Modeling for the FE-Simulation of Warm Metal Forming Processes

L. Tong, S. Stahel and P. Hora

Institute of Virtual Manufacturing, Swiss Federal Institute of Technology, Zurich

Abstract. Better formability, less forming force and satisfactory quality are the most important characteristics of warm forming processes. However, the material models for either cold forming or hot forming cannot be directly adopted for the numerical simulation of warm forming processes. Supplement and modification are necessary. Based on the Zener-Hollomon formulation, additional terms are proposed in the presented work to describe the softening effect observed during warm forming processes as well as the strain hardening effect. The numerical simulation provides detailed information about the history and distribution of both deformation and temperature, the phase transformation can then also be evaluated, provided the experimental data are available.

INTRODUCTION

New types of high strength steel have been put into use in the automobile industry in order to reduce the weight of the vehicles. Unfortunately, the materials possess often insufficient formability under ordinary cold forming conditions. This disadvantage can be remedied by introducing warm forming processes. However, the material properties in the temperature range of warm forming exhibit remarkable differences from that of cold or hot forming processes.

First of all, the hardening behavior of the material is not only a function of strain and strain rate. It depends also strongly on the temperature. Recovery, re-crystallization and possible phase transformation make the behavior more complex. Secondly, the temperature of warm forming covers a large range. For example, the temperature decreases from 900°C at the beginning of a sheet forming process to only 400°C in just a couple of seconds. The thermal parameters such as conductivity, heat flux and specific heat vary considerably according to the temperature. Besides, the lubrication condition is affected considerably by the temperature. It is very difficult to describe the tribological phenomenon.

In order to describe the behaviors of the forming materials in a wide range of temperature, many works have been published. Examples are the model proposed by Grosman:

\[ \sigma = C \varepsilon^n \exp(n_1 \varepsilon) \dot{\varepsilon}^{m_1+T} \exp(a_1 T) \]

the description according to Schotten:

\[ \sigma = c_2 \varepsilon^\dot{\varepsilon}^{c_2} \exp(c_1 T) \]

and the model used in the program Forge3:

\[ \sigma = A \varepsilon^{m_0} T^{m_0} \varepsilon^{m_1} (1 + \varepsilon)^{m_2} \varepsilon^{m_3} \varepsilon^{m_4} \]

Obviously the last one is not very easy to use because of the difficulty in determining so many parameters and the lack of physical explanation of each term.

The model from Zener and Hollomon

\[ \sigma = A \exp(Q / RT) \dot{\varepsilon}^n \]

has been widely accepted to describe the viscous plasticity of material behavior at high temperatures.

Based on the Zener-Hollomon description, we proposed a modified form to calculate the yield stress in the warm forming processes. Not only strain rate and temperature but also strain has been included in this description. The softening effect caused by the recovery and re-crystallization has been also considered in the formulation.

The comparison with the experimental data shows the validity of this description. Computation examples
are also presented in this work. Since the numerical simulation delivers the history as well as the distribution of both deformation and temperature, the possible phase transformation can also be evaluated provided that the experimental data are available.

**MATERIAL MODELING**

The yield behavior of the materials is generally a function of strain, stain rate and temperature. The effect of temperature and strain rate is usually considered as negligible at room temperature. In contrast, the function is dominated by these two variables at the high temperature in hot forming processes.

In the temperature range for warm forming processes, the influences of all variables have to be investigated systematically, especially the influences of plastic strain. On the one hand, strain hardening effect exists; on the other hand, the strain softening effect appears due to the recovery and re-crystallization.

As supplement to the Zener-Hollomon description, we suggest the following form to evaluate the yield stress for the simulation of warm metal forming processes:

\[
\sigma = A \exp(Q/RT) \dot{\varepsilon}^n \left(1 + \alpha \exp[-c(\varepsilon - \varepsilon_0)^2] \right) \left[1 - \beta \exp(-N \varepsilon^*) \right].
\]

The expression is composed of 3 parts. The first one \(A \exp(Q/RT) \dot{\varepsilon}^n\) is taken directly from the Zener-Hollomon model. A slight modification is made to separate the functions of temperature and strain rate. The parameter \(Q\) used here equals \(m^*Q\) in the original Zener-Hollomon model. The second term \(1 + \alpha \exp[-c(\varepsilon - \varepsilon_0)^2]\) describes the softening effect caused by either recovery or re-crystallization. The third term \(1 - \beta \exp(-N \varepsilon^*)\) possesses the Hocket-Sherby type behavior and takes the strain hardening effect into account.

The function satisfies the general requirement that it increases with higher strain rate and decreases with higher temperature, as shown in Figure 1.

Figure 2 shows the influence of the plastic strain. The softening effect is described as well as the classical strain hardening effect.

**Discussion and Comparison**

Although 9 parameters are used in this formulation, it is by no means a very complex description because each parameter has its own affect and is independent from each other. For example, the coefficient \(\alpha\) specifies the maximum peak value and \(\varepsilon_0\) defines approximately the position of the peak value. For a material which doesn’t exhibit softening effect, \(\alpha\) can be simply set as zero.

![FIGURE 1. Yield stress as function of temperature and strain rate](image)

![FIGURE 2. Yield stress as function of plastic strain](image)

In order to determine the parameters in the function, many experiments have to be performed at different temperatures and using different strain rates. The least square method is widely used to handle the large mount of data to get the optimum combination of the parameters. Because the equations derived from the least square method are generally nonlinear, iterations are necessary. However, the convergence of the procedure is often conditional. Experience shows that the better the initial values are set, the better the convergence is. With the expression proposed in this work, it is easy to estimate a set of reasonable initial values to start the iteration. Satisfactory convergence is achieved.
Figure 3 shows the comparisons of the calculated curves and the experiment data of the steel 100Cr6. 7 different combinations of temperature and strain rate are investigated. Figure 4 is the comparison using the temperature as variable. Obviously the accuracy is sufficient for the aim of numerical simulation.

![Figure 3. Calculated curves and experiment data](image1)

![Figure 4. Comparison with the experiment data](image2)

**Improvement**

The behaviors of different alloys at high temperature are very complicated. As pointed out by the researchers from the industry, the strains corresponding to the peak values of yield stresses for different strain rates are not a constant. They increase as the strain rate becomes higher because the recovery and re-crystallization possess the property of time-lag.

The improvement is implemented immediately since our formulation is very flexible. Instead of a constant value, the $\varepsilon_0$ increases with increasing strain rate. The result is shown in Figure 5.

Another well know phenomenon is that the recovery and re-crystallization take place only at higher temperatures. As the temperature decreases, they get weaker and weaker and cease at a certain temperature lever.

![Figure 5. Shift of the peak value with different strain rate](image3)

![Figure 6. Re-crystallization by different temperature](image4)

However, it should be kept in mind that the Zener-Hollomon model uses actually only one parameter $Q$ to describe the influence of the temperature. It cannot be expected to cover very wide range of temperatures. Either some more complicated formulations are needed, or we have to set a temperature limit under which the process is actually cold forming and the influence of the temperature is excluded.

**COMPUTATION EXAMPLES**

The model can be applied for the simulation of sheet forming processes as well as for the simulation of bulk forming processes.

**Deep Drawing of thick Sheet**

The first example is simply the simulation of a deep drawing process. The data for steel 100Cr6 is used in the simulation. The sheet thickness $t = 2.4$ mm and the drawing ratio $\beta = 2.2$. In comparison with a
typical deep drawing process with $\beta < 2$, the risk of rupture exists.

<table>
<thead>
<tr>
<th>$A$</th>
<th>$m$</th>
<th>$Q$</th>
<th>$\alpha$</th>
<th>$c$</th>
<th>$\varepsilon_0$</th>
<th>$\beta$</th>
<th>$N$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.186</td>
<td>56620</td>
<td>0.3</td>
<td>10</td>
<td>0.05</td>
<td>0.5</td>
<td>8.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The material parameters for the evaluation of yield stress are listed in Table 1. The initial temperature of the sheet is taken to be $900^\circ$ C.

Figure 7 shows the simulation result when the temperature of all forming tools are kept as room temperature $T = 30^\circ$C. Rupture appears in the wall and the process cannot be performed successfully.

In contrast, if the punch keeps cold but the drawing die and the holder are pre-heated to $550^\circ$C, the process can be performed successfully despite the large drawing ratio. Figure 8 shows the temperature distribution at the end of the forming process.

The example demonstrated that warm forming processes not only improve the formability and reduce the forming force, but also provide more possibilities to achieve better performance of processes.

**A complex forming part**

Figure 9 is the simulation of a complex sheet forming part. The simulation showed that if the forming process is performed within 9 seconds, the temperature of the forming parts can drop from $900^\circ$C to $450^\circ$C if the tools temperatures are set as room temperature. The distribution of the thickness is also shown in Figure 9 b.

However, the simulation of warm sheet forming processes is very complicated because not only the material data are necessary but also the thermal parameters such as the heat flux to the forming tools and the convection coefficient etc. These parameters are very difficult to obtain using simple experiments. If these parameters are not set properly, the distribution of temperature are also incorrect which in turn has strong influences on the mechanical properties of the material. In this case, deviation from the real process is inevitable.

Sometimes the forming processes are accompanied with phase transformations. The phase transformations are usually determined by the distribution and history of temperature and deformation. Since the distribution and the developing of the temperature are evaluated in the simulation as well as the deformation, phase transformations can be calculated provided the TTT (Time-Temperature-Transformation) diagram is available. Figure 10 shows a typical TTT diagram.

In case the phase transformations appear, the yield stress is also a function of the states of microstructure. However, it is beyond the range of this work and should be investigated in the future.
The model proposed in this work can well describe the material behaviors in the warm forming process. Even as many as 9 parameters are used in the model; it is not difficult to determine them using enough experimental data. The model can also be used to fit more complicated phenomenon with some slight modifications.

Computational examples verified the validity of this model. However, in order to get sufficient accuracy, the experiments must be well designed to get correct material data. Furthermore, the most important task of FE-simulation is the prediction of possible failures in the processes. Since the concept of classic forming limit diagrams (FLD) cannot be directly transplanted for the warm forming processes, new measures are needed to perform this task.

FIGURE 10. A typical TTT diagram for steels

ACKNOWLEDGMENTS

The authors are grateful to Mr. L. Burkhardt for performing the comparison shown in Figure 3 and the valuable discussions.

REFERENCES

7. Spittel, M., Neubauer, S., Betrachtungen zur mathematischen Fließkurvenbeschreibung, Neue Hütte 28 (1983), S. 21-25