Chapter 14

Process Design in Impression Die Forging

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FORGING is a process by which a billet of simple cross section is plastically deformed by applying compressive forces through dies or tools to obtain a more complex shape. In impression die forging, two or more dies are moved toward each other to form a metal billet that is heated to the appropriate forging temperature. This process is capable of producing components of high quality at moderate cost. It offers a high strength-to-weight ratio, toughness, and resistance to impact and fatigue. Forged components find application in the automobile/automotive industry and in aircraft, railroad, and mining equipment.

Some parts can be forged in a single set of dies, while others, due to shape complexity and material flow limitations, must be shaped in multiple sets of dies. In a common multistage forging process, the part is first forged in a set of busting dies, then moved to one or more sets of blocking dies, and finally, forged in finisher dies. Finisher dies are used to enhance geometrical details without significant material flow. The quality of the finished part depends greatly on the design of the previous stages. If the material has been distributed improperly during the blocking stage, defects may appear in the finishing stage. In a good-quality forging, all sections of the die cavity must be filled, and the part must not contain flow defects, such as laps, cold shuts, or folds.

Before being used in production, forging dies are tested to verify proper filling of the die cavities. The most commonly used method of process verification is die tryout, in which full-scale dies are manufactured and prototype parts are forged to determine metal flow patterns and the possible occurrence of defects. This method often takes several iterations and is very costly in terms of time, materials, facilities, and labor. Alternatively, two other methods for modeling metal flow, namely, physical modeling and process simulation using finite-element method (FEM)-based software, can be used to obtain information about the effects of die design and process variables on the forging process.

The design of any forging process begins with the geometry of the finished part (Fig. 1). Consideration is given to the shape of the part, the material to be forged, the type of forging equipment to be used, the number of parts to be forged, the application of the part, and the overall economy of the process being designed. The finisher die is then designed with allowances added for flash, draft, shrinkage, fillet and corner radii, and positioning of the parting line. When using multistage forging, the shapes of the preforms are selected, the blocker dies are designed, and the initial billet geometry is determined. In making these selections, the forging designer considers design parameters such as grain flow, parting line, flash dimensions, draft angles, and fillet and corner radii.

The terminology used to describe the flash zone in impression and closed-die forging can

![Flow chart illustrating forging process design](image-url)

Fig. 1 A flow chart illustrating forging process design. CNC, computer numerical control; FEM, finite-element method
be seen in Fig. 2. The flash dimensions and billet dimensions influence:

- Flash allowance, that is, the material that flows into the flash zone
- Forging load
- Forging energy
- Die life

The overall design of a forging process requires the prediction of:

- Shape complexity and volume of the forging
- Number and configurations of the preforms or blockers
- The flash dimensions in the dies and the additional flash volume required in the stock for preforming and finishing operations

Forging Process Variables

The interaction of the most significant variables in forging is shown in a simplified manner in Fig. 3. It is seen that for a given billet material and part geometry, the ram speed of the forging machine influences the strain rate and flow stress. Ram speed, part geometry, and die temperature influence the temperature distribution in the forged part. Finally, flow stress, friction, and part geometry determine metal flow, forging load and forging energy, and, consequently, influence the loading and the design of the dies. Thus, in summary, the following three groups of factors influence the forging process:

- Characteristics of the stock or preform to be forged, flow stress and the workability at various strain rates and deformation conditions, stock temperature, preform shape, and so on
- Variables associated with the tooling and lubrication: tool materials, temperature, design of drafts and radii, configuration, flash design, friction conditions, forging stresses, and so on
- Characteristics of the available equipment: load and energy capacities, single or multiblow availability, stiffness, ram velocity under load, production rate, availability of ejectors, and so on

Forging Materials. Table 1 lists different metals and alloys in order of their respective forging difficulty (Ref 2). The forging material influences the design of the forging itself as well as the details of the entire forging process. For example, Fig. 4 shows that, owing to difficulties in forging, nickel alloys allow for less shape definition than do aluminum alloys.

In most practical hot forging operations, the temperature of the workpiece material is higher than that of the dies. Metal flow and die filling are largely determined by:

- Forging material resistance to flow and ability to flow, that is, its flow stress and forgeability
- Friction and cooling effects at the die-material interface
- Complexity of the forging shape

For a given metal, both the flow stress and forgeability are influenced by the metallurgical characteristics of the billet material and by the temperatures, strain, strain rates, and stresses that occur in the deforming material. The flow stress determines the resistance to deformation, that is, the load, stress, and energy requirements. Forgeability has been used vaguely in the literature to denote a combination of both resistance to deformation and ability to deform without fracture. A diagram illustrating this type of information is presented in Fig. 5.

In general, the forgeabilities of metals increase with increasing temperature. However, as

### Table 1 Hot forging temperatures of different metals and alloys

<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Approximate range of forging temperature, °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys (least difficult)</td>
<td>400–500 (750–930)</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>250–350 (480–660)</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>600–900 (1110–1650)</td>
</tr>
<tr>
<td>Carbon and low-alloy steels</td>
<td>850–1150 (1560–2100)</td>
</tr>
<tr>
<td>Martensitic stainless steels</td>
<td>1100–1250 (2010–2280)</td>
</tr>
<tr>
<td>Maraging steels</td>
<td>1100–1250 (2010–2280)</td>
</tr>
<tr>
<td>Austenitic stainless steels</td>
<td>1100–1250 (2010–2280)</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>1000–1150 (1830–2100)</td>
</tr>
<tr>
<td>Semiaustenitic PH stainless steels</td>
<td>1100–1250 (2010–2280)</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>700–950 (1290–1740)</td>
</tr>
<tr>
<td>Iron-base superalloys</td>
<td>1050–1180 (1920–2160)</td>
</tr>
<tr>
<td>Cobalt-base superalloys</td>
<td>1180–1250 (2160–2280)</td>
</tr>
<tr>
<td>Niobium alloys</td>
<td>950–1150 (1740–2100)</td>
</tr>
<tr>
<td>Tantalum alloys</td>
<td>1050–1350 (1920–2460)</td>
</tr>
<tr>
<td>Molybdenum alloys</td>
<td>1150–1350 (2100–2460)</td>
</tr>
<tr>
<td>Nickel-base superalloys</td>
<td>1050–1200 (1920–2190)</td>
</tr>
<tr>
<td>Tungsten alloys (most difficult)</td>
<td>1200–1300 (2190–2370)</td>
</tr>
</tbody>
</table>

PH, precipitation-hardenable. Source: Ref 2

Fig. 4 Comparison of typical design limits for rib-web-type-structural forgings of (a) aluminum alloys and (b) nickel-base superalloys. All dimensions in millimeters. Source: Ref 2
temperature increases, grain growth occurs, and in some alloy systems, forgeability decreases with increasing grain size. The forgeabilities of metals at various deformation rates and temperatures can be evaluated by using various tests, such as torsion, tension, and compression tests. In all these tests, the amount of deformation prior to failure of the specimen is an indication of forgeability at the temperature and deformation rates used during that particular test.

Forging Equipment. In hot and warm forging, the behavior and the characteristics of the forging press influence:

- Contact time between the material and the dies under load. This depends on the ram velocity and the stiffness of a given press. The contact time is extremely important because it determines the heat transfer between the hot or warm material and the colder dies. Consequently, the contact time also influences the temperatures of the forging and that of the dies. When the contact time is large, the material cools down excessively during deformation, the flow stress increases, and the metal flow and die filling are reduced. Thus, in conventional forging operations, that is, non-isothermal, it is desirable to have short contact times.
- Rate of deformation, that is, the strain rate. In certain cases, for example, in isothermal and hot die forging of titanium and nickel alloys, that are highly rate dependent, the large rate of deformation leads to an increase in flow stress and excessive die stresses.
- Production rate. With increasing stroke rate, the potential production rate increases, provided the machine can be loaded and unloaded with billet or preforms at these increased rates.
- Part tolerances. Hydraulic and screw presses, for example, operate with kitting dies, that is, the dies have flat surfaces that contact each other at the end of each working stroke of the forging press. This allows very close control of the thickness tolerances, even if the flow stress and friction conditions change during a production run. Ram guiding, stiffness of the press frame, and drive also contribute to tolerances that can be achieved in forging.

Friction and Lubrication. The flow of metal in forging is caused by the pressure transmitted from the dies to the deforming material; therefore, the friction conditions at the die-material interface are extremely important and influence the die stresses and the forging load as well as the wear of the dies. In order to evaluate the performances of various lubricants and to be able to predict forming pressures, it is necessary to express the interface friction quantitatively, in terms of a factor or coefficient. In forging, the frictional shear stress, \( \tau \), is most commonly expressed as:

\[
\tau = \sigma f = \frac{m \sigma}{\sqrt{3}} \quad \text{(Eq 1)}
\]

where \( \tau \) is the frictional shear stress, \( \sigma \) is effective stress, \( f \) is the friction factor, and \( m \) is the shear friction factor (0 ≤ \( m \) ≤ 1).

For various forming conditions, the values of \( m \) vary as follows:

- \( m = 0.05 \) to 0.15 in cold forging of steels, aluminum alloys, and copper, using conventional phosphate soap lubricants or oils
- \( m = 0.2 \) to 0.4 in hot forging of steels, copper, and aluminum alloys with graphite-based lubricants
- \( m = 0.1 \) to 0.3 in hot forging of titanium and high-temperature alloys with glass lubricants
- \( m = 0.7 \) to 1 when no lubricant is used, for example, in hot rolling of plates or slabs and in nonlubricated extrusion of aluminum alloys

Heat Transfer and Temperatures. Heat transfer between the forged material and the dies influences the lubrication conditions, die life, properties of the forged product, and die fill. Often, temperatures that exist in the material during forging are the most significant variables influencing the success and economics of a given forging operation. In forging, the magnitudes and distribution of temperatures depend mainly on:

- The initial material and die temperatures
- Heat generated due to plastic deformation and friction at the die-material interface
- Heat transfer between the deforming material and the dies as well as between the dies and the environment (air, coolant, lubricant)

The effect of contact time on temperatures and forging load is illustrated in Fig. 6, where the load-displacement curves are given for hot forging of a steel part using different types of forging equipment. These curves illustrate that, due to strain rate and temperature effects, for the same forging process, different forging loads and energies are required by different presses. For the hammer, the forging load is initially higher, due to strain-rate effects, but the maximum load is lower than for either hydraulic or screw presses. The reason for this is that in the presses, the extruded flash cools rapidly, whereas in the hammer, the flash temperature remains nearly the same as the initial stock temperature. Thus, in hot forming, not only the material and the formed shape but also the type of equipment used (rate of deformation and die chilling effects) determine the metal flow behavior and the forming load and energy required for the process. Surface tearing and cracking or development of shear bands on the formed material often can be explained by excessive chilling of the surface layers of the formed part near the die-material interface.

Production Lot Size and Tolerances. As is the case in all manufacturing operations, these two factors have a significant influence on die design in forging. If the production lot size is large, the main reason for changing the dies is die wear. In this case, die materials and their hardennesses are selected to be especially wear resistant, even if they are made from somewhat expensive alloys. The preforming and finishing dies are designed such that relatively little material movement is allowed in the finisher dies; thus, the finisher dies, which determine the final part dimensions, do not wear out easily.

If the production lot size is small, as is the case in the aerospace forging industry, die wear is not a major problem, but die costs are very significant because these costs must be amortized over a smaller number of parts. As a result, some of the preforming or blocker dies may be omitted, even if this would cause the use of more billet material. Also, in this case, the dies must be changed more often than in large-scale production. Therefore, quick die changing and automatic die-holding mechanisms are required for economic production.

Forging tolerances are very important in design-
Design of Finisher Dies

The most critical information necessary for forging die design is the geometry of the forging to be produced. The forging geometry, in turn, is obtained from the machined part drawing by modifying this part to facilitate forging. Starting with the forging geometry, the die designer first designs the finisher dies by selecting the appropriate die block size and the flash dimensions and estimating the forging load and stresses to ascertain that the dies are not subjected to excessive loading.

The geometry of the finisher die is essentially that of the finish forging augmented by flash configuration. In designing finisher dies, the dimensions of the flash should be optimized. The designer must make a compromise; on the one hand, to fill the die cavity, it is desirable to increase the die stresses by restricting the flash dimensions (thinner and wider flash on the dies), but, on the other hand, the designer should not allow the forging pressure to reach a high value, which may cause die breakage due to mechanical fatigue. To analyze stresses, the slab method of analysis or process simulation using FEM-based computer codes is generally used.

By modifying the flash dimensions, the die and material temperatures, the press speed, and the friction factor, the die designer is able to evaluate the influence of these factors on the forging stresses and loads. Thus, conditions that appear most favorable can be selected. In addition, the calculated forging-stress distribution can be used for estimating the local die stresses in the dies by means of elastic FEM analysis. After these forging stresses and loads are estimated, it is possible to determine the center of loading for the forging in order to locate the die cavities in the press, such that off-center loading is reduced.

Flash Design in Closed-Die Forging. As mentioned earlier, the flash dimensions and the billet dimensions influence the flash allowance, forging load, forging energy, and the die life. The selection of these variables influences the quality of the forged part and the magnitude of flash allowance, forging load, and the die life.

The influence of flash thickness and flash land width on the forging pressure is reasonably well understood from a qualitative point of view. The forging pressure increases with:

- Decreasing flash thickness
- Increasing flash land width because of the combinations of increasing restriction, increasing frictional forces, and decreasing metal temperatures at the flash gap

### Flash Dimensions

The variations in the flash dimensions influence the forging load, forging energy, and the flash allowance used to determine the initial material (billet) volume. The dimensions of the flash can be varied in three ways:

- Changing the flash width with constant thickness
- Changing the flash thickness with constant width
- Changing the flash width and thickness with constant width-thickness ratio

Choosing the Flash Width and Thickness. Several factors influence the choice of a good flash thickness. The choice of the flash thickness is influenced by the part weight as well as the shape complexity (Fig. 7). Based on the complexity, the majority of forging parts are classified into:

- Compact shape, spherical and cubical (class 1)
- Disc shape (class 2)
- Oblong shape (class 3)

The first group of compact shapes has the three major dimension, namely, the length (l), breadth or width (w), and the height (h), approximately equal. The number of parts that fall into this group is rather small. The second group consists of disk shapes for which two of the three dimensions (length and...
width) are approximately equal and are larger than the height. All the round forgings belong to this group, which includes approximately 30% of all the commonly used forgings. The third group of forgings consists of long shapes, which have one dimension significantly larger than the other two (l > w ≥ h).

These three basic groups are further subdivided into subgroups, depending on the presence and type of elements subsidiary to the basic shape. This classification is useful for practical purposes, such as estimating costs and predicting preforming steps. This method, however, is not entirely quantitative and requires some subjective evaluation based on past experience. Depending on the shape complexity of the part that the user desires to produce, a range of graphs can be selected for each group.

Figure 8 shows a graph for selecting the flash thickness based on the weight, Q, of the forging for a particular group of forgings. This graph shows the relationship between the flash width-thickness (w/t) ratio and the forging weight. Thus, knowing the weight of the part to be forged, it is possible to find the corresponding flash dimensions that are a good compromise between flash allowance and the forging load are not too high. There has to be a compromise between these two.

Empirical Formulae. There are different sets of formulae, based on billet dimensions, to determine the flash dimensions. These dimensions are used to obtain little flash allowance and to minimize the forging energy.

For round forgings, Eq 2 and 3 predict flash dimensions that are a good compromise between flash allowance and forging load (Ref 4):

\[
t = 0.017D + \left[ \frac{1}{\sqrt{D + 5}} \right] \quad \text{(Eq 2)}
\]

\[
w = \frac{30}{\sqrt{1 + \frac{2D^2}{H(2R + D)}}} \quad \text{(Eq 3)}
\]

where \(w\) is the flash width, (mm). \(t\) is the flash thickness, (mm). \(H\) is the height of the ribs or shaft. \(D\) is the outside diameter of the forging, and \(R\) is the radial distance of the center of a rib from the axis of symmetry of the forging.

Preform (Blocker) Design in Impression-Die Forging

One of the most important aspects of closed-die forging is the design of preforms or blockers to achieve adequate metal distribution. The determination of the preform configuration is an especially difficult task and an art by itself, requiring skills achieved only by years of extensive experience.

In preforming, round or round-cornered square stock with constant cross section is deformed in such a manner that a desired volume distribution is achieved prior to impression die forging. In blocking, the preform is forged in a blocker cavity prior to finish forging. Designing a correct preform allows the control of the volume distribution of the part during forging as well as control over the material flow. The objectives of preform design are:

- Ensure defect-free metal flow and adequate die filling
- Minimize the amount of material lost as flash
- Minimize die wear in the finish-forging cavity by reducing the metal movement in the operation
- Achieve desired grain flow and control mechanical properties

Basic Rules of Preform Design. In forging steel parts, a correct preform can be designed by using the following three general design rules (these rules do not apply to forging nonferrous materials):

- The area of cross section of the preform equals the area of cross section of the finished product plus the flash allowance (metal flowing into flash). Thus, the initial stock distribution is obtained by determining the areas of cross sections along the main axis of the forging.
- All the concave radii, including the fillet radii, on the preform must be greater than the corresponding radii on the finished part.
- In the forging direction, the thickness of the preform should be greater than that of the finished part so that the metal flow is mostly by upsetting rather than extrusion. During the finishing stage, the material is then squeezed laterally toward the die cavity without additional shear at the die-material interface. Such conditions minimize friction and forging load and reduce wear along the die surfaces.

In attempting to develop quantitative or objective engineering guidelines for preform design, a thorough understanding of metal flow is essential. Metal flow during forging occurs in two basic modes:

- Parallel to the motion of the dies, that is, extrusion
- Perpendicular to the motion of the dies, that is, upsetting

Conventionally, blocker dies were designed using some guidelines, which are summarized as follows. Prior to the advent of computer-aided design methods, blocker dies and preforms were designed by tryouts. The guidelines used depend on the material and the forging machines used:

- The blocker is slightly narrower than the finisher in the top view by approximately 0.5 to 1.0 mm (0.02 to 0.04 in.) and has larger fillet and corner radii. This helps enhanced metal distribution.
- The areas of the various blocker cross sections are augmented from those of the finisher by the flash allowance.

![Fig. 8 Variation in flash thickness (t) and width-thickness (w/t) ratio for carbon and alloy steel forgings of different weights. Source: Ref 3](image-url)
To forge high ribs in the finisher, those in the blocker are, at times, shorter. Additionally, the web thickness in the blocker is larger than that in the finisher.

To enhance the metal flow toward the ribs, an opening taper may be useful from the center of the web toward the ribs.

In the case of steel forgings, whenever possible, the ribs in the blocker sections should be narrower but slightly higher than those in the finisher sections to reduce the die wear.

The common practice in preform design is to consider planes of metal flow, that is, selected cross sections of the forging (Fig. 9). Understanding the principles of the material flow during the forging operation can help attain a better understanding of the design rules. Any complex shape can be divided into axisymmetric or plane-strain flow regions, depending on the geometry in order to simplify the analysis.

The example steel forging presented in Fig. 10 illustrates the various preforming operations necessary to forge the part shown. The round bar from rolled stock is rolled in a special machine called a reducer roller for volume distribution, bent in a die to provide the appropriate shape, blocked in a blocker die cavity, and finish forged. In determining the forging steps for any part, it is first necessary to obtain the volume of the forging based on the areas of successive cross sections throughout the forging. The volume distribution can be obtained in the following manner:

1. Lay out a dimensioned drawing of the finish configuration, complete with flash.
2. Construct a baseline for area determination parallel to the centerline of the part.
3. Determine the maximum and minimum cross-sectional areas perpendicular to the centerline of the part.
4. Plot these area values at proportional distances from the baseline.
5. Connect these points with a smooth curve.
6. Above this curve, add the approximate area distribution can be obtained in the following manner:
7. Convert the minimum and maximum area values to rounds or rectangular shapes having the same cross-sectional area.

Figure 11 shows two examples of obtaining a volume distribution through the previously mentioned procedure.

The applications of the design rules for preforming are illustrated by examples shown in Fig. 12. Figure 13 shows some suggested blocker and finish cross sections for various steel forgings.

The preform is the shape of the billet before the finish operation. In certain cases, depending on the ratio of the height of the preform to its width, there might be more than one preform operation involved.

**Guidelines for Aluminum Parts.** For rib-web-type aluminum alloy parts, the recommended preform dimensions fall into the ranges given in Table 3. The preform is usually designed to have the same draft angles as the finish part. However, when very deep cavities are present in the finisher die, larger draft angles are provided in the preform. A greater web thickness in the preform is selected when the web area is relatively small and when the height of the adjoining ribs is very large. A comparison of the preform and the finished part is illustrated in Fig. 15.

**Guidelines for Titanium Alloys.** The guidelines for designing titanium alloy preforms (Table 4) are similar to those for aluminum alloys.

**Prediction of Forging Stresses and Loads.**

In designing forging dies, the forging stresses and load must be estimated in order to predict whether the dies may break under load or not and to select the forging machine with adequate load and energy capacity. In most multistage forging operations, the finish-forging operation requires the highest load because in the finisher die, the thickness of the forging and all the fillet and corner radii are reduced to obtain the final part geometry.

Prediction of the forging load and pressure in closed- or impression-die forging is difficult due to the nonsteady state of the process, that is, variables affecting the process, such as temperature, stresses, and so on. In addition, forgings comprise an enormously large number of geometrical shapes and materials that require different, even though similar, techniques of engineering analysis. The following methods are generally used for determination of the forging stresses and loads:

- By empirical formulae, based on past experience.
By performing approximate calculations through one of the well-known methods of plasticity, such as slab, upper bound, slip line, or FEM.

Load-Stroke Curves. A typical load-versus-stroke curve for a closed-die forging operation indicates that loads are relatively low until the more difficult details are partly filled and the metal reaches the flash opening (Fig. 16, 17). This stage corresponds to point $P_3$ in Fig. 17. For successful forging, two conditions must be fulfilled when this point is reached (Ref 8):

- A sufficient volume of metal must be trapped within the confines of the die to fill the remaining cavities.
- By performing approximate calculations through one of the well-known methods of plasticity, such as slab, upper bound, slip line, or FEM.

The extrusion of metal through the narrow gap of the flash opening must be more difficult than the filling of the more intricate detail in the die.

As the dies continue to close, the load increases sharply to point $P_3$ (Fig. 17), the stage at which the cavity is filled completely. Ideally, at this point, the cavity pressure provided by the flash geometry is just sufficient to fill the entire cavity, and the forging is completed. However, $P_3$ represents the final load reached in normal practice for ensuring that the cavity is completely filled and that the forging has the proper dimensions. During the stroke from $P_2$ to $P_3$, all the metal flow occurs near or in the flash gap, which in turn becomes more restrictive as the dies close. Thus, the detail most difficult to fill determines the minimum forging load required to produce a fully filled forging.

The dimensions of the flash determine the final load required to close the dies. The formation of flash, however, is greatly influenced by the amount of excess material available in the cavity because that amount determines the instantaneous height of the extruded flash and therefore the die stresses.

Studies have revealed that it is possible to fill a cavity with various flash geometries, provided there is always a sufficient supply of material in the die. Thus, it is possible to fill a die cavity using a less restrictive flash, that is, a thicker flash, and to do this at a lower total forging load if the necessary excess material is available or if the workpiece is properly preformed. In the former, the advantages of low forging load and cavity stress are offset by increased scrap loss. In the latter, lower stresses and material losses are obtained by extra preforming (Ref 8).

Empirical Methods for Estimation of Forging Pressure and Load. In estimating the forging load empirically, the surface area of the forging, including the flash zone, is multiplied by an average forging pressure known from experience. The forging pressures encountered in practice vary from 275 to 950 MPa (20 to 70 tons/in.2), depending on the material and the geometry of the part. Forging experiments were conducted (Ref 9) with various carbon steels (up to 0.6% C) and with low-alloy steels using flash ratios, $w/t$ (where $w$ is flash-land width, and $t$ is the flash thickness), from 2 to 4 (Fig. 18). It was found that the variable that most influences the forging pressure, $P_s$, is the average height, $H_s$, of the forging. The lower curve relates to relatively simple parts, whereas the upper curve relates to slightly difficult ones (Ref 9).
The slab method has been used successfully for predicting forging loads and stresses with acceptable engineering accuracy. For this purpose, a forging is divided into various plane-strain and axisymmetric sections, and then, simplified equations are used to predict the stress at the entrance from the cavity into the cross section and hence the load acting on each section before all these load components are added together. This method, used in the practical prediction of forging loads, is shown in Fig. 19 (Ref 7). In this analysis, it is assumed that the cavity is not rectangular, the cross section is simplified to conform to this model.

As seen in Fig. 19, the cavity height is denoted by $H$, the radius (or half-width of the cavity) by $r$, the flash thickness by $t$, and the flash width by $w$. The stresses at various locations of the cross section and hence the load acting on the cross section can be estimated according to the following equations.

With the flow stress in the flash region denoted by $\sigma_{ff}$ and the frictional shear factor by $m$, the stress at the entrance from the cavity into the flash of an axisymmetric cross section, $\sigma_{ax}$, is given by:

$$\sigma_{ax} = \left( \frac{2}{\sqrt{3}} \frac{m}{t+1} \right) \sigma_{ff}$$  

(Eq 4)

Because of rapid chilling and a high deformation rate, the flow stress in the flash region is considered to be different from the flow stress in the cavity. Hence, two different flow stresses are...
Fig. 19 Schematic of a simple closed-die forging and forging stress distribution. H, cavity height; r, radius; t, flash thickness; w, flash width; \( \sigma_{f} \), flow stress in flash region; \( \sigma_{s} \), flow stress in cavity. \( \sigma_{r} \), flow stress at edge, Source: Ref 8

used for the flash and cavity regions. The total load, \( P_{w} \), on the cross section is the summation of the load acting on the flash region and the load acting on the die cavity:

\[
P_{w} = 2\pi \sigma_{f} \left[ \frac{2}{3} \frac{m}{\sqrt[3]{3}} \left( R^{3} - r^{3} \right) \right] + 2\pi \sigma_{s} \left[ \frac{m}{\sqrt[3]{3}} \frac{r}{2} + \frac{w}{t} \right] \]

where \( R = r + w; \sigma_{f} \) is the flow stress in the flash region, and \( \sigma_{s} \) is the flow stress in the cavity.

For the plane-strain cross sections, the equations corresponding to Eq 4 and 5 are:

\[
\sigma_{w} = 2 \sigma_{f} \left( 1 + \frac{m}{t} \right) \]

\[
P_{w} = 2\pi w \sigma_{f} \left( 2 + \frac{m w}{t} \right) + \left( \sigma_{w} + \frac{L}{2H} \frac{m}{\sqrt[3]{3}} \sigma_{w} \right) L
\]

where \( L \) is the cavity width, that is, \( L = 2t \), in Fig 19. The previous equations are relatively simple and can be programmed for practical use. The following information is required to perform these calculations:

- Geometry of the part
- Flow stresses in the cavity and the flash during the final stages of the forging operation
- Friction at the die-forging interface

**Process Simulation to Predict Metal Flow and Forging Stresses**

One of the major concerns in the research of manufacturing processes is to find the optimal production conditions in order to reduce production costs and lead time. In order to optimize a process, the effect of the most important process parameters has to be investigated. Conducting experiments, as stated earlier, can be very time-consuming and expensive. Therefore, various computational methods have been developed and used to reduce the number of necessary experiments. One of these methods, FEM, has proved to be the most powerful analysis tool. With the increasing use of computers in industry, FEM has steadily gained importance in the simulation of metal-forming processes.

**Investigation of Defect Formation in Ring Gear Forging.** The process analyzed was the forging of an automotive ring gear blank (Ref 10). In production, the part is hot forged from American Iron and Steel Institute (AISI) 4320 steel in three sets of dies. The dies were of H11 steel, lubricated with a graphite-and-water mixture and maintained at approximately 150 °C (300 °F).

The first step in the manufacturing process involves cold shearing the billets from stock and induction heating them to 1200 °C (2200 °F). Next, a billet is placed in the bursting dies and upset (Fig. 20a). It is then transferred to a blocker die and forged (Fig. 20b) and finally transferred to and forged in a finisher die (Fig. 20c). During initial forging trials, buckling flow in the blocker dies caused a lap to be formed intermittently around the circumference of the part (Fig. 20d). As the finish dies filled, the lap worsened. Because of this defect, the part was rejected, and hence, a new blocker die design was required.

The following observations were made during simulation of the process:

- The sharp corner radius and steep angle of the inside wall on the upper die resulted in the formation of a gap between the inside die wall and the workpiece.
- As the workpiece contacted the uppermost surface of the top die and began upsetting, the inside surface of the blocker began to buckle.
- The radial flow from the web region forced the buckle out toward the outer die walls, and as the upsetting and radial flow combined, the buckling became more severe.

To counter the previously stated problem, the following modification was made to the original blocker design:

- The corner radius (region “A” of Fig. 21) was increased by a factor of 2, to aid the metal flow around the corner.
- The angle of the top surface of the upper die (region “B” of Fig. 21) was decreased until it was horizontal, to increase the height of the blocker.
- The outer wall of the lower die (region “C” of Fig. 21) was modified so that upsetting flow from the top die would fill voids in the upper die cavity instead of voids in the lower die cavity.

Figure 22 shows the die fill in the simulation run with the new blocker design. At the start of the working stroke, the workpiece followed the walls of the upper and lower die. With further deformation, the workpiece contacted the uppermost wall of the top die, and a gap formed between the inside wall of the top die and the workpiece. At the final stroke position, a small gap remained along the inside wall of the upper die, but no buckle was formed. Figures 22 (a–c) show the finish die operation with the modified
life in the hot extrusion of the automotive component shown in Fig. 23 (Ref 11). The resulting stresses in this process are a combination of the purely mechanical stresses due to forging and the thermomechanical stresses as a result of thermal cycling of the punch surface due to the alternating hot forging and waiting periods. The stresses due to thermal cycling were found to comprise approximately 75% of the total stress field. This cycling causes tool damage known as heat checking. Originally, the punch had to be changed approximately every 500 cycles, due to cracking as a result of thermal cycling (Fig. 24). It is a commonly known fact that geometry changes are not the best way to reduce the stress level with regard to thermal stresses. From this study, it was determined that increased tool life could be achieved by modifying the hot forging process parameters, such as billet temperature and the forging rate.

Finite-element modeling simulation and experimental work were used to conduct a parametric study to determine the optimal process parameters to achieve higher life expectancy of the tools. This combined numerical and experimental approach can be summarized as:

- A two-step numerical simulation:
  a. Process simulation to determine the purely mechanical stresses, forging loads, and thermal boundary conditions for the punch
  b. Thermoelastic simulation for thermal-stress analysis of the punch
- A two-step experimental stage:
  a. Metallurgical validation of the constitutive laws of the workpiece material
  b. Industrial forging tests for validation of the thermal boundary conditions for the punch

The surface temperatures on the punch are a factor of the heat-transfer coefficient at the tool-workpiece interface. This coefficient is a function of various factors, such as surface topography, contact pressures, temperature difference, and duration of contact (Ref 12). Forging tests were conducted on an industrial press using a test punch with five thermocouples. Several numerical iterations (FEM simulations) were performed by using different heat-transfer coefficients until the calculated temperature distribution was in agreement with that from the experiments.

In order to reduce the thermal stresses, a reduction of the thermal gradient during forging must be obtained. There are two options: modification of process parameters to decrease the temperature (reduction of the punch speed, thus reducing the flow stress, or decreasing workpiece temperature, resulting in an increase in flow stress) or use of lubricating/insulating products during forging to reduce the heat transfer, which is an empirical approach. The first option was selected, because the available press could handle increased forging loads as a result of increased flow stress.

A parametric study was conducted to investigate the influence of forging speed and initial workpiece temperature on the final thermomechanical stresses. The optimal process parameters were thus determined, resulting in a 30% decrease in the stresses. Thus, a combination of process simulation and experimental verification resulted in an increase in the tool life for the punch in this hot forging process.

Multistage Forging Simulations of Aircraft Components. Multistage forging simulations of two aircraft components (a titanium fitting and an aluminum wheel) were run to study metal flow, temperature distribution, die filling, and die stresses (Ref 13). The commercial FEM code "DEFORM-3D" (Scientific Forming Technologies Corporation, Columbus, Ohio) was used for these simulations. The two components considered for this study are produced by closed-die forging with flash. Because the parts are forged at elevated temperatures, it was necessary to run nonisothermal simulations. Flash removal between the forging stages also had to be considered for the simulations in order to ensure appropriate material volume in the dies for the subsequent forging stage. Each of the components was forged in three stages, namely, two blocker stages followed by a finisher stage. Figures 25 and 26 show the forging sequence of the titanium fitting and the aluminum wheel, respectively. The results obtained at the end of the simulations were the effective stress distribution, die filling, metal flow during forging, temperature distribution, and strain distribution.

Flash removal between the forging stages also had to be considered because the amount of
flash to be removed influences the volume of material available for the subsequent forging stage and thus, the die filling and the die stresses. The simulation strategy adopted for the two components was to remove the flash in between stages. This was done by using the Boolean capability of DEFORM, that is, volume manipulation. Die filling was checked by examining various cross sections along the length of the forging (Fig. 27, 28).

The simulations were stopped when die filling was achieved, and it was this stage of the simulation, that was used to determine the stresses in the dies. In order to reduce computational time, the dies were kept rigid throughout the simulation. At the last step, they were changed to elastic, and the stresses from the workpiece were interpolated onto the dies. The results obtained from the die stress analysis simulations were the effective stress, the maximum principal stress, and the temperature distribution. Using these results, an effective die design was established.

Cold and Warm Forging

The current chapter is devoted to impression-die forging, which is essentially a hot forging process with flash, where the workpiece material is at a higher temperature than the dies. The dies are designed to provide for flash that ensures proper filling of the die cavity and the flow of excess material outside the die cavity. However, it is appropriate to discuss, very briefly, cold and warm forging processes that use die designs without flash.

Cold forging is a process wherein metal at room temperature is forced to flow plastically under compressive force into a variety of shapes. These shapes are usually axisymmetric, with relatively small, nonsymmetrical features, and they generally do not generate flash. The terms cold forging and cold extrusion are often used interchangeably and refer to well-known forming operations, such as extrusion, upsetting or heading, coining, ironing, and swaging. Through a combination of these techniques (Fig. 29), a very large number of parts can be produced.

Due to the limitations with regard to load on the tooling and the formability of certain materials at room temperature, the extrusion process is also carried out above room temperatures and below hot forging temperatures. This process is classified as warm extrusion. For low-carbon steel, warm extrusion is carried out between 400 and 800 °C (750 and 1475 °F). The tooling used for this process is similar to that used for cold extrusion. Because the flow stress of steel is lower at higher temperatures, larger reduction in area is achievable, allowing a subsequent reduction in the number of stages required to manufacture a part. There is also a possibility for using combined cold and warm extrusion.

Cold and warm forging are extremely important and economical processes, especially for producing round or nearly round parts in large quantities. Some of the advantages of these processes are:

- High production rates
- Excellent dimensional tolerances and surface finish
- Significant savings in material and machining
- Higher tensile strengths in the forged part than in the original material because of strain hardening
- Favorable grain flow to improve strength

The most common extrusion processes encountered are forward rod and backward cup extrusion (Fig. 29). Several combinations of extrusion processes are possible, and other operations, such as upsetting, heading, coining, embossing, and ironing, can be used in conjunction with extrusion. Figure 30 gives an overview of the production sequence for cold forging of a gear blank. The operations consist of combined forward rod and backward cup extrusion followed by the simultaneous upsetting and coining of the shoulder.

The main advantages of the cold extrusion process are the large material savings compared with processes such as machining and other metal-
A final advantage is the option of using steel of lower strength for machine and construction elements without the need for further hardening. In cold forging, the forming load and stresses are relatively higher than in hot forging, up to 2070 MPa (300 ksi). Therefore, the tool or die design is quite elaborate, and cold forging dies are relatively expensive. Thus, production of a large quantity of parts is required to amortize the tool costs.

These advantages, combined with the wide possibilities of shapes that can be manufactured by extrusion, have increased the popularity of this process in the industry.

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