CHAPTER 6

Evaluation of Friction in Warm Conditions
6.1 APPROACH IN THE INVESTIGATION

In deep drawing operations, good lubrication helps to reduce wrinkling, premature fracture, and localized thinning \[65,78\]. Furthermore, lubrication also reduces tool wear in large-volume production. Determination of reliable friction data associated with a given lubrication system is also important for successful process design and simulation by Finite Element analysis. Especially, when the deep drawing operation is being performed under warm conditions, the prediction of the friction becomes complex as its value increases with temperature.

In deep drawing, severe friction takes place at the flange area. The lubrication in the flange area influences the thinning, and possibly, failure of the side wall in the drawn cup.

In the investigation, the draw ratio (diameter of blank/diameter of punch) is selected to be 2.2. Round blanks of Extra Deep Drawn (EDD) quality steel with 64 mm diameter and 1mm thickness were prepared for experimentation. These blanks are drawn into cups both at room temperature and at \(200^\circ\text{C}\) and their punch-displacement curves are recorded using data acquisition system. Since the sticking tendency of blank due to friction increases by increase in temperature, so a high
temperature Mo base lubricant Molykote is used between the blank and tooling both at room temperature and at 200°C.

6.2 **FINITE ELEMENT ANALYSES AND EVALUATION OF FRICTION**

LS Dyna is a simulation tool to mimic the operations, deep drawing, bending stretching, fluid assisted deep drawing etc. The stresses and strains that come out of the drawn cup at variable design and process parameters can be seen in the post processor and the process parameters can be optimized. Input models are constructed in the pre-processor (DYNAFORM 5.6.1). The relevant properties of EDD steel found out at room temperature and at 200°C are shown in Table 6.1.

**Table 6.1 Properties of EDD steel at 200°C**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Property</th>
<th>Rolling direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>Room</td>
<td>Yield Strength (N/mm²)</td>
<td>187.7</td>
</tr>
<tr>
<td>Temperature</td>
<td>Ultimate Tensile Strength (N/mm²)</td>
<td>331.5</td>
</tr>
<tr>
<td>0°</td>
<td>n</td>
<td>0.32</td>
</tr>
<tr>
<td>45°</td>
<td>K (N/mm²)</td>
<td>615.3</td>
</tr>
<tr>
<td>90°</td>
<td>r</td>
<td>1.59</td>
</tr>
<tr>
<td>200°C</td>
<td>Yield Strength (N/mm²)</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td>Ultimate Tensile Strength (N/mm²)</td>
<td>301.5</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>K (N/mm²)</td>
<td>615.3</td>
</tr>
<tr>
<td></td>
<td>r</td>
<td>1.59</td>
</tr>
</tbody>
</table>
Four node quadrilateral and triangular shell elements of thickness 1.0 mm were used for the blank and the tool components were treated as rigid bodies. Blank was discretized into 400 elements.

It is reported by researchers [79-82] that explicit analysis can be accelerated by increasing the process speed, for instance, by increasing the punch speed in stamping or the pressurizing rate in a hydro-mechanical forming operation, which is called time scaling technique. Simulations are performed in the code at variable process parameters like punch speed, blank holding force and blank diameter etc. which are taken similar to the experiment as recorded by data acquisition system. Since the material under investigation is EDD steel which is highly anisotropic, Barlat 3 parameters model was used in the study. Simulations were carried out at 2 different punch speeds and the load displacement curves can be plotted from the post processor files of LS DYNA.

It was observed during the characterization of material that up to 200 °C, the material shows small regions of work hardening and there is also some anisotropy related to the material. So during simulation at room temperature and at 200 °C, transversely anisotropic elastic plastic
model was used to simulate the process and also to calculate the friction in the deep drawing process.

This fully iterative plasticity model is available only for shell elements. The input parameters for this model are: Young's modulus $E$; Poisson’s ratio $\nu$; the yield stress; the tangent modulus $E_t$; and the anisotropic hardening parameter $R$.

Consider Cartesian reference axes which are parallel to the three symmetry planes of anisotropic behavior. Then the yield function suggested by Hill can be written

$$F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2$$

$$+ 2L\sigma_{yz}^2 + 2M\sigma_{zx}^2 + 2N\sigma_{xy}^2 - 1 = 0 \quad \text{-------- (6.1)}$$

Where $\sigma_{ox}$, $\sigma_{oy}$ and $\sigma_{ox}$ are the tensile yield stresses and $\sigma_{xy}$, $\sigma_{yz}$ and $\sigma_{zx}$ are the shear yield stresses. $F = G = H = \frac{1}{2\sigma_0^2}$ is also the mean flow stress if the material is showing some work hardening characteristics. The constants $F$, $G$, $H$, $L$, $M$ and $N$ are related to the yield stress by

$$2L = \frac{1}{\sigma_{yz}^2} \quad \text{-------- (6.2)}$$
\[ 2M = \frac{1}{\sigma_{zx}} \]  
\[ 2N = \frac{1}{\sigma_{xy}} \]  
\[ 2F = \frac{1}{\sigma_{oy}} + \frac{1}{\sigma_{oz}} - \frac{1}{\sigma_{ox}} \]  
\[ 2G = \frac{1}{\sigma_{oz}} + \frac{1}{\sigma_{ox}} - \frac{1}{\sigma_{oy}} \]  
\[ 2H = \frac{1}{\sigma_{ox}} + \frac{1}{\sigma_{oy}} - \frac{1}{\sigma_{oz}} \]

The isotropic case of Von Mises plasticity can be recovered by setting

\[ F = G = H = \frac{1}{2\sigma_o^2} \]  
\[ L = M = N = \frac{1}{2\sigma_o^2} \]

For the particular case of transverse anisotropy, where the properties do not vary in the x-y plane

\[ 2F = 2G = \frac{1}{2\sigma_{oz}^2} \]  
\[ 2H = \frac{2}{\sigma_o^2} - \frac{1}{\sigma_{oz}^2} \]
\[ N = \frac{2}{\sigma_0^2} - \frac{1}{2\sigma_{o2}^2} \]  

--- (6.12)

Where it has been assumed that \( K = \frac{\sigma_0}{\sigma_{o3}} \)

Letting \( K = \frac{\sigma_0}{\sigma_{o3}} \), the yield criterion can be written

\[ F(\sigma) = \sigma_x = \sigma_y \]  

--- (6.13)

\[ F(\sigma) = [\sigma_{xx}^2 + \sigma_{yy}^2 + K^2\sigma_{zz}^2 - K^2\sigma_{zz}(\sigma_{xx} + \sigma_{yy}) - (2 - K^2)\sigma_{xx}\sigma_{yy} \]

\[ +2L\sigma_y^2(\sigma_{yz}^2 + \sigma_{zx}^2) + 2\{2 - \frac{1}{2}K^2\}\sigma_{xy}^2] \]  

--- (6.14)

The rate of plastic strain is assumed to be normal to the yield surface so is found from

\[ \dot{\varepsilon}_{ij}^p = \lambda \frac{\partial F}{\partial \sigma_{ij}} \]  

--- (6.15)

Now consider the case of plane stress, where \( \sigma_{zz} = 0 \). Also, define the anisotropy input parameter \( R \) as the ratio of the in-plane plastic strain rate to the out-of-plane plastic strain rate:

\[ R = \frac{\dot{\varepsilon}_{22}^p}{\dot{\varepsilon}_{33}^p} \]  

--- (6.16)
It then follows that

\[ R = \frac{2}{K^2} - 1 \]  \hspace{2cm} (6.17)

Using the plane stress assumption and the definition of \( R \), the yield function may now be written

\[ F(\sigma) = \left[ \sigma_{xx}^2 + \sigma_{yy}^2 - \frac{2R}{R+1} \sigma_{xx} \sigma_{yy} + 2 \frac{2R+1}{R+1} \sigma_{xy} \right]^{\frac{1}{2}} \]  \hspace{2cm} (6.18)

Using this material model it was found that there was accurate predictions of LDR by simulations both at room temperature and at 200°C.

It can be observed in the Fig. 6.1 that by varying punch speeds in the simulation there is a drastic change in the punch load.

![Fig. 6.1 Punch load Vs displacement diagram from the simulation at 2 different punch speeds](image-url)
This study also confirms the research carried out by Taylan [82] that simulation must be carried out at the same punch speed used in the experiment.

The ram speed used in the experiment is 5 mm/sec and after giving all the material properties to the code like UTS, YS, strength coefficient, strain hardening exponent and anisotropies in three different directions, on a dual core 2.2 GHz processor with 4GB ram one simulation took around 26 hours with 30 mm punch displacement and writing 100 plot states. Punch load Vs displacement graph from the experiments are superimposed with simulations at different coefficient of friction at room temperature and at 200°C are given in Fig. 6.2 and 6.3 respectively.

![Fig. 6.2 A comparison of punch load Vs displacement diagram from the simulation at different coefficient of friction and from experiments at room temperature](image)

It can be observed in the load displacement curves of simulated cups that there are some fluctuations in the load. It is due to oscillation of nodes [82]. The coefficient of friction used in the mathematical model as developed in the present investigation is calculated by this finite element technique. Since coefficient of friction is a property of two mating surfaces (material) and by increasing the temperature, coefficient of friction increase. For drawing to happen, the friction between the dies and the blank material should be as less as possible and the friction between the punch and die should be as high as possible.

Fig. 6.3 A comparison of punch load Vs displacement diagram from the simulation at different coefficient of friction and from experiments at 200° C
To decrease the coefficient of friction between the die and the blank material, a molybdenum based lubricant called ‘Molycote’ is used in the present research. This lubricant is specifically effective at high temperatures. By varying coefficient of friction in the simulation, the load displacement curve that matches with the experimentation (at a particular temperature) is the coefficient of friction between the blank material and die under that environment. It is found that the coefficient of friction at 200°C is 0.02 and at room temperature is 0.09.