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TEMPERATURE DEPENDENT FRICTION MODELING FOR SHEET METAL FORMING

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ABSTRACT: Stainless steel in sheet metal forming processes show a hardening behavior, which can be described only in dependency of the deformation and temperature history. Because of the temperature influence to the material properties, the temperature dependence of the friction in the process has to be taken into account. Friction tests using different temperatures showed a change of the friction regime. From the experimental observation the temperature and velocity dependence of the friction was modeled and integrated in a finite element code for metal forming. On the macroscopic scale the temperature and velocity dependent friction was integrated in a FEM code of metal forming. The FEM simulation has been applied to the biaxial stretching test and compared with the experiment. The numerical results showed a good agreement with the failure behavior of the stainless steel.

KEYWORDS: Friction modeling, FEM simulation, Lubrication

1 INTRODUCTION

In the manufacturing of stainless sheet metal products process are optimized to the requirement for efficiency as well as for quality improvement and for the augmentation of piece variety. Different lubrication regimes may occur in different areas of the interface or at different time due to different factors influencing the friction like temperature, normal force, velocity. Since strain distribution in the workpiece is influenced by friction, the formability of the workpiece depends not only on the material property but also on the friction.

There are different approaches to include the dependencies of the friction. Keum et al. [1] measured experimentally the effects of lubricant viscosity, surface roughness and hardness of the sheet, punch velocity and die corner radius on the friction. He suggested a mathematical model of the friction coefficient as a function of friction parameters. This is an empirical model on the macroscale easy to use in a computer simulation but it does not consider the physical processes. For a more theoretical approach the processes in the microscopic scale has to be considered. In this scale it's possible to divide the friction in the different regimes. For the boundary friction regime a lot of models consider the asperity contact, most of them with the static equilibrium solution in pure flattening [2], [3], [4] and [5]. The asperity contact in sliding flattening is more complicated, because of the additional tangential stress. Lo and Yang [6] proposed a new concept of asperity flattening. The different friction regimes depends on the surface topography affecting the formation and transport of lubricant. Results of different textured surfaces modeled with a finite element simulation on the microscopic scale were presented in [7]. This model distinguishes explicitly between the different friction regimes by calculating the boundary friction at the real contact area and the hydrodynamic friction in between.

The friction in sheet metal forming of autenitic stainless steel has an important impact because of the deformation and temperature dependent hardening behaviour because of the strain-induced martensitic transformation. For the modeling of the forming process the deformation, temperature and phase structure are essential factors for a proper description of the material properties. So the influence of temperature and velocity to the friction coefficient has to be considered.

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2 FRICTION IN SHEET METAL FORMING

The tribosystem in metal forming processes consists of the elastic tool, the elasto-plastic sheet, and the visco-elastic lubricant in between. In the commonly used FEM simulation the explicit consideration of the lubricant in the calculation is ignored as well as the topography of the surfaces. The friction is taken into account with simple friction models such as the Amontons law

$$\tau_F = \mu \sigma_N \tag{1}$$

or the shear friction model

$$\tau_F = mk \tag{2}$$

with τ_F the shear friction, μ and m the friction coefficient, σ_N the normal pressure and k the shear stress of the softer material. With this equations the influence of the lubricant and the topography of the surfaces are integrated in the friction coefficient without the dependence of velocity and temperature. However, the friction depends on the contact formation of the tool and sheet metal with the lubricant in between. The force of the tool is applied by asperities in contact as well as by the lubricant between the asperities in lubricant pockets. The first friction regime results into boundary friction, where the size of this contact zone and the composition of the additives play an important role. For the boundary friction regime in the sheet metal forming process the friction stress can be expressed as:

$$\tau_b = \tau_a A + \tau_p A \tag{3}$$

where A is the fractional contact area and τ_a and τ_p are the adhesion and plowing friction stress components. In the case of smooth tool and relatively rough workpiece as the normal condition in sheet metal forming, the plowing component can be neglected.

The full film lubrication or hydrodynamic friction regime depends on the viscosity of the lubricant and can be written as

$$\tau_h = \eta \frac{v_{rel}}{h} \tag{4}$$

where η is the viscosity, v_{rel} the relative velocity and h the thickness of the lubricant layer.

Because in sheet metal processes local temperature variations can occur, the temperature dependence of the viscosity has to be considered. The temperature dependence can be described with the equation of Vogel[8]:

$$\eta = Ae^{\frac{B}{T+C}} \tag{5}$$

where A,B and C are constants and T the temperature in Kelvin.

The contact formation is directly connected to the viscosity of the lubricant. With lower viscosity the boundary friction is becoming more dominant because of the increase in the real contact area. This temperature-viscosity dependence of the friction can be expressed similar to the temperature dependence of the viscosity in equation 5:

$$\mu = 1 - ae^{\frac{b}{T+c}} \tag{6}$$

.

The velocity dependence of the friction is assumed as linear decreasing:

$$\mu = k_1 v_{rel} + k_2 \tag{7}$$

where k_1 and k_2 are constants. This has been validated by the friction tests later on.

As mentioned in the introduction the friction in sheet metal forming of stainless steel takes place in the mixed lubrication regime. This regime is the combination of the boundary friction and the hydrodynamic friction regime and can be written as

$$\tau_F = \tau_b A + \tau_h (1 - A)\,. \tag{8}$$

The problem is to determine the friction in the mixed lubrication. So the real contact area A_R has to be known. In the macroscopic finite element simulation the determination of the real contact area A_R is not possible, because the surface geometry with the asperities are not considered. For this reason the mixed lubrication can not be simulated from the hydrodynamic and boundary friction. However a way to model the friction regimes is to measure the friction dependence of the velocity and temperature in the tribosystem and to use the measured friction dependencies in the simulation with the according characteristics of equation 6 and 7. The two equations are composed together by multiplication:

$$\mu = (k_1 v_{rel} + k_2)(1 - av_{rel}e^{\frac{b}{T+c}}) \tag{9}$$

This is an macroscopic friction description in contrast to the equation 8 with 3 and 4. So it is not possible to distinguish between the boundary and hydrodynamic friction.

3 RESULTS

The determination of the friction for the macroscopic finite element simulation of the sheet metal forming of stainless steel has been done by pin-on-disk tests. The measured data have been approximated by the theoretical model shown in section 2. Then the biaxial stretch forming process is used to compare the simulation with the experiment.

3.1 EXPERIMENTS

Several Experiments were carried out to measure the friction behavior of the stainless sheet metal forming. The hydrodynamic friction depends on the viscosity, which itself is strongly temperature dependent. This temperature dependence is important for the contact formation between sheet metal and tool. With increasing temperature the viscosity decreases and the real contact area grows. The temperature dependence of the viscosity was measured on a Paar Physica MCR 300 Rheometer and approximated with the equation 5.

In the sheet metal forming of stainless steel the contact conditions are varying among others in temperature and speed. According to this the friction is changing depending on the conditions. With the pin-on-disk test it is possible to measure the friction coefficient at different velocities and temperatures. However the pin-on-disk test simulates rather the boundary lubrication regime. It exists only a small contact area and the influence of the hydrodynamic friction is low compared to the contact condition in sheet metal forming. This results in a higher friction coefficient for the pin-on-disk test compared to the sheet metal forming.

To get the velocity and temperature dependency of the tribosystem stainless steel - lubricant - tool, several pin-on-disk tests were carried out.

The friction coefficient of this tribosystem was measured for three different velocities $v_1 = 0.0007$ m/s, $v_2 = 0.01$ m/s and $v_3 = 0.16$ m/s and for three different temperatures $T_1 = 23°$ C, $T_2 = 60°$ C and $T_3 = 100°$ C. In figure

1 the results of the measured friction coefficients are plotted.

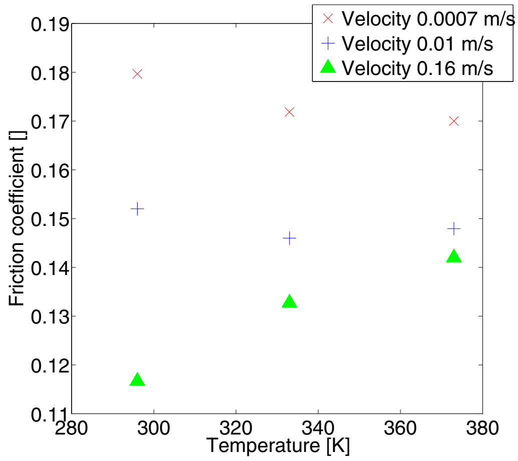

Figure 1: *Friction coefficient for three velocities and three temperature measured with the pin-on-disk test*

For the temperature dependence of the hydrodynamic lubrication regime the parameter of equation 6 can be approximated by the data of the Pin-on-disk tests in figure 1.

In sheet metal forming the full film lubrication regime contributes more to the mixed friction than in the pin-on-disk test. This test shows the dependency of the influencing parameters.

3.2 MODELING

In order to investigate the friction the biaxial stretch forming process is simulated and compared with experimental data. The temperature dependence of the friction was implemented in a finite element code for sheet metal forming and compared with the experimental measurement of the stretch forming process. The blank is 1.4301 (AISI304) steel of 0.7 mm thickness. The diameter of the punch is 100 mm. The setup of the biaxial stretching test is shown in figure 2.

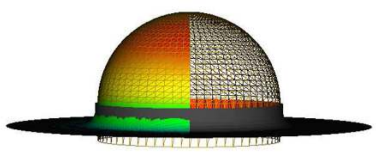

Figure 2: *Setup of the biaxial stretching test*

Figure 3 shows the radial strain distribution predicted by the simulation for the two different velocities. With the lower velocity and therefore the higher friction the highest strain appears at the side. However with the higher velocity the highest strain arises at the pole.

The biaxial stretch forming process had been conducted by two different velocities to simulate two different tribological conditions. A punch speed of 0.167 mm/s and 0.83 mm/s has been used. Due to the different velocities there is a difference in the temperature due to the heat flux.

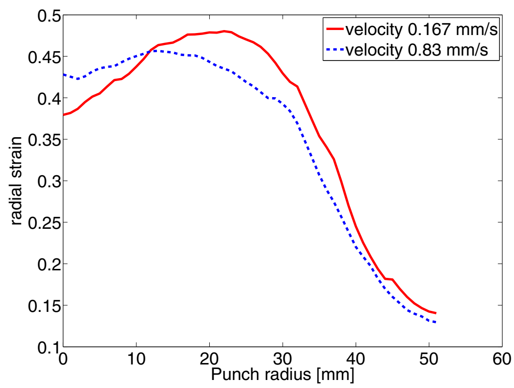

Figure 3: *Radial strain distribution in the simulation for the two velocities.*

The punch speed of 0.167 mm/s simulates the mixed lubrication with more importance of the boundary friction. Besides the slow speed results in moderate temperature because of the heat conduction. With a punch speed of 0.83 mm/s the higher velocity implies more importance of the hydrodynamic friction.

For the slow punch speed the failure occures at the side of the sphere. But for the faster speed the sheet metal fails at the pole of the biaxial stretching test. In figure 6 the failure for the two different speeds are shown

The finite element simulation were conducted by using the macroscopic friction model. In figure 4 the radial strain for the simulation with a constant friction coefficient is shown. The distribution is similar for the two different velocities, for the higher velocity the highest strain values tends to move toward the side of the punch.

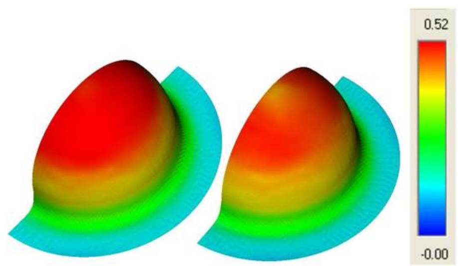

Figure 4: *Radial strain distribution of the simulation with constant friction coefficient: left 0.167 mm/s, right 0.83 mm/s*

The influence of the temperature and velocity dependent friction is shown in figure 5. For the slow velocity the highest strain appears at the side of the punch. In the case of the higher velocity the highest strain occurs at the pole. This behaviour has been confirmed by the biaxial stretching test in figure 6.

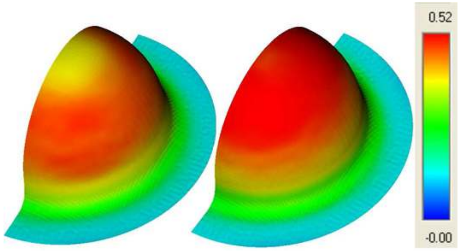

Figure 5: *Radial strain distribution of the simulation with thermal and velocity dependent friction: left 0.167 mm/s, right 0.83 mm/s*

Figure 6: *Failure of the biaxial stretching test for different speeds and different lubrication: left 0.167 mm/s, right 0.83 mm/s*

4 DISCUSSION

The tribological tests show the temperature and velocity dependence of the friction. In the hydrodynamic lubrication regime the friction has a similar temperature dependence as the viscosity. For slow velocities, i.e. in the boundary friction regime the temperature dependency is very low and tends to decrease with higher temperature (figure 1). This can be explained by the temperature dependence of the material in the interface layer.

In the biaxial stretching test the temperature and velocity have an important influence to the friction. For the slow punch speed the temperature is low. The failure occur at the side of the specimen. With the simulation this can be explained by the high friction because of the low velocity. The temperature influence is small because of the low heating of the sheet metal due to the slow forming velocity. In the case of the higher punch speed the friction is lower because of the higher velocity. The higher temperature is less important for the friction than the velocity. Because of the lower friction the sheet metal fails at the pole. The peak value of the radial strain is greater in the slow velocity case and the position of the peak value of the radial strain is about 22 mm. For the higher velocity case the peak value of the radial strain is smaller and the position of the peak value of the radial strain is near the center of the punch. The distribution of the friction coefficient due to the velocity and temperature dependence effects the strain distribution significantly. The lower friction results in a lower peak value of the radial strain.
The failure behaviour of the biaxial stretching test using the two velocities can be explained with the temperature and velocity dependent friction.

5 CONCLUSIONS

The temperature dependence of friction has been found to be connected to the temperature dependence of the viscosity. The pin-on-disk test showed this dependence for high relative velocities. This shows the higher importance of the hydrodynamic friction for higher velocities in the mixed lubrication. In contrast for slow velocities the boundary lubrication regime contribute more to the friction. With the finite element simulation these two effects could be shown in the biaxial stretching process. For slow velocities and therefore low temperature the friction is high and the radial strain shows the highest values at the side of the punch. The higher velocity causes lower friction and the highest strain values moves to the pole. Hence it is important to consider the temperature and velocity dependence of the friction for stainless sheet metal forming. It is possible to implemente the dependencies by empirical models in the FE-simulation. However it is not possible to calculate the exact fraction of hydrodynamic friction and the boundary friction with the macroscopic friction model.

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