A study of forming loads and metal flow characteristics during the backward extrusion of aluminium

This item was submitted to Loughborough University’s Institutional Repository by the/an author.

Additional Information:

- A Masters Dissertation, submitted in partial fulfilment of the requirements of the award of Master of Science of Loughborough University.

Metadata Record: https://dspace.lboro.ac.uk/2134/24714

Publisher: © Malcolm Francis Kimm

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
LONDOM

With my deepest gratitude,

14/1/77.
A STUDY OF FORMING LOADS AND METAL FLOW CHARACTERISTICS
DURING THE BACKWARD EXTRUSION OF ALUMINIUM

by


A Master's Thesis
Submitted in partial fulfilment of the requirements
for the award of
Degree of Master of Science of the Loughborough University of Technology

September 1976

Supervisor: G.F. Modlen, M.A., Ph.D., F.I.M.
Department of Engineering Production

© by Malcolm Francis Kimm, 1976
# CONTENTS

<table>
<thead>
<tr>
<th>LIST OF FIGURES</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF PLATES</td>
<td>3</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>4</td>
</tr>
<tr>
<td>SYNOPSIS</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>INTRODUCTION</th>
<th>7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Chapter 2</th>
<th>LITERATURE REVIEW</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Extrusion Tooling</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Friction and Lubrication</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>Can Extrusion</td>
<td>11</td>
</tr>
<tr>
<td>2.4</td>
<td>Viscoplasticity and Upper Bound Techniques</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>Metal Flow and Extrusion Defects</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 3</th>
<th>EXPERIMENTAL EQUIPMENT</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Extrusion Tool Design</td>
<td>15</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Basic Design Principles</td>
<td>15</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Indirect Extrusion</td>
<td>16</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Direct Extrusion</td>
<td>17</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Die Design</td>
<td>17</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Punch Design</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Compression Tool Design</td>
<td>20</td>
</tr>
<tr>
<td>3.3</td>
<td>Ancillary Equipment</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>EXPERIMENTAL TECHNIQUES</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Billet Preparation</td>
<td>27</td>
</tr>
<tr>
<td>4.2</td>
<td>Extrusion Techniques</td>
<td>27</td>
</tr>
<tr>
<td>4.3</td>
<td>Yield Strength Determination</td>
<td>27</td>
</tr>
</tbody>
</table>
## Chapter 5 FORMING LOADS

5.1 General
5.2 External Friction
5.3 Effect of Extrusion Ratio
5.4 Effect of Billet Length
5.5 Effect of Extrusion Direction
5.6 Conical Punch Extrusion
5.7 Nosed Punch Extrusion

### Page
31

## Chapter 6 METAL FLOW DURING EXTRUSION

6.1 General
6.2 Steady State Flow
6.3 Dead Metal Regions
6.4 Microstructures
6.5 Extrusion Direction
6.6 Incremental Forming
6.7 Flow with Conical Punches
6.8 Flow with Nosed Punches

### Page
50

## Chapter 7 UPPER BOUND SOLUTIONS TO BACKWARD EXTRUSION

7.1 The Upper Bound Technique
7.2 The Early Stage of Extrusion
7.3 Use of a Nosed Ram for Extrusion
7.4 Extrusion at the End of the Stroke

### Page
68

## Chapter 8 EXTRUSION DEFECTS

8.1 General
8.2 Cavitation
8.3 Internal Cracking
8.4 Shearing

### Page
76

## Chapter 9 CONCLUSIONS

9.1 Forming Loads
9.2 Metal Flow
9.3 Extrusion Defects
9.4 Practical Implications

### Page
83

## Chapter 10 RECOMMENDATIONS FOR FURTHER WORK

### Page
86
REFERENCES

APPENDIX (1) DIE STRESS CALCULATIONS

(2) EXTRUSION AND COMPRESSION TOOL DESIGN DETAILS AND HEAT TREATMENTS

(3) AVITZURS UPPER BOUND SOLUTION

(4) TABULATED DATA
## List of Figures

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Page No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>21</td>
<td>Sectional Diagram of Extrusion Tool</td>
</tr>
<tr>
<td>3.2</td>
<td>22</td>
<td>Schematic Representation of Direct and Indirect Extrusion</td>
</tr>
<tr>
<td>3.3</td>
<td>19</td>
<td>Extrusion Edge</td>
</tr>
<tr>
<td>3.4</td>
<td>23</td>
<td>Simple Compression Tool</td>
</tr>
<tr>
<td>4.1</td>
<td>29</td>
<td>Compression Test Curve</td>
</tr>
<tr>
<td>4.2</td>
<td>30</td>
<td>True Stress/True Strain Curve for 99% Pure Aluminium</td>
</tr>
<tr>
<td>5.1</td>
<td>36</td>
<td>Extrusion Pressure Displacement Characteristics for Various Lubricants</td>
</tr>
<tr>
<td>5.2</td>
<td>37</td>
<td>Comparison Between Continuous and Incremental Forming Loads</td>
</tr>
<tr>
<td>5.3</td>
<td>38</td>
<td>Punch Load/Displacement Curves For Indirect Extrusion of Billets of H:D=1</td>
</tr>
<tr>
<td>5.4</td>
<td>39</td>
<td>Effect of Reduction on Maximum Extrusion Pressure</td>
</tr>
<tr>
<td>5.5</td>
<td>40</td>
<td>Effect of Reduction on Punch Stress</td>
</tr>
<tr>
<td>5.6</td>
<td>41</td>
<td>Steady Pressure Extrusion Efficiency Assuming Homogeneous Deformation</td>
</tr>
<tr>
<td>5.7</td>
<td>42</td>
<td>Effect of Billet Length on Extrusion Pressure</td>
</tr>
<tr>
<td>5.8</td>
<td>43</td>
<td>Effect of Billet Length on Maximum Punch Load</td>
</tr>
<tr>
<td>5.9</td>
<td>43</td>
<td>Effect of Billet Length on Maximum Ejection Load</td>
</tr>
<tr>
<td>5.10</td>
<td>44</td>
<td>Differing Extrusion Characteristics with Direction</td>
</tr>
<tr>
<td>5.11</td>
<td>45</td>
<td>Differing Extrusion Characteristics with Direction</td>
</tr>
<tr>
<td>5.12</td>
<td>46</td>
<td>Punch Loads for Partial Extrusion, 12.7mm Indentation</td>
</tr>
<tr>
<td>5.13</td>
<td>47</td>
<td>Punch Load/Displacement Characteristics for Various Punch Angles</td>
</tr>
<tr>
<td>5.14</td>
<td>48</td>
<td>Effect of Punch Angle on Maximum Extrusion Pressure for Direct and Indirect Extrusions</td>
</tr>
<tr>
<td>5.15</td>
<td>49</td>
<td>Effect of Nose Profile on Maximum Extrusion Load</td>
</tr>
<tr>
<td>6.1</td>
<td>50</td>
<td>Metal Flow Regions</td>
</tr>
<tr>
<td>6.2</td>
<td>56</td>
<td>Displacement Vector Diagram Illustrating Metal Flow During Extrusion Using a Flat Punch</td>
</tr>
<tr>
<td>7.1</td>
<td>69</td>
<td>Avitzur's Representation of the Early Stage of Impact Extrusion</td>
</tr>
<tr>
<td>Fig No.</td>
<td>Title</td>
<td>Page No.</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>7.2</td>
<td>Effect of Reduction on Dead Zone Angle With Flat Ram</td>
<td>72</td>
</tr>
<tr>
<td>7.3</td>
<td>Upper Bound Ram Pressures for Extrusion With Flat Ram</td>
<td>73</td>
</tr>
<tr>
<td>7.4</td>
<td>Comparison Between Upper Bound Extrusion Loads for Flat and Nosed Rams</td>
<td>74</td>
</tr>
<tr>
<td>7.5</td>
<td>2 Zone Representation of sound Flow During the Final Stage of Impact Extrusion</td>
<td>70</td>
</tr>
<tr>
<td>7.6</td>
<td>Upper Bound Solution for Minimum Slug Thickness to Prevent Cavitation Versus Reduction and Friction</td>
<td>75</td>
</tr>
<tr>
<td>7.7</td>
<td>Critical Slug Thickness for Prevention of Cavitation</td>
<td>71</td>
</tr>
<tr>
<td>8.1</td>
<td>Sketches Showing Extrusion Defect Formations</td>
<td>79</td>
</tr>
</tbody>
</table>
## LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Title</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Extrusion Tool</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>Extrusion Punches and Punch Ends</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Compression Tool</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Sawing Jig</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Turning Fixture</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Extrusion With Flat Punch, $R=1.33$</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Selection of Sectioned Cups</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Extrusion With Flat Punch, etched, $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>Dead Metal Region, etched, $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>Extrusion With Flat Punch, etched, $RR=1.56$</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>Dead Metal Region, etched, $R=1.56$</td>
<td></td>
</tr>
<tr>
<td>6.7</td>
<td>Slip Bands in Tube Wall $\times 100$</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>&quot; &quot; &quot; &quot; &quot; $\times 400$.</td>
<td></td>
</tr>
<tr>
<td>6.9</td>
<td>Collapse of Dead Metal Regions</td>
<td></td>
</tr>
<tr>
<td>6.10</td>
<td>Incremental Forming $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.11</td>
<td>&quot; &quot; $R=1.33$</td>
<td></td>
</tr>
<tr>
<td>6.12</td>
<td>&quot; &quot; $R=1.56$</td>
<td></td>
</tr>
<tr>
<td>6.13</td>
<td>&quot; &quot; $R=1.96$</td>
<td></td>
</tr>
<tr>
<td>6.14</td>
<td>Split Sections with Conical Punches, etched $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.15</td>
<td>Extrusion with Conical Punch, $\theta=90^\circ$, $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.16</td>
<td>&quot; &quot; &quot; $\theta=30^\circ$, $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>6.17</td>
<td>&quot; &quot; &quot; $\theta=90^\circ$, $R=1.56$</td>
<td></td>
</tr>
<tr>
<td>6.18</td>
<td>Comparison Between Billets Formed with Flat and Nosed Rams, $R=1.56$</td>
<td></td>
</tr>
<tr>
<td>6.19</td>
<td>Comparison Between Billets Formed with Flat and Nosed Rams, $R=1.33$</td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Split Billet Showing Cavitation, $R=1.33$</td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>&quot; &quot; &quot; &quot; etched, $R=1.19$</td>
<td></td>
</tr>
<tr>
<td>8.3</td>
<td>Specimens Showing Internal Cracking</td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>Example of Internal Cracking, $R=1.96$</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>&quot; &quot; &quot; &quot; $R=2.78$</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF TABLES
(Appendix 4)

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compression test data</td>
</tr>
<tr>
<td>2</td>
<td>Re-lubricated compression test data</td>
</tr>
<tr>
<td>3</td>
<td>Data for indirect flat punch extrusion</td>
</tr>
<tr>
<td>4</td>
<td>&quot; &quot; direct &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>5</td>
<td>Homogeneous deformation punch loads</td>
</tr>
<tr>
<td>6</td>
<td>Loads for 12.7mm punch travel</td>
</tr>
<tr>
<td>7</td>
<td>Effect of punch angle on extrusion load</td>
</tr>
<tr>
<td>8</td>
<td>Effect of billet length on punch and ejection loads</td>
</tr>
<tr>
<td>9</td>
<td>Effect of reduction on dead zone angle with flat punch</td>
</tr>
<tr>
<td>10</td>
<td>Extrusion with nosed profiles</td>
</tr>
<tr>
<td>11</td>
<td>Upper bound ram pressures for extrusion with flat ram</td>
</tr>
<tr>
<td>12</td>
<td>&quot; &quot; &quot; &quot; &quot; &quot; &quot; nosed &quot;</td>
</tr>
<tr>
<td>13</td>
<td>&quot; &quot; &quot; solution for prevention of cavitation</td>
</tr>
</tbody>
</table>
categories, namely cavitation, internal cracking and shearing of the corner. Cavitation was found to occur when the base thickness becomes smaller than the wall thickness, which was also proved theoretically. Also cracking was found to occur only at large extrusion ratios during direct extrusion.

Finally, in the light of conclusions drawn from the work, recommendations were made as to suggestions for further work which could usefully continue the present work.
# Nomenclature

### Chapters 1-6

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Deflection</td>
</tr>
<tr>
<td>( \omega )</td>
<td>End load</td>
</tr>
<tr>
<td>( L )</td>
<td>Length</td>
</tr>
<tr>
<td>( E )</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>( I )</td>
<td>Second moment of area</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Friction coefficient</td>
</tr>
<tr>
<td>( R )</td>
<td>Extrusion ratio</td>
</tr>
<tr>
<td>( H )</td>
<td>Billet height</td>
</tr>
<tr>
<td>( D )</td>
<td>Billet diameter</td>
</tr>
<tr>
<td>( V_p )</td>
<td>Punch velocity</td>
</tr>
<tr>
<td>( V_e )</td>
<td>Extrudate velocity</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Longitudinal strain</td>
</tr>
<tr>
<td>( r )</td>
<td>Relieved punch radius</td>
</tr>
<tr>
<td>( R )</td>
<td>Full punch end radius</td>
</tr>
<tr>
<td>( L )</td>
<td>Land length on punch end</td>
</tr>
<tr>
<td>( V_d )</td>
<td>Die velocity</td>
</tr>
<tr>
<td>( \ln )</td>
<td>Naperian logarithm</td>
</tr>
<tr>
<td>( h_o )</td>
<td>Billet height</td>
</tr>
<tr>
<td>( h )</td>
<td>Current billet height</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>Yield strength in uniaxial tension</td>
</tr>
<tr>
<td>( m )</td>
<td>Friction factor</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Punch angle</td>
</tr>
<tr>
<td>( \theta' )</td>
<td>Transition angle</td>
</tr>
<tr>
<td>( V )</td>
<td>Velocity of metal flow</td>
</tr>
<tr>
<td>( E )</td>
<td>Longitudinal strain</td>
</tr>
<tr>
<td>( d )</td>
<td>Punch diameter</td>
</tr>
<tr>
<td>( V_p )</td>
<td>Punch velocity</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Dead zone angle</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>Radius of dead zone IV</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>Radius of zone II</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Ram radius</td>
</tr>
<tr>
<td>( R_o )</td>
<td>Chamber radius</td>
</tr>
<tr>
<td>( V )</td>
<td>Velocity</td>
</tr>
<tr>
<td>( V_f )</td>
<td>Extrudate velocity</td>
</tr>
<tr>
<td>( h )</td>
<td>Land length</td>
</tr>
<tr>
<td>( D )</td>
<td>Depth of punch from top of die cavity</td>
</tr>
<tr>
<td>( T )</td>
<td>Can base thickness</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Angle of base-wall intersection</td>
</tr>
<tr>
<td>( M )</td>
<td>Friction factor</td>
</tr>
<tr>
<td>( h )</td>
<td>Height of ram</td>
</tr>
<tr>
<td>( P )</td>
<td>External pressure on extrudate</td>
</tr>
<tr>
<td>( P_{\text{R}} )</td>
<td>Average ram pressure</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>Yield strength in uniaxial tension</td>
</tr>
<tr>
<td>( P )</td>
<td>Extrusion pressure</td>
</tr>
<tr>
<td>( \bar{Y} )</td>
<td>Mean yield strength</td>
</tr>
<tr>
<td>( R )</td>
<td>Extrusion ratio</td>
</tr>
<tr>
<td>( P_{\text{MAX}} )</td>
<td>Max. extrusion pressure</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>Outer radius of outer cylinder</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>Inner radius of inner cylinder</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>Common cylinder radius</td>
</tr>
<tr>
<td>( \sigma_r )</td>
<td>Radial stress</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>Hoop stress</td>
</tr>
<tr>
<td>( b )</td>
<td>Constant</td>
</tr>
<tr>
<td>( a )</td>
<td>Constant</td>
</tr>
<tr>
<td>( r )</td>
<td>Cylinder radius</td>
</tr>
<tr>
<td>( c )</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>( Y )</td>
<td>Yield strength</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Shear stress</td>
</tr>
<tr>
<td>( P )</td>
<td>Internal pressure</td>
</tr>
<tr>
<td>( P_{\text{R}} )</td>
<td>Average ram pressure</td>
</tr>
</tbody>
</table>

### Chapter 7 and Appendix III

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{U} )</td>
<td>Punch velocity</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Dead zone angle</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>Radius of dead zone IV</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>Radius of zone II</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Ram radius</td>
</tr>
<tr>
<td>( R_o )</td>
<td>Chamber radius</td>
</tr>
<tr>
<td>( V )</td>
<td>Velocity</td>
</tr>
<tr>
<td>( V_f )</td>
<td>Extrudate velocity</td>
</tr>
<tr>
<td>( h )</td>
<td>Land length</td>
</tr>
<tr>
<td>( D )</td>
<td>Depth of punch from top of die cavity</td>
</tr>
<tr>
<td>( T )</td>
<td>Can base thickness</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Angle of base-wall intersection</td>
</tr>
<tr>
<td>( M )</td>
<td>Friction factor</td>
</tr>
<tr>
<td>( h )</td>
<td>Height of ram</td>
</tr>
<tr>
<td>( P )</td>
<td>External pressure on extrudate</td>
</tr>
<tr>
<td>( PR )</td>
<td>Average ram pressure</td>
</tr>
</tbody>
</table>

\( \sigma_0 \) - Yield strength in uniaxial tension
\( P \) - Extrusion pressure
\( \bar{Y} \) - Mean yield strength
\( R \) - Extrusion ratio
\( P_{\text{MAX}} \) - Max. extrusion pressure
\( R_1 \) - Outer radius of outer cylinder
\( R_2 \) - Inner radius of inner cylinder
\( R_3 \) - Common cylinder radius
\( \sigma_r \) - Radial stress
\( \sigma_0 \) - Hoop stress
\( b \) - Constant
\( a \) - Constant
\( r \) - Cylinder radius
\( c \) - Modulus of elasticity
\( Y \) - Yield strength
\( \tau \) - Shear stress
\( P \) - Internal pressure
SYNOPSIS

Backward extrusion is a popular industrial technique for the manufacture of tube and cans. This report serves to examine the forming loads, metal flow and extrusion defects arising during the backward extrusion of aluminium cups.

The report surveys the literature of extrusion with particular interest in backward extrusion. Extrusion was carried out with the aid of a specially constructed 50mm backward extrusion tool designed and manufactured by the author. Five extrusion ratios were examined, using both the direct and indirect extrusion directions and flat, conical and nosed punch ends were used to examine metal flow and forming loads for various punch profiles.

Forming loads were found to be much greater for direct extrusion and the usual relationship was derived for load/extrusion ratio characteristics. The effects of friction and lubrication were examined and these effects on load and flow patterns were noted.

Incremental forming of split billets with grids scribed on the mid-plane was carried out for a variety of punch profiles. This revealed the evidence of a dead metal region forming an arc below the end of flat punches. The geometry of dead metal regions was compared with that derived by an upper bound technique and found to agree well. Also upper bound loads using this model were derived and found to compare favourably.

Forming using conical punch profiles showed that the adoption of a smooth profile similar in geometry to the dead metal zone reduced extrusion loads significantly.

Extrusion defects were examined and found to fall into three
Chapter 1

Introduction
The aim of this thesis is to further the fundamental understanding of deformation mechanics, as applied to backward extrusion, by examining forming loads during deformation under a variety of conditions and more importantly to examine metal flow and defect formation during the process. Deformation mechanics has reached an advanced stage in the analysis of forward extrusion, and features prominently in deformation mechanics literature. Forward extrusion is probably more easy to analyse because of its more continuous nature. This continuity is often essential as far as many analytical techniques are concerned, and many analytical solutions are based upon the steady state region of the process. Steady states are easily achieved in forward extrusion but their existence in the more restricted backward extrusion process is very short-lived, if present at all. The present work examines the extent of the steady state during the process, which is highly dependant upon such factors as the punch height/diameter ratio and billet length to be extruded. Punch lengths are obviously limited due to the possibility of failure by buckling, this limits the duration of the process to relatively short times.

An extrusion tool was specially designed and constructed to carry out the present work, having a die diameter of 50mm and a maximum pressure capacity of 1000 N/mm². Five extrusion ratios were produced with punches varying from 20 to 40mm dia. in 5mm steps. The tool was found to perform most satisfactorily in both direct and indirect directions, enabling the differences between the processes to be observed in terms of load, metal flow and defect formation. A compression tool was also designed to establish the yield strength of the material. The experimental material used was annealed 99% pure aluminium, although the die was designed to cater for higher strength materials in consideration of possible further work.
By studying and comparing forming loads much can be gained in terms of understanding how deformation progresses and how friction contributes towards the process. Considerable differences in friction conditions between direct and indirect extrusion exist, the results of which were examined. These differences produce differing influences upon defect formation which are likely to be different for each method of extrusion.

A critical examination of metal flow during extrusion was possible by using split billets scribed with a square grid on the mid plane. This enabled much information to be drawn about the way in which deformation is progressing at various stages of the process. Photographs were taken in increments of the forming operation, this enabled a history of the deformation to be obtained. The existence of dead metal regions was critically examined. Such regions influence the state of metal flow and also the setting up of a steady state situation.

A study of metal flow inevitably involves an examination of extrusion defects. Defects are usually to be avoided and this can often be accomplished if their cause is fully understood. The causes of such defects were examined and methods of eliminating or reducing defects suggested. The two most prominent defects in backward extrusion are cavitation and internal cracking, and attention was mainly given to these in the general examination of extrusion defects. These defects are similar to those found in forward extrusion where piping is exhibited in place of cavitation.

Various upper bound techniques exist for the analysis of extrusion problems. Slip line fields are the most popular techniques but are mainly restricted to plain strain situations. Visioplasticity and flow function analysis have been successfully applied to forward extrusion, but is reliant upon the existence of a steady state
situation; the approach yields the complete solution in terms of strain rates, strains and stresses. It is hoped that the present work will serve as a feasibility study for the possibility of applying such a technique to backward extrusion. The upper bound solution proposed by Avitzur (1) was used to analyse the process. This solution splits the body into a number of deformation zones, the boundaries of which were found to be accurately predicted. The model was used to establish upper bound loads and also to predict the onset of defect formation.

Finally in the light of conclusions drawn from the work, recommendations were made for possible further work which could usefully continue the present study.
CHAPTER 2

LITERATURE REVIEW
2.1 EXTRUSION TOOLING

The design of extrusion tooling and choice and heat treatment of tool materials is of fundamental importance to any study in extrusion. The extrusion process subjects tooling to very high pressures and particular care is needed to ensure efficient and long life tooling. Extrusion punches in backward extrusion are of particular importance in this respect as they are subjected to particularly high pressures.

A variety of suitable tool materials exist for application to extrusion tooling. Everhart\(^{(2)}\) suggests that a survey of extrusion of aluminium and aluminium alloys indicates the use of 12% chromium steels favoured both for punches and die, he also outlines a number of different alloys proposed by other workers. A number of guides to the selection of tool steels for extrusion are in publication\(^{(3)}\) and the use of carbide tools are also surveyed\(^{(4)}\).

Heat treatment of extrusion tooling steels is of great importance if reliable results are to be attained. A survey of suitable treatments is outlined in a P.E.R.A. report\(^{(5)}\) in which a variety of tool steels and treatments for extrusion punches are examined.

A variety of designs exist for both dies and punches. Punch failure due to change of punch section is common along with other defects\(^{(6)}\). Morgan\(^{(7)}\) has conducted a thorough investigation into punch profiles and their effect on resulting internal stress concentration using photoelastic stress analysis; here the use of non-composite punches is recommended. A variety of punch profiles and die base profiles are examined in a P.E.R.A. report\(^{(8)}\) on the effects of tool geometry on backward extrusion. A hemispherical punch end profile is found to produce a considerably lower punch load than a flat punch. Concerning punch relief, a survey by Everhart\(^{(9)}\) reveals how punch end
geometry affects extrusion load and performance for a variety of experimental materials; a diametral clearance of 0.004 inch is recommended for aluminium by a number of workers as being the optimum value.

Concerning die design, this is relatively straightforward in backward extrusion as the profile is relatively simple. Compound rings of tool steel are usually adapted to cope with the high stresses. Literature on die design is usually found to apply to forward extrusion, but some more general papers exist\(^{(10)}\). Die design in forward extrusion has reached a sophisticated level with a number of theoretical design techniques in existence\(^{(11,12)}\). Shabaik’s paper\(^{(12)}\) uses the results of visioplasticity analysis of forward extrusion to examine die performance under a variety of friction conditions.

2.2 **FRICITION AND LUBRICATION**

Friction and lubrication are important factors in any type of extrusion. An excellent publication by Schey\(^{(13)}\) looks at all aspects of friction and lubrication as applied to deformation processes in general. A wider variety of lubricants are recommended by a number of workers, although lanoline, tallow and waxes seem to produce best results with aluminium. The use of lanoline with aluminium is reputed to give a friction coefficient of \(\mu = 0.02\).

Watkins\(^{(10)}\) used sulphonated tallow but found it inefficient at slow speeds. Lanolin, tallow, various soaps, and graphite in tallow were found to give better performance in terms of maximum extrusion pressure.

2.3 **CAN EXTRUSION**

Much more attention is given to forward extrusion than backward
extrusion and relatively few papers are to be found on detailed experiments in backward extrusion. Many reports on backward extrusion relate to extrusion of steels but a number do deal with aluminium extrusion.

A.P.E.R.A. report\(^{(8)}\) deals with the effect of punch and die geometry on backward extrusion. The report examines 11 different punch profiles and their effect on metal flow and extrusion load. Five different die base profiles are also examined. Another paper concerned with backward extrusion of steel is by Watkins\(^{(14)}\). This paper examines a variety of combinations of forward and backward extrusions, and the differences in terms of pressure characteristics between the different types of extrusion.

The effect of ram speed in the extrusion of lead and aluminium is examined by Ashcroft\(^{(15)}\). The effect of billet length, diameter ratio and base/wall thickness ratio is examined in detail by Cruden\(^{(16)}\). This report examines in detail the aforementioned topics. In conclusion, the report finds that the final base/wall thickness ratio profoundly influences the extrusion pressure, particularly in operations at the longer extrusion ratios (R>2.0), when pressures greater than those normally defined as the maximum pressures may be attained, if base/wall thickness ratios less than 0.5 are attempted. The onset of cavitation is also examined.

Extrusion pressures are predicted for backward extrusion within a very practical paper by Kaspar\(^{(17)}\), in which a range of extrusion ratios between 1.28 and 2.72 are examined.

A very thorough historical survey of extrusion techniques has been published by Pearson\(^{(18)}\). This book also introduces many other aspects concerning extrusion techniques and characteristics.
2.4 VISIOPLASTICITY AND UPPER BOUND TECHNIQUES

Among a variety of upper bound techniques in existence for the solution of extrusion problems visioplasticity has developed as one of the more recent and most successful technique. Here, the billet is scribed with a grid on the mid-plane so that flow lines during steady state flow can be monitored. These are used to set up a mathematical model constructed along the existing flow lines which eventually reveals the complete solution in terms of stress and strain fields and their distributions. The founders of the technique in its present form, Shabaik and Thomsen have produced a number of papers in which the technique is applied to forward extrusion through conical dies. The technique is outlined in detail in two papers by Lambert and Kobayashi \(^{19,20}\) and computer application to the technique is outlined by Shabaik \(^{21,22}\). A further paper by Shabaik \(^{23}\) pays particular attention to friction coefficients during the extrusion of aluminium. Another paper by Medrano and Gillis \(^{24}\) outlines the technique in a slightly different manner. A paper by Farag \(^{25}\) illustrates the solutions in terms of plots of stress, strain and temperature profiles within the billet.

The only application of visioplasticity to backward extrusion is by Mehta \(^{26}\). This thesis examines backward extrusion using conical punches. The results are interesting but the data is not smoothed and therefore does not allow easy comparison with the present work.

Apart from visioplasticity a number of techniques exist for solution of extrusion problems by the upper bound technique. Kudo's \(^{27}\) technique of defining velocity fields by splitting the body into zones is well known. This technique is enlarged and applied to extrusion by Kobayashi \(^{28,29}\). Avitzur's technique \(^{30,31}\) is critically examined in this thesis and is similar to the Kudo's technique of analysis.
Other techniques of analysis are outlined by Thomsen et al.\textsuperscript{(32)} and a survey of slip line fields is produced by Johnson\textsuperscript{(33)} although this is restricted to plane strain deformation.

2.5 METAL FLOW AND EXTRUSION DEFECTS

The study of metal flow and extrusion defects forms a major part of this thesis. Metal flow is analysed by examining the deformation of scribed grids on the mid-plane of the billet. This is a commonly used method of analysing forward extrusion but it has been scarcely used as a tool for the analysis of backward extrusion and no literature was found which analysed flow during backward extrusion in detail.

The P.E.R.A. and N.E.L. reports previously mentioned deal with extrusion defects as a part of a general survey of backward extrusion. The study of metal flow in these reports is restricted to the examination of etched specimens which is a limited technique.
CHAPTER 3

EXPERIMENTAL EQUIPMENT
The basic requirement for the present work was a backward extrusion tool capable of extruding aluminium slugs of reasonably large size, so as to enable flow patterns, and extrusion defects, to be readily observed. It was also necessary to provide a compression tool to determine the yield strength characteristics of the material being extruded.

Both extrusion and compression tools were designed and manufactured by the author.

3.1 EXTRUSION TOOL DESIGN

The design and manufacture of a suitable extrusion tool formed a large part of the present work. During extrusion the tools are subjected to extremely high pressures; so that the choice of tool materials and their heat treatments, together with dimensional accuracy (in terms of tolerances and alignment) are critical factors.

A 3MN Denison Compression Testing Machine was used for the extrusion experiments. As this machine does not provide an ejection system, the tool had to be designed so that both extrusion and ejection could be achieved via the compression stroke.

The tool was designed to extrude billets of various lengths (with H:D ratios of up to 1.75:1) both by the direct and indirect methods, enabling the differences between the two methods in terms of extrusion loads, metal flow, and extrusion defects to be observed.

A photograph of the tool is shown in plate 3.1.

3.1.1 Basic Design Principle

The tool was designed with a die bore of 50mm diameter and five punches of 20, 25, 30, 35 and 40mm diameter, giving extrusion ratios of 1.19, 1.33, 1.56, 1.96 and 2.78 respectively.

*Plates and Figures at the end of each Chapter.
With reference to the sectional diagram, (Fig. 3.1) the die and punch assembly were mounted in a bolster to maintain accurate alignment. The die was designed in the form of a compound cylinder (8,9)* mounted within a die housing (10). The die assembly was aligned with the lower punch (13) by two pillars (17), and was supported on springs to enable the support (16) to be easily removed. During indirect extrusion the die assembly is securely clamped against the support, which is removed for ejection. The die insert (12), enables the die depth to be varied, and pressure pads (2.14) serve to distribute the high pressures from the upper and lower punches.

3.1.2 Indirect Extrusion

Fig. 3.2 illustrates the fundamental differences between direct and indirect extrusion. In indirect extrusion the die is rigidly held against the support, and the punch advances into the billet with velocity \( V_p \). The emerging product flows in the opposite direction to the punch with velocity \( V_e \), which is obviously dependent on the punch velocity and extrusion ratio as \( V_e = V_p (1-R) \).

To eject the extrudate the support is removed, and a spacer placed on top of the die, so that compression causes the die to lower until the extrudate is effectively pushed out of the die.

Depending upon the depth of punch indentation and extrusion ratio, the punch sometimes sticks in the die prior to ejection; in which case the punch is detached from the bolster prior to ejection, and the punch and extrudate are ejected together.

*Figures in brackets refer to details in Fig. 3.1.*
3.1.3 Direct Extrusion

For direct extrusion, Fig. 3.2, the support is removed and a spacer placed between the top of the die and the bolster. The spring loaded die is moved with the same velocity as the punch $V_p$, relative to the stationary lower punch. This is effectively the same as keeping the die and punch stationary, and performing the operation by advancing the lower punch, as is common in forward extrusion of rods.

Ejection is achieved in a similar manner as indirect extrusion. Unless otherwise stated, all extrusions were performed by the indirect method.

3.1.4 Die Design

As previously stated, the stresses arising in extrusion tools are usually very large, the die in particular is often subjected to pressures which can exceed the strength of the die material; this can however be overcome as will be discussed.

For the purpose of calculating die stresses, the extrusion pressure is assumed to be distributed hydrostatically, so that the extrusion pressure produces an equivalent radial compressive force in the die. This force results in the setting up of hoop stresses, the greatest stress occurring at the die bore, thus establishing a criterion for maximum permissible die pressure. If the die is considered to be a thick cylinder Lamé's equations allow these stresses to be calculated.

Where the maximum hoop stresses exceed the strength of the die material, the die can be constructed in the form of compound rings. The outer ring puts the inner one in compression, thus lowering the hoop stress to an acceptable level; the outer ring is obviously in
tension, but as the hoop stress reduces with increasing diameter, the outer ring may also assume an acceptable level of maximum stress.

The level of interference between compound rings, the number of rings and their diameters and materials all influence the distribution of die stresses, which must lie within safe working limits.

For the present work a compound die consisting of two rings was designed to withstand a maximum die pressure of 1000 N/mm$^2$; this pressure being estimated as suitable for the extrusion of materials with mean yield strengths of up to 460 N/mm$^2$, thus allowing for the extrusion of hard aluminium alloys in consideration of further work.

The complete die stress calculations are given in Appendix (1), the maximum shear stress criterion being used to establish safe working stresses. The die was constructed of two rings, the inner one of die steel and the outer one of EN25. The interference fit of 0.48mm on a 110mm diameter was accomplished thermally by fitting the outer ring immediately after withdrawal from the annealing furnace. The inner ring was also cooled to provide a larger safety margin.

After fitting the two rings the die surfaces were re-ground and the die bore ground and honed to ensure accuracy of alignment. A surface finish of 0.1 μ/mm was achieved at the die bore.

3.1.5 Punch Design

Extrusion punches impose limitations upon the length of products which can be extruded, as the length/diameter ratio of punches reaches a limiting value due to failure by buckling under high compressive loads. Howard$^{(34)}$ suggests a length/diameter ratio of 5.7 to 1 for aluminium and soft aluminium alloys. In the present work, punches were designed with a maximum H:D ratio of 3.3:1.
Punch shape and construction influence the distribution and concentration of stresses. An extensive study of the stress distribution in punches of varying shapes has been conducted by Morgan (7), using photoelastic stress analysis. This would strongly oppose the use of compound punches with shrunken heads, which would at first sight appear to be an economical way of locating various sizes of punches. Punches used in the present work were constructed from one piece, with large blending shoulder radii, and were found to perform quite satisfactorily.

When extruding steel, punch stresses reach the limiting capacity of the tool materials. As stresses encountered when extruding aluminium are not so high it was possible to produce punches with differing end adaptors having different profiles. This enabled studies to be made using flat, conical and nosed ends to be made without the necessity for a large number of individual punches. The main body of the punch was made from die steel and the ends, which are subjected to more arduous conditions, from high speed steel.

The relief of punches by the provision of a land or extrusion edge (L, Fig. 3.3) has a marked effect upon extrusion pressure. This is due to a reduction in friction between the punch and emerging product. Van Zeelander and Van Berg (35) have compared the effect of punch relief on aluminium and various aluminium alloys; their results indicate that a reduction of approximately 50% in extrusion pressure could be achieved by adopting punch relief.

FIG 3.3: EXTRUSION EDGE
The extent of punch relief is usually of the order of 0,1 mm on diameter, and this was used for all punches.

The extrusion punches together with a selection of punch ends are shown in plate 3.2.

Complete detail drawings for the extrusion tool, together with heat treatments are to be found in Appendix II.

3.2 COMPRESSION TOOL DESIGN

Extrusion pressure is often normalized by taking into account the yield strength of the material being extruded. Yield strength is also required in upper bound calculations of extrusion pressure. A true stress true strain curve relates yield strength for various strains, and these data are readily obtained from a simple compression test.

The simple compression tool designed and manufactured for these tests is illustrated in Fig. 3.4 and plate 3.3. It consists simply of two anvils, the lower one fixed and the upper one attached to a punch whereby pressure is applied. Both anvils were lapped to a surface finish of 0,1 \( \mu \)m to minimise frictional effects. An alignment pad is allowed to float and thus take up any mis-alignment in the press, ensuring parallel faces between the anvils.

Complete detail drawings of the compression tool, together with heat treatments are to be found in Appendix II.

3.3 ANCILLARY EQUIPMENT

To assist in the manufacture of the extrusion billets as will be described in Chapter 4, it was necessary to manufacture two tooling aids; a sawing jig and turning fixture, these are illustrated in plates 3.4 and 3.5.
FIG 3.1 SECTIONAL DIAGRAM OF THE EXTRUSION TOOL

Scale: Approx. $\frac{1}{3}$ full size.
FIG 3.2 (A) SCHEMATIC REPRESENTATION OF INDIRECT EXTRUSION

FIG 3.2 (B) SCHEMATIC REPRESENTATION OF DIRECT EXTRUSION

FIG 3.2 (C) PRESSURE/ DISPLACEMENT CHARACTERISTICS FOR DIRECT(—) AND INDIRECT(----) EXTRUSION
FIG 3.4 SIMPLE COMPRESSION TOOL SHOWN IN HALF SECTION

Scale: Approx $\frac{2}{3}$ full size.
PLATE 3.1: EXTRUSION TOOL

PLATE 3.2: EXTRUSION PUNCHES & PUNCH ENDS
PLATE 3.3: COMPRESSION TOOL
PLATE 3.4: SAWING JIG

PLATE 3.5: TURNING FIXTURE
CHAPTER 4

EXPERIMENTAL TECHNIQUES
4.1 BILLET PREPARATION

The material used for experimental tests was 99% pure aluminium, BS 1476 EICM, which was supplied with a diameter of \(2\frac{1}{4}\)". Prior to use, the material was annealed at \(360^\circ\)C \(\times\) 1 hr., with a resulting hardness of 63 HV.

As a large number of split billets were required, their manufacture was accomplished with the aid of two tooling aids. The supplied bar was firstly turned to fit a sawing jig (plate 4.1) in which each billet was split across the diameter. After machining each face, these halves were then re-turned in a turning fixture (plate 4.2) to the correct diameter. A diametral clearance of 0.13 was left between the diameter of the billet and die bore to allow for lubrication coating.

Where split billets were to be used, a 2.5mm square grid of parallel lines was scribed on one half of the billet, thus allowing flow patterns to be observed.

All billets were lubricated with a solution of Abryl wax immersed in trichlorethylene, which left a thin coating of wax lubricant on the billet surface.

4.2 EXTRUSION TECHNIQUES

The extrusion tool was found to perform admirably and a number of tests were completed using a variety of punch profiles by both the direct and indirect methods. Various heights of billet were used and split as well as full billets were used. In all extrusions the speed of extrusion was approximately 1mm/sec (punch advance).

4.3 YIELD STRENGTH DETERMINATION

To determine the yield strength of a material a compression test
is usually carried out as this allows for much greater deformation than in a simple tensile test.

A significant error can arise during such tests by the introduction of friction between the slug being tested and the anvils of the compression tool. This can lead to an increased load for a given amount of deformation. The frictional effect can be reduced by efficient lubrication which can be repeatedly applied between loads in an incremental test. In some tests, a height to diameter ratio of 1 is maintained by re-machining after increments of compression, this reduces the 'barreling' effect and maintains a bi-axial stress state.

In the present work the specimens were re-lubricated at intervals which produced satisfactory results. The same wax lubricant as for extrusion was used, although several tests were made using a different set of lubricants. The load displacement curve and yield strength curves are shown in Figs. 4.1 and 4.2.
FIG 4.1 COMPRESSION TEST CURVE

- CONTINUOUS COMPRESSION
- RE-LUBRICATED COMPRESSION

SPECIMEN DIMENSIONS:
19.05MM DIA x 19.05MM
FIG 4.2: TRUE STRESS/STRAIN CURVE FOR 99% PURE ALUMINIUM

(Annealed @ 360°C x 1 HR)

\[ \text{TRUE STRESS (N/mm}^2\text{)} \]

\[ \text{TRUE STRAIN (} \varepsilon \text{)} = L_n\left(\frac{h}{h_0}\right) \]
CHAPTER 5

FORMING LOADS
5.1 GENERAL

The load required for forming arises due to the overcoming of various forces, namely shear and friction losses, and the power of internal deformation. These vary according to the geometry and nature of the process. Extrusion forces can be most readily reduced by reductions in friction and variation in the process geometry, for example in backward extrusion by the alteration of punch profile.

Both direct and indirect extrusion was examined at several values of extrusion ratio, using differing billet lengths. Also the effect of using conical and nosed punch profiles was noted, as to its effect on metal flow characteristics and extrusion loads.

5.2 EXTERNAL FRICTION

External friction gives rise to an increase in extrusion load, which can be reduced by efficient lubrication. Several lubricants were examined for performance, the results of extrusion tests being shown in Fig. 5.1. Here two extrusion ratios were examined, and in both cases a wax (Abryl wax) suspended in trichlorethylene resulting in a fine coating on the billet was found to result in the lowest extrusion pressure. This was chosen as the most efficient lubrication and was used for all subsequent extrusion experiments. The results shown for Helvium 'O' + graphite at an extrusion ratio of 3.37 in Fig. 5.1 is characteristic of using no lubricant, here a linear increase in pressure is found with increasing punch penetration.

Incremental forming experiments were carried out in order to examine the extent of flow photographically at various stages of extrusion. These billets were re-lubricated at each interval, and the resulting extrusion load was slightly reduced compared with that of continuous extrusion as shown in Fig. 5.2. This reduction is
attributed to a reduction in friction largely due to more efficient lubrication.

5.3 EFFECT OF EXTRUSION RATIO

Obviously as the extrusion ratio increases the load required to deform an increasing amount of material increases as illustrated in Fig. 5.3, which shows the load/displacement characteristics for five extrusion ratios.

The effect of reduction on maximum extrusion pressure is shown in Fig. 5.4, the maximum pressure being apparently proportional to the log. of the extrusion ratio, this is a common finding in extrusion load characteristics. The punch stress varies with extrusion ratio as shown in Fig. 5.5. As can be seen the punch stress has a minimum at an extrusion ratio of about 2.8.

If homogeneous deformation is assumed, the steady state extrusion efficiency can be derived, which increases with extrusion ratio (Fig. 5.6) reaching a maximum of 40% at the highest extrusion ratio. The results compare favourably with those of other workers.

5.4 EFFECT OF BILLET LENGTH

Billet length has a pronounced effect both on metal flow and extrusion pressure. Punch load/displacement characteristics for various billet lengths are shown in Fig. 5.7, and in Fig. 5.8 the maximum punch load is plotted against billet length for a particular extrusion ratio. It is apparent that as billet length increases so the maximum extrusion load increases due to the deforming of a larger amount of material. Also, as billet length increases so does the ejection load, in an almost linear fashion as shown in Fig. 5.9.
5.5 EFFECT OF EXTRUSION DIRECTION

Extrusion experiments were carried out by both the direct and indirect methods. The fundamental difference between these two methods is described in Fig. 3.2. In direct extrusion the whole of the billet is moved relative to the die during the extrusion process, whereas in indirect extrusion the billet remains stationary relative to the die. As the billet is under pressure in direct extrusion whilst it is moved relative to the die, an extra load is encountered as compared with indirect extrusion. This gives rise to an increase in overall extrusion load. As can be seen from the load/displacement characteristics in Figs. 5.10 and 5.11 the loads for both direct and indirect extrusion remain substantially constant once a peak has been reached, but the level for direct extrusion is greater by up to 10% this being due to the additional friction encountered. This is found to prevail at all extrusion ratios (Fig. 5.12) where the maximum punch loads for a range of extrusion ratios are plotted for both methods of extrusion.

The effect of extrusion direction on metal flow and extrusion defects will be discussed in subsequent chapters.

5.6 CONICAL PUNCH EXTRUSION

A series of punch ends were designed with conical profiles to examine the effect of punch core angle on extrusion load. The punch load/displacement characteristics, showing the effect of angle on punch load, are plotted in Fig. 5.13. A transition in these characteristic curves can be seen as the punch fully enters the billet, this transition being that from an operation of indentation to one of extrusion. It is apparent for this figure that as the punch angle increases, i.e. the punch becomes more pointed, the punch load increases. It is apparent that as in forward extrusion of rods,
an optimum punch angle must exist, at which the extrusion load is least.

Experiments were performed with a wide range of punch angles, noting for each the maximum extrusion load, they are plotted in Fig. 5.14. The extrusion load drops dramatically with reducing angle until an optimum angle is reached at about 10° for direct extrusion and 17° for indirect extrusion. The differences in these optimum angles is probably attributed to the differing friction characteristics between the two processes. It is again apparent from Fig. 5.14 that extrusion loads for direct extrusion are always greater than those for indirect extrusion.

In forward extrusion the optimum die angle is small (inclusive angle), but it is often not adopted due to its giving rise to high bursting stresses in the die. The comparatively 'large' angle obtained in backward extrusion (when both angles are measured from the same datum) is probably due to the lack of lubrication along the punch face, as most of the applied lubricant is removed during the initial indentation.

In hydrostatic forward extrusion \(^{(42)}\), optimum die angles of about 20° (inclusive) exist for extrusion of 99.5% aluminium, here the high bursting stresses are counteracted by virtue of the hydrostatic stress.

Extrusion with conical ends completely changes the state of metal flow within the billet and will be discussed in Chapter 6.

5.7 NOSED PUNCH EXTRUSION

When extruding with a flat ended punch, a dead metal zone appears ahead of the punch in the form of an arc. When this zone is well established the flowing metal shears over itself in the region of

-34-
the 'nose' caused by the build up material under the punch face. Since shear losses are proportional to $\sigma_0/\sqrt{3}$ whereas friction losses are proportional to $m\sigma_0/\sqrt{3}$, where $m$ is a friction factor which varies between 0 and 1, it would be desirable to eliminate the dead zone by replacing it with an appropriately nosed ram. The result is that an appropriately nosed ram would produce lower extrusion loads, the magnitude of which would depend on the friction at the face of the nosed ram.

To simulate $m=1$ rough profiles were produced, and for $m=0$ smooth punches were produced. The profiles of these punches were manufactured to the same geometry as the dead metal zone geometry, this being established from photographs of incremental forming operations using split billets. The results of experiments are plotted in Fig. 5.15.

Where smooth punch ends were used, a reduction in extrusion loads of about 15-20% was established. The loads for rough ends were much more than those for smooth punches, but lay below the loads for flat punch extrusion. Theoretically if the punches were perfectly rough, i.e. $m=1$, the results should be identical to those for flat punch extrusion; it is however difficult to produce ideally rough profiles, and a factor of about $m=0.7$ would probably prevail for the rough profiles. The effect of punch surface roughness has a profound effect on the state of metal flow which is discussed in Chapter 6.

In Chapter 7 an upper bound theory is examined which predicts the differences in loads encountered by the use of punches where $m=1$ and $m=0$. Here the order of magnitude of difference between the two is comparable with practical results.
FIG 5.1: EXTRUSION PRESSURE DISPLACEMENT CHARACTERISTICS
FOR VARIOUS LUBRICANTS

MATERIAL: 99.9% PURE ALUMINIUM
BILLET SIZE: 12.70MM DIA x 19.05MM
EXTRUSION SPEED: 1.2MM/SEC.

LEGEND:
- CASTROL 'HELUEUM O' GREASE
- ABRYL WAX
- HELUEUM O + GRAPHITE
- HELUEUM O + P.T.F.E.

EXTRUSION RATIO 3.37
EXTRUSION RATIO 1.43
FIG 5.2: COMPARISON BETWEEN CONTINUOUS AND INCREMENTAL FORMING LOADS

LOAD REDUCTION DUE TO MORE EFFICIENT LUBRICATION

CONTINUOUS EXTRUSION
INCREMENTAL EXTRUSION

LOAD (KN)

TRAVEL (MM)
FIG 5.3: PUNCH LOAD/DISPLACEMENT CURVES FOR INDIRECT EXTRUSION OF BILLETS OF H:D = 1
FIG 5.4: EFFECT OF REDUCTION ON MAXIMUM EXTRUSION PRESSURE

![Graph showing the effect of reduction on maximum extrusion pressure. The graph plots maximum extrusion pressure (in MPa) against natural logarithm (ln) of reduction (ln(R)). The data points are differentiated between indirect and direct extrusion, with a ratio of \( H/D = 1\).]
FIG 5.5: EFFECT OF REDUCTION ON PUNCH STRESS
(INDIRECT EXTRUSION)
FIG 5.6: STEADY PRESSURE EXTRUSION EFFICIENTLY ASSUMING HOMOGENEOUS DEFORMATION

PRESENT WORK
■ COPPER. REF. (36)
△ EN.2 REF. (37)
FIG 5.7: EFFECT OF BILLET LENGTH ON EXTRUSION PRESSURE

$R = 1.33$

Punch Displacement (mm) vs. Punch Load (kN) for different H/D ratios:
- • 0.25
- • 0.50
- • 0.75
- ▲ 1.00
- ○ 1.25
FIG 5.8: EFFECT OF BILLET LENGTH ON MAXIMUM PUNCH LOAD

FIG 5.9: EFFECT OF BILLET LENGTH ON MAXIMUM EJECTION LOAD
FIG 5.10: DIFFERING EXTRUSION CHARACTERISTICS WITH DIRECTION

\[ R = 1.33 \]

\[ H: D = 1 \]

PUNCH LOAD (KN) vs. PUNCH DISPLACEMENT (MM)
FIG 5.11: DIFFERING EXTRUSION CHARACTERISTICS WITH DIRECTION

R = 2.78
H:D = 1

PUNCH DISPLACEMENT (MM)
FIG 5.12: PUNCH LOADS FOR PARTIAL EXTRUSION, 12.7mm INDENTATION

![Graph showing punch loads for partial extrusion. The graph plots punch load (kN) against extrusion ratio (R). Two curves represent DIRECT EXTRUSION and INDIRECT EXTRUSION, with corresponding load values at different extrusion ratios.]
FIG 5.13: PUNCH LOAD/DISPLACEMENT CHARACTERISTICS
FOR VARIOUS PUNCH ANGLES

INDENTATION/EXTRUSION TRANSITION

INDIRECT EXTRUSION $R = 1.33$

PUNCH ANGLE $\theta^o$

- 0
- 30
- 45
- 60

PUNCH LOAD (KN)

PUNCH DISPLACEMENT (MM)
FIG 5.14: EFFECT OF PUNCH ANGLE ON MAXIMUM EXTRUSION PRESSURE FOR DIRECT AND INDIRECT EXTRUSIONS

R = 1.33

DIRECT EXTRUSION
INDIRECT EXTRUSION

PUNCH ANGLE θ (DEGREES)
FIG. NO. 5.15

EFFECT OF NOSE PROFILE ON MAX. EXTRUSION LOAD

H:D RATIO=1
- FLAT END
× ROUGH ENDS
○ SMOOTH ENDS

MAX. EXTRUSION LOAD (KN)

1.1 1.2 1.3 1.4 1.5 1.6
EXTRUSION RATIO
CHAPTER 6

METAL FLOW DURING EXTRUSION
6.1 GENERAL

During the extrusion of cans flow patterns are set up in the billet as the metal flows continuously upwards past the punch end. Metal flow usually starts well below the punch end in region 2 (Fig. 6.1), the flow is complete when entering region 3. The transition between regions 2 and 3 is usually quite well defined, and takes up an angle $\theta \approx 45^\circ$. Region 1 is a dead metal region which takes the form of an arc below the punch. This region travels downwards with the punch during extrusion, during which time it remains substantially unchanged. Until the dead zone is fully established the metal flow is unsteady. The states of flow can be divided into three types, namely,

1) Unsteady flow, setting up of dead metal regions and establishment of even flow patterns.

2) Steady state flow which is time invariant.

3) Unsteady flow, at the end of the stroke, this occurs when zone 2 reaches the bottom of the container.

External friction and lubrication affect flow patterns. Changes in frictional conditions at the billet/die interface affect the angle of intersection of radial marking lines on split billets with the die wall. Lack of lubrication or greater frictional effects produces a retardation of lines at these intersections.

Billet length also affects flow patterns, especially if the length is such that zone 2 in Fig. 6.1 cannot be fully established. In this case the extrusion operation becomes completely unsteady.
state flow, as there is insufficient material for a steady state to be fully established. The state of flow at the end of the stroke will be fully discussed in Chapter 8.

6.2 STEADY STATE FLOW

Once the dead metal regions are fully established a steady state of flow takes place during which time vertical flow lines remain unchanged and a repeatable or time invariant flow pattern predominates. Steady state flow is easily achieved in forward extrusion, but in backward extrusion the limited height/diameter ratio of the punch means that the steady flow period exists for only a short time, if at all when punches are short or billets small in height.

If billets are deformed in increments and the displacement of material plotted from one stage to the next, a displacement vector diagram can be drawn (see Fig. 6.2). This is a steady state pattern showing the nil velocity at the dead metal region, and indicating how metal flows from the main body of the billet to form the tube wall; the material velocity increases from 1 at the outset to R after deformation.

When a steady state predominates it is then possible to use the results for visioplasticity analysis which can be used to calculate strain rates, strains and stress distributions throughout the billet as has been done by Thomsen et al.\(^{(23)}\) for forward extrusion. Such work involving much computer programming is very time consuming but yields very useful results. An analysis similar to that of Thomsen\(^{(26)}\) was carried out by Mehta for backward extrusion using conical ended punches. Unfortunately the data from the flow line points is not smoothed, and the results are subsequently rather inaccurate.

The establishment of the dead metal zone takes longer at larger extrusion ratios, hence the length of time during which steady state
flow exists is shorter at larger extrusion ratios, particularly as
the onset of the final stage occurs sooner also at high extrusion
ratios. In fact at very large extrusion ratios, the steady state may
not exist in backward extrusion, although it almost certainly does at
low extrusion ratios.

6.3 DEAD METAL REGIONS

As described previously, the dead metal region in flat punch
extrusion takes the form of an arc below the punch, the dimensions of
which are plotted in Fig. 7.2 of Chapter 7. The dimensions of the arc
for a particular extrusion ratio are those which will tend to minimise
the extrusion load. The dead metal region is very well defined at low
extrusion ratios but less so at high ratios. At $R=2.78$ the characteristic
arc is very difficult to define as shown in section 6.5.

Dead metal regions are found frequently in forming operations,
typically in the forward extrusion of rods through dies of $180^\circ$, here
metal collects in the die corner in a similar way to backward
extrusion. A typically well formed dead metal region is shown in
Plate 6.1. More detailed photographs showing dead metal regions are
shown in the section dealing with incremental forming.

6.4 MICROSTRUCTURES

Plate 6.2 shows the macrostructures of several extruded cans.
The material is more heavily worked at the inside of the can where it
is much harder. Plates 6.3 to 6.6 show more close-up macrostructures
including close-ups of dead metal regions which are clearly seen.

Along the sides of the extruded cans 'slip' bands can be found in
some cases, Plates 6.7 and 6.8. These bands, which are similar to
those found by Cockcroft in forward extrusion, radiate outwards from
the inner wall of the can at an angle of approximately 45° and are probably formed in the transition zone which exists between the deforming material and that which has completed deformation. There again a line of approximately 45° is observed radiating downwards from the punch corner. Such bands are undoubtedly formed during the transition through this region.

Another interesting feature seen in Plate 6.9 is the way the dead metal zone collapses on reaching the bottom of the die. At such high extrusion ratios the zone is seen to split up into two circular arcs at the bottom of the punch; such flow is not observed in extrusions at low extrusion ratios.

6.5 EXTRUSION DIRECTION

Extrusion direction has an effect on forming loads and on defect formation. Differing frictional effects do however produce slight differences in flow patterns between the two methods. In the case of indirect extrusion, transverse marker lines meet the edge of the extruded product at an angle of 90°; whereas in the case of direct extrusion a lag is observed in the intersection of such lines. This is due to additional friction at the interface between the billet and the die wall.

6.6 INCREMENTAL FORMING

Each extrusion ratio was examined using split marked billets formed in increments during the extrusion process. Photographs were taken of the billets after each forming increment and these are shown in Plates 6.10 to 6.13.

The setting up of the dead metal regions is clearly seen and it is noted that the establishment of the dead metal region at larger extrusion ratios takes longer than at lower ratios. Hence
the existence of a steady state is much less likely or short lived at larger extrusion ratios.

Several plates, notably 6.10G, 6.11E and 6.12G show clearly the boundary between the metal flow and tube wall as being a well defined line at approximately 45° to the cup wall.

The onset of cavitation can be clearly observed, particularly in plates 6.10F, 6.10H and 6.11E and 6.11F. Again it is clearly observed that cavitation commences when the remaining billet thickness becomes less than the wall thickness of the cup.

The metal flow region compares well with the model constructed by Avitzur with the wall/flow boundary and dead metal zones comparing almost exactly. The differences lie in the lower boundary of the deforming zone which extends in practice much further than the zone as predicted by Avitzur. In most cases once half of the billet has been extruded, where H:D=1, the metal flow boundary has already reached the bottom of the die, this again points to the fact that steady state flow is very short lived in the backward extrusion of cups.

6.7 FLOW WITH CONICAL PUNCHES

Metal flow was observed using a variety of conical punch end profiles. Plate 6.14 shows the state of metal flow for a variety of punch angles. Except at very low angles, cavitation* is absent.

Plates 6.15 to 6.17 show how flow lines are formed when conical ends are used. The less pointed the ends, the more likely is the existence of a dead metal region around the profile. The deformation zone is much smaller than for flat punches, starting just below the end point. It can again be seen that the inner edge of the formed tube is much more highly worked than the outer edge.

*Cavitation is a lifting of the corner of the billet which occurs towards the end of the extrusion process, and is discussed fully in Chapter 8.
6.8 FLOW WITH NOSED PUNCHES

Experiments were conducted using nosed punch ends, one set rough and one set smooth. Different loads were observed and the state of metal flow was observed using split billets with scribed grids on the mid plane.

Plates 6.18 and 6.19 show a comparison between the flat punch and rough and smooth nosed punch profiles in the form of formed split billets. As seen from these plates the rough end produces comparable results to that of flat punch extrusion; whereas the smooth end profile produces better flow with less evidence of built up edge. Build up in front of the nosed profile exists in both the rough end extrusion and the flat punch extrusion. The depth of deformation zone is much less with the smooth end than the rough, where it compares with flat punch extrusion.
FIG 6.2 DISPLACEMENT VECTOR DIAGRAM

ILLUSTRATING METAL FLOW DURING EXTRUSION (R 1.19) USING A FLAT PUNCH
PLATE 6.1: EXTRUSION WITH FLAT PUNCH R=1.33

PLATE 6.2: SELECTION OF SECTIONED CUPS
PLATE 6.3: EXTRUSION WITH FLAT PUNCH, ETCHED R=1.19

PLATE 6.4: DEAD METAL REGION, ETCHED R=1.19
PLATE 6.5: EXTRUSION WITH FLAT PUNCH, ETCHED R=1.56

PLATE 6.6: DEAD METAL REGION, ETCHED R=1.56
Position of 'slip' lines within billet wall

Plate 6.7: Slip bands in tube wall x100

Plate 6.8: Slip bands in tube wall x400
PLATE 6.9: COLLAPSE OF DEAD METAL REGIONS

PLATE 6.14: SPLIT SECTIONS WITH CONCIAL PUNCHES, ETCHED

$R=1.19$
PLATE 6.10: INCREMENTAL FORMING, R=1.19
PLATE 6.11: INCREMENTAL FORMING R=1.33
PLATE 6.12: INCREMENTAL FORMING, R=1.56

-64-
PLATE 6.13: INCREMENTAL FORMING R = 1.96
PLATE 6.15: EXTRUSION WITH CONICAL PUNCH $\theta=90^\circ$, $R=1.19$

PLATE 6.16: EXTRUSION WITH CONICAL PUNCH $\theta=30^\circ$, $R=1.19$

PLATE 6.17: EXTRUSION WITH CONICAL PUNCH $\theta=90^\circ$, $R=1.56$
PLATE 6.18: COMPARISON BETWEEN BILLETS FORMED WITH FLAT AND NOSED RAMS, R=1.56

PLATE 6.19: COMPARISON BETWEEN BILLETS FORMED WITH FLAT AND NOSED RAMS, R=1.33
CHAPTER 7

UPPER BOUND SOLUTIONS TO BACKWARD EXTRUSION
7.1 THE UPPER BOUND TECHNIQUE

The bounding technique, or limit analysis, is a useful theory for the estimation of forming loads. Upper bounds predict the upper limit of such loads, and lower bounds the lower limits. As lower bounds are difficult to define accurately one usually concentrates on the upper bound technique. As the load in practice cannot exceed the upper bound load, the problem reduces to that of finding the lowest, and therefore most accurate, upper bound solution.

The upper bound predicts the maximum power required for deformation. The total power is the sum of the individual power required to overcome shear and friction losses plus the power of internal deformation. Fundamental to the upper bound technique is the division of the body into zones, for each of which a velocity field (mathematical description of the flow of the material) is derived. The velocity field is then used to define a strain rate field. The better the zones, or nearer to describing the actual deformation taking place, the more the power required reduces, and thus brings the solution closer to the actual value.

In order for a solution to be kinematically admissible, three conditions must be satisfied, namely:-

1. Incompressibility equations must be satisfied.
2. Continuity across the velocity discontinuity must be satisfied.
3. Velocity boundary conditions must be satisfied.

A number of slip line field solutions exist for plain strain extrusion, but a model described by Avitzur (1,30) for axially symmetric backward extrusion was thought to describe very well the conditions prevailing during extrusion in practice.
7.2 THE EARLY STAGE OF EXTRUSION

In his papers Avitzur divides the body into four zones, Fig. 7.1.

From initial experimental work, it appears that the transition line from zone 2 to zone 3 is accurately described, and also that the existence of the dead metal zone 4 is verified. This accurate description of the actual flow tends to indicate that the solutions should be reasonably accurate.

As stated previously the geometry of the model is varied until the lowest value of load is achieved. In Avitzur's model the angle $\alpha$ is varied, which in turn alters the whole geometry of the model, until the lowest upper bound load is achieved, which is the one which predominates. In Fig. 7.2 comparison is made between the dead zone angle $\alpha$ and the relative wall thickness for differing friction coefficients. These are compared with actual values of $\alpha$ as measured from photographs of actual extrusions. The trends are found to compare favourably, but the measured angles are larger than experimental values. The discrepancies can be explained by the difficulty in accurately determining the actual values of $\alpha$; and also as shown in Fig. 3 of Appendix III the relative average ram pressure remains substantially constant for a wide range of dead zone angles. The upper bound ram pressures are shown in Fig. 7.3, and compared with experimental values. Obviously the upper bound loads are in
excess of the experimental values.

7.3 USE OF A NOSED RAM FOR EXTRUSION

Where a dead metal zone exists, the metal must shear over itself in order to flow; since shear losses are proportional to \( \frac{\mu}{\sqrt{3}} \) whereas friction losses are proportional to \( \frac{m\mu}{\sqrt{3}} \), where \( m \) is a friction factor and varies between 0 and 1, it would be desirable to eliminate the dead zone by replacing the flat ram with an appropriately nosed ram. The geometry of the nose is again optimised in a similar way to the original model. Fig. 7.4 illustrates the difference between upper bound loads for both flat and nosed rams.

7.4 EXTRUSION AT THE END OF THE STROKE

At the end of the stroke, the original model breaks down; so Avitzur has constructed a new model which applies to the end of the extrusion stoke, Fig. 7.5. Here, the body is split into 2 zones, one below the punch and the other flowing up by the punch sides. One of the most important aspects of such models is the prediction of defects. The major defects encountered in extrusion, namely cavitation and internal cracking or fishskin are examined.

An expression is derived which examines the minimum external pressure required to prevent cavitation. If this expression is re-arranged and minimized, an expression can be derived for the
minimum slug thickness to prevent cavitation. This is plotted in Fig. 7.6.

In practice it has been observed that cavitation most often occurs when the slug thickness becomes less than the wall thickness of the extrudate, see Fig. 7.7, i.e. cavitation will occur when

$$T < R_o - R_f \quad \text{or} \quad \theta < 45^\circ$$

If this criterion is taken, and \(T/R_o\) is plotted against \(R_o/R_f\) as in Fig. 7.5, by plotting \(T/R_o\) against \(1 - \frac{1}{(R_o/R_f)}\), the results lie within those of Avitzur's model, which is found to predict reasonably well the onset of cavitation.

All the calculations and computer programs involved in the calculation of the upper bound solutions are to be found in Appendix III.

---

**Fig. 7.7 : CRITICAL SLUG THICKNESS FOR PREVENTION OF CAVITATION**
FIG 7.2

EFFECT OF REDUCTION ON DEAD ZONE ANGLE WITH FLAT RAM

![Diagram showing the effect of reduction on dead zone angle with flat ram.](image-url)
FIG No 7.3

UPPER BOUND RAM PRESSURES FOR EXTRUSION

WITH FLAT RAM

\[ \frac{P}{\infty} = 0, \quad \frac{h}{R_f} = 0.1, \quad PR = \text{Average ram pressure} \]

INERTIA EFFECTS NEGLECTED

\[ \text{EXPERIMENTAL VALUES} \]
FIG NO 7.4

COMPARISON BETWEEN UPPER BOUND EXTRUSION LOADS
FOR FLAT AND NOSED RAMS

\[ \frac{P}{\sigma_0} = 0, \quad \frac{h}{R_f} = 0.1, \quad PR = \text{Average ram pressure} \]

**INERTIA EFFECTS NEGLECTED**

- \( m = 1 \) (FLAT AND NOSED)
- \( m = 0 \) (FLAT)
- \( m = 0 \) (NOSED)
FIG 7.6

UPPER BOUND SOLUTION FOR MINIMUM SLUG THICKNESS
TO PREVENT CAVITATION VERSUS REDUCTION AND FRICTION

\[ \frac{P}{\rho g} = 0 \]

INERTIA EFFECTS NEGLECTED

\[ T = \text{Base thickness} \]
CHAPTER 8

EXTRUSION DEFECTS
8.1 GENERAL

Extrusion defects in backward extrusion arise due to a variety of reasons including friction, lubrication and the nature of metal flow. Differing defects arise at various stages of the process and at different extrusion ratios.

Three main defects arising during extrusion are a) cavitation, or a lifting of the lower edge of the cup b) the formation of a dead metal ring around the bottom edge of the cup which separates from the body of the cup, and c) fishskin or internal tearing of the product at stages along the inside of the cup wall. Fig. 8.1 illustrates these defects.

8.2 CAVITATION

Cavitation is a common extrusion defect and is found to occur at the end of the process when the base thickness becomes less than the wall thickness. This has been proved in Chapter 7 theoretically by upper bound techniques, and has been observed in practice. This means that for a given base thickness, cavitation occurs more readily at lower extrusion ratios.

Examples of cavitation are shown in Plates 8.1 and 8.2. Here the lifting of the side walls is clearly apparent, especially in Fig. 8.2. This is a very short specimen where contact with the side walls is short and therefore the restriction in terms of friction which oppose cavitation is minimal.

The effect of friction between the formed cup and the die wall acts as a restraining force to prevent cavitation, and it is found that at higher extrusion ratios where these forces are large, and where friction is high due to a long length of emerging product in contact with the die cavitation or its onset is prevented or delayed.
Fig. 7.6 illustrates the base thickness criterion for the onset of cavitation.

Cavitation in backward extrusion can be compared with piping in forward extrusion which also occurs at the end of the extrusion process.

8.3 INTERNAL CRACKING

Circumferential cracks occur on the inner wall surface of pierced cups. Theoretically, cavitation occurs before cracking, but this is not so in practice.

Cracking is governed by the magnitude of the local hydrostatic pressure, the ductility of the material at the point in question and by the stress field around the point.

The defect is illustrated in Plates 8.3, 8.4 and 8.5 and is found to occur only at high extrusion ratios. Cracking was found to occur only during direct extrusion and not during indirect extrusion. Also it occurs during incremental forming by indirect extrusion, this is due to the lack of pressure by the friction between the formed cup wall and the die wall.

The presence of an imposed pressure on the wall of the emerging product would reduce and probably eliminate both cavitation and cracking.

Cracking also occurs in the form of circumferential cracks in forward extruded rods.

Cracking in the backward extrusion of aluminium has been reported before by Dipper (39) and also by Gobuyu and others in the cold piercing of magnesium.
8.4 SHEARING

The third defect is characterised by the shearing away of the bottom edge of the can. Here a ring completely shears off from the corner of the can. The defect only occurs at very high extrusion ratios and is due to the state of flow at the very end of the stroke. At the end of the stroke at high extrusion ratios there is very restricted metal flow which at the very edge means an almost $45^\circ$ flow upwards past the cover. As cavitation is unlikely at this stage the metal is unable to flow at the very edge of the can, and consequently a shearing process takes place which results in the defect. The amount of material removed is small and the defect therefore minimal compared with cavitation and cracking.
FIG (8.1) SKETCHES SHOWING EXTRUSION DEFECT FORMATIONS

A) CAVITATION

B) DEAD METAL RING

C) INTERNAL CRACKING OR FISHSKIN
PLATE 8.1: SPLIT BILLET SHOWING CAVITATION, R=1.33

PLATE 8.2: SPLIT BILLET SHOWING CAVITATION, ETCHED, R=1.19
PLATE 8.3: SPECIMENS SHOWING INTERNAL CRACKING

PLATE 8.4: EXAMPLE OF INTERNAL CRACKING, R=1.96
PLATE 8.5: EXAMPLE OF INTERNAL CRACKING, R=2.78
Chapter 9

Conclusions
The following conclusions can be drawn from the discussions of previous chapters:-

9.1 FORMING LOADS

a) The load/extrusion ratio relationships obtained for backward extrusion agreed well with published data.
b) Extrusion load increases both with extrusion ratio and billet length.
c) The extrusion load for direct extrusion is greater by up to 10% than that for indirect extrusion.
d) Optimum angles exist for extrusion with conical punches.
e) Extrusion loads are decreased by using nosed punch ends with rough profiles similar in geometry to dead metal regions; and are reduced by up to 10% further by the use of smooth nosed punch ends.

9.2 METAL FLOW

a) Dead metal regions exist for all extrusion ratios, using flat punches, with increasing angle of zones for increasing extrusion ratios. These compare well with theoretically defined fields derived from an upper bound model.
b) The depth of deformation region is such that the existence of a steady state is very short lived.
c) The process can be roughly divided into three types of flow, i) Initial setting up of dead metal regions, ii) Steady state flow, iii) Flow at the end of the stroke.
d) Deformation is much heavier at the inside wall of the formed cup.
e) The dividing zone between the deforming region and the cup wall forms a boundary line of approximately 45° to the die wall.
f) Incremental forming has revealed details of flow during the
extrusion process.

g) Metal flow without dead metal formation exists for conical punch profiles.

h) Metal flow for rough nosed punch ends produces similar flow profiles to that of flat punch extrusion; whereas flow with smooth punch ends produces a more streamline flow with less depth of deformation.

i) Avitzur's upper bound model produces very reliable results in terms of metal flow boundaries.

j) The state of flow at the end of the stroke is inclined to induce defect formation.

9.3 EXTRUSION DEFECTS

a) Three main extrusion defects are found to occur, these being

i) Cavitation, ii) Internal circumferential cracking and iii) Shearing of the corner of the can.

b) Cavitation commences once the billet base thickness becomes less than the wall thickness of the can. This is also proved theoretically in Avitzur's upper bound technique.

c) Cavitation can be reduced by imposing an external pressure on the emerging cup wall.

d) Cavitation can be reduced as wall length increases and die wall friction increases.

e) Internal cracking occurs only at high extrusion ratios during incremental forming or during direct extrusion only. It does not give way in favour of cavitation as has been suggested by Avitzur. Its onset is pronounced at the end of the stroke.

f) Internal cracking can also be reduced or eliminated by external pressure on the emerging die wall or by increased die wall friction. The reduction of cracking by direct pressure application has not been proved in this thesis, but the effect of high friction forces which reduce or eliminate the defect has been noted.
g) Shearing of the very corner of the extruded can occurs at the very end of the stroke at high extrusion ratios due to restriction of metal flow. Its appearance is absent in the presence of cavitation.

9.4 PRACTICAL IMPLICATIONS OF THE WORK

From a practical point of view, the thesis illustrates the origins of defect formation and their cures; also how metal flow influences grain structure and therefore product properties throughout the component.

More wide reaching practical implications lie in a furthering of the fundamental understanding of metal flow during backward extrusion. Taken further, the work could be combined with visioplasticity analysis in order to yield large amounts of data on stress formation throughout the billet.
CHAPTER 10

RECOMMENDATIONS FOR FURTHER WORK
Several recommendations for useful further work can be made in the light of conclusions drawn from this work. These are briefly as follows:

a) Further studies of incremental forming using more exact measuring techniques could be carried out to define exactly when the onset of steady state flow occurs, and how long it prevails, i.e. to establish the transition point between the three metal flow states.

b) Having established where steady flow occurs, it would then be possible to construct a full visioplasticity analysis to the process, in a similar way to that of Thomsen et al in their examination of forward extrusion through conical dies. The analysis would be relatively easy for concial punch profiles, but none too difficult for flat punch extrusion as it has been shown that the deformation boundaries, especially dead metal zones, are clearly defined. Such a detailed analysis would be a useful contribution to metal flow mechanics and would yield much interesting data on metal flow and forming loads.

c) Defect formation can be prevented by the application of pressure to the emerging can wall. The magnitude of pressure required to prevent such defects arising could be measured and would be valuable practical information. As the difference in friction between direct and indirect extrusion is sufficient to prevent internal cracking, the magnitude of pressure required to prevent this defect will undoubtedly be small.

d) Further work could be carried out to examine the effect after ejection of residual stresses and expansion of the extruded cans. This would
also provide useful data on the effect of friction by interference on defect formation.

e) Further work could be done using a modified version of Avitzur's model in which deformation zone boundaries are modified to agree more fully with those found in practice in the hope of establishing more accurate results.
ACKNOWLEDGEMENTS

The author wishes to thank the Science Research Council for providing the award which enabled this work to be carried out, and also Professor R.J. Sury, Director of Research, for the use of departmental facilities. My sincere thanks are extended to Dr. G.F. Modlen, Project Supervisor, for his continual advice, support and encouragement throughout the work.

Acknowledgements are also due to Mr. W.R. Abrey for technical assistance, and Mr. R. Withers for assistance with photography.

Finally, grateful thanks are extended to my fiancée, Miss J.M. Briers, for her unfailing support and encouragement throughout the entire project, and for her proficient typing of this thesis.
REFERENCES


7. MORGAN, R.A.P. 'Tooling for cold extrusion' Sheet Metal Industries, February 1961, pp.100-120.


35. VON ZEERLEDER, A. & VON BERG, E. 'Relationship of the force requirements in the extrusion of tubes of pure aluminium and various aluminium alloys. SCHWEIZER ARCHIV, 3:109, 1937.


38. COCKCROFT M.G. & MACLEAN, M.S. 'Mechanical Properties of Cold Extruded Products' 4th International Meeting on Cold Forging, Dusseldorf, 18.10.70.


41. RYDER, G.H. 'Strength of Materials'.

APPENDIX I

DIE STRESS CALCULATIONS
(i) Required Die Strength

Experimental materials of pure aluminium or soft aluminium alloys were originally proposed for the present work; but in order to enhance the scope of the apparatus, the die was designed to withstand forming pressures to be expected in the extrusion of hard aluminium alloys, with a mean yield strength in the order of 460 N/mm$^2$.

Equation (1) has been found to yield reasonably accurate predictions of forming loads for lead and aluminium, under axially-symmetrical conditions

\[
\frac{P}{Y} = 0.8 + 1.5 \ln R \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)
\]

where:

\[ P = \text{extrusion pressure} \]
\[ \bar{Y} = \text{mean yield strength} = 460 \, \text{N/mm}^2 \]
\[ R = \text{extrusion ratio} \]

Maximum load occurs at the maximum extrusion ratio of 2.78. Hence, from (1)

\[ P_{\text{MAX}} = 1072 \, \text{N/mm}^2. \]

The extrusion die must therefore withstand an internal pressure of 1072 N/mm$^2$.

(ii) Die Stress Calculations

Die Materials:— Inner die ring ... Hardened die steel, yield strength 2009 N/mm$^2$

Outer die ring ... Hardened EN25, yield strength 1236 N/mm$^2$
The die was constructed in the form of a compound cylinder, where the outer ring having radii $R_1$, $R_3$ is shrunk onto the inner die of radii $R_3$, $R_2$.

The choice of radii can be optimised in such a way that both rings are subjected to their maximum permissible hoop stress, with the result that

$$(R_3 - R_2) < (R_1 - R_3).$$

However, as the working surface at $R_2$ may possibly become sored under arduous extrusion conditions the inner die ring becomes more susceptible to failure arising from crack propagation, thus lowering the effective maximum permissible hoop stress.

By making $(R_3 - R_2) = (R_1 - R_3)$ this automatically implies that the inner die is stressed well below its maximum limit.

"... let $R_2 = 25$mm
$R_3 = 55$mm = $2.2R_2$
$R_1 = 85$mm = $3.4R_2$

The required interference fit at $R_3$ must be established in order for the die to safely withstand an internal pressure of
1072 N/mm\(^2\), as outlined by Ryder\(^{(41)}\).

The following analysis treats the die as a compound thick cylinder with open ends.

Lamé's thick cylinder equations are:

Radial stress \( \sigma_r = \frac{b}{r^2} - a \) .......................... (2)

Hoop stress \( \sigma_\theta = \frac{b}{r^2} + a \) .......................... (3)

where \( a \) and \( b \) are constants, and \( r \) is the radius at which the stresses are to be found.

**STRESS DUE TO INTERNAL PRESSURE:**

Letting \( \sigma_\theta, r, i = \sigma_\theta, r \text{ at } R \)

\[
\sigma_r = 1072 = \frac{b}{R_2^2} - a
\]

\[
\sigma_r = 0 = \frac{b}{R_1^2} - a = \frac{b}{3.4R_2^2} - a
\]

\[
\sigma_r - \sigma_r = 1072 = \frac{b}{R_2^2} - \frac{b}{3.4R_2^2}
\]

Hence \( b = 1174R_2^2 \); and by substitution \( a = 101.5 \)

Hoop stresses due to internal pressure can now be calculated:

\[
\sigma_\theta_2 = \frac{1174R_2^2}{R_2^2} + 101.5 = 1275.5 \text{ N/mm}^2
\]

\[
\sigma_\theta_3 = \frac{1174R_2^2}{4.84R_2^2} + 101.5 = 344 \text{ N/mm}^2
\]

\[
\sigma_\theta_1 = \frac{1174R_2^2}{11.56R_2^2} + 101.5 = 203 \text{ N/mm}^2
\]
STRESS DUE TO SHRINK FIT:

The yield strength of the outer ring is approximately \( 1236 \text{ N/mm}^2 \) after heat treatment. For safety reasons and to allow for slight variation due to heat treatment, let it be subjected to a maximum hoop stress of \( \frac{3}{4} \times \) yield strength

\[ \sigma_{\text{MAX}} = 927 \text{ N/mm}^2 \text{ for the outer ring.} \]

Let a suffix 0 denote stresses in the outer ring, and i those in the inner ring.

Consider the outer ring \( R_1, R_3 \):

\[ (\sigma_3)^0 \text{ due to shrink fit} = (\sigma_{\text{MAX}})^0 - (\sigma_3)^i \text{ due to internal pressure} \]

\[ (\sigma_3)^0 = 927 - 344 = 583 \text{ N/mm}^2 \]

Now, \( (\sigma_3)^0 = 583 = \frac{b}{R_3^2} + a = \frac{b}{4.84R_2^2} + a \)

and \( (\sigma_1)^0 = 0 = \frac{b}{R_1^2} - a = \frac{b}{11.56R_2^2} - a \)

\[ (\sigma_3)^0 + (\sigma_1)^0 = 583 = \frac{b}{4.84R_2^2} + \frac{b}{11.56R_2^2} \]

hence \( b = 1992R_2^2 \); and by substitution \( a = 172.4 \).

The unknown hoop and radial stresses in the outer ring can now be calculated:

\[ (\sigma_1)^0 = \frac{1992R_2^2}{11.56R_2^2} + 172.4 = 344.8 \text{ N/mm}^2 \]

\[ (\sigma_3)^0 = \frac{1992R_2^2}{4.84R_2^2} - 172.4 = 239.4 \text{ N/mm}^2 \]

Now \( (\sigma_3)^0 = (\sigma_3)^i \) so the stresses imposed upon the inner ring due to the shrink fit can now be calculated.
Consider the inner ring $R_2, R_3$:

$$\sigma_3 i = 239.4 = \frac{b}{R_3} - a = \frac{b}{4.84R_2} - a$$

and

$$\sigma_2 i = 0 = \frac{b}{R_2} - a$$

$$\therefore (\sigma_3) i - (\sigma_2) i = 239.4 = \frac{b}{4.84R_2} - \frac{b}{R_2}$$

hence $b = -301.7R_2^2$; and by substitution $a = -301.7$

the unknown hoop stresses in the inner ring can now be calculated:

$$\sigma_3 i = \frac{-301.7R_2^2}{4.84R_2^2} - 301.7 = -366 \text{ N/mm}^2$$

$$\sigma_2 i = \frac{-301.7R_2^2}{R_2^2} - 301.7 = -603.4 \text{ N/mm}^2$$

The hoop stresses at $R_1, R_2$ and $R_3$ both due to internal pressure and shrink fit have now been completely defined, the total combined hoop stress is found by numerical addition. The complete hoop stresses are as tabulated.

<table>
<thead>
<tr>
<th>Inner Ring</th>
<th>Outer Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (Due to internal pressure)</td>
<td>1275.5</td>
</tr>
<tr>
<td>$\sigma$ (Due to shrink fit)</td>
<td>-603.4</td>
</tr>
<tr>
<td>$\sigma$ (Resulting maximum)</td>
<td>672.1</td>
</tr>
</tbody>
</table>
Total absolute hoop stress due to shrink fit = 366 + 583 = 949 N/mm²

Let E for steel = 216.3 x 10³ N/mm²

'.'. Initial difference in diameter at common surface =

\[
\frac{1}{E} \text{(total absolute hoop stress)} = \frac{949}{216.3 \times 10^3} \times 110 = 0.4826 \text{ mm}
\]

The required interference fit is 0.4826 mm

As the inner die is to be fitted into the outer by a temperature differential, the required temperature difference between the rings must be calculated such that they will fit with ease.

Temperature differential to accommodate 0.4826 mm =

\[
\frac{\text{Hoop strain}}{\text{Coefficient of expansion for steel}}
\]

the coefficient of linear expansion for steel is approximately

\[
= 0.00001116 \text{ mm/mm/°C}
\]

'.'. Temperature differential = \[
\frac{949}{216.3 \times 10^3} \times \frac{1}{0.00001116} = 393^\circ \text{C}
\]

The tempering temperature of EN25 to attain a yield strength of 1236 N/mm is 450°C, which indicates that the interference fit can be attained by fitting the outer ring on to the inner one immediately after its withdrawal from the tempering furnace. To ease the operation, the inner die may be previously immersed in liquid nitrogen so as to increase the clearance at the common surface during fitting.
(iii) **Criterion for failure**

Although a cylinder fails due to hoop stress rather than radial stress, the shear stresses play a critical role in determining the load at which failure occurs: the Huber-von-Mises yield criterion is therefore applied.

Since yielding, if it occurs, will be under plane strain conditions, this criterion reduces to the condition that the difference between the principal stresses in the plane of strain \((\sigma_0-\sigma_r)\) should equal \(\frac{2Y}{\sqrt{3}}\) at yielding; this is equivalent to a maximum shear stress criterion, \(\text{since } \tau_{\text{MAX}} = \frac{(\sigma_0-\sigma_r)}{2}\) the critical shear stress being \(\frac{Y}{\sqrt{3}}\).

Consider the inner ring:

\[
\text{CRITICAL } \tau_{\text{MAX}} = \frac{Y}{\sqrt{3}} = \frac{2009}{\sqrt{3}} = 1160 \text{ N/mm}^2 \text{ for no yielding}
\]

now \(\tau_{\text{MAX}} = \frac{1}{2}(\sigma_0_{\text{MAX}}+P)\) where \(P\) = internal pressure.

From previous calculations \(\sigma_0_{\text{MAX}} = 672 \text{ N/mm}^2\); \(P = 1072 \text{ N/mm}^2\)

\[
\therefore \tau_{\text{MAX}} = \frac{1}{2}(672+1072) = 872 \text{ N/mm}^2
\]

The criterion is satisfied as \(\tau_{\text{MAX}} < \frac{Y}{\sqrt{3}}\)

Consider the outer ring:

\[
\tau_{\text{MAX}} = \frac{1}{2}(\sigma_0_{\text{MAX}}+P)
\]

\(P\) now becomes the effective internal pressure at \(R_3\) both due to the internal pressure and the shrink fit.
\[ \sigma_3 = \frac{927}{R^2} + a = \frac{b}{4.84R^2} + a \]

\[ \sigma_1 = 0 = \frac{b}{R^1} - a = \frac{b}{11.56R^2} - a \]

\[ \sigma_3 + \sigma_1 = 927 = \frac{b}{4.84R^2} + \frac{b}{11.56R^2} \]

hence \( b = 3167R^2 \) and by substitution \( a = 274 \).

Now \( P(\text{effective}) = \sigma_3 = \frac{b}{R_3} - a = \frac{23167R^2}{4.84R^2} - 274 \)

hence \( P = -\sigma_3 = 381 \text{ N/mm}^2 \)

and \( \sigma_{\text{MAX}} = 927 \text{ N/mm}^2 \)

\[ \therefore \tau_{\text{MAX}} = \frac{1}{2}(927 + 381) = 654 \text{ N/mm}^2. \]

Applying von-Mises yield criterion, CRITICAL \( \tau_{\text{MAX}} = \frac{Y}{\sqrt{3}} \)

actual \( Y \) expected = 1236 N/mm\(^2\)

\[ \therefore \text{CRITICAL } \tau_{\text{MAX}} = \frac{1236}{\sqrt{3}} = 715 \text{ N/mm}^2. \]

The criterion is satisfied as \( \tau_{\text{MAX}} < \frac{Y}{\sqrt{3}} \).

In conclusion, it can be safely assumed that the maximum permissible extrusion pressure for the die is 1000 N/mm\(^2\); this corresponds to a maximum punch pressure of 1963 KN.
APPENDIX II

EXTRUSION AND COMPRESSION TOOL

DESIGN DETAILS AND HEAT TREATMENT
EXTRUSION TOOL DETAIL DRAWINGS

THIRD ANGLE PROJECTION USED THROUGHOUT

ALL DIMENSIONS IN MM UNLESS OTHERWISE STATED

TOLERANCES AS SPECIFIED (NOMINAL ±0.5MM)

✓ MACHINE
✓ GRIND
✓ POLISH TO 0.1 μ/MM
See page no. 2 for parts list

FIG 1 SECTIONAL DIAGRAM OF THE EXTRUSION TOOL

'Scale: Approx. \( \frac{1}{3} \) full size.
# Parts List for Extrusion Tool (Fig. 1)

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Description</th>
<th>Material</th>
<th>Heat Treatment Spec.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DIE SET</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>PRESSURE PAD</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>UPPER LOCATION RING</td>
<td>EN.25</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>EXTRUSION PUNCHES</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>DRAW BAR</td>
<td>SILVER STEEL</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>PUNCH ENDS</td>
<td>M2.H.S.S.</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>CLAMPING RING</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>OUTER DIE RING</td>
<td>EN.25</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>INNER DIE RING</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>DIE HOUSING</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>DIE CLAMP PLATE</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>DIE INSERT</td>
<td>M2.H.S.S.</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>LOWER PUNCH</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>14</td>
<td>PRESSURE PAD</td>
<td>D2.DIE STEEL</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>LOWER LOCATION RING</td>
<td>EN.25</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>DIE SUPPORT</td>
<td>EN.25</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>EJECTOR RODS</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>COMPRESSION SPRINGS</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>BUSHES</td>
<td>BRASS</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>WASHER</td>
<td>MILD STEEL</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>CAMPING NUTS</td>
<td>MILD STEEL</td>
<td></td>
</tr>
</tbody>
</table>

*See pages 4 and 5
HEAT TREATMENT SPECIFICATIONS FOR EXTRUSION AND COMPRESSION TOOL MATERIALS

**Specification 1**
Material: EN25

Preheat to 600°C, raise to 830°C, soak for 1 hour, light temper at 100°C-150°C.

Hardness: 52 Roc.C.

**Specification 2**
Material: EN8

Raise to 850°C, soak for 1 hour, oil quench, temper at 550°C.

Hardness: 39 Roc.C.

**Specification 3**
Material: H.S.S.(M2)

Preheat to 800°C, raise quickly to 1210°C x 3-4 minutes soak, quench into salts at 560°C and allow to equalise, temper twice by 1 hour at 620°C.

Hardness: 62-63 Roc.C.

**Specification 4**
Material: Die Steel(D2)

Preheat to 800°C, raise quickly to 1020°C x 45 minutes soak, martemper by quenching into salts at 200-220°C and allow to equalise, temper twice by 1 hour at 200°C.

Hardness: 61 Roc.C.
Material: EN25

Preheat to 600°C, raise to 830°C, soak for 1 hour,
oil quench, temper to 450°C

Hardness: 44 Roc.C.
3 HOLES DRILL & C/BORE
TO SUIT 3/8" BSF ON 131 P.C.D.

2 HOLES REAM
3/8" ON 131 P.C.D.

+0,00
-0,01
TAP 5/16 BSF
ON 90 P.C.D.

SECTION ON AA

1 OFF UPPER LOCATION RING - EN25 - HT.SPEC.1

DRILL 5/16"
CLEARANCE

1 OFF CLAMPING RING - MILD STEEL.
EXTRUSION PUNCHES - DIE STEEL - HT.SPEC.4
HEX. HEADS
TO SUIT
WELD & TURN
OFF FLUSH

DIMENSION 'A', 15
DIA.B

5 OFF DRAW BARS - SILVER STEEL

<table>
<thead>
<tr>
<th>TO FIT PUNCH OF NOMINAL SIZE (MM)</th>
<th>'A' (MM)</th>
<th>'B' DIA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>124</td>
<td>1/4 B.S.F.</td>
</tr>
<tr>
<td>25</td>
<td>124</td>
<td>1/4 B.S.F.</td>
</tr>
<tr>
<td>30'</td>
<td>130</td>
<td>5/16 B.S.F.</td>
</tr>
<tr>
<td>35</td>
<td>132</td>
<td>3/8 B.S.F.</td>
</tr>
<tr>
<td>40</td>
<td>165</td>
<td>3/8 B.S.F.</td>
</tr>
</tbody>
</table>
### 2 RADI

**'A' DIA.**

**'B' DIA**

**'C' DIA**

**THREAD 'D'**

10MM DEEP

---

<table>
<thead>
<tr>
<th>NOMINAL PUNCH SIZE (MM)</th>
<th>'A' DIA (MM)</th>
<th>NOMINAL 'B' DIA (INS)</th>
<th>'C' DIA (MM)</th>
<th>ANGLED PUNCHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20,00</td>
<td>3/8&quot;</td>
<td>19,90</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>25,00</td>
<td>1/2&quot;</td>
<td>24,90</td>
<td>$\theta = 60^\circ, 90^\circ, 120^\circ$</td>
</tr>
<tr>
<td>30</td>
<td>30,00</td>
<td>1/2&quot;</td>
<td>29,90</td>
<td>$\theta = 90^\circ$</td>
</tr>
<tr>
<td>35</td>
<td>35,00</td>
<td>3/4&quot;</td>
<td>34,90</td>
<td>$\theta = 90^\circ$</td>
</tr>
<tr>
<td>40</td>
<td>40,00</td>
<td>3/4&quot;</td>
<td>39,90</td>
<td></td>
</tr>
<tr>
<td>±0,005</td>
<td>TO SUIT PUNCHES</td>
<td></td>
<td>±0,005</td>
<td></td>
</tr>
</tbody>
</table>

**10 OFF PUNCH ENDS - H.S.S. - HT.SPEC.3**

---

[Diagram of punch dimensions and angles]
### RADII PUNCHES

<table>
<thead>
<tr>
<th>NOMINAL PUNCH DIAMETER (MM)</th>
<th>RADII ANGLE $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>73°</td>
</tr>
<tr>
<td>25</td>
<td>70°</td>
</tr>
<tr>
<td>30</td>
<td>64°</td>
</tr>
</tbody>
</table>

ALL DIMENSIONS AS DET.6

3 OFF PUNCH ENDS - H.S:S. - HT.SPEC.3
9

1 OFF INNER DIE RING - DIE STEEL - HT.SPEC.4

8

1 OFF OUTER DIE RING - EN25 - HT.SPEC.5

*Finish Grind after assy. to det.10.
6 HOLES DRILL 7 DIA.
EQUISPACED ON 190 P.C.D.

1 OFF DIE CLAMP PLATE - MILD STEEL

2 OFF EJECTOR RODS - MILD STEEL
6 HOLES TAP 5/16" B.S.W. EQUISPACED ON 190 DIA.

C/BORE 30 DIA.

SECTION ON AA

1 OFF DIE HOUSING - MILD STEEL

Bore to suit det. 10 after assy. with det. 9.
1.5 RAD.

1 @ 45°

13  1 OFF LOWER PUNCH - DIE STEEL - HT.SPEC.4

MAINTAIN SHARP EDGES

-0.03

50.00
DIA

-0.05

12  2 OFF DIE INSERTS - H.S.S. - HT.SPEC.3

-0.03

50.00
DIA

-0.05

2  2 OFF PRESSURE PADS - DIE STEEL - HT.SPEC.4
2 HOLES REAM 3/8" DIA. ON 131 P.C.D.

3 HOLES DRILL & C/BORE TO SUIT 3/8" BSW ON 131 P.C.D.

3 HOLES DRILL & C/BORE 3/16" B.S.F. ON 63 P.C.D.

SECTION ON AA

15 1 OFF LOWER LOCATION RING - EN25 - HT.SPEC.1

19 2 OFF BUSHES - BRASS

20 2 OFF WASHERS - MILD STEEL
22 HOLES DRILL & TAP 3/8 B.S.F. & G/BORE

1 OFF DIE SUPPORT - EN25 - HT, SPEC. 1

12, 5 RAD.
BLEND
RADIUS

2 OFF SUPPORT HANDLES - ALUMINIUM
COMPRESSION TOOL DETAIL DRAWINGS

THIRD ANGLE PROJECTION USED THROUGHOUT

ALL DIMENSIONS IN MM UNLESS OTHERWISE STATED

TOLERANCES AS SPECIFIED (NOMINAL ±0,5MM)

✓ MACHINE

✓ GRIND

✓ POLISH TO 0,1 μ/MM
# PARTS LIST

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base</td>
<td>EN25</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Shaft Support</td>
<td>Mild Steel</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Shaft</td>
<td>EN8</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Upper Anvil</td>
<td>M2. H.S.S.</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Lower Anvil</td>
<td>M2. H.S.S.</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Alignment Pad</td>
<td>M2. H.S.S.</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>Bush</td>
<td>Brass</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pillars</td>
<td>Mild Steel</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Washer</td>
<td>Rubber</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Transducer Support</td>
<td>Mild Steel</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Linear Transducer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Specimen</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*see pages 4 and 5

**Det 8 3 Off, one only shown for clarity

---

** FIG 2 SIMPLE COMPRESSION TOOL SHOWN IN HALF SECTION **

Scale: Approx $\frac{2}{3}$ full size.
3  1 OFF SHAFT - EN8 - HT.SPEC.2

45  2 OFF ANVILS - H.S.S. - HT.SPEC.3
3 HOLES EQUISPACED ON 120 P.C.D. DRILL 3/8" CLEARANCE

C/BORE

TO SUIT 3/8" BSF

SECTION ON AA

1 OFF BASE - EN25 - HT SPEC 1
3/8" CLEARANCE

5/8" REAM

1/8" REAM

3 HOLES ON 120 P.C.D.

89 DIA

70 DIA

P/F/T

3/8" CLEARANCE

5/8" REAM

150 DIA

45

32

4/3

SECTION ON AA

1 OFF SHAFT SUPPORT - MILD STEEL
1 OFF ALIGNMENT PAD - H.S.S. - HT.SPEC.3

1 OFF BUSH - BRASS

3 OFF PILLARS - MILD STEEL

*All 3 same ±0.005mm.
REAM 3/8"

2 HOLES TAP
2 B.A.

TAP THRO'
4 B.A.

DIA. 63.15 ± 0.005
DIA. 76

1 OFF TRANSDUCER SUPPORT - MILD STEEL
APPENDIX III

AVITZUR'S UPPER BOUND SOLUTION
The early stage of impact extrusion is represented as in Fig. (1) where the billet is split into four zones. Zone 3 moves upwards as a rigid body, zone 2 is undergoing deformation whilst zone 1 has yet to be deformed. Zone 4 is a dead metal region and moves downwards into the punch; the angle $\alpha$ which defines the geometry of the model is critical, and is optimised to establish the upper bound load.

For convenience Fig. (1) is redrawn as Fig. (2) which simplifies calculation, and a velocity field is established for zone 2. An equation for the normalized ram pressure is derived, (eqon. 4 ref. 1) and when inertia and external pressure effects are neglected, becomes
\[
\frac{PR}{\sigma_0} = \frac{2}{\sqrt{3}} \left[ \frac{1}{1 - \left(\frac{R_f}{R_o}\right)^2} \right] \left\{ \sqrt{3} \, f(\alpha) \ln \frac{R_o}{R_f} + \frac{\alpha}{\sin \alpha} - \cot \alpha \right. \\
+ (\cot \alpha) \ln \frac{R_o}{R_f} + m \left[ \frac{h}{R_f} + \frac{R_f}{R_o} \left( \frac{D}{R_f} + \left(\frac{R_o}{R_f} - 1\right) \cot \alpha \right) \right] \right\}
\]

where

\[
f(\alpha) = \frac{1}{\sin \alpha} \left[ 1 - (\cot \alpha) \sqrt{1 - \frac{11}{12} \sin^2 \alpha} \ + \ \frac{1}{\sqrt{11.12}} \ln \left( \frac{1 + \sqrt{\frac{11}{12}}}{\sqrt{\frac{11}{12} \cos \alpha + \sqrt{1 - \frac{11}{12} \sin^2 \alpha}}} \right) \right]
\]

and

\begin{align*}
PR & = \text{average ram pressure} \\
\sigma_0 & = \text{yield strength in uniaxial tension} \\
R_f & = \text{ram radius} \\
R_o & = \text{chamber radius} \\
\alpha & = \text{dead zone angle} \\
h & = \text{height of ram} \\
D & = \text{see Fig. (2)} \\
m & = \text{friction factor}
\end{align*}
The optimum value of $\alpha$ is the one which minimises the value of ram pressure under that particular set of conditions.

The solution to equation (4) is found simply by computer programme which establishes an optimum value of $\alpha$ and consequently an optimum ram pressure for a variety of friction conditions.

As illustrated by Fig. (3) (Fig.3 ref. 1) the ram pressure remains substantially constant for a wide range of values of $\alpha$, and the actual optimum value is difficult to establish. When comparing $\alpha_{\text{opt.}}$ with real experimental values of $\alpha$, this point should be born in mind.

**FIGURE 3**: RELATIVE RAM PRESSURE AS A FUNCTION OF DEAD ZONE ANGLE

**COMPUTER PROGRAMME FOR SOLUTION OF UPPER BOUND LOADS**

The following computer programme was written for the solution of equations (1) and (2). Figs. (7.2 and 7.3) chapter (7) illustrate the results graphically and are used to compare practical values of $\alpha$ and PR/\$\sigma_0$

```
0001    LIST
0002    SEND TO (ED, SEMICOMPUTER.AXXX)
0003    DUMP ON (ED, PROGRAM USER)
0004    WORK (ED, WORKFILEUSER)
0005    RUN
0006    LIBRARY (ED, SUBGROUP NAGF)
0007    PROGRAM (AVITZUR)
0008    COMPACT
0009    COMPRESS INTEGER AND LOGICAL
```
INPUT 1 = CRO
OUTPUT 2 = LPO
TRACE 2
END

MASTER FIRST
DIMENSION RT(12)
COMMON/B1/RAT,F,DEPTH
EXTERNAL FUN
READ(1,100) (RT(I),I=1,12)
100 FORMAT(F0.0)
DO 1 I1=1,2
DEPTH=0.1+0.4*(I1-1.)
DO 1 I2=1,5
F=0.+0.25*(I2-1.)
WRITE(2,200) DEPTH,F
200 FORMAT(' NEW VALUES DEPTH = ',F6.2,' F = ',F6.2 />
DO 1 13=1,12
RAT=RT(13)
ALPA=60.
XSTEP=10.
ABSACC=0.5E-01
RELACC=0.5E-06
MAX=30
IF=1
CALL E04AAF(ALPA,ABSP,ABSACC,RELACC,XSTEP,FUN,MAX,IFA)
IF(IFA.GE.1)
WRITE(2,202)
202 FORMAT(' PROBLEMS IN OPT. ROUTINE IFA = 1,12)
WRITE(2,201) RAT,ABSP,ALPA
201 FORMAT('X.F5.2,5X,F10.6,5Y.,F6.2)
CONTINUE
STOP
END

END OF SEGMENT, LENGTH 164, NAME FIRST

SUBROUTINE FUN(ALPA,ABSP)
COMMON/B1/RAT,F,DEPTH
PI=3.1415926536
LAND=RAT/25.
FR=0.9166667
DR=0.2998801
RALP=ALPA*PI/180.
SRA=SIN(RALP)
SSRA=SRA*SRA
FAL01./SSRA*(1.-COS(RALP)*SQRT(1.-FR*SSRA)
+DR*ALOG((1.+SQRT(FR))/(SQRT(FR*COS(RALP)))+SQRT(1.-FR*SSRA))))
ABSP=2./SQRT(3.)*(1.-1./((RAT*RAT)))
1.*(SQRT(3.)*FAL*Aalog(RAT)+(RALP/SSRA)-COT(RALP)+COT(RALP)*Aalog
2(RAT)+F*(LAND+1./RAT*(DEPTH+(RAT-1.)*COT(RALP))))
100 FORMAT(3(2X,E16.9))
RETURN
END
(2) SOLUTION FOR NOSED RAM

Where a dead metal zone prevails, material must shear over itself, thus increasing the ram pressure. As shear losses are proportional to \( \frac{\sigma_0}{\sqrt{3}} \) and friction losses proportional to \( \mu \frac{\sigma_0}{\sqrt{3}} \) (where \( \mu \) varies between 0 and 1) it is desirable to replace the flat ram with a nosed ram, the dimensions of which \((\alpha)\) are optimised to minimise the ram pressure.

In this case equation (1) becomes

\[
\frac{PP}{\sigma_0} = \frac{2}{\sqrt{3}} \left[ \frac{1}{1 - \left( \frac{R_f}{R_o} \right)^2} \right] \left\{ \sqrt{3} f(\alpha) \ln \frac{R_o}{R_f} + \frac{\alpha}{2 \sin^2 \alpha} - \frac{\cot \alpha}{2} \right. \\
+ \left( \cot \alpha \right) \ln \frac{R_o}{R_f} + m \left[ \frac{h}{R_f} + \frac{R_f}{R_o} \left[ \frac{D}{R_f} + \left( \frac{R_o}{R_f} - 1 \right) \cot \alpha \right] \right. \\
+ \frac{1}{2} \left[ \frac{\alpha}{\sin \alpha} - \cot \alpha \right] \right\}
\]

The original computer programme is now modified to accommodate the changes which result, as follows:

for lines 55 and 56 insert

55 \((1* (\text{SQRT}(3.)*\text{FAL})*\text{ALOG}(\text{RAT})+(\text{RALP/SSRA/2.})-\text{COT}(\text{RALP})/2.+\text{COT}(\text{RALP})*\text{ALO})\)

56 \(2G(\text{RAT})+F*(\text{LAND+1./RAT}*(\text{DEPTH+RAT-1.})*\text{COT}(\text{RALP}))+.5*(\text{RALP/SSRA-COT})\)

The solutions for both flat and nosed rams are compared in Fig.(7.4) chapter (7).
Avitzur's equation for the minimum external pressure to prevent cavitation (eqn. 16 ref 30) is found to be:

\[
P = \frac{1}{\rho_0} \left[ 1 + \ln \left( \frac{\rho_0}{\rho_f} \right)^2 \right] + \frac{1 - \left( \frac{\rho_0}{\rho_f} \right)^2}{3\sqrt{3}} \left( 2 \frac{T}{\rho_0/\rho_f} \right)^2
\]

\[
\frac{4 \rho_0/\rho_f - 3 - \left( \frac{\rho_f}{\rho_0} \right)^2}{\left( \frac{\rho_0/\rho_f}{\rho_0/\rho_f} - 1 \right)^{3/2}} - \frac{3 \rho_0}{2T}
\]

\[
- \ln \left( \frac{\rho_0}{\rho_f} \right)^2 \left( 1 - \frac{\rho_0}{\rho_f} \right)^2 \left( \frac{H \rho_0}{\rho_f \rho_f} + h \right)
\]

where

- \( P \) = pressure applied to annular cross section of emerging can
- \( T \) = distance between ram and bottom of chamber
- \( H \) = height of chamber wall

and inertia effects are neglected, see Fig.4.

Where no external pressure is applied, the value of \( T/\rho_0 \) becomes critical, and a value of minimum slug thickness to prevent cavitation versus reduction and friction can be calculated. This is plotted in Fig.(7.6) chapter (7).

For the solution of eqn.(4) let \( P/\rho_0 = 0 \) and solve for \( T/\rho_0 \).

This is done as follows.

Let \( x = \rho_0/\rho_f \)

\[ y = \rho_0/T \]

Multiply R.H.S. of equation by \( y \), then

\[ 0 = Ay^2 + by + C \]
where
\[ A = -\frac{(1-x^2)(1+m)}{2\sqrt{3}} \]
\[ B = 1 + \frac{\ln(x^2)}{(1-x^2)} + \frac{2m}{3(1-x^2)} \left( \frac{H}{R_f}x + \frac{h}{R_f} \right) \]
\[ C = -\frac{2x^2(4x-3-\frac{1}{x})}{3\sqrt{3}(1-x^2)^2} \]

COMPUTER PROGRAMME FOR SOLUTION OF CAVITATION EQUATION

Equation (5) is simply solved by computer programme as follows

```
   1. MASTER MALAKA
   2. C1=0.3
   3. C2=0.01
   4. DO 1 I=1,2
   5. F=FLOAT(I-1)
   6. WRITE(2,200) F
   7. DO 1 J=1,20
   8. X=1.+FLOAT(J)/100.
   9. XSQ=X*X
  10. X1=1.-XSQ
  11. X2=X1/3./SQRT(3.)
  12. A=-1.5*X2*(1.+F)
  13. B=1.+ALOG(XSQ)/X1+6.*F*X2/X1/X1*(C1*X+C2)
  14. C=2.*X2*XSQ*(4.*X-3.-1./X/X)/X1/X1/X1
  15. C=-C
  16. Z=(B*B-4.*A*C)
  17. SQR=SQRT(Z)
  18. Y1=2.*A/(B+SQR)
  19. Y2=2.*A/(-B-SQR)
 20. WRITE(2,201) X,Y1,Y2
21. 200 FORMAT(///'NEW VALUE OF M = ',F6.2///'X=RO/RF  T/RO  T/1',/)
22. 201 FORMAT (/,4(1X,F7,3))
23. 1 CONTINUE
24. STOP
25. END
```

The solution is plotted graphically in Fig.(7.6) chapter (7).
APPENDIX IV

TABULATED DATA
TABLE NO. 1

COMPRESSION TEST DATA

SLUG DIMENSIONS: 19.05MM DIA x 19.05MM

<table>
<thead>
<tr>
<th>SLUG HEIGHT (MM)</th>
<th>LOAD (KN)</th>
<th>TRUE STRESS σ (N/MM²)</th>
<th>ho/h</th>
<th>TRUE STRAIN ε = Ln ho/h</th>
<th>MEAN YIELD STRESS τ (N/MM²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.42</td>
<td>35</td>
<td>119</td>
<td>1.032</td>
<td>0.032</td>
<td>58</td>
</tr>
<tr>
<td>17.78</td>
<td>57</td>
<td>188</td>
<td>1.068</td>
<td>0.068</td>
<td>111</td>
</tr>
<tr>
<td>16.47</td>
<td>80</td>
<td>244</td>
<td>1.153</td>
<td>0.142</td>
<td>166</td>
</tr>
<tr>
<td>15.24</td>
<td>98</td>
<td>276</td>
<td>1.250</td>
<td>0.223</td>
<td>210</td>
</tr>
<tr>
<td>13.97</td>
<td>114</td>
<td>295</td>
<td>1.362</td>
<td>0.309</td>
<td>232</td>
</tr>
<tr>
<td>12.70</td>
<td>130</td>
<td>306</td>
<td>1.500</td>
<td>0.406</td>
<td>248</td>
</tr>
<tr>
<td>11.43</td>
<td>150</td>
<td>316</td>
<td>1.664</td>
<td>0.509</td>
<td>261</td>
</tr>
<tr>
<td>10.16</td>
<td>173</td>
<td>324</td>
<td>1.874</td>
<td>0.628</td>
<td>273</td>
</tr>
<tr>
<td>8.89</td>
<td>202</td>
<td>332</td>
<td>2.142</td>
<td>0.760</td>
<td>282</td>
</tr>
<tr>
<td>7.62</td>
<td>237</td>
<td>334</td>
<td>2.500</td>
<td>0.916</td>
<td>290</td>
</tr>
<tr>
<td>6.35</td>
<td>287</td>
<td>336</td>
<td>3.000</td>
<td>1.100</td>
<td>326</td>
</tr>
<tr>
<td>5.08</td>
<td>358</td>
<td>336</td>
<td>3.750</td>
<td>1.322</td>
<td>327</td>
</tr>
<tr>
<td>3.81</td>
<td>472</td>
<td>336</td>
<td>5.000</td>
<td>1.609</td>
<td>330</td>
</tr>
</tbody>
</table>
# TABLE NO. 2

## RE-LUBRICATED COMPRESSION TEST DATA

<table>
<thead>
<tr>
<th>PUNCH TRAVEL (MM)</th>
<th>PUNCH LOAD (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>42</td>
</tr>
<tr>
<td>0.58</td>
<td>59</td>
</tr>
<tr>
<td>1.27</td>
<td>78</td>
</tr>
<tr>
<td>2.13</td>
<td>95</td>
</tr>
<tr>
<td>3.02</td>
<td>109</td>
</tr>
<tr>
<td>4.06</td>
<td>122</td>
</tr>
<tr>
<td>4.93</td>
<td>135</td>
</tr>
<tr>
<td>5.92</td>
<td>150</td>
</tr>
<tr>
<td>7.52</td>
<td>173</td>
</tr>
<tr>
<td>7.77</td>
<td>195</td>
</tr>
<tr>
<td>8.66</td>
<td>218</td>
</tr>
<tr>
<td>9.68</td>
<td>253</td>
</tr>
<tr>
<td>10.57</td>
<td>289</td>
</tr>
<tr>
<td>11.48</td>
<td>334</td>
</tr>
<tr>
<td>12.19</td>
<td>383</td>
</tr>
<tr>
<td>13.02</td>
<td>439</td>
</tr>
<tr>
<td>13.61</td>
<td>501</td>
</tr>
</tbody>
</table>
### TABLE NO. 3

**DATA FOR INDIRECT FLAT PUNCH EXTRUSION**

**(BILLET H:D=1)**

<table>
<thead>
<tr>
<th>EXTRUSION RATIO</th>
<th>MAX. PUNCH LOAD (KN)</th>
<th>EXTRUSION PRESSURE (N/mm²)</th>
<th>PUNCH STRESS (N/mm²)</th>
<th>Ln(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.19</td>
<td>409</td>
<td>208</td>
<td>1300</td>
<td>0.174</td>
</tr>
<tr>
<td>1.33</td>
<td>590</td>
<td>301</td>
<td>1200</td>
<td>0.285</td>
</tr>
<tr>
<td>1.56</td>
<td>808</td>
<td>412</td>
<td>1140</td>
<td>0.445</td>
</tr>
<tr>
<td>1.96</td>
<td>1145</td>
<td>584</td>
<td>1190</td>
<td>0.673</td>
</tr>
<tr>
<td>2.78</td>
<td>1536</td>
<td>782</td>
<td>1220</td>
<td>1.022</td>
</tr>
</tbody>
</table>
TABLE NO. 4

DATA FOR DIRECT FLAT PUNCH EXTRUSION

(BILLET H/D=1)

<table>
<thead>
<tr>
<th>EXTRUSION RATIO</th>
<th>MAX. PUNCH LOAD (KN)</th>
<th>EXTRUSION PRESSURE (N/mm²)</th>
<th>PUNCH STRESS (N/mm²)</th>
<th>ln(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.33</td>
<td>625</td>
<td>318</td>
<td>1270</td>
<td>0.285</td>
</tr>
<tr>
<td>1.56</td>
<td>835</td>
<td>425</td>
<td>1180</td>
<td>0.445</td>
</tr>
<tr>
<td>1.96</td>
<td>1155</td>
<td>588</td>
<td>1200</td>
<td>0.673</td>
</tr>
<tr>
<td>2.78</td>
<td>1550</td>
<td>790</td>
<td>1230</td>
<td>1.022</td>
</tr>
</tbody>
</table>
### TABLE NO. 5

**HOMOGENEOUS DEFORMATION PUNCH LOADS**

<table>
<thead>
<tr>
<th>PUNCH DIA (mm)</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXTRUSION RATIO</td>
<td>1.19</td>
<td>1.33</td>
<td>1.56</td>
<td>1.96</td>
<td>2.78</td>
</tr>
<tr>
<td>( \log e ) STRAIN ( e )</td>
<td>0.174</td>
<td>0.285</td>
<td>0.445</td>
<td>0.673</td>
<td>1.022</td>
</tr>
<tr>
<td>( \sigma _n (N/mm^2) )</td>
<td>194</td>
<td>226</td>
<td>254</td>
<td>277</td>
<td>295</td>
</tr>
<tr>
<td>THEORETICAL PUNCH FORCE</td>
<td>68</td>
<td>131</td>
<td>229</td>
<td>378</td>
<td>612</td>
</tr>
<tr>
<td>( L_h ) (KN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OBSERVED PUNCH FORCE</td>
<td>409</td>
<td>590</td>
<td>808</td>
<td>1145</td>
<td>1536</td>
</tr>
<tr>
<td>( L_e ) (KN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RATIO ( L_h / L_e ) %</td>
<td>16.7</td>
<td>22.2</td>
<td>28.4</td>
<td>33.1</td>
<td>39.9</td>
</tr>
</tbody>
</table>

**DATA FROM REFS. (36, 37)**

<table>
<thead>
<tr>
<th>EXTRUSION RATIO</th>
<th>1.43</th>
<th>1.92</th>
<th>2.49</th>
<th>3.37</th>
<th>5.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATIO ( L_h / L_e ) %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COPPER*</td>
<td>24.8</td>
<td>30.8</td>
<td>37.7</td>
<td>42.9</td>
<td>48.0</td>
</tr>
<tr>
<td>EN**</td>
<td>16.2</td>
<td>26.7</td>
<td>32.8</td>
<td>38.1</td>
<td>44.1</td>
</tr>
</tbody>
</table>

*REF(36)
**REF(37)
### Table No. 6

**Loads for 12.7mm Punch Travel**

<table>
<thead>
<tr>
<th>Extrusion Ratio</th>
<th>1.33</th>
<th>1.56</th>
<th>1.96</th>
<th>2.78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect Extrusion</td>
<td>515</td>
<td>725</td>
<td>1000</td>
<td>1350</td>
</tr>
<tr>
<td>Direct Extrusion</td>
<td>600</td>
<td>825</td>
<td>1100</td>
<td>1500</td>
</tr>
</tbody>
</table>
TABLE NO. 7

EFFECT OF PUNCH ANGLE ON EXTRUSION LOAD

(R=1.33)

<table>
<thead>
<tr>
<th>PUNCH ANGLE</th>
<th>MAXIMUM PUNCH LOAD (KN)</th>
<th>DIRECT EXTRUSION</th>
<th>INDIRECT EXTRUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>625</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>2.5°</td>
<td>620</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>5°</td>
<td>610</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>10°</td>
<td>585</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>590</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>595</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td>620</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>670</td>
<td>645</td>
<td></td>
</tr>
</tbody>
</table>
TABLE NO. 8

EFFECT OF BILLET LENGTH ON PUNCH AND EJECTION LOADS

<table>
<thead>
<tr>
<th>BILLET H:D RATIO</th>
<th>MAX. PUNCH LOAD (KN)</th>
<th>MAX EJECTION LOAD (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>420</td>
<td>16</td>
</tr>
<tr>
<td>0.50</td>
<td>515</td>
<td>30</td>
</tr>
<tr>
<td>0.75</td>
<td>560</td>
<td>41</td>
</tr>
<tr>
<td>1.00</td>
<td>590</td>
<td>64</td>
</tr>
<tr>
<td>1.25</td>
<td>600</td>
<td>77</td>
</tr>
</tbody>
</table>
TABLE NO. 9

EFFECT OF REDUCTION ON DEAD ZONE ANGLE
WITH FLAT PUNCH

<table>
<thead>
<tr>
<th>EXPERIMENTAL VALUES Ro/Rf</th>
<th>$\alpha$</th>
<th>$\alpha^o_{opt}$ (M=1)</th>
<th>$\alpha^o_{opt}$ (M=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>73</td>
<td>46.68</td>
<td>32.23</td>
</tr>
<tr>
<td>2.0</td>
<td>70</td>
<td>52.57</td>
<td>39.83</td>
</tr>
<tr>
<td>1.66</td>
<td>64</td>
<td>59.36</td>
<td>46.25</td>
</tr>
<tr>
<td>1.25</td>
<td></td>
<td>64.63</td>
<td>51.93</td>
</tr>
<tr>
<td>1.46</td>
<td></td>
<td>68.74</td>
<td>56.95</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>70.89</td>
<td>59.96</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td>72.22</td>
<td>62.04</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>73.11</td>
<td>63.55</td>
</tr>
<tr>
<td>3.5</td>
<td></td>
<td>73.75</td>
<td>64.70</td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td>74.22</td>
<td>65.61</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>74.59</td>
<td>66.35</td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td>74.91</td>
<td>66.96</td>
</tr>
<tr>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## TABLE NO. 10

**EXTRUSION WITH NOSED PROFILES**

<table>
<thead>
<tr>
<th>EXTRUSION RATIO</th>
<th>MAX. EXTRUSION LOAD (KN)</th>
<th>MAX. EXTRUSION LOAD (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROUGH END</td>
<td>SMOOTH END</td>
</tr>
<tr>
<td>H:D RATIO=1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.19</td>
<td>374</td>
<td>322</td>
</tr>
<tr>
<td>1.33</td>
<td>542</td>
<td>502</td>
</tr>
<tr>
<td>1.56</td>
<td>796</td>
<td>670</td>
</tr>
</tbody>
</table>

*still increasing*
TABLE NO. 11

UPPER BOUND RAM PRESSURES FOR EXTRUSION
WITH FLAT RAM

\( \frac{P}{\rho_0} = 0, \frac{h}{R_f} = 0.1 \)

<table>
<thead>
<tr>
<th>( \frac{R_0}{R_f} )</th>
<th>( \frac{PR}{\rho_0} )</th>
<th>EXPERIMENTAL VALUES ( \frac{PR}{\rho_0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( m=0 )</td>
<td>( m=1 )</td>
</tr>
<tr>
<td>1.25</td>
<td>3.73</td>
<td>4.81</td>
</tr>
<tr>
<td>1.43</td>
<td>3.62</td>
<td>4.43</td>
</tr>
<tr>
<td>1.67</td>
<td>3.71</td>
<td>4.36</td>
</tr>
<tr>
<td>2.00</td>
<td>3.95</td>
<td>4.50</td>
</tr>
<tr>
<td>2.50</td>
<td>4.34</td>
<td>4.82</td>
</tr>
<tr>
<td>3.00</td>
<td>4.71</td>
<td>5.15</td>
</tr>
<tr>
<td>3.50</td>
<td>5.06</td>
<td>5.47</td>
</tr>
<tr>
<td>4.00</td>
<td>5.37</td>
<td>5.76</td>
</tr>
<tr>
<td>4.50</td>
<td>5.65</td>
<td>6.03</td>
</tr>
<tr>
<td>5.00</td>
<td>5.91</td>
<td>6.28</td>
</tr>
<tr>
<td>5.50</td>
<td>6.15</td>
<td>6.51</td>
</tr>
<tr>
<td>6.00</td>
<td>6.37</td>
<td>6.72</td>
</tr>
</tbody>
</table>
**TABLE NO. 12**

**UPPER BOUND RAM PRESSURES FOR EXTRUSION**

**WITH NOSED RAM**

\[ \frac{p}{\sigma_0} = 0, \quad \frac{h}{R_f} = 0.1 \]

<table>
<thead>
<tr>
<th>Ro/Rf</th>
<th>PR/σ₀</th>
<th>OPT.α₀</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m=0</td>
<td>m=1</td>
<td>m=0</td>
<td>m=1</td>
</tr>
<tr>
<td>1.25</td>
<td>3.00</td>
<td>4.81</td>
<td>43.81</td>
<td>43.68</td>
</tr>
<tr>
<td>1.43</td>
<td>2.97</td>
<td>4.43</td>
<td>52.47</td>
<td>52.57</td>
</tr>
<tr>
<td>1.67</td>
<td>3.10</td>
<td>4.36</td>
<td>58.78</td>
<td>59.36</td>
</tr>
<tr>
<td>2.00</td>
<td>3.35</td>
<td>4.50</td>
<td>63.55</td>
<td>64.63</td>
</tr>
<tr>
<td>2.50</td>
<td>3.76</td>
<td>4.82</td>
<td>67.24</td>
<td>68.74</td>
</tr>
<tr>
<td>3.00</td>
<td>4.13</td>
<td>5.15</td>
<td>69.18</td>
<td>70.89</td>
</tr>
<tr>
<td>3.50</td>
<td>4.47</td>
<td>5.47</td>
<td>70.43</td>
<td>72.22</td>
</tr>
<tr>
<td>4.00</td>
<td>4.78</td>
<td>5.76</td>
<td>71.40</td>
<td>73.11</td>
</tr>
<tr>
<td>4.50</td>
<td>5.05</td>
<td>6.03</td>
<td>72.11</td>
<td>73.75</td>
</tr>
<tr>
<td>5.00</td>
<td>5.31</td>
<td>6.28</td>
<td>72.41</td>
<td>74.22</td>
</tr>
<tr>
<td>5.50</td>
<td>5.47</td>
<td>6.51</td>
<td>72.79</td>
<td>74.59</td>
</tr>
<tr>
<td>6.00</td>
<td>5.77</td>
<td>6.72</td>
<td>73.11</td>
<td>74.91</td>
</tr>
</tbody>
</table>
TABLE NO. 13

UPPER BOUND SOLUTION FOR PREVENTION OF CAVITATION

<table>
<thead>
<tr>
<th>RELATIVE WALL THICKNESS Ro/Rf</th>
<th>SLUG THICKNESS/CYL. RADIUS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m=0</td>
</tr>
<tr>
<td>1.01</td>
<td>0.010</td>
</tr>
<tr>
<td>1.02</td>
<td>0.020</td>
</tr>
<tr>
<td>1.03</td>
<td>0.031</td>
</tr>
<tr>
<td>1.04</td>
<td>0.041</td>
</tr>
<tr>
<td>1.05</td>
<td>0.052</td>
</tr>
<tr>
<td>1.06</td>
<td>0.063</td>
</tr>
<tr>
<td>1.07</td>
<td>0.074</td>
</tr>
<tr>
<td>1.08</td>
<td>0.085</td>
</tr>
<tr>
<td>1.09</td>
<td>0.096</td>
</tr>
<tr>
<td>1.10</td>
<td>0.108</td>
</tr>
<tr>
<td>1.11</td>
<td>0.120</td>
</tr>
<tr>
<td>1.12</td>
<td>0.131</td>
</tr>
<tr>
<td>1.13</td>
<td>0.143</td>
</tr>
<tr>
<td>1.14</td>
<td>0.155</td>
</tr>
<tr>
<td>1.15</td>
<td>0.167</td>
</tr>
<tr>
<td>1.16</td>
<td>0.179</td>
</tr>
<tr>
<td>1.17</td>
<td>0.192</td>
</tr>
<tr>
<td>1.18</td>
<td>0.204</td>
</tr>
<tr>
<td>1.19</td>
<td>0.217</td>
</tr>
<tr>
<td>1.20</td>
<td>0.229</td>
</tr>
</tbody>
</table>