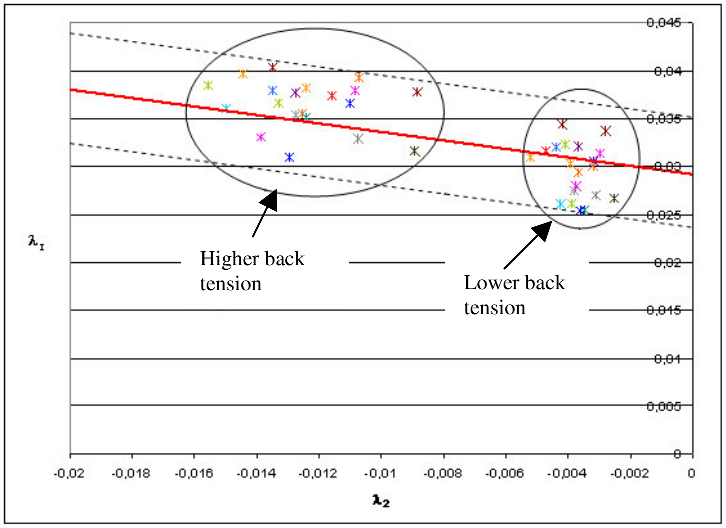


Figure 7–Influence of tension, according to Hill [3]

From figure 8, also based on the experiments of Pawelski e Lindemann [13], it may be observed that, during the introduction stage, the rolling torque is systematically larger than during actual rolling process. The ratio *w* (lever arm/ arc of contact) is larger than the experimental data presented for a given rolling torque. During the rolling process, for adequate operational conditions, there is a reduction in the rolling torque and the ratio *w* converges to the values obtained in ref [13], shown in Figure 8 by the lines A and B. This may be explained by the displacement of the neutral plane in the rolling direction for a high back tension and in the opposite direction for a high forward tension. Hence *w* may reach values that are higher than the experimental contour line in that figure and, in some cases, being larger than the projected arc of contact.

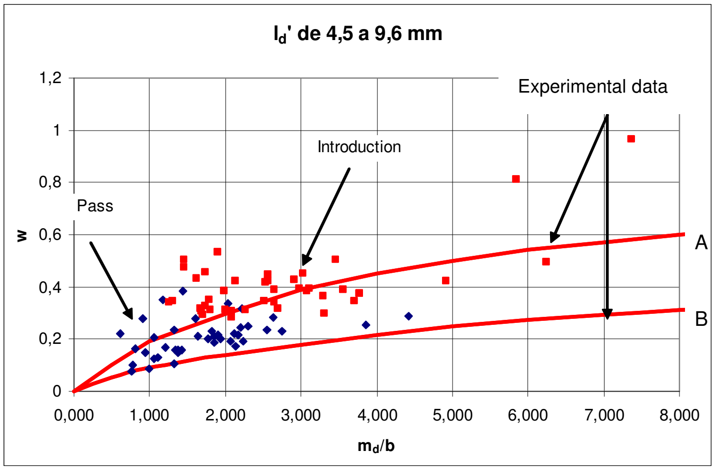


Figure 8- Lever arm during the introduction stage [13].

6.2. OPTIMIZATION OF THE PASS SCHEME

The objective of the optimization of the pass scheme is to attain a pass scheme that provides a more homogeneous distribution of the rolling loads and torque for all rolling passes, hence minimizing starting torque.

Figure 9 shows the results obtained for pass optimization. If the pass sequence is exclusively analyzed in relation to the TAF amplitude (graph 3 of Figure 9), we must conclude that the "usual" method is the recommended one. This is due to a TAF of 1. 34 while in the "proposed" method the TAF is 1. 55. However, evaluating processing on a global basis, we may verify that the last one is more favorable because:

- The rolling torque during introduction is smaller (graph 3 of Figure 9).
- There is a more homogeneous distribution of torque during the rolling pass (graph 3 of Figure 9). The first and second pass torque is lower, implying improved pin life, if fatigue is considered.
- There is a more homogenous rolling load distribution for the passes (graph 1 of Figure 9)

Concerning the neutral point position along the arc of contact (graph 2 of Figure 9), it may be observed that during introduction (with the proposed method associated with a low back tension and a new pass distribution), there is a displacement of the neutral plane towards the strip entry plane. However, during the first pass, it is observed that the neutral plane moves towards the entry plane, tending to move outside the arc of contact. In that case, with a simple correction on the forward tension, the neutral plane will move back to the region of the arc of contact.

During data collection there were situations in which the initial torque during the introduction stage was larger than the average pass torque, configuring the existence of TAF. This situation however never exceeded the torque limit of the rolling mill. Therefore, it was concluded that one of the reasons that causes pin breakage is related to fatigue, caused by the high cyclic loads to which the pin is submitted.

Figure 10 presents the evolution of the number of cycles that the pin will reach under cyclic loads. In this case, the usual and the proposed pass schemes are compared. It may be observed that in the case of the proposed method, there is an increased concentration in the number of cycles that the pin will reach better conditions if compared to the usual working method. In the case of a TAF, an initial torque reduction will also increase the pin life.

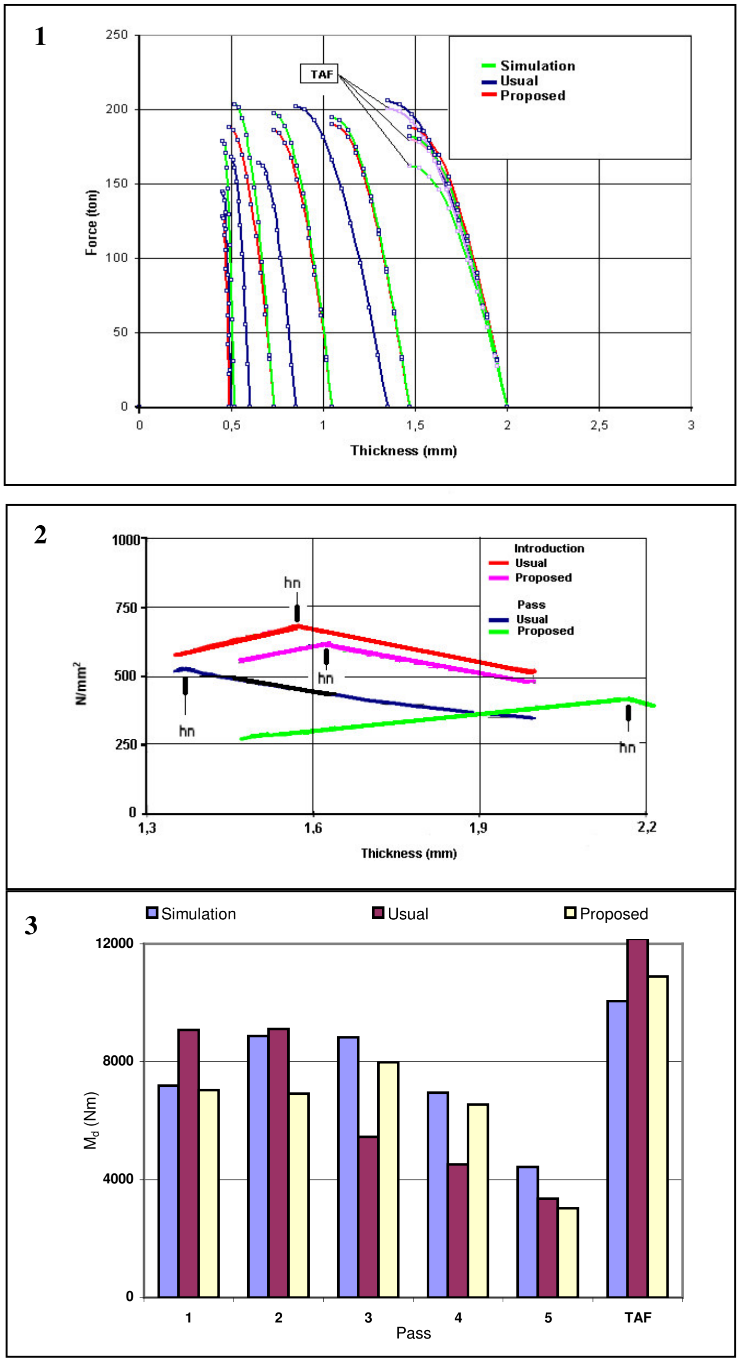


Figure 9 – Results for optimized rolling pass design

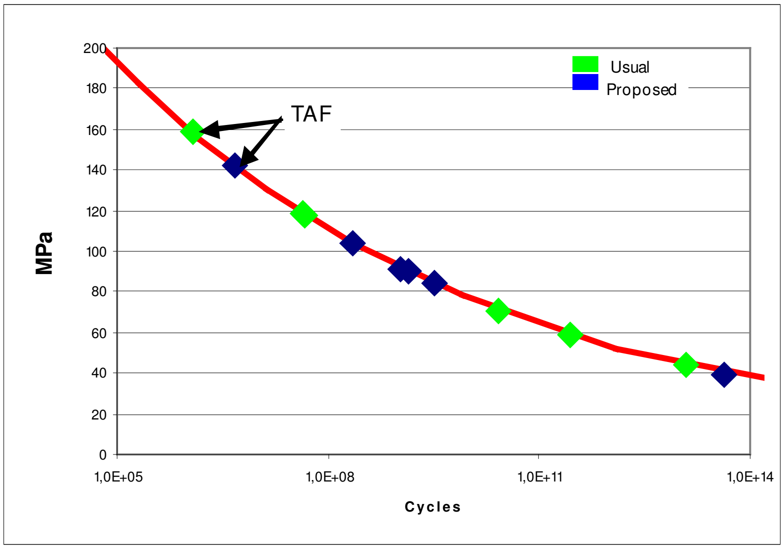


Figure 10 – Stress-cycles curve

7. CONCLUSIONS

Based on the results of this work, it was observed that increasing back tension in the steel strip, leads to an increase in the rolling torque and, consequently, on the TAF amplitude. The experimental results indicate that the operation of "sheet introduction", with a minimum back tension is an efficient method to reduce the initial torque. On the other hand, with the exception of accidents, nominal rolling torque was never over passed during TAF. This fact leads to the conclusion that the systematic occurrence of TAF, caused by the high initial torque, causes pin breakage due to fatigue, even after a reduced number of cycles.

From the point of view of fatigue, practical runs showed that optimizing rolling passes, in addition to control of the back tension during introduction conduce (for the analyzed cases), to an increased pin life. Optimizing the pass sequence leads to a better roll torque distribution, hence submitting the pins to a lower stress level. Furthermore, in terms of fatigue, pass sequences cannot be evaluated solely on the TAF amplitude criterion. The higher the torque the higher will be the stress on the pin and, consequently, lowering the operational pin life.

Due to the great diversity of specifications of the processed products, large difficulties are associated with parameter reproduction in the rolling process. Adaptive Neural Networks were used as a tool to raise the relevant operational aspects that interfere in the initial torque and, consequently, on the TAF. The utilization of the ANN, via the Neurosolutions software, was efficient in the identification of these parameters.

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