and the attendant heavy surface scraping apparently counteracted any beneficial effects of the second reduction. Clearly, more work is necessary in this area of die design with the aim of preventing galling or failure of the lubricant film. Such a design might be a double-reduction die similar to D5 but without relief after the first reduction, or perhaps even a long straight or tapered bearing single-reduction die.

A single trial (No. 503) with the double-reduction die, Die D4, was conducted at 500 F. In this die, the second reduction immediately follows the 1/8-in. -long bearing at the first reduction. TZM was extruded crack free with this die under the same conditions. However, the resulting beryllium extrusion was badly cracked indicating that elevated temperature alone may be sufficient to prevent cracking of TZM but not of beryllium and that the die design with adjacent bearings apparently was not effective under the extrusion conditions used. More trials would be necessary to substantiate these findings.

## The Potential of Die Design

To date, sound hydrostatic extrusions of beryllium and TZM have been obtained by other workers[17, 18] when the product was extruded into a high fluid pressure environment (fluid-to-fluid extrusion). The extrusion ratios were in the order of 2:1. The provision of a fluid back pressure requires expensive tooling on the exit side of the die sufficient in length to accommodate the long extrusion. Also, the main pressure chamber must contain pressures in excess of those required in fluid-to-air extrusion by the amount of back pressure. This severely limits the pressure level available for extrusion.

In the double-reduction die, a compressive stress is applied to the exiting extrusion. The magnitude of this stress is small because the results obtained so far indicate that the second reduction of 2.0 percent does not require any appreciable extra fluid pressure over that required for the first reduction. For this reason, it is believed that the function of the die is different from that obtained in fluid-to-fluid extrusion, where counter pressures up to 200,000 psi are required to obtain sound extrusions from brittle materials. The double-reduction die probably prevents cracking by setting up a different pattern of residual stresses in the material leaving the die. The critical effect results from the small deformations obtained at the second reduction.

Clearly, the results obtained so far are very encouraging and open up new potential applications of the hydrostatic extrusion process. For example, it appears possible that brittle materials may now be extruded into long lengths economically at temperatures previously considered impossible. Unique mechanical properties may well be obtained with these materials. Improvements in lubrication, dimensional tolerances, and contamination control can be expected at low working temperatures. In the case of beryllium, the problem of toxicity can be avoided without difficulty.

Mechanical Properties of Hydrostatic Extrusions of Beryllium

Four tensile specimens were prepared from the extrusion obtained in Trial 520. Special preparation techniques for this material were used, i. e., machining followed by chemical etching to remove damaged surface layers. The tensile properties of the specimens are given in Table XXVIII below along with those for the as-received material.

TABLE XXVIII. TENSILE PROPERTIES OF BERYLLIUM HYDROSTATICALLY EXTRUDED COLD AT AN EXTRUSION RATIO OF 4:1

| Specimen | UTS, 1000 psi | 0.2 Percent Yield Strength, 1000 psi | Elongation, percent in 2 inches |
|---|---|---|---|
| As Received | 51.2 | 36.9 | 2.5 |
| 1 | 124.5 | 98.4 | <1 |
| 2 | 120.0 | 105.7 | <1 |
| 3 | 112.1 | 104.1 | <1 |
| 4 | 117.8 | 100.0 | <1 |

The material has been markedly strengthened by cold working. In fact, the ultimate and yield strengths obtained are about 50 and 100 percent higher, respectively, than typical values for commercial hot-extruded bar having the same oxide content. It is believed that hydrostatic extrusion of this material at higher ratios and at temperatures up to about 500 F could increase strength even further. Working at 500 F would permit an increase in extrusion ratio while still being within the cold working range.