Cold forging of sintered polygonal disc with bulging of sides

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Investigations on various aspects of cold forging of iron powder preforms, compacted and sintered from atomized iron powder, are reported here. During forging, both the bulging of sides and barreling along the thickness take place. Solution is given for forging without considering inertia effect of an N-sided polygonal sintered disc between two flat dies, taking into account the bulging of sides only. An attempt has been made to determine the die pressures developed during the cold forging of square iron powder preform by using an upper bound approach. The results so obtained are discussed critically to illustrate the interaction of various involved process parameters.

Metal-powder components are assuming an important position in industry. Both the mechanical and the metallurgical properties of the metal powder components compare favorably with those of wrought materials. Bulk processing of metal powder preforms is a convenient method of reducing or eliminating the porosity from the conventional powder metallurgy products. The process avoids a large number of operations, high scrap losses and high-energy consumption associated with the conventional manufacturing processes such as casting, machining, etc. The sintered porous powder preforms are used as starting materials in metal forming processes. Metal powder products, thus manufactured, are comparable and in some cases even superior to those of cast and wrought products.

Although many investigations are reported on various technological aspects of the industrial processing of metal-powder preforms, no systematic attempt has been made so far to study the processing load and deformation characteristics during forging of N-sided sintered polygon considering bulging of sides. Bulging (non-uniformity of flow along the thickness) is the common phenomenon in forging process. It is expected that the present work will be of great importance for the assessment of die load during the forging of metal powder preforms.

Theoretical

Friction condition between deforming tool and work piece in metal forming are of the greatest importance concerning a number of factors such as force and mode of deformation, properties of the finished specimen and resulting surface roughness. The relative velocity between the work piece material and the die surface together with high interfacial pressure and/or deformation modes will create the conditions essential for adhesion in addition to sliding.

The pattern of the metal flow during the forging of a metal powder preform is such that two zones exist; an inner one where no relative movement between work piece and die occurs (the sticking zone) and an outer zone where sliding occurs. Therefore, the appropriate friction laws for particular condition is:

\[ \tau = \mu \left[ \rho + \rho_0 \left( 1 - \frac{r}{n \sin(\pi/N)} \right) \right] \]

where \( r \) denotes the sticking zone radius and which may be approximated by the relation gives by Rooks and \( n \gg 1 \), \( N \) = number of sides.

Velocity field and strain rates—The material flow developed during the forging of a regular polygonal disc is not symmetrical, but the complete disc can be divided into triangular regions in which identical flow is developed. Fig. 1 shows a section of a regular polygon disc being forged between two flat dies with its center at \( O \). POQ is one of the symmetrical triangle into which it can be divided. The line ON is perpendicular to PQ. During the forging the sides of the polygon bulge out and become curved in the plane section of the test piece. Because of symmetry the radial lines OP, OQ and ON remain straight and retain
the angular relationship between them. Moreover, there is no shear deformation on the vertical planes passing through these lines. The flow patterns in the triangles PON and QON are mirror images of each other. In the triangle PON, the metal flow is described by the velocity field, expressed in cylindrical coordinates, as:

\[ U_r = \frac{(1-2\eta)}{2(1+\eta)} \left( \frac{U}{h} + rB\cos(N\theta) \right) \]  

... (2)

\[ U_\theta = \frac{(1-2\eta)}{2(1+\eta)} \left( 2rB\sin(N\theta) \right) \]  

... (3)

\[ U_z = -\frac{zU}{h} \]  

... (4)

The strain rates are calculated from the relations (2), (3) and (4) as:

\[ \dot{\varepsilon}_r = \frac{(1-2\eta)}{2(1+\eta)} \left( \frac{U}{h} + B\cos(N\theta) \right) \]  

... (5)

\[ \dot{\varepsilon}_\theta = \frac{(1-2\eta)}{2(1+\eta)} \left( \frac{U}{h} - B\cos(N\theta) \right) \]  

... (6)

\[ \dot{\varepsilon}_z = -\frac{U}{h} \]  

... (7)

\[ \dot{\varepsilon}_\theta = \frac{(1-2\eta)}{2(1+\eta)} \frac{hB\sin(N\theta)}{2} \]  

... (8)

The above normal strain components satisfy the compressibility equation for powder compacts:

\[ \varepsilon_r + \varepsilon_\theta + \varepsilon_z = \pm 2\eta(\varepsilon_z - \varepsilon_r) \]  

... (9)

\[ U \] denotes the velocity of the top die, the bottom die is assumed stationary. 'B' is unknown constant. Rate of dissipation of deformation energy (\( W_i \)) is given by:

\[ W_i = \frac{2}{\sqrt{3}} \sigma_0 \left[ \frac{1}{2} \left( \dot{\varepsilon}_r + \dot{\varepsilon}_\theta + \dot{\varepsilon}_z + \dot{\varepsilon}_\theta \right) \right] \frac{1}{2} dV \]  

... (10)

The yield stress for powder material is given as:

\[ \sigma_0 = \frac{\rho \sigma_0}{(1-2\eta)} \]

After putting the value of strain rates from Eqs (5), (6), (7) and (8), we get,

\[ \Rightarrow \frac{\sqrt{2/3} \sigma_0}{h} \left[ \frac{(1-2\eta)^2}{4(1+\eta)^2} \right] + \frac{(1-2\eta)^2}{2} + 2B^2\cos^2(N\theta) \]

\[ + \frac{N^2B^2\sin^2(N\theta)}{2} + \frac{U^2}{h^2} \right] dV \]

\[ \Rightarrow \frac{\sqrt{2/3} \sigma_0}{h} U \left[ \frac{(1-2\eta)^2}{4(1+\eta)^2} + \frac{(1-2\eta)^2}{2} + \frac{K^2N^2}{4(N^2/4)} \right] \frac{1}{2} dV \]

\[ \left( \frac{\cos^2(N\theta) - (N^2/4)\cos^2(N\theta)}{N^2/4} \right) \] is very small compared to unity because the value of \( K \) is quite small. Therefore, above equation can be simplified to:

\[ dW_i = \frac{\sqrt{2/3} \sigma_0}{h} U \left[ \frac{(1-2\eta)^2}{2(1+\eta)^2} \right] + 1 \frac{1}{2} dV \]
Here \( V \) is the volume of polygon disc and is equal to \( NA^2 \cdot tana \), and \( A \) is the perpendicular distance from center to side of disc.

So,

\[
W_v = \sqrt{2/3} \sigma_y U N A^3 \left[ \frac{(1-2\eta)^2}{2(1+\eta)} + 1 + \frac{K^2 N^2}{4} \right]^{1/2} \tan \alpha
\]

Rate of dissipation of frictional energy \((W_f)\) is given by:

\[
W_f = \int_0^h \tau \left( \Delta v \right) ds
\]

\[\Delta v = \left( U_v + U_o \right)\]

After pitting the value of \( U_v \), \( U_o \) and \( \tau \) from relations \( (2) \), \( (3) \) and \( (1) \) respectively and integration, we get:

\[
W_f = \frac{N(1-2\eta) \mu A^3}{3(1+\eta)h} \left[ F(\alpha) + K \cdot f(\alpha) \right]
\]

\[
= \left[ p + \rho_0 \phi_0 \left( 1 - \frac{3}{4n \cdot \sec(\pi / N)} \right) \right]^{1/2}
\]

where, \( F(\alpha) = \frac{1}{4} \left[ \log(\tan \alpha + \sec \alpha) + \tan \alpha \cdot \sec \alpha \right] \)

and \( f(\alpha) = \int_0^\pi \left[ \cos(N\theta) + \frac{2}{N} \sin(N\theta) \right] \sec^3 \theta \ d\theta \)

\[\alpha = \frac{\pi}{N}\]

The value of \( f(\alpha) \) can be calculated by partial integration or numerical. The values of \( f(\alpha) \) for a few polygonal discs are given in the Table 1.

Die load—For plastic deformation of a metal powder the external power \( J \) supplied by the platen is given as:

\[
J = W_i + W_f + W_o + W_f
\]

The first term on the right hand side denotes the rate of internal energy dissipation \( W_i \), the second term denotes the frictional shear energy losses \( W_f \), the third term denotes the energy dissipation due to inertia forces \( W_o \), and the last term covers power supplied by predetermined body tractions \( W_f \). In this case forces due to inertia are negligibly small and no external surface traction is stipulated. Therefore, \( W_o = W_f = 0 \).

Now the external power \( J \) supplied by the press through the platen is:

\[
J = \int F U \ ds = P \cdot U = W_i + W_f
\]

After putting the value of \( W_i \) and \( W_f \) from Eqs \( (11) \) and \( (13) \) respectively and rearranging, we get:

\[
P = \left[ \frac{N(1-2\eta) \mu A^3}{3(1+\eta)h} \left\{ F(\alpha) + K \cdot f(\alpha) \right\} \right]^{1/2}
\]

\[
\times \left\{ \frac{2}{3} \sigma_y N A^2 \tan \alpha \left[ (1-2\eta)^2 \left\{ \frac{K^2 N^2}{4} \right\} \right] \right\}^{1/2}
\]

Also,

\[
\rho = \frac{P}{N A^2 \tan \alpha}
\]

\( \eta \ll 1 \), where \( x = 0.1, 0.2, 0.3, \ldots \ldots \)

For square Plate:

\( A = b \) (half the side of the plate)

\( \alpha = \frac{\pi}{4} \) and \( N = 4 \) (\( N \) = number of sides)

For \( P \) to be minimum with respect to \( K \), gives \( \frac{\partial P}{\partial K} = 0 \) which will give the value of \( K \).

<table>
<thead>
<tr>
<th>No. of sides</th>
<th>Value of ( \alpha )</th>
<th>Value of ( f(\alpha) )</th>
<th>Value of ( F(\alpha) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>( \pi/3 )</td>
<td>-0.15896</td>
<td>1.19525</td>
</tr>
<tr>
<td>4</td>
<td>( \pi/4 )</td>
<td>0.09680</td>
<td>0.5738</td>
</tr>
<tr>
<td>5</td>
<td>( \pi/5 )</td>
<td>0.09097</td>
<td>0.393</td>
</tr>
<tr>
<td>6</td>
<td>( \pi/6 )</td>
<td>0.07267</td>
<td>0.3039</td>
</tr>
<tr>
<td>9</td>
<td>( \pi/9 )</td>
<td>0.03069</td>
<td>0.1859</td>
</tr>
<tr>
<td>12</td>
<td>( \pi/12 )</td>
<td>0.02910</td>
<td>0.1355</td>
</tr>
<tr>
<td>18</td>
<td>( \pi/18 )</td>
<td>0.108636</td>
<td>0.0886</td>
</tr>
</tbody>
</table>
Experimental

Atomised iron powder of purity more than 98% and finer than 150 microns was used throughout the experiment. The iron powder was supplied by M/s Mahindra Sintered Products Limited, Pune, India. The physical and chemical properties of iron powder supplied are given in Table 2 and Table 3.

Iron powder was compacted in a closed square die. The die wall was lubricated with graphite. The five green compacts were prepared at 1000 psi. These compacts were sintered at 1300°C under endothermic sand atmospheric temperature for 2 h. The specimens were re-sintered for the purpose of uniform distribution of density. The average relative density was found to be 0.80. The specimens were made by machining the compacts to the dimensions 20 mm square plate and 10 mm height. These compacts were placed between flat dies until cracks were observed at peripheral surfaces. The load versus deformation curves were drawn after noting the values of deformation under different loads. This same procedure was repeated for rest of the specimen. Thus, an experimental load versus percentage reduction in height curve was obtained for iron powder preforms having an initial relative density of 0.80.

Results and Discussion

Fig. 2 shows the theoretical forging load distribution against the percentage reduction in height curves at a particular value of coefficient of friction for iron powder preform of various initial relative densities of compacts. The experimental load versus percentage reduction in height curve has been superimposed on the theoretical curves. It is observed that the relative density of the preform increases sharply during initial phase of loading. It is due to the fact that initially large amount of load is consumed in compaction and then after gaining sufficient relative density, it is deformed and gives a uniform proportionate curve. To study the relative density variation with increase in load a few arbitrary points are chosen on the experimental curve and corresponding load and relative density values are obtained. Fig. 3 shows the variation of forging load with percentage reduction in height at different coefficient of friction values. Forging load increases as coefficient of friction increases. Similarly in Fig. 4, the forging load increases with increasing the value of x.

Table 2—Physical characteristics of the atomised iron powder used (Apparent density=3.90 g/mL; Tap density=4.30 g/mL)

<table>
<thead>
<tr>
<th>Screen Analysis (micron)</th>
<th>+150</th>
<th>−150</th>
<th>−106</th>
<th>−75</th>
<th>−63</th>
<th>−45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retained (Wt%)</td>
<td>0</td>
<td>38.00</td>
<td>12.50</td>
<td>9.00</td>
<td>22.00</td>
<td>17.00</td>
</tr>
</tbody>
</table>

Table 3—Chemical analysis of sintered powder compacts (wt%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.35</td>
<td>0.15</td>
<td>0.43</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fig. 2—Theoretical forging load variation with percentage reduction in height of the preform at different initial relative density

Fig. 3—Theoretical forging load variation with percentage reduction in height of the preform at different coefficient of friction
Fig. 4—Theoretical forging load variation with percentage reduction in height of the preform at different value of $x$

Fig. 5—Relative density variation with forging load

Fig. 6—Theoretical forging load variation with percentage reduction in height of the preform at different value of bulging constant

Fig. 7—Theoretical forging load variation with percentage reduction in the height of the preform, the forging load rapidly increases for a particular value of coefficient of friction and bulging constant. Initially, the closing of pores dominates the compression process. The larger amount of applied load is utilized in densification and lesser amount is consumed for compression. The weaker orientation breaks down to form a much stronger orientation. After attaining $\rho = 1$, the preform deforms significantly. The compressibility of metal powder preforms improves with increase in initial relative density. Density distribution will be more uniform for a higher initial relative density of the preform. The density of the preform increases with an increase in the forging load. The amount of barreling depends mainly on the degree of densification and friction conditions. Here, the general equation for polygonal disc is derived. But, for the analysis of problem and checking the validity of equation, square disc is taken. A composite interfacial frictional conditions, i.e. both sliding and sticking phenomenon between die and preform have been taken. The results are expected to be effective for the determination of die loads during the forging of porous metals by Upper Bound approach.

Conclusions
During forging of powder preforms, the mode of deformation is quite different from wrought materials and it is function of both density and hydrostatic stress and density. In powder forging, mass constancy is to be assumed. During forging of metal powder preforms by flat dies, it is seen that both compaction and compression take place simultaneously. It is clearly seen from the results that up to 7.5% of percentage reduction in the height of the preform, the forging load rapidly increases for a particular value of coefficient of friction and bulging constant. Initially, the closing of pores dominates the compression process. The larger amount of applied load is utilized in densification and lesser amount is consumed for compression. The weaker orientation breaks down to form a much stronger orientation. After attaining $\rho = 1$, the preform deforms significantly. The compressibility of metal powder preforms improves with increase in initial relative density. Density distribution will be more uniform for a higher initial relative density of the preform. The density of the preform increases with an increase in the forging load. The amount of barreling depends mainly on the degree of densification and friction conditions. Here, the general equation for polygonal disc is derived. But, for the analysis of problem and checking the validity of equation, square disc is taken. A composite interfacial frictional conditions, i.e. both sliding and sticking phenomenon between die and preform have been taken. The results are expected to be effective for the determination of die loads during the forging of porous metals by Upper Bound approach.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Perpendicular distance from center to side of disc</td>
</tr>
<tr>
<td>$B$</td>
<td>Bulging constant</td>
</tr>
<tr>
<td>$2b$</td>
<td>Sides of the square</td>
</tr>
<tr>
<td>$h$</td>
<td>Instantaneous thickness of preform</td>
</tr>
<tr>
<td>$J_2'$</td>
<td>Second invariant of deviatoric stress</td>
</tr>
<tr>
<td>$k$</td>
<td>Constant equal to 2 in yield criterion</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of sides in a polygon</td>
</tr>
<tr>
<td>$n$</td>
<td>A constant quantity much greater than 1</td>
</tr>
<tr>
<td>$P$</td>
<td>Die load</td>
</tr>
<tr>
<td>$p$</td>
<td>Ram pressure</td>
</tr>
</tbody>
</table>
\( r \) = Radius of the sticking zone
\( r, \theta, z \) = Cylindrical co-ordinates
\( \varepsilon_r, \varepsilon_\theta, \varepsilon_z \) = Principal strain increment
\( \mu \) = Coefficient of friction
\( \eta \) = Constant and a function of \( \rho \) only
\( \lambda \) = Flow stress of metal powder preform
\( \rho \) = Relative density of the preform
\( \tau \) = Shear stress
\( \rho_r, \rho_t \) = Densities of apparent and real contact areas
\( \sigma_0 \) = Yield stress of the non-work hardening matrix metal

References