RECENT IMPROVEMENTS ON THE 3D FINITE ELEMENT METHOD/MULTI-SLAB METHOD FOR FLAT ROLLING SIMULATION*

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Abstract

The quality of flat rolling process depends highly on multiple factors such as applied forces, materials involved for both strip and rolls, roll geometry and its positioning. To calculate the strip shape, a mathematical/numerical model can be applied, showing the final product and how the equipment behaves when changing some parameters. This is usually a time-consuming task for both user and computer, especially when it involves thin and hard strips. By coupling a quick rolling load calculation method as Bland-Ford and Finite Element Method (FEM) for roll stack deformation, it is possible to create an accurate and user-friendly rolling simulator. This paper presents the improvements done in the 3D FEM/multi-slab method and its actual capabilities by simulating two cases of a 6-High rolling mill. Different analysis in this equipment can be easily done in about 10 minutes by using the developed an electronic spreadsheet program interface and the folder generated with relevant results and logs. An operation manual and a commercial FE program plugins were made to aid construction of a completely new model. The code was created in a modularized way to assist the application of this simulator for other operational conditions.

Keywords: Flat rolling simulation; Roll stack deformation; Finite element method; Parameterized model.

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1 INTRODUCTION

In flat rolling industry high quality strips are demanded, being its profile and flatness very important characteristics. Stringent tolerances must be satisfied, and the trend for producing finer and harder strips is very challenging.

In order to achieve the best control system over the rolling mill process, it is imperative to use reliable and accurate mathematical models.

Concerning the strip profile, many roll stack deformation models were developed. Many attempts to simulate the rolling mill deformation has being made since the 1950's, initially with Stone and Gray [1] with the beam and elastic foundation method, Shohet and Townsend [2] with beam models and variable pressure along their length (sometimes called "influence method"), and more recently models based on the Finite Element (FE) method. Among these, we can list full FE models [3][4] and hybrid models, mixing FE for roll stack deformation and an analytical/numerical method for rolling load calculation [5], and influence method for roll stack deformation and FE model for the strip elastoplastic deformation [6], in both cases with a good coupling method.

Classified as one of hybrid methods, the 3D FEM/Multi-slab method presented here will be briefly described and many improvements made in order to become user-friendly will be shown in the next sections. The method is applied to model a 6-high rolling mill for different roll shift values and the strip crown is calculated.

2 TRIDIMENSIONAL FEM/MULTI-SLAB METHOD

The method presented in this work uses FEM to model roll stack and a equilibrium method, also called Slab method, to calculate the rolling load.

The coupling between both roll stack deformation/rolling load is given just applying the load on the FE model in an iterative way.

One of the major advantages of this model is the fact that it adopts symmetrical and asymmetrical planes in order to simplify the roll stack FE model without compromising accuracy, solving complex mills in much less time than a full FE model. The rolling mill type can be modeled easily from the simplest 4-high until the most complex ones, e.g. Sendzimir mills. Figure 1 shows a 6-High rolling mill modeled for this hybrid method with rolls names.

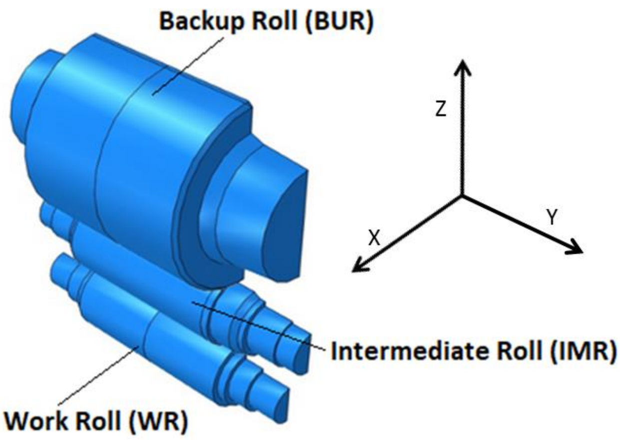

Figure 1. A 6-High mill modeled and nomenclature.

For the rolling load it is possible to apply a Bland-Ford-Hitchcock method for strips with common steel grades and thicknesses or a more advanced one, e.g. Noncirc [7] for thin and harder strips.

The hybrid model works in an iterative way, first applying a uniform load on the FE roll stack model (already modeled taking into account the symmetry and anti-symmetry planes, if it is the case). The deformation of the lowest line of the work roll is adopted as the new profile of the strip. After imposing the desired final thickness to the "new" strip with this new shape, a distributed new rolling load is recalculated for a new final thickness distribution. In order to capture the load variation along the width of the strip, this and the work roll are slitted in small areas.

More details on this method may be found in [5].

A 6-High and a 4-High rolling mill were modeled and results showed to be very accurate when compared with industrial data. For these models, only 6 to 10 iterations were enough to converge to the strip final profile.

3 NEW IMPLEMENTATIONS

The hybrid model has received improvements in order to facilitate inputting new rolling mills parameters and to receive different geometries, like roll shifting position, new roll cambers, new roll diameters, etc.
Starting from a basic model, the hybrid model runs smoothly until the final strip profile converged.

The next sections present the improvements made on the code.

3.1 Bland-Ford-Hitchcock

The only changes made to analytical calculation were to improve performance and friction coefficient calculation.

3.1.1 Code optimizations

To reduce the execution time, the algorithm was made mostly on C language, with multicore support and using, as an initial guess of the Hitchcook radius, those obtained in adjacent sections.

3.1.2 Friction coefficient calculation

The friction coefficient can be inserted as an input data or calculated to match the experimental total rolling load. This trial and error process originally was made manually.
This part of the process was programmed, in order to do it automatically.

3.2 FEM model

The FE model was changed in order to make it more parameterized. A new mesh strategy was needed in order make the results obtained with a generic contact arc format acceptable.

3.2.1 Variation of the contact arc length along the strip width

Due to the variation of the arc of contact length along the strip width, a new process to take it into consideration was necessary. In the new version, this variation is represented by the desired curve and the mesh is generated at each iteration.

3.2.2 Rolling load distribuition

The rolling load is inserted as a mapped field, instead of being input point by point, which allows the simulator to insert the most adequate force to each of the elements of the contact arc.

3.2.3 Mesh strategy

The mesh of each roll was made with quadratic tetrahedron elements (named C3D10 in Abaqus) by fixing the sizes of the overall elements of each roll except for the region of the contact arc. For the latter it was developed an algorithm that inserts smaller elements in the region of the edges of the strip and separates the contact area from the rest by a transition zone. This feature (shown in Figure 2), associated with its correct setup, helps to reduce the number of distorted elements for the various contact arc formats of each iteration.

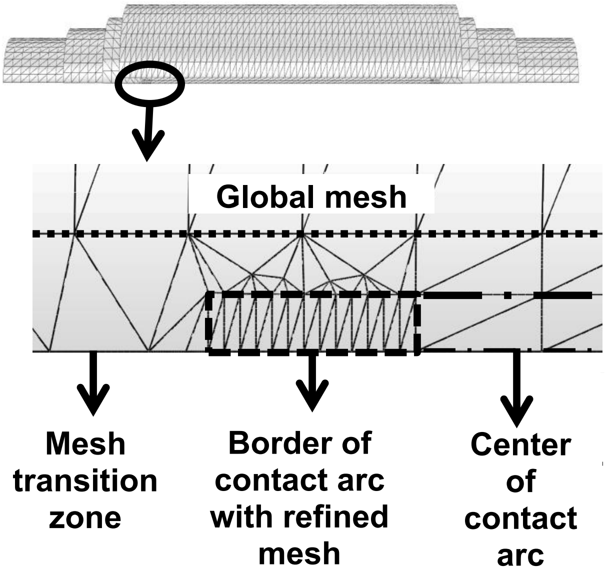

Figure 2. Contact arc mesh

3.2.4 Settable roll profile

The barrell length shape can be inserted by informing roll's diameter at multiple positions along the length. This allows to insert a more realistic geometry, considering wear and thermal profiles when needed.

3.3 Code characteristics

One of the main features of this work is the focus on making it easier to be used. The implementations made for this purpose were: The usage of object orientation, creation of an interface based on Excel, development of Abaqus plugins, parameterization of important values of the model and preparation of a manual of operation.

3.3.1 Easy data insertion

The input data is inserted through Excel spreadsheet (3) and organized in a similar way as the used by the object orientation in main code. This promotes compatibility between the programing commands and the end user interface. Data from other models can also be inserted together in this tool, creating a kind of database. A group of parameters can be easily changed by referencing all of them at once. The options choice shown in 3 exemplifies this: The "default" and "precise" leads to a similar sheet where the users can see and change its details. These characteristics result in an easy data reuse avoiding reworking every time a set is changed.

	A	B	C	D	E
1	\	File name	Parts name	Meshes size	Options
2	6_HIGH	6HIGH.cae	{"WR","IMR","BUR"}	[30,39,70]	*Options.default
3	6_HIGH_precise	6HIGH.cae	{"WR","IMR","BUR"}	[20,30,50]	*Options.precise
4	4_HIGH	4HIGH.cae	{"WR","BUR"}	[30,70]	*Options.default

Options | MEF_Model | Bland_Ford | Material

Figure 3. Example of the input Excel sheet

3.3.2 Usability by non-programmers

Several important inputs of the Hybrid Model can be inserted into the mentioned interface, such as roll radius and crown, rolling load and arc, strip thicknesses and its strain hardening. This coupled with the help boxes feature and the feature to start simulation by Excel, allows the usage by a non-programmer person. The parameterization mentioned can also be used in the code to facilitate the sensitivity analyzes.

3.3.3 Creation of users' tools

The construction of the numerical model is considered the most difficult step involved. Several of the values inserted must be generic and are changed during execution. To assist this, there is a description of the procedures in the operation manual and Abaqus plug-ins for the more complex parts.

3.3.4 Easy access of results and logs.

During each run a folder and subfolders with results are generated, calculation logs, parameters and input files. Among them are the summary of occurrences, value of variables at predetermined time, Finite Elements models of first and last iterations and worksheets with the result's curves. For the latter, Excel macros were developed that generate the graphs after the model is executed and facilitate the comparison of results.

4 CASE STUDY

The 6-High rolling mill modeled formerly in [5] was taken as example to be remodeled with the new improved hybrid model. In a next step, multiple values of IMR shift in the Y direction (shown in Figure 1) are applied to calculate the strip crown. This will allow to compare the advances of the method, to validate it and to serve as an example its use as a way of predicting the process. The main parameters are shown in Table 1.

Table 1. Main parameters

Parameter	Value
Mean entry strip thickness (mm)	2,2
Expected exit strip thickness (mm)	1,34
Strip width (mm)	980
Working roll radius (mm)	200
Intermediate roll radius (mm)	210
Backup roll radius (mm)	600
Strain Hardening (MPa)	$\boldsymbol{Y = 230 * 500\varepsilon^{0,5}}$
Front applied tension (MPa)	200
Back applied tension (MPa)	20
Roll bending Load (N)	1e5
Total measured load (N)	9e6
Roll shift of the original case (mm)	70

5 RESULTS AND DISCUSSION

The output strip profile obtained in the validation simulation and the experimental data are compared below (Figure 4). They have a crown of respectively 40.5 μm (2.92% of the thickness of the sheet) and 32.7 μm (2.39% of the thickness of the sheet). The results also show good agreement on the edges. In the experiments of Shigaki, Montmitonnet and Silva [5] the value found was 35.6 μm. This represents an accuracy reduction of the model which still needs to be studied better.

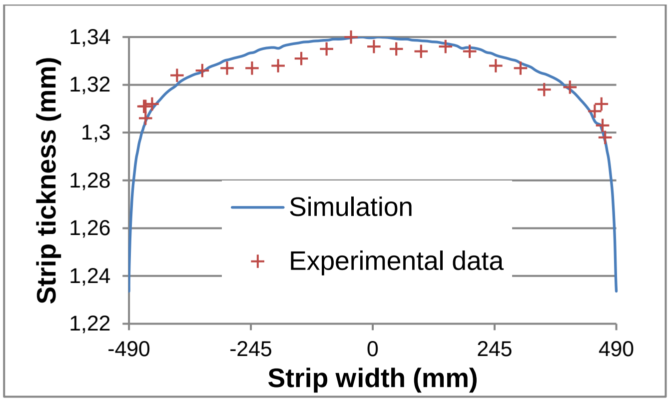

Figure 4. Hybrid Model results and experimental data

The total execution time of the 3 required iterations was 7.9 minutes, 40% of the total spent by Shigaki, Montmitonnet and Silva [5]. The total number of elements for each iteration was 62.000 approximately. A more detailed analysis (Figure 5) shows that the Finite Elements execution time is what defines the efficiency of the Hybrid Method and the Bland Ford method has been optimized until it almost does not have impact in the total time processing. The fraction denominated "other" mainly includes the operations of reading input data and the copy of the final folder's files.

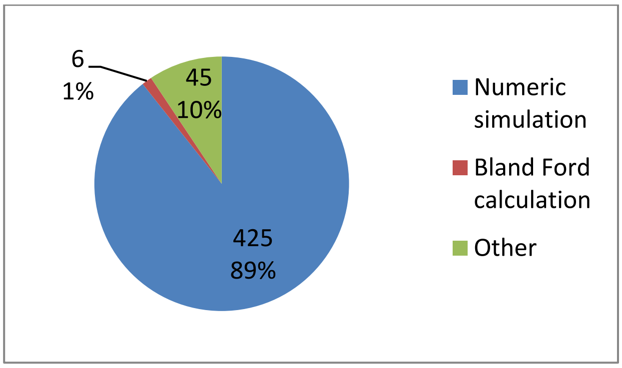

Figure 5. Execution time (seconds)

The convergence of the method occurred in only 3 iterations (Figure 6), compared to

5 required in the modeling of Shigaki, Montmitonnet and Silva [5]. It is believed that this difference was obtained by the more realistic representation of the load and rolling arc.

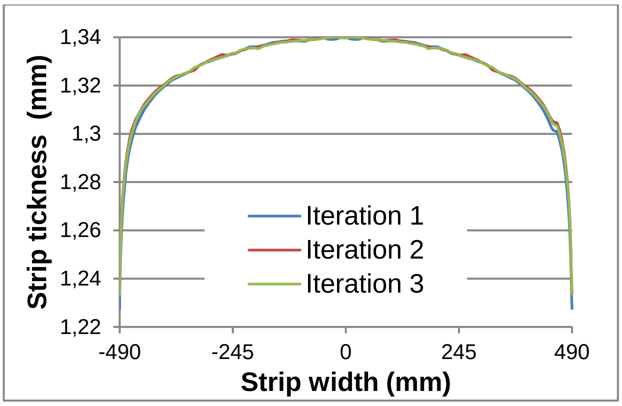

Figure 6. Hybrid Model iterations

The iterations showed a good execution of the model (Table 2), presenting an acceptable amount of distorted elements and a neglectable adjustment of the rolling load. This shows that the transition zone between of the contact arc acted as desired, and that the calculated coefficient of friction was accurate enough to generate loads that are similar to the experimental one, even after calculating with multiple sections.

Table 2. Data of each iteration

Iteration number	Number of distorted elements	Difference between actual and calculated loads (%)
1	1	0,021%
2	1	-0,063%
3	2	-0,032%

With the translation of the roll it was possible to obtain the new strip profiles (Figure 7). The strip crowns obtained for IMR shifting at positions -115 mm and -125 mm are respectively 19.8 μm and 14.8 μm. These two cases were executed in a total of 18 minutes with 3 distorted elements in all 6 iterations. The relation between the strip crown and roll shift is close to a linear pattern and is represented in Figure 8. To calculate this configuration it was only necessary to modify the previously mentioned parameters via interface. All other adjustments such as interpolations and changes in the numerical model are made automatically by the program.

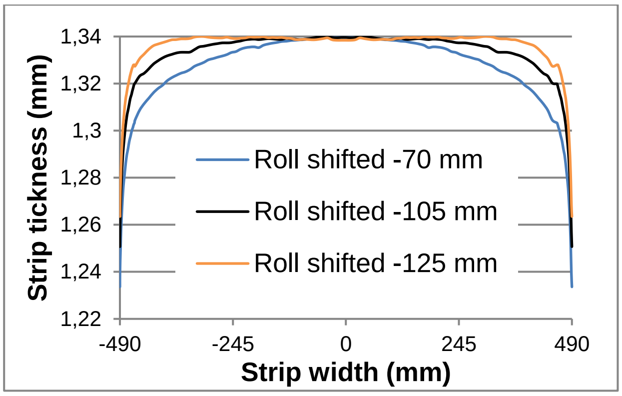

Figure 7. Hybrid Model results with different values of roll shift

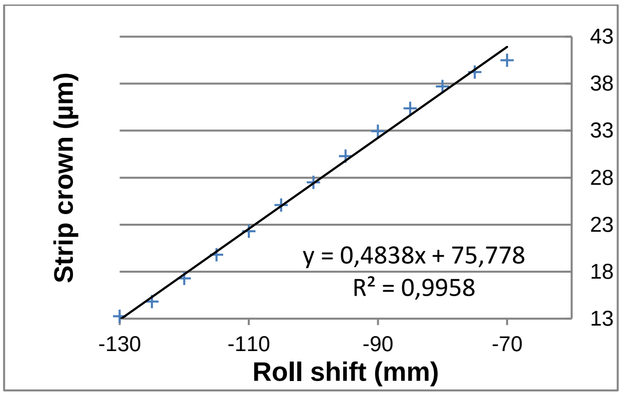

Figure 8. Sensibility analysis between roll shift and strip crown

6 CONCLUSIONS

The Hybrid Model and the program to manage it are easy to operate, quick to execute and show promising results. It is modularized enough to facilitate the modeling for different conditions. The characteristic of being able to use any analytical method of load allows its application in multiple complex cases.

Further tests are still needed, both to confirm the applicability of the model in different rolling mills and to ensure accessibility for users who do not know programming.

The Hybrid Model showed versatility that is comparable to the finite element model. It is possible to apply details to the model such as the worn roll profile, position of the rolls and roll bending forces. This makes it possible to model several cases with the accuracy and speed demonstrated.

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