

CHAPTER 2

Forging Processes: Variables and Descriptions

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2.1 Introduction

In forging, an initially simple part—a billet, for example—is plastically deformed between two tools (or dies) to obtain the desired final configuration. Thus, a simple part geometry is transformed into a complex one, whereby the tools “store” the desired geometry and impart pressure on the deforming material through the tool/material interface. Forging processes usually produce little or no scrap and generate the final part geometry in a very short time, usually in one or a few strokes of a press or hammer. As a result, forging offers potential savings in energy and material, especially in medium and large production quantities, where tool costs can be easily amortized. In addition, for a given weight, parts produced by forging exhibit better mechanical and metallurgical properties and reliability than do those manufactured by casting or machining.

Forging is an experience-oriented technology. Throughout the years, a great deal of know-how and experience has been accumulated in this field, largely by trial-and-error methods. Nevertheless, the forging industry has been capable of supplying products that are sophisticated and manufactured to very rigid standards from newly developed, difficult-to-form alloys.

The physical phenomena describing a forging operation are difficult to express with quantitative relationships. The metal flow, the friction at the tool/material interface, the heat generation and transfer during plastic flow, and the relationships between microstructure/properties and

process conditions are difficult to predict and analyze. Often in producing discrete parts, several forging operations (preforming) are required to transform the initial “simple” geometry into a “complex” geometry, without causing material failure or degrading material properties. Consequently, the most significant objective of any method of analysis is to assist the forging engineer in the design of forging and/or preforming sequences. For a given operation (preforming or finish forging), such design essentially consists of (a) establishing the kinematic relationships (shape, velocities, strain rates, strains) between the deformed and undeformed part, i.e., predicting metal flow, (b) establishing the limits of formability or producibility, i.e., determining whether it is possible to form the part without surface or internal failure, and (c) predicting the forces and stresses necessary to execute the forging operation so that tooling and equipment can be designed or selected.

For the understanding and quantitative design and optimization of forging operations it is useful to (a) consider forging processes as a system and (b) classify these processes in a systematic way [Altan et al., 1983].

2.2 Forging Operation as a System

A forging system comprises all the input variables such as the billet or blank (geometry and material), the tooling (geometry and material), the conditions at the tool/material interface, the mechanics of plastic deformation, the equipment

used, the characteristics of the final product, and finally the plant environment where the process is being conducted.

The “systems approach” in forging allows study of the input/output relationships and the effect of the process variables on product quality and process economics. Figure 2.1 shows the different components of the forging system. The key to a successful forging operation, i.e., to obtaining the desired shape and properties, is the understanding and control of the metal flow. The direction of metal flow, the magnitude of deformation, and the temperatures involved greatly influence the properties of the formed components. Metal flow determines both the mechanical properties related to local deformation and the formation of defects such as cracks and folds at or below the surface. The local metal flow is in turn influenced by the process variables summarized below:

Billet

- Flow stress as a function of chemical composition, metallurgical structure, grain size, segregation, prior strain history, temperature of deformation, degree of deformation or strain, rate of deformation or strain, and microstructure
- Forgeability as a function of strain rate, temperature, deformation rate
- Surface texture
- Thermal/physical properties (density, melting point, specific heat, thermal conductivity and expansion, resistance to corrosion and oxidation)
- Initial conditions (composition, temperature, history/prestrain)
- Plastic anisotropy
- Billet size and thickness

Tooling/Dies

- Tool geometry
- Surface conditions, lubrication
- Material/heat treatment/hardness
- Temperature

Conditions at the Die/Billet Interface

- Lubricant type and temperature
- Insulation and cooling characteristics of the interface layer
- Lubricity and frictional shear stress
- Characteristics related to lubricant application and removal

Deformation Zone

- The mechanics of deformation, model used for analysis
- Metal flow, velocities, strain, strain rate (kinematics)
- Stresses (variation during deformation)
- Temperatures (heat generation and transfer)

Equipment

- Speed/production rate
- Binder design and capabilities
- Force/energy capabilities
- Rigidity and accuracy

Product

- Geometry
- Dimensional accuracy/tolerances
- Surface finish
- Microstructure, metallurgical and mechanical properties

Environment

- Available manpower
- Air, noise, and wastewater pollution
- Plant and production facilities and control

2.2.1 Material Characterization

For a given material composition and deformation/heat treatment history (microstructure), the flow stress and the workability (or forgeability) in various directions (anisotropy) are the most important material variables in the analysis of a metal forging process.

For a given microstructure, the flow stress, $\bar{\sigma}$, is expressed as a function of strain, $\bar{\epsilon}$, strain rate, $\dot{\bar{\epsilon}}$, and temperature, T :

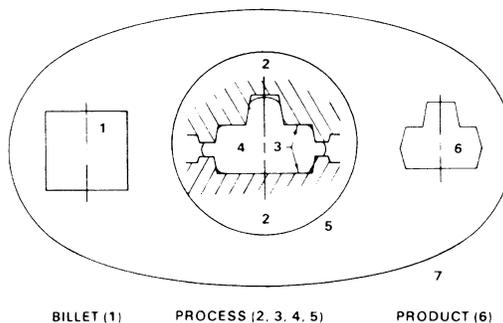


Fig. 2.1 One-blow impression-die forging considered as a system: (1) billet, (2) tooling, (3) tool/material interface, (4) deformation zone, (5) forging equipment, (6) product, (7) plant environment

$$\bar{\sigma} = f(\bar{\epsilon}, \dot{\bar{\epsilon}}, T) \quad (\text{Eq 2.1})$$

To formulate the constitutive equation (Eq 2.1), it is necessary to conduct torsion, plane-strain compression, and uniform axisymmetric compression tests. During any of these tests, plastic work creates a certain increase in temperature, which must be considered in evaluating and using the test results.

Workability, forgeability, or formability is the capability of the material to deform without failure; it depends on (a) conditions existing during deformation processing (such as temperature, rate of deformation, stresses, and strain history) and (b) material variables (such as composition, voids, inclusions, and initial microstructure). In hot forging processes, temperature gradients in the deforming material (for example, due to local die chilling) also influence metal flow and failure phenomena.

2.2.2 Tooling and Equipment

The selection of a machine for a given process is influenced by the time, accuracy, and load/energy characteristics of that machine. Optimal equipment selection requires consideration of the entire forging system, including lot size, conditions at the plant, environmental effects, and maintenance requirements, as well as the requirements of the specific part and process under consideration.

The tooling variables include (a) design and geometry, (b) surface finish, (c) stiffness, and (d) mechanical and thermal properties under conditions of use.

2.2.3 Friction and Lubrication at the Die/Workpiece Interface

The mechanics of interface friction are very complex. One way of expressing friction quantitatively is through a friction coefficient, μ , or a friction shear factor, m . Thus, the frictional shear stress, τ , is:

$$\tau = \mu \sigma_n \quad (\text{Eq 2.2})$$

or

$$\tau = f \bar{\sigma} = \frac{m}{\sqrt{3}} \bar{\sigma} \quad (\text{Eq 2.3})$$

where σ_n is the normal stress at the interface, $\bar{\sigma}$ is the flow stress of the deforming material

and f is the friction factor ($f = m/\sqrt{3}$). There are various methods of evaluating friction, i.e., estimating the value of μ or m . In forging, the most commonly used tests are the ring compression test, spike test, and cold extrusion test.

2.2.4 Deformation Zone/Mechanics of Deformation

In forging, material is deformed plastically to generate the shape of the desired product. Metal flow is influenced mainly by (a) tool geometry, (b) friction conditions, (c) characteristics of the stock material, and (d) thermal conditions existing in the deformation zone. The details of metal flow influence the quality and the properties of the formed product and the force and energy requirements of the process. The mechanics of deformation, i.e., the metal flow, strains, strain rates, and stresses, can be investigated by using one of the approximate methods of analysis (e.g., finite-element analysis, finite difference, slab, upper bound, etc.).

2.2.5 Product Geometry and Properties

The macro- and microgeometry of the product, i.e., its dimensions and surface finish, are influenced by the process variables. The processing conditions (temperature, strain, strain rate) determine the microstructural variations taking place during deformation and often influence the final product properties. Consequently, a realistic systems approach must include consideration of (a) the relationships between properties and microstructure of the formed material and (b) the quantitative influences of process conditions and heat treatment schedules on microstructural variations.

2.3 Types of Forging Processes

There are a large number of forging processes that can be summarized as follows:

- Closed/impression die forging with flash
- Closed/impression die forging without flash
- Electro-upsetting
- Forward extrusion
- Backward extrusion
- Radial forging
- Hobbing
- Isothermal forging
- Open-die forging

- Orbital forging
- Powder metal (P/M) forging
- Upsetting
- Nosing
- Coining

2.3.1 Closed-Die Forging with Flash
(Fig. 2.2a and 2.2b)

Definition. In this process, a billet is formed (hot) in dies (usually with two halves) such that the flow of metal from the die cavity is restricted. The excess material is extruded through a restrictive narrow gap and appears as flash around the forging at the die parting line.

Equipment. Anvil and counterblow hammers, hydraulic, mechanical, and screw presses.

Materials. Carbon and alloy steels, aluminum alloys, copper alloys, magnesium alloys, beryllium, stainless steels, nickel alloys, titanium and titanium alloys, iron and nickel and cobalt superalloys, niobium and niobium alloys, tantalum and tantalum alloys, molybdenum and molybdenum alloys, tungsten alloys.

Process Variations. Closed-die forging with lateral flash, closed-die forging with longitudinal flash, closed-die forging without flash.

Application. Production of forgings for automobiles, trucks, tractors, off-highway equipment, aircraft, railroad and mining equipment, general mechanical industry, and energy-related engineering production.

2.3.2 Closed-Die Forging without Flash
(Fig. 2.3)

Definition. In this process, a billet with carefully controlled volume is deformed (hot or

cold) by a punch in order to fill a die cavity without any loss of material. The punch and the die may be made of one or several pieces.

Equipment. Hydraulic presses, multiram mechanical presses.

Materials. Carbon and alloy steels, aluminum alloys, copper alloys.

Process Variations. Core forging, precision forging, cold and warm forging, P/M forging.

Application. Precision forgings, hollow forgings, fittings, elbows, tees, etc.

2.3.3 Electro-Upsetting (Fig. 2.4)

Definition. Electro-upsetting is the hot forging process of gathering a large amount of material at one end of a round bar by heating the bar end electrically and pushing it against a flat anvil or shaped die cavity.

Equipment. Electric upsetters.

Materials. Carbon and alloy steels, titanium.

Application. Preforms for finished forgings.

2.3.4 Forward Extrusion (Fig. 2.5)

Definition. In this process, a punch compresses a billet (hot or cold) confined in a container so that the billet material flows through a die in the same direction as the punch.

Equipment. Hydraulic and mechanical presses.

Materials. Carbon and alloy steels, aluminum alloys, copper alloys, magnesium alloys, titanium alloys.

Process Variations. Closed-die forging without flash, P/M forging.

Application. Stepped or tapered-diameter solid shafts, tubular parts with multiple diameter

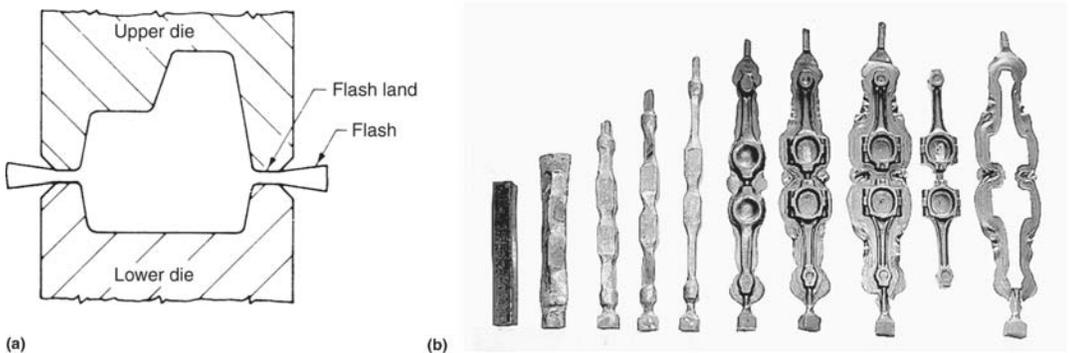


Fig. 2.2 Closed-die forging with flash. (a) Schematic diagram with flash terminology. (b) Forging sequence in closed-die forging of connecting rods

holes that are cylindrical, conical, or other non-round shapes.

2.3.5 Backward Extrusion (Fig. 2.5)

Definition. In this process, a moving punch applies a steady pressure to a slug (hot or cold) confined in a die and forces the metal to flow around the punch in a direction opposite the direction of punch travel (Fig. 2.5).

Equipment. Hydraulic and mechanical presses.

Materials. Carbon and alloy steels, aluminum alloys, copper alloys, magnesium alloys, titanium alloys.

Process Variations. Closed-die forging without flash, P/M forging.

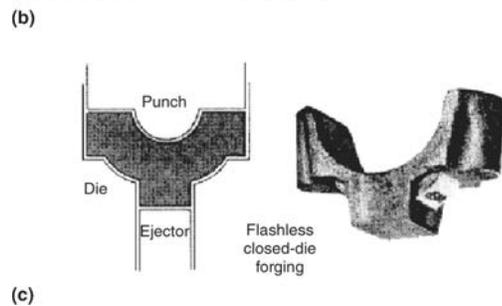
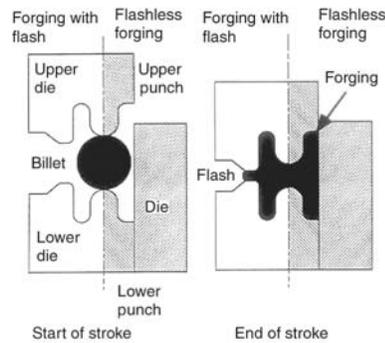
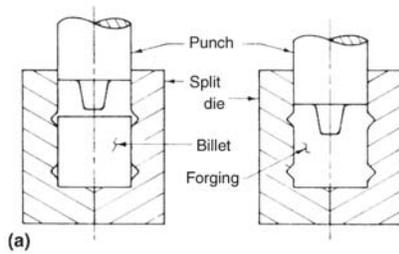


Fig. 2.3 Closed-die forging without flash

Application. Hollow parts having a closed end, cupped parts with holes that are cylindrical, conical, or of other shapes.

2.3.6 Radial Forging (Fig. 2.6)

Definition. This hot or cold forging process utilizes two or more radially moving anvils or dies for producing solid or tubular components with constant or varying cross sections along their length.

Equipment. Radial forging machines.

Materials. Carbon and alloy steels, titanium alloys, tungsten, beryllium, and high-temperature superalloys.

Process Variations. Rotary swaging.

Application. This is a technique that is used to manufacture axisymmetrical parts. Reducing the diameters of ingots and bars, forging of stepped shafts and axles, forging of gun and rifle barrels, production of tubular components with and without internal profiles.

2.3.7 Hobbing (Fig. 2.7)

Definition. Hobbing is the process of indenting or coining an impression into a cold or hot die block by pressing with a punch.

Equipment. Hydraulic presses, hammers.

Materials. Carbon and alloy steels.

Process Variations. Die hobbing, die typing.

Application. Manufacture of dies and molds with relatively shallow impressions.

2.3.8 Isothermal Forging (Fig. 2.8)

Definition. Isothermal forging is a forging process where the dies and the forging stock are at approximately the same high temperature.

Equipment. Hydraulic presses.

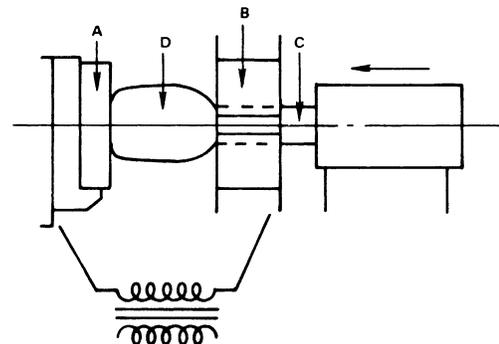


Fig. 2.4 Electro-upsetting. A, anvil electrode; B, gripping electrode; C, workpiece; D, upset end of workpiece

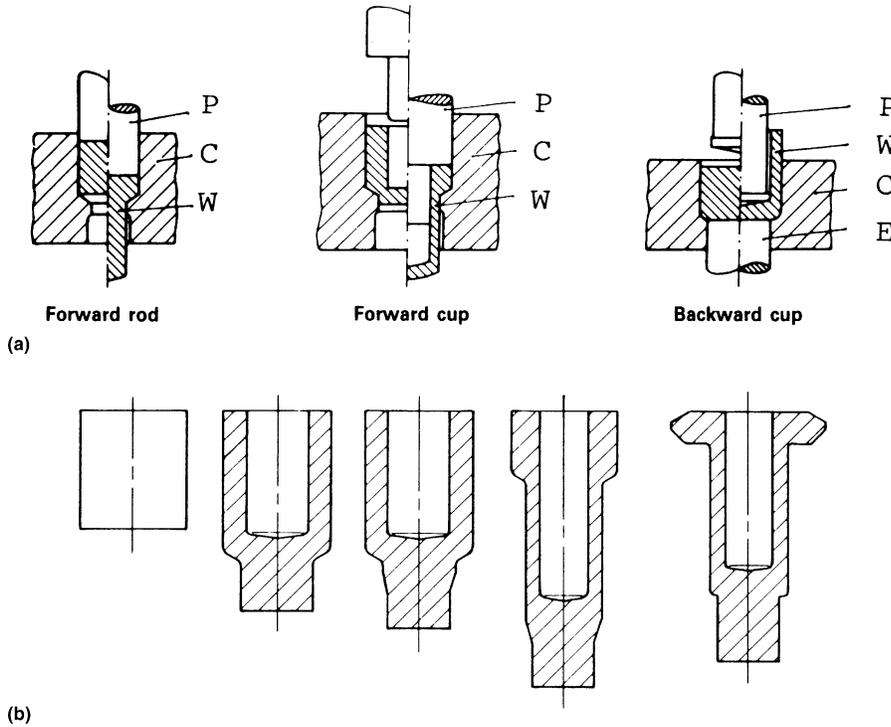


Fig. 2.5 Forward and backward extrusion processes. (a) Common cold extrusion processes (P, punch; W, workpiece; C, container; E, ejector). [Feldman, 1977]. (b) Example of a component produced using forward rod and backward cup extrusion. Left to right: sheared blank, simultaneous forward rod and backward cup extrusion, forward extrusion, backward cup extrusion, simultaneous upsetting of flange and coining of shoulder. [Sagemuller, 1968]

Materials. Titanium alloys, aluminum alloys.

Process Variations. Closed-die forging with or without flash, P/M forging.

Application. Net- and near-net shape forgings for the aircraft industry.

2.3.9 Open-Die Forging (Fig. 2.9)

Definition. Open-die forging is a hot forging process in which metal is shaped by hammering or pressing between flat or simple contoured dies.

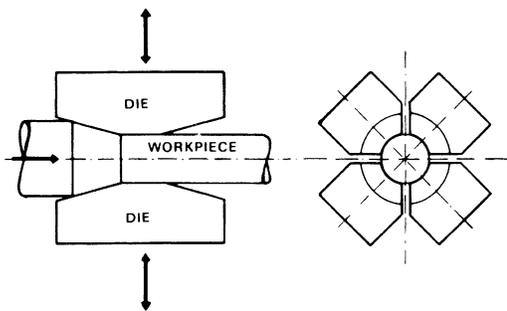


Fig. 2.6 Radial forging of a shaft

Equipment. Hydraulic presses, hammers.

Materials. Carbon and alloy steels, aluminum alloys, copper alloys, titanium alloys, all forgeable materials.

Process Variations. Slab forging, shaft forging, mandrel forging, ring forging, upsetting between flat or curved dies, drawing out.

Application. Forging ingots, large and bulky forgings, preforms for finished forgings.

2.3.10 Orbital Forging (Fig. 2.10)

Definition. Orbital forging is the process of forging shaped parts by incrementally forging

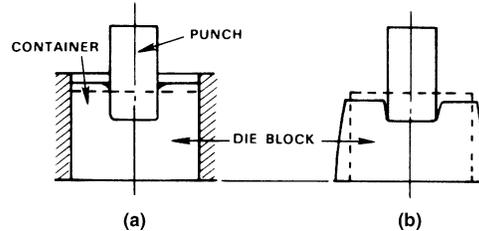


Fig. 2.7 Hobbing. (a) In container. (b) Without restriction

(hot or cold) a slug between an orbiting upper die and a nonrotating lower die. The lower die is raised axially toward the upper die, which is fixed axially but whose axis makes orbital, spiral, planetary, or straight-line motions.

Equipment. Orbital forging presses.

Materials. Carbon and low-alloy steels, aluminum alloys and brasses, stainless steels, all forgeable materials.

Process Variations. This process is also called rotary forging, swing forging, or rocking die forging. In some cases, the lower die may also rotate.

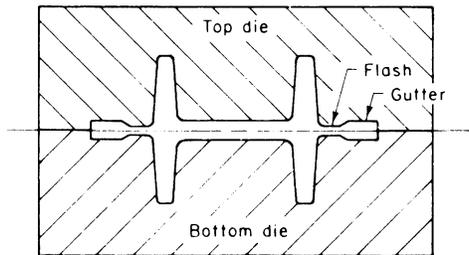


Fig. 2.8 Isothermal forging with dies and workpiece at approximately the same temperature

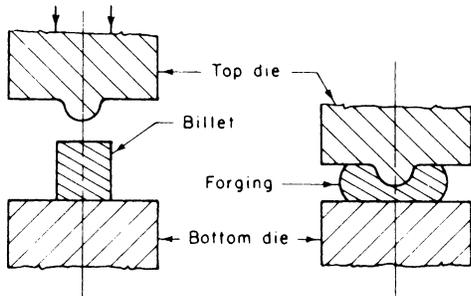


Fig. 2.9 Open-die forging

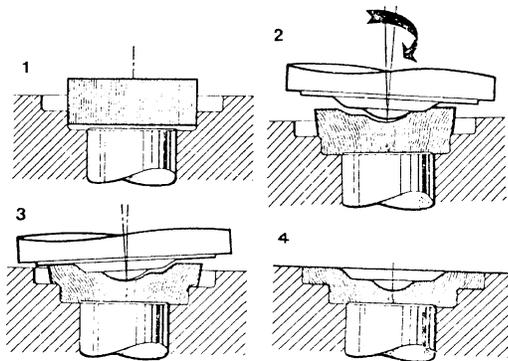


Fig. 2.10 Stages in orbital forging

Application. Bevel gears, claw clutch parts, wheel disks with hubs, bearing rings, rings of various contours, bearing-end covers.

2.3.11 Powder Metal (P/M) Forging (Fig.2.11)

Definition. P/M forging is the process of closed-die forging (hot or cold) of sintered powder metal preforms.

Equipment. Hydraulic and mechanical presses.

Materials. Carbon and alloy steels, stainless steels, cobalt-base alloys, aluminum alloys, titanium alloys, nickel-base alloys.

Process Variations. Closed-die forging without flash, closed-die forging with flash.

Application. Forgings and finished parts for automobiles, trucks, and off-highway equipment.

2.3.12 Upsetting or Heading (Fig. 2.12)

Definition. Upsetting is the process of forging metal (hot or cold) so that the cross-sectional area of a portion, or all, of the stock is increased.

Equipment. Hydraulic, mechanical presses, screw presses; hammers, upsetting machines.

Materials. Carbon and alloy steels, stainless steels, all forgeable materials.

Process Variations. Electro-upsetting, upset forging, open-die forging.

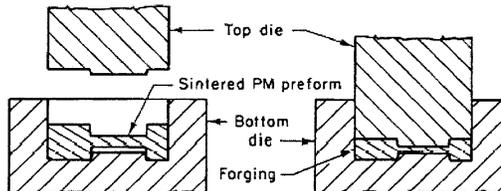


Fig. 2.11 Powder metal (P/M) forging

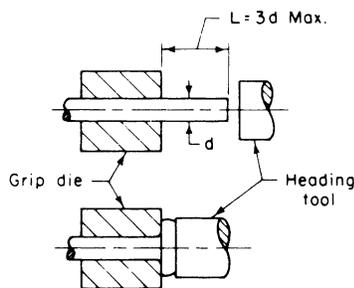


Fig. 2.12 Upset forging

Application. Finished forgings, including nuts, bolts; flanged shafts, preforms for finished forgings.

2.3.13 Nosing (Fig. 2.13)

Definition. Nosing is a hot or cold forging process in which the open end of a shell or tubular component is closed by axial pressing with a shaped die.

Equipment. Mechanical and hydraulic presses, hammers.

Materials. Carbon and alloy steels, aluminum alloys, titanium alloys.

Process Variations. Tube sinking, tube expanding.

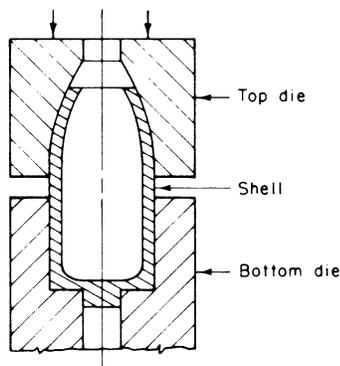


Fig. 2.13 Nosing of a shell

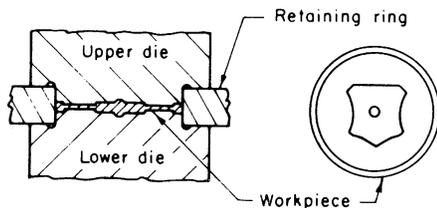


Fig. 2.14 Coining operation

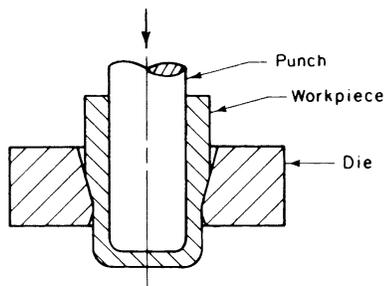


Fig. 2.15 Ironing operation

Applications. Forging of open ends of ammunition shells; forging of gas pressure containers.

2.3.14 Coining (Fig. 2.14)

Definition. In sheet metal working, coining is used to form indentations and raised sections in the part. During the process, metal is intentionally thinned or thickened to achieve the required indentations or raised sections. It is widely used for lettering on sheet metal or components such as coins. Bottoming is a type of coining process where bottoming pressure causes reduction in thickness at the bending area.

Equipment. Presses and hammers.

Materials. Carbon and alloy steels, stainless steels, heat-resistant alloys, aluminum alloys, copper alloys, silver and gold alloys.

Process Variations. Coining without flash, coining with flash, coining in closed die, sizing.

Applications. Metallic coins; decorative items, such as patterned tableware, medallions and metal buttons; sizing of automobile and aircraft engine components.

2.3.15 Ironing (Fig. 2.15)

Definition. Ironing is the process of smoothing and thinning the wall of a shell or cup (cold or hot) by forcing the shell through a die with a punch.

Equipment. Mechanical presses and hydraulic presses.

Materials. Carbon and alloy steels, aluminum and aluminum alloys, titanium alloys.

Applications. Shells and cups for various uses.

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