Numerical and Analytical Analysis of Load in Rolling Process

João Pedro Silva Oliveira
Seção de Engenharia Mecânica e de Materiais (SE/4)
Instituto Militar de Engenharia
Rio de Janeiro, RJ, Brasil.

Georgyson Dias Neo
Seção de Engenharia Mecânica e de Materiais (SE/4)
Instituto Militar de Engenharia
Rio de Janeiro, RJ, Brasil.

Carlos Eduardo Lima dos Santos
Seção de Engenharia Mecânica e de Materiais (SE/4)
Instituto Militar de Engenharia
Rio de Janeiro, RJ, Brasil.

Bruno Berner dos Santos
Seção de Engenharia Mecânica e de Materiais (SE/4)
Instituto Militar de Engenharia
Rio de Janeiro, RJ, Brasil.

Gustavo Simão Rodrigues*
Seção de Engenharia Mecânica e de Materiais (SE/4)
Instituto Militar de Engenharia
Rio de Janeiro, RJ, Brasil.
E-mail: gustavosimao@uol.com.br

*Autor para correspondência

ABSTRACT

The rolling process is of great importance to the industry and the understanding is a fundamental function for its design and use. Currently there are two traditional processes for steel rolling: Hot rolling (from 1300 °C to 700 °C) and cold rolling (at room temperature). The process consists in reducing the cross section of a billet by means of compressive forces, applied by rolling rolls, mounted in a rolling mill. In order to control the efforts in the mill, the billet usually passes several times between the rollers, with a thinner thickness each time less. Between each rolling, annealing processes may be applied to recover the ductility of the reduced metal by the scrubbing and pickling to remove the oxide layer formed on the surface. A good calibration of the rolling mill and material is important to avoid rolling defects, generating products with imprecise dimensions and undesirable deformations. Two mathematical models can be presented: Homogeneous
Deformation Method and Equilibrium Method. A case study is proposed. The study consists in calculating the efforts required to laminate a defined steel billet, comparing both analytical formulations to the results obtained by Finite Element Method developed in ABAQUS software. The results of the analytical path are compared with the simulation results. Finally, the difference of the presented results can be explained by the consideration of the increase of the tension for plastic deformation due to the hardening by ABAQUS software.


1 INTRODUCTION

Rolling is a process of mechanical transformation that consists of reducing the cross-section by compression of the metal, through the passage between two steel or cast iron cylinders with parallel axes that revolve around themselves, as shown in Fig 1. There are two traditional aluminum rolling processes: hot rolling and cold rolling. Today, the industry also uses continuous rolling.

![Figure 1 - Schematic representation of the lamination process (MACHADO, 2008).](image)

The main types of rolled products are: coiled or flat sheets and discs. These semi manufactured products have various applications in sectors such as transport (bus bodies, road equipment, structural elements etc.), civil construction (roofing, façades, etc.), packaging (cans, disposable and flexible) and consumer goods (pans, household utensils, etc.).

Rolling is a process that allows high productivity and good dimensional accuracy comparing with others process, in addition to a certain variety of shapes. In this process the material is subjected to high compressive stresses, resulting from the direct action of two rollers and it is also subjected to surface shear stresses, resulting from the friction between the rollers.
and the material. These friction stresses are also responsible for traction of the material, thus drawn out of the space between the rolling rolls (URIFÉR, 2017).

The rolling can be carried out at relatively high temperature, usually higher than the material’s recrystallization temperature (half of the melting temperature in K), then known as hot rolling, or at room temperature defined as cold rolling.

Typically, the initial process is hot rolling, which aims to roughen (greatly decrease the thickness) of the solidified ingot in the continuous casting, destroying the gross molten microstructure of coarse grains, which is then replaced by a more refined grain microstructure, resulting from mechanical conformation.

Already transformed from ingot to thick plate, it can be submitted to cold rolling, which allows better control of thickness and result in a semi-processed product (thin sheet, strip or sheet with excellent mechanical properties resulting from the refined microstructure obtained by material hardening). This semi-processed product is then sold by the steel mills to manufacturers of various types of product, which use it as raw material for the manufacture of these products (MACHADO, 2008).

1.1 Roller Components

The rolling mill consists of a set of rollers, bearings, a casing ("cage", whose function is to wrap and support the whole assembly) and a motor (whose function is to supply power to the rollers and control the speed of rotation) (DA CUNHA, 2013).

The simplest type is the duo rolling mill, in which two rollers of the same diameter turn in the same direction. In the reversible duo laminator, the material can pass back and forth between the rollers, which invert the direction of rotation. There are also rolling mills with more than two rollers, in which two are in contact with the material being rolled, the other rollers acting as support rollers. This is the case of four high rolling mills (4 rollers) and cluster rolling mills (several rollers).

1.2 The Rolling Process

Performed at the beginning of the rolling process, the first hot rolling operation is carried out at the primary roughing mill, which receives the solidified ingot and turns it into a still rather thick sheet. This type of rolling mill usually has a reversible duo configuration. Generally, the hot rolling of steels begins at temperatures between 1100
and 1300 °C and ends between temperatures of the order of 700 to 900 °C, but generally above the recrystallization temperature in order to produce evenly equiaxed ferrite grains.

Cold rolling is a complementary forming operation, which happens to hot rolling and has as its objective the production of steel plates, strips and sheets with better dimensional tolerances and more refined microstructure, allowing the achievement of mechanical properties adequate to the applications of these steel products. Generally, cold rolling is intercalated with annealing heat treatments, which restore the ductility of the material (usually by recovery and/or recrystallization), which is substantially diminished by the hardening associated with the plastic deformation introduced in the process of mechanical forming, such as rolling or drawing.

To remove the oxide layer that forms on the surface of annealed and rolled steel as a result of the heating performed in annealing, the material is usually dipped into tanks containing acid solutions that dissolve this oxide layer. This process of removal of the oxide layer by acid solutions is known as pickling. By performing these intercalated annealing heat treatments with successive laminations, it is possible to reduce the thickness of the laminated sheets by between 50 and 90%.

In the case of certain steels with a discontinuous flow limit associated with the formation of the so-called Lüder strips, the usual practice is to perform a small final cold reduction on the annealed steel, called a surface roughness pass, or a surface finishing pass, which eliminate the elongation of the discontinuous flow limit. In addition, this finishing pass also improves the surface finish of the material and also it provides better control of the thickness (gage). Other methods used to improve gauge control are roller rolling and traction performance (ZÁRATE; HELMAN; GÁLVEZ, 2013).

A roller planning machine consists of two groups of rollers of small diameter, arranged such that the upper row and the lower row are offset from each other. When the plate passes in the planer it is flexed up and down, leaving rectified the rollers. The tensile perforator consists of two claws that hold the ends of the sheets and stretch it by applying a pure tensile tension.

Steel bars with a circular and hexagonal cross section as well as structural profiles (I-beams and rails) can be produced in large scale by hot rolling through the use of rolling mills with grooved rollers.
Unlike flat lamination (of sheets and strips), the cross section of the material is reduced in two directions. However, at each pass the material is compressed in a single direction, being rotated 90° in the subsequent pass (USIMINAS, 2014).

Non-flat products are manufactured using specific laminators and different from those used in flat laminating. This is the case with the commercial bar mill and profile mill. The bar mills can be duos and are provided with guides to guide the material into the grooves as well as having repeaters which invert the direction of the bar and lead it to the next pass. They consist of a group consisting of a thinning chair, a forming chair and a finishing chair, which can form the so-called "rolling mill" consisting of several mills situated next to each other side by side and the mills in a chair are driven by a connection, which connects them to the adjacent chair (DA CUNHA, 2013).

2 MATERIALS AND METHODS

We can define the problem definition as the desired to find the approximate load to reduce a steel plate (Y = 350 MPa) from 50 mm to 30 mm thick, in a rolling mill pass, with 500 mm diameter cylinders, as shown in Fig. 2.

![Figure 2 - Model to be analyzed.](image)

Helman and Cletlin (1993) present two formulations for the calculation of the rolling stresses: the first, also known as homogeneous deformation method; and the second, known as the equilibrium method. For both formulations it is necessary to define the length of the contact arc and the contact angle, as shown in Fig. 3.
Figure 3 - Rolling parameters. HELMAN and CLETLIN, 1993.

The contact arc length and the contact angle are defined by Eq. (1) and Eq. (2), respectively:

\[ l = \sqrt{R^2 - \left( R - \frac{\Delta h}{2} \right)^2} \approx \sqrt{R\Delta h} \quad \text{once } R\Delta h \gg \frac{\Delta h^2}{4} \]  

\[ \sin \alpha = \frac{l}{R} = \frac{\sqrt{R\Delta h}}{R} \quad \text{but } \sin \alpha \approx \alpha = \frac{\sqrt{R\Delta h}}{R} \]  

2.1 Homogeneous Deformation Method

The Homogeneous Deformation Method is defined as a constant pressure, \( P \), applied to the material over the cross section area, \( A \), and considering a constant yield strength, \( \bar{Y} \), as depicted in Eq. (3) and Eq. (4).

\[ A = lw = \sqrt{R\Delta h}w \]  

\[ P = \bar{Y}A = \bar{Y}\sqrt{R\Delta hw} = 1.154Y\sqrt{R\Delta hw} \]  

As suggested by Helman and Cletlin (1993), we include 20% to consider the effect of friction, resulting in:

\[ \frac{P}{w} = 1.21 \cdot 1.54Y\sqrt{R\Delta h} \]
2.2 Equilibrium Method

The other method, known as the Equilibrium Method takes into account the following hypotheses:

1. Flat Deformation;
2. Homogeneous deformation in each plane;
3. Constant Coefficient of friction;
4. Relative circular contact arc by Hitchcock’s expression, given by Eq. (6)

\[ R' = \frac{1}{\Delta h} \left[ Y \left(1 - \frac{1.2\Delta h}{h_i + h_f} \right) \pm \sqrt{Y^2 \left(1 - \frac{1.2\Delta h}{h_i + h_f} \right)^2 + 4 \left(\frac{1}{cR} - \frac{1.6\mu Y}{h_i + h_f}\right) \frac{\Delta h}{c}} \right] \]

where \( c = \frac{16 - v^2}{\pi E} \)

5. Neutral point inside the arc; and

Once the assumptions are made, the method is initiated by the analysis of forces in a given section of the material subjected to the rolling process.

Considering an infinitesimal element in the region of the cylinders, the strength sum in the direction of rolling is given by Eq. (7)

\[ \sigma_x h + \sigma_x dh + hda_x + d\sigma_x dh - h\sigma_x + 2P_r dx \tan \varphi \mp 2\mu P_r dx = 0 \]

But geometrically we have \( dh = 2dx \tan \varphi \), so one simplify Eq. (7) to:

\[ d(ha_x) = -P_r (1 \pm \mu cot \varphi) dh \]

From the yield condition (Tresca Criteria):

\[ \sigma_1 - \sigma_3 = Y \therefore \sigma_x + P = Y \text{ and } dh = 2(R' d\varphi) sen \varphi \]

Thus:
\[ hY \frac{d}{d\varphi} \left[ 1 - \frac{P}{Y} \right] + \left( 1 - \frac{P}{Y} \right) \frac{dh}{d\varphi} = -2R'P \sin\varphi (1 \pm \mu \cot \varphi) \]  

(10)

Applying simplification:

\[(1 - \frac{P}{Y}) \frac{d(hY)}{d\varphi} \ll hY \frac{d}{d\varphi} \left[ 1 - \frac{P}{Y} \right] \]

(11)

As a result:

\[ hY \frac{d}{d\varphi} \left[ \frac{P}{Y} \right] = 2R'P(\sin \varphi \pm \mu \cos \varphi) \]

(12)

Admitting small angles:

\[ \sin \varphi \approx \varphi ; \cos \varphi \approx 1 - \frac{\varphi^2}{2} \text{ and } h = h_f + 2R'(1 - \cos \varphi) \approx h_f + 2R' \frac{\varphi^2}{2} \]

(13)

Thus

\[ (h_f + R' \varphi^2)Y \frac{d}{d\varphi} \left[ \frac{P}{Y} \right] = 2R'P(\varphi \pm \mu) \lessgtr \frac{d}{d\varphi} \left[ \frac{P}{Y} \right] = 2R'P \left( \frac{\varphi \pm \mu}{h_f + R' \varphi^2} \right) \]

(14)

\[ s \frac{d(P/Y)}{P/Y} = \frac{2\varphi d\varphi}{h_f + \varphi^2} \pm \frac{2\mu d\varphi}{h_f + R' + \varphi^2} \]

(15)

\[ \frac{d(P/Y)}{P/Y} = \frac{2\varphi d\varphi}{h_f + \varphi^2} \pm \frac{2\mu d\varphi}{h_f + R' + \varphi^2} \]

(16)

Applying the appropriate integration limits, we finally have:
3 RESULTS

3.1 Analytical results

By the Homogeneous deformation method, we have:

\[ P = 1.38 \cdot 350 \cdot 200\sqrt{250(50 - 30)} = 6.8 \, MN \]  (18)

By the equilibrium method, we generate the following friction hill graph, as presented in Fig. 4:

![Friction Hill graph](image)

Figure 4 - Friction hill graph

By integrating the area of the friction hill graph:

\[ P = 200 \cdot 364.655 \cdot 425.49 \cdot \frac{10^2 \pi}{180} = 7.4 \, MN \]  (19)
Comparing both results, a percentage error of 8% was obtained.

3.2 Numerical results

For the numerical method it is necessary to detail the steps of data entry. A finite element model ABAQUS software was developed, which presented interesting and realistic results.

To perform the simulation of a rolling operation, two parts were created:

- the laminating roller - cylindrical surface that cannot be defined in 3D space, made with Shell elements;
- metal billet to be laminated - solid body of rectangular section in 3D space.

The characteristics of the rolling roll and the properties and geometrical features of the material are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 - ABAQUS Simulation Inputs</th>
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</thead>
<tbody>
<tr>
<td><strong>Rolling roll</strong></td>
</tr>
<tr>
<td>Diameter (mm)</td>
</tr>
<tr>
<td>Width (mm)</td>
</tr>
<tr>
<td><strong>Billet</strong></td>
</tr>
<tr>
<td>Width (mm)</td>
</tr>
<tr>
<td>Height (h/2) (mm)</td>
</tr>
<tr>
<td>Length (mm)</td>
</tr>
<tr>
<td><strong>Material: 1020 Steel</strong></td>
</tr>
<tr>
<td>Young Module - E (GPa)</td>
</tr>
<tr>
<td>Poisson coefficient</td>
</tr>
<tr>
<td>Yield point (MPa)</td>
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<tr>
<td>Property</td>
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<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>UTS (MPa)</td>
</tr>
<tr>
<td>UTS Stretch (%)</td>
</tr>
<tr>
<td>Density (kg/cm³)</td>
</tr>
<tr>
<td>Coefficient of friction</td>
</tr>
</tbody>
</table>

Once the parts and materials were defined, the assembly of the structure was made, with the roller positioned to cause a deformation \( \Delta h/2 = 10 \text{ mm} \) in the billet. The contact surfaces between the two parts and the movement of each one was defined in order to reproduce the actual movement. To simplify, some symmetry conditions were assumed at the base of the billet, which is the plane of symmetry with respect to the roll below, reducing the number of points required for the simulation. The mesh size of the roll was made with flat quadratic elements (R3D4) and dimension 40mm. It was used the cubic element for the billet (C3D8R) of size 17mm. The simulation was performed on an ASUS computer, 3rd generation i7 processor with 3.4 GHz and 8 GB of DDR3 RAM, and it was used 1091 nodes, for 756 elements. The results of simulation are shown in Fig. 5 and 6.

![Figure 5 - ABAQUS Simulation](image)
In Fig. 6, one can see that the maximum force varies between 7.5 to 10 MN. The processing time to run the simulation was 577.6 seconds.

The difference between the analytical and the numerical results can be explained by the consideration of constant stress in the deformation by the analytical model, while the numerical model takes into account the increase of stress during the plastic regime due to the hardening. The more accurate modeling of the material used can bring more reliable results. It is important to emphasize that the numerical analysis must be validated through experimental tests before its results are used.

4 CONCLUSION

The lamination process, its operation and its applications represent an important knowledge to all those involved in its design and use. The analytical formulations present satisfactory results and are already recognized by the industry as a good initial approximation to the system design. The finite element analysis represents another method for estimating the forces acting on the process. However, this method must be used with caution because it requires good input parameters to obtain usable results, besides a mandatory validation of the developed model. A next step for this study is the refinement of the material properties and the insertion of deformations in the roll, guaranteeing a more plausible simulation.
5 REFERENCES

DA CUNHA, M.A. Modelo híbrido para previsão de desgaste em cilindros de laminadores de produtos não planos. 2013. 81 f. Dissertação (Mestrado em Modelagem Matemática e Computacional) – Centro de Educação Tecnológica de Minas Gerais, Belo Horizonte, 2013.


