extrusion of AISI 4340 tubing. The extrusion data obtained with the modified mandrel are given in Table 5.

AISI 4340 steel tubing with excellent surface quality was extruded at reduction ratios of 2.58:1 and 3.77:1 (61 and 74 percent reduction in area, respectively). No tube sticking occurred on the mandrel during extrusion, indicating that the modified mandrel design was effective. Examples of tubing produced at the two extrusion ratios are shown in Figure 2.

An attempt (Trial 357) was made to extrude AISI 4340 tubing at the next highest extrusion ratio (7:1) as determined by the die sizes that were available. Prior to this, the highest ratio attempted and achieved with this material by hydrostatic means was 6:1 for extrusion of solid rounds. At 7:1, tubing was not extruded at a fluid pressure of about 250,000 psi, the point at which the trial was halted and the maximum design pressure of the container. A plot of pressure versus ln (extrusion ratio) for tubing indicates that the runout fluid pressure for a 7:1 ratio should be in the order of 230,000 psi. It appears that it will be possible, therefore, to extrude tubing at 7:1 with the present tooling provided the breakthrough fluid pressure can be lowered to 250,000 psi or less.

Some 7075-0 aluminum tubing was also extruded with the modified mandrel at ratios of 3.77, 7, and 12.2:1. The extent of stick-slip increased as the extrusion ratio was increased. Although a stem speed of 80 ipm eliminated stick-slip during runout in the extrusion of 7075-0 Al solid rounds at a ratio of 20:1, it apparently did not have the same effect with tubing, as seen from Trial 350.

Some transverse cracks were observed on the outer surface of the tubing extruded at ratios of 7 and 12.2:1. The location of the cracks along the tubing length suggests that they were associated with the periodicity of stick-slip. The cause of cracking may be due partly to inertial effects and partly to excessive surface temperatures developed during the slip portion of stick-slip.

## DIE DESIGN

Some effort is being directed toward die design with the aim of reducing extrusion pressures. One important variable that already has been studied in the current program is die angle[3, 4]. Another factor which may have an effect on pressure is the configuration of the entry surface apart from the entry angle itself. One concept that has been investigated is the idea of a grooved entry surface. The thought here is that the groove would be occupied by the hydrostatic fluid during extrusion, thereby reducing the amount of billet-die contact area. In this case, the die is "roughened" with a groove to function in a manner similar to a roughened billet which drags fluid in at the die-billet interface. The grooved die evaluated in the program is shown in Figure 3. The groove is about 0.050 inch deep and has a 1/4-inch pitch. The peaks between the grooves are rounded to a 1/8-inch radius. The groove does not intersect the die bearing surface but stops at about 1/4 inch above it.

TABLE 5. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION OF 4340 STEEL AND 7075 ALUMINUM TUBING

Die angle ------- 45 degrees
Fluid ------- Castor oil

Billet size ------- 1.750 OD x 0.750 ID
Mandrel ------- 0.7485 diameter at top
0.7395 diameter at bottom

| Die rifice, nches | Extrusion Ratio | Stem Speed, ipm | Billet Lubricant | Extrusion Pressure, 1000 psi | | | | Length of Extrusion, inches | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Breakthrough | | Runout | | | |
| | | | | Stem | Fluid | Stem | Fluid | | |
| | | | | 4340 Steel | | | | | |
| 1.237 | 2.58 | 6 | L17 | 112.0 | 109.5 | 105.0 | 105.0 | 7 3/4 | Slight $P_b$ peak; unifo Pr |
| 1.107 | 3.77 | 6 | L17 | 166.5 | 158.0 | 162.0 | 153.5 | 6 7/8 | Slight $P_b$ peak; mode stick-slip |
| 1.107 | 3.77 | 6 | L48 | 170.0 | 159.0 | 164.0 | 153.0 | 10 1/8 | Slight $P_b$ peak; unifo Pr |
| 1.107 | 3.77 | 20 | L48 | 169.0 | 158.5 | 165.0 | 153.0 | 11 | Slight $P_b$ peak; unifo Pr with slight pres increase toward er |
| 0.959 | 7.0 | 6 | L48 | 280.0 | 249.0 | -- | -- | 0 | $P_b$ not reached; stop at indicated pressu |
| | | | | 7075 Aluminum | | | | | |
| 1.107 | 3.77 | 20 | L17 | 49.5 | 49.5 | 48.0 | 48.5 | 12 3/4 | No $P_b$ peak; uniform |
| ).959 | 7.0 | 20 | L17 | 77.6 | 73.0 | 73.0 | 71.0 | 17 3/4 | Slight $P_b$ peak; mode stick-slip |
| ).875 | 12.2 | 80 | L17 | 112.0 | 105.5 | 96.0 | 97.0 | 27 3/4 | Slight $P_b$ peak; seve stick-slip |