the working chamber acts on a comparatively small surface, equilibrium can be maintained with small jacket pressures. For the particular apparatus shown, for example, the jacket pressure does not exceed 60,000 psi when the working pressure is 500,000 psi. Furthermore, the inner cylinder expands and contracts by only a slight amount that is well within the elastic limit of the material. The limiting factor in the design is thus the compressive strength of the piston.

SEALS AND FLUID

The seals used in high-pressure forming are quite simple. As shown in Figure 6, a typical seal consists of a beryllium copper anti-extrusion ring mounted against a tapered seat and supported by a soft cup packing. When pressure is applied through the packing, the ring, which is pressed against the tapered seat, moves so as to seal the interface of piston and cylinder. For repeated cycling it is best to use the minimum possible shoulder angle. In addition, it is much better to mount the seal in the cylinder wall than in the piston. In the former position less extrusion and flexure of the beryllium ring occurs, and it also becomes unnecessary to fill the chamber to a precise level.

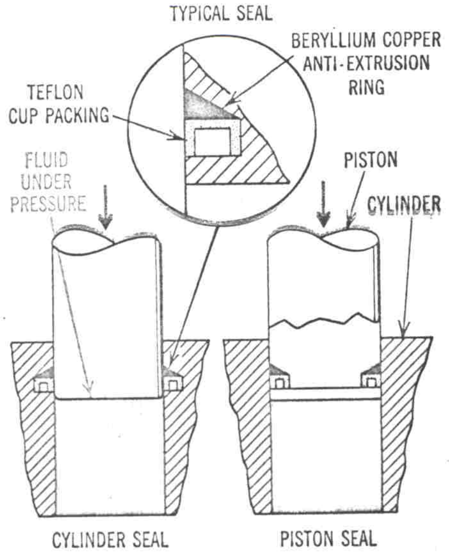

Figure 6. Typical high-pressure seals.

Another major area of concern is selection of a suitable working fluid. For a given forming operation the ideal fluid would be one that possessed a reasonably high viscosity at the beginning of the pressure cycle and a much higher viscosity with still reasonable mobility at the height of the pressure cycle. The increasing viscosity is helpful because it makes sealing easier. This consideration very often turns out to be the deciding factor determining the success or failure of high-pressure forming, because the seal is necessarily at a tool and workpiece interface where gaskets cannot be used. In addition, the fluid should possess good lubricity.

At present castor oil, kerosene, and gasoline with additives to increase lubricity are being used successfully, but these fluids leave much to be desired. Better fluids must be discovered or developed. Furthermore, since most fluids solidify at pressures within the 500,000 psi range, work should be done to determine the properties of fluids after solidification. There will be processes in which it could be helpful to have the fluid solidify providing it retains a certain amount of plasticity.

EXTRUSION

The first high-pressure forming process to be used successfully was extrusion. Bridgman extruded copper with a 16 to 1 reduction of cross-sectional area by high-pressure methods, and he proved the practicality of the process.[10]

As shown in Figure 7, high-pressure extrusion is similar to conventional ram extrusion except for the fact that fluid rather than mechanical ram pressure is applied to the billet. In addition, the billet is surrounded by high-pressure fluid. With this arrangement friction between the billet and container is entirely eliminated, and more radial force is applied to the outer surface of the billet than is conventionally the case.

[10] P. W. Bridgman, *Op. Cit.*, p. 178.

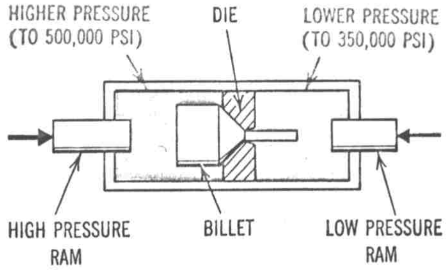

Figure 7. High-pressure extrusion.

The result of this more favorable stress field is that greater reductions of area can be made with lower ram pressures. A further advantage is found in better lubrication of the die. Finally, material extruded in this fashion has a much more uniform hardness across the diameter than material extruded conventionally.

For some materials the extrusion pressure required is not high enough to cause the transition to ductility previously described. In these cases it is only necessary (as shown in Figure 7) to create an environmental pressure at the exit end of the extrusion die to prevent extrusion until a higher pressure is built up within the chamber.

A number of researchers have used this technique successfully to extrude difficult materials. Pugh used it to extrude magnesium, bismuth, and titanium.[11] Bobrowsky has extruded sound rod of tungsten, beryllium, and molybdenum.[12] R. J. Fiorentino at Battelle Memorial Institute has done a great deal of research into the extrusion of 4340-steel round and shaped rod and has also succeeded in extruding aluminum at a 200 to 1 reduction of area.[13] In the light of this work it is evident that high-pressure extrusion may soon become commercially important in the manufacture of wire and high-strength rod.

[11] H. L. D. Pugh, "The Mechanical Properties and Deformation Characteristics of Metals and Alloys under Pressure," *NEL Report No.* 142, Mechanical Engineering Laboratory, Glasgow.

[12] A. Bobrowsky, E. A. Stack, and A. Austen, "Extrusion in Drawing Using High-Pressure Hydraulics," *Technical Paper No. SP*65-33, American Society of Mechanical Engineers, 1964.

[13] F. J. Fiorentino, *Final Report on Investigations of Hydrostatic Extrusion*, Battelle Memorial Institute, January 1965.