Selection of Forging Equipment

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DEVELOPMENTS in the forging industry are greatly influenced by the worldwide requirements for manufacturing ever larger, more precise, and more complex components from more difficult-to-forge materials. The increase in demand for stationary power systems, jet engines, and aircraft components as well as the ever-increasing foreign technological competition demand cost reduction in addition to continuous upgrading of technology. Thus, the more efficient use of existing forging equipment and the installation of more sophisticated machinery have become unavoidable necessities. Forging equipment influences the forging process because it affects deformation rate, forging temperature, and rate of production. Development in all areas of forging has the objectives of (a) increasing the production rate, (b) improving forging tolerances, (c) reducing costs by minimizing scrap losses, by reducing preforming steps, and by increasing tool life, and (d) expanding capacity to forge larger and more intricate and precise parts. Forging equipment greatly affects all these aforementioned factors.

The purchase of new forging equipment requires a thorough understanding of the effect of equipment characteristics on the forging operations, load and energy requirements of the specific forging operation, and the capabilities and characteristics of the specific forging machine to be used for that operation. Increased knowledge of forging equipment would also specifically contribute to:

- More efficient and economical use of existing equipment
- More exact definition of the existing maximum plant capacity
- Better communication between the equipment user and the equipment builder
- Development of more advanced processes such as precision forging of gears and of turbine and compressor blades

This section details the significant factors in the selection of forging equipment for a particular process. The article "Hammers and Presses for Forging" in this Volume contains information on the principles of operation and the capacities of various types of forging machines.

Process Requirements and Forging Machines

The behavior and characteristics of the forming machine influence:

- The flow stress and workability of the deforming material
- The temperatures in the material and in the tools, especially in hot forming
- The load and energy requirements for a given product geometry and material
- The "as-formed" tolerances of the parts
- The production rate

Figure 1 illustrates the interaction between the principal machine and process variables for hot forging conducted in presses. As shown at the left in Fig. 1, flow stress $\bar{\sigma}$, interface friction conditions, and part geometry (dimensions and shape) determine the load L_p at each position of the stroke and the energy E_p required by the forming process. The flow stress $\bar{\sigma}$ increases with increasing deformation rate $\dot{\bar{\varepsilon}}$ and with decreasing workpiece temperature, θ. The

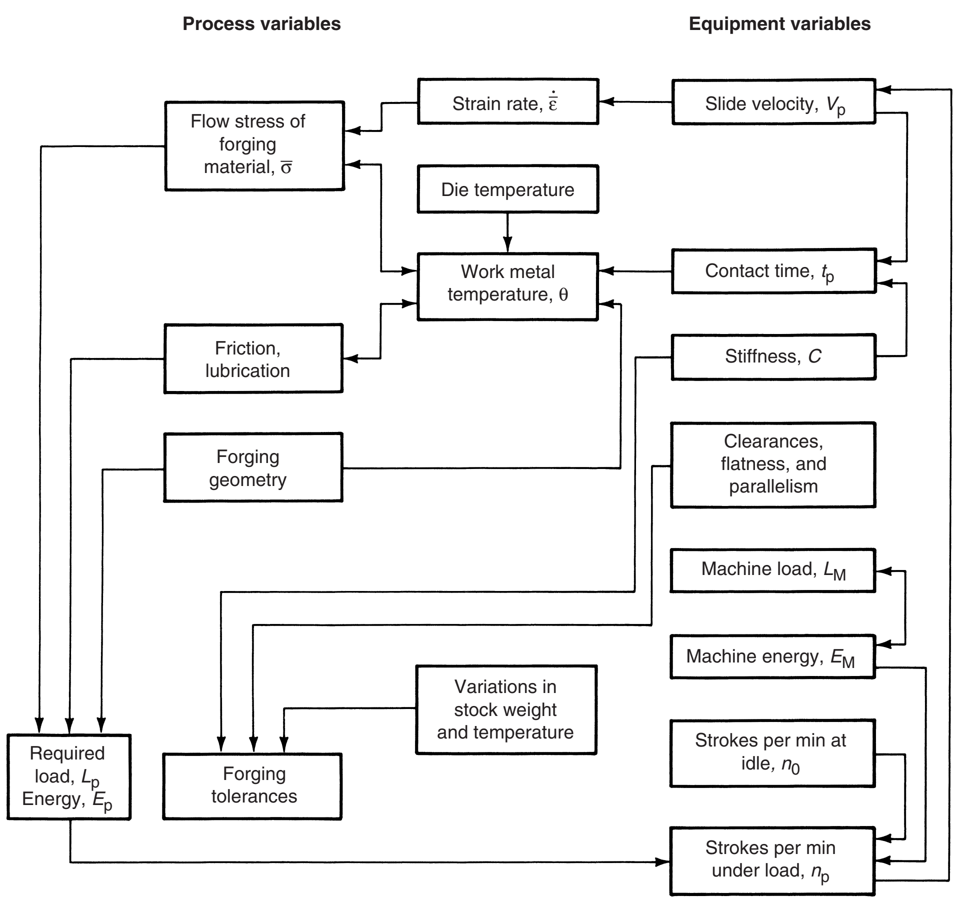


Fig. 1 Relationships between process and machine variables in hot-forging processes conducted in presses

magnitudes of these variations depend on the specific work material (see the Sections on forging of specific metals and alloys in this Volume). The frictional conditions deteriorate with increasing die chilling.

As indicated by the lines connected to the "Work metal temperature" block in Fig. 1, for a given initial stock temperature, the temperature variations in the part are largely influenced by (a) the surface area of contact between the dies and the part, (b) the part thickness or volume, (c) the die temperature, (d) the amount of heat generated by deformation and friction, and (e) the contact time under pressure t_p.

The velocity of the slide under pressure V_p determines mainly t_p and the deformation rate $\dot{\varepsilon}$. The number of strokes per minute under no-load conditions n_0, the machine energy E_M, and the deformation energy E_p required by the process influence the slide velocity under load V_p and the number of strokes under load n_p; n_p determines the maximum number of parts formed per minute (the production rate) if the feed and unloading of the machine can be carried out at that speed. The relationships illustrated in Fig. 1 apply directly to hot forging in hydraulic, mechanical, and screw presses.

For a given material, a specific forging operation, such as closed-die forging with flash, forward or backward extrusion, upset forging, or bending, requires a certain variation of the load over the slide displacement (or stroke). This is illustrated qualitatively in Fig. 2, which shows load versus displacement curves characteristic of various forming operations. For a given part geometry, the absolute load values will vary with the flow stress of the material and with frictional conditions. In forming, the equipment must supply the maximum load as well as the energy required by the process.

The load-displacement curves, in hot forging a steel part under different types of forging equipment, are shown in Fig. 3. 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 machines. For the hammer, the forging load is initially higher, due to strain-rate effects, but the maximum load is lower than that for either hydraulic or screw presses. The reason is that the extruded flash cools rapidly in the presses, while in the hammer, the flash temperature remains nearly the same as the initial stock temperature.

Thus, in hot forging, not only the material and the forged shape, but also the rate of deformation and die-chilling effects and, therefore, the type of equipment used, determine the metal flow behavior and the forging load and energy required for the process. Surface tearing and cracking or development of shear bands in the forged material often can be explained by excessive chilling of the surface layers of the forged part near the die/material interface.

Classification and Characterization of Forging Machines

In metalforming processes, workpieces are generally fully or nearly fully formed by using two-piece tools. A metalforming machine tool is used to bring the two pieces together to form the workpiece. The machine also provides the necessary forces, energy, and torque for the process to be completed successfully, ensuring guidance of the two tool halves.

Based on the type of relative movement between the tools or the tool parts, the metal forming machine tools can be classified mainly into two groups:

- Machines with linear relative tool movement
- Machines with nonlinear relative tool movement

Machines in which the relative tool movements cannot be classified into either of the two groups are called special-purpose machines. The machines belonging to this category are those operated on working media and energy. Various forming processes are associated with a large number of forming machines, including:

- Rolling mills for plate, strip, and shapes
- Machines for profile rolling from strip
- Ring rolling machines
- Thread rolling and surface rolling machines
- Magnetic and explosive forming machines
- Draw benches for tube and rod, wire and rod drawing machines
- Machines for pressing-type operations, that is, presses

Among those listed above, "pressing"-type machines are most widely used and applied for a variety of different purposes. These machines can be classified into three types:

- Load-restricted machines (hydraulic presses)
- Stroke-restricted machines (crank and eccentric presses)
- Energy-restricted machines (hammers and screw presses)

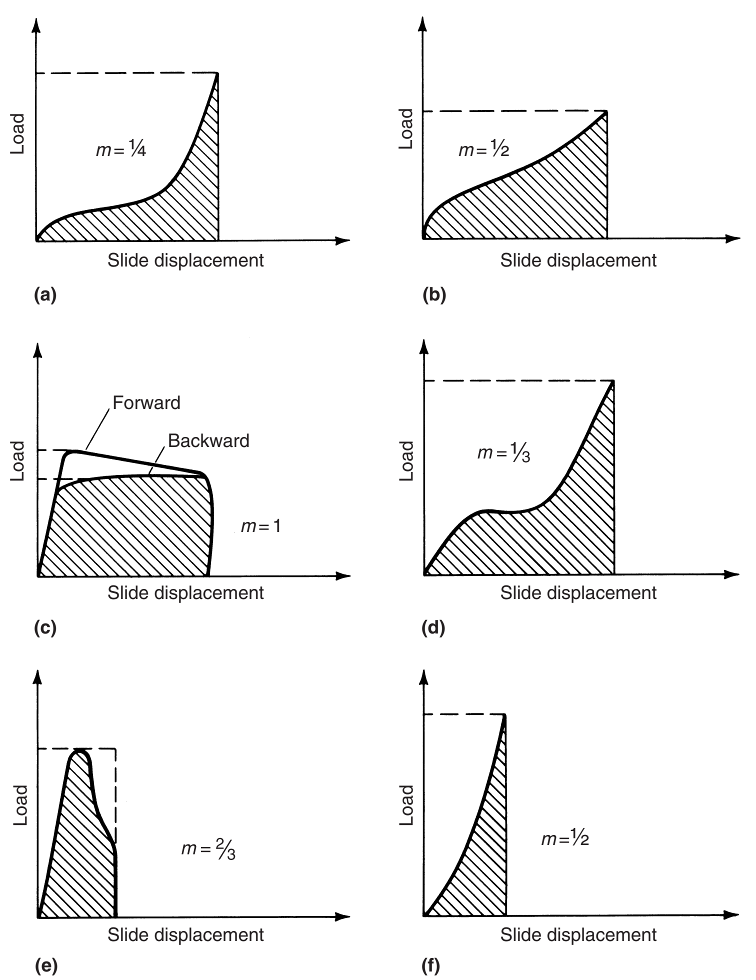


Fig. 2 Load versus displacement curves for various forming operations. Energy developed in the process = load × displacement × *m*, where *m* is a factor characteristic of the specific forming operation. (a) Closed-die forging with flash. (b) Upset forging without flash. (c) Forward and backward extrusion. (d) Bending. (e) Blanking. (f) Coining. Source: Ref 1, 2

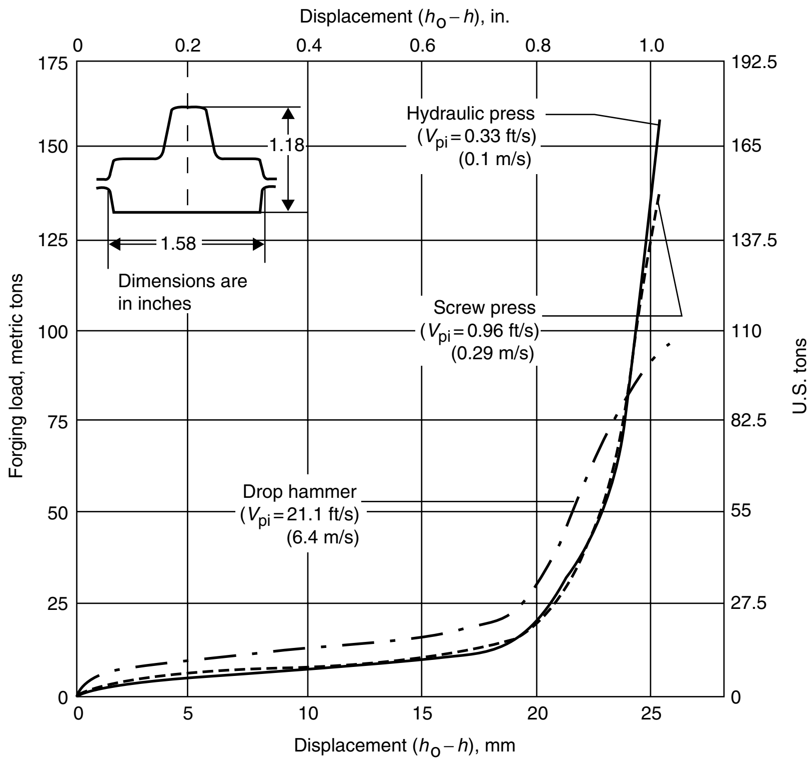


Fig. 3 Load-versus-displacement curves obtained in closed-die forging an axisymmetric steel part at 1100 °C (2012 °F) in three different machines with different initial velocities (V_{pi})

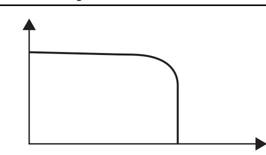
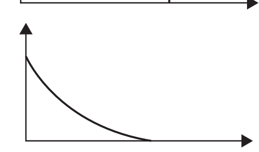
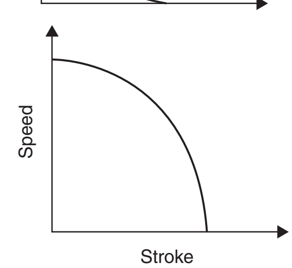
Hydraulic presses are essentially load-restricted machines; that is, their capability for carrying out a forming operation is limited mainly by the maximum load capacity. Mechanical (eccentric or crank) presses are stroke-restricted machines, since the length of the press stroke and the available load at various stroke positions represent the capability of these machines. Hammers are energy-restricted machines, since the deformation results from dissipating the kinetic energy of the hammer ram. The hammer frame guides the ram, but is essentially not stressed during forging. The screw presses are also energy-restricted machines, but they are similar to the hydraulic and mechanical presses since their frames are subject to loading during forging stroke. The speed range and the speed stroke behavior of different forging machines vary considerably according to machine design, as illustrated in Table 1.

The significant characteristics of these machines comprise all machine design and performance data, which are pertinent to the economic use of the machine. These characteristics include:

- Characteristics for load and energy
- Time-related characteristics
- Characteristics for accuracy

In addition to these characteristic parameters, the geometric features of the machine such as the stroke in a press or hammer and the dimensions and features of the tool-mounting space (shut height) are also important. More information on these machines is available in the article "Hammers and Presses for Forging" in this Volume. Other important values are the general machine data, space requirements, weight, and the associated power requirements.

Table 1 Speed-range and speed-stroke behavior of forging equipment

Forging machine	Speed range ft/s	Speed range m/s	Speed-stroke behavior
Hydraulic press	0.2–1.0(a)	0.06–0.30(a)	
Mechanical Press	0.2 – 5	0.06–1.5	
Screw press	2–4	0.6–1.2	
Gravity-drop hammer	12–16	3.6–4.8	
Power-drop hammer	10–30	3.0–9.0	
Counterblow hammer	15–30	4.5–9.0	
Total speed	20–80	6.0–12.0	
HERF(b) Machines	8–20	2.4–6.0	

(a) Lower speeds are valid for larger-capacity presses
(b) High energy rate forging. Source: Ref 3

Horizontal forging machines or upsetters are essentially horizontal mechanical presses with dies that can be split in a direction perpendicular to the ram motion. More information on these machines is available in the article "Hot Upset Forging."

Apart from the features mentioned previously, some of the basic requirements that are expected of a good horizontal forging machine are:

- Tool pressure must be high, which requires the stock to be tightly gripped and upsetting forces completely absorbed.
- Tool length must be sufficient to permit rigid bar reception apart from filling up the impression.
- The gripping tools must not open during the upsetting process.
- The device for moving the tools must be secured against overloading.
- The heading slide must be provided with long and accurate guides.
- The whole machine must be elastically secured against overloading.
- Crankshaft must be designed for special rigidity.
- Gripping and heading tools must be readily interchangeable.
- The driving motor and the machine must be connected through a security coupling.
- The machine must have central lubrication.

Characteristic Data for Load and Energy

Available energy, E_M (in ft · lbf or m · kg), is the energy supplied by the machine to carry out the deformation during an entire stroke.

Available energy, E_M, does not include either E_f, the energy necessary to overcome the friction in the bearings and slides, or E_d, the energy lost because of elastic deflections in the frame and driving system.

Available load, L_M (in tons), is the load available at the slide to carry out the deformation process. This load can be essentially constant as in hydraulic presses, but it may vary with the slide position with respect to "bottom dead center" (BDC) as in mechanical presses.

Efficiency factor, η, is determined by dividing the energy available for deformation, E_M, by the total energy, E_T, supplied to the machine; that is, $\eta = E_M/E_T$. The total energy, E_T, also includes in general: the losses in the electric motor, E_e, the friction losses in the gibs and in the driving system, E_f, and the losses due to total elastic deflection of the machine, E_d.

The following two conditions must be satisfied to complete a forming operation: first, at any time during the forming operation:

$$L_M \geq L_P \quad \text{(Eq 1)}$$

where L_M is the available machine load and L_P is the load required by the process; and second, for an entire stroke:

$$E_M \geq E_P \quad \text{(Eq 2)}$$

where E_M is the available machine energy and E_P is the energy required by the process.

If the condition expressed by Eq 1 is not fulfilled in a hydraulic press, the press will stall without accomplishing the required deformation. In a mechanical press, the friction clutch would slip and the press run would stop before reaching the bottom dead center position. If the condition expressed by Eq 2 is not satisfied, either the flywheel will slow down to unacceptable speeds in a mechanical press or the part will not be formed completely in one blow in a screw press or hammer.

Time-Dependent Characteristic Data

Number of strokes per minute, n, is the most important characteristic of any machine, because it determines the production rate. When a part is forged with multiple and successive blows (in hammers, open-die hydraulic presses, and screw presses), the number of strokes per minute of the machine greatly influences the ability to forge a part without reheating.

Contact time under pressure, t_p, is the time during which the part remains in the die under the deformation load. This value is especially important in hot forming. The heat transfer between the hotter formed part and the cooler dies is most significant under pressure. Extensive studies conducted on workpiece and die temperatures in hot forming clearly showed that the heat-transfer coefficient is much larger under forming pressure than under free-contact conditions. With increasing contact time under pressure, die wear increases. In addition, cooling of the workpiece results in higher forming-load requirements.

Velocity under pressure, V_p, is the velocity of the slide under load. This is an important variable because it determines the contact time under pressure and the rate of deformation or the strain rate. The strain rate influences the flow stress of the formed material and consequently affects the load and energy required in hot forming.

Characteristic Data for Accuracy

Under *unloaded* conditions, the stationary surfaces and their relative positions are established by (a) clearances in the gibs, (b) parallelism of upper and lower beds, (c) flatness of upper and lower beds, (d) perpendicularity of slide motion with respect to lower bed, and (e) concentricity of tool holders. The machine characteristics influence the tolerances in formed parts. For instance, in backward extrusion a slight nonparallelism of the beds, or a slight deviation of the slide motion from ideal perpendicularity, would result in excessive bending stresses on the punch and in nonuniform dimensions in extruded products.

Under *loaded* conditions, the tilting of the ram and the ram and frame deflections, particularly under off-center loading, might result in excessive wear of the gibs, in thickness deviations in the formed part, and in excessive tool wear. In multiple-operation processes, the tilting and deflections across the ram might determine the feasibility or the economics of forging a given part. In order to reduce off-center loading and ram tilting, the center of loading of a part, that is, the point where the resultant total forming load vector is applied, should be placed under the center of loading of the forming machine.

In presses (mechanical, hydraulic, or screw), where the press frame and the drive mechanism are subject to loading, the stiffness, C, of the press is also a significant characteristic. The stiffness is the ratio of the load, L_M, to the total elastic deflection, d, between the upper and lower beds of the press, that is:

$$C = L_M/d \quad \text{(Eq 3)}$$

In mechanical presses, the total elastic deflection, d, includes the deflection of the press frame (~25 to 35% of the total) and the deflection of the drive mechanism (~65 to 75% of the total). The main influences of stiffness, C, on the forming process can be summarized:

- Under identical forming load, L_M, the deflection energy, E_d, that is, the elastic energy stored in the press during buildup, is smaller for a stiffer press (larger C). The deflection energy is given by:

$$E_d = dL_M/2 = L_M^2/2C \quad \text{(Eq 4)}$$

- The higher the stiffness, the lower the deflection of the press. Consequently, the variations in part thickness due to volume or temperature changes in the stock are also smaller in a stiffer press.
- Stiffness influences the velocity-versus-time curve under load. Since a less-stiff machine takes more time to build up and remove pressure, the contact time under pressure, t_p, is longer. This fact contributes to the reduction of tool life in hot forming.

Using larger components in press design increases the stiffness of a press. Therefore, greater press stiffness is directly associated with increased costs, and it should not be specified unless it can be justified by expected gains in part tolerances or tool life.

Hydraulic Presses

The operation of hydraulic presses is relatively simple and is based on the motion of a hydraulic piston guided in a cylinder. Hydraulic presses are essentially load-restricted machines; that is, their capability for carrying out a forming operation is limited mainly by the maximum available load.

The operational characteristics of a hydraulic press are essentially determined by the type and design of its hydraulic drive system. The two types of hydraulic drive systems—direct drive and accumulator drive (see Fig. 19 in the article "Hammers and Presses for Forging" in this Volume)—provide different time-dependent characteristic data.

In both direct and accumulator drives, a slowdown in penetration rate occurs as the pressure builds and the working medium is compressed. This slowdown is larger in direct oil-driven presses, mainly because oil is more compressible than a water emulsion.

Approach and initial deformation speeds are higher in accumulator-drive presses. This improves hot-forging conditions by reducing die contact times, but wear in the hydraulic elements of the system also increases. Wear is a function of fluid cleanliness; no dirt equals no wear. Sealing problems are somewhat less severe in direct drives, and control and accuracy in manual operation are generally about the same for both types of drives.

From a practical point of view, in a new installation, the choice between direct and accumulator drive is based on the capital cost and the economics of operation. The accumulator drive is usually more economical if one accumulator system can be used by several presses or if very large press capacities (89 to 445 MN, or 10,000 to 50,000 tonf) are considered. In direct-drive hydraulic presses, the maximum press load is established by the pressure capability of the pumping system and is available throughout the entire press stroke. Therefore, hydraulic presses are ideally suited to extrusion-type operations requiring very large amounts of energy. With adequate dimensioning of the pressure system, an accumulator-drive press exhibits only a slight reduction in available press load as the forming operation proceeds.

In comparison with direct drive, the accumulator drive usually offers higher approach and penetration speeds and a shorter dwell time before forging. However, the dwell at the end of processing and prior to unloading is longer in accumulator drives. This is shown in Fig. 4, in which the load and displacement variations are given for a forming process using a 22 MN (2500 tonf) hydraulic press equipped with either direct-drive (Fig. 4a) or accumulator-drive (Fig. 4b) systems.

Mechanical Presses

The drive system used in most mechanical presses is based on a slider-crank mechanism that translates rotary motion into reciprocating linear motion. The eccentric shaft is connected, through a clutch and brake system, directly to the flywheel (see Fig. 9 in the article "Hammers and Presses for Forging" in this Volume). In designs for larger capacities, the flywheel is located on the pinion shaft, which drives the eccentric shaft.

Kinematics of the Slider-Crank Mechanism. The slider-crank mechanism is illustrated in Fig. 5(a). The following valid relationships can be derived from the geometry illustrated.

The distance w of the slide from the lowest possible ram position (bottom dead center, BDC; the highest possible position is top dead center, TDC) can be expressed in terms of r, l, S, and α, where (from Fig. 5) r is the radius of the crank or one-half of the total stroke S, l is the length of the pitman arm, and α is the crank angle before bottom dead center.

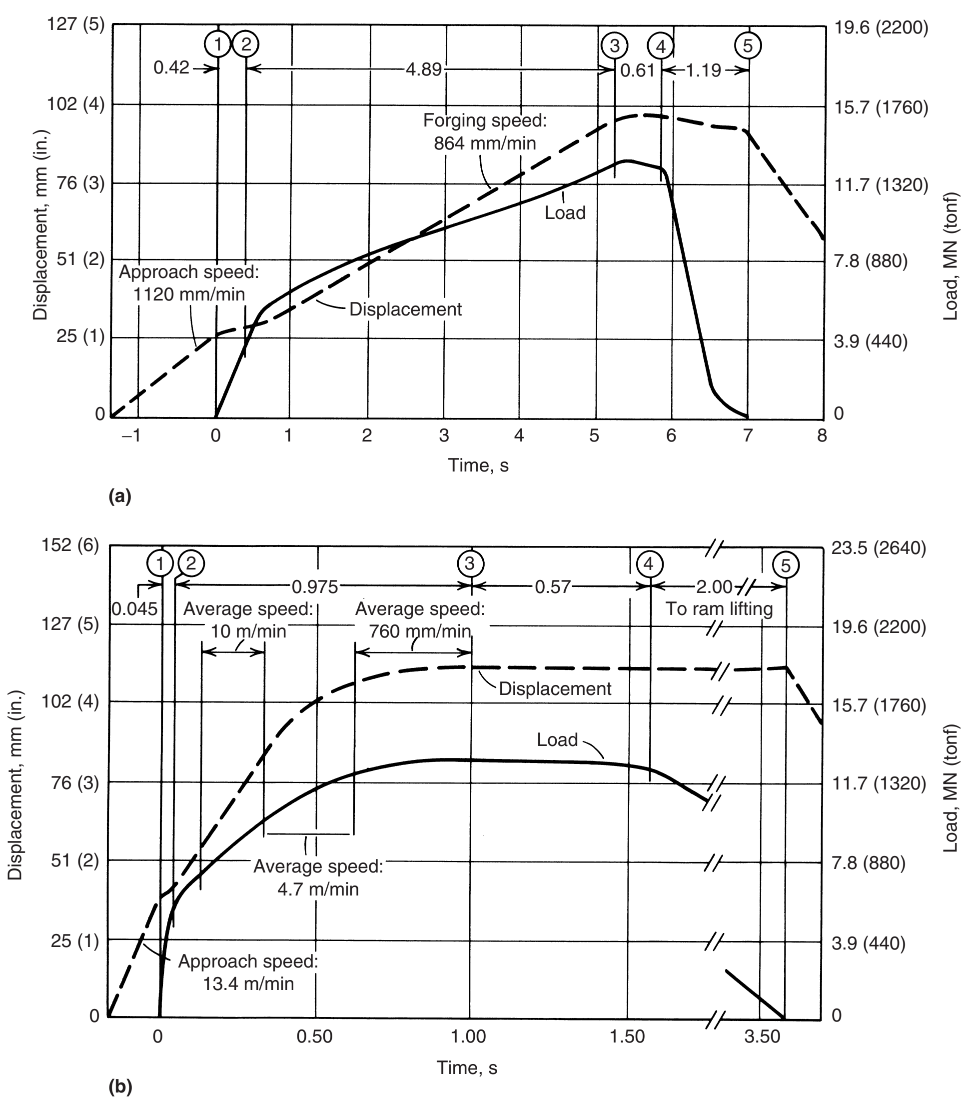


Fig. 4 Load- and displacement-versus-time curves obtained on a 22 MN (2500 ton) hydraulic press in upsetting with (a) direct drive and (b) accumulator drive. 1, start of deformation; 2, initial dwell; 3, end of deformations; 4, dwell before pressure release; 5, ram lift. Source: Ref 3

Because the ratio of r/l is usually small, a close approximation is:

$$w = S/2\ (1 - \cos\alpha) \quad \text{(Eq 5)}$$

Equation 5 gives the location of the slide at a crank angle α before bottom dead center. This curve is plotted in Fig. 5(b) along with the slide velocity, V, which is given by the close approximation:

$$V = S\pi n/60\ \sin\alpha \quad \text{(Eq 6)}$$

where n is the number of strokes per minute.

The slide velocity V with respect to slide location w before bottom dead center is given by:

$$V = 0.015wn\sqrt{S/w - 1} \quad \text{(Eq 7)}$$

Therefore, Eq 5 and 6 give the slide position and the slide velocity at an angle α above bottom dead center. Equation 7 gives the slide velocity for a given position w above bottom dead center if the number of strokes per minute n and the press stroke S are known.

Load and Energy Characteristics. An exact relationship exists between the torque M of the crankshaft and the available load L at the slide (Fig. 5a and c). The torque M is constant, and for all practical purposes, angle β is small enough to be ignored (Fig. 5a). A very close approximation then is given by:

$$L = 2M/S \sin\alpha \quad \text{(Eq 8)}$$

Equation 8 gives the variation of the available slide load L with respect to the crank angle α above bottom dead center (Fig. 5c). From Eq 8, it is apparent that as the slide approaches bottom dead center—that is, as angle α approaches zero—the available load L may become infinitely large without exceeding the constant clutch torque M or without causing the friction clutch to slip.

The following conclusions can be drawn from the observations that have been made thus far:

- Crank and the eccentric presses are displacement-restricted machines. The slide velocity V and the available slide load L vary accordingly with the position of the slide before bottom dead center. Most manufacturers in the United States and the United Kingdom rate their presses by specifying the nominal load at 12.7 mm ($^1/_2$ in.) before bottom dead center. For different applications, the nominal load can be specified at different positions before bottom dead center, according to the standards established by the American Joint Industry Conference.
- If the load required by the forming process is smaller than the load available at the press—that is, if curve EFG in Fig. 5(c) remains below curve NOP—then the process can be carried out, provided the flywheel can supply the necessary energy per stroke.
- For small angles α above bottom dead center, within the OP portion of curve NOP in Fig. 5(c), the slide load L can become larger

than the nominal press load if no overload safety (hydraulic or mechanical) is available on the press. In this case, the press stalls, the flywheel stops, and the entire flywheel energy is transformed into deflection energy by straining the press frame, the pitman arm, and the drive mechanism. The press can be freed in most cases only by burning out the tooling.

- If the applied load curve EFG exceeds the press load curve NOP (Fig. 5c) before point O is reached, the friction clutch slides and the press slide stops, but the flywheel continues to turn. In this case, the press can be freed by increasing the clutch pressure and by reversing the flywheel rotation if the slide has stopped before bottom dead center.

The energy needed for the forming process during each stroke is supplied by the flywheel, which slows to a permissible percentage, usually 10 to 20% of its idle speed. The total energy stored in a flywheel is:

$$E_{FT} = I\omega^2/2 = I/2\,(\pi\ n/30)^2 \qquad \text{(Eq 9)}$$

where I is the moment of inertia of the flywheel, ω is the angular velocity in radians per second, and n is the rotation speed of the flywheel.

The total energy, E, used during one stroke is:

$$\begin{aligned} E_s &= I/2\,(\omega_0^2 - \omega_1^2) \\ &= I/2\,(\pi/30)^2\,(n_0^2 - n_1^2) \qquad \text{(Eq 10)} \end{aligned}$$

where ω_0 is the initial angular velocity, ω_1 is the angular velocity after the work is done, n_0 is the initial flywheel speed, and n_1 is the flywheel speed after the work is done.

The total energy E_s also includes the friction and elastic deflection losses. The electric motor must bring the flywheel from its slowed speed n_1 to its idle speed n_0 before the next stroke for forging starts. The time available between two strokes depends on the mode of operation, namely, continuous or intermittent. In a continuously operating mechanical press, less time is available to bring the flywheel to its idle speed; consequently, a larger horsepower motor is necessary.

Frequently, the allowable slowdown of the flywheel is given as a percentage of the nominal speed. For example, if a 13% slowdown is permissible, then:

$$\begin{aligned} &(n_0 - n_1)/n_0 = 13/100 \ \text{or} \\ &n_1 = 0.87\ n_0 \end{aligned} \qquad \text{(Eq 11)}$$

The percentage energy supplied by the flywheel is obtained by using Eq 9 and 10 to give:

$$\begin{aligned} E_s/E_{FT} &= (n_0^2 - n_1^2)/n_0^2 \\ &= 1 - (0.87)^2 = 0.25 \qquad \text{(Eq 12)} \end{aligned}$$

Equations 11 and 12 illustrate that for a 13% slowdown of the flywheel, 25% of the flywheel energy will be used during one stroke.

As an example, the variation of load, displacement, and flywheel speed in upset forming of a copper sample under 1600 ton mechanical press is illustrated in Fig. 6. This press was instrumented with strain bars attached to the frame for measuring load, an inductive transducer (linear variable differential transformer, or LVDT) for measuring ram displacement, and a direct-current (dc) tachometer for measuring flywheel speed. Figure 6 shows that, due to frictional and inertial losses in the press drive, the flywheel slows down by about 5 rpm before deformation begins. The flywheel requires 3.24 s to recover its idling speed; that is, in forming this part the press can be operated at a maximum speed of 18 (60/3.24) strokes/min. For each mechanical press there is a unique relationship between strokes per minute, or production rate, and the available energy per stroke. As shown in Fig. 7, the strokes per minute available on the machine decreases with increasing energy required per stroke. This relationship can be determined experimentally by upsetting samples, which require various amounts of deformation energy, and by measuring load, displacement, and flywheel recovery time. The energy consumed by each sample is obtained by calculating the surface area under the load-displacement curve.

Time-Dependent Characteristics. The number of strokes per minute n has been discussed previously as an energy consideration. As can be seen in Eq 6, the ram velocity is directly proportional to the number of strokes per minute, n, and to the press stroke, S. Thus, for a given press, that is, a given stroke, the only way to increase ram velocity during deformation is to increase the stroking rate, n. For a given idle flywheel speed, the contact time under pressure t_p and the velocity under pressure V_p depend primarily on the dimensions of the slide-crank mechanism and on the total stiffness C of the press. The effect of press stiffness on contact time under pressure t_p is shown in Fig. 8. As the load increases, the press deflects elastically. A stiffer press (larger C) requires less time t_{p1} for pressure to build up and less time t_{p2} for pressure release (Fig. 8a). Consequently, the total contact time under pressure ($t_p = t_{p1} + t_{p2}$) is less for a stiffer press.

Characteristics for Accuracy. The working accuracy of a forging press is substantially characterized by two features: the tilting angle of the ram under off-center loading and the total deflection under load (stiffness) of the press. The tilting of the ram produces skewed surfaces and an offset on the forging; the stiffness influences the thickness tolerance.

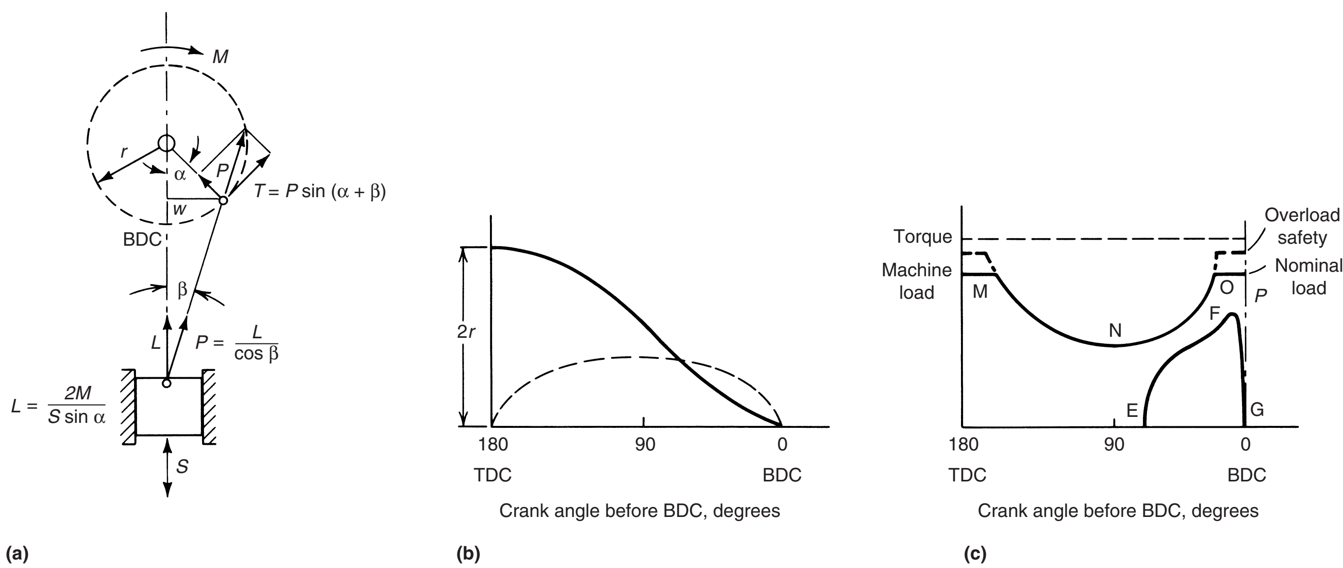


Fig. 5 Load displacement, velocity, and torque in a simple slider-crank mechanism. (a) Slider-crank mechanism. (b) Displacement (solid curve) and velocity (dashed curve). (c) Clutch torque, M, and machine load, L_M. Source: Ref 3

Under off-center loading conditions, two- or four-point presses perform better than single-point presses, because the tilting of the ram and the reaction forces into gibways are minimized. The wedge-type press, developed in the 1960s, has been claimed to reduce tilting under off-center stiffness. The design principle of the wedge-type press is shown in Fig. 10 in the article "Hammers and Presses for Forging" in this Volume. In this press, the load acting on the ram is supported by the wedge, which is driven by a two-point crank mechanism.

Assuming the total deflection under load for a one-point eccentric press to be 100%, the distribution of the total deflections was obtained after measurement under nominal load on equal-capacity two-point and wedge-type presses (Tables 2 and 3). It is interesting to note that a large percentage of the total deflection is in the drive mechanism, that is, slide, Pitman arm, drive shaft, and bearings.

Figure 9 shows table-load diagrams for the same presses discussed previously. Table-load diagrams show, in percentage of the nominal load, the amount and location of off-center load that causes the tilting of the ram. The wedge-type press has advantages, particularly in front-to-back off-center loading. In this respect, it performs like a four-point press.

Another type of press designed to minimize deflection under eccentric loading uses a scotch-yoke drive system. The operating principle of this type of press is shown in Fig. 11 in "Hammers and Presses for Forging" in this Volume.

Determination of the Dynamic Stiffness of a Mechanical Press. Unloaded machine conditions such as parallelism and flatness of upper and lower beds, perpendicularity of slide motion and so forth are important and affect the tolerances of the forged part. However, much more significant are the quantities obtained under load and under dynamic conditions. The stiffness of a press C (the ratio of the load to the total elastic deflection between the upper and lower dies) influences the energy lost in press deflection, the velocity versus time curve under load, and the contact time. In mechanical presses, variations in forging thickness due to volume or temperature changes in the stock are also smaller in a stiffer press. Very often the stiffness of a press (ton/in.) is measured under static loading conditions, but such measurements are misleading. For practical purposes, the stiffness has to be determined under dynamic loading conditions.

In an example study to obtain the dynamic stiffness of a mechanical press, copper samples of various diameters, but of the same height were forged under on-center conditions. A 500 ton Erie scotch yoke type press was used for this study. The samples of wrought pure electrolytic copper were annealed for 1 h at 480 °C (900 °F); the press setup was not changed throughout the tests. Lead samples of about 25 mm (1 in.) square and 38 mm (1.5 in.) height were placed near the forged copper sample, about 125 mm (5 in.) to the side. As indicated in Table 4, with increasing sample diameter the load required for forging increased as well. The press deflection is measured by the difference in heights of the lead samples forged with and without the copper at the same press setting. The variation of total press deflection versus forging load, obtained from these experiments is illustrated in Fig. 10. During the initial nonlinear portion of the curve, the play in the press driving system is taken up. The linear portion represents the actual elastic deflection of the press components. The slope of the linear curve is the dynamic stiffness, which was determined as 5800 ton/in. for the 500 ton Erie forging press.

The method described previously requires the measurement of load in forging annealed copper samples. If instrumentation for load and displacement would be impractical for forge-shop measurements, the flow stress of the copper can be used for estimating the load and energy for a given height reduction. Pure copper was selected in this study because its flow stress could be easily determined. However, other materials such as aluminum or mild steel can also be used provided the material properties are known or can be determined easily.

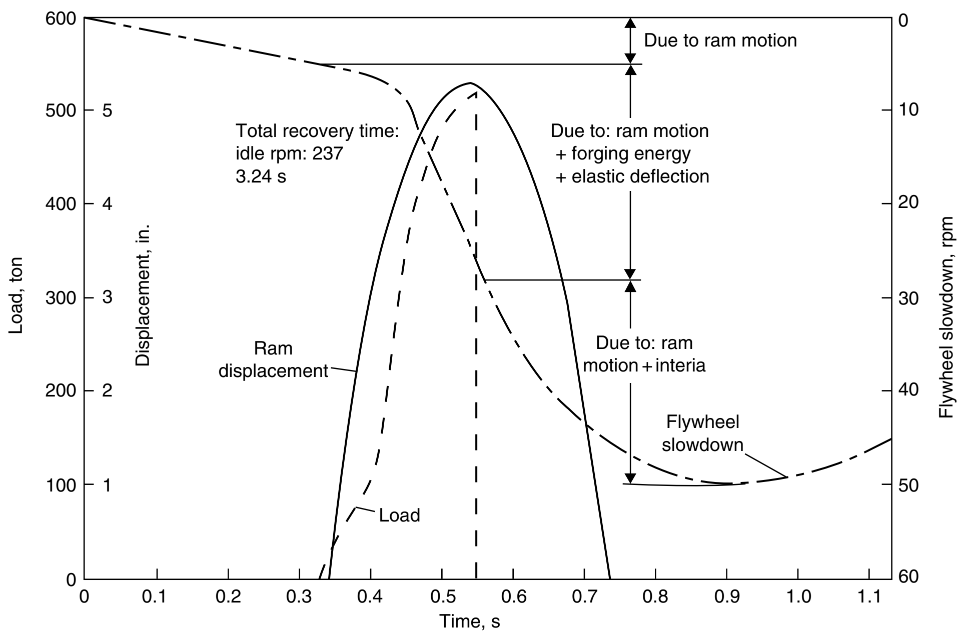


Fig. 6 Flywheel slowdown, ram displacement, and forming load in upsetting of copper samples in a 1600 ton mechanical press. Source: Ref 4

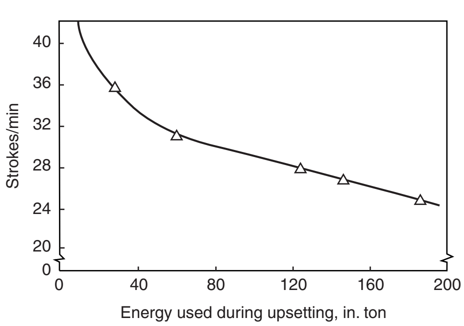


Fig. 7 Variation of strokes per minute with the energy available for forming in a 500 ton mechanical press. Source: Ref 4

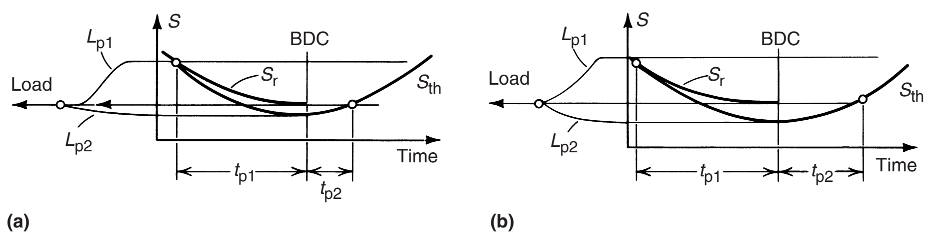
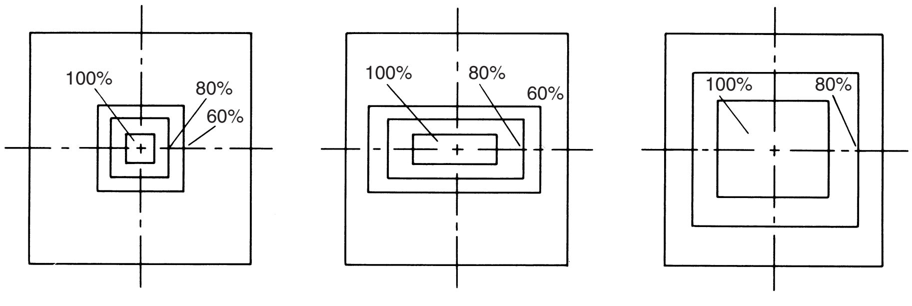


Fig. 8 Effect of press stiffness C on contact time under pressure t_p. (a) Stiffer press (larger C). (b) Less stiff press (smaller C). S_r and S_{th} are the real and theoretical displacement-time curves, respectively; L_{p1} and L_{p2} are the load changes during pressure buildup and pressure release, respectively. Source: Ref 5



(a) (b) (c)

Fig. 9 Amount and location of off-center load that causes tilting of the ram in eccentric one-point presses (a), eccentric two-point presses (b), and wedge-type presses (c). Source: Ref 6

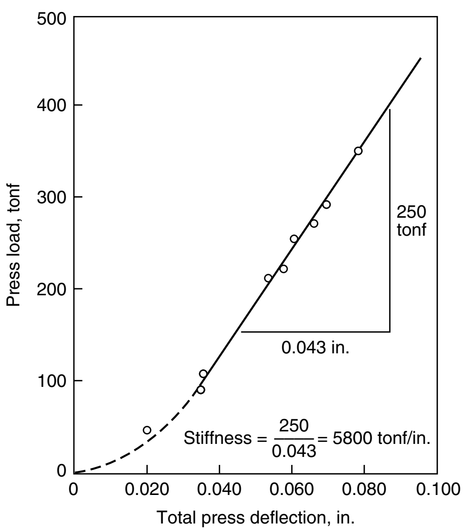


Fig. 10 Total press deflection versus press loading obtained under dynamic loading conditions for a 500 ton Erie scotch yoke type press. Source: Ref 7

Table 2 Distribution of total deflection in three types of mechanical presses

	Distribution of total deflection, %			
Type of press	Slide and pitman arm	Frame	Drive shaft and bearings	Total deflection
One-point eccentric	30	33	37	100
Two-point eccentric	21	31	33	85
Wedge-type	21(a)	29	10	60

(a) Includes wedge. Source: Ref 6

Table 3 Total deflection under nominal load on one- and two-point presses of the same capacity

	Deflection	
	One-point eccentric press	Two-point eccentric press
Slide + Pitman arm	30	21
Frame	33	31
Drive shaft + bearings	37	33
Total deflection	100	85

Source: Ref 6

Ram Tilting under Off-Center Loading. Off-center loading conditions occur often in mechanical press forging when several operations are performed in the same press. Especially in automated mechanical presses, the finish blow (which requires the highest load) occurs on one side of the press. Consequently, the investigation of off-center forging is particularly significant in mechanical press forging.

In the example study, the off-center loading characteristics of the 500 ton Erie press were evaluated using the following procedure. During each test, a copper specimen, which requires 220 tons to forge, was placed 125 mm (5 in.) from the press center in one of the four directions: left, right, front, or back. A lead specimen, which requires not more than 5 tons, was placed an equal distance on the opposite side of the center. On repeating the test for the remaining three directions, the comparison of the final height of the copper and lead forged during the same blow gave a good indication of the non parallelism of the ram and bolster surfaces over a 250 mm (10 in.) span. In conducting this comparison, the local elastic deflection of the dies in forging copper must be considered. Therefore, the final thickness of the copper samples was corrected to counteract this local die deflection. Here again, materials other than copper (such as aluminum alloys or mild steel) can be used to conduct such a test.

In off-center loading with 220 tons (or 44% or the nominal capacity) an average ram-bed nonparallelity of 0.0315 mm/cm (0.038 in./ft) was measured in both directions, front-to-back and left-to-right. In comparison, the nonparallelity under unloaded conditions was about 1.7×10^{-3} mm/cm (0.002 in./ft). Before conducting the experiments described previously, the clearance in the press gibs was set to 0.254 mm (0.010 in.) The nonparallelity in off-center forging would be expected to increase with increasing gib clearance.

Screw Presses

The screw press uses a friction, gear, electric, or hydraulic drive to accelerate the flywheel and the screw assembly, and it converts the angular kinetic energy into the linear energy of the slide or ram. Figure 23 in the article "Hammers and Presses for Forging" in this Volume shows two basic designs of screw presses.

Load and Energy. In screw presses, the forging load is transmitted through the slide, screw, and bed to the press frame. The available load at a given stroke position is supplied by the stored energy in the flywheel. At the end of the downstroke after the forging blow, the flywheel comes to a standstill and begins its reversed rotation. During the standstill, the flywheel no longer contains any energy. Therefore, the total flywheel energy E_{FT} has been transformed into:

- Energy available for deformation E_p to carry out the forging process
- Friction energy E_f to overcome frictional resistance in the screw and in the gibs
- Deflection energy E_d to elastically deflect various parts of the press

Thus, the following relationship holds:

$$E_T = E_P + E_F + E_d \qquad \text{(Eq 13)}$$

At the end of a downstroke, the deflection energy E_d is stored in the machine and can be released only during the upward stroke.

If the total flywheel energy, E_T, is larger than necessary for overcoming machine losses and for carrying out the forming process, the excess energy is transformed into additional deflection energy and both the die and the press are subjected to unnecessarily high loading. This is illustrated in Fig. 11. To annihilate the excess energy, which results in increased die wear and noise, the modern screw press is equipped with an energy-metering device that controls the flywheel velocity and regulates the total flywheel energy. The energy metering can also be programmed so that the machine supplies different amounts of energy during successive blows. In Fig. 11(b), the flywheel has excess energy at the end of the downstroke. The excess energy from the flywheel stored in the press frame at the end of the stroke is used to begin the acceleration of the slide back to the starting position immediately at the end of the stroke. The screw is not self-locking and is easily moved.

In a screw press, which is essentially an energy-bound machine (like a hammer), load and energy are inversely proportional to each other. For given friction losses, elastic deflection properties, and available flywheel energy, the load available at the end of the stroke depends mainly on the deformation energy required by the process. Therefore, for constant flywheel energy, low deformation energy E_p results in high-end load L_M, and high E_p results in low L_M. These relationships are shown in Fig. 12.

The screw press can generally sustain maximum loads L_{max} up to 160 to 200% of its

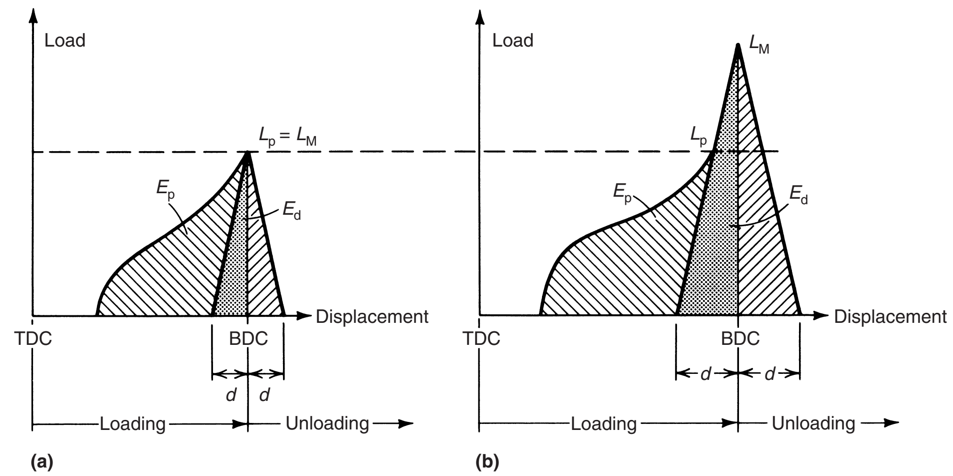


Fig. 11 Load versus displacement curves for die forging using a screw press. (a) Press with load or energy metering. (b) Press without load or energy metering (E_p, energy required for deformation; L_M, maximum machine load; E_d, elastic deflection energy; *d*, elastic deflection of the press. Source: Ref 8

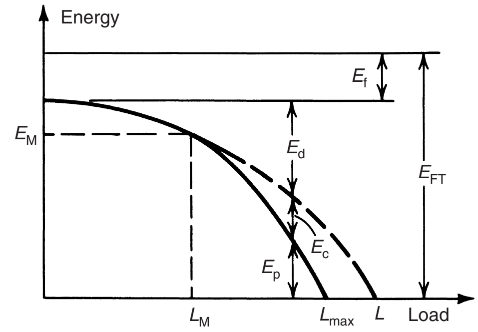


Fig. 12 Energy versus load diagram for a screw press both without a friction clutch at the flywheel (dashed line) and with a slipping friction clutch at the flywheel (solid line). E_W, nominal machine energy available for forging; L_M, nominal machine load; E_P, energy required for deformation; E_c, energy lost in slipping clutch; E_d, deflection energy; E_f, friction energy; E_{FT}, total flywheel energy. Source: Ref 9

Table 4 Copper samples forged under on-center conditions in the 500 ton mechanical press

Sample	Sample size, in. height	Sample size, in. diameter	Predicted load(a), tons	Measured load, tons	Predicted energy(b), tons	Measured energy, tons
1	2.00	1.102	48	45	24	29
2	2.00	1.560	96	106	48	60
3	2.00	2.241	197	210	98	120
4	2.00	2.510	247	253	124	140
5	2.00	2.715	289	290	144	163
6	2.00	2.995	352	350	176	175

(a) Based on an estimate of 50,000 lb/in^2, flowstress for copper at 50% reduction in height. (b) Estimated by assuming that the load-displacement curve has a triangular shape; that is, energy = 0.5 load × displacement. Source: Ref 7

nominal load L_M. Therefore, the nominal load of a screw press is set rather arbitrarily. The significant information about the press load is obtained from its energy versus load diagram (Fig. 12). Many screw presses have a friction clutch between the flywheel and the screw. At a preset load, this clutch starts to slip and uses part of the flywheel energy as friction heat energy E_c at the clutch. Consequently, the maximum load at the end of downstroke is reduced to L from L_{max} and the press is protected from overloading.

The energy versus load curve has a parabolic shape so that energy decreases with increasing load. This is because the deflection energy, E_d, is given by a second-order equation:

$$E_d = L^2/2C \qquad \text{(Eq 14)}$$

where L is load and C is the total stiffness of the press.

A screw press can be designed so that it can sustain die-to-die blows without any workpiece for maximum energy of the flywheel. In this case, a friction clutch between the flywheel and the screw is not required. It is important to note that a screw press can be designed and used for forging operations in which large deformation energies are required or for coining operations in which small energies but high loads are required. Another interesting feature of screw presses is that they cannot be loaded beyond the calculated overload limit of the press.

Time-Dependent Characteristics. In a screw press, the number of strokes per minute under load, n_p, largely depends on the energy required by the specific forming process and on the capacity of the drive mechanism to accelerate the screw and the flywheel. Because modern screw presses are equipped with energy-metering devices, the number of strokes per minute depends on the energy required by the process. In general, however, the production rate of modern screw presses is comparable with that of mechanical presses.

During a downstroke, a velocity under pressure, V_p, increases until the slide hits the workpiece. In this respect, a screw press behaves like a hammer. After the actual deformation starts, the velocity of the slide decreases depending on the energy requirements of the process. Thus, the velocity, V_p, is greatly influenced by the geometry of the stock and of the part. As illustrated in Fig. 13, this is quite different from the conditions found in mechanical presses, where the ram velocity is established by the press kinematics and is not influenced significantly by the load and energy requirements of the process.

The contact time under pressure t_p is related directly to the ram velocity and to the stiffness of the press. In this respect, the screw press ranks between the hammer and the mechanical press. Contact times for screw presses are 20 to 30 times longer than for hammers. A similar comparison with mechanical presses cannot be made without specifying the thickness of the forged part. In forging turbine blades, which require small displacement but large loads, contact times for screw presses have been estimated to be 10 to 25% of those for mechanical presses.

Accuracy in Screw Press Operation. In general, the dimensional accuracies of press components under unloaded conditions, such as parallelism of slide and bed surfaces, clearances in the gibs, and so forth, have basically the same significance in the operation of all presses—hydraulic, mechanical, and screw presses.

The off-center loading capacity of the press influences the parallelism of upset surfaces. This capacity is increased in modern presses by use of long gibs and by finish forming at the center, whenever possible. The off-center loading capacity of a screw press is less than that of a mechanical press or a hammer.

A screw press is operated like a hammer; that is, the top and bottom dies "kiss" at each blow. Therefore, the stiffness of the press, which affects the load and energy characteristics, does not influence the thickness tolerances in the formed part.

Determination of Dynamic Stiffness of a Screw Press. The static stiffness of the screw press, as given by the manufacturer does not include the torsional stiffness of the screw, which occurs under dynamic conditions. As pointed out by Watermann (Ref 10), who conducted an extensive study of the efficiency of screw presses, the torsional deflection of the screw may contribute up to 30% of the total losses at maximum load (about 2.5 times nominal load). Based on experiments conducted in a Weingarten press (Model P160, nominal load 180 metric ton, energy 800 kg·m), Watermann concluded that the dynamic stiffness was 0.7 times the static stiffness. Assuming that this ratio

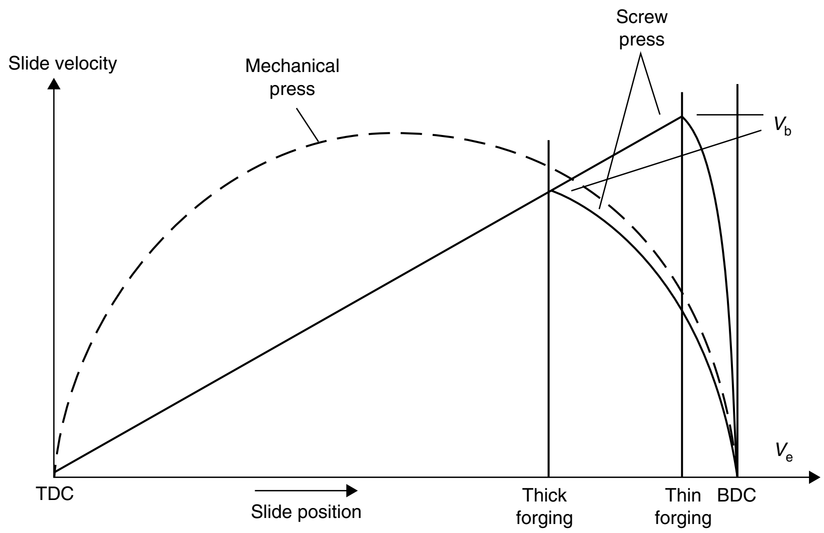


Fig. 13 Representation of slide velocities for mechanical and screw presses in forming a thick and a thin part (V_b, V_e, velocity at the beginning and end of forming, respectively)

is approximately valid for the 400 ton press, the dynamic stiffness is $0.7 \times 8400 \approx 5900$ ton/in.

During the downstroke, the total energy supplied by the screw press E_T is equal to the sum total of the machine energy used for the deformation process E_P, the energy necessary to overcome friction in the press drive E_F, and the energy necessary elastically to deflect the press E_D (Eq 13). Expressing E_D in terms of the press stiffness, C, Eq 13 can be written as:

$$E_T - E_F = E_P + \frac{L_M^2}{2C} \quad \text{(Eq 15)}$$

In a forging test, the energy used for the process E_P (surface area under the load-displacement curve) and the maximum forging load L_P can be obtained from load-stroke recordings. By considering two tests simultaneously, and by assuming that E_F remains constant during tests, one equation with one unknown C can be derived from Eq 15. However, in order to obtain reasonable accuracy, it is necessary that in both tests considerable press deflection is obtained; that is, high loads L_P and low deformation energies E_P are measured. Thus, errors in calculating E_P do not impair the accuracy of the stiffness calculations.

Variations in Screw Press Drives. In addition to direct friction and electric drives, several other types of mechanical, electric, and hydraulic drives are commonly used in screw presses. A relatively new screw press drive is shown in Fig. 24 in "Hammers and Presses for Forging" in this Volume; the principle of operation of this press is also detailed in that article.

Hammers

The hammer is the least expensive and most versatile type of equipment for generating load and energy to carry out a forming process. Hammers are primarily used for the hot forging, coining, and, to a limited extent, sheet-metal forming of parts manufactured in small quantities—for example, in the aircraft industry. The hammer is an energy-restricted machine. During a working stroke, the deformation proceeds until the total kinetic energy is dissipated by plastic deformation of the material and by elastic deformation of the ram and anvil when the die faces contact each other. Therefore, the capacities of these machines should be rated in terms of energy. The practice of specifying a hammer by its ram weight, although fairly common, is not useful for the user. Ram weight can be regarded only as model or specification number.

There are basically two types of anvil hammers: gravity-drop and power-drop. In a simple gravity-drop hammer, the upper ram is positively connected to a board (board-drop hammer), a belt (belt-drop hammer), a chain (chain-drop hammer), or a piston (oil-, air-, or steam-lift drop hammer) (see the article "Hammers and Presses for Forging" in this Volume). The ram is lifted to a certain height and then dropped on the stock placed on the anvil. During the downstroke, the ram is accelerated by gravity and builds up the blow energy. The upstroke takes place immediately after the blow; the force necessary to ensure quick lift-up of the ram can be three to five times the ram weight.

The operation principle of a power-drop hammer is similar to that of an air-drop hammer. In the downstroke, in addition to gravity, the ram is accelerated by steam, cold air, or hot-air pressure. Electrohydraulic gravity-drop hammers, introduced in the United States in the 1980s, are more commonly used in Europe. In this hammer, the ram is lifted with oil pressure against an air cushion. The compressed air slows the upstroke of the ram and contributes to its acceleration during the downstroke. Therefore, the electrohydraulic hammer also has a minor power hammer action.

Counterblow hammers are widely used in Europe; their use in the United States is limited to a relatively small number of companies. The principal components of a counterblow hammer are illustrated in Fig. 4 in the article "Hammers and Presses for Forging" in this Volume. In this machine, the upper ram is accelerated downward by steam, but it can also be accelerated by cold or hot air. At the same time, the lower ram is accelerated by a steel band (for smaller capacities) or by a hydraulic coupling system (for larger capacities). The lower ram, including the die assembly, is approximately 10% heavier than the upper ram. Therefore, after the blow, the lower ram accelerates downward and pulls the upper ram back up to its starting position. The combined speed of the rams is about 7.6 m/s (25 ft/s); both rams move with exactly one-half the total closure speed. Due to the counterblow effect, relatively little energy is lost through vibration in the foundation and environment. Therefore, for comparable capacities, a counterblow hammer requires a smaller foundation than an anvil hammer. Modern counterblow hammers are driven by hydraulic pressure.

Characteristics of Hammers. In a gravity-drop hammer, the total blow energy E_T is equal to the kinetic energy of the ram and is generated solely through free-fall velocity, or:

$$E_T = 1/2 m_1 V_1^2 = {}^1\!/_2 G_1/g\, V_1^2 = G_1 H \quad \text{(Eq 16)}$$

where m_1 is the mass of the dropping ram, V_1 is the velocity of the ram at the start of deformation, G_1 is the weight of the ram, g is the acceleration of gravity, and H is the height of the ram drop.

In a power-drop hammer, the total blow energy is generated by the free fall of the ram and by the pressure acting on the ram cylinder, or:

$$E_T = {}^1\!/_2 m_1 V_1^2 + pAH = (G_1 + pA)H \quad \text{(Eq 17)}$$

where, in addition to the symbols given previously, p is the air, steam, or oil pressure acting on the ram cylinder in the downstroke and A is the surface area of the ram cylinder.

In counterblow hammers, when both rams have approximately the same weight, the total energy per blow is given by:

$$\begin{aligned} E_T &= 2\,(m_1\, V_1^2/2) = m_1\, V_t^2/4 \\ &= G_1\, V_t^2/4g \end{aligned} \quad \text{(Eq 18)}$$

where m_1 is the mass of one ram, V_1 is the velocity of one ram, V_t is the actual velocity of the blow of the two rams, which is equal to $2V_1$, and G_1 is the weight of one ram.

During a working stroke, the total nominal energy E_T of a hammer is not entirely transformed into useful energy available for deformation, E_A. A certain amount of energy is lost in the form of noise and vibration to the environment. Therefore, the blow efficiency η

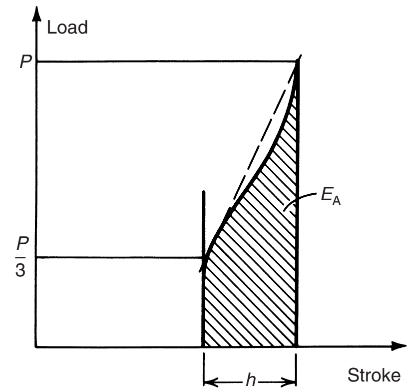


Fig. 14 Example of a load-stroke curve in a hammer blow. Energy available for forging: $E_A = \eta E_T$ (see text for explanation). Source: Ref 11

($\eta = E_A/E_T$) of hammers varies from 0.8 to 0.9 for soft blows (small load and large displacement) and from 0.2 to 0.5 for hard blows (high load and small displacement).

The transformation of kinetic energy into deformation energy during a working blow can develop considerable force. An example is a deformation blow in which the load P increases from $P/3$ at the start to P at the end of the stroke h. The available energy E_A is the area under the curve shown in Fig. 14. Therefore:

$$E_A = P/3 + P/2\,h = 4Ph/6 \qquad \text{(Eq 19)}$$

For a hammer with a total nominal energy E_T of 47.5 kJ (35,000 ft · lbf) and a blow efficiency η of 0.4, the available energy is $E_A = \eta E_T = 19$ kJ (14,000 ft · lbf). With this value, for a working stroke h of 5 mm (0.2 in.) Eq 19 gives:

$$P = 6E_A/4h = 1{,}260{,}000 \text{ lbf} = 630\,\text{tonf} \qquad \text{(Eq 20)}$$

If the same energy were dissipated over a stroke h of 2.5 mm (0.1 in.), the load would reach approximately double the calculated value. The simple hypothetical calculations given previously illustrate the capabilities of relatively inexpensive hammers in exerting high forming loads.

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Note: Tables are keyed.