Optimization of Flat Rolling Process through a Simulation Approach Using Simufact Forming

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Abstract

Rolling process is implemented in the production of structures that are regularly utilized in vast applications such as pipes, frames, shells, and discs. Flat rolling is one of the widely used rolling processes that involves reducing the thickness of a metal sheet by feeding it between two rollers that are separated by a pre-specified distance, and this can be done under hot conditions (hot flat rolling) or cold conditions (cold flat rolling). Due to the significance of flat rolling applications, optimizing this process became a crucial necessity in today's industrial revolution. In this paper, Simufact Forming Simulation Software was utilized to extract critical results such as effective plastic strain, effective stress, lateral spread, and maximum rolling force under different rolling conditions such as the rotational speed of the rollers and the friction between the rollers and the workpiece to identify their effect on the process. The general trends of the extracted data showed either a linear or a quadratic relationship between the parameters verses the rotational speed and the friction. Finally, the trends were used to characterize the best conditions for flat rolling applications.

Keywords

Simulation, Rolling process, Flat rolling, Forming, Simufact Forming.

1. Introduction

Rolling is one of the common metal forming process which is used to manufacture structural I beams, rails, and different kinds of stocks such as channel stocks and angle stocks and many other applications. One of the basic rolling processes is flat rolling in which a piece of metal stock such as steel, aluminum, etc. is pressed against two or more rollers and the thickness of the stock gets reduced to a desired value. Depending on the working temperature, rolling is divided into either hot or cold rolling. The temperature of recrystallization is the one used to classify them (hot rolling: $T_{recrystallization} > T_{working}$, cold rolling: $T_{recrystallization} < T_{working}$). A schematic of the process is displayed in Figure 1.

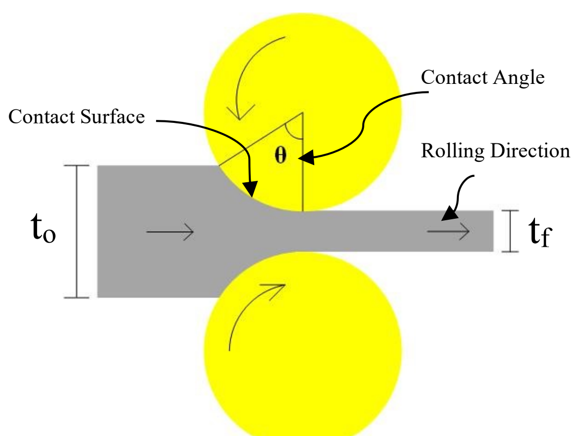


Figure 1: Flat rolling process (where t_o is the initial thickness and t_f is the final thickness)

In order to achieve an accurate flat rolling process, the process specifications such as the rollers rotational speed, the friction between the rollers and the workpiece are crucial to determine. A number of these process parameters were investigated in many studies in an aim to optimize it.

Babak Moazeni and Mahmoud Salimi (2015) have conducted a simulation of a cold flat rolling process using finite element method (FEM) to study the stresses and the material flow on a plate with varying thickness. It was concluded that the shift from a flat shape to an undesirable shape with consideration of the ratio between the final thickness to the plate's width is due to the fluctuations in the thickness of the plate [1]. In addition C.H. Moon and Y. Leeb (2012) researched a way to approximate the temperature distribution during a hot flat rolling process since the analytical method is time consuming. A polynomial function of the sixth-order was used to approximate the initial conditions of the cool off conditions. Finding a set of finite eigenvalues rather than infinite was the approach applied that was used to estimate the temperature distribution along the thickness of the material. The authors reported that, the time required dropped to lower than 3% of that needed for the analytical method [2]. Moreover, the flat rolling process can be done on either a single pass or multi stage passes. Weitao Jia and Qichi Le (2016) presented a heat-transfer analysis of AZ31B Magnesium alloys during a single-pass flat rolling. They studied the temperature distribution in the Magnesium alloy plate along the thickness direction [3]. Additionally, multi- pass processes were examined by Weitao Jia et. al (2017) in another paper were they discussed the relationship between the microstructure and the properties during a multi-pass, variable routes and different initial temperatures hot flat rolling of AZ31B magnesium alloy. The authors revealed that the relationship between the tensile strength and $dm\ -1/2$ is approximately characterized as a quadratic function where the coefficients were influenced greatly by the texture and the dispersion of microstructural distribution [4].

Nonetheless, due to its significance, many analytical models were developed to study flat rolling process such as in the publications of C. D. Barbu and N. Şandru (2018) and Hong Xiao et. al (2013) [5-6]. C. D. Barbu and N. Şandru (2018) determined the neutral point position and the equations for the discontinuity surfaces limiting the deformation zone. The revealed model could predict wave-like distribution of the roll pressure [5].

On the other hand, friction between the rollers and the workpiece is considered the main driving mechanism for any rolling process. Without friction, the rollers will slip and the desired reduction in the thickness cannot be achieved. V. Yadav et. al (2017) presented an experimental validation of strategy for the inverse estimation of mechanical properties and coefficient of friction in Flat Rolling. The study verified experimentally a methodology to determine input data about material properties and friction parameters online by the measurement of exit temperature and slip. It was revealed that the inverse prediction of input parameters could be done with a reasonable accuracy [7]. Furthermore, V. Yadava et. al (2015) created an inverse estimation of thermal parameters and friction coefficient during warm flat rolling process. The results of the study registered an error less than ±7% between the actual and estimated thermal parameters and friction coefficient [8].

The effect of rolling parameters on the rolling process is also studied extensively. Mahdi Bagheripoor and Hosein Bisadi (2011) proposed a model based on thermo-mechanical analysis using the finite element method (FEM) to study hot strip rolling of aluminum alloys. The study considered the effects of various process parameters such as rolling speed, the thickness reduction, initial thickness of the strip and the interface of heat transfer [9].

Finally, Olive Chakraborty and Sushant Rath (n.d.) developed a hybrid modeling for hot flat rolling process. The study integrated two mathematical models and ANN model for the prediction of the rolling force of steel products [10].

The primary aim of this research is to study the effect of the rotational velocity of the rollers and the friction between the rollers and the workpiece on the resulted effective plastic strain, effective stress, spread, and rolling force. Beside that, the study has two primary objectives, namely, to develop a simulation model for flat rolling process and to characterize the best conditions for flat rolling applications. To achieve these objectives a simulation model developed in Simufact Forming and rolling conditions were varied for each trial as it is discussed below.

3. Simulation Model

3.1 Simulation setup

This study used Simufact forming software to develop the flat rolling process. The flat rolling process is modeled by Simufact rolling module which is shown in Figure 2.

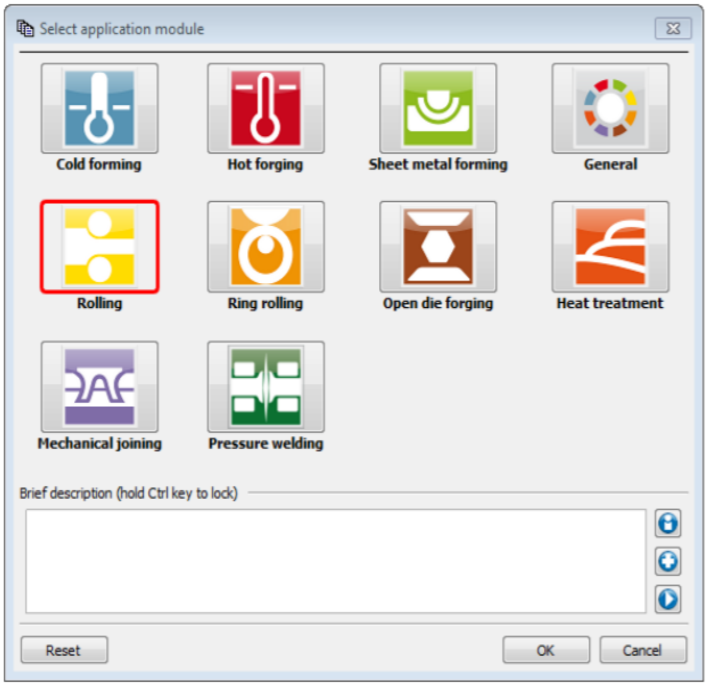


Figure 2: Simufact application module

The flat rolling process was defined in the simulation model with the following settings:

- 2D planar simulation type was used at first.
- The process was considered a hot process where the temperature range from an initial workpiece and die temperature of 20 ºC to 1000 ºC and a heat transfer coefficient to environment of 50 W/m^2K.
- The process used a tabular motion press with both translation and rotation and a constant specified velocity for each run in RPM. The velocities ranged from 25 rpm to 190 RPM.
- A manual friction coefficient of coulomb law type was varied from 0.3 to 0.5 throughout the analysis.
- The applied force on the workpiece to initialize the rolling process was 4 kN done over 0.02 parts of a second.
- The initial mesh of the workpiece was a quad mesh with an element size of 0.5 mm and FEM was used by Simufact to perform the calculations.
- The process was expanded to 3D format.

Figure 3 shows the developed model.

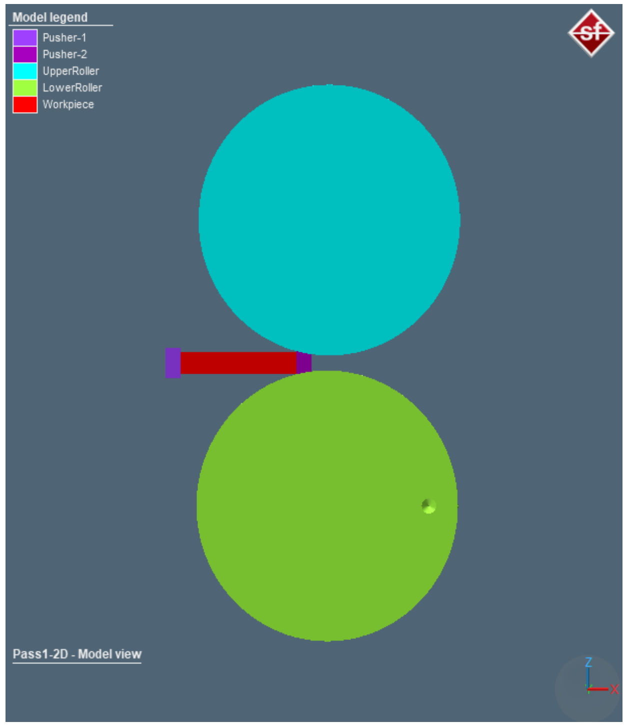


Figure 3: Simulation model

3.2 Parameters levels

The simulation was ran for 37 trials with different setting. A general steel AISI material from MATILDA-database was chosen for the workpiece which was general steel (Ck15_h3) with a 40 mm thickness. The workpiece was rolled to a 10 mm thickness. The parameters were varied in order to assess their effect. Each parameter had different values, as shown in Table 1.

Table 1: Parameters levels

	Levels
Roller rotational speed (RPM)	25, 30, 35, 40, ... ,185 ,190
Friction coefficient	0.3, 0.32, 0.35, 0.38, 0.42, 0.44, 0.45, 0.48, 0.5

4. Simulation results and discussion

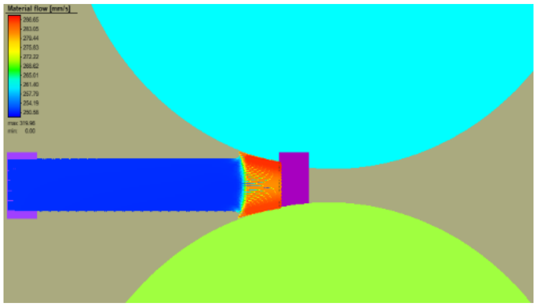
For each simulation run, the maximum value of the effective plastic strain, effective stress, effective strain rate, Y displacement, and the force along the Z direction were obtained. The input parameters and their corresponding results are given in Table 2. The rotational speed was varied from 25 RPM to 190 RPM under the same friction coefficient (0.44), whereas the same rotational speed was used (30 RPM) when varying the friction coefficient from 0.3 to 0.5.

Table 2: Simulation results.

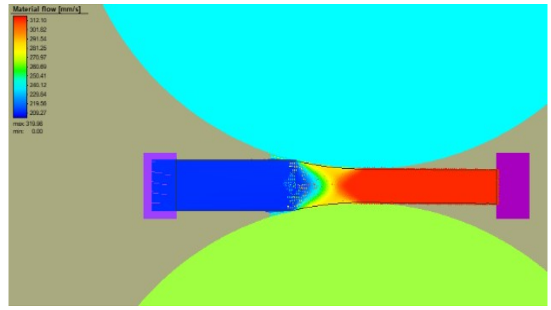
Trial	Friction	Roller rotational speed (RPM)	Max. effective plastic strain	Max. effective stress (MPa)	Max. effective strain rate (1/s)	Max. Y displacement (mm)	Max. rolling force/ Z force (kN)
1	0.30	25	1.02	217.69	16.34	3.58	175.417
2	0.30	30	1.23	239.60	18.26	3.51	181.165
3	0.32	30	0.97	218.35	18.19	3.51	184.671
4	0.35	30	0.91	215.10	19.60	3.58	191.220
5	0.38	30	0.99	217.47	19.96	3.57	196.668
6	0.42	30	0.96	223.88	24.05	3.6	206.510
7	0.44	30	0.99	229.16	25.97	3.57	209.374
8	0.45	30	0.96	227.10	24.25	3.62	211.758
9	0.48	30	1.02	223.36	21.36	3.64	218.602
10	0.50	30	0.98	230.88	26.49	3.77	221.941
11	0.44	35	0.93	222.14	23.84	3.49	219.714
12	0.44	40	1.07	228.66	28.62	3.39	223.880
13	0.44	45	1.01	230.20	31.75	3.39	230.670
14	0.44	50	0.88	232.10	33.36	3.23	238.003
15	0.44	55	0.96	236.51	39.59	3.25	243.697
16	0.44	60	1.04	231.61	39.89	3.34	251.475
17	0.44	65	0.97	230.07	45.01	3.25	249.345
18	0.44	70	0.95	235.05	44.36	3.20	255.728
19*	0.44	75	0.95	232.18	49.22	3.29	252.706
20	0.44	80	1.00	245.97	60.02	3.33	246.657
21	0.44	85	1.06	247.22	59.88	3.32	246.765
22*	0.44	90	1.03	245.89	67.31	3.63	254.904
23	0.44	95	1.01	243.54	62.64	3.31	255.362
24*	0.44	100	1.16	246.4	67.17	3.25	259.503
25	0.44	105	1.22	239.69	83.41	3.23	266.479
26*	0.44	110	1.16	249.81	86.230	3.32	266.584
27*	0.44	125	1.34	262.13	131.73	3.54	271.646
28	0.44	140	0.93	255.73	102.07	3.47	276.199
29*	0.44	145	0.96	259.71	113.53	3.27	281.879
30*	0.44	150	1.11	263.17	125.68	3.66	282.14
31*	0.44	155	1.06	247.05	103.16	3.33	312.210
32	0.44	160	1.21	248.37	107.45	3.89	415.325
33**	0.44	165	N/A	N/A	N/A	N/A	N/A
34**	0.44	170	N/A	N/A	N/A	N/A	N/A
35	0.44	180	1.14	259.55	142.19	3.35	283.969
36**	0.44	185	N/A	N/A	N/A	N/A	N/A
37**	0.44	190	N/A	N/A	N/A	N/A	N/A

* Simulation was completed but disturbed (inadequate settings)
** Simulation was not completed (inadequate settings)

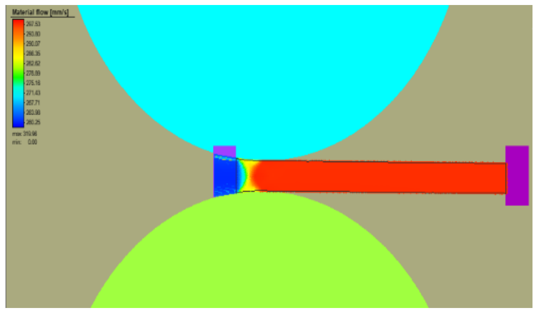
The 2D simulation of the material flow for trial 7 with progressions of beginning, during and end of the process are shown in Figure 4.



a) Beginning of the



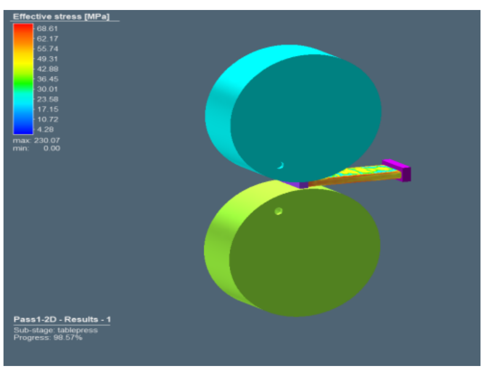
b) During the process

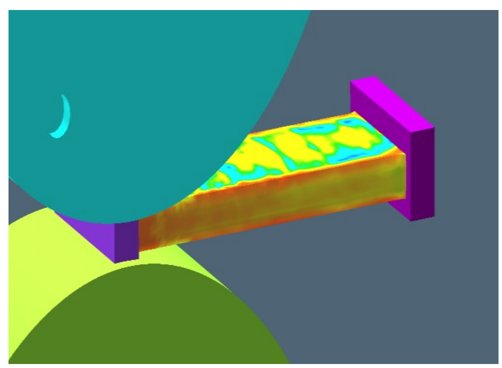


c) End of the process

Figure 4: The material flow for trail 7 during simulation at different progresses

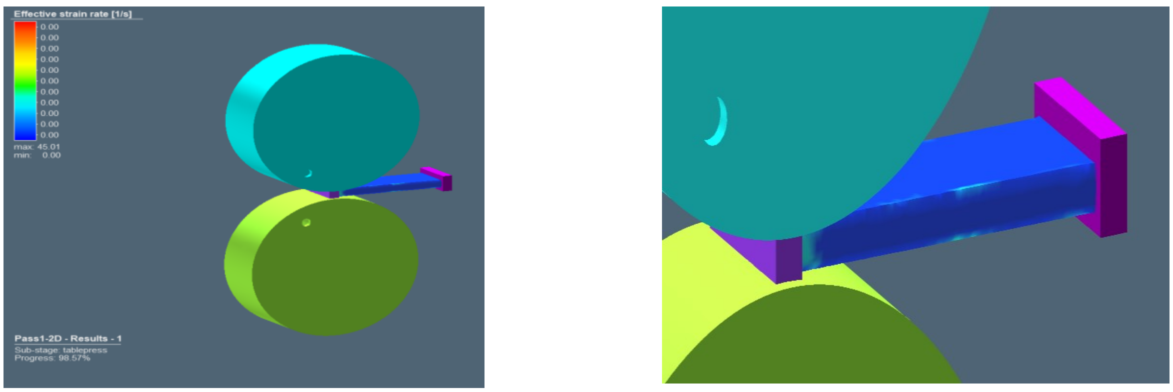
Result samples of a selected trial (trial 17) are displayed in Figure 5.





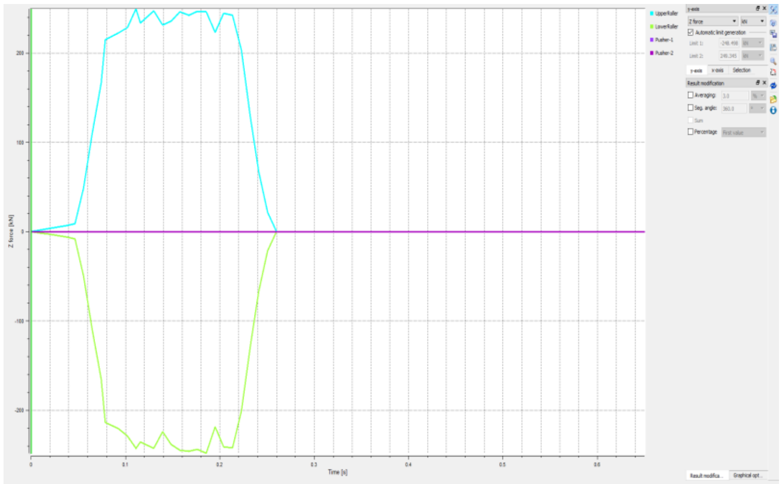
a) Effective stress

b) Effective plastic strain



c) Strain rate

d) Lateral spreading (Y displacement)



e) Rolling force

Figure 5: Results of the simulations of trial 17

4.1 Effect of roller rotational speed and friction on rolling force

After many trails of simulation, the relationship between the rolling force and both rotational speed and friction force are found as presented in Figures 6 and 7 receptively.

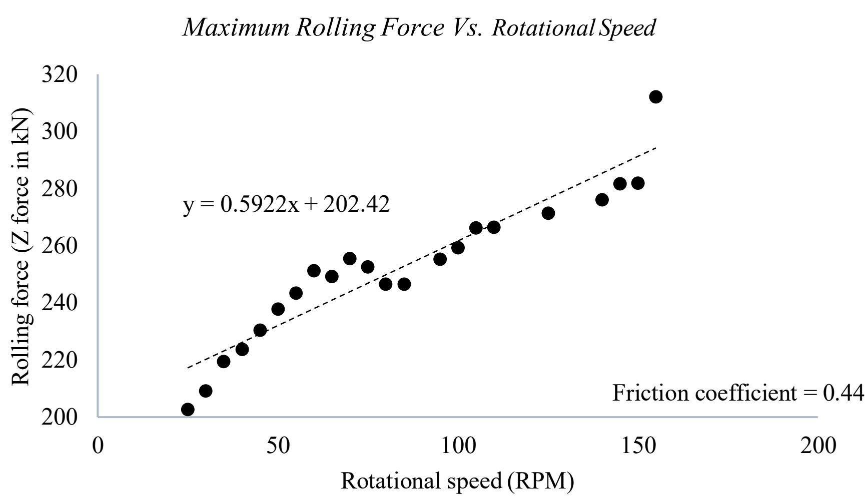


Figure 6: Relationship between rotational speed and maximum rolling force

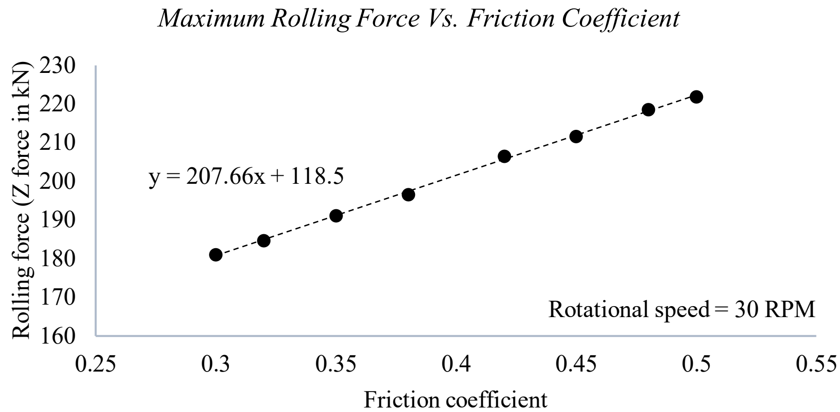


Figure 7: Relationship between friction coefficient and maximum rolling force

As it is illustrated in Figures 6 and 7, there is an approximately linear relationship between the rotational speed of the rollers and the friction with the rolling force exerted to reduce the thickness of the plate to 10 mm. There is a clear increase in the rolling force applied versus any increase in the rotational speed. Furthermore, speed values around 140 RPM to 190 RPM exhibit large required forces which is not ideal in mass productions of sheet metals since higher forces means faster degradation of the rollers and equipment along with an increase in the load that is supplied by the motors. The reason behind the higher forces is due to the slippage that happens between the rollers and the workpiece which is obstructing the rolling process. The slippage happens because of the elevated temperatures that develop at larger speeds which reduces the friction and increase the ductility of the material. The obstruction can be overcome by exerting a higher rolling force (force along the Z direction) that ensures a tighter grip of the rollers on the workpiece which facilitate the movement of the plate between the rollers. Therefore, appropriate values of the rotational speed can be 90 RPM or less that result in acceptable rolling forces. Nonetheless, the linear representation is more fitted on the friction data in Figure 9. Higher values of friction coefficient spike the rolling forces to larger numbers for a particular rotational speed. Consequently, lowering the friction can be a better option since it will reduces the applied forces, however caution should be considered since friction cannot be lowered to the point where slippage between the rollers and the workpiece happen since that will result in a failed rolling process. Intermediate values such as 0.3 to 0.4 of friction coefficient can be considered sufficient for industrial applications.

4.3 Effect of roller rotational speed and friction on lateral spreading and strain rate

Furthermore, the lateral spreading is often neglected in rolling processes since the deformation in the thickness and length of the workpiece is much higher than the expansion of its width. Nevertheless, spreading can have a significant effect on applications that are in need of accurate tolerances. Figure 8 shows that as the rotational speed increases, there is a decrease in the lateral spreading followed by another increase in the form of a second order polynomial function. In addition, since decreasing the deformation in directions other than the one along the thickness of the workpiece is desired, using rotation speeds between 70 RPM and 90 RPM will result in the lowest distortion. Despite that, a linear relationship was found between the friction and the lateral spreading as Figure 9 displays.

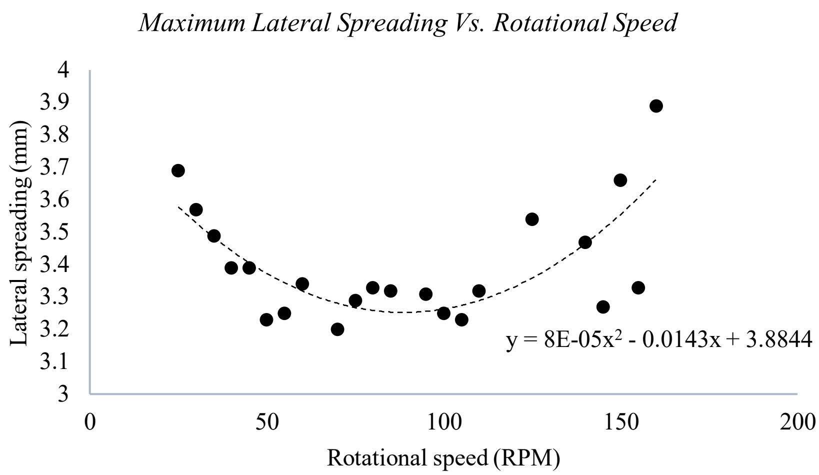


Figure 8: Relationship between rotational speed and maximum lateral spreading

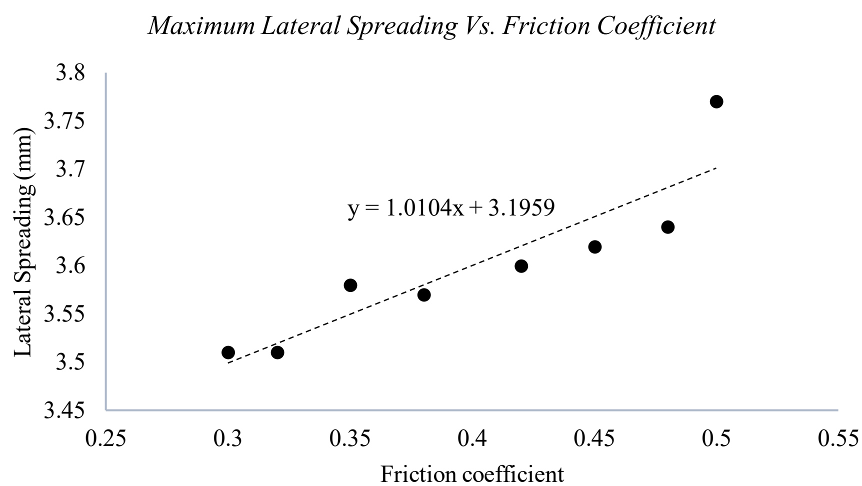


Figure 9: Relationship between friction coefficient and maximum lateral spreading

There is a relatively steady expansion of the workpiece width as the friction coefficient is enlarged. This can be explained from Figure 7 which indicated that the applied force increases with the friction and that this force is the main contributor to the lateral spreading.

As for the strain rate, the relationship between the rotational speed of the rollers along with the friction coefficient on strain rate was of a linear fashion as shown in Figures 10 and 11.

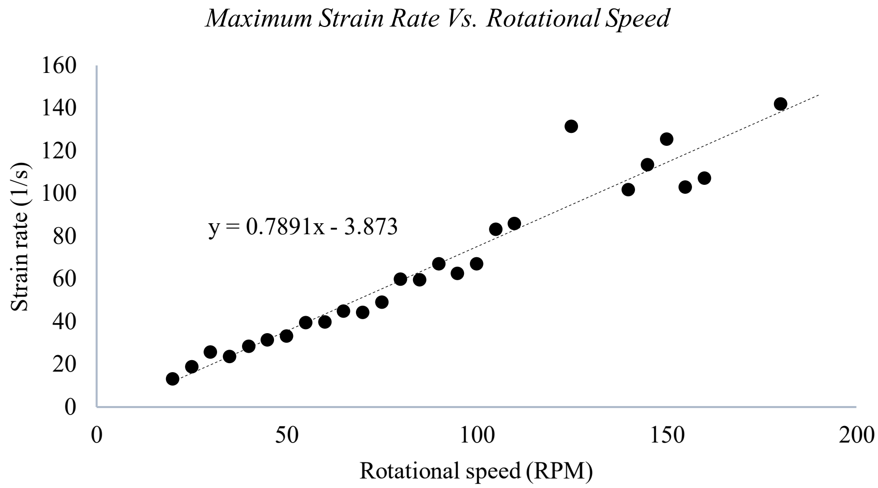


Figure 10: Relationship between rotational speed and maximum strain rate

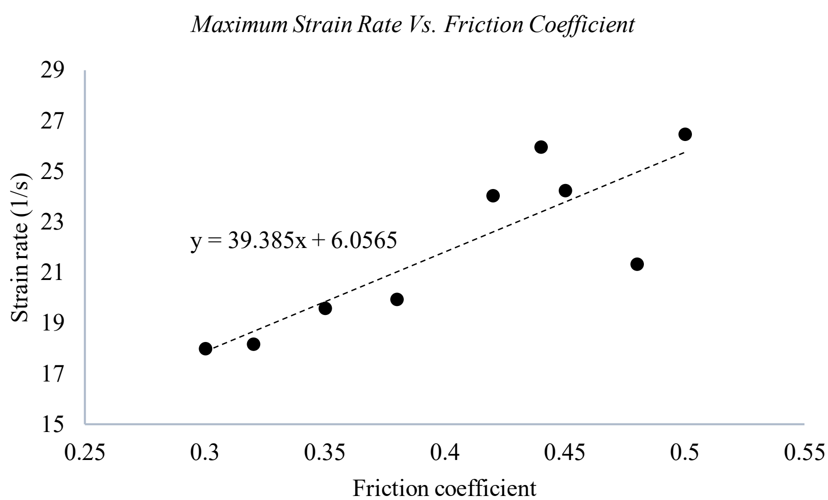


Figure 11: Relationship between friction coefficient and maximum strain rate

The higher is the rotational speed or the friction, the higher is the deformation rate. This is logical since if a workpiece is rolled faster or the friction between its surface and the rollers' surface is higher, the driving rolling force becomes larger as discussed above and that speeds up the process of reducing the thickness of the workpiece (quicker deformation).

4.4 Effect of roller rotational speed and friction on effective stress and effective plastic strain

The relationship between the effective stress and both rotational speed and friction force are found as presented in Figures 12 and 13 receptively.

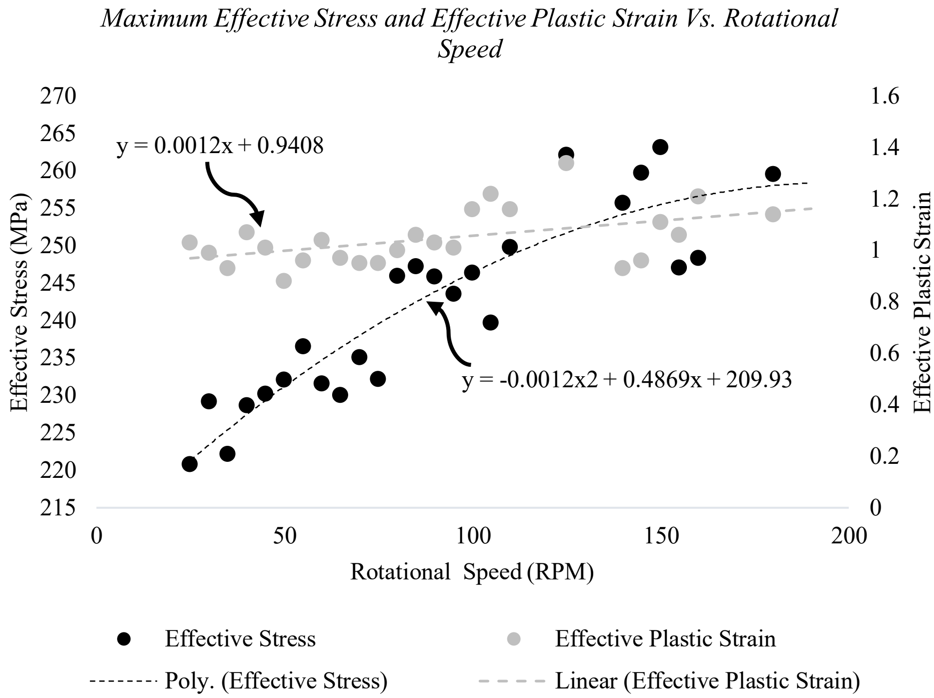


Figure 12: Relationship between rotational speed and maximum effective stress, effective plastic strain

Additionally, the effective stress and effective plastic strain are important parameters to lookout for when performing any flat rolling process. The reason behind that is related to the possible failure zones that can be produced during and after the rolling process. Figure 12 present the variation of the maximum values of the stress and strain along a wide range of rotational speeds of the rollers. The strain exhibit a positive linear behavior with increasing rotational speeds, however the slope of the line is very small which leads to the assumption of a consistent strain values for every rotational speed used. This is expected since the main deformation of the workpiece for each trial is the same which is a reduction of the 30 mm in its thickness. As for the stress, the change of its value is distinct and significant as the rotational speed varies. It is best fitted on an inverted second order polynomial function which means that at elevated rotational speed values, the increase in the stress becomes smaller compared to its previous value as it is clear in the figure. Nonetheless, even though the values of the stress gets steadier around high speeds, the stress becomes too high there. Values around 80 RPM or less produce acceptable magnitudes of stresses, since high stresses will compromise the integrity of the produced sheet and could lead to catastrophic failures.

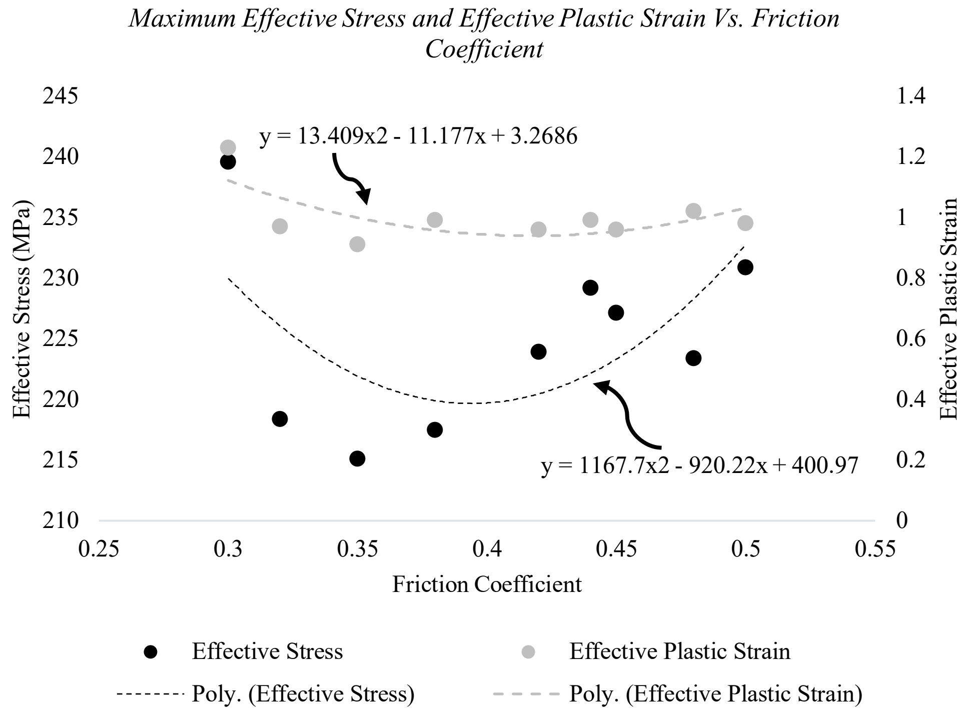


Figure 13: Relationship between friction coefficient and maximum effective stress, effective plastic strain

On the other hand, the friction plays another role in the fluctuation of the stress and strain of the rolled workpiece. Both parameters follow a positive quadratic function trend as the friction coefficient changes from 0.3 to 0.5. Then again, intermediate values of the friction coefficients resulted in the lowest stress and strain values (0.35 to 0.45) as Figure 13 illustrates.

6. Further Research

As for future research, further exploration of other important parameters of the flat rolling process can be studied such as the effect of the rollers diameter, initial force that pushes the workpiece between the rollers, workpiece initial thickness and the maximum thickness reduction. All of these parameter can have a significant impact on the flat rolling process and can affect the integrity of the material and the final product. Furthermore, multi rolling passes and their enhancement of the rolling process can be another area of research. Understanding their influence on the rolled specimen and the production rates of products along with their cost can be beneficial on an industrial level. In addition to that, studying different materials behavior during flat rolling processes can be of high importance in automobile and aerospace applications.

7. Conclusion

In conclusion, this researched focused on the simulation of multiple flat rolling processes which were run under different conditions of rolling speed and friction coefficient. The aim was to understand the behavior and the state of the workpiece during and after the each process. The results of each run that includes the effective stress, effective plastic strain, strain rate, lateral spreading and the rolling force were extracted after the simulations were done. These results were summarized in graphs to understand basic trends and relationships. It was found that the best conditions to perform the flat rolling process for the studied material is at speeds of 70 to 90 RPM with friction coefficient between 0.35 to 0.45. These conditions resulted in reasonable values for the measured stresses, forces and deformations. The trends were characterized by a positive linear relationship or a positive quadratic relationship. From that, it can be concluded that increasing the speed or the friction coefficient to high values or decreasing them significantly can be a disservice to the production of sheet metals by flat rolling.

By applying the suggested process conditions that were stated above, higher production rates and less failure zones formed on the sheet metal can be predicted for the flat rolling process.

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Biographies

Shafaa Al-Maqdi is a Mechanical Engineering student studying currently at UAE University in her senior year. She have been involved in research projects that covers topics of material science, mechanical characterization, manufacturing processes, reverse engineering and education. She has participated in a number of conferences within the country and is in the process of publishing some research papers. Her research interests include mechatronics, simulation, optimization, and material science. She is also a member of ASME and AIAA associations.

Jaber Abu Qudeiri joined UAEU in 2017 as an Associate Professor. He received his BSc. degree in mechanical engineering from the University of Jordan in 1992. In 2002, he got a scholarship (Monbukagakusho) under which he earned his M.Sc. and Ph.D. degrees (Manufacturing Engineering) from Gifu University, Japan, in 2005 and 2008, respectively. He worked as an Assistant Professor at Philadelphia University in Jordan for two years from Sept. 2008 to Aug. 2010. Afterwards he worked as an Assistant Professor at King Abdulaziz University from Sept. 2010 to Aug. 2012 and prior to joining UAEU he worked as an Assistant Professor at Advanced Manufacturing Institute, King Saud University for about four and half years. In December 2016 he was promoted to the Associate Professor rank at King Saud University. Dr. Abu Qudeiri has a Letter's Patent registered at Ministry of Industrial and Tried under No. P/1775. Also, he has a best paper award at ICACTE 2014. His current research interests include Modeling and Optimization of Manufacturing Systems, Optimization of Sequence of Operations in CNC, Predict Springback in Sheet Metal Bending Process. He is a co-author on 43 journal and 28 conference publications as well as 2 book chapters.

Aiman Ziout is assistant professor at mechanical engineering department at UAEU. He obtained his Bachelor and master degree from University of Jordan in Industrial Engineering. He accumulated professional experience in production management, mainly in steel industry. He obtained his PhD from University of Windsor-Canada. His main focus is sustainable production and sustainable product design. Currently he searches application of SMA in sustainable product design.