closed-die forging as opposed to open-die forging is the term applied to all forging operations ultimately involving three-dimensional confinement and control.

In the course of the design of a part that may be produced by closed-die forging, the following steps may, in general, be followed:

1. The design of the part itself, which in many cases is a finished machined part such as a connecting rod for an internal combustion engine. This stage in the design process provides the required geometry and the necessary mechanical properties. The design may originally have been made with or without a forging in mind. With perhaps some redesign, the part may finally be made from a ductile (nodular) cast iron or even from a heavy metal stamping, for example, instead of a forging.
2. Once the decision is made to make the part by the hot-forging process, the finished forging and its dies are designed by the addition of the machining allowance and the necessary taper or draft so that the part may be readily removed from the die during the forging operation. At this stage, the forging and its die are designed so as to fill the die cavity completely (by the addition of some extra metal that overflows to form the flash) and to forge the part without any defects such as folds or overlaps. The power and energy requirments for making the finished forging are also determined at this stage.
3. If the forging is complex at all, it may have to be made in stages, so that the necessary preform or blocker dies may have to be designed to distribute the metal adequately. The geometry of the forging slug (stock) or multiple is determined

CAD of Elongated Hot Forgings and Dies

A high proportion of forgings, such as connecting rods, etc., have a long straight axis. Usually elongated forgings are made from bar stock and normally require several preforming stages, the number employed being determined by process limitations and economic considerations of the quantity required. If the cross-sectional area varies appreciably, the metal must be distributed along the length of the workpiece by drawing down the bar at various locations. For hammer forging this is achieved by fuller and edging (roller) dies, but for press forging these dies are replaced by reducer rolls as shown in Fig. 9.38. These initial preforming stages result in a rough forged workpiece with metal distributed axially in a manner similar to the final forging so as to facilitate the flow of metal into the dies without the formation of forging defects or die lock. The size and volume of the forging of the initial forging blank used is dependent on the largest cross-sectional area of the forging and on the total volume of the forging including the estimated flash.

The basis for the design of the fuller and edging (roller) dies, and for the determination of the stock size, is the mass distribution diagram of the forging as shown in Figs. *9.3S(b)* and 9.39(fc). These diagrams are plots of the cross-sectional area of the forging and of the flash at various critical points along the axis of the forging. The area under the curve gives the total volume of the material required to produce a sound forging. Enough cross sections of the forging must be chosen as shown in Fig. 9.38(a) to determine this diagram with sufficient accuracy.

The mass distribution diagram can be reduced to a block form, corresponding to major changes in the cross-sectional area of the forging as shown in Fig. 9.38(c). The stock size is then determined from the volume of the largest sectioned block of material divided by its length. The bar may generally be round or square as appropriate.

The block form of the mass distribution represents the idealized form of the stock after the fullering operation is completed, without any radii, etc., omitted. The length of bar required is determined by reducing the smaller sectioned blocks of material to the bar size as shown in Fig. 9.38. During the forging operation, the stock form is then altered to the idealized block form shown in Fig. 9.38(c), by one or more fullering operations, to reduce the bar down to the next largest section size, and so forth. It is unusual for more than two fullering stages to be used.

As indicated above, the object of fullering is to reduce the cross-sectional area of the stock in various regions while at the same time increasing the length of the drawn down portion. In hammer forging, this is accomplished by giving repeated blows to the bar between the horizontal faces of the fuller dies, while rotating the bar, usually by 90°, after each blow. For hammer forging, the mass distribution preforming is done largely by open-die forging techniques as described above, whereas for press forging preforming is usually done by the use of reducer rolls as shown in Fig. 9.38(e) and (/). An alternate procedure to obtain the preforming mass distribution is by use of forging rolls as shown in Fig. 9.40(a) and *(b).*

One of the purposes of using a blocking impression in a forging operation is to control the flow of material in the individual cross sections of the final die. Also, optimum die design should ensure die filling with a minimum of stock and of die wear. Large radii are used to promote good metal flow.

OUTLINE OF THE CAD PROCEDURE FOR ELONGATED FORCINGS.

The general flow of information for a series of computer-aided die design procedures for elongated forgings is shown in Fig. 9.41. Since forging die cavities are relatively simple volumetric shape elements such as truncated cones, cylinders, etc., these elements may be combined to build up forgings of various types. Thus, it may be more convenient to describe the finished forging geometry as a combination of these simple shapes rather than to use a programming language such as APT which might be considered as an overkill, in this case.

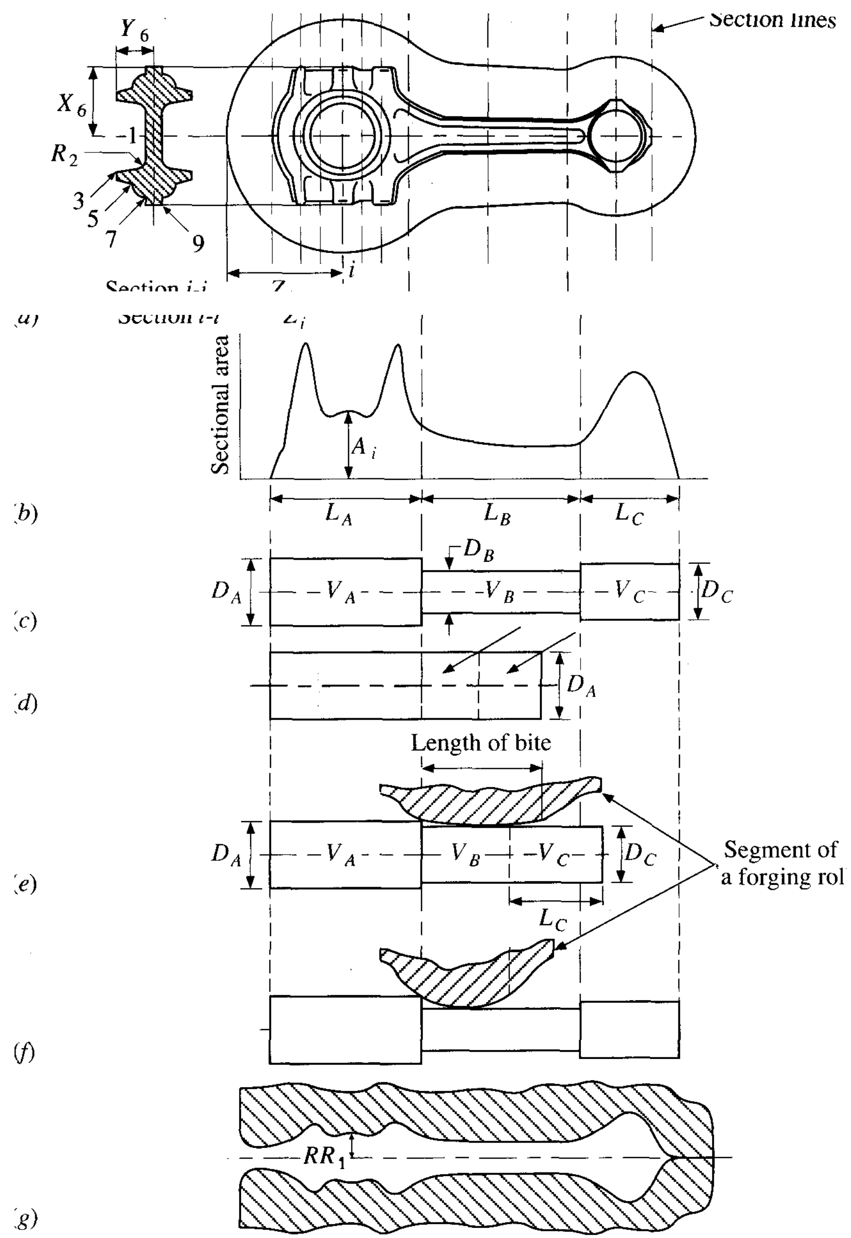


FIGURE 9.38

General design procedure for mass distribution in the preforms: (a) final forging including the flash; *(b)* mass distribution diagram for the final forging; (c) block form of the mass distribution of the preform (idealized fullered stock); *(d)* equivalent bar stock or forging multiple; (e) first fuller stage formed by roll forging; (/) second fuller stage formed by roll forging; and *(g)* longitudinal roller die profile for forming the final preform for the blocker die impression.

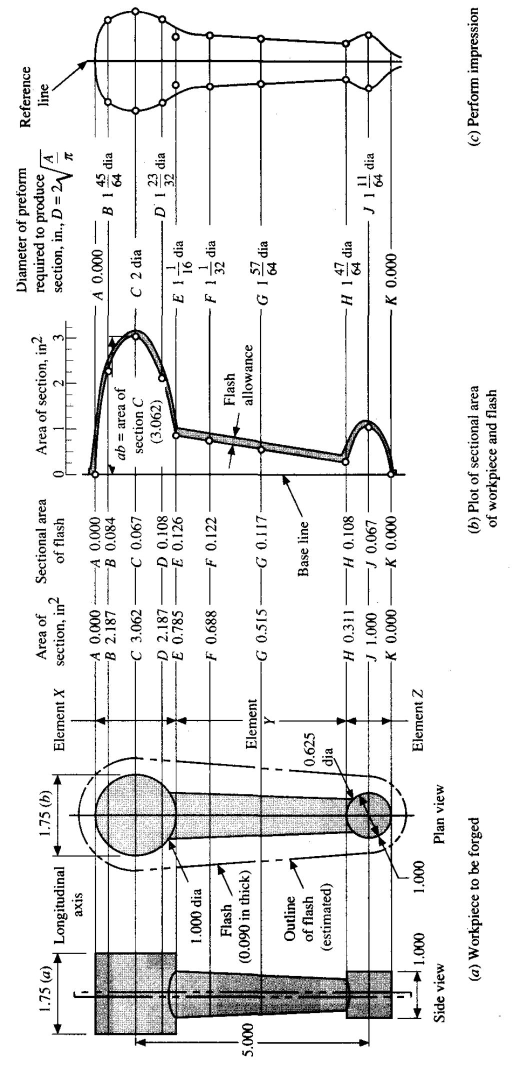


FIGURE 9.39
Example of a layout procedure of a forging to determine the shape of the preform impression and the equivalent stock or blank diameters. (*After L. G. Drabing.*) [9.25]

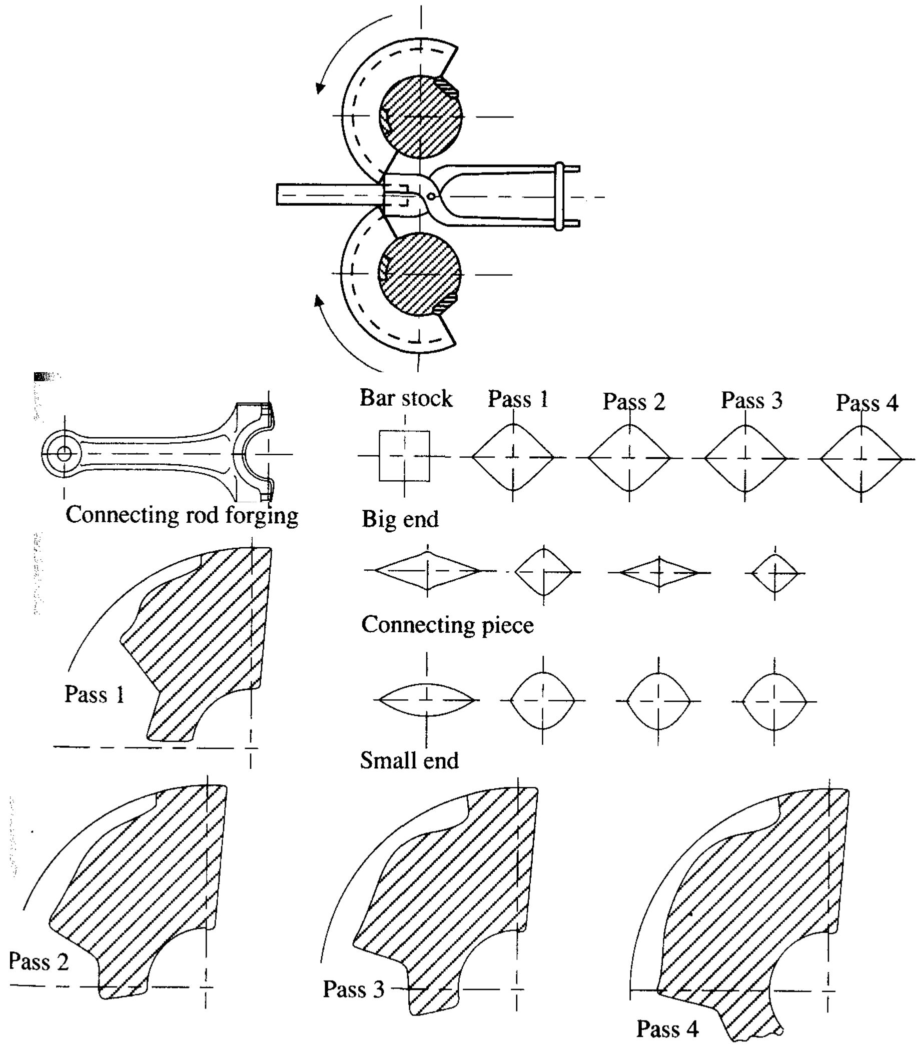


FIGURE 9.40
a) Positioning of bar stock in forging rolls, *(b)* Cross sections of the workpiece at three different cations for each pass and the corresponding roll design for each pass [9.18].

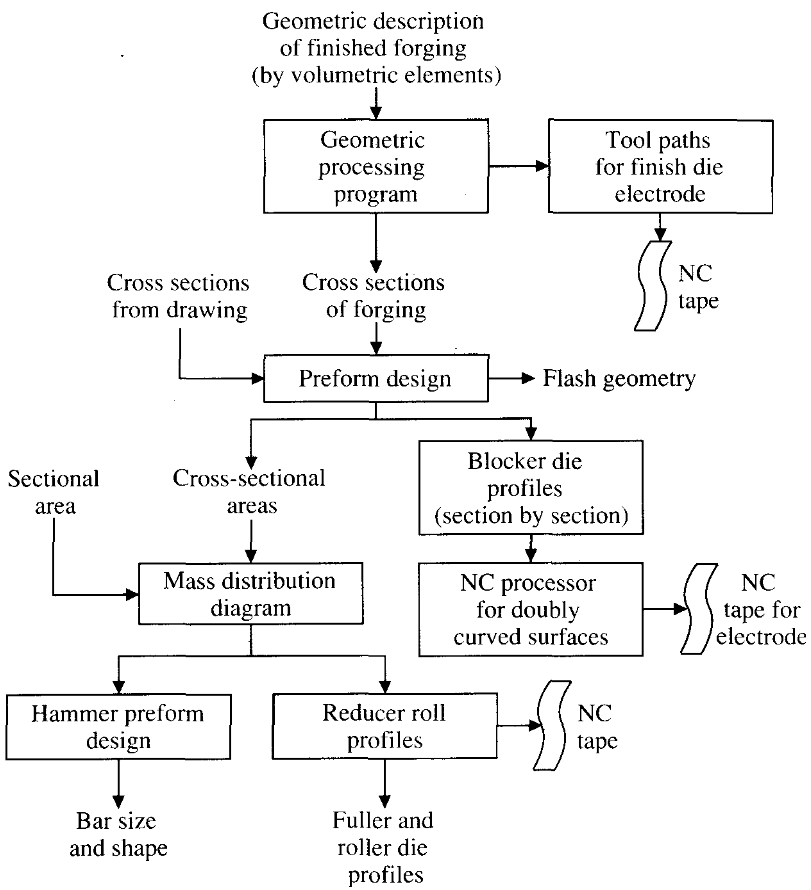
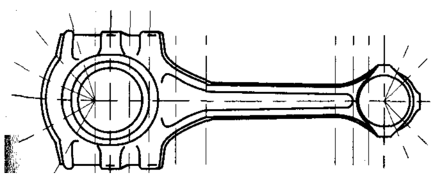


FIGURE 9.41
Flowchart showing the general information flow in a computer program for the design of "long" hot forging preforms from the input of such information as the mass distribution diagram [9.18].

A computer program using this approach has been developed. It can be used to provide input information for preform design programs in the form of selected sections of the forging, and also to generate the tool paths for the machining of the EDM electrode on an NC machine to produce the die cavities [9.16].



A computer program has been developed for the design of hammer preforms, which from an input of the mass distribution diagram of the forging enables the profiles of the fuller and edging (roller) dies to be generated, together with the details of the appropriate bar stock size and length required for forging. Up to six fullering stages can be covered in the program, but in practice more than two such stages are rarely used. Empirical design rules in current industrial use have been incorporated in this program. A related program for reducer roller profiles has been developed as indicated in Fig. 9.41 .

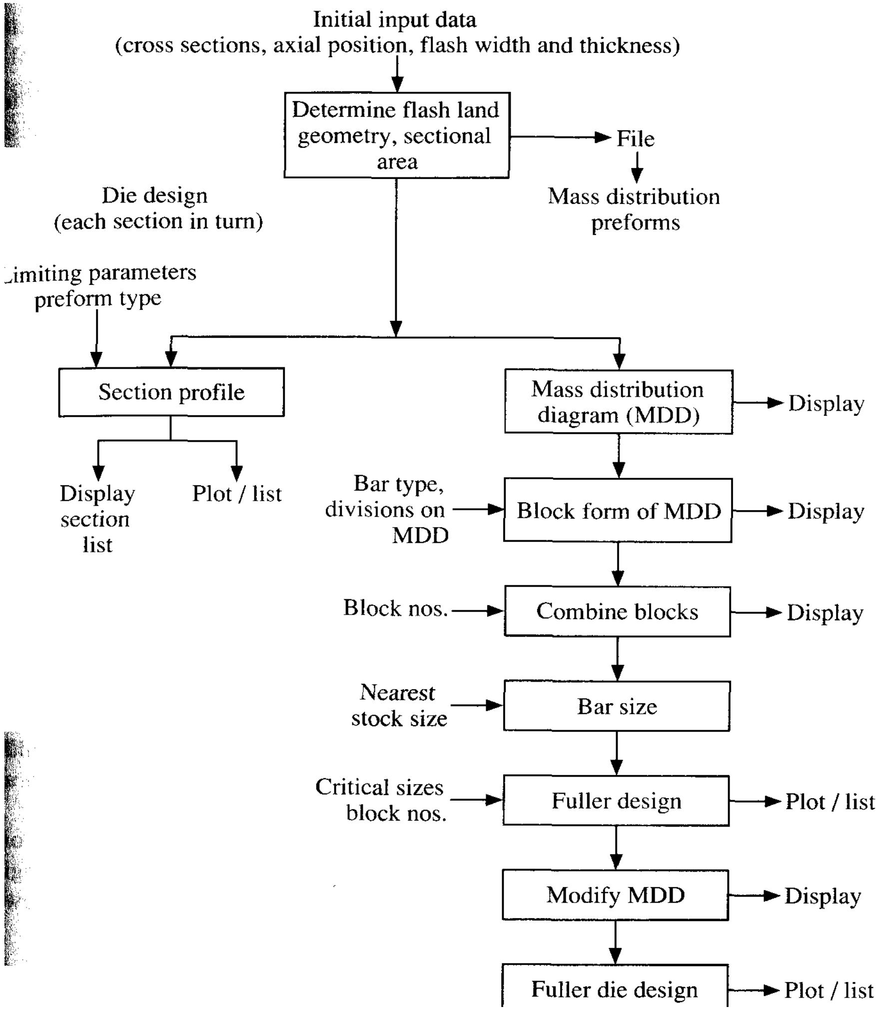


FIGURE 9.42
General information flow diagram for the generation of the mass distribution diagram (MDD) and the fuller die design directly from the input of the data of the final impression design [9.15].

FIGURE 9.43 Selection of cross sections for use in the preform computer design program for long forgings .

In accordance with Figs. 9.42 and 9.43 the computer design procedure is as follows [9.17 and 9.18]:

1. A selected number of cross sections as in Fig. 9.43 is entered in terms of the change points and radii in the profiles, together with the width and thickness of the expected flash and the axial positions of the cross sections to be considered.

2. From the input data, the areas of the cross sections and the width and thickness of the flash lands are calculated. The separate elements are merged together in producing the EDM electrode to produce the finished forging dies.

3. If required, the profile of the blocker impression is developed by modifying the selected cross sections of the finished forging as shown in Fig. 9.43.

4. The general design procedure for mass distribution preforms for hammer forging is as follows:

a. The mass distribution diagram of Fig. *9.3S(b)* is divided at various points corresponding to the major changes in cross-sectional area of the forging, from which the volume of material in each length section is determined. *b.* A block form of the distribution diagram is then displayed as shown in Fig. 9.38(c). The designer may then combine any blocks of stock to a workable number of fullers, usually not more than two. c. The bar size and volume are then determined as in Fig. *9.3S(d)*. *d.* The designer now enters the sequence of fullering operations and designs the fullering die cavities. Extra material and features may be added in order to conform to the empirical design rules and limitations. (For example, the flash gap or thickness h is assumed constant, while the flash land width varies as follows: $bp=63h/w$, when w is the width of the cross section at the die line.)

e. The edging (roller) die profile is then obtained by reducing the areas on the mass distribution diagram to diameter equivalents to obtain the longitudinal profile of the edging die, as shown in Fig. *9.3S(g)* and other views of the die.

Thus, from the same input data, the profiles of the various dies are obtained, together with the bar or billet size, flash geometry, etc.

НАЙТИ ГЛАВУ И ВСТАВИТЬ РИСУНКИ!!!!!!!!

The blending of comer radii on forgings should be carefully avoided to an even greater degree than the blending of fillets (discussed in the next section). Forging comer radii, as expressed physically in the die cavity, constitute fillets sunk by mill-ing cutters of similar sized radii and, ac-cordingly, are much more difficult to blend. Constant comer radii, as shown in Figure 2-23, will reduce die costs.

At rib or flange ends, a larger radius than the comer radius is recommended to per-mit forging fill without excessive diffi-culty. The die cavity is sunk by moving the die milling cutter in the same arc as the large radius at such an end. (This is not the same as the blending of radii, which requires difficult die sinking.) The sug-gested Rx radius (Figure 2-24) may be (1) equal to edge distance plus hole radius, (2) three times RR, or (3) as large as possible. While it is recommended that Rx be as large as possible, the size of the radius in the plan view is also important. A full radius, as shown in Figure 2-25, is recom-mended. Such a die cavity is sunk by moving a full width diameter cutter in the same arc as Rx, a simple die sinking op-eration. If the arc is not a full radius, ad-ditional die sinking cuts are required to blend these radii throughout the distance ofRx.

A rib or flange edge that is rounded with a full radius will reduce die problems. The top or edge of a rib should be rounded (Figure 2-26) with a minimum radius of RH, the value depending on the height from the parting line. Die life is reduced when

BACK DRAFT FORGING
BACK DRAFT FORGING
DIMENSION "&"--PERPENDICULAR TO THE PORTING LINE--IS AFFECTED 8Y THE DIE CLOSURE AND STRttlGHTNESS TOLERBNCES
FIGURE 2-19.
Source: Ref. 4.
Back draft forgings showing lip sections preformed by a secondary operation.
FIGURE 2-20. The relationship of a dimen-sion to the parting line. Source: Ref. 4.

TABLE 2-4. Suggested Dimensional Tolerances
Forging typeShrinkage variation per in.Per each surface on Per each surface on forgings with forgings with maximum dimensions maximum dimensions to 60 in. over 60 in.
Blocker ....+0.002 .... +0.002-0.002 -0.002 -0.0015+0-047 -0.015 +0-020 -0.010 +0.010 -0.010+0.078 -0.015 +0.047 -0.015 +0.020 -0.010
Precision ....+0.0015
PASTINO LINE

Note: Dimensional tolerances apply to any dimensions other than those covered by die closure tolerances, even to dimensions perpendicular to the parting line. Dimensions are (I) between opposite outside surfaces. (2) between opposite inside surfaces. (3) between ccnterlincs. (4) between center and outside surface. (5) between center and inside surface, and (6) between steps. Figure shows only how dimensional tolerances apply with various types of dimensions, but the method of dimensioning is unfavorable and not recommended. Source: Rcf. 4.

TABLE 2-5. Suggested erancesMatch Tol-
Weight, Ib (within)Overall length,in. (within)Precision typeForging ——————) Conventional and blocker types
0-1 ..... . 100.010 0.015 0.020 0.030 0.045 0.0600.015 0.020 0.030 0.045 0.060 0.080 0.100 0.120
1-5 17
5-20 ... 20-50 .... 25 50
50-100 ...75
100-200. 100
200-500 .. 500 UD 150 250
Note: Use the larger tolerance wher not on same line. Source: Ref. 4.

weight and overall length are slightly out of line with those on the other side because of this shift. Mismatching is caused when the forging forces are exerted parallel to the forging plane. To counteract these forces and maintain match on the forging, guide holders, guide pins, and counterlocks are employed. Match tolerances are applied separately from, and independently of, all other tolerances. They depend on the weight or overall length of the forging, whichever is greater, as indicated in Table 2-5.

allowance per surface. The shrinkage tolerance is solely for the oversize or under-size variations that may occur because of shrinkage differences. The per surface al-lowance is a "plus material" amount on the forging, frequently called "die wear allowance." This allowance includes the die sinking limits, die wear, and die dress-outs; it results in larger outside dimen-sions and smaller inside dimensions.

Suggested dimensional tolerances that depend on both the size and type of di-mensions are listed in Table 2-4. The individual dimension may be affected by shrinkage only or by both shrinkage and die wear; center dimensions are affected only by shrinkage. Dimensions from a center line to a surface are affected by both shrinkage and die wear allowance. Dimensions from a center line to a surface are affected by both shrinkage and die wear allowance. Dimensions to two surfaces are affected by shrinkage and two die wear al-lowances. Die wear is principally the re-sult of abrasion by the forging or die cav-ity polishing that is used whenever it is necessary to maintain the smoothness of die surfaces required for proper metal flow. On cold-worked die forgings, greater-than-normal dimensional tolerances may be necessary and are determined on an indi-vidual basis.

Match Tolerances

Match tolerance is the maximum shift or misalignment variation allowed be-tween the two die halves at and parallel to the parting line, as shown in Figure 2-64. The features on one side of the forging are

Straightness Tolerances

Straightness tolerance is a deviation ap-plicable generally to flat surfaces and has a total indicator reading (T.I.R.) limit. On a continuous flat surface, it is the total maximum deviation from a plane surface. On noncontinuous surfaces, the deviation is a total flatness relationship of all par-allel surfaces; however, it does not in-clude the step tolerance that may exist be-tween any two surfaces, nor is it applicable to any surfaces that are inclined to the ma-jor surfaces being measured. Contoured or tapered surfaces are not covered by the specified Straightness tolerance, but must be within the specified dimensional tol-erances, which should be large enough to allow for any warpage existing at these areas. The contour envelope tolerance

PARTING LINE
MISMATCH

FIGURE 2-64. A misalignment between the dies. Source: Ref. 4.

TABLE 2-3. Recommended Die Closure Tolerances (in.)
Weight, Ib (within)Plan area, in.2 (within)1 Precision typeConventional typeBlocker 1 type
0-'/2 ....10+0.020 -0.010+0.020 -0.010+0.031 -0.016
'/2 1 .... 30+0.020 -0.010+0.031 -0.016+0.047 -0.031
1 5 .... 100+0.031 -0.010+0.047 -0.016+0.062 -0.031
5 20 ....400+0.047 -0.016+0.062 -0.031+0.093 -0.062
20 50 .... 750+0.062 -0.016+0.093 -0.031+0.125 -0.062
50 100.......... 1000+0.093 -0.016+0.125 -0.031+0.187 -0.062
100 200 .... 2000+0.125 -0.016+0.187 -0.031+0.250 -0.062
')(v\ son.......... 3500
+0.250 -0.031+0.375 -0.062
500 UD 5000
+0.500 -0.062
Note: Use the larger tolerance when weight and plan area are not on same line. Source: Ref. 4.

Full-die closure tolerance
• All thicknesses, whether the forging impression is all in one die half or in two die halves
• Center dimensions across parting line or from center to parting line when the impression is all in one die
One-half die closure tolerance plus a symmetry tolerance of ±0.015
• Dimensions from surface to parting line when impression is in both dies
• All center dimensions to parting line when impression is in both dies
All other dimensions covered by dimen-sional tolerances

Recommended die closure tolerances are listed in Table 2-3. Note, however, that the applicable tolerance is determined by the weight or the plan area of the forg-ing—whichever is greater. The larger tol-erance should be used when weight and plan area are not on same line.

Coining Tolerances

Coining tolerance is ±0.005 in. mini-mum. Similar to die closure tolerance, it is applied to the surface across and par-allel to the parting line. It is limited to small areas only and usually to portions of forg-ings, such as boss faces. The coining op-eration is performed on cold forgings after heat treating and prior to aging.

When two or more sets of bosses are coined simultaneously (Figure 2-63), each set of bosses will have the faces parallel to one another and within coining toler-ance. However, the coining operation may not straighten the forging, and it may spring back to its original distorted shape if any warpage existed before the coining.

Dimensional Tolerances

Dimensional tolerances (sometimes called length and width tolerances) usu-ally apply to dimensions essentially par-allel to the fundamental parting line. They also actually apply to all dimensions not otherwise covered by the die closure tol-erances. Dimensional tolerances consist of two factors, a shrinkage tolerance and an

COIN SIZE t 005
COIN SIZE 1.005
, PAIRS OF SURFACES COINED SIMULTANEOUSLY
V
/
SIMULTANEOUS /
COINING WILL NOT T IMPROVE TOLERANCE ON THIS DIMENSION
COIN SIZEt.005
FIGURE 2-63. Example of coin sizing to refine dimensional relationships between opposing flat surfaces. Source: Ref. 4.

INSPECTION
SPECIAL PREPARATION (IF REQUIRED)
DIE SINKING
1 DRILLING
2 SHANKING
5 BENCH WORK
6 PROOF CAST
7 INSPECTION
HEATING FOR FORGING
FORGING EQUIPMENT
2 FULLERING
3 BLOCKING
4 FINISHING
5 (CUTOFF)
FIGURE 4-1. Flow chart of typical operations in the production of hot forgings.

ing modifications, particularly where tol-erances, draft angles, and comer and fillet radii are involved.

Unnecessarily tight tolerances, thin webs and ribs, small draft angles, and sharp comer and fillet radii result in needless manufacturing problems and high costs. Close straightness tolerances may cause an additional hand straightening or cold

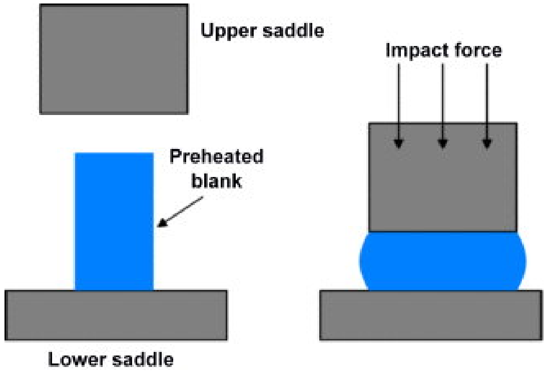
restrike operation (requiring additional dies and possibly checking fixtures for large parts), and special flash-grinding opera-tions may be necessary to meet restrictive flash extension tolerances. Tight toler-ances can also shorten the life of forging dies, because dies commonly are designed to take advantage of the dimensional al-lowance to compensate for die wear, pol-

ishing, and repair. Considerations such as these are taken into account by the forging engineer and are reflected in the cost es-timate.

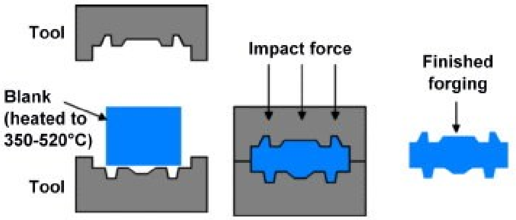
In addition, designs with small radii and restrictive tolerances can create higher die costs. Additional die machining time is al-most always necessary, and in extreme cases, extra steps in the forging process must be contemplated.

General principle of forging

Forging is a massive forming process; the temperature of the workpiece is increased to such an extent that the deformation forces required are considerably less than would be needed to cold work it. The two most important forging processes are open-die forging (in which forming of the workpiece takes place locally and mostly using simple dies) and **closed-die forging** (where the workpiece is fully enclosed in a die whose form determines the shape of the forging) (cf. illustrations).



Opem-die forging



Closed-die forging

For large-scale production, closed-die forging is usually used because it is regarded as being a very reliable process. Thanks to the superior mechanical properties obtained, the process can compete with the most advanced casting processes. Compared with casting, however, the range of possible shapes that can be produced is more limited. In particular, it is difficult to produce sharp corners, undercuts and cavities by use of forging.

The Institut für Integrierte Produktion Hannover (Institute for Integrated Production) has developed the hydroforging process to produce hollow parts; this involves forging aluminium components using an active fluid medium. In order to maintain a constant forging temperature, molten tin solder, for example, is used as the active medium. By using a sealed piston to increase the internal pressure, whilst at the same time closing both open ends of the hollow profile, the process can be used to produce hollow aluminium bodies having a uniform wall thickness. The forging process usually consists of the following steps:

- sawing the **extruded or continuously cast** feedstock,
- heating the blank,
- upsetting or bending,
- forging (rough and final forging),
- deburring and, if necessary, punching,
- **heat treatment** ,
- **pickling** or blasting and
- final inspection.

Unlike **sheet forming**, in forging there is always a change in the cross section of the feedstock. Generally speaking, changes to the cross-section are achieved either by material displacement (forging, **extrusion**, **rolling**, and **cold impact extrusion**) or by material accumulation (upsetting) (c.f. figure).

At the same, the processes mentioned enable a change in the direction of flow of the material to occur. Cavities are an added design possibility of massive forming.

Cutting processes are also always a part of the forging process. They are used to cut the feedstock, produce openings in forgings or produce blanks.

Forging alloys

In principle, all **wrought and cast alloys** can be hot worked by **forging**. However, only selected wrought alloys (non-heat-treatable and age-hardenable) are usually used because of the generally high mechanical demands (i.e. safety parts) and for economic reasons. Typical forging alloys are:

Alloy	**EN-AW**	**Temper**	**Applications**
AlMg3	5754	H112	decoratively anodisable, shipbuilding, chemical engineering
AlMg4.5Mn0.7	5083	H112	high corrosion resistance, shipbuilding, chemical engineering
AlSi1MgMn	6082	T6	standard for vehicle manufacturing, shipbuilding and mechanical engineering
AlCu4Mg1	2024	T4	highly stressed parts in vehicle manufacturing and mechanical engineering
AlCu4SiMg	2014	T6	more highly stressed parts in vehicle manufacturing and mechanical engineering
AlZn5.5MgCu	7075	T6 T73	most highly stressed parts in mechanical engineering

Non-heat-treatable wrought alloys are mostly only used where there is a need for decorative **anodisability**, high **corrosion resistance** and **weldability**. In the hot-formed condition, the alloy is almost soft and is designated **H112** (DIN EN 573 and DIN EN 586). An **increase in strength** can only be achieved by cold working, although this has an effect amongst other things on the corrosion resistance, elongation to failure and **high-temperature strength**).

Age-hardenable wrought alloys are used preferentially for structural parts. Higher strength values are obtained by artificial ageing (**T6** and **T73** tempers). Alloy 2024 (**T4**ductility and toughness. The following table shows typical mechanical properties for forging alloys:

Legierung	**EN-AW**	**Zustand**	**$R_{p0.2}$** [N/mm^2]	**R_m** [N/mm^2]	**A_5** [%]	**HB**	**Scherfestigkt.** [N/mm^2]	**Dauerfestigkt.** [N/mm^2]
AlMg4.5Mn0.7	5083	H112	145	300	23	70	175	250
AlSi1MgMn	6082	T6	310	340	11	95	210	210
AlCu4Mg1	2024	T4	330	460	20	120	285	280
AlCu4SiMg	2014	T6	425	485	12	140	290	290
AlZn5.5MgCu	7075 7075	T6 T73	505 435	570 505	10 13	150 140	350 305	300 300

Minimum strength values are given in DIN EN 586; the values given in the table are only intended to characterise the alloys.

The microstructure of the feedstock for forging is important for strength. Continuously cast billets as well as extruded rods and **profiles** are used. In the case of extruded feedstock, there is a fibrous microstructure in the longitudinal direction, which is beneficial for the strength of the subsequent forging, whereas with cast alloys the grain structure is equiaxed.

Forgin Defects

The forging process, by its nature, produces a superior product, especially in comparison with castings and machined components. Defects can occasionally occur during the forging process, but it should be understood that forging defects are not inherent to the process itself. If a forge shop begins to experience defects in their process, they should try to find the root cause of the problem, initiate corrective action and implement procedures to prevent its recurrence.

In this two-part article we plan to cover a number of possible forging defects and provide some insight into their cause as well as recommendations for corrective action. In this first part we will cover geometrical defects. In the second we plan to discuss material-related defects due to microstructure and ductile failure.

Remember that in an optimum environment, many defects could be avoided. Cost pressures and lead-time reduction efforts result in pushing the forging process to its limits. Although some phenomena require additional research, there are many defects that have been characterized and studied. Many of these can be corrected. Economically, as well as from a quality perspective, it is better to understand and control your process so as to avoid defects rather than scrapping defective parts during a final inspection.

Defects can result from a less-than-optimum process design or poor execution of the design in manufacturing or material-related problems. It should be noted that a robust process would be designed so as to allow some variation in material without causing a defect. This article addresses the defects generally related to process design – usually described as geometrical defects.

There are a number of different geometrical defects that can occur during forging. These include:

- Laps and folds
- Underfills
- Piping
- Forging shape does not match design
- Die deflection, yielding or wear
- Eccentricity or buckling

Less-than-optimum process and preform design is the principal cause of most geometrical defects. By understanding the process issues, the forge is better able to design its processes to minimize the occurrence of such defects.

When the press or hammer dies close, the workpiece will move in a path of least resistance. It is imperative that the die and pre-form design create this least resistant path so that the net result is a sound forging. On occasion, the die design may create a situation in which the path of least resistance is the one that results in a defect during forging. By examining the various types of geometrical defects, the fundamental cause can be understood and the die designer can produce a die that creates a sound, defect-free product.

LAPS AND FOLDS

Enlarge this picture

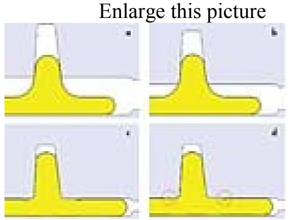


Figure 2. A "peeling" lap forms in an aluminum rib-web forging as the corner of the die forces surface material ahead of the contact region. With a redesign of the upper die or preform, this type of defect can be prevented.

The most common type of geometrical defect is a lap. Laps are the result of:

- A section of the workpiece flowing into itself.
- A "flow-by" in which the workpiece surface is in contact with a die and is subsequently pulled away by a tensile stress component and closes on itself.
- "Peeling" that can form when the surface of a billet or preform is sheared by a die, resulting in an area of localized folding. A die corner is frequently involved, as it forces material ahead of a moving contact region, without significant subsurface deformation. This defect can be the result of a poor design or inadequate process control.
- Flow localization that can also show up as a forging lap in alloys where flow softening exists. (These will be discussed in more detail in part 2).

Most laps are resolved by changing the forging preform, forged shape or process. The prevention of laps is primarily a process-design issue due to improper preform geometry or improper impression geometry. The use of simulation tools is a very effective way to evaluate several preform shapes and avoid forging laps.

Figure 1 shows several frames of a simulation for the forging of a gear blank in which the die design produces a "flow-

by" lap. As the upper die descends and the workpiece is compressed, the material "flows by" – does not maintain continuous contact with – the side surface of the punch. The material hits the outer bottom surface of the punch and folds back onto itself, creating the lap defect as indicated. The preform shape in conjunction with the punch design causes the defect.

Figure 2 illustrates the formation of a "peeling" lap for the forging of an aluminum rib. The shape of the preform, together with the shape of the upper die, causes this defect to occur. As the upper die compresses the workpiece material, it begins to shear, or "peel," the surface of the rib region. In the finished component the defects appear on the part's top surface in spite of the fact that they were generated on the side surface of the rib. The use of the simulation program to study this defect provides insight into how it was generated and where remedial changes should be made to the die design. To correct this defect, a redesign of the rib region in the preform shape would be advisable.

UNDERFILLS

Underfills are another geometrical defect commonly caused by inadequate press force, energy and/or power. These may be symptomatic of the use of undersized equipment on jobs that are too big for it. Also, the improper control of lubricant vapors can cause this type of defect.

Enlarge this picture

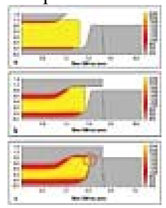


Figure 3. A steel forging with an underfill (orange) is the result of using an undersized hydraulic press with inadequate power and force to completely fill the die cavity.

Underfilling is typically a problem when a large part is manufactured on a small press with a less-than-optimum preform geometry. Smaller equipment does not provide the option of overpowering a less-than-optimum design or leave much margin for process variation. Depending on the equipment, force, power, speed or energy can be the culprit for an underfill.

Figure 3 shows a steel forging being produced on an undersized hydraulic press. Because the press is slow, there is significant chilling of the workpiece, as indicated by the temperature profiles in the figure. This causes the flow strength of the steel to increase and require more force to deform it. Because of its small size, the press will stall before the component is completely forged, leaving an underfilled region. To avoid this, equipment of the right capacity must be used.

Underfills can also result from air, gas or lubricant being trapped in a corner feature of a forging. These can be eliminated by a redesigned preform, which provides a vent for gas, or by adding corner closure to the final forging. The ideal gas law can be used to describe the behavior of gas being compressed in a die corner:

$$PV = nRT$$

where P is the pressure, V is the volume, n is the number of gas molecules, R is the ideal gas constant and T is temperature. For a fixed amount of gas at a constant temperature, the right side of the equation is constant. However, when gas is trapped inside the die cavity and compressed (i.e. volume decreases), the gas pressure increases. When the pressure of the trapped gas is equal to the surface pressure on the forging, no further reduction in volume occurs, resulting in an underfill.

High temperatures compound this effect by heating the trapped gas first with a resulting increase in pressure and subsequently larger underfill. Finally, trapping lubricant, glass or water vapor may change the dynamics of the compression process since these materials may not precisely follow the compressibility of the ideal gas law. Glass coatings used when forging titanium alloys are virtually incompressible.

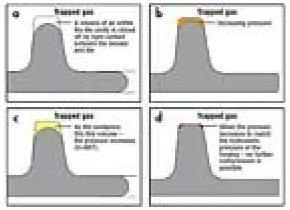


Figure 4. Underfilled corners are the result of trapped gas during the forging process. This type of underfill can be prevented by redesign of the preform, by providing a vent (or relief gutter) for gas or by adding corner closure to the final forging.

Figure 4 shows an underfill created by trapped gas in a rib corner. As the dies close, a fixed amount of gas is trapped. As the volume available for the gas decreases, the pressure of the gas increases (via the ideal gas law). Eventually, the gas pressure gets so high it reaches the same level as the surface pressure on the forging and further compression cannot occur. At this point, some volume of the die cavity will remain unfilled.

At times, underfills can result from blockers with less-than-optimum volume distribution. Blockers are designed to approximate the volume distribution of the final forging with less detail. With a perfect preform, the cavity is finished filling as the flash starts to form. The flash formation increases die-cavity pressure and is used to ensure complete die filling. With an incorrect volume distribution, the flash can form prematurely, resulting in an underfill.

Figure 5 shows a forging simulation using an improperly designed preform, which causes an underfill. In this web-rib forging the volume distribution of the preform is incorrect. Note that the flash begins to form (Figure 5c) well before the web cavity is filled. To correct this problem the blocker must leave more material in the web region so that the cavity can be filled at the time the flash begins to form. In this case the simulation aids the die design to see how the distribution of material affects the final shape.

During extrusion, die forging or other processes with significant changes in section sizes, it is possible for a feature to be starved for volume. This starvation can result in defects ranging from a shallow underfill to a severe seam. These defects are commonly referred to as pipes.

Piping defects are closed underfills. Piping, or "flow-through," defects are resolved by changes in the die impression or the preform geometry. Figure 6 shows a piping or suck-in defect in an aluminum impact extrusion. The pipe occurs at the end of the stroke when there is an insufficient volume of material in that location.

GEOMETRICAL DISCREPANCIES

During open-die forging or forging without any die contact, the workpiece may flow in a manner that is different from the design plan. Even though we would like the material to flow in a prescribed manner, if it is unconstrained it may move in an undesirable fashion, leaving a part that does not meet the customer's specifications. This type of material movement is not random or arbitrary and will take the path of least resistance in determining its flow. Simulation programs can aid the forger in understanding actual material flow. These packages incorporate the flow along the path of least resistance within their calculations and provide a detailed view of the actual geometry that a part would take when the dies do not provide constraint.

Enlarge this picture

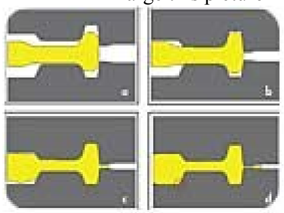


Figure 5. Underfill due to incorrect volume distribution in the blocker for a rib-web forging. The underfill is shown in d. The preform must be redesigned to prevent this type of underfill.

SIMULATION PROGRAMS

Simulation programs can be effectively used to see the formation of defects. These tools allow the forger to "see" inside the die and the workpiece during deformation. The simulation tool can also provide a serial view of the process dynamics in both forward and backward directions. These can provide the forger with significant insights into the origin and evolution of the geometrical defects that are described in this paper.

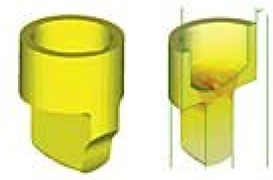


Figure 6. An aluminum impact extrusion – note the piping defect (i.e. suck-in defect) at the end of the die stroke. The forging has been starved for material in this region. A redesign of the die or preform is needed in order to correct this.

Simulation has allowed us to clearly illustrate die designs that contribute to geometrical defects of laps and underfills. The programs also allow the forging engineer to test a number of "what if" scenarios without having to actually sink a die and run tests in the forge shop.

FINAL COMMENTS

During the forging process, workpiece material follows the path of least resistance rather than the forging print. Improper die design or improper preform design can cause the workpiece to flow in an undesirable fashion, resulting in a geometrical defect. The main types of geometrical defects are laps and underfills. If such defects are encountered in your forgings, corrective action needs to be taken. The use of simulation tools can provide insight into the fundamental cause and the appropriate adjustment.

Part 2 of this article will address the problems and solutions associated with the second major class of forging defects – material induced defects.

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In addition to surface cracking during forging, other defects can develop as a result of the material flow pattern in the die. Excess material in the web may buckle during forging and develop laps {Fig. 14.27a). But if the web is thick, the excess material flows past the already forged portions of the forging and develops internal cracks

Die
(a)

Blocked forging

Die Begin finishing

Rib Web
Web buckles

Laps

Laps in finished forging

Ib)

Forging begins

Die cavities
are being
filled

Cracks develop in
ribs

Cracks
propagate through ribs

FIGURE 14.27

(a) Laps formed by web buckling during forging. Web thickness should be increased to avoid this problem, (b) Internal defects caused by oversized billet. Die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

(Fig. 14.27b). The various radii in the forging die cavity can significantly influence the formation of such defects. Internal defects may also develop from nonuniform deformation of the material in the die cavity, temperature variations throughout the workpiece during forging, and microstructural changes caused by phase transfor-mations.

Forging defects can cause fatigue failures and lead to other problems such as corrosion and wear during the service life of the component. The importance of inspecting forgings before they are put into service, particularly in critical applica¬tions, is obvious.