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FINITE ELEMENT ANALYSIS OF ROUGHNESS TRANSFER ANALYSIS: MODELLING FOR TEMPER ROLLING PROCESS

Yukio Shigaki
Paulo Rezende da Silva Dutra
Marllon Tadeu Silva Cézar
Arthur Farias Neiva
Rafael Narciso Mendes Alvarenga Romie
Centro Federal de Educação Tecnológica de Minas Gerais CEFET-MG/ PPGEM – Campus Nova Gameleira
Av. Amazonas, 7675, CEP 30510-000, Belo Horizonte, Minas Gerais, Brazil
e-mails yukio.shigaki@cefetmg.br, powdutra26@gmail.com, , marlloncezar64@gmail.com, arthurfarias2303@gmail.com, rafael.narcisoo@gmail.com

Abstract. *Automotive industry demands steel strips with high peak density to get good surface finish after painting and, at the same time, be good for stamping. Finding a way to predict if the final strip has these qualities is of fundamental matter. This roughness transfer is usually done at the final flat cold rolling process called temper rolling (or skin-pass). This finishing process aims at correcting small bad flatness, cut out the initial yield stress instability and applying a desired roughness to the strip. Many authors have studied the roughness transfer mechanism, but none of them have analyzed it more deeply modelling asperity itself on the surfaces both for the strip and roll geometrically for a finite element model till the present day. The interaction of both surfaces – work roll and strip surfaces – is very complex, considering the crushing and ploughing mechanisms, the high roll deformation, the sliding and sticking friction in the roll/strip contact surface, etc. The first step towards a sound finite element model for this study must work on the precise modelling of the asperities on the contacting surfaces. Due to the huge size differences between the roll diameter (something around 500 mm) and surface roughness (micrometers), roughness modelling is not so straightforward. In this work, a finite element model for the temper rolling process was developed, showing an arc-of-contact with 5 distinct regions: on the entering part there is an elastic deformation, followed by a plastic one, and in the middle a plastic contained region (where apparently there is no thickness reduction), and then a plastic and finally an elastic deformation to the exit of the strip. Roughness was modeled on the strip and roll surfaces. This work includes a step-by-step guide on how to model roughness on the strip and roll surfaces using a Python code, and its results were implemented on the 2D temper rolling finite element model. Average roughness was generated both on the strip and roll surfaces, and three different reductions were simulated for an industrial temper rolling mill. It was concluded that strip's average roughness drops down when the strip is rolled. Abbott curves show that high roughness transfer occurs for the highest roll gap, but this result should be analyzed with caution, as until now our objective was to develop a sound FE model including roughness for rolls and strip. Ploughing and crushing mechanisms could not be clearly identified in this study, as it requires capturing more frames during simulation and more refinement of the FE mesh. This will be done for the next studies.*
Keywords: *roughness transfer, temper rolling, skin pass, finite element method, tutorial*

1. INTRODUCTION

Automotive and packaging industries demand steel strips with high peak density to get good surface finish after painting and, at the same time, be good for stamping. A closed lubricant pocket is needed in this last case (require a negative skewness). Also, a high peak density favors a good painting finish, and it is related to the average roughness *Ra*.

Average roughness, peak density and skewness are essential tribological variables that must be attended by strip metal industries in order to meet the quality aspects required by customers (Legrand et al., 2019), and they are produced along the flat cold rolling process and/or at the final finishing step by a temper rolling or skin pass, where the asperities of rolls and operational variables are controlled to meet the required roughness to the strips.

Furthermore, according to Mekicha and colleagues (Mekicha et al., 2020), the real contact area between the work roll and the strip plays an important role in characterizing friction, wear and material transfer, and it is well known that it influences the strip sub-surface bulk deformation.

Thus, the roughness transfer mechanism is not fully understood yet (Ataka et al., 2008), and many researchers have attempted to explain it using analytical and numerical models.

In general, the analytical models are based on upper bound method (Wilson and Sheu, 1988; Sutcliffe, 1988; Kimura and Childs, 1999) and have many restricting assumptions: regular asperities deforming as a rigid-plastic material with rigid and smooth tools, velocity field limiting other modes of deformation, etc.

Legrand et al. (2019) developed a roughness prediction model based on mixed Abbott curve, a crushing model and a rolling model. Doing that they could consider the crushing and ploughing deformation of asperities with reasonable accuracy, except for the exiting region in the arc of contact.

Çolak and Kurgan (2018) carried out rolling tests with 36 specimens in a 2-high laboratory mill, for strips with 0.8 to 1.83 mm thicknesses, and concluded that 1- roughness transfer is more effective when rolling load is higher in high speed rolling, high reduction and thinner materials; 2 – roughness decreased due to lubrication, though more homogeneously distributed than when dry rolling was used; and, roughness at small reduction ratios was obtained within a narrower range.

Numerical models have played a key role in better understanding the roughness transfer mechanism. Kijima (2014) and Kijima and Bay (2008a,b) modelled the temper rolling process in Abaqus R.6 Implicit analysis, considering elastic rolls and elastic-plastic strips, first considering only normal pressure (Kijima and Bay, 2008a), and then simulating a plane strain upsetting test for sliding (Kijima and Bay, 2008b), both only for strips without asperities.

It is worth to mention statistical models based on mass production of strips. Xia et al. (2017) analyzed 90 cold rolled/temper rolled coils and developed a roughness prediction model applying a step regression method.

None of the above cited researches have analyzed the roughness transfer process more deeply modelling asperity itself on the surfaces geometrically for a finite element model. The interaction of both surfaces – work roll and strip surfaces – is very complex, considering the crushing and ploughing mechanisms, the high roll deformation, the sliding and sticking friction in the roll/strip contact surface, etc.

The first step towards a sound finite element model for this study must work on the precise modelling of the asperities on the contacting surfaces. Due to the huge size differences between the roll diameter (something around 500 mm) and surface roughness (micrometers), roughness modelling is not so straightforward.

Simultaneously, a finite element model for the temper rolling process was developed, showing an arc-of-contact with 5 distinct regions: on the entering part there is an elastic deformation, followed by a plastic one, and in the middle a plastic contained region (where apparently there is no thickness reduction), and then a plastic and finally an elastic deformation to the exit of the strip. It shows that the highest thickness reduction occurs at this last part.

This work includes a step-by-step guide on how to model roughness on the strip and roll surfaces using a Python code, and its results were implemented on the temper rolling finite element model. We aim at better understand the roughness behavior in the contact interface, verify the crushing and ploughing of peaks inside the arc-of-contact, and calculate the exit strip roughness.

We are still developing the 2D finite element model with realistic asperities for both strip and elastic rolls. For the present article, we focused on the roughness modeling in Abaqus v. 2016 and present some preliminary results for three different thickness reductions for a thin annealed steel strip (0.18mm).

2. ROUGHNESS MODELING

In order to perform the contact simulation between rolls and strip, both with roughness, it was first defined how the roughness would be modeled and the method that would be used. Considering that the scope of this work is to model and simulate such interactions, initially on a line/curve, the roughness was modeled as distortions (peaks and valleys) on the surface of a straight line or a curve. In addition, all the distortions were generated from a displacement normal to the original surface.

With a defined roughness model, it was then chosen the method that would be used to generate it and which parameters would be necessary to achieve this goal. As the formation of distortions is based on displacements perpendicular to the surface, they were easily modeled by generating points connected by straight lines on the original surface and performing individual displacements in the desired direction.

This method allowed the insertion of roughness with pre-defined height and density of peaks on the surfaces of both rolls and strip, based on the choice of the maximum displacement and the number of points, in any region of the surface of a part along a line/curve.

2.1 Roughness implementation with Python for Abaqus

It is important to emphasize that this entire roughness model is implemented during the part creation process of the FE model, in which the surfaces of rolls and strip are created. Due to the large number of points that were generated, it was essential to use a program to automate the process of creating these points and to link them together, forming the desired surface.

The creation of this program was made using the Python programming language. The program is responsible for generating all the commands necessary to create the part with roughness and writing them in a text document to create a script that can be read by Abaqus. This Script contains all the points that must be generated and the part dimensions already implemented in the commands.

It is worth to note that Abaqus uses a Python interpreter to read the scripts, so, although we could make programs in other languages, the document that is generated and the commands must always be written in Python.

2.2 Programming a point generator

In order to automate the roughness creation process, we made some simplifying assumptions. Every peak is equidistant from each other in the transversal direction, and we defined a maximum height for the roughness peaks.

To create a code that generates the coordinates of these points automatically, we linked them to the roughness parameters and guaranteed the equidistance of the points. In this way we defined an increment, a value that is added to the coordinates of each new point and allow us to draw all the desired asperities.

Regarding roughness, we used a Python module called "random", which contains the function "random()" (generates a pseudorandom number between 0 and 1). This function was used to generate perpendicular displacements responsible for creating distortions in the surface and characterizing the roughness.

Finally, for each new point generated we wrote in the script the command "s.Line(point1=(x1, y1), point2=(x2, y2))", which is responsible for connecting the points with a straight line, allowing the rough surface to be created.

Table 1. Code example for a Strip centered on the y axis and above the x axis, from random import random.

```
# Setting the dimensions of the strip and defining the section where the roughness is created
strip_height = 10
strip_length = 110
peak_height = 0.1
rough_section = strip_length
points = range(200)
# Set of coordinates that form the bottom of the strip
x = - strip_length /2
y = strip_height
coord_1 = (x, y)
coord_2 = (x, 0)
coord_3 = (-x, 0)
coord_4 = (-x, y)
# Spacing between points (Strip length/Number of points)
increment = rough_section /len(points)
# Start and end of rough surface
x1 = - rough_section /2
x2 = rough_section /2
starting_point = (x1, y)
ending_point = (x2, y)
# Creation of the text document that is read by Abaqus
with open(r"C:\Users\User\Desktop\strip_script.py", "w") as archive:
    # Creates the bottom and sides of the strip
   archive.write(f"""s.Line(point1={coord_1}, point2={coord_2})
s.Line(point1={coord_2}, point2={coord_3})
s.Line(point1={coord_3}, point2={coord_4})\n”””)
    # Point generator
    point1 = starting_point
    x_point = x1
    for point in points:
        x_point += increment
        # Connects the penultimate point with the predefined end point
        if point == (len(points) - 1):
            point2 = ending_point
           archive.write(f"s.Line(point1={ point1 }, point2={ point2 })\n")
            break
        y_point = strip_height + (random() * peak_height)
        point2 = (x_ point, y_ point)
        archive.write(f"s.Line(point1={ point1 }, point2={ point2 })\n")
        point1= point2
```

As it can be seen in Table 1, the roughness peaks and valleys are generated by multiplying the maximum height of the peak by the return of the random() function (which varies between 0 and 1), this value is added to the original height of the sheet, creating a small random offset with an upper bound. After the creation of each point, it is connected to the previous one by a straight line from the Abaqus line creation command, thus, at the end of the process, we had all the interconnected points and the roughness profile ready.

To create the roughness on a circle we had to change some of the parameters used in the code, however the model responsible for generating it is basically the same. First, we adapted the code to the circular surface of the cylinder, to do this we worked with angles in radians. As we have to guarantee the equidistance between the points, the increment was the rough section angle in radians divided by the number of points. In addition, we used the trigonometric functions to be able to transform these data into Cartesian coordinates.

Finally, we programed how the roughness distortions are applied in this case, as the displacements are always perpendicular to the part surface. We used the cylinder radius itself as a parameter. Our point generator was responsible for traversing the desired cylindrical surface region and creating points with Cartesian coordinates from an angular increment, always adding a random displacement in the radial direction. The code is presented in Table 2.

Table 2. Code fragment of a cylinder with roughness centered on the x axis.

```
# Sets starting point angle
angular_increment = rough_section / len(points)
point_angle  =  -rough_section /2
    for point in points:
        point_angle += angular_increment
        rough_radius  = cylinder_radius + (random() * peak_height)
        x = cos(point_angle) * rough_radius
        y = sin(point_angle) * rough_radius
        # Rounds x and y values to the eighth decimal place
        x = round(x, 8)
        y = round(y, 8)
        point2 = (x, y)
        archive.write(f"s.Line(point1={ point1 }, point2={ point2 })\n")
        point1 = point2
```

It is noteworthy that although we only used the random() function to generate distortions on our surface, several other roughness models could be implemented. We could change the function used to randomize the displacements, use other commands to connect the points (such as a spline) or even use a database to supply our code with real information on roughness measured by devices, from an Abbott curve, for example.

2.3 Script Assembly

After we managed to create the code to form the entire rough section and the commands necessary to generate it, we then inserted this information into a text document that can be read and executed by Abaqus. For this, we easily used the macro recording tool, that assists us in obtaining the necessary commands and all needed information to execute a certain task.

This is a built-in Abaqus tool, and it works by identifying all user actions in the GUI and writing in a file the commands used by the software to perform them. With this file we could understand which parameters and information are needed to do certain tasks and how we could create a script (Table 3) to achieve those same objectives using the commands recorded.

Table 3. Example of recording macros when creating a circle (2Dplanar–Deformable body–Shell).

```
def 2D_Cylinder():
    from abaqus import *
    from abaqusConstants import *
    # Part draft creation
    s = mdb.models['Model-1'].ConstrainedSketch(name='__profile__', sheetSize=200.0)
    g, v, d, c = s.geometry, s.vertices, s.dimensions, s.constraints
```

```
s.setPrimaryObject(option=STANDALONE)
# Performing the commands for creating the part
s.CircleByCenterPerimeter(center=(0.0, 0.0), point1=(100.0, 0.0))
#  Definition of part parameters
p = mdb.models['Model-1'].Part(name='Part-1', dimensionality=TWO_D_PLANAR,
   type=DEFORMABLE_BODY)
p = mdb.models['Model-1'].parts['Part-1']
p.BaseShell(sketch=s)
s.unsetPrimaryObject()
p = mdb.models['Model-1'].parts['Part-1']
session.viewports['Viewport: 1'].setValues(displayedObject=p)
del mdb.models['Model-1'].sketches['__profile__']
```

As we can see, the script has the entire structure of a Python code and is responsible for accessing all the functions and classes in the Abaqus database and passing the parameters that we pre-selected in order to execute all the commands necessary to create the part. As the software has many functionalities, the macro recording function is highly effective in discovering the commands needed to perform the desired action.

Following this procedure, it was possible to model roughness on the strip and on the roll. Figure 1 shows an example of roughness generated on a strip and on a roll.

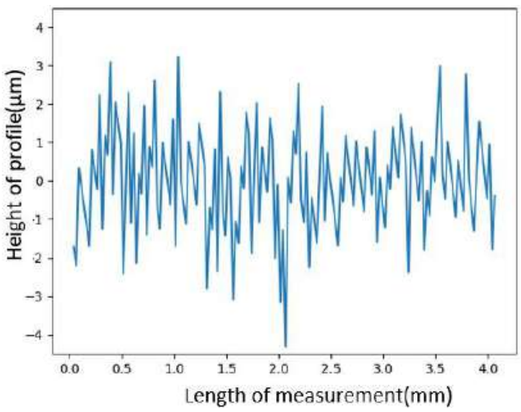


Figure 1. Example of roughness generated on the roll.

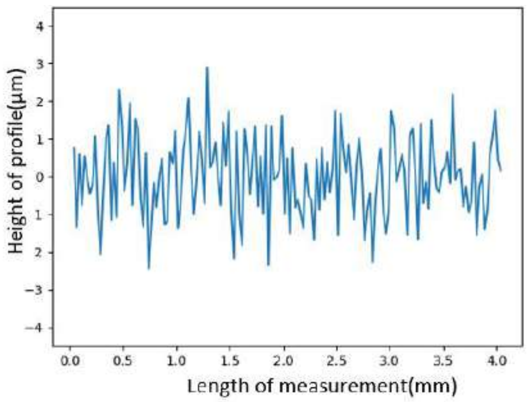


Figure 2. Example of roughness generated on the strip.

For this paper, an average roughness of 2.8 ~ 3.3μm with a constant 20μm spacing was modeled both on the strip and roll. The average roughness applied on the surfaces of the FE model are based on technical literature and were taken initially with the purpose of implementation of the methodology and to successfully run the job.

2.4 Extracting data from created roughness

In addition to creating the roughness, it is essential that we have some basic information, such as the average roughness, the maximum and minimum height of peaks and valleys, the peak density and any other data that is of interest. In order to do it, we added to the point generator code itself other functions that allow us to extract this data directly when creating the parts script.

An information of great importance for studies in the field of rolling process and roughness transfer is the calculation of the Abbott curve of each generated roughness. To do this, we stored all the height values of each point in a list in the code itself and then put them in an ascending order. With this data we created charts of the accumulated height distribution and obtained the desired Abbott curves.

Similarly, it would also be possible to create the roughness that meets the previously defined parameters. As an example, if we have an Abbott curve, we can extract the height values and link them to intervals between 0 and 1, following the curve pattern. After that, we could use a random uniform distribution function to select the height of each point using the extracted data, thus ensuring that the final roughness fits the curve.

3. TEMPER ROLLING 2D FINITE ELEMENT MODEL

The steel strip production usually has a finishing step done in a temper rolling mill (also called skin-pass). This finishing process aims at correcting small bad flatness, cut out the initial yield stress instability (Piobert-Lüders bands) and applying a desired roughness to the strip.

Figure 2 shows a sketch of the geometry of a typical temper rolling mill. Five regions are identified inside the arc of contact: elastic deformation of the strip at entrance, followed by a plastic reduction of thickness, and in the middle a plastic contained region, where a sticking friction occurs; Then follows a plastic region and, finally, an elastic deformation at the exit of the roll gap.

In many cases a flat region inside the arc of contact can be observed. This shows how the rolls are heavily deformed in the temper rolling process.

Figure 3 shows the results of simulation of a typical temper rolling mill inside the arc of contact, and respectively are: 3a) normal pressure; 3b) roll deformation imprinted over the strip, and 3c) sliding between the strip and roll.

These results were calculated with a computer program called Noncirc (Shigaki et al., 2015), without inputting the roughness. But it can be seen that the greatest amount of sliding occurs at the entrance and at the exit regions, and at the center region there is sticking friction. This suggests that the ploughing mechanism of asperities deformation would be done mostly at the entrance and at the exit region, and the crushing mechanism should occur mostly in the middle of the arc of contact.

In Noncirc and FE model we used elastic rolls and elasto-plastic strip, in order to capture the roll elastic deformation.

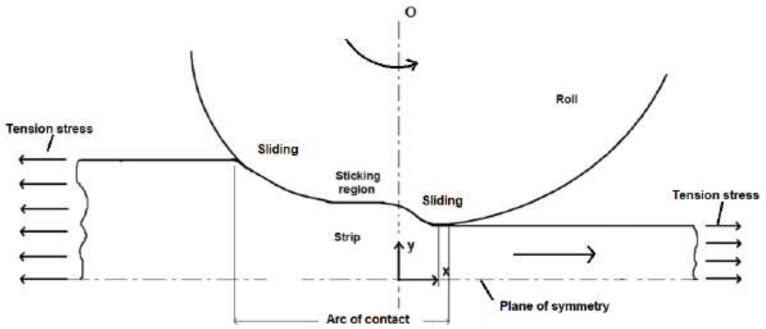


Figure 2. Schematic diagram of the temper rolling mill.

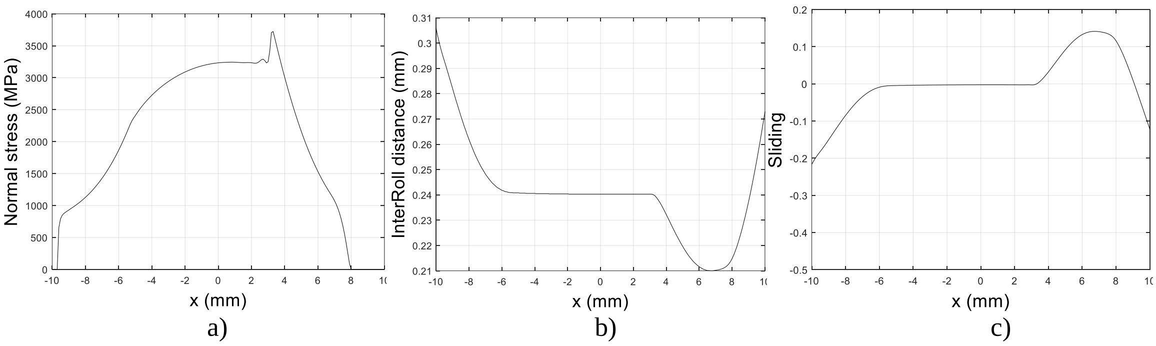


Figure 3. a) Normal pressure inside the arc of contact, b) inter-roll distance, and c) sliding inside the arc of contact.

The specifications of the temper rolling mill and strip modeled in 2D finite element method are listed in Table 4. It is a real industrial temper rolling mill from a Brazilian steel rolling company. Shigaki et al. (2016) contains more information on the FE model. The FEM software Abaqus Ver. 2016 was used in our simulations.

It was validated and used to include the roughness on both the strip and the roll.

Table 4 – Temper rolling mill data.

Parameters		**Parameters**	
Initial thickness (mm)	0.248	Strip modulus of elasticity (GPa)	200
Final thickness (mm)	0.241	Roll modulus of elasticity (GPa)	200
Strip width (mm)	885	Poisson coefficient for the roll	0.3
Strip length (in the model) (mm)	110	Work roll diameter (mm)	508
Forward tension (MPa)	126.6	Roll speed (m/min)	700
Back tension (MPa)	56.8	Rolling load measured (t)	1183

Figures 5 and 6 show the mesh on the roll and strip, and the extremely refined region inside the arc that will be in touch with the strip. In Figure 6 it is possible to note the asperities introduced, both on the strip and on the roll.

The strip material was modeled with a bilinear flow curve, with a yielding stress of 280 MPa and an ultimate tensile stress of 400 MPa for 0.8 strain.

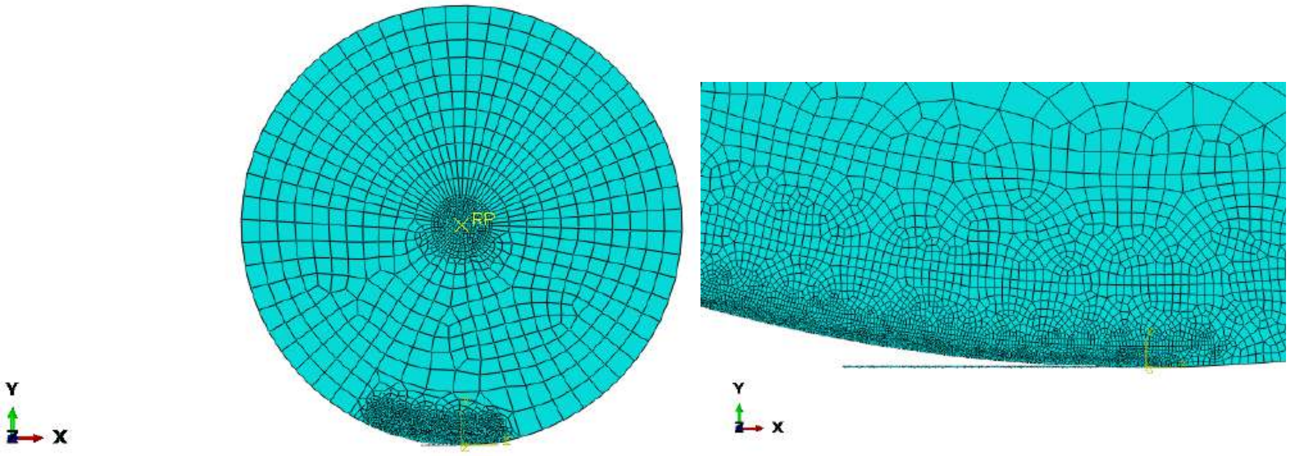


Figure 5. FE model mesh used in the simulations.

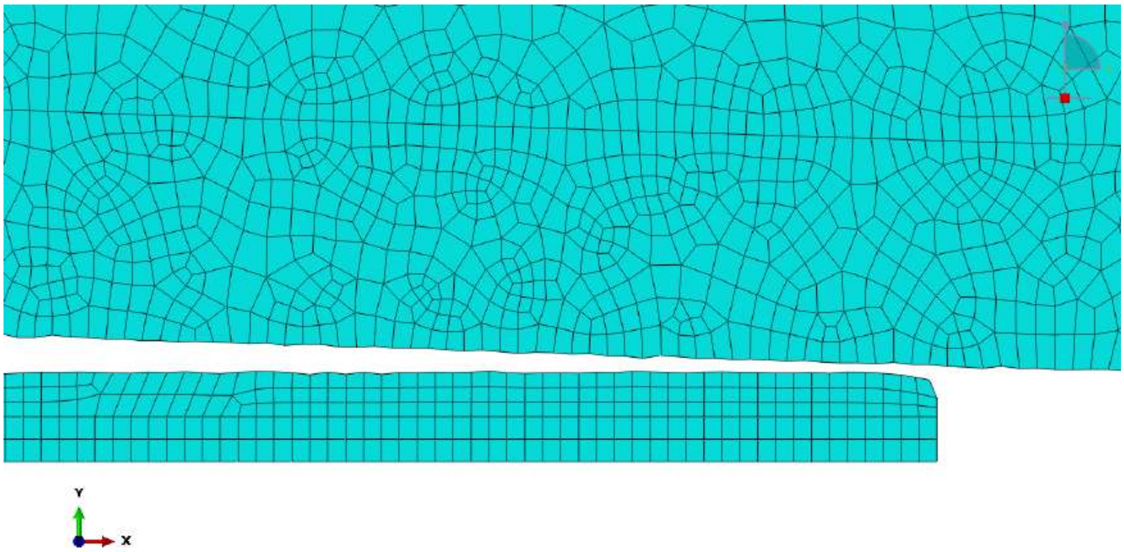


Figure 6. Mesh and asperities modeled both on the roll surface and strip, upper half only.

4. RESULTS AND DISCUSSION

Three cases were run in Abaqus for different roll gaps, and their results are summarized in Tables 5 and 6.

Table 5 – Results from simulations – average roughness, Ra.

Roll gap (mm)	Thickness reduction (%)*	Initial strip Ra (μm)	Roll Ra (μm)	Rolled strip Ra (μm)
0.144	0.07	3.4	4.4	3.3
0.072	1.94	2.8	4.2	2.7
0.036	1.13	3.1	4.1	3.0

* Based on average thickness of the strip.

Table 6 – Results from simulations – peak and valley counts*.

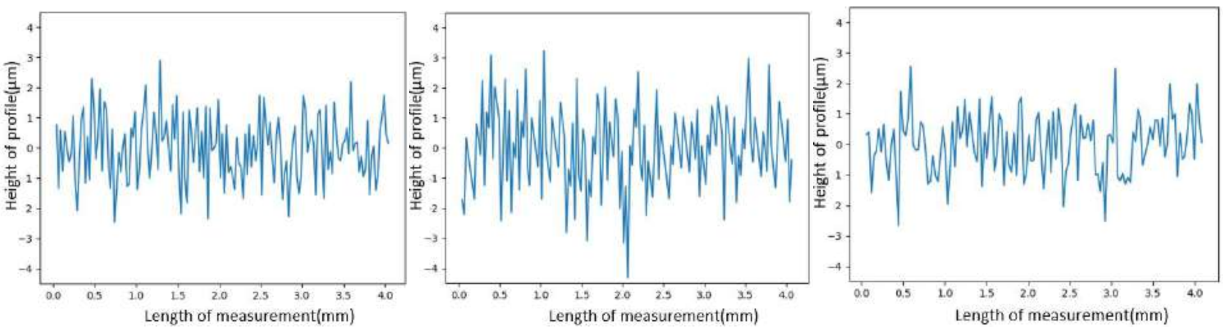
Roll gap (mm)	Peak count before rolling (mm^{-1})	Peak count after rolling (mm^{-1})	Valley count before rolling (mm^{-1})	Valley count after rolling (mm^{-1})
0.144	12.9	11.9	12.3	10.1
0.072	13.2	10.9	12.4	9.5
0.036	13.2	10.5	12.4	8.8

* Peaks are counted for those above the average line, and valley for those below the same line.

The thickness reduction for the case with a gap of 0.144mm was extremely small (of the order of micrometers). In this case, the rolling load was just enough to deform plastically the superficial asperities of the strip. On the other hand, the thickness reduction for the 0.036mm gap was smaller than the one for the 0.072mm gap. It probably happened because of the effect of roll flattening, which may result in less reduction even though the gap is smaller. From Table 5, it can also be noted that the average roughness decreased slightly for all the three cases.

For all the three passes, the peak and valley counts dropped down after rolling, being more pronounced as the roll gap becomes smaller. These results confirm the temper rolling process can make the strip surface smoother.

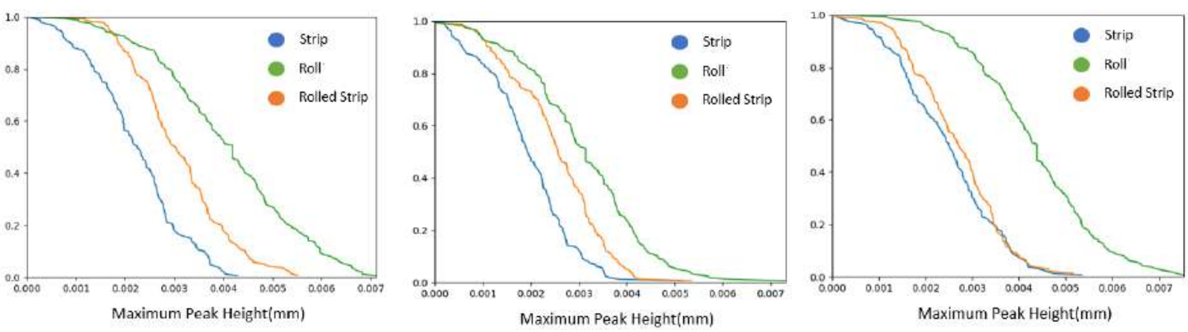
Results of surface roughness for the original strip, roll and rolled strip – for the case of 0.036mm roll gap – are shown in Figure 7. The lengths of measurement are equally positioned for the three readings. It can be seen in the figure that the density of peaks and valleys in the surface of the strip dropped down after temper rolling.



a) b) c)

Figure 7 a) strip roughness profile before rolling (0.036mm), b) roll roughness profile (0.036mm), and c) strip roughness profile after rolling (0.036mm).

In Figure 8, the Abbott curves are plotted for the three reductions, following the same order from left to right. It can be clearly seen that the roll roughness profile is imprinted over the strip surface.



a) b) c)

Figure 8 Abbott curves for a) 0.144mm roll gap, b) 0.072mm roll gap, and c) 0.036mm roll gap.

According to Figure 8, it is clear the effect of roughness transfer especially for the 0.144mm and 0.072mm roll gaps (Figs. 8a and 8b, respectively), but less effect could be noticed for the smallest gap (Fig. 8c), and this result must be studied more deeply.

Figures 9 shows von Mises stresses for the third rolling case, and some red areas can be seen where there is more plastic deformation, probably due to peak shocks.

In Figure 10 are represented the von Mises stresses just for the strip in the arc-of-contact. It is possible to see a very nonhomogeneous stress field inside the strip. Nevertheless, it can be noted that the region with highest von Mises stresses is between the middle and the exit of the arc-of-contact.

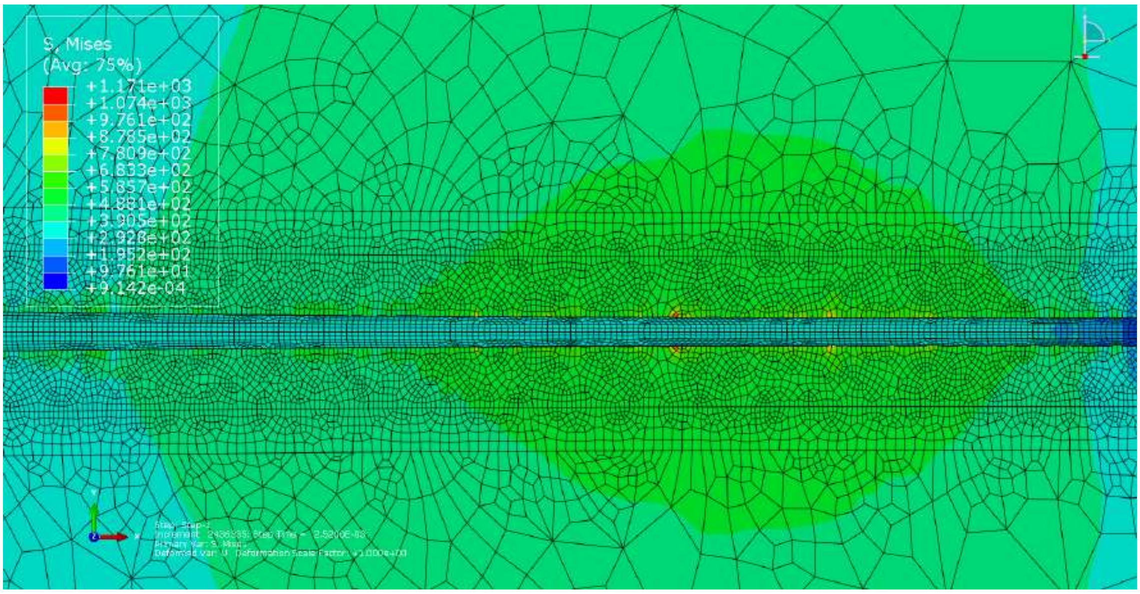


Figure 9 Von Mises stress for 0.036mm roll gap, rolls and strip.

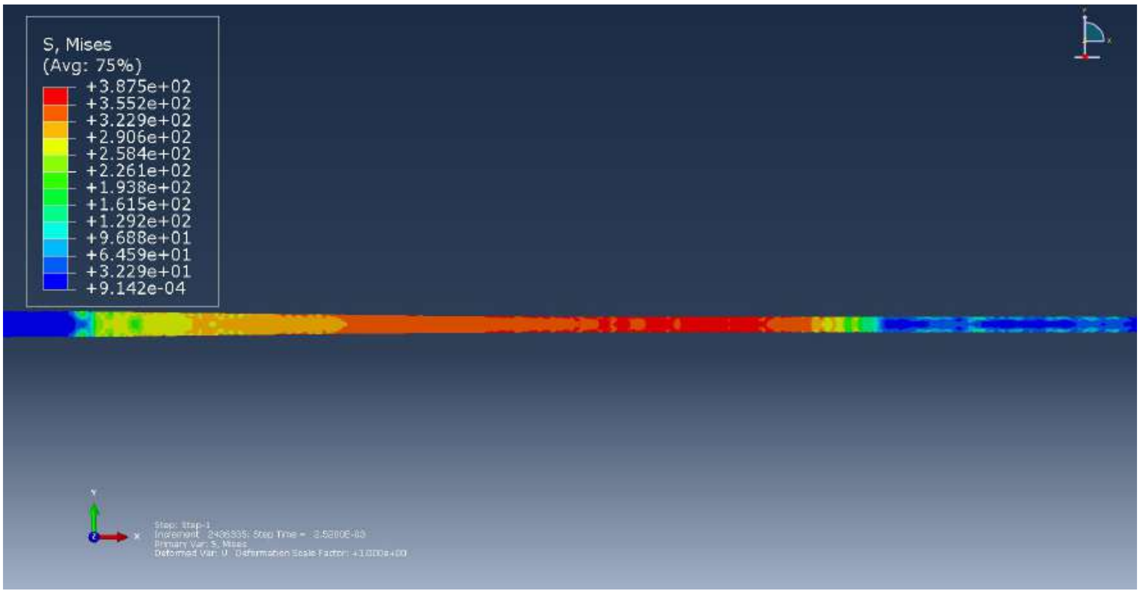


Figure 10 Von Mises stress for 0.036mm roll gap, strip only.

5. CONCLUSIONS

A FE temper rolling model with roll and strip roughness was developed and some tests were made. The rolling process was modelled using plane strain elements for simplicity, elastic rolls and elasto-plastic material for the strip.

A tutorial on how to draw roughness on lines and curves was presented, as its modeling is not trivial due to huge differences of the roll dimension and asperities.

For the three reductions analyzed, we concluded that:

- In general, the number of peaks and valleys dropped in the rolled strip, and the higher the reduction (consequently higher loads), more peaks were cancelled on the rolled strip (Table 6); this result corroborates with Xia et al., (2017), that state that after temper rolling, "high asperities are scrapped and large valleys are increased".
- Average roughness before and after the rolling process were approximately constant (Table 5), but more simulations should be carried out, as these are only preliminary results aiming at developing the FE model;
- Abbott curves show that roll roughness is imprinted over the strip (Fig. 8), though these results should be accepted with caution. The aim of this project till now was to develop a sound FE model for the temper rolling

process including roughness both for the strip and the roll. Some values were chosen from literature for the roughness values only with the purpose of making tests. A design of experiments will be done in the next step;
- The plane strain assumption of the process was adopted for simplification, and it was our objective to detect the crushing and ploughing mechanisms on the surfaces contact. Some stress peaks could be noted in the arc of contact (Fig. 9). Detecting crushing and ploughing mechanisms could not be done until now, but it is being resolved in a near future just capturing more frames or substeps to be plotted in Abaqus;
- Now that the model is running smoothly, we will refine the roughness and develop a sensitivity analysis, for different rolling speeds, work roll diameters and Abbott curves for the rolls, and compare the results with industrial measurements.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE