Investigation of Influence Parameters on the Hot Rolling Process Using Finite Element Method

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Abstract:

Rolling process is one of the most popular processes in manufacturing industries in order to make different parts with a long range variety of dimensions. In this procedure the internal raw material transform into desirable shape by at least two rolls. In comparison with other methods for analyzing the rolling process, the finite element method is the most practical and accurate one, so a coupled thermo elastic plastic three dimensional finite element model is considered to analyze the hot rolling process. In present research the influence of various parameters such as geometry of the slab, temperature, friction between work-rolls and slab, percentage of thickness reduction, rotational speed of work-roll have been studied on process. Outputs like temperature distribution, stress, strain and strain rate fields, roll force have been obtained through different inputs. The outputs of finite element simulation are used to investigate the effects of parameters on product integrity and mechanical properties of part.

Introduction:

The rolling process is one of the most popular processes in manufacturing industries in that almost 80% of metallic equipment has been exposed to rolling, at least one time in their production period. Among all kinds of the rolling processes, the flat rolling is the most practical one. In industrial countries, about 40-60% of rolling products are produced with this type of rolling. [3]

Rolling is a fabricating process in which the metal, plastic, paper, glass, etc is passed through a pair (or pairs) of rolls. In flat rolling the final shape of the product is either classed as sheet (typically thickness less than 3 mm, also called "strip") or plate (typically thickness more than 3 mm). Flat rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its recrystallization temperature, then the process is termed as hot rolling and if the temperature of the metal is below its recrystallization temperature, the process is termed as cold rolling.
There are many studies concentrating on evaluating the temperature field during the hot rolling process. For example, Hollander (1970) has used a one-dimensional FDM model and the assumption of homogenous deformation to estimate the temperature distribution during the hot strip rolling. Devadas and Samarasekara (1986) have predicted the temperature distribution in the hot strip rolled metal as well as in the work roll. In their work the effects of process parameters on the temperature field have been evaluated. Chen et al. (1993) calculated the temperature and strain fields by a coupled FEM and FDM code. The kinetic of iron oxidation during hot rolling has also been investigated in their paper. The temperature variations in work-rolls have been considered in a few papers. Sluzalec (1984) has utilized a two-dimensional finite element method to predict the temperature distribution during hot rolling and Teseng et al. (1990) have estimated the temperature variations in the work-roll in order to evaluate the thermal stress distribution in the rolls. Mori et al. (1982) have developed a finite element method, using the assumptions of rigid-plastic and slightly compressible material to predict the velocity field during isothermal steady and unsteady plane strain rolling conditions. Hwu and Lenard (1988) have used a finite element formulation for flat rolling process to assess the effects of work-roll deformation and various friction conditions on the strain field. Yarita et al. (1988) have analyzed the plane strain rolling process utilizing an elastic–plastic finite element model. They have attempted to predict the stress and strain distribution within the deformation zone using an updated Lagrangian code. Hwnag and Joun (1992) have assessed the hot strip rolling process. The temperature distributions in the rolled metal and in the work-roll and the strain field have been determined in their work. Serajzadeh et al. (2002) investigated strain in homogeneity in hot strip rolling using a two-dimensional unsteady-state finite element method. Duan and Sheppard (2004) investigated the influence of the constitutive equation on the FE modeling of hot rolling of aluminum alloy.

The contact problem has not much been considered in past literature. However, because of its nonlinear nature and its complex condition, it is very important to consider it particularly. Combining the finite element and boundary element methods, Shangwu et al. (1999) carried out the 3D modeling of hot rolling process of flat strips. They predicted rolling force, rolling torque and contact pressure on the roll for both rigid and flexible roll cases. Cavaliere et al. (2001) did research on the influence of parameters such as coefficient of friction and temperature on the distribution of contact stresses. Duan and Sheppard (2002) besides studying the effect of three friction models, considered the contact pressure distribution. They concluded that contact pressure distribution, as a convergence criterion, is greatly sensitive to the number of elements. Arif et al. (2004) simulated roll and strip interaction for a cold rolling process. The main object of this study is to predict roll stresses and deformation behavior by considering both mechanical and thermal loads. Studying the influence of number of elements on the tangential and normal components of contact stresses, they showed that the contact stresses are much sensitive to the number of contact elements. Phaniraj et al. (2005) compared the contact pressure of the roll surface for five rolling stands of a steel strip.
Although the finite element method is a very powerful tool for simulation of the engineering problems, the FE simulation of nonlinear problems is a time-consuming procedure. Nowadays, steel and aluminum manufacturing industries go ahead toward online fault detection in the rolling process with the aim of elimination of these faults during the manufacturing process. For this to be achieved, faster prediction methods for predicting the behavior of the slab under rolling are needed. In the present paper, the hot rolling process of a strip is simulated with commercial FEM program - DEFORM 2D. The roll is assumed to be rigid and for the deformable aluminum strip, the thermo-elastoplastic analysis, through 2D sequential transient thermal and incremental lagrangian analyses, is carried out. This way the effect of different process parameters such as initial thickness of the strip, rolling speed and roll diameter, thickness reduction are studied.

**Finite element modeling:**

A 2D rolling model has been developed to simulate a single pass of the hot rolling process for aluminum alloys using the commercial finite element software, DEFORM-2D.

The rolling parameters use in this work is shown in table 1 and the finite element model is shown as fig 1. Due to the symmetric nature of flat rolling only a quarter of the slab is modeled.

<table>
<thead>
<tr>
<th>Width</th>
<th>Length</th>
<th>Inlet thickness</th>
<th>Outlet thickness</th>
<th>reduction</th>
<th>Temperature</th>
<th>Roll Speed</th>
<th>Roll diameter</th>
<th>Roll Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800 mm</td>
<td>500 mm</td>
<td>580 mm</td>
<td>522 mm</td>
<td>10%</td>
<td>300 °C</td>
<td>40 rpm</td>
<td>495 mm</td>
<td>2000 mm</td>
</tr>
</tbody>
</table>

![Fig1. The FEM model](image)

The deformed material is AA5083. Its flow stress is expressed as Norton-Hoff equation:

\[
\tilde{\sigma} = k_0 (\sqrt{3})^{m+1} \exp (\beta T) \bar{\varepsilon} (\bar{\varepsilon} + \bar{\varepsilon}_0)^n
\]  

(1)
Where $k_0$, $\beta$ are the materials constants, $m$ the strain rate sensitively index, $n$ the strain-hardening index, $\varepsilon_0$ the equivalent strain, $\bar{\varepsilon}$ the equivalent strain rate and $\varepsilon_0$ is the small constant 0.001. For AA5083, [2].

\[ k_0 = 216.29 \text{ Mpa} \quad \beta = -0.00524 \quad m = 0.11 \quad n = 0.0198 \quad \varepsilon_0 = 0.001 \]

Material mechanical and thermal property parameters used in this simulation are given in Table 2&3.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Heat capacity (J/kg.n)</th>
<th>Thermal conductivity (w/m.k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>930</td>
<td>143.4</td>
</tr>
<tr>
<td>280</td>
<td>990</td>
<td>167.1</td>
</tr>
<tr>
<td>306</td>
<td>1010</td>
<td>170.2</td>
</tr>
<tr>
<td>410</td>
<td>1050</td>
<td>174.1</td>
</tr>
</tbody>
</table>

Table 3. Thermal properties

| Heat transfer between the slab and the air | 30 $\frac{KW}{m^2k}$ |
| Heat transfer between the slab and the roll | 25 $\frac{KW}{m^2k}$ |

The slab model is elastoplastic and young’s modulus is 70Gpa and possion ratio is 0.33.

The friction model is coulomb friction model:

\[ \tau = \mu P \]  

(2)

Where $\mu$ is the coefficient of friction and $P$ is the normal pressure [4].

Cook and Maccrum proposed the following formulas for roll separating force $P$ and torque $M$.

\[ P = R' wC_p I_p \]  

(3)

\[ M = 2RR' wC_g I_g \]  

(4)

Where

$C_p$, $I_p$: geometrical coefficients used for force calculations

$C_g$, $I_g$: geometrical coefficient used for torque calculations

The value for these geometrical factors $C_p$, $I_p$, $C_g$ and $I_g$ can be determine from reference [5].
During the rolling process, the temperature distribution in the strip and the work roll can be calculated using the governing partial differential equation shown in the following equation:

\[ k \nabla^2 T + \dot{q} = \rho C \frac{\partial T}{\partial t} \]  \hspace{1cm} (5)

Where \( \rho (kgm^{-3}) \) is the density, \( C (Jkg^{-1}c^{-1}) \) is the specific heat, \( k (Wm^{-1}c^{-1}) \) is the thermal conductivity and \( \dot{q} (Wm^{-3}) \) is a heat generation term representing the heat released due to plastic work.

The thermal boundary conditions in the model are defined as:

At the centerline of the strip, symmetry condition is assumed:

\[ -k_{\text{strip}} \frac{\partial T}{\partial y} = 0 \text{ at } t > 0; \ y = 0 \]  \hspace{1cm} (6)

And at the contact interface between the strip and the work roll, an interfacial heat transfer coefficient is assumed:

\[ q_{\text{strip}} = -q_{\text{roll}} = h(T_{\text{strip}} - T_{\text{roll}}) \text{ at } t > 0; \ y = \frac{Y(t)}{2} \]  \hspace{1cm} (7)

In this paper a FEM with 16000 elements and 18954 nodes is used with a Lagrange incremental solver.

Verification of the results:

The model developed in this investigation is validated by comparing the model predictions of rolling force, temperatures and strains with experimental and theoretical results of Duan and Sheppard [2] (fig 2-4):

Table 4 & 5 shows the rolling parameters using for validation.

<table>
<thead>
<tr>
<th>Inlet thickness</th>
<th>Outlet thickness</th>
<th>Width</th>
<th>Roll radius</th>
<th>Temperature</th>
<th>Roll Speed</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>47.3 mm</td>
<td>1050 mm</td>
<td>465 mm</td>
<td>283 °C</td>
<td>10 rpm</td>
<td>9.46 %</td>
</tr>
</tbody>
</table>

Table 5: Thermal properties

<table>
<thead>
<tr>
<th>Heat transfer between the slab and the air</th>
<th>( \frac{kw}{m^2k} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer between the slab and the roll</td>
<td>( \frac{kw}{m^2k} )</td>
</tr>
</tbody>
</table>
Discussion of results:

The rolling process is analyzed in terms of the rolling speed, the rolling diameter, reduction and temperature of the slab.

- Rolling speed:

Fig 5. Shows the effect of rolling speed on strain rate. It is seen that increasing the rolling speed increases the strain rate.
Fig 6&7. Shows the effect of rolling speed on roll force. It is seen that increasing the rolling speed increases the roll force. This is because of increasing the strain rate results in hardening which causes material to be more resistant to the deformation.

![Fig5. Strain rate versus roll speed](image1)

![Fig6. Roll force versus time with variation of roll speed](image2)

![Fig7. Roll force versus roll speed](image3)

The temperature history of the slab surface for different rolling speed is shown in fig8. The temperature distribution of the slab center versus the time is also shown in fig9.

With paying attention to Fig 8, we can explain that increasing rolling speed results in shorter contact time which decreases heat flow from the strip to the roll and environment. On the other hand, increasing rolling speed can results in more strain rate in the deformation region together with more internal heat generation due to rate of plastic-work.
So we can observe that the minimum temperature of the slab surface is decrease with decreasing of rolling speed with this behavior. From Fig 9, it can be seen that the temperature of the center of the slab increases with time until it reaches its maximum. This is because of heat generation due to the rate of plastic deformation. We can conclude that the maximum temperature of the slab surface is not very much influence by rolling speed.

Fig 8. Temperature on surface versus time with variation of rolling speed

Fig 9. Temperature on center versus time with variation of rolling speed

- **Roll diameter:**

  Fig 10. shows the effect of roll diameter on roll force. It is seen that increasing the roll diameter increases the roll force. This is because of increasing the strain rate results in hardening which causes material to be more resistant to the deformation.

Fig 10. Roll force versus roll diameter
Reduction:

The temperature history of the slab surface for different thickness reductions is shown in Fig. 11. The temperature distribution of the slab center versus the time is also shown in Fig. 12.

From these figures, it can be seen that the minimum temperature of the top surface not vary largely different in all of reductions. It can be explained that more reduction results in longer contact length, which increases heat flow from the strip to the roll. On the other hand, high reduction in constant rolling speed can result in more strain and strain rate in the deformation region together with more internal heat generation due to rate of plastic work. So we can observe the maximum temperature on the slab surface is increase with increasing of reduction.

Temperature:

Fig. 13. Shows the effect of rolling speed on roll force. It is seen that increasing the rolling temperature decrease the roll force. This is because of increasing the flow stress of material.
Conclusion

Through the simulation of the hot flat rolling of aluminum alloy 5083, the following conclusions may be presented:

- Temperature of the strip, during rolling process, depends on several parameters such as interface heat transfer coefficient, rolling speed, and the amount of thickness reduction.
- Roll force of rolling process, depends on several parameters such as temperature, roll diameter and rolling speed.
- All of the parameters on the Hot Rolling Process have been optimized.

References


Fig 13. Roll force versus time with variation of temperature