EXPERIMENTAL INVESTIGATION AND SIMULATION OF HOT ROLLING OF AL6061

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Abstract: *The process of deforming a metal plastically by passing it between rollers is an age old metal forming process called rolling. The main aim of this paper is to find the optimal process parameters on roll separating force in hot rolling process for Al6061 material. Experimental investigation was carried on Al6061 using Taguchi Design of Experiments and linear regression model is generated using MiniTab software. Simulation is also carried using explicit analysis of the hot rolling process in Abaqus CAE software.*

Index Terms: *DoE, Explicit Analysis, Hot Rolling, Regression Analysis, Taguchi Method*

1. INTRODUCTION

The friction and the squeezing action between the rolls decreases the thickness or changes the cross section and also help in imparting special properties to the material undergoing the explained process. In current scenario applications, rolling is one of the most important metal working operations. All metal products require rolling to be performed at some point of their manufacturing process. Most of the materials are subjected to rolling before they can be converted into proper raw materials.

Whatever the type of rolling process be hot or cold, the main objective is to decrease the size or more precisely the thickness of the metal.

All the rolling process which involve simple flat rolling of the work can be classified under plain strain conditions (material gets longer and thinner but not wider) since the length of contact, L, between the work piece and the rolls is generally much smaller than the sheet width, W. The sheet or the plastic region of the sheet is free to expand in the rolling direction, x, because of the compressive stress, σ_z, acting on the sheet. The lateral expansion (in the y-direction) has to be neglected or is assumed to be zero as it is limited by the un-deformed material on both sides of the roll gap.

Hot Rolling

Hot rolling like any other hot forming operation is carried out at a temperature greater than the recrystallization temperature (0.3~0.5 melting temperature) of the metal being deformed.

The recrystallization temperature can be defined as the minimum temperatures at which formation of new grains occur. Recrystallization is followed by grain growth and preceded by recovery. The driving force for both recrystallization and recovery processes comes from the difference between the energies of the strained and the unstrained material as shown in figure 1. There are two ways in which recrystallization can take place i.e. static or dynamic recrystallization. The static one occurs after the process if the metal is kept high

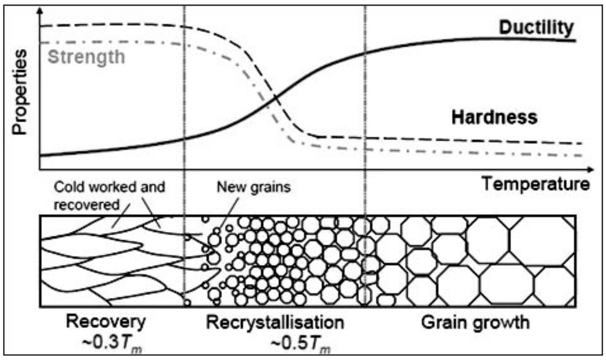


Fig 1: Effect of Temperature on the Metal During Hot Rolling

temperature. The dynamic ones occur during the operation itself which can lead to a more isotropic microstructure.

During recovery the kinetic energy of the dislocations present within the crystals increase and they annihilate or come down to lower energy configurations leading the way for nucleation of new grains at the dislocation clusters or the grain boundaries. There are several recovery mechanism involved during the static and the dynamic recovery as in case of recrystallization. These are:

Dislocation pile-ups - at the site of a dislocation pile up the increase in the strain at the pile up origin can lead to cross slipping of the dislocation from one plane to releasing strain energy.

Climb - the edge dislocations climb because of the high vacancy diffusion at this elevated temperature leading to a reduction in strain at the pile up.

Polygonization - besides annihilation an important phenomena that leads to recovery is polygonization. There are regions of dense and sparse dislocations, the dense ones arrange themselves in a particular fashion leading to formation of dislocation cluster or cells within the crystal and hence these clusters act as the nucleation sited for the new grains.

Grain growth is the final stage where the newly formed grains grow. Larger grains grow at the expense of smaller ones and this involves all kinds of boundary energy calculations. The driving force for grain growth mechanism comes from the reduction in grain boundary energy of the grains because as the grain size increase with time the grain boundary area decreases which results in total decrease in the energy of the metal. This final stage has to be controlled if a finer microstructure is desired, hence the temperature is brought down during the final stages to ensure that the newly formed grains do not undergo coarsening.

Roll separating force at normal friction condition is calculated using the formula below:

$$P = \frac{2}{\sqrt{3}} \bar{\sigma}_o \left[\frac{1}{Q} \left(e^Q - 1 \right) b \sqrt{R \Delta h} \right]$$

$$Q = \frac{\mu * \sqrt{R * \Delta h}}{h}$$

Where R is radius of roller, Δh is reduction,h is average of inlet and oulet thickness.

2. METHODOLOGY

A mathematical model is developed using Minitab to understand the relationship between the input parameters and the target variable. Aluminium 6061 alloy was chosen for the study and the chemical composition of the material is tabulated in table 1.

The process parameters shown in table 2 were

Table 1: Al6061 Composition

Component	Percentage %
Aluminum	Balance
Magnesium	0.8 - 1.2
Silicon	0.4 - 0.8
Copper	0.15 - 0.4
Zinc	0.05 - 0.25
Manganese	0.05 - 0.15
Iron	0.05 - 0.7
Chromium	0.04 - 0.35

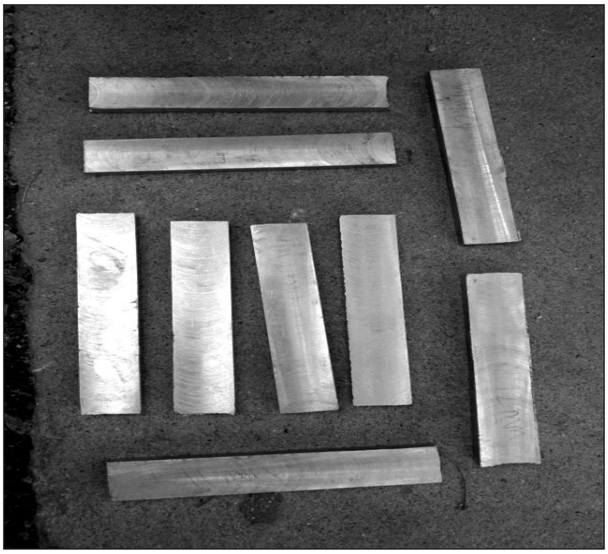


Fig 2. Workpiece Samples

Table 2: Process Parameters

Process Parameter	Level 1	Level 2	Level 3
Thickness of job	10mm	11mm	12mm
Speed of rollers	10	15	20
Reduction	10%	15%	20%

taken into consideration and Taguchi Method using Orthogonal Arrays was adopted to perform the experiment.

Nine trials are conducted according to the design matrix shown in table 3.

Experiment was carried using the design matrix mentioned above and the same used to perform explicit analysis in Abaqus.

Ordinary least squares approach was used in Minitab to perform regression analysis.

$$\arg\min\left\{\frac{1}{N}\sum_{i=1}^{N}(y_i - \beta_o - x_i^T\beta)^2\right\}$$

The same is written in Lagrangian form as:

$$\min\left\{\frac{1}{N}\sum_{i=1}^{N}\left\{y_i - \sum_{j=0}^{M} w_j x_{ij}\right\}^2\right\}$$

3. FINITE ELEMENT ANALYSIS

The Finite Element Method is a numerical analysis procedure used to obtain approximate solutions to boundary value problems that are found in many fields of engineering. Finite Element Method (FEM) is widely being used to solve problems on complicated non-linear metal deformation processes.

Explicit analysis was performed using Abaqus 6.13. The geometry of the exact dimensions was created and the model was meshed using hexagonal element and the same was shown in figure 3.

The following steps were followed while performing the simulation:

- Generate geometry.
- Assign material properties.
- Mesh the geometry.
- Assign initial field and boundary conditions.
- Define interactions and contact surfaces.
- Analyze Stress in work piece.

The results of the simulation are shown in the figure below:

4. EXPRIMENTATION AND OBSERVATIONS

Experimentation is conducted on a computerized hot rolling machine. The equipment is shown in figure 5 and consists of :

- Rollers: Two types of rollers hot and cold with 300mm diameter.
- Motor: An electric motor to control the speed

The observations made from the experiments were recorded in table 4.

These values were taken as input and the analysis was done using the Minitab software. The signal to noise ratios was calculated based on Lower-the-better category and the results were tabulated in table 5.

ANOVA was performed for the obtained

Table 3 – Design Matrix

Trial Number	Inlet thickness of job	Reduction (%)	Speed of rollers (rpm)
1	10	10	10
2	10	15	15
3	10	20	20
4	11	10	15
5	11	15	20
6	11	20	10
7	12	10	20
8	12	15	10
9	12	20	15

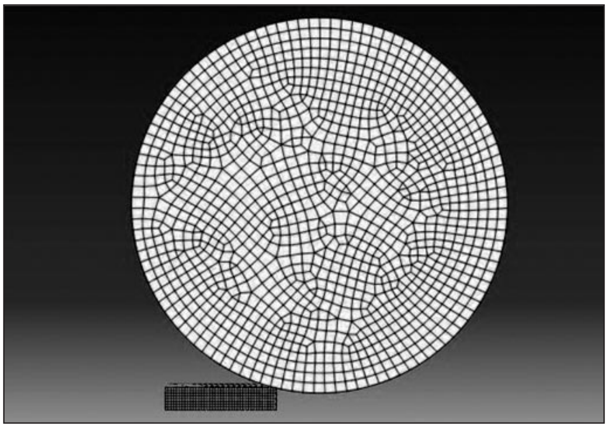
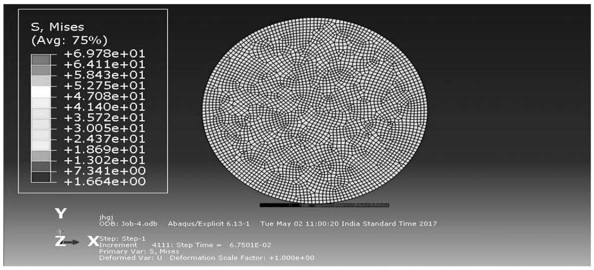
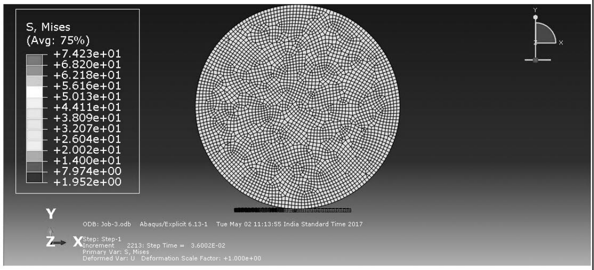


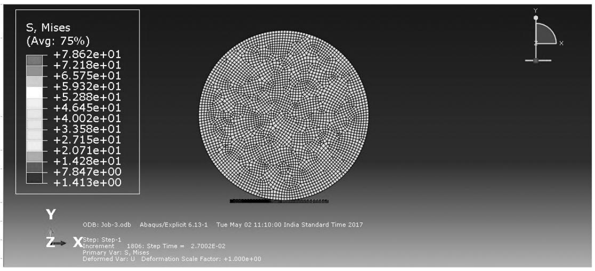
Fig 3. Rolling Finite Element Model



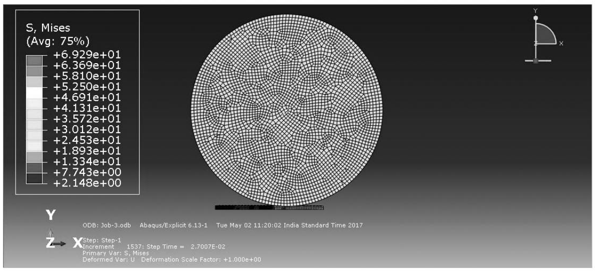
Trail 1:-Maximum von Misses Stress – 69.78 MPa



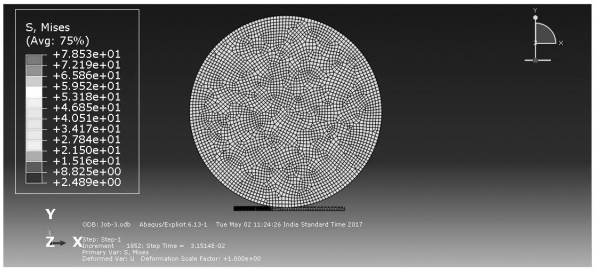
Trail 2:-Maximum von Misses Stress – 74.23 MPa



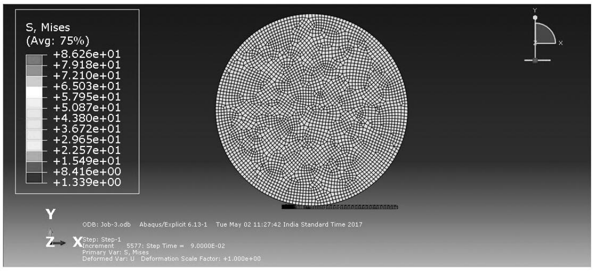
Trail 3:-Maximum von Misses Stress – 78.62MPa



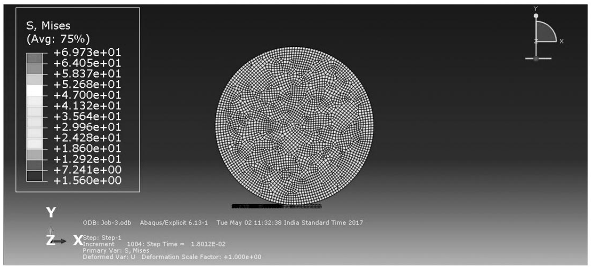
Trail 4:-Maximum von Misses Stress – 69.29 MPa



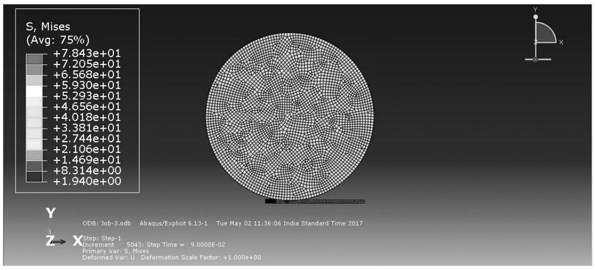
Trail 5:-Maximum von Misses Stress – 78.53MPa



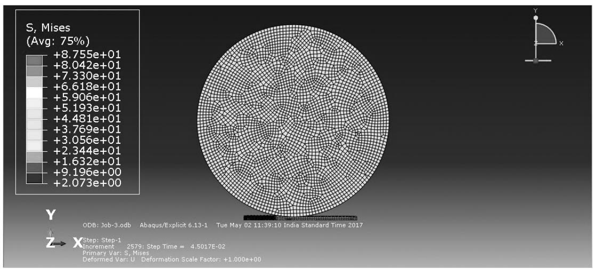
Trail 6:-Maximum von Misses Stress – 86.26 MPa



Trail 7:-Maximum von Misses Stress – 69.73 MPa



Trail 8:-Maximum von Misses Stress – 78.43 MPa



Trail 9:-Maximum von Misses Stress – 87.55 MPa

Fig 4. Von Mises Stresses

Fig 5. Experimental Setup

Fig 6. Workpieces after Experimentation

Table 4: Observations

Trial No.	Inlet thickness of job	Reduction (%)	Speed of rollers (rpm)	Roll Separating Force (MN)
1	10	10	10	0.0306
2	10	15	15	0.0279
3	10	20	20	0.0581
4	11	10	15	0.0313
5	11	15	20	0.0473
6	11	20	10	0.0651
7	12	10	20	0.0262
8	12	15	10	0.0424
9	12	20	15	0.0674

Table 6: Percentage Contribution

Source	Degrees of Freedom	Seq. Sum of Squares	F-Value	% Contribution
Inlet thickness	2	5.655	0.84	7.34
% of reduction	2	69.723	10.35	90.55
Speed of rollers	2	1.648	0.24	2.099
Residual error	2	6.736		
Total	8	83.761		

Table 5: S/N Ratio

S.No	Force	S/N Ratio
1	0.0306	30.2856
2	0.0279	31.0879
3	0.0581	24.7165
4	0.0313	30.0891
5	0.0473	26.5028
6	0.0651	23.7284
7	0.0262	31.6340
8	0.0424	27.4527
9	0.0674	23.4268

Table 7: Validation

S	R^2	Adj. R^2	Pred. R^2
0.007	85.81%	77.30%	59.81%

Table 8: Determination of Coefficients of Model

Term	Coeff	SE Coeff	T value	P value
Constant	-0.0395	0.0374	-1.06	0.339
Inlet thickness	0.000323	0.00317	1.02	0.354
% of reduction	0.003417	0.000634	5.39	0.003
Speed of roller	-0.000217	0.000634	-0.34	0.746

experimental results and the percentage contribution of each parameter on the roll separating force is calculated in table 6.

The effects of those parameters on roll separating force will depend on the percentage contribution. The order is as follows:

Percentage of reduction > Inlet thickness > Speed of rollers

Regression analysis is performed on the above obtained results and a mathematical model is generated. It is as follows

Roll separating force = -0.0395+0.00323*Inlet thickness + 0.003417*Percent of reduction - 0.000217*Speed of roller

The adequacy of the model can be tested by using the residual values at 95 % confidence level. The higher the value of residuals, the higher is the adequacy of the model.

From model summary in table 7, it is clearly known that values of R^2 and R^2 adj are close to 100%, so the adequacy of predicted model is very high.

5. RESULTS AND CONCLUSIONS

Graphical relation between the process parameters and the roll separating force are shown below.

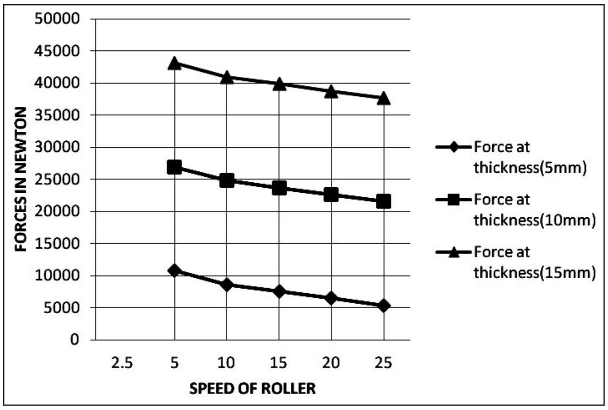


Fig 7. Force vs Speed of Roller

It is observed from this plot that as the magnitude of speed of roller increases from 5 rpm to 25 rpm, the magnitude of force decreases from 10814 N to 5395 N for 5mm thickness sheet, from 26961 N to 21545 N for 10 mm thickness sheet and from 43118 N to 37695 N for 15mm thickness sheet.

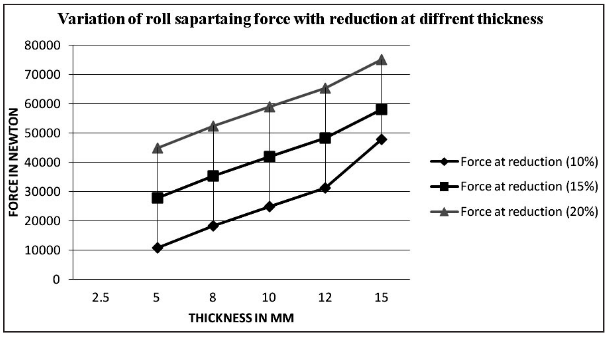


Fig 8. Force vs Thickness at Different Thicknesses

It can be inferred from this plot that as the thickness of sheet increases from 5mm to 15mm, the magnitude of force increases in 3 levels of reduction

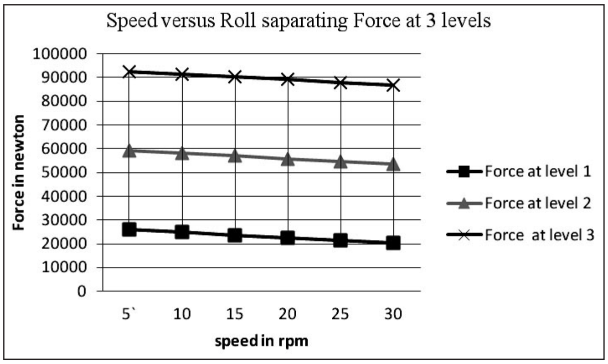


Fig 9. Force vs Speed at Different Levels

In the above plot as the speed varies from 5 rpm to 30 rpm, the force decreases in each step.

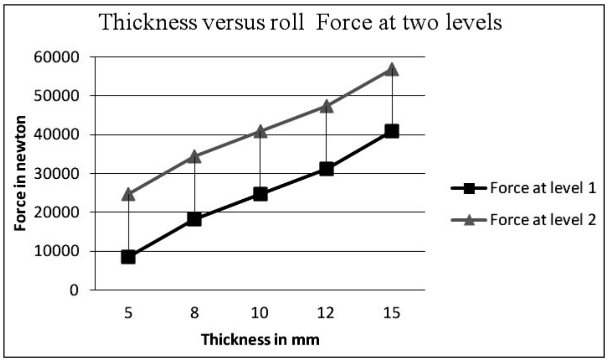


Fig 10. Force vs Thickness at Different Levels

In the above plot as the thickness of sheet increases from 5 mm to 15 mm, the force increases in each step.

From the simulation it is observed that Von Mises Stresses are maximum of 87.55MPa for the

9th trial, where Inlet thickness of job is 12mm, Percentage Reduction is 20% and Speed of rollers is 15 rpm.

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