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Cold Extrusion

Revised by Murali Bhupatiraju, Metaldyne and Robert Greczanik, American Axle and Manufacturing

COLD EXTRUSION is a push-through compressive forming process with the starting material (billet/slug) at room temperature. During the process, however, the deforming material undergoes deformation heating (conversion of deformation work to heat) to several hundred degrees. Typically, a punch is used to apply pressure to the billet enclosed, partially or completely, in a stationary die. Aluminum and aluminum alloys, copper and copper alloys, carbon steels, alloy steels, and stainless steels can be cold extruded.

Based on the punch and die design and the resulting material flow, cold extrusion can be classified into three primary processes: forward extrusion, backward extrusion, and lateral extrusion. In forward extrusion, the material flows in the same direction as the punch displacement. In forward extrusion, the diameter of a rod or tube is reduced by forcing it through an orifice in a die (Fig. 1a). In backward extrusion, the material flows in the opposite direction of the punch displacement. The billet is enclosed in a die and is forced to flow backward through the annular region between the punch and the die (Fig. 1b). Backward extrusion is differentiated from impact extrusion where typically a nonferrous material is extruded backward by a rapidly moving punch and a shallow die with minimal material contact. Forward and backward extrusion can also be simultaneously achieved through die design (Fig. 1c). In lateral extrusion, the material flows perpendicular to the direction of punch displacement. The material is enclosed by the die and the punch and is forced through radially placed orifices (Fig. 1d). Hooker extrusion is a variation of the forward extrusion process where a tubular billet is forced through a forward extrusion die with a punch that acts as a pusher and a mandrel to reduce the outer diameter and elongate the tubular portion (Fig. 1e). Although not strictly a compressive forming operation, draw wiping or ironing is also commonly used as a cold extrusion process. In ironing, the wall thickness of a tubular billet is reduced by forcing it under tension (and or compression) through a die similar to a forward extrusion die (Fig. 1f). Figure 2 shows various parts made by these cold forging operations.

Cold extrusion, being a forging operation, has the typical advantages of material savings, work hardening (strengthening), and grain flow or directional strengthening. Compared to other forging operations cold extrusion is particularly attractive for the following reasons: dimensional precision, superior surface finish, net-shaped features, lower energy consumption, higher production rates, and cleaner work environment. Drawbacks of cold extrusion are higher loads, lubrication cost, limited deformation, and limited shape complexity.

Extrusion Pressure

The punch pressure in extrusion depends on the flow stress of the material being extruded, the degree of deformation (strain), billet geometry, billet/die interface friction, and die design. Punch speed available in conventional presses has little effect on extrusion pressure. Punch speed, however, affects the extrusion process in other ways: tool heating, lubricant deterioration, and dynamic loading. Hardness of the material is representative of its flow stress, and consequently softer materials require lower extrusion pressure. Thermal softening processes of annealing and normalizing also reduce extrusion pressure. Apart from hardness, the degree of deformation has the greatest impact on extrusion pressure and is expressed as either extrusion ratio R or reduction ratio r:

$$R = \frac{A_0}{A_f}$$

$$r = \frac{A_0 - A_f}{A_0} \times 100$$

where A_0 is the initial cross-sectional area and A_f is the final cross-sectional area.

Billet geometry factors such as length-to-diameter ratio are significant in forward extrusion. Die design aspects such as die entry angle (forward extrusion) and punch geometry (backward extrusion) also affect extrusion pressure. Bethlehem Steel developed the following equations for extrusion pressure:

Forward extrusion:

$$P_f = 0.5[\sigma_{ys} + K(\ln R)^n](a_f + b_f \ln R)(e^{4\mu Z})$$

Backward extrusion:

$$P_b = 0.4[\sigma_{ys} + K(\ln R)^n](a_b + b_b \ln R)\left(\frac{R}{R-1}\right)$$

where

$$a_f = 1.15\left(\frac{\alpha}{57.3 \sin^2 \alpha} - \cot \alpha\right) + 4\mu y$$

and

$$b_f = 1.1 + \mu(1 + 0.5 \ln R) \cot \alpha$$

where $a_b = 0.28$; $b_b = 2.36$; σ is the 0.2% yield strength, psi; K is the true flow strength at unit strain, psi; R is the extrusion ratio; n is the strain-hardening exponent; μ is the coefficient of friction; Z is the ratio of preform length to die bore diameter at entry; α is the die half angle, degrees; and y is the ratio of length to diameter for the extrusion die land.

Nomograms and empirical equations have traditionally been used to calculate extrusion pressure; more recently, however, finite-element analysis has provided another method for estimation of extrusion pressure especially for complex shapes. Figure 3 shows that extrusion pressure increases with extrusion ratio. It also shows that extrusion ratio has a larger effect on ram pressure in the forward extrusion of carbon steel than either carbon content or type of annealing treatment. Figure 4 illustrates the effect of tensile strength on extrudability in terms of ram pressure for both the backward and forward extrusion of low-carbon and medium-carbon steels of the 1000, 1100, and 1500 series at different extrusion ratios.

Steel for Cold Extrusion

Carbon steels up to 0.3% C can be easily cold extruded. Higher-carbon steels up to 0.5% C can also be extruded, but the extrusion ratios are limited and spheroidize annealing may be required. Backward extrusion generally requires spheroidize annealing for both low- and high-carbon steels. Alloy steels are harder than their carbon steel counterparts and hence require higher pressures for extrusion. They also work harden more rapidly, thus limiting their extrudability and intermediate annealing is often required to restore extrudability. Alloying elements differ in their effects on strength and hardenability. If possible, it is desirable to choose alloying elements so as to minimize strengthening while achieving the required hardenability: for example, boron increases hardenability with minimal strengthening. Steels in the AISI 4000, 4100, 5000, 5100, 8600, and 8700 series can be cold extruded without difficulty up to 0.35% C. The AISI 4300, 4600, and 4800 steels are more difficult to extrude and less desirable for cold extrusion. Free-cutting resulfurized steels also have lower forgeability than their carbon steel counterparts, as they are more susceptible to rupture during cold forging due to their higher occurrence of sulfide inclusions. Sulfur is typically limited to 0.02%. Low-carbon resulfurized steels can be extruded if care is taken to keep metal in compression throughout the process. Internal purity of steel is critical in cold extrusion especially at high extrusion ratios. Central segregations increase the tendency for internal fracture along the axis of the extrusion (chevrons). Killed steels are specified for cold forging to ensure homogeneous structure. Aluminum-killed steel is preferred over silicon-killed steel for difficult extrusions due to the reduction in strain hardening and reduction in strain aging achieved. Silicon is kept in the low range of 0.2%. Silicon-killed steels, however, have better surface quality, which might be critical in any postextrusion operations. Seams, laps, and scratches on steel surface can be tolerated up to 1% of the bar diameter if cold extrusions are machined at the surface. However, if net-shaped features are being cold extruded, then the seams and laps have to be removed prior to forging by peeling or turning the steel bars. Although cold extrusion is a compressive process, it is typically preceded or followed by processes of cold heading and heat treatments, which require defect-free surfaces. The steel manufacturer often certifies steels meeting the cold extrusion requirements as "cold extrusion quality" or "cold working quality." To ensure surface quality of steel hot-scarfing during semifinshed state (blooms) and eddy-current testing in the finished state (bars) is sometimes required.

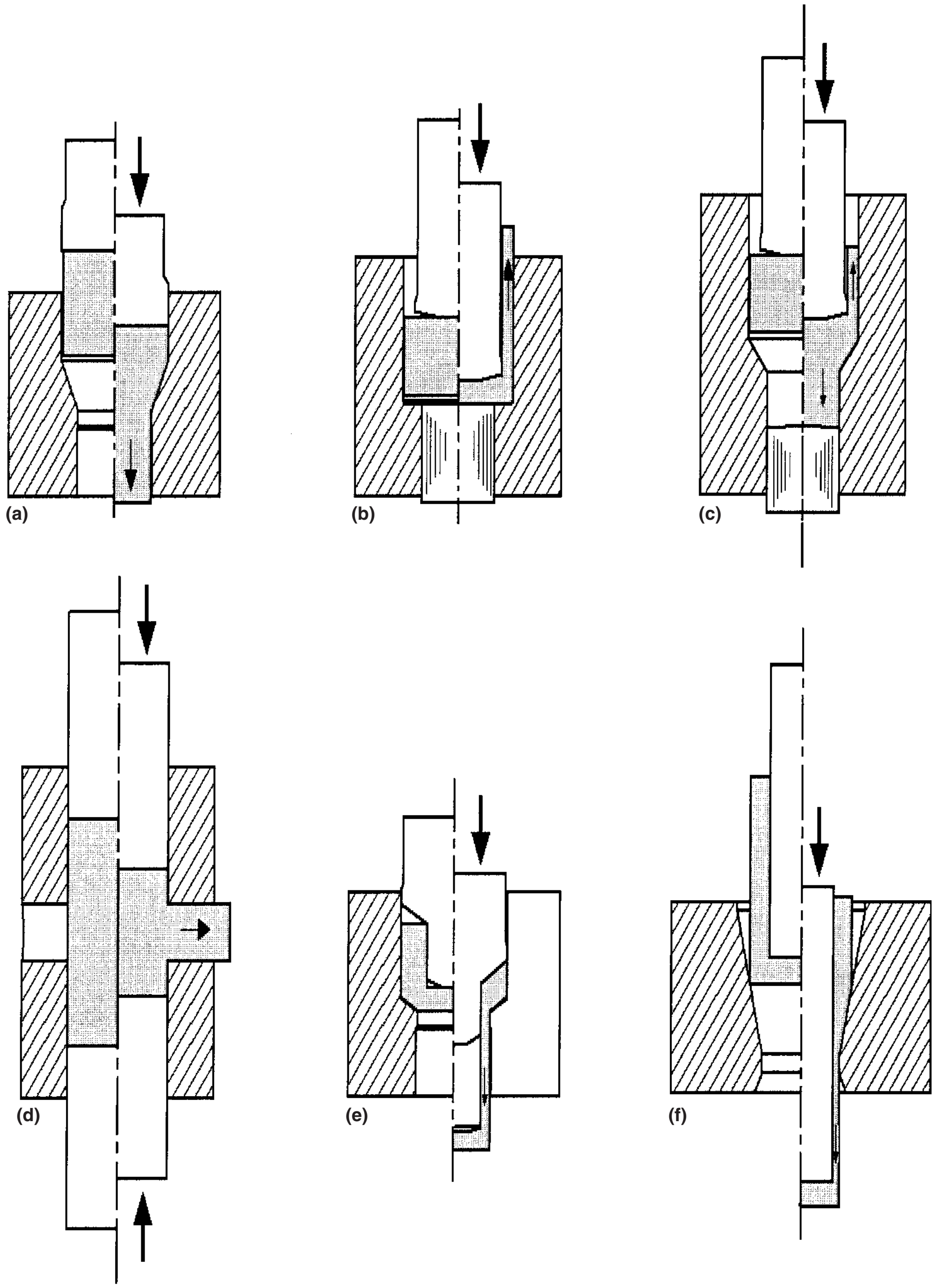


Fig. 1 Displacement of metal in cold extrusion. (a) Forward extrusion. (b) Backward extrusion. (c) Combined backward and forward extrusion. (d) Lateral extrusion. (e) Hooker extrusion. (f) Ironing

Steel bars are available as normal hot rolled, precision hot rolled and cold finished. Normal hot-rolled bar is made to standard AISI tolerances and is the least costly form of steel for making slugs. It is also likely to have deeper surface seams and greater depth of decarburized layers. In addition, the variation in the outside diameter of hot-rolled bars will cause considerable variation in weight or volume of the slug, despite close control in cutting to length. Whether or not the surface seams and decarburization can be tolerated depends largely on the severity of extrusion and the quality requirements of the extruded part. In many applications, acceptable extrusions can be produced with slugs cut from hot-rolled bars. Precision hot-rolled bars have 50% better tolerances on size than normal hot-rolled bars and smaller decarburization layer. These bars are made by performing a special precision-sizing operation during hot rolling.

Cold-finished bars are made by taking the hot-rolled bar through a costly series of cold-drawing steps to give them tighter dimensional tolerances (25% of normal hot-rolled bar tolerances). Therefore, the size variation in cold-finished bars is considerably less than that in hot-finished bars. However, some seams and decarburization will also be present in cold-finished bar stock unless removed by grinding, turning, or other means. Some users gain the advantage of cold-drawn bars by passing hot-rolled bars or rods through a cold-drawing attachment directly ahead of the slug-cutting operation. Turning, peeling, or grinding of cold-finished bars will eliminate the difficulties caused by decarburization and seams. For some extrusions, especially those subjected to surface treatments that cannot tolerate a decarburized layer, previously machined bars or machined slugs must be used. Another practice is to turn and burnish normal hot-rolled bars to

Fig. 2 Parts made by (a) forward extrusion, (b) backward extrusion, and (c) lateral extrusion. Courtesy of Metaldyne Corporation

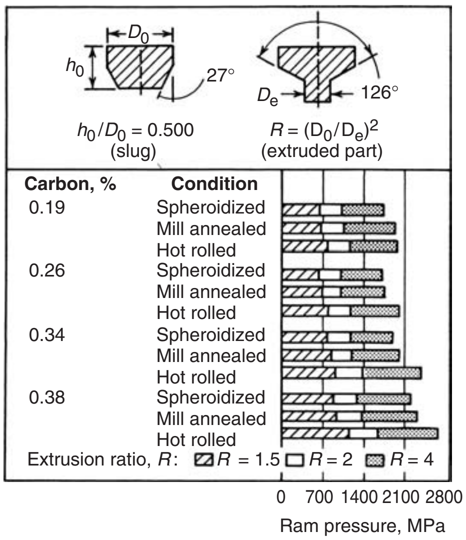


Fig. 3 Effect of carbon content, annealing treatment, and extrusion ratio on maximum ram pressure in the forward extrusion of the carbon steel part from the preformed slug

remove surface defects. These practices are mandatory for precision net spline/gear forming or products requiring induction hardening, which cannot withstand a decarburized surface.

Equipment

Mechanical presses and hydraulic presses are specifically designed for cold extrusion with high rigidity, accurate alignment, and long working strokes. Mechanical presses are preferred because of lower maintenance and higher production rates. Mechanical presses also require higher investment and are preferred for large production volumes and large batch sizes. Horizontal mechanical presses with bar or coil feeds with multiple stations and integrated billet shearing are used for small forgings. These presses are capable of applying loads up to 1000 metric tons (1100 tons) and producing up to 150 parts/min. Vertical mechanical presses can be single station or multistation and are typically used to make larger forgings with loads around 1000 to 2000 metric tons (1100 to 2200 tons) at 25 parts/min. For annual production volumes of more than 500,000, these vertical presses are typically automated with loading and transfer systems. The drive mechanisms on mechanical presses also vary: crank, knuckle, link, and eccentric. Knuckle-joint presses offer lower and more constant velocities during work stroke than crank-drive presses, reducing dynamic loads. However, the working stroke and loads available above bottom dead center with knuckle drives are lower than with a crank press. Link-drive presses have similar forming velocities to knuckle-joint presses and have longer strokes. Eccentric presses fill the gap between knuckle and crank presses. It is important to analyze the force-displacement curve of the press and of the process to ensure that sufficient deformation energy is available during the cycle. In multistation transfer presses, careful study of time-displacement curves of the press, transfer, part, and ejector is essential to ensure proper transfer.

Hydraulic presses are typically vertical, less complex, more versatile, and have longer work strokes than mechanical presses and are usually selected for long or large extrusions. They also provide full-rated tonnage throughout the stroke. Hydraulic presses operate at lower speeds and are less suitable for automation than mechanical presses; consequently, they are typically used for lower production volumes.

Tooling

Tool design is critical in cold extrusion not only for the success of the process, but also for the safety of the operator. Although part dimension is the predominant factor in tool design the following also have to be considered: alignment, excess volume, friction (load, heating, and wear), lubricant availability, balanced metal flow, uniform metal flow velocity, ease of assembly, stress concentration, load distribution, and elastic deflection. Cold extrusion tooling can be separated into perishable and nonperishable. The perishable toolings are typically in direct contact with metal flow and are highly stressed. These include punches, forming dies, guide sleeves, and mandrels. The nonperishable toolings are used to support the perishable tooling and are not directly exposed to the forging pressure. These include shrink rings, backup plates, spacers, and retainer rings. Nonperishable tools are designed to be flexible and are used across different tooling setups, whereas perishable tooling tends to be part specific. Figure 5 shows a typical tool layout for backward extrusion. The punch, the die, and the shrink rings are the most critical components of cold extrusion tooling.

Punch Design. The backward extrusion punch (Fig. 6) is subjected to high pressures approaching 3000 MPa (450 ksi). Punches made typically from AISI tool steels M2 and M4 material heat treated to a hardness of 62 to 66 HRC provide the required strength. Tungsten carbide is also used when high loads and stiffness are required. At these high loads, it is also important to limit the effective length-to-diameter ratio of the extruded hole to around 3 to 1 for rigidity. The punch nose contour controls the metering of the lubricant during the process. A hemispherical nosed punch, although desirable from a load point of view, results in rapid depletion of the lubricant. A tapered punch nose with a 170° included angle is found to be optimal for controlling the lubricant escape to avoid lubricant depletion before the end of the process and prevent punch-splitting failures. The edge radius of the punch controls the material overshoot as it negotiates the corner. This overshoot affects the extruded diameter and the tendency to form folds. Typically, a waterfall radius of 5% of bearing land diameter is used. The bearing land of the punch should be minimal to reduce friction, yet long enough to impart dimensional control to the extruded diameter. The common practice is to use 1.5 to 4.5 mm ($^1/_{16}$ to $^3/_{16}$ in.) long land. The punch stem and shoulder should be designed with gradual angles and radii to decrease stress concentration. Surface finish on the punch is also critical. Grinding marks should be removed, and working surfaces should be lapped in the direction of metal flow.

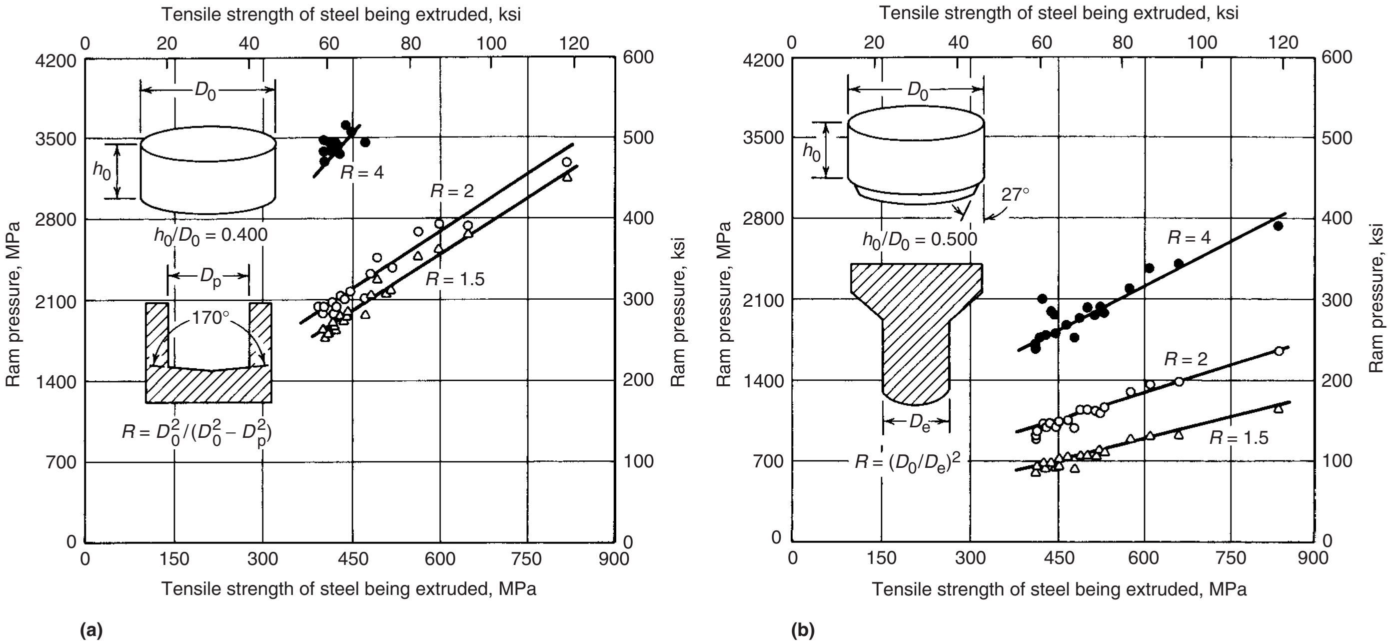


Fig. 4 Effect of tensile strength on ram pressure required for backward (a) and forward (b) extrusion of low- and medium-carbon steels at different extrusion ratios. Data are for AISI 1000, 1100, and 1500 series steels containing 0.13 to 0.44% C.

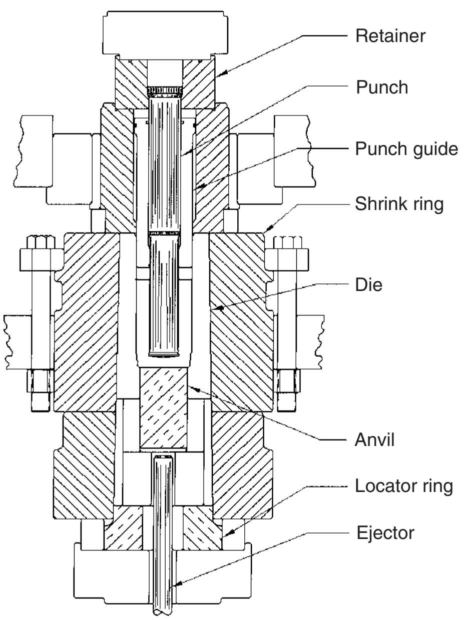


Fig. 5 Tools constituting a typical setup for the backward extrusion of steel parts

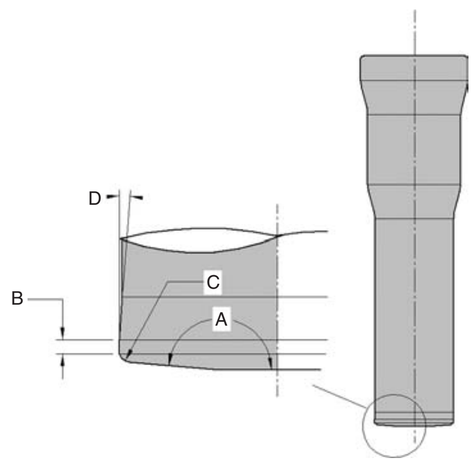


Fig. 6 Backward extrusion punch. A, nose angle; B, punch land; C, corner radius; D, relief angle

A 0.125 μm (5 μin.) finish has been found to be satisfactory. In forward extrusion, the punch design is simpler because the stress seen is much lower and the metal flow against the punch is minimal. Issues of stress concentration and strength have to be considered, and the punch nose is not as critical as in backward extrusion. It is typically flat with a bearing land of 3.25 mm (1/8 in.) and diameter that is very close to the bore of the die (0.025 to 0.125 mm, or 0.001 to 0.005 in., smaller) to prevent metal squirt between the punch and die. The closing-in of the die bore when the die is assembled in shrink rings should be considered when designing this diameter.

Die Design. The high forming pressure in cold extrusion leads to high hoop stress in the cylindrical dies. Rather than increase the amount of material in the die to resist these loads, shrink-fit or press-fit rings are used to induce favorable compressive stresses in the die. Shrink-fit assemblies are made by heating the outer ring and allowing it to cool around the die. More commonly, the die insert is force fitted mechanically into the shrink ring, using tapered interference surfaces and molybdenum disulfide as a lubricant. The most commonly used taper angle is 1/2 to 1°. In general, no further advantage is gained by making the outside diameter of shrink-ring more than four to five times the die diameter. The holding power of a shrink fit is typically greater than that of press fit because greater interference can be achieved. The external pressure from the shrink ring on the die balances the internal pressure from extrusion on the die. The design of the interferences and the diameters for the rings is based on Lame's theory of thick compound cylinders. The tool designer must calculate the hoop stresses on the inner die wall and provide adequate reinforcement with shrink rings. Ordinarily, pressures of less than about half the yield strength of the die do not require reinforcement, while those in excess of this value do require reinforcement. The reduction of stress in the die due to shrink rings also prolongs the dies fatigue life. Often an intermediate shrink ring is added to the assembly for a more efficient design. Commercially available multiple-ring shrink rings utilizing strip winding are also used in severe forming applications. Outer shrink rings are made from 4340 or H13 heat treated to 46 to 48 HRC. Care must be taken to ensure that the yield strength of the outer ring is not exceeded during die assembly. Premium grades of H13 are typically used to provide the greatest fatigue life and safe assembly. Figure 5 shows a typical backward extrusion die in a shrink ring assembly. The die is designed so that the anvil absorbs the axial load, and the load on the die is minimized. This is required to prevent cracking at the die corners. The length of anvil is designed to allow for elastic deflection under extrusion load. The forward extrusion die design involves more factors (Fig. 7). The internal diameters are prescribed by the product requirements. The design of the extrusion die angle (Fig. 8) is dependent on the extrusion ratio. Typically, the extrusion die angle (half angle) varies from 5 to 30°. Standards published by Bethlehem (Ref 1) and Chrysler (Ref 2) are commonly used for designing the extrusion die angle. When using higher angles, care has to be taken to prevent chevrons during multiple extrusions. Chevrons or central bursts are internal arrow-shaped defects occurring along the axis of a forward extrusion (Fig 9). Typically, lower angles are preferred for higher reductions. The safe zone decreases with work hardening; therefore, extra care is required in designing multiple forward extrusions. For high reductions (>35%) a radius is preferred in place of the angle because it requires lower extrusion loads. The die land is typically 0.75 to 3.25 mm (1/32 to 1/8 in.) long. For high reductions (>35%), the billet has to be fully contained within the die and consequently a long lead die is used for this purpose. An angle of 30 to 60° is preferred for extruding hollow parts, the angle varying inversely with wall thickness. Extrusion dies are usually made from M2 (60–62 HRC). Tungsten carbide is also used for high volume or critical extrusions. Ejection pressure on the work increases with decreasing die angle, because greater friction must be overcome due to the greater surface area. The ejection pressure also increases with an increase in the length of the part. Extrusion pressure also causes elastic expansion of the die, which shrinks when the pressure is discontinued. Accordingly, very high wall pressures are developed, and these require correspondingly high ejection pressures. This has to be considered when designing ejector pins. Ejector pins are typically made from S7 heat treated to 54 to 56 HRC, and M2 heat treated to 60 to 62 HRC can be used in higher-pressure applications.

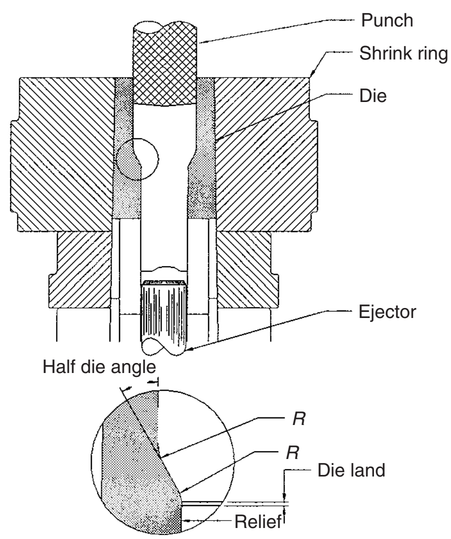


Fig. 7 Tooling for forward extrusion

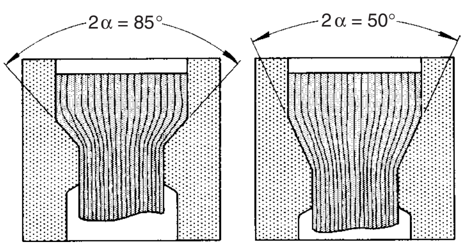


Fig. 8 Measurement of die angle in dies for forward extrusion

Process Limits. Free (open-die) forward extrusion of solid bars is limited to 30 to 35% reduction in area. However, if the billet is fully enclosed in a die (closed die), the reduction in area can be increased to 70 to 75%. Figure 1 shows the difference between open- and closed-die forward extrusions. The ratio of length of forward extruded parts to diameter of the billet is usually limited to 8 to 1. In backward extrusion, the reduction ratio should be kept between a minimum of 20 to 25% and a maximum of 70 to 75%. The maximum depth of extruded hole is limited to three times the hole diameter. In most cases, the bottom thickness of the cup has to be equal to or greater than the wall thickness of the cup. In lateral extrusion, up to 60% reduction in area is achievable. The width or the diameter of the extrudate has to be at least half the starting blank diameter. Draw ironing is usually limited to 30%; however, if the tube is being pushed instead of being drawn this can be increased to 50%.

Preparation of Slugs

The preparation of billets/slugs often represents a substantial fraction of the cost of producing cold-extruded parts.

Billet Cutoff. Sawing and shearing are the two common methods for creating the billet. The advantages of sawing are dimensional accuracy, freedom from distortion, and minimal work hardening. The disadvantages are material loss as saw kerf and slower production rates. The use of circular saws instead of band saws and double cuts per cycle has considerably improved the production rates. The cycle time and material losses increase with billet diameter. The quality and roughness of the cut has an important effect on quality of the extrusion. Shearing is a chipless process and is a more economical means of producing billets due to much higher production rates. Variation in the sizes and shape of the billet is a major disadvantage of shearing. Extrusion process design has to allow for this variation. If precise shape is required, then the billets have to be coined to desired dimensions in a press. In shearing, the ends of the billet are work hardened and consequently their ductility is reduced. Another billet-cutting method is the adiabatic cutoff process involving high-speed/high-energy impact processing. The cycle time with this process is about a millisecond, so the production rates can be very high. Production rates of several hundred parts per minute are possible, based on the capabilities of the material-handling system. This process produces precision cutoff blank that is burr-free, with minimum pulldown and end distortion and is also capable of cutting steels in hardened condition.

Surface Preparation of Steel Slugs. Phosphate coating for cold extrusion is the common practice. The primary purposes of this coating are, first, to form a nonmetallic separating layer between the tools and workpiece, and, second, by reaction with or absorption of the lubricant, to prevent its migration from bearing surfaces under high unit pressures. During extrusion, the coating flows with the metal as a tightly adherent layer.

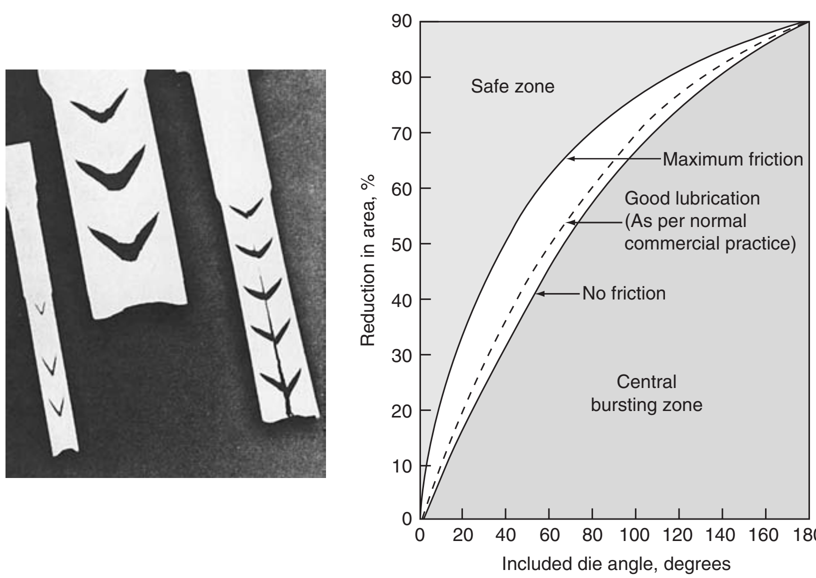


Fig. 9 Chevrons in forward extrusion. Source: Ref 2

The recommended preparation of steel slugs for extrusion consists of alkaline cleaning, water rinsing, acid pickling, cold and hot water rinsing, phosphate coating, and rinsing. These methods are discussed in this section.

Alkaline cleaning is done to remove oil, grease, and soil from previous operations so that subsequent pickling will be effective. Alkaline cleaning can be accomplished by spraying the slugs with a heated (65–70 °C, or 150–160 °F) solution for 1 to 2 min or by immersing them in solution at 90 to 100 °C (190 to 212 °F) for 5 to 10 min.

Water rinsing is done to remove residual alkali and to prevent neutralization of the acid pickling solution. Slugs are usually rinsed by immersion in overflowing hot water, but they may also be sprayed with hot water.

Acid Pickling. Most commercial installations use a sulfuric acid solution (10% by volume) at 60 to 90 °C (140 to 190 °F). Pickling can be accomplished by spraying for 2 to 15 min or by immersion for 5 to 30 min, depending on surface conditions (generally, the amount of scale). Three times are usually sufficient to remove all scale and to permit a good phosphate coating. Bright annealing or mechanical scale removal, such as shot blasting, as a substitute for pickling has proved unsatisfactory for severe extrusion if significant scale is present. However, the use of a mechanical scale removing method prior to pickling can reduce pickling time, and for producing extrusions of mild severity the mechanical (or bright annealing) methods have often been used without subsequent pickling or combined with cold pickling process.

Cold and hot water rinsing can be carried out by immersion or spraying for $1/2$ to 1 min for each rinse. Two rinses are used to ensure complete removal of residual pickling acid and iron salts. Cold water rinsing is usually of short duration, with heavy overflow of water to remove most of the residual acid. Hot water at about 70 °C (160 °F) increases the temperature of the workpiece and ensures complete rinsing.

Phosphate coating is performed by immersion in zinc phosphate at 70 to 80 °C (160 to 180 °F) for 3 to 5 min. Additional information is available in the article "Phosphate Coating" in Volume 5 of *ASM Handbook.*

Rinsing with cold water, applied by spraying for $1/2$ min or by immersion for 1 min, removes the major portion of residual acids and acid salts left over from the phosphating solution. This rinse is followed by a neutralizing rinse applied by spraying or immersion for $1/2$ to 1 min using a well-buffered solution (such as sodium carbonate), which must be compatible with the lubricant. In the second rinse, the remaining residual acid and acid salts in the porous phosphate coating are neutralized so that absorption of, or reaction with, the lubricant is complete.

Stainless steels are not amenable to conventional phosphate coating, oxalate coatings have been developed with reactive soaps; copper plating of stainless steel slugs is preferred. Lime coating is sometimes substituted successfully for copper plating. In extreme cases, the stainless steel can be zinc plated and then coated with zinc phosphate and a suitable soap lubricant. Methods of surface preparation for nonferrous metals are discussed in the sections "Cold Extrusion of Copper and Copper Alloy Parts" and "Cold Extrusion of Aluminum Alloy Parts" in this article.

Lubricants for Steel

A soap lubricant has traditionally provided the best results for the extrusion of steel. Slugs are immersed in a dilute (45 to 125 mL/L, or 6 to 16 oz/gal) soap solution at 65 to 90 °C (145 to 190 °F) for 3 to 5 min. Some soaps are formulated to react chemically with the zinc phosphate coating, resulting in a layer of water-insoluble metal soap (zinc stearate) on the surfaces of the slugs. This coating has a high degree of lubricity and maintains a film between the work metal and tools at the high pressures and temperatures developed during extrusion.

Other soap lubricants, with or without filler additives, can be used effectively for the mild extrusion of steel. This type of lubricant does not react with the phosphate coating, but is absorbed by it.

Although the lubricant obtained by the reaction between soap and zinc phosphate is optimal for extruding steel, its use demands precautions. If soap accumulates in the dies, the workpieces will not completely fill out. Best practice is to vent all dies so that the soap can escape and keep a timed air blast into the dies to remove the soap. Polymer lubricants are gaining wider use for all but the most severe applications where coating buildup in the dies is a concern.

When steel extrusions are produced directly from coiled wire (similar to cold heading), the usual practice is to coat the coils with zinc phosphate, using the procedure outlined in the section "Preparation of Slugs" in this article. This practice, however, has one deficiency; because only the outside diameter of the work metal is coated, the sheared ends are uncoated at the time of extrusion. This deficiency is partly compensated for by constantly flooding the work with sulfochlorinated oil. Because the major axis of a heading machine is usually horizontal, there is less danger of entrapping lubricant than when extruding in a vertical press.

Nonphosphate Coatings. New lubricants are replacing soap-phosphate treatments for the cold forging process. Soap-phosphate treatments, although very effective for extrusion process, are not conducive to continuous processing because of the long cycle time (30 min). Another disadvantage is the waste liquid treatment and disposal required for the solutions used in the process. Oil- and water-based lubricants are available that can be applied through a simple process of tank-dip, air-blowing, and hot air drying, which can be used in a continuous production line. The waste liquid treatment is significantly reduced. The application of these new lubricants are gaining acceptance slowly.

Selection of Procedure

The shape of the part is usually the primary factor that determines the procedure used for extrusion. Typically, short cuplike parts are produced by backward extrusion, while solid shaftlike parts and thin-walled hollow shafts are produced by forward extrusion. Semihollow shapes and thick-walled hollow shafts are made with both forward and backward extrusion. Other factors that influence procedure are the composition and condition of the steel, the process limits, the required dimensional accuracy, quantity, and cost. For difficult extrusions, it may be necessary to incorporate several steps and one or more intermediate annealing operations into the process. Some shapes may not be completely extrudable from difficult-to-extrude steels, and one or more machining operations may be required.

Cold extrusion is ordinarily not considered unless a large quantity of identical parts must be produced. The process is seldom used for fewer than 100 parts, and more often it is used for hundreds of thousands of parts or continuous high production. Quantity requirements determine the degree of automation that can be justified and often determine whether the part will be completed by cold extrusion (assuming it can be if tooling is sufficiently elaborate) or whether, for low quantities, a combination of extruding and machining will be more economical.

Cost per part extruded usually determines:

- The degree of automation that can be justified
- Whether a combination of extruding and machining should be used for low-quantity production
- Whether it is more economical to extrude parts for which better-than-normal dimensional accuracy is specified or to attain the required accuracy with secondary operations

It is sometimes possible to extrude a given shape by two or more different procedures. Under these conditions, cost is usually the deciding factor. Several procedures for extruding specific steel parts, categorized mainly by part shape, are discussed in the following sections.

Cuplike Parts

The basic shape of a simple cup is often produced by backward extrusion, although one or more operations such as piercing or coining are frequently included in the operations sequence. For cuplike parts that are more complex in shape, a combination of backward and forward extrusion is more often used. Example 1 describes combined backward extrusion and coining for the fabrication of 5120 steel valve tappets.

Example 1: Backward Extrusion and Coining for Producing Valve Tappets. The valve tappet shown in Fig. 10 was made from fine-grain, cold-heading quality 5120 steel. Slugs were prepared by sawing to a length of 25.9 to 26.0 mm (1.020 to 1.025 in.) from bar stock 22.0 to 22.1 mm (0.867 to 0.871 in.) in diameter. Slugs were tumbled to round the edges, then phosphated and lubricated with soap.

The slugs were fed automatically into the two loading stations of the eight-station dial, then extruded, coined, and ejected. One part was produced in each set of four stations (two parts per stroke). This technique helped to keep the ram balanced, thus avoiding tilting of the press ram, prolonging punch life, and reducing eccentricity between the outside and inside diameters of the extruded part. An eccentricity of less than 0.25 mm (0.010 in.) total indicator reading (TIR) was required. The cup could not be extruded to the finished shape in one hit, because a punch of conelike shape would pierce rather than meter-out the phosphate coating. Therefore, two hits were used—the first to extrude and the second to coin. Punches are shown in Fig. 10(b) and (c). Axial pressure on the punch was about 2205 MPa (320 ksi).

Tubular Parts

Backward and forward extrusion, drawing, piercing, and sometimes upsetting are often combined in a sequence of operations to produce various tubular parts. Example 2 describes a procedure for extruding a part having a long tubular section.

Example 2: Producing Axle-Housing Spindles in Five Operations. An axle-housing spindle was produced from a slug by backward extruding, piercing, and three forward extruding operations, as shown in Fig. 11. The 10 kg (22.5 lb) slug was prepared by sawing and then annealing in a protective atmosphere at 675 to 730 °C (1250 to 1350 °F) for 2 h, followed by air cooling. The slug was then cleaned, phosphate treated, and coated with soap. After backward extruding and piercing, and again after the first forward extruding operation, the workpiece was reannealed and recoated.

A 49 MN (5500 tonf) crank press operated at 14 strokes/min was used. The punches were made of D2 tool steel, and the die inserts of A2 tool steel.

Stepped Shafts

Three methods are commonly used to cold form stepped shafts. If the head of the shaft is relatively short (length little or no greater than the headed diameter), it can be produced by upsetting (heading). For a head more than about 2.5 diameters long, however, upsetting in a single operation is not advisable; buckling will result because of the excessive length-to-diameter ratio of the unsupported portion of the slug. Under these conditions, forward extrusion or multiple-operation upsetting should be considered.

Forward extrusion can be done in a closed die or an open die (Fig. 12). In a closed die, the slug is completely supported, and the cross-sectional area can be reduced by as much as 70%. Closed-die extrusion gives better dimensional accuracy and surface finish than the open-die technique. However, if the length-to-diameter ratio of the slug is more than about 4 to 1, friction along the walls of the die is so high that the closed-die method is not feasible, and an open die must be used. In an open die, reduction must be limited to about 30 to 35%, or the unsupported portion of the slug will buckle. Stepped shafts can, however, be extruded in open dies using several consecutive operations, as described in Example 3.

Example 3: Transmission Output Shaft Forward Extruded in Four Passes in an Open Die. A transmission output shaft was forward extruded from a sheared slug in four passes through a four-station open die, as shown in Fig. 13. Extrusion took place in two directions simultaneously. Transfer from station to station was accomplished by a walking-beam mechanism.

Air-actuated V-blocks (not shown in Fig. 13) were used to clamp the large diameter of the shaft to prevent buckling. A hydraulic cushion (Fig. 13) contacted the slug at the start of the stroke and remained in contact with the workpiece throughout the cycle. Therefore, extrusion into the stationary tool holder took place first, ensuring that variation in finished length, caused by variation in stock diameter, was always in the movable tool holder. Each station of the die was occupied by a workpiece at all times; a finished piece was obtained with each stroke of the press. The amount of area reduction was about the same for each pass and totaled 65% for the four passes.

The cold working caused a marked change in the mechanical properties of the workpiece. Tensile strength increased from 585 to 945 MPa (85 to 137 ksi), yield strength increased from 365 to 860 MPa (53 to 125 ksi), elongation decreased from 26 to 7%, and reduction of area decreased from 57 to 25%.

Extrusion Combined with Cold Heading

The combination of cold extrusion and cold heading is often the most economical means of producing hardware items and machinery parts that require two or more diameters that are widely different (see also the article "Cold Heading" in this Volume). Such parts are commonly made in two or more passes in some type of heading machine, although presses are sometimes used for relatively small parts. Presses are required for the heading and extruding of larger parts.

Parts that have a large difference in cross-sectional area and weight distribution cannot be

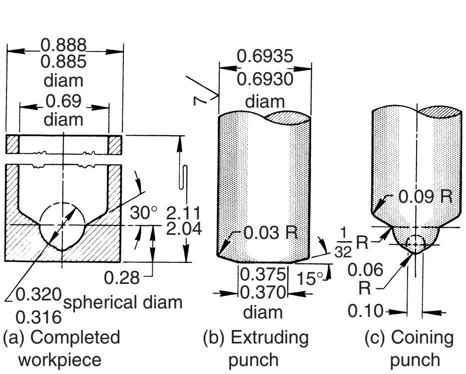


Fig. 10 5120 steel valve tappet (maximum hardness: 143 HB) produced by extrusion and coining with punches shown. Dimensions given in inches

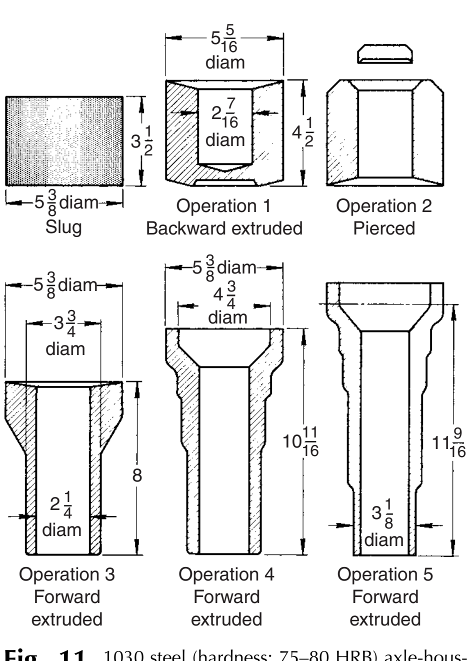


Fig. 11 1030 steel (hardness: 75–80 HRB) axle-housing spindle produced by extruding and piercing in five operations. Dimensions given in inches

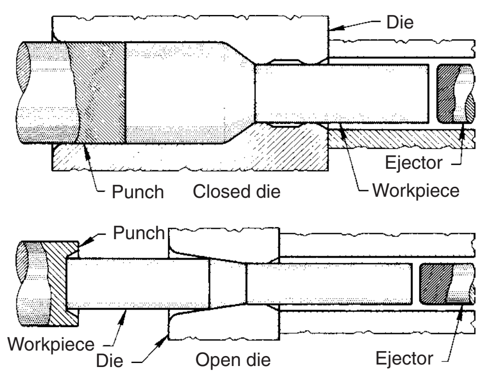


Fig. 12 End of stroke in the forward extrusion of a stepped shaft in a closed die and an open die

formed economically from material equivalent in size to the smallest or largest diameter of the completed part. The most economical procedure consists of selecting material of an intermediate size, achieving a practical amount of reduction of area during forward extrusion, and forming the large sections of the part by heading. This practice is demonstrated in Example 4.

Example 4: Adjusting Screw Blank Produced by Forward Extrusion and Severe Heading in Three Operations. The blank for a knurled-head adjusting screw, shown in Fig. 14, was made from annealed and cold-drawn rod that was coated with lime and a soap lubricant at the mill. In this condition, the rod was fed to a heading machine, in which it was first cut to slug lengths. The slugs were then lubricated with an oil or a water-soluble lubricant containing extreme-pressure additives. As shown in Fig. 14, the slug was extruded in one die, and the workpiece was then transferred to a second die, in which it was cold headed in two operations: the first for stock gathering and the second for completing the head (which represents severe cold heading). Except for the extrusion die, which was made from carbide, all dies and punches were made from M2 and D2 steels hardened to 60 to 62 HRC. Tool life for the carbide components was 1 million pieces; for the tool steel components, 250,000 pieces. Production rate was 6000 pieces/h.

Extrusion of Hot Upset Preforms

Although the use of symmetrical slugs as the starting material for extrusion is common practice, other shapes are often used as the starting slugs or blanks. One or more machining operations sometimes precede extrusion in order to produce a shape that can be more easily extruded. The use of hot upset forgings as the starting material is also common practice. Hot upsetting followed by cold extrusion is often more economical than alternative procedures for producing a specific shape. Axle shafts for cars and trucks are regularly produced by this practice; the advantages include improved grain flow as well as low cost. A typical application is described in Example 5.

Example 5: Hot Forging and Cold Extrusion of Rear-Axle Drive Shafts. The fabrication of rear-axle drive shafts (Fig. 15) for passenger cars and trucks by three-operation cold extrusion improved surfaces (and consequently fatigue resistance), maintained more uniform diameters and closer dimensional tolerances, increased strength and hardness, and simplified production. The drive shafts were hot upset forged to form the flange and to preform the shaft, and they were cold extruded to lengthen the shaft. The flange could have been upset as a final operation after the shaft had been cold extruded to length, but this would have required more passes in the extrusion press than space allowed. Hot upsetting and cold extrusion replaced a hammer forging and machining sequence after which the flange, a separate piece, had been attached.

Steel was extrusion-quality 1039 in 42.9 mm ($1\frac{11}{16}$ in.) diam bars. The bars were sheared to lengths of 757 to 929 mm ($29\frac{13}{16}$ to $36\frac{9}{16}$ in.), then hot forged and shot blasted. A continuous conveyor took the hot upset preforms through a hot alkaline spray cleaner, a hot spray rinse, a zinc phosphating bath (75 °C, or 165 °F, for 5 min), a cold spray rinse, a hot spray rinse, and finally a soap tank (90 °C, or 190 °F, for 5 min). As shown in Fig. 15, cold extrusion was a three-operation process that increased the length of the shaft and reduced the smallest diameter to 33.2 mm (1.308 in.).

Extrusion of Large Parts

Although most cold extrusion of steel is confined to relatively small parts (starting slugs seldom weigh more than 11.3 kg, or 25 lb), much larger parts have been successfully cold extruded. For press operations, the practical extremes of part size are governed by the availability of machinery and tool materials, the plasticity of the work material, and economical production quantities. Bodies for large-caliber ordnance shells have been successfully produced by both hot and cold extrusion processes. The procedure used in the production of these large parts by cold extrusion is described in Example 6.

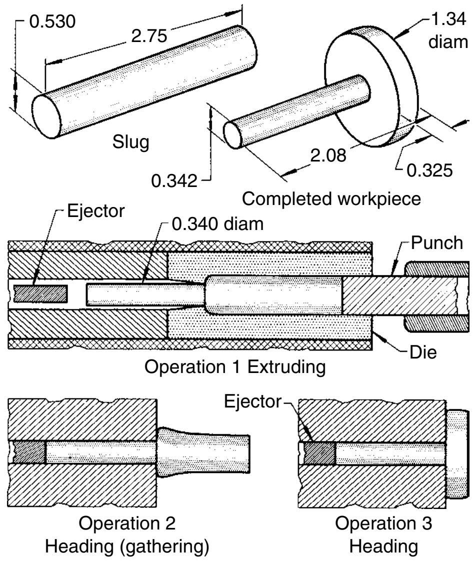


Fig. 14 1018 steel adjusting-screw blank formed by forward extruding and severe cold heading. Dimensions given in inches

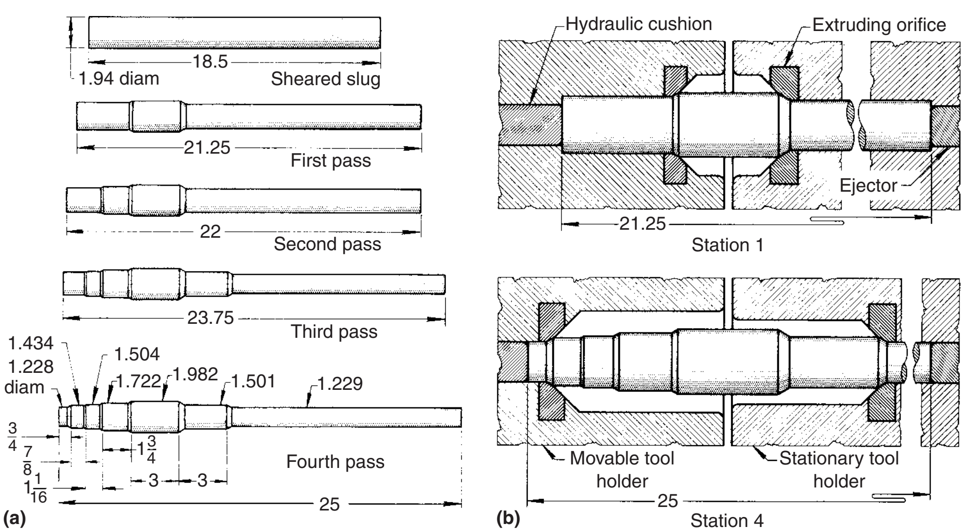


Fig. 13 4028 steel transmission shaft produced by four-pass forward extrusion in a four-station open die. (a) Shapes produced in extrusion. (b) Two of the die stations. Dimensions given in inches

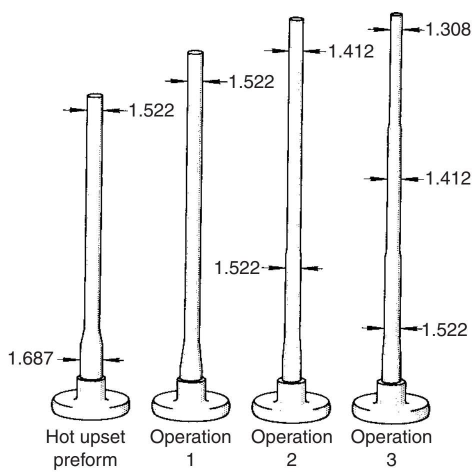
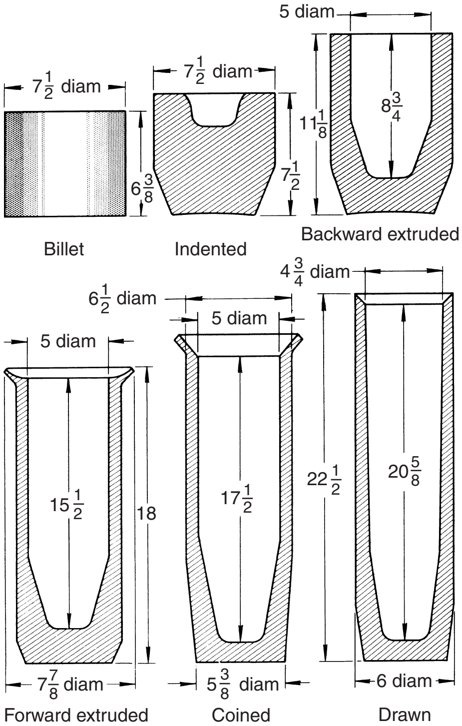


Fig. 15 1039 steel rear-axle drive shaft produced by cold extruding an upset forging in three operations. Billet weight: 9.6 kg (21.2 lb). Dimensions given in inches

Example 6: Use of Extrusion in Multiple-Method Production of Shell Bodies. Figure 16 shows the progression of shapes resulting from extrusion, coining, and drawing in a multiple-method procedure for producing bodies for 155 mm shells from descaled 1012 steel billets 190 mm (7½ in.) in diameter that weighed 36 kg (79.5 lb) each. The sequence of operations is listed with Fig. 16. Production of these shell bodies was designed for semicontinuous operation that included annealing, cleaning, and application of lubricant between press operations.



Sequence of operations

1. Cold saw the billet.
2. Chamfer sawed edges.
3. Apply lubricant as follows:
   - Degrease in boiling caustic; rinse.
   - Pickle in sulfuric acid; rinse.
   - Apply zinc phosphate.
   - Apply zinc stearate.
4. Cold size indent (see illustration above).
5. Induction normalize (925 to 980 °C, or 1700 to 1800 °F).
6. Apply lubricant as in step 3.
7. Backward extrude (see illustration).
8. Induction normalize (see step 5).
9. Apply lubricant as in step 3.
10. Forward extrude in two stages to shape in illustration.
11. Anneal lip by localized induction heating (815 to 830 °C, or 1500 to 1525 °F).
12. Apply lubricant as in step 3.
13. Coin base and form boat tail to finish dimension and coin bottom (see illustration).
14. Final draw (see illustration).
15. Turn and recess lip.
16. Induction anneal nose (790 to 815 °C, or 1450 to 1500 °F).
17. Apply lubricant as in step 3.
18. Expand bourrelet in No. 6 press.
19. Form nose.
20. Anneal for relief of residual stress.

Fig. 16 1012 steel 155 mm (6 in.) shell body produced by a multiple-step procedure that included cold extrusion. Billet weight: 36 kg (79.5 lb). Dimensions given in inches

Dimensional Accuracy

In cold extrusion, the shape and size of the workpiece are determined by rigid tools that change dimensionally only from wear. Because tool wear is generally low, successive parts made by cold extrusion are nearly identical. The accuracy that can be achieved in cold extrusion depends largely on the size and shape of the given section. Accuracy is also affected by tool material, die compression, die set design, tool guidance, and press drive rigidity.

Tolerances for cold extrusion are commonly denoted as close, medium, loose, and open. Definitions of these tolerances, as well as applicability to specific types of extrusions, are discussed in this section.

Close tolerance is generally considered to be $\pm$0.025 mm ($\pm$0.001 in.) or less. Close tolerances are usually restricted to small (<25 mm, or 1 in.) extruded diameters.

Medium tolerance denotes $\pm$0.13 mm ($\pm$0.005 in.). Extruded diameters of larger parts (up to 102 mm, or 4 in.), headed diameters of small parts, and concentricity of outside and inside diameters in backward extruded parts are typical of dimensions on which it is practical to maintain medium tolerance.

Loose tolerance denotes $\pm$0.38 mm ($\pm$0.015 in.). This tolerance generally applies to short lengths of extruded parts less than about 89 mm (3½ in.) long.

Open tolerance is generally considered to be greater than $\pm$0.38 mm ($\pm$0.015 in.). This tolerance applies to length dimensions of large, slender parts (up to 508 mm, or 20 in., and sometimes longer).

Variation. With reasonable maintenance of tools and equipment, the amount of variation of a given dimension is usually small for a production run. Some drift can be expected as the tools wear and work metal properties vary from lot to lot.

Causes of Problems

The problems most commonly encountered in cold extrusion are:

- Tool breakage
- Galling or scoring of tools
- Workpieces sticking to dies
- Workpieces splitting on outside diameter or cupping in inside diameter
- Excessive buildup of lubricant in dies

Table 1 lists the most likely causes of these problems.

Cold Extrusion of Aluminum Alloy Parts

Aluminum alloys are well adapted to cold (impact) extrusion. The lower-strength, more ductile alloys, such as 1100 and 3003, are the easiest to extrude. When higher mechanical properties are required in the final product, heat treatable grades are used.

The cold extrusion process should be considered for aluminum parts for the following reasons. High production rates—up to 4000 pieces/h—can be achieved. However, even when parts are large or of complex shape, lower production rates may still be economical. The impact-extruded part itself has a desirable structure. It is fully wrought, achieving maximum strength and toughness. It is a near-net

Table 1 Problems in cold extrusion and some potential causes

Problem	Potential cause
Tool breakage	Slug not properly located in die
	Slug material not completely annealed
	Slug not symmetrical or not properly shaped
	Improper selection or improper heat treatment of tool material
	Misalignment and/or excessive deflection of tools and equipment
	Incorrect preloading of dies
	Damage caused by double slugging or overweight slugs
Galling or scoring of tools	Improper lubrication of slugs
	Improper surface finish of tools
	Improper selection or improper heat treatment of tool material
	Improper edge or bend radii on punch or extrusion die
Workpieces sticking to die	No back relief on punch or die
	Incorrect nose angle on punch and incorrect extrusion angle of die
	Galled or scored tools
Workpieces splitting on outside diameter or forming chevron on inside diameter	Slug material not completely annealed
	Reduction of area either too great or too small
	Excessive surface seams or internal defects in work material
	Incorrect die angles
Excessive buildup of lubricant on dies	Inadequate vent holes in die
	Excessive amount of lubricant used
	Lack of a means of removal of lubricant, or failure to prevent lubricant buildup by spraying the die with an air-oil mist

shape. There is no parting line, and all that may be required is a trim to tubular sections. Surface finish is good. Impacts have zero draft angles, and tolerances are tight. Once impacted, sections can be treated in the same manner as any other piece of wrought aluminum.

From a design standpoint, aluminum impacts should be considered:

- For hollow parts with one end partially or totally closed
- When multiple-part assemblies can be replaced with a one-piece design
- When a pressure-tight container is required
- When bottoms must be thicker than the walls or the bottom design includes bosses, tubular extensions, projections, or recesses
- When a bottom flange is required
- When bottoms, sidewalls, or heads have changes in section thickness

Aluminum provides the characteristics of good strength-to-weight ratio, machinability, corrosion resistance, attractive appearance, and high thermal and electrical conductivity. It is also nonmagnetic, nonsparking, and nontoxic.

Although nearly all aluminum alloys can be cold extruded, the five alloys listed in Table 2 are most commonly used. The alloys in Table 2 are listed in the order of decreasing extrudability based on pressure requirements. The easiest alloy to extrude (1100) has been assigned an arbitrary value of 1.0 in this comparison.

Temper of Work Metal. The softer an alloy is, the more easily it extrudes. Many extrusions are produced directly from slugs purchased in the O (annealed, recrystallized) temper. In other applications, especially when slugs are machined from bars, the slugs are annealed after machining and before surface preparation. The raw material is often purchased in the F (as-fabricated) temper to improve machinability, and the cut or punched slugs are then annealed before extrusion.

When extruding alloys that will be heat treated, such as 6061, common practice is to extrude the slug in the O temper, solution treat the preform to the T4 temper, and then size or finish extrude. This procedure has two advantages. First, after solution treatment, the metal is reasonably soft and will permit sizing or additional working, and, second, the distortion caused by solution treatment can be corrected in final sizing. After sizing, the part can be aged to the T6 temper, if required.

Size of Extrusions. Equipment is readily available that can produce backward and forward extrusions up to 406 mm (16 in.) in diameter. Backward extrusions can be up to 1.5 m (60 in.) long. The length of forward extrusions is limited only by the cross section of the part and the capacity of the press. Irrigation tubing with a 152 mm (6 in.) outside diameter and a 1.47 mm (0.058 in.) wall thickness has been produced in lengths up to 12.2 m (40 ft). Small-outside-diameter tubing (<25 mm, or 1 in.) has been produced by cold extrusion in 4.3 m (14 ft) lengths.

Hydraulic extrusion and forging presses, suitably modified, are used for making very large extrusions. Parts up to 840 mm (33 in.) in diameter have been produced by backward extrusion from high-strength aluminum alloys in a 125 MN (14,00 tonf) extrusion press. Similar extrusions up to 1 m (40 in.) in diameter have been produced in large forging presses.

Presses. Both mechanical and hydraulic presses are used in the extrusion of aluminum. Presses for extruding aluminum alloys are not necessarily different from those used for steel. There are, however, two considerations that enter into the selection of a press for aluminum. First, because aluminum extrudes easily, the process is often applied to the forming of deep cuplike or tubular parts, and for this application, the press should have a long stroke. Again, because aluminum extrudes easily, the process is often used for mass production, which requires that the press be capable of high speeds.

The press must have a stroke that is long enough to permit removal of the longest part to be produced. Long shells are sometimes cold extruded in short-stroke knuckle-type presses, in which the punch is tilted forward or backward for removal of the workpiece.

Because of their high speeds, mechanical crank presses are generally preferred for producing parts requiring up to about 11 MN (1200 tonf) of force. Production of as many as 70 extrusions/min (4200/h) is not unusual, and higher production rates are often obtained. Therefore, auxiliary press equipment is usually designed for a high degree of automation when aluminum is to be extruded.

Cold-heading machines are also used for the cold extrusion of aluminum parts. Hollow aluminum rivets are formed and extruded in cold headers in mass-production quantities. In general, the extruded parts are small and usually require an upsetting operation that can be done economically in a cold header.

Tooling. Tools designed especially for extruding aluminum may be different from those used for steel, because aluminum extrudes more easily. For example, a punch used for the backward extrusion of steel should not have a length-to-diameter ratio greater than about 3 to 1; however, this ratio, under favorable conditions, can be as high as 17 to 1 for aluminum (although a 10-to-1 ratio is usually the practical maximum).

Dies. Three basic types of dies for extruding aluminum are shown in Fig. 17. Solid dies are usually the most economical to make. Generally, a cavity is provided in each end so that the die can be reversed when one end becomes cracked or worn.

Holder-and-sleeve dies are used when extrusion pressures are extremely high. This type of die consists of a shrink ring or rings (the holder), a sleeve, and an insert (button). The die sleeve is prestressed in compression in the shrink ring to match the tension stress expected during extrusion.

Horizontal split dies are composed of as many as four parts: a shrink ring, a sleeve (insert), and a one-piece or two-piece base. Figure 17 identifies the one-piece base as a die bottom, and the components of the two-piece base as a holder and a backer.

Compared to the die cavities used in the backward extrusion of steel, the die cavities for aluminum are notably shallow, reflecting a major difference in the extrusion characteristics of the two metals. Steel is more difficult to extrude, requiring higher pressures and continuous die support of the workpiece throughout the extrusion cycle. In contrast, aluminum extrudes readily, and when the punch strikes the slug in backward extrusion, the metal squirts up the sides of the punch, following the punch contours without the external restraint or support afforded by a surrounding die cavity.

Punches. Typical punches for forward and backward extrusion are shown in Fig. 18. In the

Table 2 Relative pressure requirements for the cold extrusion of annealed slugs of five aluminum alloys (alloy 1100 = 1.0)

Alloy	Relative extrusion pressure
1100	1.0
3003	1.2
6061	1.6
2014	1.8
7075	2.3

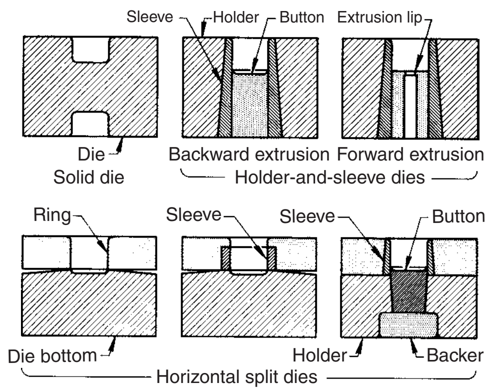


Fig. 17 Three types of dies used in the cold extrusion of aluminum alloy parts

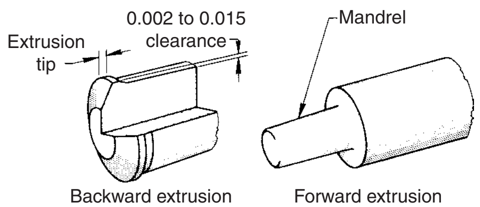


Fig. 18 Typical punches for backward and forward extrusion of aluminum alloy parts. Clearance given in inches

backward extrusion of deep cuplike parts, specially designed punches must be used to facilitate stripping.

Tool Materials. Typical tool materials and their working hardnesses for the extrusion of aluminum are given in Table 3.

Stock for Slugs. Slugs for extrusions are obtained by blanking from plate; by sawing, shearing, or machining from bars; or by casting. In general, the methods for preparing aluminum slugs are similar to those for preparing slugs from other metals and are therefore subject to the same advantages and limitations (see the section "Preparation of Slugs" in this article).

Rolled aluminum alloy plate is widely used as a source of cold extrusion stock. The high speed at which slugs can be prepared is the major advantage of blanking from rolled plate. When slug thickness is greater than about 50 mm (2 in.) or when the thickness-to-diameter ratio is greater than about 1 to 1, blanking from plate is uneconomical, if not impossible. Blanking is also excessively wasteful of metal, which negates a principal advantage of the cold extrusion process.

Sawing from bars is widely used as a method of obtaining slugs. More accurate slugs are produced by sawing than by blanking; however, as in blanking, a considerable amount of metal is lost.

When "doughnut" slugs are required, they can be sawed from tubing, or they can be punched, drilled, or extruded. Machined slugs (such as those produced in an automatic bar machine) are generally more accurate but cost more than those produced by other methods.

Cast slugs can also be used; the selection of a cast slug is made on the basis of adequate quality at lower fabricating cost. Compositions that are not readily available in plate or bar stock can sometimes be successfully cast and extruded. There is often a savings in metal when a preform can be cast to shape.

Tolerance on slug volume may vary from $\pm 2\%$ to $\pm 10\%$, depending on design and economic considerations. When extrusions are trimmed, as most are, slug tolerance in the upper part of the above range can be tolerated. When extrusions are not trimmed and dimensions are critical, the volume tolerance of the slugs must be held close to the bottom of the range. In the high-quantity production of parts such as thin-wall containers, the degree to which slug volume must be controlled is often dictated by metal cost.

Surface Preparation. Slugs of the more extrudable aluminum alloys, such as 1100 and 3003, are often given no surface preparation before a lubricant is applied prior to extrusion. For slugs of the less extrudable aluminum alloys or for maximum extrusion severity or both, surface preparation may be necessary for retention of lubricant. One method is to etch the slugs in a heated caustic solution, followed by water rinsing, nitric acid desmutting, and a final rinse in water. For the most severe extrusion, slug surfaces are given a phosphate coating before the lubricant is applied. Additional information on the alkaline etching, acid desmutting, and phosphate coating of aluminum alloys is available in the article "Cleaning and Finishing of Aluminum and Aluminum Alloys" in Volume 5 of *ASM Handbook.*

Lubricants. Aluminum and aluminum alloys can be successfully extruded with such lubricants as high-viscosity oil, grease, wax, tallow, and sodium-tallow soap. Zinc stearate, applied by dry tumbling, is an excellent lubricant for extruding aluminum. In applications in which it is desirable to remove the lubricant, water-soluble lubricants are used to reduce the wash cycle.

The lubricant should be applied to metal surfaces that are free from foreign oil, grease, and dirt. Preliminary etching of the surfaces (see above) increases the effectiveness of the lubricant. For the most difficult aluminum extrusions (less extrudable alloys or greater severity or both), the slugs should be given a phosphate treatment, followed by application of a soap that reacts with the surface to form a lubricating layer similar to that formed when extruding steel.

Impact parts range from simple cuplike parts such as compressed air filter bowls, switch housings, and brake pistons to such complex parts as aerosol cylinders and ribbed cans, electrical fittings, motor housings, and home appliance parts. Numerous examples and design criteria are given in Ref 3.

Shallow cuplike parts can be easily extruded from most of the wrought aluminum alloys. If the wall thickness is uniform and the bottom is nearly flat, shallow cups can be produced in one hit (blow) at high production rates; if the shape is more complex, two or more hits may be needed. In the following example two hits were used to produce a part with an internal boss.

Example 7: Use of a Preform for Producing a Complex Bottom. The aluminum alloy 1100-O housing shown in Fig. 19 required two extrusion operations on a hydraulic 3 MN (350 tonf) press because of the internal boss, which was formed by backward extrusion in a second operation, as shown in Fig. 19. The blended angle in the preform functioned as a support for the finishing punch during extrusion of the internal boss. This counteracted the side pressure that was created as the metal flowed into the cavity of the finishing punch.

The slug was sawed from bar and annealed; zinc stearate lubricant was used. The production rate was 350 pieces/h for the preforming operation and 250 pieces/h for finish forming. Minimum tool life was 100,000 pieces.

Deep Cuplike Parts. Although cups having a length as great as 17 times the diameter have been produced, this extreme condition is seldom found in practice, because a punch this slender is likely to deflect and cause nonuniform wall thickness in the backward-extruded product. The length of the cup and the number of operations (use of preform) are not necessarily related. Whether or not a preform is required depends mainly on the finished shape, particularly of the closed end. When forming deep cups from heat treatable alloys such as 6061, if the amount of reduction is 25% or more in the preform, the workpiece should be reannealed and relubricated between preforming and finish extruding.

Parts with Complex Shapes. Producing extrusions from aluminum and aluminum alloys in a single hit is not necessarily confined to simple shapes. The extrusion described in Example 8 was produced in a single hit despite its relatively complex shape. For extrusions with longitudinal flutes, stems, or grooves, the use of one of the most extrudable alloys, such as 1100, is helpful in minimizing difficulties. Sometimes, however, a less extrudable alloy can be used to form a complex shape in one hit.

Table 3 Typical tool steels used in extruding aluminum

Tool	AISI steel	Hardness, HRC
Die, solid	W1	65–67
Die sleeve(a)	D2	60–62
	L6	56–62
	H13	48–52
Die button(b)	H11	48–50
	H13	48–50
	L6	50–52
	H21	47–50
	T1	58–60
Ejector	D2	55–57
	S1	52–54
Punch	S1	54–56
	D2	58–60
	H13	50–52
Stripper	L6	56–58
Mandrel, forward	S1	52–54
	H13	50–52
Holder	H11	42–48
	H13	42–48
	4130	36–44
	4140	36–44

(a) Cemented carbide is sometimes used for die sleeves. (b) Maraging steel is sometimes used for die buttons.

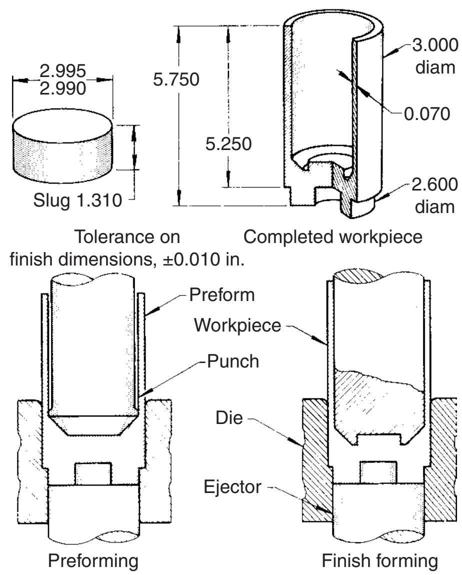


Fig. 19 Aluminum alloy 1100-O housing that was extruded in two operations because of an internal boss. Dimensions given in inches

The successful extrusion of complex shapes, especially in a single hit, depends greatly on tool design and slug design. Some developmental work is usually required for each new job before it can be put into production.

Example 8: Maximum Extrudability for a Complex Shape. The hydraulic cylinder body shown in Fig. 20 was extruded from a solid slug in one hit. Aluminum alloy 1100, which has maximum extrudability, was required for this part because of the abrupt changes in section of the cylinder body. Surface cracks and laps resulted when more difficult-to-extrude alloys were used. The different wall thicknesses and steps in this design represent near-maximum severity for extruding in one hit, even with the most extrudable alloy. During the development of this part, it was necessary to change the face angles, shorten the steps, and blend the outside ribs more gradually to ensure complete fillout. The part was produced on a 7 MN (800 tonf) mechanical press set at 4.4 MN (500 tonf). The slug was sawed from bar, annealed, and lubricated with zinc stearate. Production rate in a single-station die was 300 pieces/h, and minimum tool life was 70,000 pieces.

Dimensional Accuracy. In general, aluminum extrusions are manufactured to close tolerances. The closeness depends on size, shape, alloy, wall thickness, type and quality of tooling, and press equipment. Lubrication and slug fit in the die are also important.

Wall thickness tolerances range from ±0.025 to ±0.13 mm (±0.001 to ±0.005 in.) for relatively thin-wall cylindrical shapes of moderate size extruded from low-strength alloys, but may be as great as ±0.25 to ±0.38 mm (±0.010 to ±0.015 in.) for large parts of high-strength alloys. Wall-thickness tolerances for rectangular shells range from ±0.13 to ±0.38 mm (±0.005 to ±0.015 in.), depending on size, alloy, and nominal wall thickness. Diameter tolerances typically range from ±0.025 mm (±0.001 in.) for small parts to ±0.25 to ±0.38 mm (±0.010 to ±0.015 in.) for large high-strength alloy parts. Closer control of diameter can be achieved on small heavy-wall parts by centerless grinding of the extrusions (provided the alloy is one that can be ground satisfactorily). Dimensional tolerances in the forged portion of the impact are influenced by the same variables as those listed above, but a range of ±0.13 to ±0.38 mm (±0.005 to ±0.015 in.) is typical. Variations in extruded length usually necessitate a separate trimming operation.

Surface finish typically ranges from 0.5 to 1.8 μm (20 to 70 μin.). Smoother surfaces can sometimes be obtained by using extreme care in surface preparation and lubrication of the work metal and by paying close attention to the surface condition of the tools.

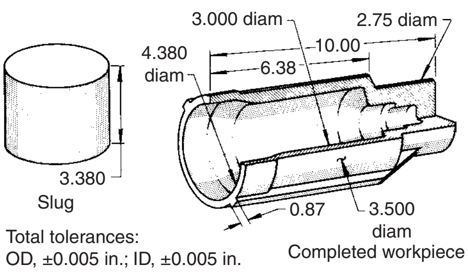


Fig. 20 Aluminum alloy 1100-O hydraulic cylinder body extruded in one hit. The complexity of this part is close to the maximum producible for one-hit extrusion of alloy 1100-O. Dimensions given in inches

Cold Extrusion of Copper and Copper Alloy Parts

Oxygen-free copper (Copper Development Association alloy C10200) is the most extrudable of the coppers and copper-base alloys. Other grades of copper and most of the copper-base alloys can be cold extruded, although there are wide differences in extrudability among the different compositions. For example, the harder copper alloys, such as aluminum-silicon bronze and nickel silver, are far more difficult to extrude than the softer, more ductile alloys, such as cartridge brass (alloy C26000), which can satisfactorily withstand cold reduction of up to 90% between anneals.

Alloys containing as much as 1.25% Pb can be successfully extruded if the amount of upset is mild and the workpiece is in compression at all times during metal flow. Copper alloys containing more than 1.25% Pb are likely to fracture when cold extruded.

The pressure required for extruding a given area for one of the more extrudable coppers or copper alloys (such as C10200 or C26000) is less than that required for extruding low-carbon steel. However, the pressure required for extruding copper alloys is generally two to three times that required for extruding aluminum alloys (depending on the copper or aluminum alloy being compared).

The length of a backward-extruded section is limited by the length-to-diameter ratio of the punch and varies with unit pressure. This ratio should be a maximum of 5 to 1 for copper. A ratio of 10 to 1 is common for the extrusion of aluminum, and ratios as high as 17 to 1 have been used. The total reduction of area for copper or copper alloys, under the best conditions, should not exceed 93%.

Equipment and Tooling. Copper and copper alloys can be extruded in hydraulic or mechanical presses or in cold-heading machines. Tooling procedures and tool materials for the extrusion of copper alloys are essentially the same as those for extruding steel.

Preparation of Slugs. Sawing, shearing, and machining are the methods used to prepare copper and copper alloy slugs. Each method has advantages and limitations. Sawing or shearing is generally used to produce solid slugs. Machining (as in a lathe) or cold forming in auxiliary equipment is seldom used unless a hole in the slug, or some other modification, is required.

Surface Preparation. In applications involving minimum-to-moderate severity, copper slugs are often extruded with no special surface preparation before the lubricant is applied. However, for the extrusion of harder alloys (aluminum bronze, for example) or for maximum severity or both, best practice includes the following surface preparation before the lubricant is applied:

1. Cleaning in an alkaline cleaner to remove oil, grease, and soil
2. Rinsing in water
3. Pickling in 10 vol% sulfuric acid at 20 to 65 °C (70 to 150 °F) to remove metal oxides
4. Rinsing in cold water
5. Rinsing in a well-buffered solution, such as carbonate or borate, to neutralize residual acid or acid salts

Lubrication. Zinc stearate is an excellent lubricant for extruding copper alloys. Common practice is to etch the slugs as described above and then to coat them by dry tumbling in zinc stearate.

Examples of Practice. The following examples describe typical production practice for extruding parts from copper and brass. The part described in Example 9 could have been made by forging, casting, or machining; however, cold extrusion produced more accurate dimensions than forging or casting, consumed less material than machining, and was the lowest-cost method.

Example 9: Shearing, Heading, Piercing, Extruding, and Upsetting in a Header. The plumbing fitting shown in Fig. 21 was made of electrolytic tough pitch copper (alloy C11000) rod cold drawn (about 15% reduction of area) to a diameter of 26.9 mm (1.06 in.). The pipe-taper diameter and the 22.2 mm (0.875 in.) diameter of the tube socket were critical, being specified within 0.064 mm (0.0025 in.).

Manufacture of the fitting consisted of feeding the rod stock into the cold-heading machine, which cut the stock into slugs 20.3 mm (0.80 in.) long and transferred the slugs progressively to dies for heading, backward extruding, piercing, forward extruding, and upsetting (Fig. 21). Only trimming on each end and tapping were required for completion. The extrusion equipment consisted of a five-die cold-heading machine.

The final cross-sectional area of the thin end after extrusion was 16.4% of the 30.7 mm (1.21 in.) diam headed preform from which the fitting was made. A reduction of this magnitude could have been made in one operation if a cylindrical rod were being extruded from the preform. The shape, however, was not suitable for production in one operation. Therefore, the fitting was made by backward and forward extrusion and mild upsetting. Production rate at 100% efficiency was 3600 pieces/h, and minimum life of the D2 tool steel dies was 200,000 pieces.

Difficult Extrusions. The part described in the following example represents a difficult extrusion for two reasons. First, the metal (tellurium copper, alloy C14500) is one of the more difficult-to-extrude copper alloys, and second, the configuration (12 internal flutes and 12 external ribs) is difficult to extrude regardless of the metal used.

Example 10: Extrusion Versus Brazed Assembly for Lower Cost. The rotor shown in Fig. 22 was originally produced by brazing a machined section into a drawn ribbed and fluted tubular section. By an improved method, this rotor was extruded from a sawed, annealed slug in one hit in a 1.7 MN (190 tonf) mechanical press. A lanolin-zinc stearate-trichloroethylene lubricant was used to produce 1800 pieces/h. The extruded rotor was produced at less cost and had better dimensional accuracy than the brazed assembly, and there were fewer rejects. Minimum tool life was 50,000 pieces.

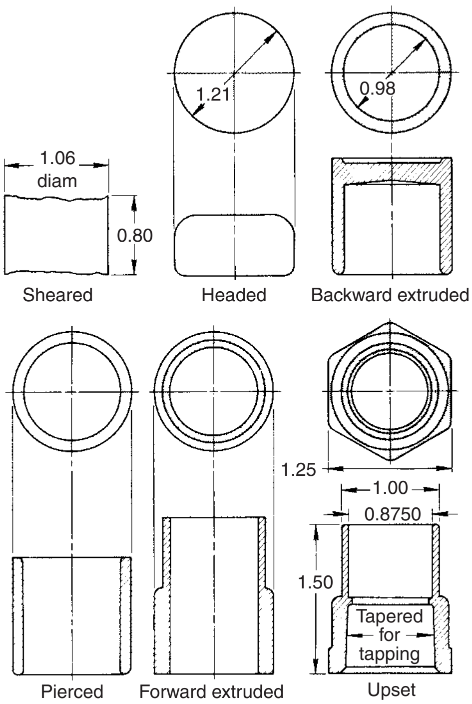


Fig. 21 Copper alloy C11000 plumbing fitting produced by the operations shown, including cold forward extrusion. Dimensions given in inches

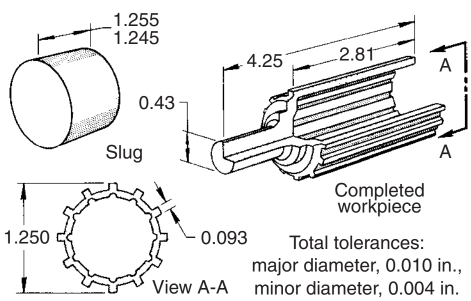


Fig. 22 Copper alloy C14500 rotor produced by combined backward and forward extrusion. Dimensions given in inches

Impact Extrusion of Magnesium Alloys

Impact extrusion is used to produce symmetrical tubular magnesium alloy workpieces, especially those with thin walls or irregular profiles for which other methods are not practical. As applied to magnesium alloys, the extrusion process cannot be referred to as cold because both blanks and tooling must be preheated to not less than 175 °C (350 °F); workpiece temperatures of 260 °C (500 °F) are common.

Length-to-diameter ratios for magnesium extrusions may be as high as 15 to 1. There is no lower limit, but parts with ratios of less than about 2 to 1 can usually be press drawn at lower cost. A typical ratio is 8 to 1, and parts with higher length-to-diameter ratios are more amenable to forward extrusion than to backward extrusion. At all ratios, the mechanical properties of magnesium extrusions normally exceed those of the blanks from which they are made, because of the beneficial effects of mechanical working.

Equipment and Tooling. Mechanical presses are faster than hydraulic presses and are therefore used more often for impact extrusion, except when long strokes are needed. Presses with a capacity of 900 kN (100 tonf) and a stroke of 152 mm (6 in.) are adequate for most extrusion applications. Up to 100 extrusions/min have been produced. Extrusion rate is limited only by press speed.

Dies for the impact extrusion of magnesium alloys differ from those used for other metals, because magnesium alloys are extruded at elevated temperature (usually 260 °C, or 500 °F). Common practice is to heat the die with tubular electric heaters. The die is insulated from the press, and an insulating shroud is built around the die. The top of the die is also covered, except for punch entry and the feeding and ejection devices. The punch is not heated, but it becomes hot during continuous operation; therefore, the punch should be insulated from the ram.

Punches and dies are usually made of a hot-work tool steel, such as H12 or H13, heat treated to 48 to 52 HRC. In one application, tools made of heat treated H13 produced 200,000 extrusions. Carbide dies can be used and can extrude up to 10 million pieces.

The sidewalls of the die cavity should have a draft of approximately 0.002 mm/mm (0.002 in./in.) of depth, which prevents the extrusion from sticking in the cavity. In normal operation, the part stays on the punch and is stripped from it on the upward stroke.

The procedure for the preparation for extrusion and extrusion practice is outlined in the following paragraphs.

Preparation of Slugs. Magnesium alloy slugs are prepared by the same methods as other metals—sawing from bar stock or blanking from plate, if rough edges can be tolerated. Slugs can also be made by casting. Slugs must be uniform in size and shape for centering in the die in order to ensure uniform wall thickness on the extrusion, which in turn depends on the clearance between die and punch. Slugs are lubricated by tumbling in a graphite suspension for 10 min until a dry coat develops.

For automatic impact extrusion of magnesium parts, the lubricated slugs are loaded into a hopper feed. The slugs are heated by an electric heater as they pass along the track between the hopper and the die.

Extrusion Practice. The heated slug is loaded onto the heated die, and the press is activated to produce the extrusion. Operating temperatures for the extrusion of magnesium alloys range from 175 to 370 °C (350 to 700 °F), depending on composition and operating speed. The operating temperature should be held constant in order to maintain tolerances.

In practice, slugs and dies are usually heated to 260 °C (500 °F) for feeding by tongs, because the rate of operation is slow. In automatic feeding, the slug and die temperature can be as low as 175 °C (350 °F), because speed is greater; dies absorb heat during operation and can increase in temperature by as much as 65 °C (150 °F). When a decrease in properties is not important, operating temperatures can be higher.

Extrusion pressures for the impact extrusion of magnesium alloys are about half those required for aluminum and depend mainly on alloy composition, amount of reduction, and operating temperature. Table 4 shows the pressures required to extrude several magnesium alloys to a reduction of area of 85% at

Table 4 Pressures required for the impact extrusion of four magnesium alloys at various temperatures

Testpieces were extruded to a reduction in area of 85%.

	Extrusion pressure at temperature													
	230 °C (450 °F)		260 °C (500 °F)		290 °C (550 °F)		315 °C (600 °F)		345 °C (650 °F)		370 °C (700 °F)		400 °C (750 °F)	
Alloy	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
AZ31B	455	66	455	66	414	60	372	54	359	52	345	50	317	46
AZ61A	483	70	469	68	455	66	441	64	428	62	414	60	400	58
AZ80A	496	72	483	70	441	68	455	66	441	64	428	62	414	60
ZK60A	469	68	455	66	441	64	428	62	400	58	372	54	359	52

Table 5 Typical tolerances for a magnesium alloy extrusion with a length-to-diameter ratio of 6 to 1

Dimension	Tolerance, mm (in.)
Diameter	±0.05 (±0.002)(a)
Bottom thickness	±0.13 (±0.005)(b)
Wall thickness, mm (in.)	
0.5–0.75 (0.020–0.029)	±0.05 (±0.002)
0.76–1.13 (0.030–0.044)	±0.076 (±0.003)
1.14–1.50 (0.045–0.059)	±0.10 (±0.004)
1.51–2.54 (0.060–0.100)	±0.13 (±0.005)

(a) Per 25 mm (1 in.) of diameter. (b) All thicknesses

temperatures ranging from 230 to 400 °C (450 to 750 °F).

Thermal Expansion. Magnesium has a relatively high coefficient of thermal expansion compared to steel. Therefore, in order to ensure that the magnesium extrusion, when cooled to room temperature, will be within dimensional tolerance, it is necessary to multiply the room-temperature dimensions of steel tools by a compensatory factor for the temperature at which the magnesium alloy is to be extruded.

The tolerances for magnesium alloy extrusions are influenced by the size and shape of the part, the length-to-diameter ratio, and the press alignment. Table 5 gives typical tolerances for a magnesium part with a length-to-diameter ratio of 6 to 1.

Cold Extrusion of Nickel Alloys

Cold heading and cold extrusion are most often used in the production of fasteners and similar cold upset parts. For nickel alloys, cold extrusion is rarely done except in conjunction with cold heading (see the article "Cold Heading" in this Volume).

The high-strength and galling characteristics of nickel alloys require slow operating speeds and high-alloy die materials. Because of the high strength and work-hardening rates of the nickel alloys, the power required for cold forming may be 30 to 50% higher than that required for mild steels. Tools should be made of oil-hardening or air-hardening die steel. The air-hardening types, such as AISI D2, D4, or high-speed steel (M2 or T1), tempered to 60 to 63 HRC, are preferred.

To prevent galling, high-grade lubricants must be used in cold heading of nickel alloys.

Lime and soap are usually used as a base coating on alloy 400. Better finish and die life can be obtained by using copper plating 7.5 to 18 μm (0.3 to 0.7 mils) thick as a lubricant carrier.

Copper plating may also be used on the chromium-containing alloys 600 and 800, but oxalate coatings serve as an adequate substitute.

Regardless of the type of carrier, a base lubricant is best applied by drawing it on in a light sizing pass to obtain a dry film of the lubricant. Any of the dry soap powders of the sodium, calcium, or aluminum stearate types can be applied this way.

If the wire rod is to be given a sizing or tempering pass before the cold-heading operation, the heading lubricant should be applied during drawing.

ACKNOWLEDGMENT

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