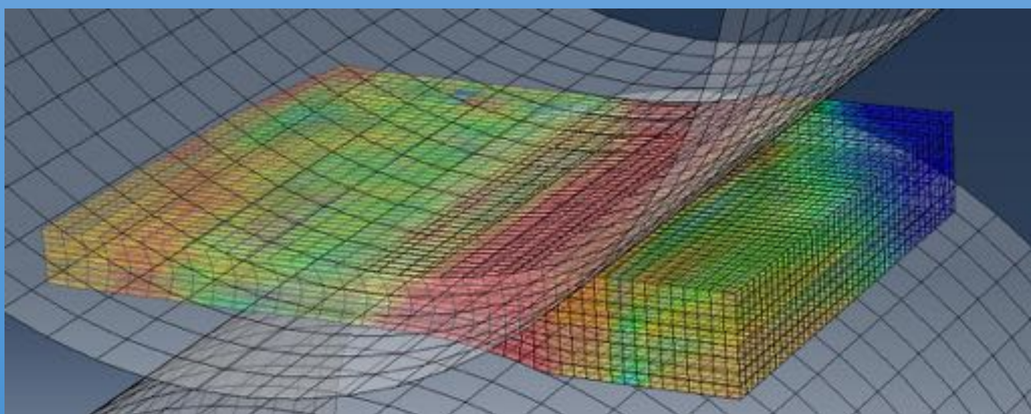

ME 563: Nonlinear Finite Element Analysis

Spring | 2016

A Semester Report on:

The Development and Analysis of Plasticity in Cold Rolling using FEM

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Executive Summary

This report summarizes a semester project on the application of nonlinear finite element methods (FEM) in cold flat-sheet rolling. Cold rolling of sheet metal produces significant plastic deformation. Because of the large plastic deformation, this topic is an example of nonlinearity. This semester project focuses on using Abaqus (FEM) to model and simulate cold rolling processes. By varying parameters associated with the meshing, sheet thickness, rolling speed, and material, a better understanding of plasticity in cold working is obtained. Simulations involving each of the parameters yielded several results that are summarized in this report.

Acknowledgements

We would like to thank our instructor, Dr. Reuben Kraft, for his guidance and instruction. We would also thank the Institute for Cyberscience at The Pennsylvania State University for providing technical assistance.

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Section 1: Background and Project Plan

This project focuses on cold working of sheet metal in rolling processes. During rolling processes, flat plates or sheets are significantly reduced in thickness, which creates large plastic deformation and residual stresses. This topic is an appropriate non-linear problem, because there is large plastic deformation in rolling. This large deformation is nonlinear, especially due to strain hardening.

Cold rolling has great significance for manufacturing. In a cold rolling process, sheets of metal are reduced in thickness at temperatures below the recrystallization temperature. The large deformation (thickness is frequently reduced by 50%) increases the strength through strain hardening. A variety of products such as metal sheets, cans, tubes, and pipes are manufactured with rolling. Because 90% of processed metal involves rolling at some stage, preventing common defects is a priority. Examples of defects include waviness, surface defects, and edge cracking[1]. This project provides a preliminary outlook on how parameters affect rolling processes.

For this project, Abaqus was used to create a model and simulation of rolling. These simulations are used to study parameters that are expected to affect rolling as shown in Table 1. These parameters of interest compose four studies or sets of simulations. For each study only one parameter is altered to isolate the effect that parameter has on the outcome of the simulation.

Table 1: Project Parameters of Interest

	Parameters Changed	Parameters Fixed
Study 1: Meshing	coarse, standard, fine meshing	h_i, RPM, material
Study 2: Initial Thickness	small to large thickness reduction	RPM, meshing, material
Study 3: Rolling Speed	low to high speed	h_i, meshing, material
Study 4: Material	6061-T6 aluminum, 1045 steel, 7030 brass	h_i, RPM, meshing
h_i: sheet thickness (initial) RPM: rotational speed		

For all simulations, three materials were used – 6061-T6 Aluminum, 1045 steel, 7030 brass. Materials properties are shown in Table 2. The rollers used 1045 steel, and sheets used any of the three materials.

Table 2: Material Properties

Material Properties Description							
Material	Density (kg/m^3)	Modulus of Elasticity (GPa)	Poisson's Ratio	Yield Stress 1 (MPa)	Plastic Strain 1	Yield Stress 2 (MPa)	Plastic Strain 2
Aluminum 6061 T6	2700	69	0.33	27.5	0	27.5	0.025
1045 Steel	7850	205	0.29	53	0	53	0.05
Brass 7030	8530	110	0.331	40	0	40	0.035

Section 2: Development and Description of the CAD Geometry

A CAD model that describes the model was produced as shown in Appendix A. This basic SolidWorks CAD model was then imported into Abaqus as shown in Figure 1 and Figure 2. In Figure 1, the roller and sheet are together in an assembly. The roller has a diameter of 2 meters and a length of 2.5 meters. The sheet has a length of 2 meters and a width of 0.5 meters. The thickness of the sheet is varied depending on the simulation.

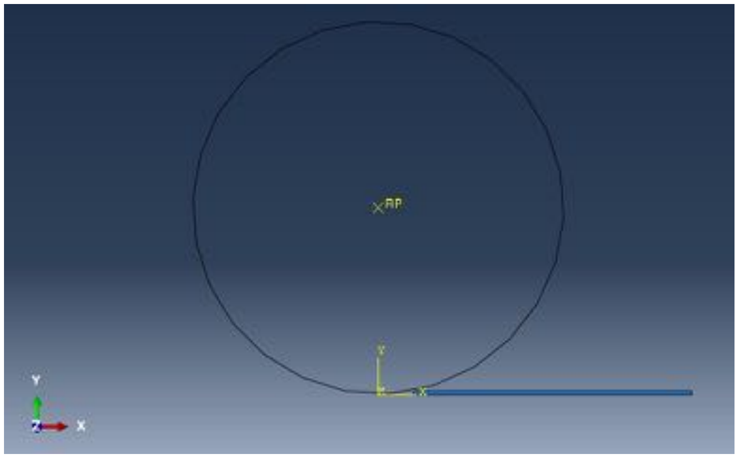


Figure 1: Basic CAD Model of Rolling Process

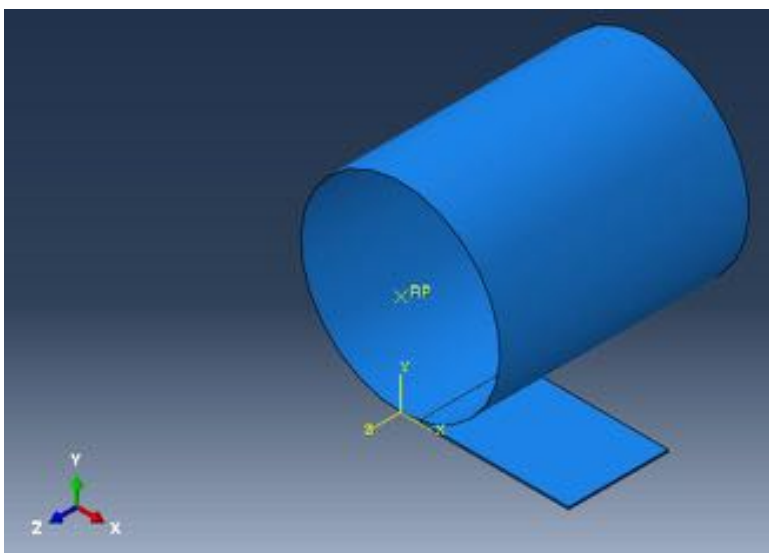


Figure 2: Roller and Sheet Isometric

The roller is hollow and is defined as non-deformable. To lower the computing demand of simulations, only the top half of the rolling process is simulated or modeled. The assembly is mirrored to produce the full-scale process. In each simulation, the sheet thickness is reduced to a thickness of 1 cm. To represent this thickness, 1 cm of space separates the rollers. The initial thickness of the sheet (before deformation) was varied from 2 cm to 6 cm when studying the effect of initial thickness. For simulations involving other parameters, the sheet thickness was 4 cm.

Section 3: Development of Finite Element Meshes

For the simulations that were completed, different mesh sizes were used. In Study 1, mesh size was the parameter of interest. Study 1 used three different mesh sizes– coarse, standard and fine. In Studies 2, 3 and 4, only the standard mesh size was used. These mesh sizes are described in Table 3. In general, meshes created by first applying a global seed size. A lower global seed size corresponds to a finer mesh. To make the sheets have more elements with respect to the sheet thickness, the mesh layers were added. The mesh thickness represents the number of mesh layers along the thickness. Higher mesh thickness means the sheet thickness was divided into more layers of elements. For instance, a mesh thickness of 1 corresponds to the half model having one layer of elements. The full mirrored model then has two layers of elements across the thickness. Hexahedral elements were used for the sheets. For the roller, all simulations had a single roller mesh. The roller mesh had a global size of 0.1.

Table 3 Mesh Description for the Sheet

Mesh Type	Mesh Thickness	Mesh Global Size
Coarse	1	.05
Standard	2	.0125
Fine	3	.00625

Through trial and error, these meshes were selected. The coarse mesh was chosen as a minimum of what could be used. Coarser meshes were quickly produced, yet their jagged output led to flawed results. The standard mesh gave better results using a reasonably amount of computing time, and the fine mesh, having significantly more elements, required hours more to simulate. Simulations with the fine mesh required approximately 24 hours. This time could have been reduced if the meshes were optimized or had fewer elements. Reducing the number of mesh layers around the thickness would help, but it would also make it difficult to observe the deformation. Examples of the meshes are shown in Figures 3 through 7.

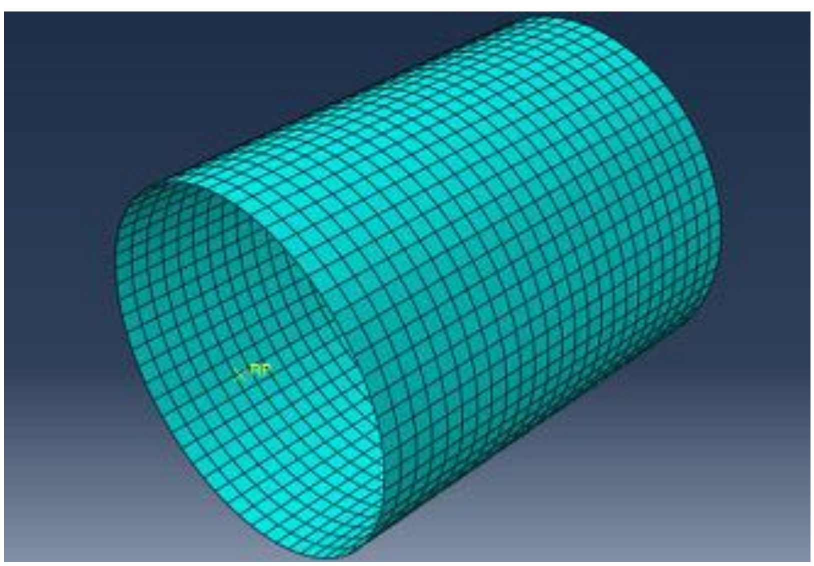


Figure 3: Roller Mesh

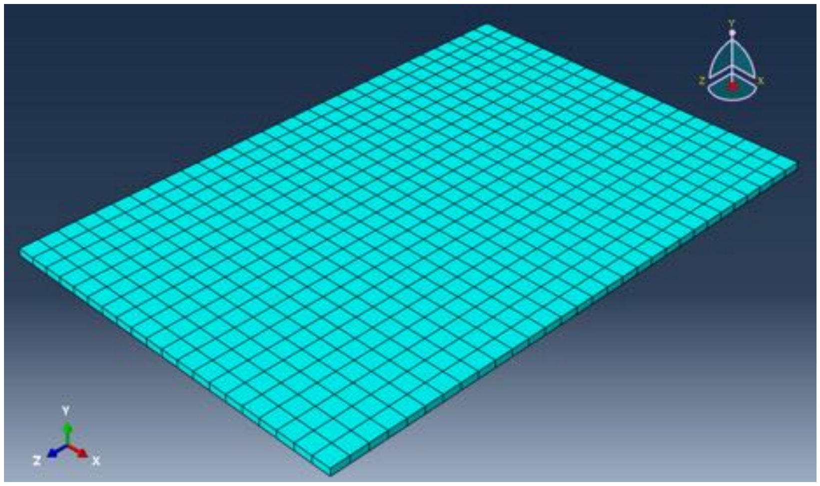


Figure 4: Coarse Mesh

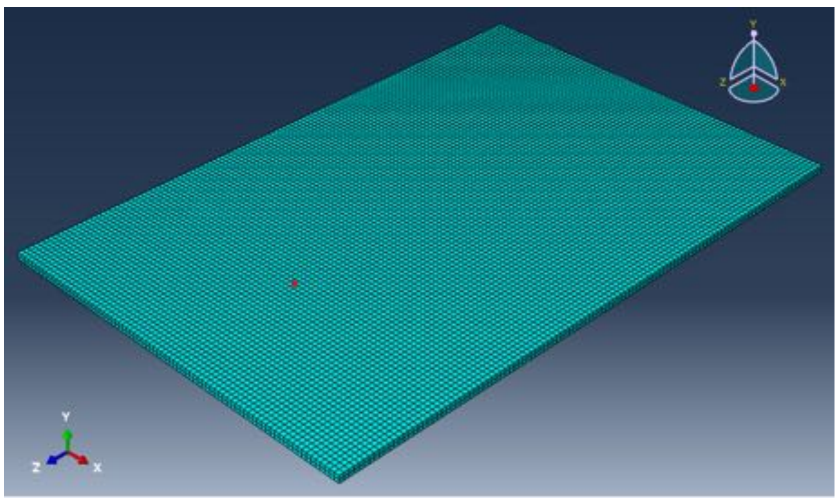


Figure 5: Standard Mesh

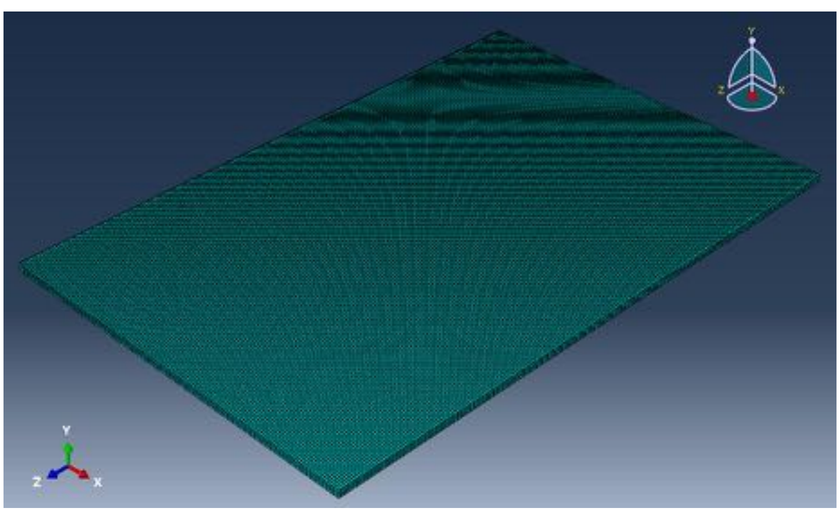


Figure 6: Fine Mesh

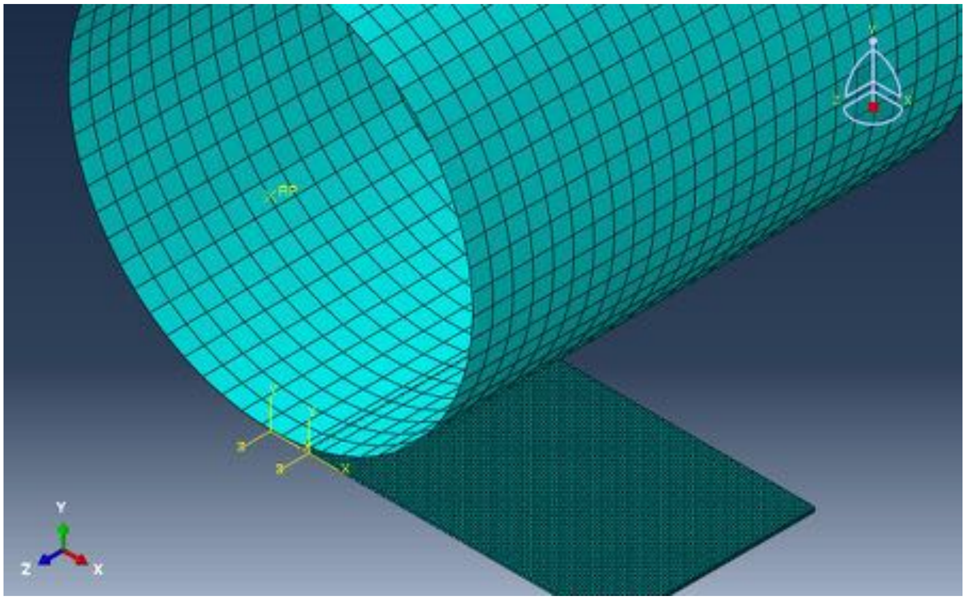
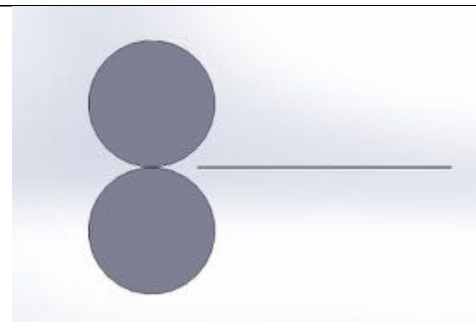


Figure 7: Assembly of Meshed Components

Section 4: Development and Description of the Model Assembly and Boundary Conditions

A model assembly with the boundary conditions corresponding to a rolling process was developed using Abaqus. The model assembly was constructed using symmetry. Only the top section of the rolling process was simulated (one roller and half-sheet). This top section and the subsequent results were mirrored to produce the full assembly as shown in Table 3. Using symmetry simplifies the boundary conditions and reduces each simulation time.

Table 3: Description of Assembly Model

Actual Half-Simulation	Mirrored Results
	

In the Abaqus, four sets of boundary conditions and a predefined field were applied. The first boundary condition was to fix the rollers on an axis of rotation and make the rollers rotate counter-clockwise at a given angular speed. This angular speed was set to match the speed at which the sheet is fed into the roller. Given the roller has a radius of 1 meter and that the tangential velocity of the roller's outer radius should be equal to the sheet's velocity, one can determine the required angular velocity. These boundary conditions for the roller were added in Abaqus as shown in Figure 8 and Figure 9.

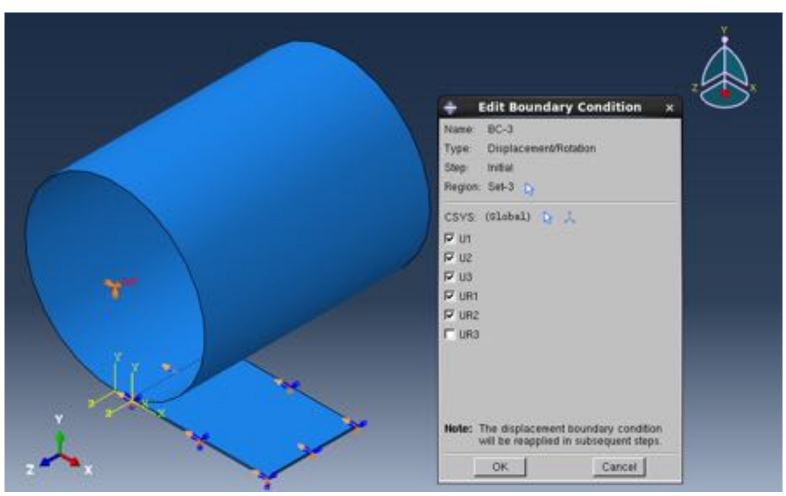


Figure 8: BC-1 for Fixed Axis of Roller Rotation

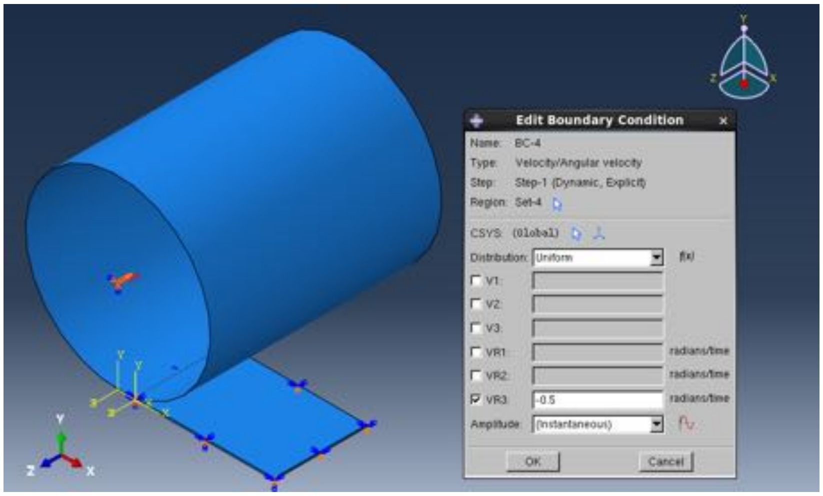


Figure 9: BC-2 for Angular Velocity of Roller

For the sheet, the following boundary conditions and pre-defined field were added. To reflect the symmetry of the half model, the bottom face of the sheet was made as if it were on a rolling surface. This boundary condition for symmetry, as shown in Figure 10, restricts the bottom face from y-displacement while allowing other displacement. Another condition was added to make the sheet pass straight through the rollers. This boundary condition, as shown in Figure 11, fixes the middle of the plate so that it will follow a straight path. A predefined field was lastly added to make the sheet translate towards the roller, as shown in Figure 12. For this example, the sheet's initial velocity is approximately 0.5 m/s.

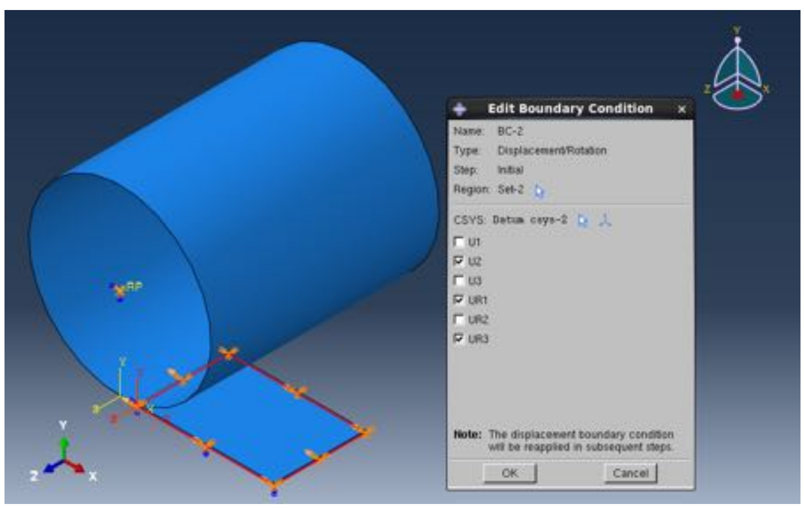


Figure 10: BC-3 for Fixing Sheet Symmetry

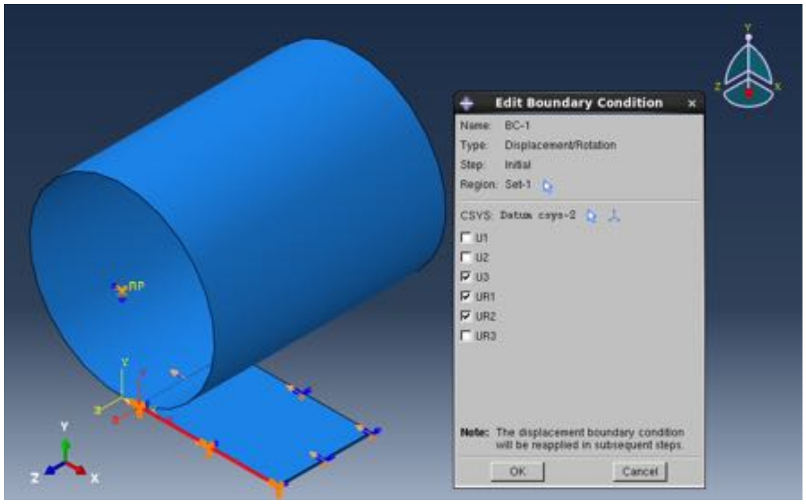


Figure 11: BC-1 for Fixing Sheet Edge

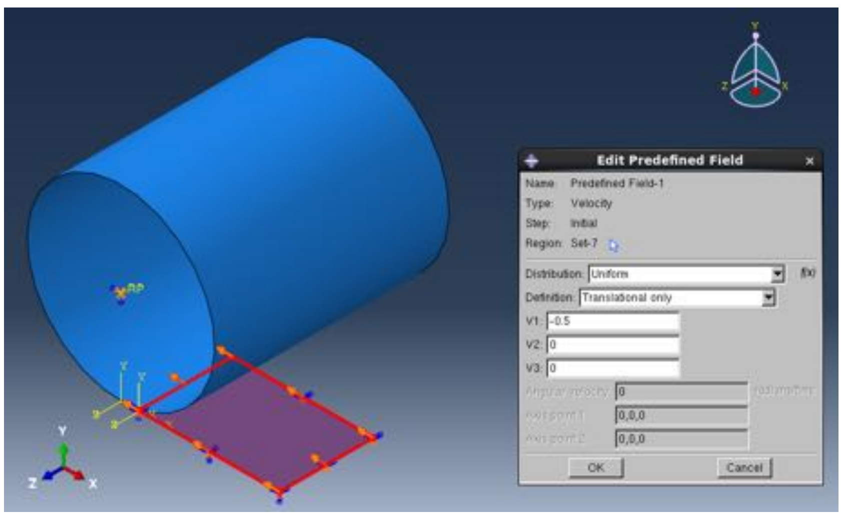


Figure 12: Predefined Field 1 for Sheet Velocity

Section 5: Development and Description of Model Interactions

Model interactions were implemented in Abaqus. For the contact interaction between the sheet and roller, a surface-to-surface contact was placed, as shown in Figure 13. The friction component was set as a penalty friction, and the normal component was set as a hard contact. The coefficient was varied during prototyping simulations (from 0 to 0.3). Adding friction significantly increased the simulation time, so for all of the final simulations, the friction coefficient was set to 0.1.

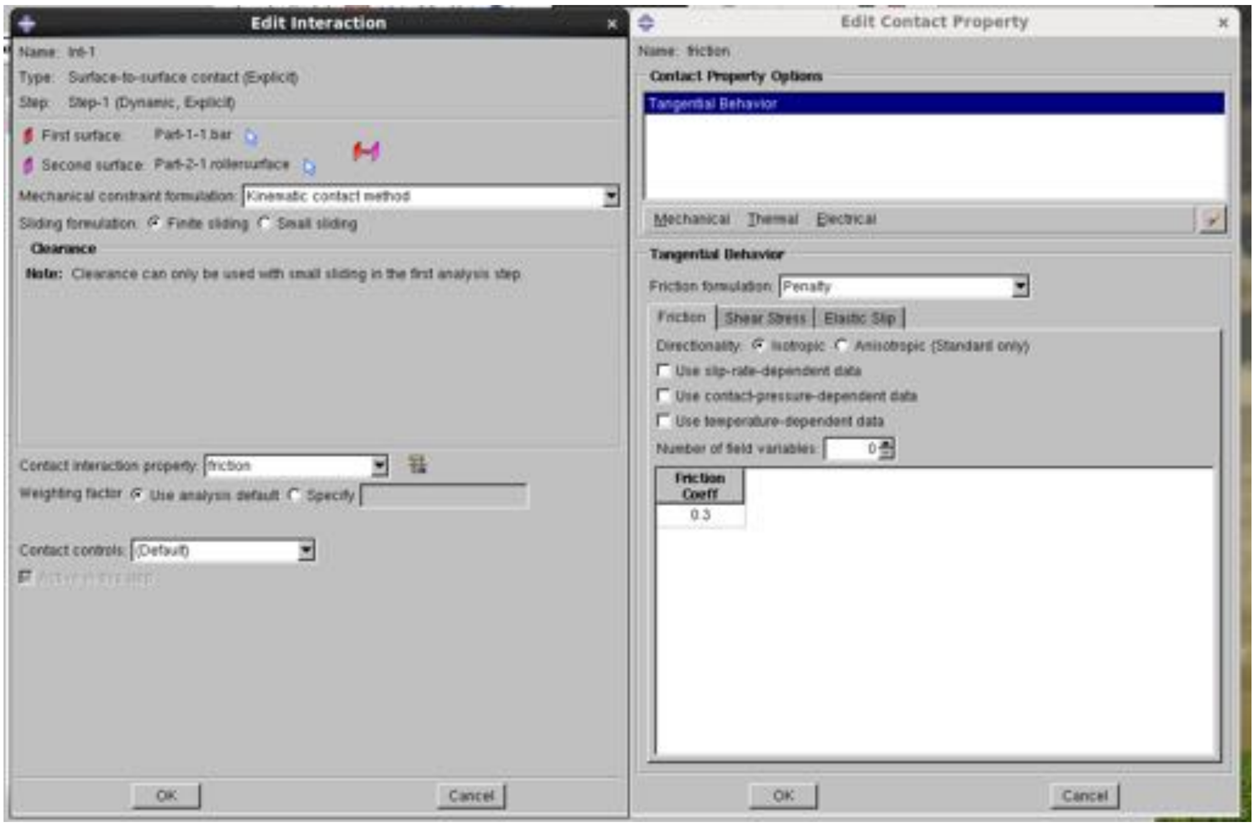


Figure 13: Contact Interaction Details

Section 6: Analysis of Finite Element Model

The finite element model was examined using 14 simulations that were separated as shown in Table 4. More information regarding these simulations or jobs can be found in Table 5. For these models and simulations, an explicit step will be used. The step was 2 seconds long and was divided into 50 intervals. Each time increment was then 0.04 seconds. During prototyping of simulations, the time step was intended to have a longer duration and a greater number of intervals; however, the time required to run all of these simulations required a scale back. The explicit step used in these select simulations is sufficient enough to show the sheet undergoing plastic deformation.

Table 4: Summary of FEM Simulations

Study 1: 3 meshing simulations
Study 2: 5 thickness simulations
Study 3: 3 rolling speed simulations
Study 4: 3 material simulations

Table 5: Detailed Description of FEM Simulations

Meshing Simulations	Job 1	Coarse mesh
	Job 2	Standard mesh
	Job 3	Fine mesh
Initial Thickness Simulations	Job 4	2 cm sheet thickness
	Job 5	3 cm sheet thickness
	Job 6	4 cm sheet thickness
	Job 7	5 cm sheet thickness
	Job 8	6 cm sheet thickness
Rolling Speed Simulations	Job 9	0.25 m/s feeding speed
	Job 10	0.50 m/s feeding speed
	Job 11	1.00 m/s feeding speed
Material Simulations	Job 12	6061-T6 Aluminum
	Job 13	1045 Steel
	Job 14	7030 Brass

<u>Initial Simulation:</u>

Preliminary results from prototype in Abaqus produced results following expectations. Figures 14 through 19 show the sheet at progressive stages of plastic deformation. In Figure 14 (time = 0 s), the sheet is about to make contact with the rollers. In Figure 15 (time = 0 s), the roller visualization has been suppressed to better show the sheet deformation. Figures 16, 17, 18, and 19 then show the Von Mises stress and deformation as the step time increases.

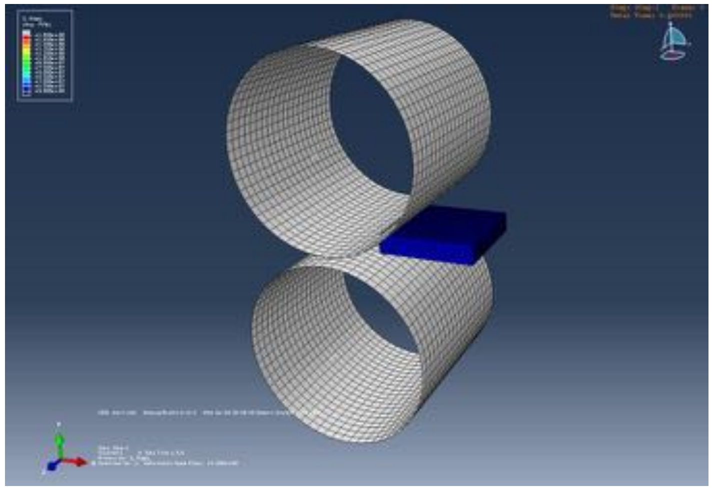


Figure 14: Undeformed Rolling Model in Abaqus

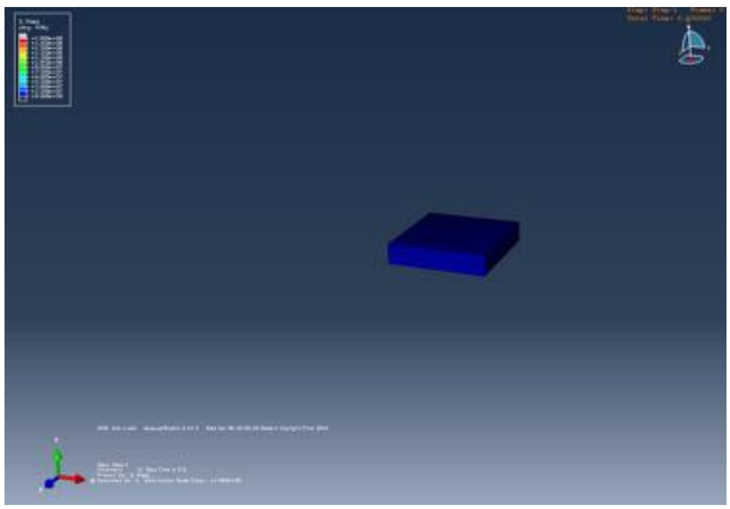


Figure 15: Undeformed Rolling Model in Abaqus (without rollers)

In Figure 16 (time = 0.5 s), the front region of the sheet is making contact with the rollers and is being deformed. The stresses have not propagated to the rear region of the sheet, which makes sense because the sheet is very long. In Figure 17 (time =1.0 s), more of the sheet has passed through the rollers and is deformed. The stresses are rising throughout the sheet. In Figure 18 (time =1.5 s), the front of the sheet is further away from the rollers, yet it still has residual stresses from deformation. In addition, even the rear of the plate has some Von Mises stress. In Figure 19 (time = 2.0 s), the highest stresses are at the point of contact with the rollers. The front region that has already passed between the rollers has lower residual stresses in comparison, and the rear region continues to be stressed even before reaching the rollers.

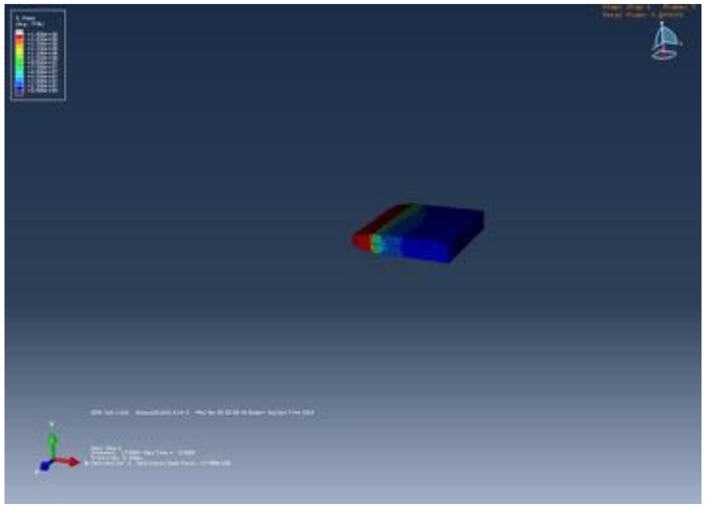


Figure 16: Rolling Response (time = 0.5 s)

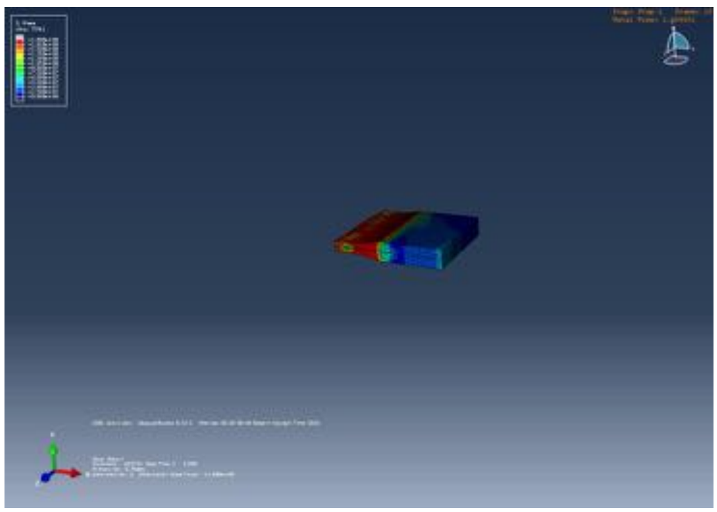


Figure 17: Rolling Response (time = 1.0 s)

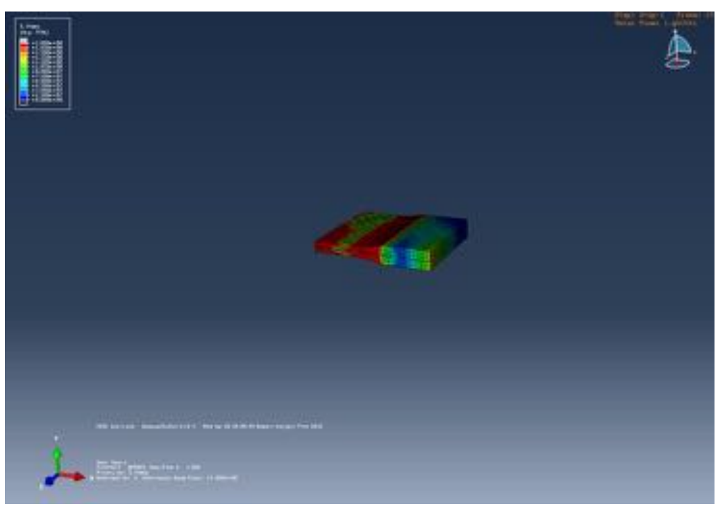


Figure 18: Rolling Response (time =1.5 s)

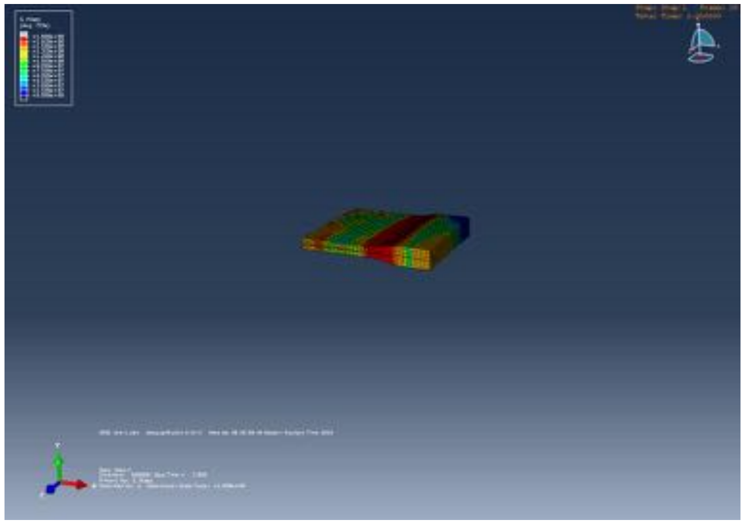


Figure 19: Rolling Response (time =2.0 s)

This initial simulation meets expectations. As the sheet progresses, its thickness gradually decreases, and the sheet narrows and elongates in conjunction. This type of deformation shows how material is being spread. The Von Mises stresses also act accordingly. When the rear region of the sheet is far from the rollers, the stress is low. As the material approaches the roller, the stress increases, and then afterwards, a portion of the stress remains due to plastic deformation.

<u>Study 1: Meshing</u>

Results from meshing simulations in Abaqus show a gradual improvement in the FEM results. In Figure 20, the response of the coarse mesh simulation show irregularities. Because there are too few elements, the deformed elements have jagged edges. The distribution or gradient of the Von Mises stress is also poor.

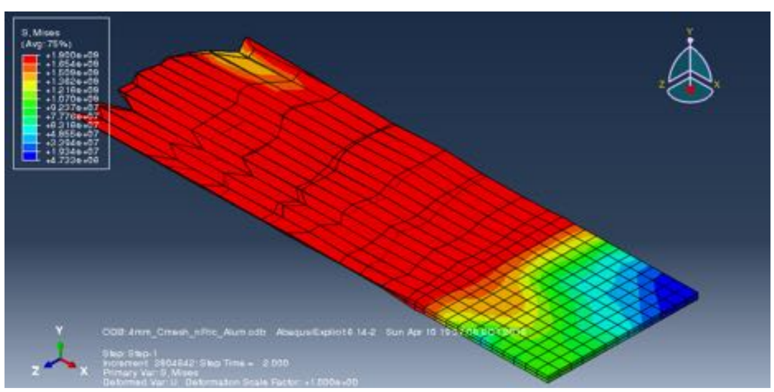


Figure 20: Coarse Rolling Response (time =2.0 s)

In Figure 21, the response of the same sheet with a standard mesh is shown. In comparison to the coarse results, these results are more realistic. Each of the elements is not overly deformed (meaning few irregularities), and the Von Mises stress shows a more gradual gradient. In addition to being more gradual, the standard mesh model has less stress over prediction. The coarse model has peak stress values of approximately 1900 MPa, whereas the standard mesh predicts a more realistic 180 MPa. Given time to optimize a finer mesh, results could converge to realistic values.

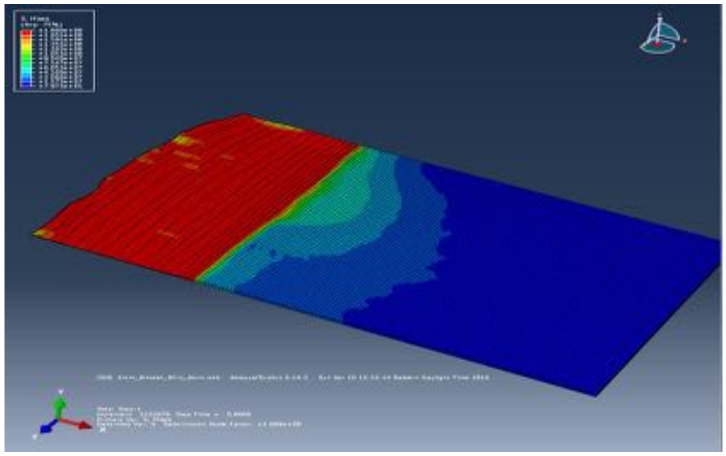


Figure 21: Standard Rolling Response (time = 0.8 s)

Study 2: Initial Thickness

Results from initial thickness simulations in Abaqus indicate that larger thickness has negative effects on the rolling process. The larger thickness (or equivalently, larger reduction) causes the deformed sheet to have more waviness. This waviness is shown well in Figure 22 and Figure 23. In Figure 22, the response of a sheet with a 3 cm initial thickness is shown. In Figure 23, the response of a sheet with a 5 cm initial thickness is shown. Looking at just the Von Mises stress, their responses are similar. For both thicknesses, the peak stress and minimum stress are of the same order of magnitude. The stress gradient is also similar (relatively uniform before and after the roller).

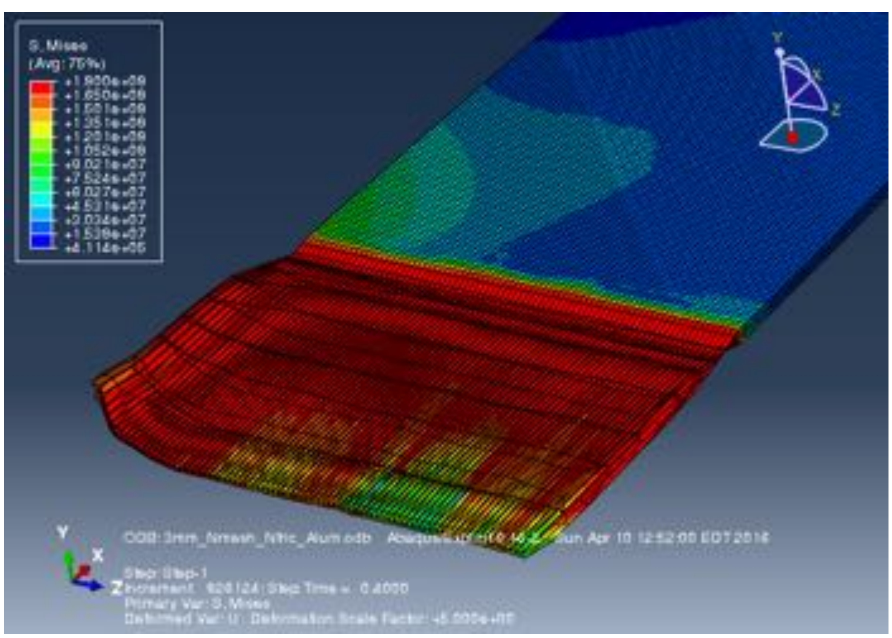


Figure 22: 3 cm Thickness Rolling Response (time = 0.4 s)

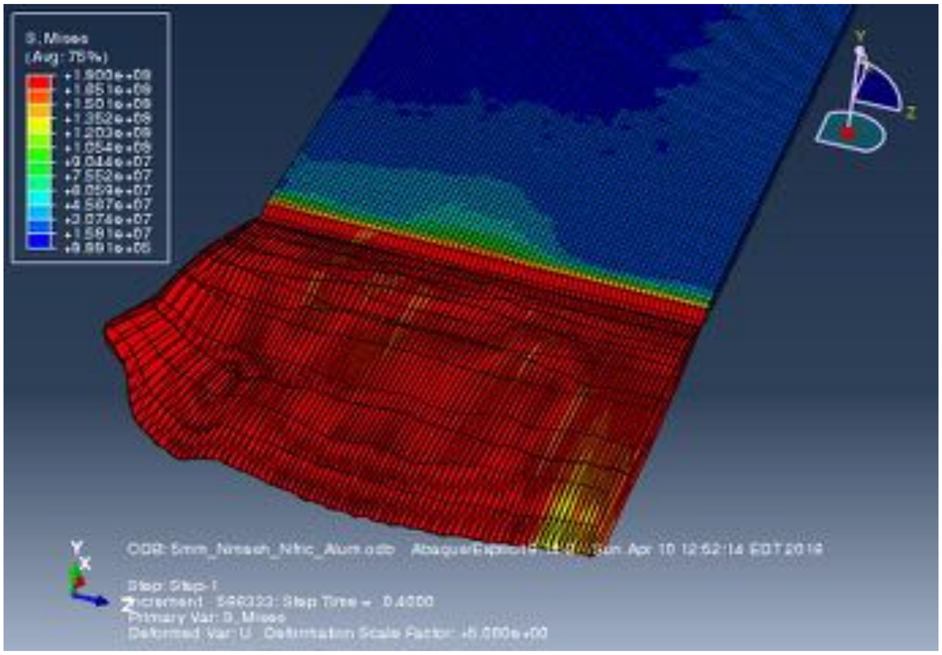


Figure 23: 5 cm Thickness Rolling Response (time = 0.4 s)

The amount of deformation though is different. The thinner sheet has less elongation, whereas the thicker sheet has more elongation. The thinner sheet also shows less waviness around its edges. To examine this waviness more closely a waviness plot was created as shown in Figure 25. The waviness plot follows elements across the leading edge, as shown in Figure 24.

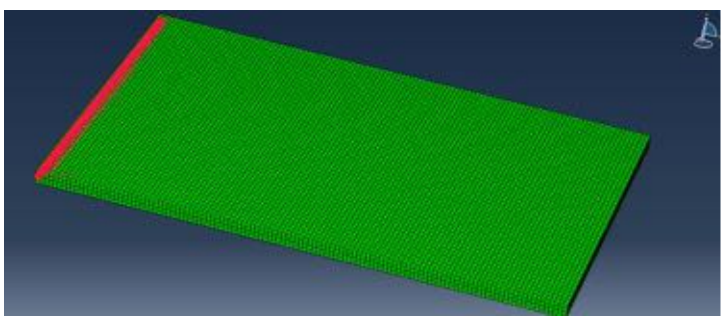


Figure 24: Waviness Path (leading edge of sheet)

One axis of the waviness plot shows each element's distance from the sheet edge. The other axis shows how far each element has been displaced after 0.40 seconds. The waviness plot for these simulations indicates that a lower initial thickness is preferable. As thickness increases, the displacement in the x-direction (direction the sheet is pushed) varies more significantly. Regardless of thickness though, elements near the outer edge deviate.

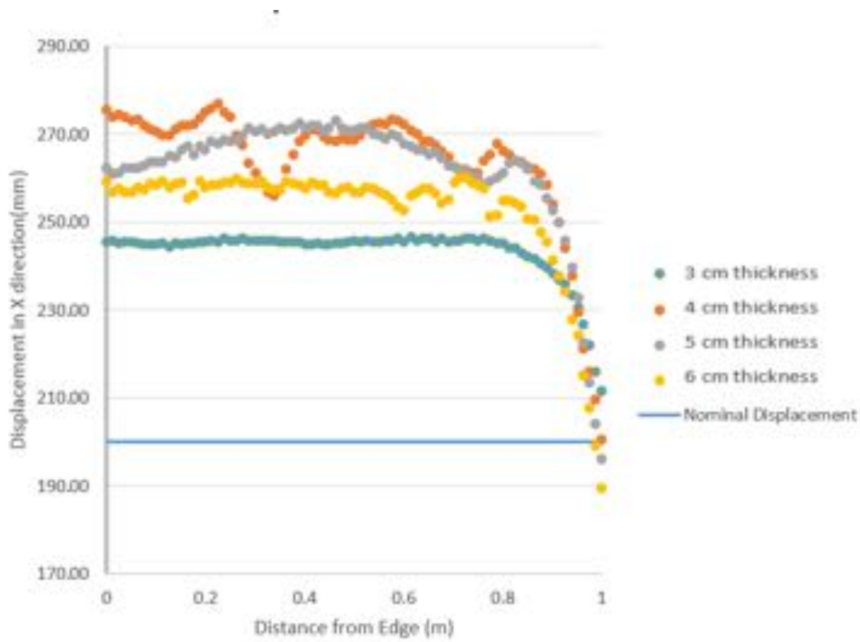


Figure 25: Waviness Plot of Rolling Response for Thickness

Another effect of changing thickness is the overall elongation. The nominal displacement line represents how far the elements would travel without deformation (i.e. no roller contact). As thickness increases, the general displacement or elongation increases. This increase in elongation is realistic because each deformation has a final thickness of 1cm regardless of initial thickness. The added elongation stems from more material with increasing thickness.

Study 3 Rolling Speed

Results from rolling speed simulations in Abaqus indicate rolling speed causes few changes in the response. As rolling speed is increased from 0.25 m/s to 1 m/s, both the waviness and stress distribution remain the same. Examples of rolling speed are shown in Figures 26, 27, and 28. In these examples, the stress distribution similar to aforementioned simulations. The peak or minimum Von Mises stress does not change.

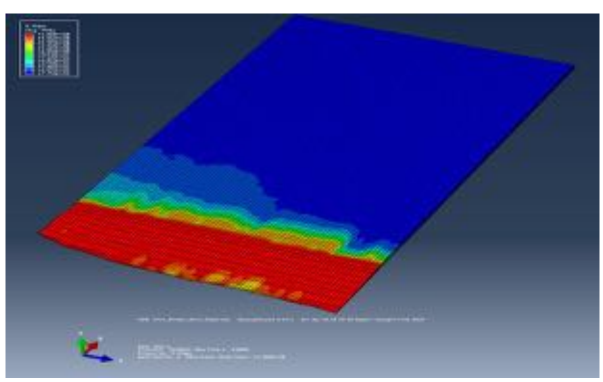


Figure 26: 0.25 m/s Rolling Response (time = 0.8 s)

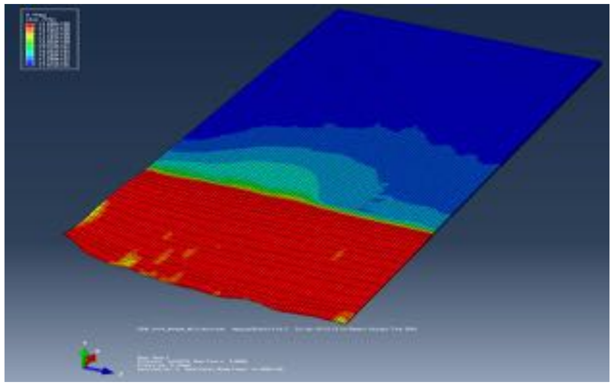


Figure 27: 0.50 m/s Rolling Response (time = 0.8 s)

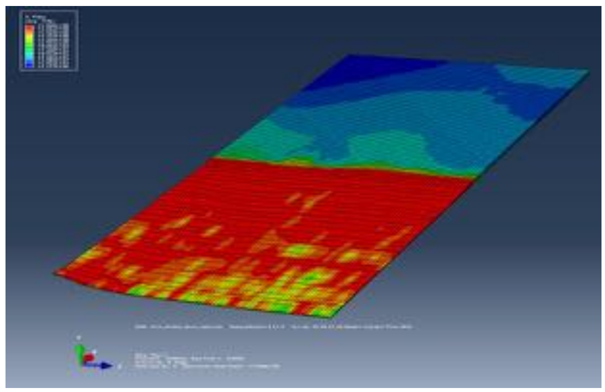


Figure 28: 1.00 m/s Rolling Response (time = 0.8 s)

In addition to the stress being the same, each simulation has similar waviness, as shown in the waviness plot of Figure 29. This waviness plot uses the path previously shown in Figure 24. The plot shows that changing rolling speeds has minor impact on how the displacement varies. Changing the rolling speed seems to only increase the average displacement.

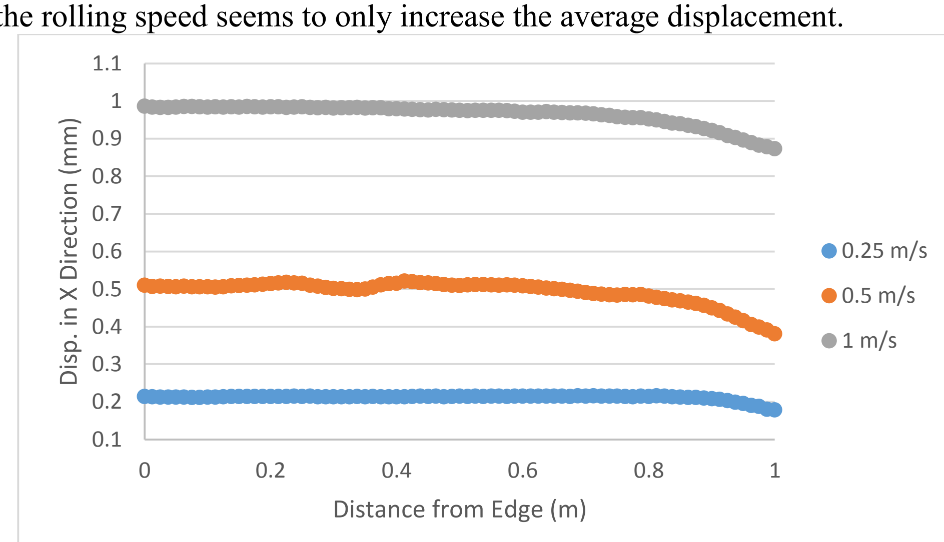


Figure 29: Waviness Plot of Rolling Response for Rolling Speed

Study 4: Material

Results from material simulations in Abaqus indicate that material properties affect the rolling process as expected. Figures 30, 31, and 32 show the response of sheets made of red brass, aluminum, and steel. By changing material, the sheet's density, elasticity, and plasticity were altered. The simulation results show that none of the materials are desirable in these rolling conditions.

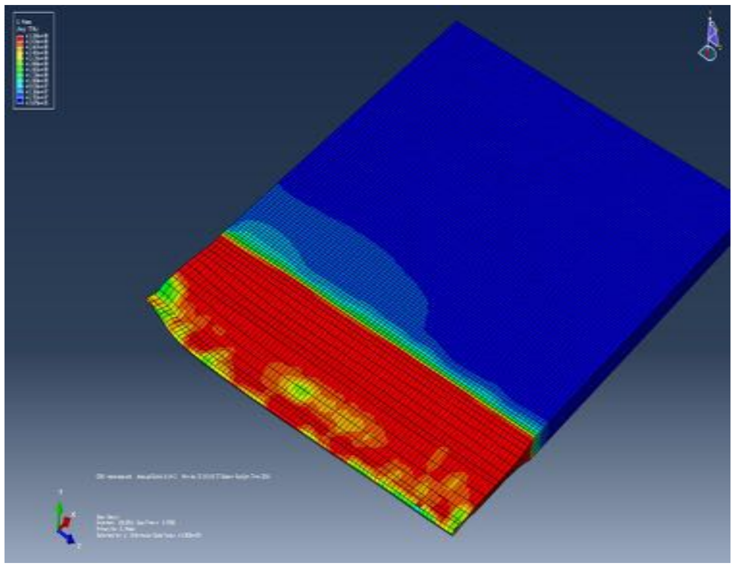


Figure 30: Red Brass Rolling Response (time = 0.7 s)

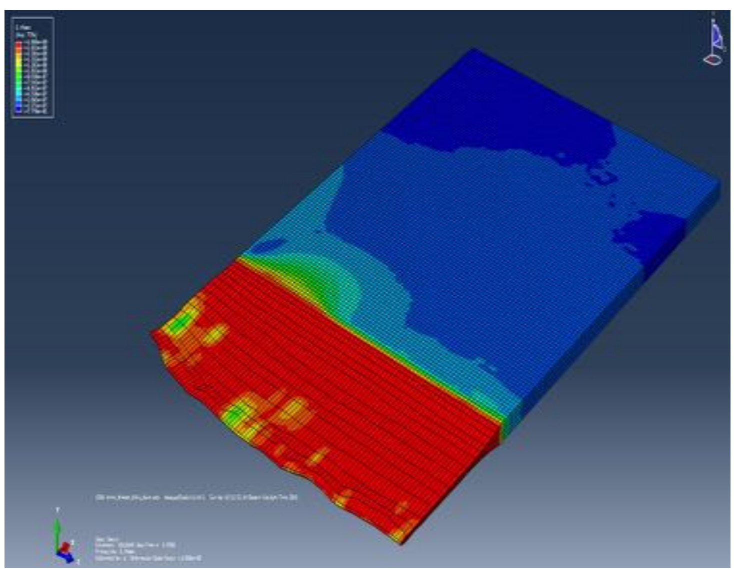


Figure 31: Aluminum Rolling Response (time = 0.7 s)

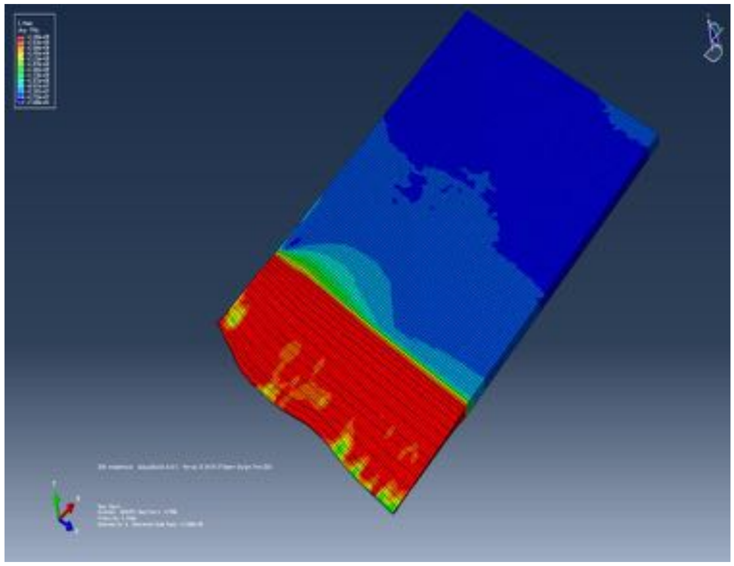


Figure 32: Steel Rolling Response (time = 0.7 s)

For instance, the waviness plot, as shown in Figure 33, suggests that the brass sheet had the least amount of waviness. It also shows that aluminum deforms or elongates the most, which is realistic because aluminum has the lower modulus of elasticity. Given this information, one would select the aluminum sheet for elongation, and one would select the brass sheet for its lack of waviness.

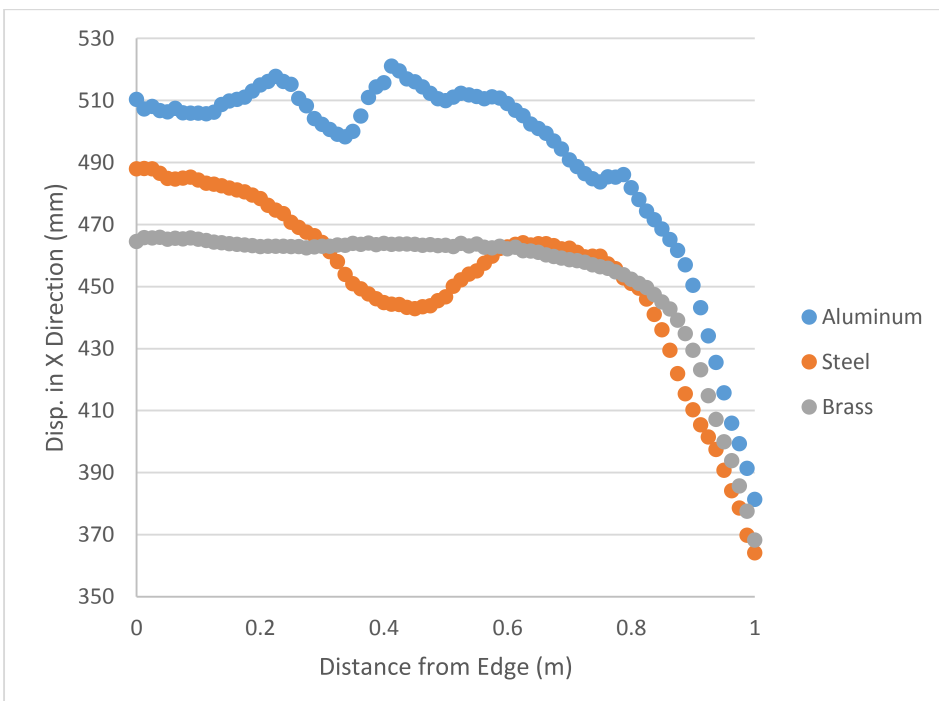


Figure 33: Waviness Plot of Rolling Response for Material

In addition to deformation, the material simulations also yielded different stress levels of stress. In Figure 34, a path of elements was chosen through the middle of each sheet. The Von Mises stress and location of each element (with respect to the leading edge) was plotted as shown in

Figure 34. All of the materials have a similar stress plot. At the leading edge, the residual stresses from plastic deformation are uniformly high. At the rolling contact, the stress has a discontinuity and decreases significantly. The stress then gradually decreases. This stress distribution or general pattern does not change for material, yet the magnitude of stress does. In the higher stress region, the steel and brass sheets have stress results that are twice the magnitude of the aluminum.

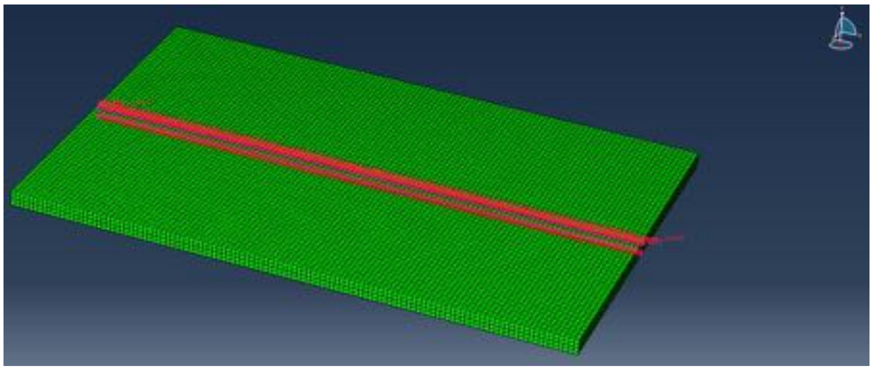


Figure 34: Path Description

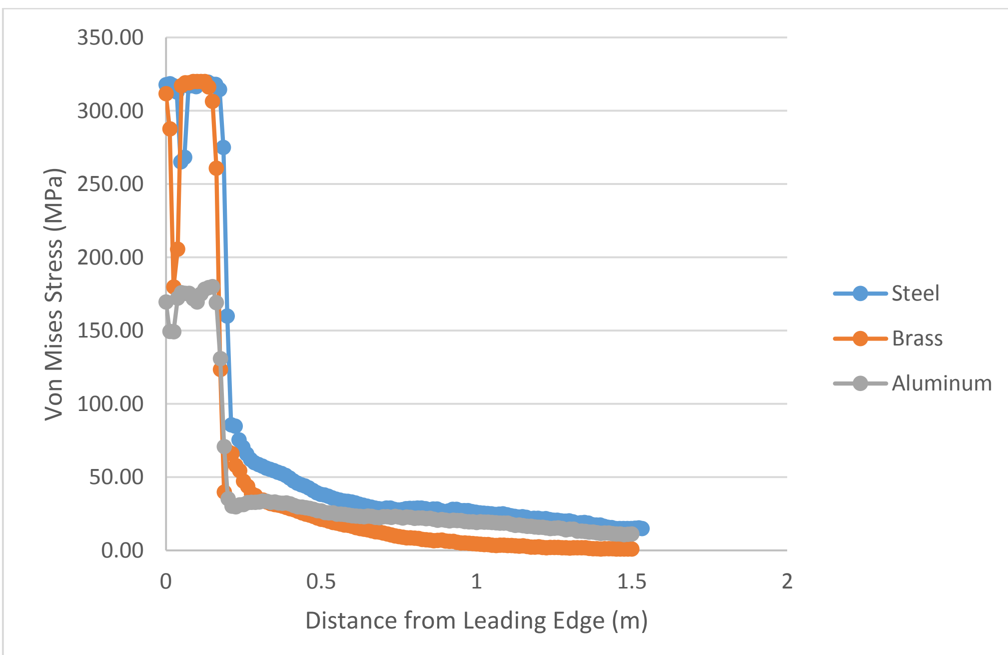


Figure 35: Stress Plot of Rolling Response for Material (time = 0.7 s)

These simulations show that the material properties affect the amount of stress and deformation that occurs. Aluminum has lower elasticity and yield stress, so it deforms more and has lower stresses.

Section 7: Summary of Major Findings

These simulations using Abaqus show the aforementioned parameters have different effects on rolling processes. The sheet thickness and material properties have the larger impact. As sheet thickness is increased, the deformed sheet has more waviness defects and a greater elongation. In industry standard practice dictates that thickness reduction should be no more than 50%, which is confirmed with these results. In general, the brass and steel sheets have higher Von Mises stress than the aluminum, and brass has the least amount of waviness. Aluminum is suitable for sheet rolling because it elongates significantly and has lower residual stresses. Unlike sheet thickness and material properties, rolling speed has less significance besides changing the rate of rolling.

For future work, these simulations could be improved and made more realistic. One common issue in rolling is vibration. Chatter and roller movement can cause waviness, so implementing simulation with vibration would be beneficial. Another issue with this work is temperature change. These simulations assume temperature is constant; however, even in cold rolling, temperatures change and cause material properties to deviate. Lastly, this work did not fully investigate the impact of lubricants and friction. A more advance model could account for friction and the movement of lubricants in cold rolling.

Section 8: Works Cited

1. Manufacturing Processes for Engineering Materials, 5th Edition
   Kalpakjian, S., and S. Schmid: Prentice Hall, NJ 2001

2. Abaqus (Dassault Systemes)

Appendix 1: Rolling Process CAD Drawing