conical nose and cylindrical portion was used. The stepped nose did not reduce the P_b peak but it effected a multistepped, more gradual transition from the maximum pressure to the runout and pressure.

These results led to the design of the compound angle billet nose shown in Figure 15. The compound-angle design was initially evaluated at the higher ratio of 40:1 where stick-slip was more of a problem. In Figure 16 the extrusion pressure-ram travel characteristics obtained with the compound-angle design (Trial 470) is compared with those for standard nose design. Clearly the compound-angle nose design not only reduced the P_b peak by about 70,000 psi but severe stick-slip was completely eliminated. These results were obtained with Lubricant L53 which was effective with the standard nose at a ratio of 20:1. Lubricant L52, which was not so good at 20:1, was also evaluated with the compound-angle nose at 40:1 and 60:1 (Trials 473 and 474 in Table VII.) At both ratios, low P_b peaks were obtained followed by smooth runouts resulting in products having an excellent finish.

The success of the compound angle nose in extending the range in extrusion ratio, for which a given lubrication system is capable, can be explained as follows:

(1) The second or upper angle on the compound-angle nose provides for more efficient "thick-film" lubrication at breakthrough, thereby, reducing the coefficient of static friction, μ, and thus, the P_b peak. This assistance in lubrication is clearly promoted by the presence of the pressurized fluid at the billet-die interface at the critical point of breakthrough.

(2) Elimination of a high P_b prevents the initiation of stick-slip during runout. This is partly because lubrication breakdown may occur during the arrest period of a stick-slip cycle due to excessive extrusion exit speeds that can occur during slip.

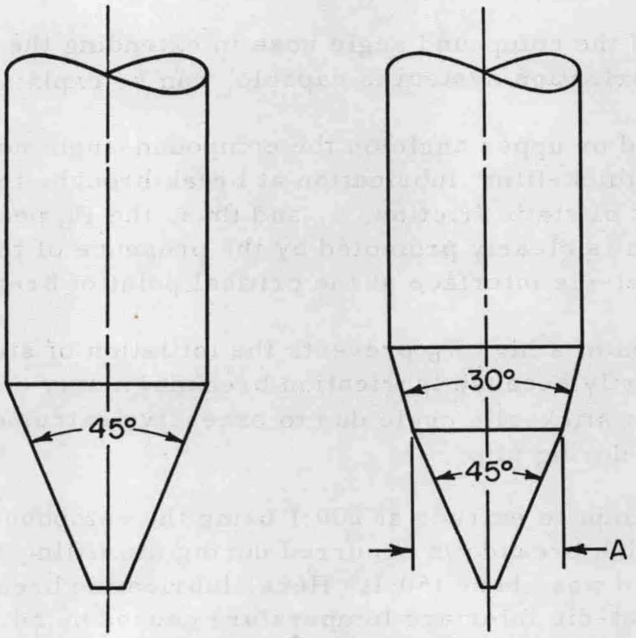
In a single attempt to extrude at 200:1 using the compound angle nose design (Trial 504), lubrication breakdown occurred during die filling at the point where the extrusion ratio achieved was about 150:1. Here, lubrication breakthrough was probably due to excessive billet-die interface temperature caused by adiabatic heating.

It is of interest to note that the compound-angle nose was evaluated in the previous program(1) on 1100-0 aluminum at a ratio of 10:1. No pressure reduction was obtained, however, because the lubrication system used was entirely adequate for the less severe extrusion conditions.

Stem Speed

Several trials were conducted at a stem speed of 80 ipm and a ratio of 20:1. Details are given in Table VII. Under these conditions the extrusion leaves the die at 250 ft/min which was the fastest exit speed accomplished in the program.

The pressure-displacement curve for each trial was characterized by a sharp breakthrough pressure peak indicating a stick-slip situation only at breakthrough followed by a smooth runout. Stick-slip during runout was prevented because the high stem speeds did not allow the billet to stop at the end of fluid decompression during slip after breakthrough, thus maintaining kinetic friction conditions. The breakthrough and runout pressure levels were approximately 150,000 psi and 130,000 psi respectively for each



a. Standard Nose b. Compound - Angle Nose

FIGURE 15. TWO BILLET NOSE DESIGNS EVALUATED IN HYDROSTATIC EXTRUSION