Thermal effects and friction in forming

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1. Thermal effects and friction in forming

1.1 Temperature in metal forming

In cold forming operations, the energy supplied for deformation of metal is converted into heat inside the metal. Some of the heat may get dissipated through the surface. The metal undergoes rise in temperature as a result of energy accumulation. If overheating occurs, localized melting or grain boundary melting may occur. This will collapse the metal. Defects such as hot tearing may happen due to excess heating. Frictional heating also leads to increase in temperature of the work piece material.

Temperature of the work piece material during forming depends on several factors. Hot forming involves heating the work piece to high temperatures. The final temperature of the material can be given by the expression:

\[ T_f = T_i + \Delta T_d + \Delta T_f - \Delta T_c \]

\( \Delta T_d \) is the increase in temperature due to deformation energy, \( \Delta T_f \) is temperature rise due to friction and \( \Delta T_c \) is the drop in temperature due to heat dissipation from the metal due to radiation, convection and conduction heat loss.

During deformation of a material, the amount of plastic work done per unit volume is given as \( \bar{\sigma} \bar{\varepsilon} \). Of the total plastic work, \( \bar{\sigma} \bar{\varepsilon} V \), a small fraction, 5%, goes into formation of vacancies, dislocations in the microstructure. The remaining fraction, \( \beta \) or 95% of strain energy is stored as internal energy \( (m C \Delta T_d) \) within the metal. Therefore we can write the temperature rise due to deformation energy as:

\[ \Delta T_d = \beta \bar{\sigma} \bar{\varepsilon} V / m C = \beta \bar{\sigma} \bar{\varepsilon} / \rho C \]

where \( m \) is mass of work piece, \( C \) is specific heat capacity of the material and \( \rho \) is density.

The above expression is obtained by equating the fraction of stored internal energy to plastic work done. If strain rate is to be included in the expression, we can modify the above expression as:

\[ \Delta T_d = \beta \bar{\sigma} \dot{\varepsilon} \Delta t / \rho C \]

where \( \Delta t \) is time.
1.2 Frictional heating:
We know that the work done in overcoming friction between the die and work piece is given by:

\[ \dot{W}_f = \text{Frictional shear force} \times \text{velocity of flow} \times \text{volume of work piece} = \tau A v V = m k A v V \]

\( v \) is the velocity of deformation, \( V \) is material volume and \( A \) is area of contact between tool and work piece. We can equate the work done to rise in internal energy of the material due to frictional heating. It is given as:

\[ m k A v \Delta t V = m C \Delta T_f \]

Therefore,

\[ \Delta T_f = \frac{k A v \Delta t V}{C} = \frac{m k A v \Delta t}{p C V} \]

\( K \) is the shear yield strength of the material.

We can now determine the temperature of the work piece as followed:

In hot forming, the work piece gets chilled out due to its contact with the cold die material. Heat loss from the work piece is assumed to occur by conduction and convection modes. The entire work piece is considered as a single lump with respect to the heat loss. The temperature of the work piece material at any instance is given by the expression:

\[ T(t) = T_i + (T_i - T_{\text{die}}) \exp(-\frac{k t A}{p C V}) \]

\( T_i \) is the initial material temperature.

We can now write the current material temperature as:

\[ T = T_i + (T_i - T_{\text{die}}) \exp(-\frac{k t A}{p C V}) + \Delta T_d + \Delta T_f \]

This expression gives us the actual temperature of the work piece at a given instance, in terms of the heat dissipated, temperature change due to strain energy and friction.

1.3 Temperature measurements in forming:
Accurate measurement of temperature of the work piece and die materials during forming is important in order to estimate the forming load and other parameters. Temperature of exposed surfaces could be measured using radiation pyrometer if the die/metal temperatures are very high. The most popular method of measuring temperature is using thermocouples. Thermocouples with high sensitivity, such as Platinum-Rhodium thermocouples could be embedded in the die or work piece material. Time response of thermocouple should be as low as possible so that within the short duration of the forming process we could measure the
temperature. Thermocouples could be inserted into bored hole inside the die and located at
different places near the die surface. Transient temperature distribution on die surface during
hot forming could be established using mathematical models for the heat transfer occurring on
the surface of die. Finite element modeling could be employed for simulating the forming
process as well as mapping the die/work piece temperatures.

Temperature of working is important from the point of view of flow stress, metallurgical
structure and final properties of the formed product. Hot working is performed at temperatures
above recrystallization temperature or above 0.5Tm. Tm is melting temperature. In hot working
strain rate effects are more pronounced. The strain rate sensitivity parameter increases with
temperature. Therefore, while performing hot forming, control of strain rate becomes
important. Excessive strain rates may result in adiabatic conditions, leading to internal heating
of work material. Excessive temperature rise may result in localized melting or hot shortness of
work material. If on the other hand, slow rates of deformation are employed in hot forming, the
material might cool down to temperatures lower enough to enhance the flow stress. As a
result, the formed product could develop cracks and other surface defects. There should be a
compromise between strain rate, temperature of working and working pressure in order to
achieve a formed product without defects. Upper limit of forming temperature is based on
surface oxidation, localized melting and hot-shortness. Lower temperature of forming is
decided by the rate of recrystallization sufficient enough to avoid strain hardening. In hot
forming, there is no work hardening due to recrystallization and recovery processes. Rapid
cooling and fast working requires higher temperatures of working. Other factors such as
dynamic recrystallization and dynamic recovery are also considered in hot forming.

The flow stress in hot forming is found to be complex function of temperature, strain rate. It
can be given by the expression:

\[ \sigma = A \dot{\varepsilon}^m e^\beta/T \]

In hot forming the flow stress of the material remains constant due to the fact that the work
hardening effects due to dislocation motion are countered by recovery and recrystallization.

1.4 Friction in forming:
Friction arises between two surfaces in contact as a result of interlocking of the asperities.
Asperities are microscopic valleys and depressions on surfaces. Friction between the tool and
work piece surfaces plays considerable role in forming. First, friction enhances the forming load.
Second, it leads to poor surface finish on the formed part. Third, it leads to considerable
increase in temperature-frictional heating. Die life is reduced due to friction. Friction also
results in non-homogeneous deformation of the material during forming. Therefore, friction
has to be understood and ways of reducing it have to be devised if forming loads are to be reduced.

Fig. 1.4.1: Asperities on surfaces of two contacting objects

There are two types or models of friction identified in forming. Coulomb friction model is applicable for sliding friction. Two surfaces in sliding contact can be modeled by the Coulomb model. This model is most appropriate in forming operations such as rolling, drawing, sheet forming etc in which the normal pressure/stress is lower than or equal to the material flow stress. According to this model, the frictional shear stress is related to normal pressure by the relation: \( \tau = \mu p. \)

In forming processes such as closed die forging, extrusion the normal pressure is considerably greater than the flow stress. As a result, the friction at the contact surface can be said to be sticking friction. This model is called Tresca model. The frictional shear stress at interface can be taken to be proportional to the shear yield strength of the material \((k)\). We can write, for Tresca model: \( \tau = mk. \)

According Coulomb's friction model, the friction force is proportional to normal reaction force. Therefore, we have: \( \mu = F/Fn. \) \( \mu \) is called coefficient of sliding friction or simply coefficient of
friction. It appears from the expression: \( \tau = \mu p \) that the coefficient of friction is dependent on normal pressure. This gives a misleading idea about \( \mu \).

According to Tresca model of friction we can write: \( \tau = mk \), where \( m \) is called friction factor. \( M \) varies between 0 and 1. If \( m = 1 \) we have the interfacial shear stress equal to the shear yield strength. In such a situation, we have sticking friction. The surfaces get interlocked with each other so that they could not slide against each other. Material beneath the surface undergoes shear deformation. The die material should not deform plastically and the work material could undergo plastic deformation. Sticking friction could happen at normal stresses greater than the flow stress by at least a factor of 3. Under the circumstances, the soft work material penetrates into the surface of the die material.

According to Coulomb model, the frictional stress increases with coefficient of friction, as the shear force is proportional to normal pressure. According to Tresca model, the frictional shear force is independent of the normal pressure, because, the shear stress is proportional to shear yield strength, which is a constant. In mixed mode of friction, both Coulombic model and Tresca model could happen simultaneously. It has been experimentally verified that when a cylindrical work piece is upset, along the outer circumference there is sticking friction, and inside – towards axis of forming there is sliding friction. This can be due to the runout of the lubricant and hence the metal-to-metal contact along the periphery.

1.5 Lubrication:
In order to avoid direct metal-to-metal contact we have to introduce a lubricant at the interface. The normal pressure or the shear stress will be transferred to the thin lubrication oil film. The oil film will support the normal pressure.

Dry friction is supposed to happen when the two surfaces are in direct contact. In this case, the oxides of the two surfaces are in direct contact. If the surface of a metal is exposed to atmosphere, it immediately forms a layer of oxide. The oxide layers may or may not act as lubricants. Therefore, dry friction is to be avoided in forming. The two oxides formed on the two surfaces may differ from each other, in terms of strength. This is due to the fact that each metal may have differing oxidation characteristics.

Hydrodynamic lubrication involves the separation of the two surfaces with the help of a thick film of lubricant. This kind of lubrication is common in extrusion, drawing, deep drawing, rolling etc. When the lubricant is drawn into the wedge shaped gap between the die and workpiece, and when the die or work piece move fast, the lubricant forms a thick film with sufficient pressure to separate the die and work piece surfaces. High forming velocity is required for hydrodynamic or thick film lubrication. Thick film lubrication is sometimes undesirable. It
reduces the surface finish—surface appears rough and matt finish like. Thin boundary lubrication is preferred for good surface finish with shiny surface.

Boundary lubrication involves the formation of a thin film of lubricant which separates the surfaces. In this type of lubrication, the load is uniformly transferred from die to work surface. Moreover, higher loads can be transferred across the film. The net result is good surface finish and uniform surface deformation. Therefore, for metal forming thin film lubrication is most desirable. Lubricants such as stearates, contain polar molecules which react with the surface oxides and establish strong bonding. This increases the shear strength of the film, thereby preventing metal to metal contact. Fatty acids, compounds of phosphorous and sulfur are also used as lubricants for boundary lubrication. Solid lubricants such as graphite, molybdenum disulfide form shear layers, which can provide the lamellae aligned parallel to the surfaces. Molten glass is used as lubricant for hot forming such as hot extrusion. Other lubricants include boron nitride, Teflon, calcium fluoride, cerium fluoride and polyethylene. Lubricant absorption on surface could be improved by phosphate treatment of steel surfaces. In cold extrusion of ferrous materials, phosphate coating is used a carrier of lubricant. For some alloy steels oxalate coating is preferred. For hot extrusion of non-ferrous alloys, graphite or lube oil are used as lubricant. Hydrodynamic lubrication is used during wet drawing of wires, in which the wire is dipped in a liquid lubricant container before drawing. The lubricating oil sticks to the surface of the wire. Due to high speed, the oil is hydro-dynamically drawn into the die and forms a film.

1.5.1 Contact stress measurement:
Contact stress between die and work piece can be measured using pins inserted in dies. Holes are made on the die surfaces, extending down through some dept. Pins ate inserted inside the holes, one pin perpendicular to the die surface and another one inserted at an angle. The other end of the pin inside the hole is provided with a force transducer. Transducer can measure the normal force and hence normal stress acting on the pin which is orthogonal to die surface. The inclined pin will sense the force exerted from which one can deduce the shear stress. Friction stress can also be measured using the pins.

1.5.2 Measurement of friction coefficient:
Conventionally, friction coefficients or friction factor could be estimated using the ring compression test. The ring compression test was described in one of the earlier lectures. Here we will try to understand one of the modern methods of measuring coefficient of friction – the pin-on-disk test. This method is quiet suitable for measuring sliding friction and friction coefficient – under lubricated or dry conditions. In this simple test, a pin shaped specimen is held against a rotating hardened disk, by applying a constant normal load. Using a cantilever and load cell arrangement, the friction force is measured. A data logging arrangement will plot the variation of coefficient of friction with respect to time duration of the test. Each time
friction force acts on the cantilever the force is measured by the load cell. The test can be conducted with lubricant supplied at the pin-disc interface in order to characterize the lubricant.

\[ \mu = \frac{F}{N} \]

**Fig. 1.5.2.1: Pin-on-disk test**  
**Fig. 1.5.2.2: Friction measurement in drawing**

For measuring the coefficient of friction under sliding – for example the sliding of a sheet metal between die surfaces a simple strip draw test can be used. In this test, the strip made from the test material is pulled through a pair of die blocks. The die blocks are held together by applying a lateral force. The force on the strip in order to draw it is measured. The ratio of this force / reaction force is the friction coefficient. In order to find the friction coefficient in drawing or extrusion, we can pass the strip or wire through a conical die or a pair of inclined dies. The force for drawing or extrusion and the force for die separation are measured. From this the coefficient of friction is can be determined.
**Typical friction coefficient values in forming:**

**Cold forming:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Rolling</th>
<th>Extrusion</th>
<th>Forging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>0.06 – 0.1</td>
<td>0.05 – 0.1</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.03 – 0.06</td>
<td>0.05 – 0.1</td>
<td>0.05 – 0.07</td>
</tr>
<tr>
<td>Mild steel</td>
<td>0.05 – 0.1</td>
<td>0.05 – 0.1</td>
<td>0.05 – 0.1</td>
</tr>
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</table>