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Original Article

Optimization of Rolling Process Parameters using ANOVA and FEM Simulation

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Abstract - *A brass material, C377, was rolled to reduce the thickness to form a plate. In this investigation, a simulation is carried out for the flat rolling process of brass material to find the influence of various process parameters on the hardness (Hv). Von Mises stress (MPa) has been analyzed. The parameters considered for this investigation are roller diameter (mm), temperature (°C), percentage reduction (%) and speed (RPM). The effect of these input parameters has been critically analyzed using the Taguchi method. It has been found that roller diameter and temperature are the most crucial process parameters affecting the hardness value. It is analyzed for different parameters. Taguchi technique is used to find out the best parameter value for roller diameter, temperature, percentage reduction, and speed of the rollers to optimize the hardness and Von Mises stress. The rolling of brass produced a 175Hv hardness and a spread of 1.6mm at a 64 MPa Von Mises stress level when the process parameters were at optimum values.*

Keywords - *Design of experiments, Finite Element Method, Metal forming, Mechanical testing, Simulation.*

1. Introduction

Metal forming is one of the primary manufacturing processes. Rolling is the reduction of the thickness of a work piece by passing it through the rolls [1]. Metal rolling is a necessary process controlled by a number of parameters, accounting for more than 80% of all metal working processes. Metals, when passed through the rollers, change mechanical and metallurgical properties. The rolling parameters can be used to enhance the properties depending on the application.

Copper alloys can be used in several applications [1]. There are mainly two types of alloys in copper, namely brass and bronze. Brass is the type of alloy when copper is mixed with zinc [2]. Depending on the application, the zinc percentage can be varied. High-strength brass is suitable for engineering applications where high strength is required to sustain heavy loads and resistance to wear and corrosion [3].

The advantage of brass is that the mechanical properties can be enhanced by further processing and heat treatment, and they are low in cost [4–6]. In the present work, C377 Brass alloy has a chemical composition of Cu 58-61%, Pb of 1.5 - 2.5% and Zn. This material has excellent corrosion resistance and vibration-absorbing properties. They are used as rod bases for hammer and press forging machines, in the plumbing industries in value bodies, fitting and other hardware. It also has extensive usage in marine applications because of excellent corrosion resistance [7].

There are many process parameters which govern the quality of rolling. Spread is nothing but an increase in the bar's breath when passed between the rollers. In hot rolling, the sheet spread is negligible because the cylindrical rolls compress the material, and the frictional resistance in the rolling direction is lesser than the transverse direction [8–11]. In general, the quality of a rolled sheet is known by testing the hardness of the sheet. Other parameters, such as Von Mises stress and temperature at which it has been deformed, help determine the quality of rolled sheets [12].

The simulation helps predict quality and optimize the process before the actual manufacturing process without actually spending any physical resources. Taguchi Optimisation technique is one of the most widely used optimization techniques and has been used to find the rolling parameters through experiments [13, 14].

Finite Element Analysis (FEA) is one of the tools developed in the last few decades for analyzing metal forming processes. Finite Element Method (FEM) is one of the established technique for static simulation [15]. The advanced algorithms, economic computation technology, and development of FEM into a user-friendly with excellent Graphical User Interface (GUI) have brought the simulation technology forward. Because of this technological development, the art of metal forming analysis has been revolutionized.

Many packages can be used for metal forming analysis, like ANSYS, DEFORM, QFORM, Forge, Statistica, auto form, and many more [16–20]. FEM models, when made particularly for the forming applications, velocity, strain rate, stress fields, and other forming parameters can be predicted easily for the particular process. The current trend is on the increased application for process optimization and simulation. Many of the FEM modelling methods have been widely used by several researchers for rolling simulation as it improves the quality of results.

The primary objective of this paper is to carry out a rolling process design analysis using AFDEX and DOE methods for the optimization of process parameters.

2. Simulation of the Rolling Process

The initial step in the simulation process involves model creation and tool selection. To facilitate this, Solidworks 2014 software is utilized to design the rollers and workpiece models, ensuring flexibility in converting the model to the desired output format. These designed models are then converted to the Stereo Lithographic (STL) format, which offers greater ease of manipulation within the simulation tool.

The design orientation is set along the Y-axis to mimic real-world processes, ensuring that the workpiece moves perpendicular to the Y-axis as the rollers rotate. AFDEX 2014, a specialized metal forming analysis software, is employed for the simulation itself. As previously designed, the CAD model is seamlessly integrated into the simulation environment, allowing for in-software adjustments to the position and placement. Following the import, essential parameters and properties are applied to the model. AFDEX is a metal-forming software package that simulates the principles of the elasto -thermoviscoplastic finite element method. The model is meshed using the quadrilateral finite elements for simulation. The auto-mapped face meshing method is employed for proper sample meshing. Before optimization for the given parameters, the process is initially simulated and analyzed with one of the determined parameters for the understanding process. The initial simulation is carried out using the parameters given in Table 1.

2.1. Temperature Distribution

The thermal condition of the workpiece is shown in Figure 1. According to the operation in this simulation model, the roller is initially at room temperature and will cool down the outer surface of the workpiece from 300ºC to 201ºC. The maximum temperature drop on the surface of the workpiece is around 100ºC. However, the heat from the interior quickly heats the surface of the workpiece upon the exit from the roll gap. The point P1 on the surface of the workpiece is far from the roller and has about 295ºC due to atmospheric loss, while the other part is between the roll gap. The thermal condition inside the workpiece, as computed by the simulation program, the maximum temperature rise on the surface of the roll gap is predicted to be 20ºC. Figure 2 showing the distribution of temperature vs the distance.

Table 1. Parameters for simulation analysis

Sl. No.	Parameter	Value
1.	Material	Brass C377
2.	Roller Material	Tool steel
3.	Element Type	Tetrahedral
4.	Number of Meshes	50,000
5.	Roller Size	70mm diameter
6.	Roller Speed	10 RPM
7.	Frictional Value	0.1
8.	Lubrication Material	Soap cold copper
9.	Simulation Time Set	100 seconds
10.	Reduction Percentage	40%
11.	Temperature	300ºC

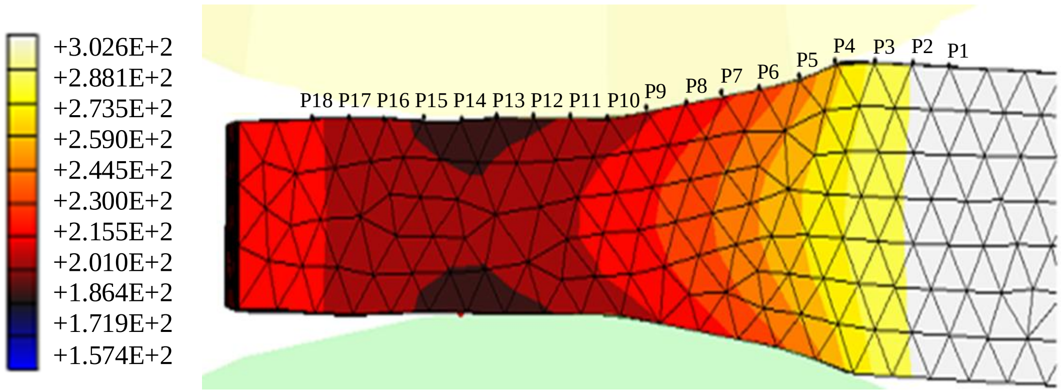

Fig. 1 Temperature distribution along the slab surface ie. points along the slab surface in the simulation model

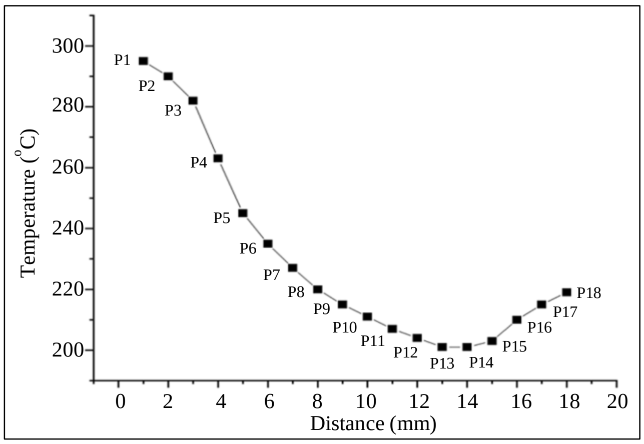

Fig. 2 Graph showing the distribution of temperature vs. Distance

2.2. Von Mises Stress

This plays an essential role in predicting the yielding stress. Figures 3(a), 3(b), and 3(c) shows the Von Mises stress distribution in three regions: the entry stage, the steady stage and the exit stage. In the entry stage, the maximum stress is below the workpiece, around 68 MPa.

The maximum stress can be observed below the rollers where the deformation happens. After passing through the rollers, the stress levels drop to near zero value. The steady stage Von Mises stress is around 64.5 MPa, which is generally taken as the stress level and increases to 67 MPa at the exit stage as there is no material at the end to absorb the load.

3. Plan of Simulation for Optimization

This study employs the Taguchi method to determine the optimal outcomes given a set of input variables. The primary objective of this method is to minimize the need for a large number of experiments while still gaining a comprehensive understanding of how these parameters influence the performance parameter.

For instance, consider a scenario in which four independent variables are being evaluated: roller diameter, speed, reduction percentage, and temperature.

Each of these parameters has three levels or distinct values. According to a factorial design approach, this would necessitate 3^4=81 experiments. This means keeping three parameters constant at one level while altering the fourth parameter three times. However, by employing the Taguchi method for experiment design, the L9 orthogonal array is chosen. In practical terms, this means that only nine experiments are sufficient to fully comprehend the combined effects of these four parameters on the overall design, significantly reducing the experimental workload.

They employed a statistical technique known as Analysis of Variance (ANOVA) to assess the impacts of rolling parameters on the brass specimen. ANOVA is a valuable tool for examining significant differences between two or more means by comparing variances. In the context of our experiment, ANOVA is applied to gauge the percentage contribution of each factor, including the rolling parameters mentioned earlier. An essential aspect of using ANOVA is its ability to provide insights into each factor's contribution, aiding in determining which rolling parameters require control and how they can be optimized to enhance rolling properties.

The steps involved in the Taguchi techniques, as outlined in [21], are as follows:

1. Identification of process input parameters along with their corresponding response functions.
2. Determination of interactions between various levels of the identified parameters.
3. Selection of an appropriate orthogonal array.
4. Utilization of ANOVA analysis to pinpoint the optimal parameter.
5. Confirmation through simulation to validate the effectiveness of the optimized parameter.

Table 2 illustrates the independent variables and their respective levels for analysis in AFDEX software. These input values were selected from a combination of simulation analyses and trial runs, where parameter adjustments were made.

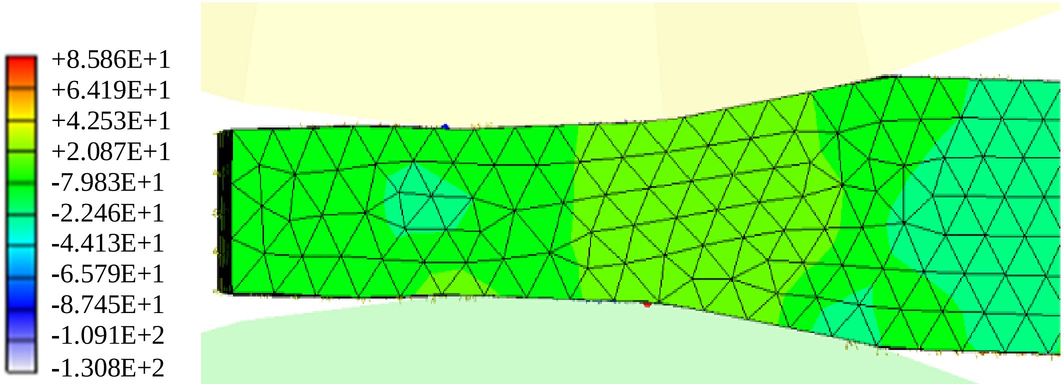

Fig. 3(a) Maximum principal stress at entrance

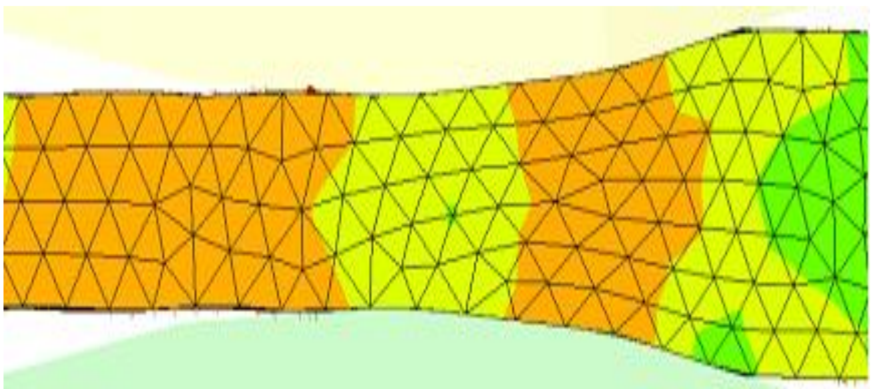

Fig. 3(b) Maximum principal stress steady-state

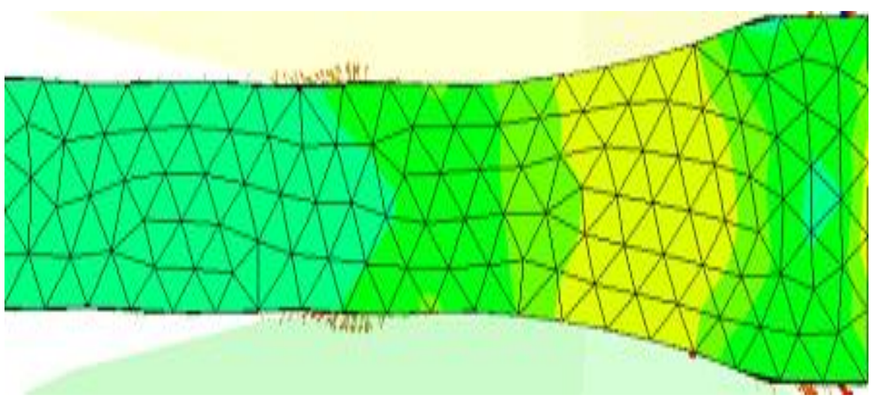

Fig. 3(c) Maximum principal stress exit

Table 2. Rolling parameters and their levels

Parameters	Level 1	Level 2	Level 3
Roller Diameter (mm)	50	75	100
Temperature (ºC)	300	400	500
Reduction Percentage (%)	20	30	40
Speed (RPM)	10	12	14

As outlined in the table, these chosen parameter levels were arrived at through a systematic process aimed at minimizing material defects, ensuring equal intervals, and drawing from the knowledge gained through experience. The rolling simulations were executed in accordance with the requirements specified by the DOE software.

3.1. Development of Design Matrix

In this study, an L9 orthogonal array is utilized with 4×9 matrices specifically designed for three-level process parameters. So, nine static design analyses in AFDEX are sufficient to compare with experimental results. The simulation arrangement adheres to the L9 orthogonal array, as outlined in Table 3.

4. Analysis of Simulation Results

Following the simulation of conditions outlined by the L9 orthogonal array, the results were thoroughly analyzed to determine optimal conditions. Each of the nine experiment sets was executed in this simulation only once. To emphasize the importance of specific output parameters in maintaining product quality, certain parameters, notably hardness and Von Mises stress, were accorded higher priority over others, such as spread.

This research aims to attain optimal values for the specified parameters with a minimal number of trials, thereby conserving valuable resources. However, it is essential to note that the parameters and their respective levels were examined using Taguchi analysis in conjunction with the DOE software during the experimentation. Data for each trial was acquired by averaging measurements taken at six distinct points. Additionally, all measurements were consistently obtained from the region beneath the rollers. The results obtained from the simulation based on the L9 orthogonal array are detailed in Table 4.

Table 3. L9 array simulation layout

Run	Control Factors			
	Roller Dia (mm)	**Temperature (°C)**	**Reduction (%)**	**Speed (RPM)**
1	50	300	20	10
2	75	300	30	14
3	50	500	40	14
4	100	400	20	14
5	100	500	30	10
6	50	400	30	12
7	75	500	20	12
8	75	400	40	10
9	100	300	40	12

Table 4. L9 Orthogonal array with results obtained from simulation

Run	Roller Diameter (mm)	Temperature (°C)	Reduction (%)	Speed (RPM)	Hardness (Hv)	Spread (mm)	Von Mises Stress (MPa)
1	50	400	30	12	188	1.7	65.6
2	50	300	20	10	176	2	61.9
3	75	300	30	14	180	1.5	64.5
4	50	500	40	14	196	1.7	81
5	100	400	20	14	176	1	76.4
6	100	500	30	10	182	1.4	81.3
7	75	500	20	12	172	0.8	78.7
8	75	400	40	10	190	2.2	72.8
9	100	300	40	12	193	2.1	66.3

Table 5. Analysis of Variance (ANOVA)

Factor	Sum of Squares, S	D.F.	Mean Square	F- Ratio	P-Value	R Squared	Adeq. Response	Adeq. Precision
Hardness	350	2	175	19.44	0.0024	0.8663	0.822	8.66
Spread	1.17	2	0.58	5.20	0.049	0.6341	0.512	4.3
Von Mises Stress	389.75	2	194.87	15.73	0.0041	0.834	0.787	7.924

Table 6. Optimized solution for the parameters

Run	Roller Diameter (mm)	Temperature (^oC)	Reduction (%)	Speed (RPM)	Hardness (Hv)	Spread (mm)	Von Mises Stress (MPa)
1	50	300	20	10	176	2	61.9

The results of the Analysis of Variance (ANOVA) are shown in Table 5. For hardness, the F- value is 19.44, which means that the model is significant, which mainly depends on the reduction factor. There is only a 0.24% chance that the F-value could occur due to noise. The more the value of Regression (R) squared close to 1, the more accurate the model is the value of R squared can further increase by performing more iterations.

The adequate response value is 0.822, which has a difference of less than 0.2, which means the model is significant, and the adequate precision is more than 4. Even though the P-value is less than 0.5% for the spread response, the R-squared value is 0.63, which is not close to 1. The spread does not have much significance in the optimization process for the given parameters. The importance of Von Mises stress is at a satisfactory level, the model is significant, and adequate precision is more than 4. This concludes that Hardness and Von Mises significantly affect the given parameters, and spread does not play a more substantial role.

4.1. Confirmation Simulation

After comparing the results from AFDEX and the experimental results, it can be concluded that experimental values validate the computer-based static analysis. It serves as a means to verify the accuracy of the model generated. In the case of a 50mm roller diameter, a temperature of 300°C, a reduction percentage of 20%, and a speed of 10 RPM, the optimal values were successfully attained, resulting in a hardness of 174.6 Hv, a spread of 1.6mm, and a Von Mises stress of 64.2 MPa.

The precise conditions for achieving the desired response are outlined in Table 6. Given that one of the performed simulations (Run 1) aligns closely with the model's predictions, additional confirmation runs are deemed unnecessary.

5. Conclusion

Simulation plays a vital role in predicting the process parameter before going into the actual production process. The analysis of the rolling process was made to determine the effect of rolling on the workpiece.

Taguchi's technique was applied to study the optimization of the process parameters for parameters like roller diameter, temperature, reduction percentage, and speed of rollers. The output responses like hardness, spread, and Von Mises stress are found for the given input. The obtained model had good desirability levels and had the model was satisfactory.

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