on entering the die it is moved inward with a radial velocity component. On exit from the die, the element is sheared back to again move axially. Both shearing processes require energy which does not contribute to the external form of the product and is therefore called "redundant work". A large die angle requires a greater amount of shearing energy than does a long small die angle. However the small angle would give more frictional drag at the billet-die interface.

(3) The work done to overcome billet-die friction

In hydrostatic extrusion, the work in overcoming billet-die friction is considered to be a small component of the overall pressure requirements because of the good lubrication conditions which are obtained.

Pugh indicated that the billet hardness (before extrusion) gave a rough indication of extrusion pressure requirements(2). Figure 12 shows his mean line relating billet hardness with fluid breakthrough extrusion pressure per unit ln A/a and two lines bounding the scatter in his results. The points plotted in Figure 12 are Battelle data for fluid runout pressures given in this report and for 1100-0 aluminum in an earlier report(1). The fact that the Battelle data are for runout rather than breakthrough pressures accounts for the fact the points generally fall below the mean line for Pugh's data. The use of runout rather than breakthrough pressures is believed to be a more accurate basis for comparison and pressure prediction purposes because breakthrough pressures are very sensitive to variations in lubrication whereas runout pressures are almost insensitive for many lubricants as will be shown later in the report. It is of interest that the runout pressure data, as with Pugh's data, also tend to fall very roughly on a straight line, so that a rough estimate of extrusion runout pressures can be made from the billet hardness prior to extrusion.

If data are available on the true stress-true strain properties of the material, then of course a value of $\overline{Y}$, the mean yield stress at the equivalent strain can be determined and substituted in Equation (1). In most instances, the true stress-true strain curve for a material can be represented by the equation:

$$Y = A \ln \epsilon + B \quad , \tag{2}$$

where Y is the uniaxial yield stress at the one strain of ϵ and A and B are constants. Equation (2) can now be integrated to develop an expression for the mean yield stress between a strain of O and ϵ, as follows

$$\overline{Y} = \frac{\int_0^{\epsilon} Y \, d\epsilon}{\epsilon} = A \ln \epsilon + B - A = Y - A \quad . \tag{3}$$

The constants A and B were determined from tensile data in the published literature for four of the materials listed in Table V. The following data are given and used to predict $\overline{Y}$ and thence extrusion pressures at given ratios.

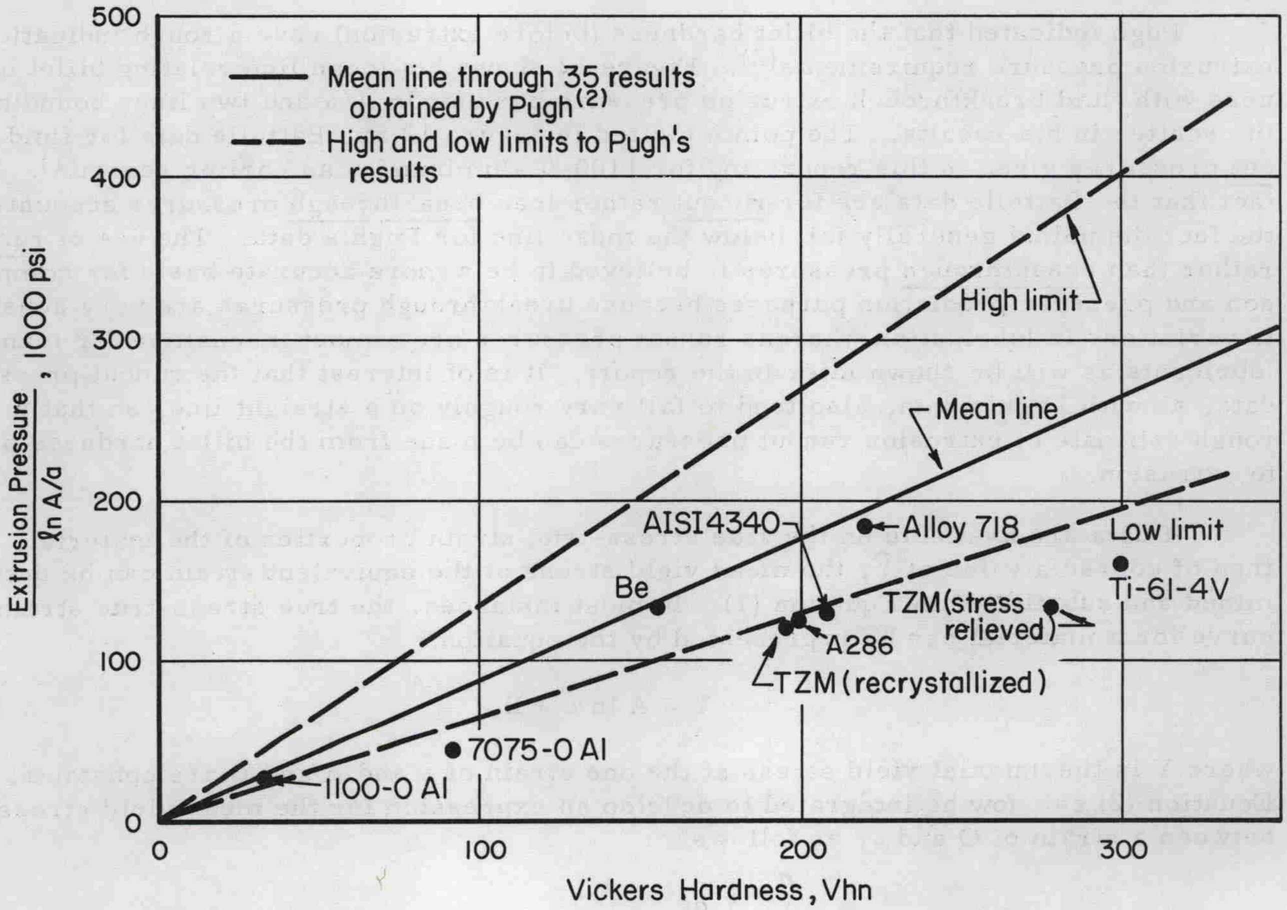

FIGURE 12. RELATIONSHIP BETWEEN EXTRUSION PRESSURE, EXTRUSION RATIO, AND BILLET HARDNESS