OVERVIEW OF MICROSTRUCTURAL MODELS APPLIED TO HOT ROLLING MILL FOR LONG PRODUCTS [1]

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Summary
This work aims to study the microstructural models available in literature for modeling applied for hot rolling of long products, as by the need for improve control of metallurgical properties and microstructure during the rolling of long steel, and reduce operating costs, as sampling, so that, the use of microstructural models in steel mills it is increasingly necessary. Initially was conducted an overview of the available studies and selected studies of some products, such as sections, round bars and/or rod and seamless tubes. Then, with the aim of facilitating future studies and research was carried out a summary of the main techniques and equations apply as well as its outcome.

Key words: Rolling mill; mathematical modeling; long products.

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1 INTRODUCTION

It is usually possible to classify steel products in basically two types, namely: long (not flat) and flat.[4]
Flat products are those with the rectangular shape in its cross section, being considered that the width is at least two times the thickness.[4-5]
Products that have cross-section of non-rectangular shape (except for blocks, billets and flat bars) are classified as long products. In general the forms are spite already well known, varied and complex.[4]
The importance of studying the microstructural models available in literature for modeling applied to the hot rolling of long products, is due to the need for improve control of metallurgical properties and microstructure during rolling of steels.
In recent years has been developed a large number of models and significant advances have been made in predicting the thermo-mechanical parameters (how to calculate the rolling force, strain, strain rate), however most of them are concentrated in hot strip mill process. And despite some progress, few studies have been made for long products, such as bars and section rolling. This is due to the need for more accurate methods for products where the strain and stress in the workpiece are not in a plan condition.[1-2] The calculation of mean strain is more complex because of the three dimensional deformation of material in roll gap.[3]
There is a growing demand to develop a reliable mathematical model to obtain the thermo-mechanical associated with long products[1], caused by the need for improve control of metallurgical properties and microstructure during rolling and reduce operating costs, such as sampling. so that, the use of microstructural models in steel mills it is increasingly necessary.
Thus, this work involves overview of the main techniques and equations apply of studies in the literature for products such as sections, rod (or bar) and seamless tubes.

3 MICROSTRUCTURAL MODELS

Sections

Reis[6], aimed to develop a mathematical model by Excel, to predict the mechanical properties to sections (yield and tensile strength).
The rolling mill line studied by Reis[6] produces structural shapes with two parallel flanges. The process is analyzed from the reheating furnace (walking beam), descaling, tandem group (six universal rolling mill and one edge rolling mill), and cooling bed. The system used in the rolling mill is called XH, due to horizontal and vertical cylinders of the tandem group that have the format of "X" and "H".
The equations described by Reis[6] in her studies and were used to calculate, Tnr, Ar3, fraction transformed, grain size produced after full recristallization, ε_c, ε_p, Z, mean grain size entry to the next stands after partial recristallization, ε_a, grain growth, ferritic grain size, flow stress are the same used in models for flat products (plates and strip) and bars (or rod). The main activity was to apply this methodology studied in section rolling.[6,7,8,9,10,11,12]
The methods used by Reis[6] to calculate main thermo-mechanical parameters, as strain, strain rate, interpass time, except temperature that was estimated from measurements taken before and after all pass, will be described below.

During the roughing rolling mill as the strain variations along the cross section was not the same and calculate the equivalent strain at each point of a given section was not relevant to the work done, a first approximation was performed to calculate the strain:

$$\varepsilon = \ln\left(\frac{Ai}{Af}\right) \qquad (1)$$

where, Ai and Af represents cross section area before and after the pass.

To calculate the projected contact length was used in the equation (2) below, but as the exit and entry cross section are complex and the exact value of the projected contact length varies with each point on the surface, Reis[6] used the mean roll diameter:

$$L = \sqrt{\frac{Dw}{2}.\Delta H} \qquad (2)$$

Where D_w is mean roll diameter and ΔH are the web thickness before and after each pass.

The roll tangential speed (V_t) are given by:

$$V_t = \frac{2.\pi.R_w.n}{60} \qquad (3)$$

Where R_w represents the roll radius and n the roll rpm.

The time for application of the strain (t_c), was calculated from the relation below:

$$t_c = \frac{L}{V_t} = \sqrt{\frac{Dw}{2}.\Delta H}.\frac{60}{2.\pi.R_w.n} \qquad (4)$$

The average strain rate during Rolling can be defined as the effective strain divided by the time for the application of strain:

$$\dot{\varepsilon} = \frac{\varepsilon}{t_c} \qquad (5)$$

The interpass times can be calculated using:

$$t_{ep} = \left(\frac{t_{\text{rolling}}}{2}\right)_{i-1} + t_{\text{dead}} + \left(\frac{t_{\text{rolling}}}{2}\right)_i \qquad (6)$$

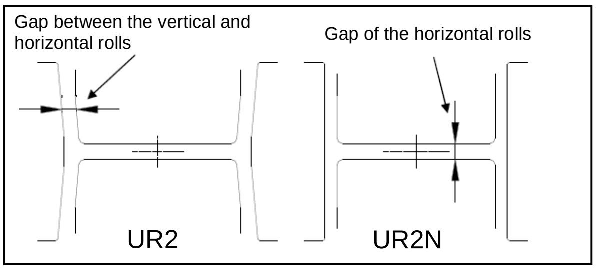
Where, t_{dead} it is the time of the material to leave the atual pass and begin in the next pass.

$t_{rolling}$ is obtained from:

$$t_{\text{rolling}} = \left(\frac{L_f}{v_t}\right) = \left(\frac{60.L_f}{2.\pi.R_w.n}\right) \qquad (7)$$

Where L_f is the o length of the material in the after of the pass and V_t is the roll tangential speed in each pass.

For tandem group, Reis[6] adopted a different strategy to calculate the same parameters, it was considered the equivalent strain using the initial and final dimensions of the web and the flange on each stand. These dimensions are obtained by the gap of the horizontal rolls and gap between the vertical and horizontal rolls, as shown below:



Authorship: Reis, 2007
Figure 1. A pair of rolls from tandem group highlighted the gap between the rolls.

The mean equivalent strain was calculated assuming that the value of length is in consequence of conservation of volume, given by (for web and flange respectively):

$$\varepsilon_w = \ln\left(\frac{h_{w1}}{h_{w2}}\right) \text{ e } \varepsilon_f = \ln\left(\frac{h_{f1}}{h_{f2}}\right) \tag{8}$$

Where h_{w1} and h_{w2} are the web thickness before and after all passes and h_{f1} e h_{f2} are the flange thickness before and after all passes.

Then, the projected contact length and strain rate can be calculated for web:

$$Ld_w = \sqrt{\frac{D_{wH}}{2}.(h_{w1} - h_{w2})} = \sqrt{R_{wH}.(\Delta h_w)} \tag{9}$$

$$\dot{\varepsilon}_w = \frac{2\pi n_H \varepsilon_w}{60}\sqrt{\frac{R_{wH}}{\Delta h_w}} \tag{10}$$

And for the flange separately:

$$Ld_f = \sqrt{\frac{D_{wV}}{2}.2(h_{f1} - h_{f2})} = \sqrt{R_{wV}.2(\Delta h_f)} \tag{11}$$

$$\dot{\varepsilon}_f = \frac{2\pi n_V \varepsilon_f}{60}\sqrt{\frac{R_{wV}}{2\Delta h_f}} \tag{12}$$

Where D_{wH}, R_{wH} e n_H are roll diameter, roll radius and roll rpm at given pass respectively from horizontal roll and D_{wV}, R_{wV} e n_V are roll diameter, roll radius and roll rpm at given pass respectively from vertical roll.

Due to the rolling mill characteristic, to obtain the interpass time for the tandem group was used a register before and after all passes, because of the passes overlap each other and was considered an equivalent sequence of two passes. Then the interpass time is given by:

$$\text{Rigth pass}: t_{ep} = \left(\frac{t_{\text{rolling UR2}} + t_{\text{rolling UR2N}}}{2}\right) - \text{Difference} \tag{13}$$

$$\text{left pass}: t_{ep} = \left(\frac{t_{\text{rolling UR2N}}}{2}\right) + t_{\text{dead}} + \left(\frac{t_{\text{rolling UR2}}}{2}\right) \tag{14}$$

Seamless tubes

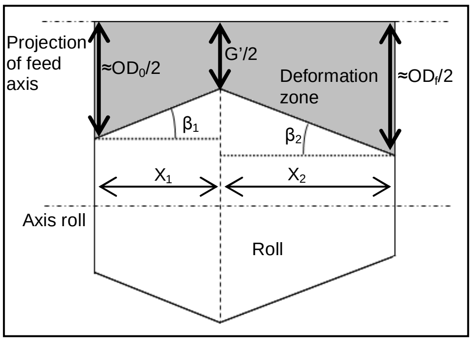
Carvalho(13) conducted a study on the Nb and Ti effect and intermediate cooling on the

microstructure evolution and characteristics of final product for a V-N steel. A mathematical model was adjusted for this alloy. The Rolling Mill line has a rotary-hearth furnace (FB), piercing mill (LP) formed by two rolls barrel-shaped whose axes have an inclination angle of 12 º, high-reduction rolling machine (LR) without mandrel (formed by trio stand willing to 120 º), a continuous rolling mill (LC) with mandrel (formed by 8 duo stands), an intermediary cooling bed (Leito I), an intermediary reheating furnace (FI), sizing or stretch-reducing rolling mill (LE) without mandrel (formed by 24 trio stand willing to 120 º), final cooling bed (Leito II) and saw.
Similar to Reis[6], the temperature considered by Carvalho[13] was estimated from measurements taken before and after all pass. Equations to calculate strain, strain rate, time for strain aplication, projected contact length and interpass time will be shown below.
For all Rolling (LP, LR, LC ou LE) was calculated the equivalent strain:

$$\varepsilon_{ep} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_l-\varepsilon_t)^2+(\varepsilon_t-\varepsilon_c)^2++(\varepsilon_c-\varepsilon_l)^2} \qquad (15)$$

$$\varepsilon_l = \ln\left(\frac{l_f}{l_i}\right)\ \varepsilon_t = \ln\left(\frac{t_f}{t_i}\right)\ \varepsilon_c = \ln\left(\frac{c_f}{c_i}\right) \qquad (16)$$

For LP, l_i e l_f are billet and hollow length, t_i e t_f are billet radius and hollow wall thickness and d_i e d_f are billet and hollow mean diameter, in other words, $d_i=OD_0/2$ e $d_f=OD_f-t_f$. Where OD_0 e OD_f are billet and hollow diameter respectively.
The deformation zone projected on axis roll (LP) is shown below:



Authorship: Carvalho, 2007
Figure 2. Deformation zone projected on the axis roll.

The equivalent strain can be calculate for all pass in LR, LC e LE, but should be observed the following comments:
For LR, as known only as the size of the hollow before and after the rolling mill and the equivalent diameter in each pass (obtained by the dimensions of each roll), then it makes the assumption that the variation of the wall is linearly distributed between the stands and the length is due the volume conservation.
For LC, the cross-sectional area before and after each pass is known, it is calculated from the mandrel diameter and the groove dimensions. With the area, it is possible to calculate the wall thickness and mean outer diameter, consider $l_f/l_i=A_i/A_f$.
Also to LR, for LE only the size of the hollow before and after the rolling mill and the equivalent diameter in each pass are known (obtained by the dimensions of each roll). It makes the assumption that the wall changes are linearly distributed between the stands

and the length is due of the conservation of volume.
With the strain known the projected contact length (L) was calculated from the equation (17):

$$L \approx \left(\frac{OD_0 + OD_f - 2G'}{2 \tan \beta_1} \right) . \cos \alpha \qquad (17)$$

Where G' is the length between the two rolls measured on its maximum diameter (figure 2), α is half the inclination between the two rolls e β_1 the roll entry angle.

Meanwhile for LR, LC, LE, the projected contact length is given by:

$$L_n = (R_n - G_n).sen\left[\cos^{-1}\left(1 - \frac{OD_{n-1} - OD_n}{2.(R_n - G_n)} \right) \right] \qquad (18)$$

Where L_n, R_n, G_n, OD_{n-1} e OD_n are the projected contact length, the roll radius, the groove profundity in pass “n”, the hollow outer diameter after the pass "n", the hollow outer diameter before the pass "n" respectively.

After calculate the projected contact length, it is possible to calculate the time for strain application and the strain rate:

$$t_c = \frac{L}{V} \qquad \dot{\varepsilon} = \frac{\varepsilon_{eq}}{t_c} \qquad (19)$$

For LP:

$$t_c = \frac{60.L}{2.\pi.R.N.sen\alpha} \qquad (20)$$

Where R and N are roll radius, roll rpm at a given pass and L the projected contact length.

For LR, LC, LE:

$$t_c = \frac{60.L_n}{2.\pi.R_n.N_n} \qquad (21)$$

Where L_n, R_n e N_n, are the projected contact length, the roll radius and the roll rpm at given pass.

The interpass time for LR, LC, LE, can be calculate using:

$$t_{ep}^{n} = \frac{60.L_{ep}^{n}}{2.\pi.R_n.N_n} \qquad (22)$$

Where, L_{ep}^{n} is interstand distance.

Rod (or bar)
There is a growing demand to develop a reliable mathematical model to obtain the thermo-mechanical parameters associated with long products process. The reason is that once these parameters are obtained it is possible to applied directly model develop for strip rolling to calculate recrystallisation behaviour and austenite grain size evolution to rod (or bar) rolling.[(1)]
The difficulty of calculating these parameters it is because of the three dimensional

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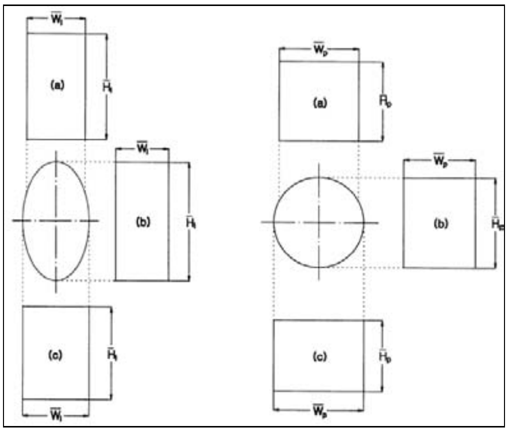
deformation of material in the roll.(3)

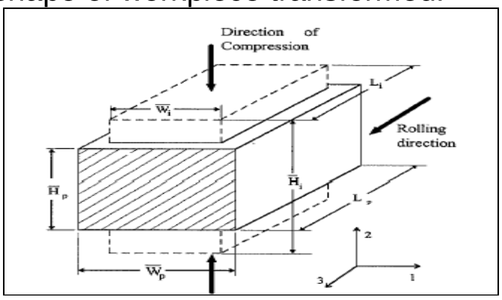
One way to solve this problem is used one of these three methods to establish equivalent rectangular sections, namely, method of maximum height, method of maximum width and method of width-height ratio, them the oval or round groove can be replaced by parallelepiped shape.(3) These methods can be applied for other type of passes such as oval-round, box-oval and diamond-square.(1) Figure 3 shown these methods: (3)



Authorship: LEE, 1999

Figure 3. Three methods of computing an equivalent cross sectional area for the oval-round pass. (a) width-height ratio (b) maximum height (c) maximum width

The definition of width and height might be arbitrary in the case of choose the method of width-height ratio.(14) After choose the method, the next step is to calculate the mean strain from the rectilinear shape of workpiece transformed: (3)



Authorship: LEE, 1999

Figure 4. Schematic representation of parallelepiped deformation of equivalent rectangular section.

In case of the direction of normal strain components is coincident with the principal strains components and elastic and shear strains components might be neglected: (3)

$$\varepsilon_1 = \ln\left(\frac{\overline{W}_i}{\overline{W}_p}\right) \quad \varepsilon_2 = \ln\left(\frac{\overline{H}_i}{\overline{H}_p}\right) \quad \varepsilon_3 = \ln\left(\frac{\overline{L}_i}{\overline{L}_p}\right) \tag{23}$$

$$\bar{\varepsilon}_p = \left[\frac{2}{3}\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right)\right]^{1/2}, \text{from the volume constant condiction } \varepsilon_3 = -\varepsilon_1 - \varepsilon_2 \tag{24}$$

$$\bar{\varepsilon}_p = \frac{2}{\sqrt{3}}\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_1\varepsilon_2\right)^{1/2} \text{ or } \bar{\varepsilon}_p = \frac{2}{\sqrt{3}}\varepsilon_2\left(1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2\right)^{1/2}, \text{then:} \tag{25}$$

$$\bar{\varepsilon}_p = \frac{2}{\sqrt{3}}\left\{\left[\ln\frac{\overline{W}_i}{\overline{W}_p}\right]^2 + \left[\ln\frac{\overline{H}_i}{\overline{H}_p}\right]^2 + \ln\frac{\overline{W}_i}{\overline{W}_p}\ln\frac{\overline{H}_i}{\overline{H}_p}\right\}^{1/2} \quad (26)$$

The method of maximum width was used in other Lee(1) works and the equations to calculate the strain rate and the projected contact length are given bellow:

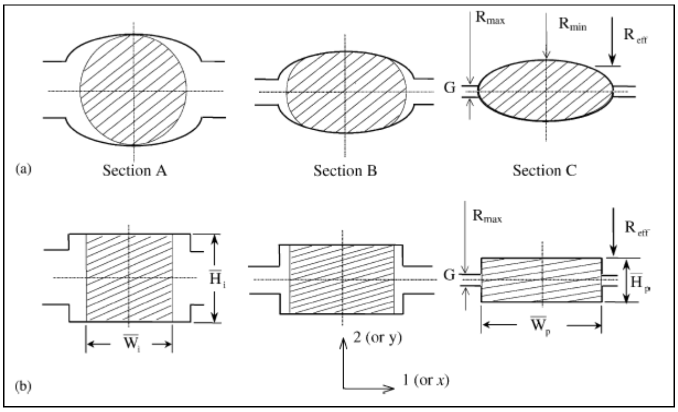
$$\dot{\bar{\varepsilon}}_p = \frac{\bar{\varepsilon}_p}{t_p} \quad (27)$$

where t_p is the interval time taken for a section A to pass through to section C (figure 5):

$$t_p = \frac{60\overline{L}}{2\pi N R_{eff}} \quad (28)$$

Where, R_{eff}, L_p and N represents the effective roll radius, the effective projected contact length of grooved roll and workpiece and roll rpm at given pass. The effective contact length is given by:

$$\overline{L} = \sqrt{\left\{R_{máx} - \left(\frac{\overline{H}_p - G}{2}\right)\right\} - (\overline{H}_i - \overline{H}_p)} \quad (29)$$

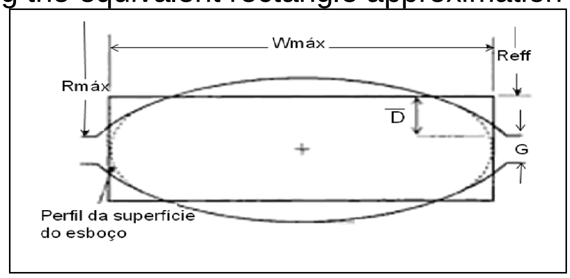


Authorship: LEE, 2002
Figure 5. Application of equivalent rectangle approximation using method of maximum width.

Lee(14) mentioned some methods to obtain R_{eff}, and one of which is described below:

$$R_{eff} = R_{máx} - \overline{D}, \text{ where } \quad \overline{D} = \frac{\left(A_p / W_{máx} - G\right)}{2} \quad (30)$$

Where A_p is the exit cross-sectional area of the deformed workpiece in each pass and $\overline{D}$ is calculated by using the equivalent rectangle approximation method:



Authorship: LEE, 2004
Figure 6. Geometrical designation for the calculation of the effective roll radius.

4 RESULTS AND DISCUSSION

The microstructural model developed by Reis[6] provided good predictions of the austenite grain size evolution and ferrite grain size after transformation and in addition to obtaining good estimates of the flow stress.
Addition to the equations used to predict the equivalent strain, strain rate, projected contact length and interpass time for seamless tubes that was described above, Carvalho[13] used data obtained in the simulation by hot torsion test in the selection and adjustment of various equations that describe the evolution of the microstructure obtained consistent results.
Lee[1], concluded that on an industrial scale, a quantitative description of thermo-mechanical and metallurgical parameters of material during all stage of rod (or bar) rolling mill process is able If the proposed model can be mutually integrated with the recrystallisation model and AGS evolution model applied in plate (strip) rolling, and a proper constitutive equation describing the deformation of the material at high temperature and high strain rate is available. But, the simulation results show that the equations for AGS evolution, based on equations used for strip rolling, can have limitations when used directly to rod (or bar) rolling where material experiences high strain rates in finishing mill.

5 CONCLUSIONS

This study demonstrate that by making some adjustments, such as for calculating the strain, strain rate and projected contact length, it is possible applied equations developed for flat rolling to obtain for example recrystalization behavior and austenite grain size evolution.
This work contributes to helping research and studies that have an interest in the area of mathematical modeling applied to the hot rolling of long products by analyzing the methods available in the literature used for predictions strain (ε), strain rate ($\dot{\varepsilon}$), time for strain application (t) and projected contact length (L) of some products, such as sections, round bars and/or rod and seamless tubes.

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