DESIGN AND MANUFACTURING OF A PLASTICINE ROLLER

Jonathan Wong, Dixun Cui, Cristian Licona, Lawrence Guo
UC Berkeley Mechanical Engineering Department

ABSTRACT

This project examined the optimization of the design of a rolling machine. Often used as hot rollers for rolling steel, other applications include cold rolling, and rolling of other materials in various industries [5]. In such a machine, many factors must be considered including, but not limited to: the load force necessary to deform the material, the strength of the machine, and cost of parts in material selection and manufacturing [6]. To examine the roller, a scaled down model of a hot strip mill was developed. Calculations and simulations were performed to generate final conclusions. It was found that the hot rolling machine can be scaled down to a machine capable of deforming plasticine. It was also found that in the design of such a machine where cost and weight are minimized, the maximum stress occurs in the top of the frame, which must be accounted for in the design.

I. Introduction

Hot strip rolling machines' primary function is to reduce the thickness of a slab of metal. These slabs, which are primarily steels, are heated to approximately 1260°C. As the steel is heated, it becomes less resistant to deformation, softening and becoming easier to work with. The steel is then pushed through two horizontal rollers, and the desired thickness is achieved gradually with smaller heights being used between the rollers [4]. The slab can be passed through several rollers with gradually decreased heights, or passed back through the original roller multiple times with decreasing height. Walls or rollers on the sides maintain a desired width, and force the slab to become thinner and longer with each pass due to conservation of volume.

The rolling machine (as shown in Figure 1) must operate at a high rate of power and exert a lot of force to flatten steel at 1200C. The length of the roller is about 1440 mm and the diameter ranges between 720-780 mm. It can operate at about 370 meters per minute exerting a rolling force of 12,000 kN. The strips are fed and reeled by a tension reel motorized by two 346kW DC motors and the final strip dimensions ranges between 320-500 mm and .2-4 mm in strip width and thickness. In order to better understand rolling machines and how to optimize their design, they can be scaled down and tested [9].

Figure 1. 1300mm 2-hi Reversing Skin Rolling Mill

In selecting our rolling material, we chose plasticine because their dynamic properties of plasticine are very similar to steel at high temperatures [1]. It does not dry or harden unlike other modelling medium which makes it an optimal material for simulation.

II. Experiment

a. Preliminary Design

Our preliminary machine (Figure 2) was made from FDM 3D printed PLA scaled down 40% from our final prototype for a concept and feel for what we needed to do. The preliminary machine was printed before the processes and materials were chosen.

Figure 2. Rolling machine prototype (3D printed)

The first step was to redesign the roller. We had to accommodate motors and allow for an adjustable, wider platform. After that, the materials and processes would be selected, and the joining methods would be considered. Then, the tests would be performed, which are shown below:

Table 1. Experimental test methods

Test	Goal
Force Calculations	Determine what forces will be experienced by the frame
Displacement Calculations	Find what displacement and extension can be expected
Force Simulation	Validate calculations and observe any unexpected occurrences

b. Testing

Should the machine be built, real-life experiments with a load cell would be performed. The load cell would measure the clamping force as the plasticine is rolled through several passes. Strain distribution in the plasticine would be measured using colored layers. These would be checked with calculation and simulation results.

The primary anticipated challenge is the simulation. Due to a lack of sufficient desktop computers for ANSYS tools, simpler simulations have been performed [10]. The constraints will have to be approximated to. Another challenge that would be expected is the formulation of conclusions. Without the machine, calculations and simulations must be analyzed deeply to yield results.

III. Results

a. Machine Design

Realizing we would need to motorize our device and include an actual load cell, we decided the best step moving forward was to redesign our CAD frame to include a platform attached to the frame to hold the motor in place as shown in Figure 3.

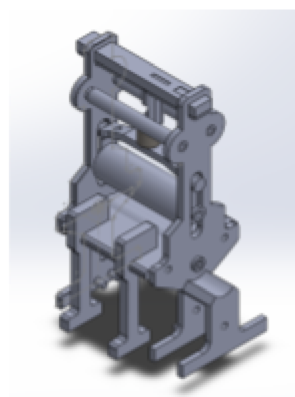


Figure 3. Roller CAD with redesigned frame

To evaluate and test our design, we must do certain calculations with respect to compressive force on plasticine and the resultant stresses and displacements that would occur throughout the machine. We also have to see if the frame and other components can withstand the reverse tensile force without breaking. After calculations, which will be shown in the next section, we end up with the final annotated design and bill of materials. A concise exploded view is provided:

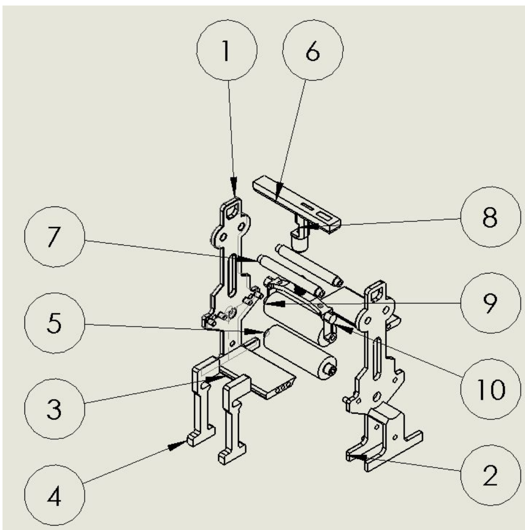


Figure 4. Exploded view

Table 2. List of parts (refer to Figure 3)

Part	Name
1	Roller Frame Left
2	Roller Frame Right
3	Roller Table
4	Width Adjustment Wall
5	Main Roller
6	Load Cell
7	Column
8	Load Cell Connector
9	Upper Roller
10	Roller Bracket

The material and processes for key components are shown below in Table 3. (See Appendix B for a full list of functions, materials, and processes)

Table 3. Function, material and processes for key components

Part	Material	Joined To	Joining Process	MFG Process
Frame	A36 Steel	3,5,6,7	Clearance Fit, Press Fit	CNC Mill
Roller Table	6061 Al	1,2	Clearance Fit	CNC Mill
Main Roller	A36 Steel	1,2	Clearance Fit	Lathe

The goal is to roll plasticine from 15 mm to 10 mm, 10 mm to 5mm, then 5 mm to 1 mm. It will be powered by two DC motors directly attached to the rollers. The rollers must be driven at the same torque and RPM so the plasticine can be flattened smoothly on the support table. The rollers are held by two frames, and a bracket which supports the motor and device vertically. In addition, a load cell will be connected to measure compressive force. All of the parts will be joined together by clearance and press fits with the exception of the load cell connector and stepper motor which will be screwed on.

b. Material Selection

The material selection of each part of rolling machines is extremely important. The material determines what rolling load, rolling strength, and rolling torque is feasible for the machine to achieve. Roll life and wear are also important and directly related to the chosen material [8]. Surface quality is also important as it affects friction, wear, and accuracy, which is crucial for quality control. The full scale example machine deforms steel, and thus the properties (mainly strength, hardness, and toughness) must be that of steel or higher performing [7]. Comparing to steel requirements of Young's Modulus 200 GPa and strength 100 MPa minimizing cost, our Ashby Chart guidelines then look like so:

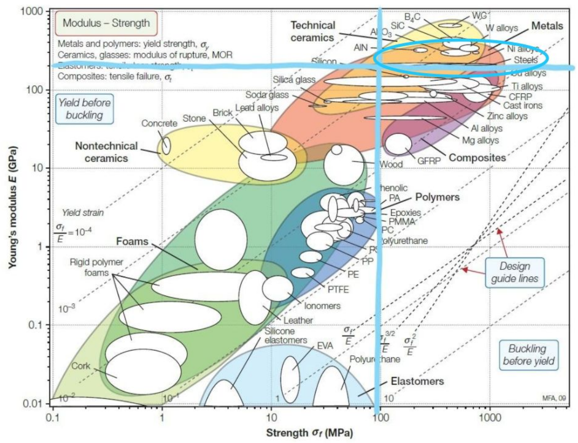


Figure 5. Strength-Young's Modulus Ashby Chart

Table 4. Final selection of materials

Material	Strength	Young's Modulus	Fracture Tough	Hardness
Cast Iron	310 MPa	120 GPa	25	96
Steel	350 MPa	200 GPa	50	80
Al	280 MPa	70 GPa	20	60

Our full scale machine would probably use a carbon forged steel roller. The steel would be water quenched at 900 C and tempered for one hour at 600 C. The choice of carbon as an alloying element increases its hardness and wear resistance, but decreases its resistance to shock [2]. Luckily, our process does not induce large shocks or vibrations. Ideally, these rollers would be forged, to increase mechanical properties. Also, forging's impact hardens and makes the steel stronger as well. Cast Iron and Aluminum do not have a high enough Young's modulus for the application.

c. Economic/Manufacturability

With regard to small scale manufacturing, forging isn't reasonable, so our rollers will be CNC'd or cut out on a lathe. Our metal options available are aluminum and steel, but steel remains much cheaper to produce our part out of. While steel is harder to work with than aluminum in terms of processing in a machine shop, we do not consider that as a major constraint, and prioritize cost above that. Therefore, we chose steel from the machine shop's selection for our rollers. Since we will not need to spray water or lubricant on our machine to quickly cool the product (as the plasticine will be a working room temperature), we do not have to look too much to coating our rollers for corrosion resistance.

With regard to experiments and measurement, our device will be equipped with a load cell to measure the vertical compressive force on the slab as it is pushed through the rollers [3]. A single motor will drive the main roller, and the top roller will freely follow, holding the correct compressive force as measured by the load cell.

d. Calculations

First, the stresses and forces required were found. The roller radius for the machine is 25 mm, and the slab width to be rolled is 100 mm, rolled in 3 passes.

We solve for the coefficient of friction needed.

$\mu^2 R = \Delta h_{max}$

$\Delta h_{max} = 10mm - 5mm = 5mm$

$\mu = \sqrt{5mm/25mm} = 0.45$

Next, we approximate L, the contact length.

$L = \sqrt{(R * d)} = \sqrt{25 * 5} = 11.18\ mm$

We can find the maximum force F:

$F = 1.15 * Y_{avg} * L * w$

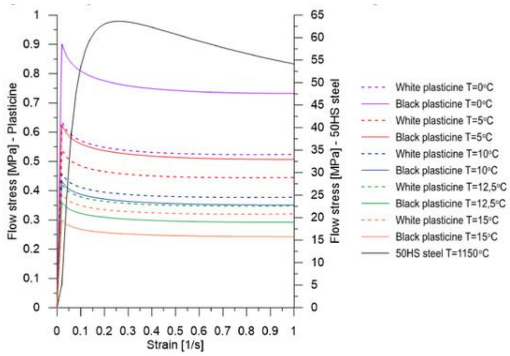


Figure 6. Strain rate to flow stress of plasticine diagram. [9]

We see the flow stress is roughly 0.35 MPa (Figure 6).

$F = 1.15 * 0.35\ MPa * 11.18 * 100mm$

$= 450N$

With a safety factor of 2, the force is 900N. The torque needed is:

$T = 0.5 * F * L$

$= 0.5 * 900N * 11.18\ mm$

$= 5.04\ N * m$

Translating the force to the frame, it means that a force of 450 N must be sustained across each side of the frame. If the frame has a cross-sectional area of 400 mm^2 at its lowest point, this means the maximum stress is 2.25 MPa. We calculate the displacement from the Young's modulus of A36 steel, which is 200 GPa.

$\varepsilon = 2.25\ MPa/200\ GPa = 1.125 * 10^{-5}$

With a total frame height of 381.37 mm, this means the total displacement is 0.0043 mm.

<u>e. Simulation</u>

A simulation of the calculated force was done on the assembly, determining the maximum elongation and the maximum first principle stress [6].

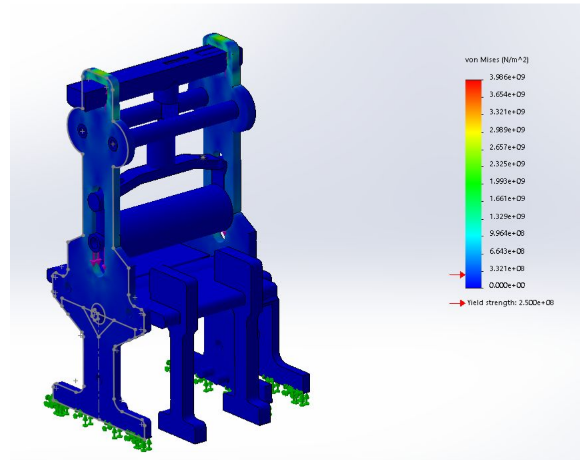


Figure 7. CAD stress simulation

As seen in Figure 7, it was found that maximum stress was at the top of the frame, with the greatest first principle stress being 9 MPa. Meanwhile, the extension of the frame was 0.01 mm. It can be seen that the expected areas in the frame take the most stress; that is, the bar holding the load cell in place, and the rail holding the roller in place, since the compressive force is along that axis.

<u>f. Project Status</u>

Regarding the status of our project, our team has finished the final calculation and designing the specification of our rollers. Asides from that, the last important task is to run simulations to test designs in-depth. Unfortunately due to COVID-19 circumstances, we will not be building our machine in full scale.

IV. Discussion

We can see from the results that our design using the A36 Steel frame can take the calculated loads without deformation in most areas [4]. The areas of highest stress and displacement are simulated and turn out as expected, being in the frame.

Within the frame, the maximum stress was found to be in the top, instead of around the middle, where the cross sectional area was the lowest (See Figure 7). In comparing simulation and calculation results, the stress at the middle of the frame was similar. The value of 2 MPa was slightly lower than the calculated value of 2.25 MPa. Also, the displacement was higher; the simulation yielded a maximum displacement of 0.01 mm, while the calculations predicted a 0.0043 mm, which can be accounted for by the increased displacement at the top.

One area that was overseen was the stress at the top of the frame. It occured from the buildup of stresses throughout the entire machine. The stress was found to be 9 MPa, higher than what would be desired for such a machine. One solution is to increase the thickness of the entire frame at that section. Another is to use the load cell on a separate frame that goes over the entire system, though this may be more costly. Moving the load cell lower, so there is more of the frame above to spread the forces, can be done too.

Ultimately, our choice of design was relatively effective, as all of the stresses within the machine were below the yield strength of the material. However, key changes such as adding an increased support for the load cell, potentially separate from the frame, as well as reinforcing the thickness of the frame, especially towards the top, can be improved for future iterations. Additionally, if possible, physical machine tests and complex rolling simulations should be used.

V. Conclusion

1. Scale modeling of the hot strip rolling machine was achieved. Adjustments of cost and additional electrical motor were incorporated.
2. Necessary calculations and simulations for the machines were performed allowing us to conclude that the frame needed extra support towards the top where stresses were highest. This was different from what we predicted.
3. It was concluded that the steel frame was very strong and the stresses generated in rolling the plasticine fall far below the yield strength of steel.
4. Due to the COVID-19 pandemic, we were not able to take the next step in manufacturing and testing our scaled model. In order to proceed with our project, we ran simulations on our project. Unfortunately due to the lack of computational power, we were only able to do light simulations. However, unexpected stresses were still uncovered in our process.
5. Moving forward in future studies, performing experimental tests using load cell plasticine would allow further testing and confirmation of the success of the machine.

VI. Acknowledgements

We would like to thank Professor Adi Ben-Artzy as well as GSI Josh Dewitt for providing guidance throughout the course of the project. In addition, we would like to thank design specialist Cody Glen for providing feedback and advice with respect to our final design.

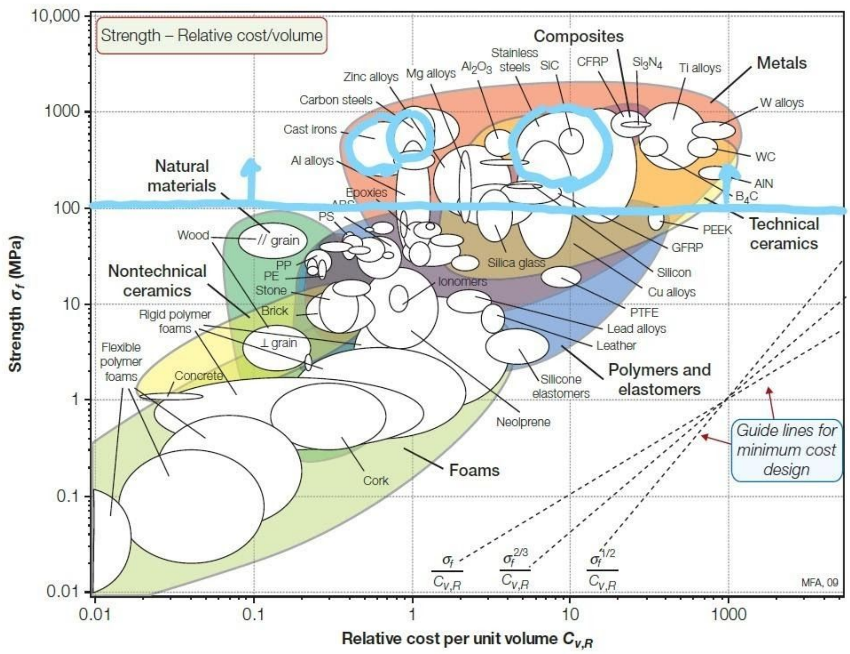
VII. Bibliography

1) Aghasafari, Parya, Salima, Mahmoud and Ali Daraei. “Flow Stress Evaluation in Hot Rolling of Steel.” *Journal of Materials Engineering and Performance*, vol. 23, August 2014. https://www.researchgate.net/publication/271741478_Flow_Stress_Evaluation_in_Hot_Rolling_of_Steel. Accessed 6 April 2020.
2) Bombač, David, et al. “Amelioration of Surface Cracking during Hot Rolling of AISI D2 Tool Steel.” *Materials Science & Technology*, vol. 34, no. 14, Sept. 2018, pp. 1723–1736. EBSCOhost, doi:10.1080/02670836.2018.1475862. Accessed 10 April 2020.
3) Bordonaro, Giancarlo, et al. “Design of Experiment as a Powerful Tool When Applying Finite Element Method: A Case Study on Prediction of Hot Rolling Process Parameters.” *Frattura ed Integrità Strutturale*, vol. 12, Jan. 2018. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2587256. Accessed 7 April 2020.
4) Hasan Nasab, M., and S. Serajzadeh. “Thermal Stresses and Kinetics of Phase Transformation on the Run-out Table after Hot Strip Rolling of Low-Carbon Steels.” *International Journal of Advanced Manufacturing Technology*, vol. 83, no. 9–12, Apr. 2016, pp. 1725–1736. EBSCOhost, doi:10.1007/s00170-015-7604-2. Accessed 10 April 2020.
5) Ma, Biao, et al. “Deformation and Recrystallization Microtextures of an Austenitic Steel during Asymmetrical Hot Rolling Process.” *Journal of Materials Science*, vol. 52, no. 22, Nov. 2017, pp. 13212–13226. EBSCOhost, doi:10.1007/s10853-017-1172-9. Accessed 10 April 2020.
6) Orlov, V., and E. Khlusova. “Simulation of through Production Processes for Manufacturing Thick-Walled Plate in Hot Rolling Reversing Mills.” *Metallurgist*, vol. 56, no. 11/12, Dec. 2012, pp. 832–843. EBSCOhost, doi:10.1007/s11015-013-9659-3. Accessed 10 April 2020.
7) Shatalov, Roman, and Arkadiy Genkin. “Sheet Mill Control in Steel Strip Hot Rolling.” *Journal of Chemical Technology & Metallurgy*, vol. 50, no. 6, Nov. 2015, pp. 624–628. EBSCOhost, search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=110461974&site=ehost-live. Accessed 7 April 2020.
8) Song, Guangyi, et al. “Study on Mathematical Model of Work Roll Wear in Skin-Pass Rolling of Hot Steel Strip.” *International Journal of Advanced Manufacturing Technology*, vol. 97, no. 5–8, July 2018, pp. 2675–2686. EBSCOhost, doi:10.1007/s00170-018-2076-9. Accessed 6 April 2020.

9) Wójcik, Łukasz, et al. “Physical Modeling of Cross Wedge Rolling Limitations.” *Materials*, vol. 13, Feb. 2020. https://www.mdpi.com/1996-1944/13/4/867/htm. Accessed 12 April 2020.
10) Zaaf, Mohamed, et al. “Simplified Two-Dimensional Model for the Prediction of Pressures and Velocities in Hot Strip Rolling.” *International Journal of Advanced Manufacturing Technology*, vol. 100, no. 1–4, Jan. 2019, pp. 13–23. EBSCOhost, doi:10.1007/s00170-018-2691-5. Accessed 10 April 2020.

APPENDIX

A. Additional Roller Selection Ashby Charts



B. Full Parts List

Part #	Part	Function	Material	JoinedTo	Joining Process	Manufacturing Process	No. of Part
1	Roller Frame Left	Support Device Vertically	A36 Steel	3, 5, 6, 7	Clearance Fit, Press Fit	CNC Mill	1
2	Roller Frame Right	Support Device Vertically, Support Motor Vertically	A36 Steel	3, 5, 6, 7, 11	Clearance Fit, Press Fit	CNC Mill	1
3	Roller Table	A Support Platform for Samples to Be Rolled Across	6061 Aluminum	1, 2	Press Fit	CNC Milled	2
4	Width Adjust Wall	Adjusts the Final Width of the Product	6061 Aluminum	3	Press Fit	Laser Cut	2
5	Main Roller	Rolls and Compresses Samples	A36 Steel	1, 2,	Clearance Fit	CNC Lathe	1
6	Load Cell	Measures Compressive Force on Sample	N/A	5, 9	Clearance Fit	CNC Lathe	1
7	Column	Joining and Spacing the Frame Horizontally	6061 Aluminum	1, 2	Press Fit	CNC Lathe	2
8	Load Cell Connector	Connects Load Cell to Roller Bracket	PLA	6, 8	Press Fit, Screwed	FDM 3D Printed	1
9	Upper Roller	Rolls Along the Top of the Sample Freely	A36 Steel	10	Press Fit	CNC Lathe	1
10	Roller Bracket	Holds Upper Roller in Vertical Position	6061 Aluminum	8, 10	Screwed, Press Fit	CNC Milled	1
11	Stepper Motor	Drives the Main Roller	N/A	5	Motor Key with Set Screw	N/A	1