Abstract: - Closed die forging is a very complex process and the measurement of actual forces for real material is difficult and cumbersome. Hence the Computer Simulation modelling technique has been adopted to get the estimated load requirement. The objective of this work is to simulate and analyze the closed die forging process. The main focus is on the load requirement which has been compared to the actual load requirement and the deviation has been reported in the form of percentage error.

Key words: - Algorithm, Design, Simulation, Modular approach, Modeling, Closed die forging, H/D ratio.

1 Introduction

In the present highly competitive era, the mass production requirements in the engineering industries have increased the demand for forged components. Forging process, usually involve multiple pre-forming processes followed by a specified finishing process. Process simulation has become an increasingly important tool for the development of new or improved processes. With simulation tools the costs and the time necessary for the development of new products could be reduced. These processes require a lot of experience & skill to optimize the quality, costs and lead time.

The objective of this work is to simulate and analyze the closed die forging process. The main focus is on load requirement, die cavity filling at different stages of forging of AISI 1016 by a computer simulation technique. In this paper, a method has been applied to simulate and analyze the complete closed die forging in two stages i.e. deformation before flash formation & deformation after flash formation.

The designs based on results of simulation are required to be evaluated to make sure that the material would flow as per the requirement in the die cavity.

2 Modeling of Forging

For the purpose of simulation of closed die forging process, a cylindrical shape billet with different H/D ratio have been deformed between two die halves as shown in Fig. 1. The deformation before flash formation has been depicted in Fig. 2 where as Fig. 3 shows the deformation during the flash formation stage.
2.1 Estimation of the Flow Stress

Forging is a deformation process which involves several variables interconnected by more or less complex function. The method discussed here, used to simulate the hot die forging process to determine the stresses and the load. The flow stress relationship has been implemented as a subroutine.

\[ \sigma_f = C \dot{\varepsilon}^m \]  

(1)

Where, \( C = f(\varepsilon, T) \)

The parameters \( C \) and \( m \) are available in the tables for the various materials for the various forming processes.

2.2 Strain Calculations

The strains and the stresses have been calculated in the die cavity and in the flash.

The strain before flash formation (Fig. 2) could be computed as,

\[ \varepsilon = \ln(H/h) \]  

(2)

During flash formation (Fig. 3), the strain in flash may be evaluated as,

\[ \varepsilon_1 = \varepsilon_{ic} + \ln(\bar{t} / \bar{\varepsilon}) \]  

(3)

At the end of forging, the material is assumed to flow in to flash by shearing along the surface indicated in Fig. 3 by dashed line. Therefore in the zone between the shearing line and the die, the strain \( \varepsilon_2 \) is equal to \( \varepsilon_{ic} \) and strain \( \varepsilon_3 \) in the shearing zone is:

\[ \varepsilon_3 = \varepsilon_{ic} + \ln(\bar{h} / \bar{h}) \]  

(4)

\[ \bar{h} = 0.8\bar{t}(L/2\bar{t})^{0.92} \]  

(5)

In the convergence region 4 (Fig. 3), the height \( h_1 \) could be calculated as:

\[ h_1 = (\bar{h} + \bar{t}) / 2 \]  

(6)

And the strain,

\[ \varepsilon_4 = \varepsilon_{ic} + \ln(\bar{h} / \bar{h}) \]  

(7)

2.3 Strain Rate Calculation

The strain rates are calculated according to the following:

Before flash formation, Fig. 1(b):

\[ \dot{\varepsilon} = v / \bar{h} \]  

(8)

The strain rates after Flash formation (Fig. 3) may be computed as,

\[ \dot{\varepsilon}_1 = v / \bar{t} \]  

(9)

\[ \dot{\varepsilon}_3 = v / \bar{h} \]  

(10)

\[ \dot{\varepsilon}_4 = v / \bar{h}_1 \]  

(11)

2.4 Stress Calculation

The stress before flash formation as shown in Fig. 2 may be computed as,

\[ \sigma_{max} = \sigma_f (1 + (\mu_i D / h)) \]  

(12)

The stresses after flash formation (Fig. 3) could be evaluated as,

\[ \sigma_{z2} = 2\mu_i \sigma_f \left( w / \bar{t} \right) + \sigma_f \]  

(13)

\[ \sigma_{z1} = (K_2 / K_1) \ln(\bar{t} / K_2 + K_2 r_2) + \sigma_{z2} \]  

(14)

\[ \sigma_{max} = ((2\mu_i \sigma_f r_1) / h) + \sigma_{z1} \]  

(15)

Where,

\[ K_1 = -2 \tan \beta \]  

(16)

\[ K_2 = -\sigma_{f2} K_1 + 2\mu_2 \sigma_{f2} (1 + \tan^2 \beta) \]  

(17)

\[ K_3 = \bar{h} - r_2 K_1 \]  

(18)

\[ \tan \beta = \left[ 1 - \{(\bar{h} / \bar{t} - 1) \ln(\bar{h} / \bar{t})\} \right]^{1/2} \]  

(19)

2.5 Force Calculation

The force required for deformation before flash formation for the geometry as shown in Fig. 2 could be,

\[ F = 2\pi \sigma_f ((h^2 / 4\mu_i^2) \exp(D/h - 1) - hD/4\mu_i)] \]  

(20)

The force required for deformation after flash formation for the geometry as shown in Fig. 3 would be,

\[ F = F_1 + F_2 \]  

(21)

Where,

\[ F_1 = 2\pi \sigma_f ((\bar{h}^2 / 4\mu_i^2) \exp(\mu_i L / \bar{h} - 1) - \bar{h}L/4\mu_i)] \]  

(22)

\[ F_2 = \sigma_f (\pi / 4)(2Lw + w^2)(1 + (\mu_i w / 3\bar{t})) \]  

(23)

\( F_1 \) is the average force on the billet and \( F_2 \) is the average force on the flash land.

3 The Modular Approach

In the modular approach, the part geometry may be divided in to eight basic regions as shown in Fig. 4. The eight regions are divided in such a manner so that, as the top surface descends vertically, as a result of an external force of unit velocity, the inner and outer surfaces of the
rings move inward or outward from the axis as shown in Fig. 4 & 5.

The boundaries of these regions may be considered as either rigid tools or as rigid parts of adjacent elements of the work piece. For each of these eight regions shown, a general admissible velocity field may considered as shown in Fig. 4 & 5 for rectangular and triangular flow; both inward and outward, which could be given as below. The parameters A, B, R, z and \( \alpha \) are defined in Fig. 6. \( \dot{u} = du/dt \) and \( \dot{w} = dw/dt \) are the radial and axial velocities, respectively.

Rectangular flow inward
\[
\begin{align*}
\dot{u} &= -(1 - R^2) / 2AR \\
\dot{w} &= -z / A \\
\dot{w} &= (1 - B)z / 2AR
\end{align*}
\]

(24)  \( \dot{w} = -z / A \)

(25)  \( \dot{w} = (1 - B)z / 2AR \)

Rectangular flow outward
\[
\begin{align*}
\dot{u} &= (R^2 - B^2) / 2AR \\
\dot{u} &= (1 - B)(B + R) / 2AR \\
\dot{w} &= -z / A \\
\dot{w} &= (1 - B)z / 2AR
\end{align*}
\]

(28)  \( \dot{u} = (R^2 - B^2) / 2AR \)

(29)  \( \dot{u} = (1 - B)(B + R) / 2AR \)

(30)  \( \dot{w} = -z / A \)

(31)  \( \dot{w} = (1 - B)z / 2AR \)

Triangular flow inward
\[
\begin{align*}
\dot{u} &= -\cot \alpha (1 + (1 / R)) / 2 \\
\dot{w} &= (z \cot \alpha / 2R) + 1
\end{align*}
\]

(32)  \( \dot{u} = -\cot \alpha (1 + (1 / R)) / 2 \)

(33)  \( \dot{w} = (z \cot \alpha / 2R) + 1 \)

Triangular flow outward
\[
\begin{align*}
\dot{u} &= \cot \alpha (1 + (1 / R)) / 2 \\
\dot{w} &= -(z \cot \alpha / 2R) + 1
\end{align*}
\]

(34)  \( \dot{u} = \cot \alpha (1 + (1 / R)) / 2 \)

(35)  \( \dot{w} = -(z \cot \alpha / 2R) + 1 \)
Once the velocity components for any of the eight basic regions are known then the strain rates could be evaluated as,

\[ \dot{\varepsilon}_R = \frac{\delta \dot{u}}{\delta R} \]  
(36)

\[ \dot{\varepsilon}_Z = \frac{\delta \dot{w}}{\delta R} \]  
(37)

\[ \dot{\varepsilon}_\phi = - (\dot{\varepsilon}_R + \dot{\varepsilon}_Z) \]  
(38)

\[ \dot{\gamma}_{RZ} = (\delta \dot{u} / \delta z + \delta \dot{w} / \delta R) \]  
(39)

The rate of internal energy dissipation would be calculated for that field as follows:

\[ \dot{E} = (\sqrt{2}/3)\sigma_f \int (\dot{\varepsilon}_R^2 + \dot{\varepsilon}_Z^2 + \dot{\varepsilon}_\phi^2 + \dot{\gamma}_{RZ}^2/2) dV + \sigma_f \int m\dot{S} ds \]  
(40)

The first volume integration in Eq. (40) has to be carried out throughout the entire volume of the part geometry and the second surface integration is required to be carried out for over all surfaces. When considering the total rate of energy dissipation may be represented as,

\[ \dot{E}_t = \sigma_f \sum_{i=1}^{i=n} e_i A_i V_i \]  
(41)

### 4 Simulation Algorithm

A computer simulation algorithm has been developed consisting of two separate loops for the two stages of forging process viz. deformation process before flash formation and deformation process after flash formation. For the process simulation, initially the material is required to be selected from the material data base. The die parameters, billet parameters, no. of stages of deformation are required to be provided then the algorithm start simulations & computations. Simulation gives the output results step by step for height, diameter, die temperature, billet temperature, strain, strain rate, flow stress and load requirement. At the end of the simulation, the algorithm asks for any modifications, if any, may be change of material or dimensions for the next simulation & computations.

### 5 Results and Discussion

Fig. 7, 8 & 9 shows the graph of Actual Load (kN), Estimated Load from simulation (kN) and % error plotted against the Stroke length (mm) for the H/D ratio of 1.9, 1.4 & 1.0 respectively for the flash thickness of 2 mm.

From the fig. 7, 8 & 9, it could be clearly seen that as the stroke proceeds, the load requirement for the deformation increases. At a particular stroke length, the increase in the load is steep; this is the point where the flash formation starts. The stroke length for flash formation to start is different for different H/D ratio. As the H/D ratio decreases, the billet diameter would increase to keep the constant volume of the billet material. The actual load and estimated load have been plotted and are in good agreement for all the cases studied as shown in Fig. 7, 8 & 9.
The value of percentage error between actual load requirement and the estimated load for the H/D ratio of 1.9 varies from 1.12 % to 4.14 %. For the H/D ratio of 1.4, the percentage error ranges from 1.21 % to 3.72 %. The percentage error for the H/D ratio of 1.0 has been found to vary between 2.01 % to 4.51 %.

6 Conclusions

Finally, it may be concluded that the success of the simulation technique to estimate the deforming load requirement for the closed die forging operation would depend upon the following:

- The selection of material parameters from the Material property database should match with the actual metallic material. If the percentage error is more than 10 % then the material properties are required to be obtained by the suitable material testing method.
- The friction conditions prevailing between the die & billet material during the actual deformation process and the simulation are required to be nearly same.
- Accuracy of the simulation would be governed by the parameters such as the H/D ratio, Strain rate, the flow of material in the die cavity and strain hardening property of the actual material.

However, due to the complexity of forging operations, the material and process condition, the manufacturing by forging process is still a very much dependent upon trial runs, which results into increased lead-time. An integrated forging simulation and optimization approach would significantly improve the overall process of the components manufactured by closed die forging.

7 Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>(\sigma_f)</td>
<td>Flow stress</td>
</tr>
<tr>
<td>(C)</td>
<td>Strain hardening constant</td>
</tr>
<tr>
<td>(m, n)</td>
<td>Strain rate sensitivity exponent</td>
</tr>
<tr>
<td>(L)</td>
<td>Die diameter</td>
</tr>
<tr>
<td>(H)</td>
<td>Initial Height of Billet</td>
</tr>
<tr>
<td>(D_o)</td>
<td>Initial Diameter of Billet</td>
</tr>
<tr>
<td>(l_i)</td>
<td>Initial distance between flash lands of two die halves</td>
</tr>
<tr>
<td>(T)</td>
<td>Temperature</td>
</tr>
<tr>
<td>(\sigma_{\text{max}})</td>
<td>Maximum stress during forging</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Strain</td>
</tr>
<tr>
<td>(\dot{\varepsilon})</td>
<td>Strain rate</td>
</tr>
<tr>
<td>(\varepsilon_c)</td>
<td>Strain at the beginning of the flash formation</td>
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<tr>
<td>(v)</td>
<td>Ram speed</td>
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</tbody>
</table>

8 References


