COMPUTER SIMULATION
OF PRODUCT AUGMENTED HYDROSTATIC EXTRUSION

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by

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CHAPTER ONE  INTRODUCTION

1.1 Historical Development

Extrusion is a deformation process in which a billet is forced through a shaped die by a mechanically or hydraulically driven ram in a rigid container and consequently a continuous product of uniform cross-section is produced. Figure 1.1 illustrates the simplest form of the extrusion process.

![Diagram of the extrusion process](image)

**Figure 1.1 Diagram of the extrusion process**

Although the techniques of extrusion are successfully used in industry today, it is believed that the earliest perception of the principles of extrusion was made by a British engineer Joseph Bramah by which he granted a patent
in 1797 [1]. Bramah’s idea was not developed immediately until Thomas Burr constructed his hydraulically powered press in 1820 which was modified by J. and C. Hanson to produce lead pipes in 1837 [1].

By mid-century, the process of producing lead pipes by extrusion had become firmly established; however, the problem of corrosion became obvious and coating molten tin inside the extruded pipes was one simple solution often practiced. In 1863, Shaw used a press in which precast hollow billets of lead, with an internally cast sleeve of tin, were charged into the container to produce a bimetallic pipe [1]. Four years later, Hamon modified the process by heating the container [1].

In 1870, the indirect, or inverted, extrusion was introduced by two independent sources — Haines and J. and W. Weems which made it possible to produce a more uniform coating of tin in the pipes [1]. Ten years later, Eaton designed a vertical press to produce lead-shielded cables [1].

After almost one century’s development in extrusion techniques, the material used in extrusion process still limited to lead until Alexander Dick invented the hot extrusion process in 1883, which now has become one of the major metal working processes after being extended [1]. At the same time Alexander Dick was developing his versatile press by employing hydrostatic pressure, but the first
patent was granted to Robertson in 1894 [1]. Experimental results of hydrostatic extrusion were not available until Bridgman [2] invented his high-pressure seal in 1949 and spent the rest of his life doing experiments which led to a mountain of research papers on the subject [2].

Systematic research in hydrostatic extrusion of materials was started in England by Pugh who developed the process to the extent of industrial production [3]. In the Soviet Union, Vereshehayin of the High Pressure Laboratory of the Academy of Sciences began the study of high pressure, and the first result appeared in 1957 [4]. The first seminar on hydrostatic metal working process was held at Battelle Columbus Laboratories in 1967 [3]. Today, the techniques of hydrostatic extrusion have been established as an industrial process and applied to the manufacture of copper tubing, aluminum wire, and so on.

1.2 Types of Extrusion

1.2.1 Direct Extrusion

Direct extrusion is a conventional process and is the most common production method in use. As illustrated in Figure 1.2, a billet which placed in a strong-walled container is extruded through a suitably shaped die under the powerful pressure exerted by a ram.
In the process of direct extrusion, the material is in contact with three components: die, container and ram; thus, part of the extrusion energy is wasted in overcoming the friction. Also, if the material has a strong tendency to adhere the container, then the peripheral layer of the material close to the wall moves more slowly than the inner layer which will cause product defects. To solve this problem lubricants were introduced and in most of the cases they did serve very well; however, several noted cases of surface defects have been caused by an excess or shortage of lubricants [5].

![Diagram of Direct Extrusion](image)

**Figure 1.2 Direct extrusion**

### 1.2.2 Indirect Extrusion

In indirect extrusion, as illustrated in Figure 1.3, the die is placed at the end of the ram which moves
relative to the container, hence the friction between the billet and the container is eliminated.

![Diagram of indirect extrusion](image)

**Figure 1.3 Indirect extrusion**

### 1.2.3 Hydrostatic Extrusion

Hydrostatic extrusion is essentially the process by which a billet is extruded through a die by a high-pressure liquid acting as the pressure medium, instead of by direct application of force by a ram, as in conventional direct extrusion. In the process of hydrostatic extrusion, as seen in Figure 1.4, the billet is forced through the die from a high-pressure chamber into an atmospheric-pressure or a low-pressure chamber. Here the material is surrounded by the pressurized liquid and is in contact with the die
only. In fact, when hydrodynamic lubrication prevails, even contact with the die is avoided.

In an attempt to obtain a large extrusion ratio with low hydrostatic pressure, the process of augmented hydrostatic extrusion has been developed, in which a supplementary mechanical force is applied to improve the displacement of the billet or of the product. Depending on the manner in which the additional axial load is applied, the process is classified as either billet-augmented hydrostatic extrusion or product-augmented hydrostatic extrusion. In the former, the supplementary load is transmitted onto the back end of the billet by a ram. In the latter, the additional axial load is a tensile force applied to the front end of the product by a cable.

Figure 1.4 Hydrostatic extrusion
1.3 Scope of the Study

This investigation is a study of product augmented hydrostatic extrusion of aluminum. The problem is investigated both analytically as well as numerically. The two techniques are namely the slab method and the finite element method. In the first one, formulas are derived and a Fortran program is written. The investigation includes three different die angles (30°, 45° and 60°), four friction coefficients (0.03, 0.05, 0.1 and 0.15) and four extrusion ratios (4, 6, 10 and 15) with different pulling stresses each separated by 1000 psi until yielding stress is reached. In the finite element method, an implicit, static and dynamic, finite-deformation, finite element program (NIKE2D) is used to investigate cases of one die angle (45°), two extrusion ratios (4 and 6), one friction coefficient (0.05) and five pulling stresses (1000 psi, 3000 psi, 5000 psi, 7000 psi and 9000 psi).
Even though the idea of using hydrostatic pressure in extrusion process was proposed in nineteenth century, experiments to prove that pressure can induce ductility in materials were not available until Bridgman’s study. The results of his investigation were published in the form of a monograph in 1949 [6] which were compiled into a seven-volume monograph titled *Collected Experimental Papers of P. W. Bridgman* [2].

The first report on hydrostatic extrusion in the Soviet Union was done by Vereshehayin of the High Pressure Laboratory of the Academy of Sciences in 1957 [4]. In Great Britain, meanwhile, systemic research on the same subject was started by H. H. D. Pugh at the National Engineering Laboratory in Glasgow [3].

In Japan, M. Nishihara did a series of research of the effect of hydrostatic pressure on the mechanical properties of materials at room temperature [7,8] and at elevated temperatures [9,10] at Doshisha University in Tokyo.
2.1 Theoretical Background

2.1.1 Introduction

Several analytical methods have been applied to hydrostatic extrusion to estimate the stresses as well as the extrusion pressure. Examples are the slab method, the lower bound theory and the upper bound theory [11]. Various slip line fields for extrusion were cited by Johnson and Kudo [12].

Recently, the finite element technique has been employed in the analysis of extrusion process. The finite element method is a numerical technique for solving differential equations governing engineering problems by dividing the materials into many hypothetical elements interconnected at nodal points, hence, more accurate results can be obtained.

2.1.2 Basic Concepts

In order to express the equations of mechanics in Cartesian coordinates, it is convenient to use the stress tensor:

\[
\sigma_{ij} = \begin{bmatrix} 
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz} 
\end{bmatrix} = \begin{bmatrix}
\tau_{yx} & \tau_{xy} & \tau_{xz} \\
\tau_{zx} & \tau_{zy} & \tau_{yz}
\end{bmatrix} (2.1)
\]
where the first subscript of a stress component refers to the direction of the normal to the surface, and the second subscript refers to the direction of the force component, as described in Figure 2.1.

Equilibrium indicates the absence of rotation about any axis, so:

\[ \sigma_{xy} = \sigma_{yx} \quad (2.2) \]

or, more generally,

\[ \sigma_{ij} = \sigma_{ji} \quad (2.3) \]

Figure 2.1 Stress element for a homogeneous state of stress
The stress components should satisfy the equations of equilibrium in the body, therefore,

\[
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x = 0
\]

\[
\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y = 0
\]

\[
\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + F_z = 0
\]

where \( F_x \), \( F_y \) and \( F_z \) are components of body force per unit volume.

Tensorial representation of the above equations is:

\[
\frac{\partial \sigma_{ij}}{\partial x_i} + F_i = 0
\]

(2.5)

The hydrostatic stress component is the average value of normal stress components:

\[
\sigma_m = (\sigma_x + \sigma_y + \sigma_z) / 3 = \sigma_{ii} / 3
\]

(2.6)

The deviatoric stress tensor is defined as:

\[
\sigma'_{ij} = \sigma_{ij} - \delta_{ij} \sigma_m
\]

(2.7)

where \( \delta_{ij} \) is the Kronecker delta, which is 1 when \( i=j \) and 0 when \( i \neq j \).

The strain at a point of the body is defined as:
\[ \varepsilon_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \]  

(2.8)

where \( u_i \) and \( u_j \) are the components of displacement.

The strain rate is defined as the time rate at which the strain changes, so:

\[ \dot{\varepsilon}_{ij} = \frac{d\varepsilon_{ij}}{dt} = \frac{1}{2} \left[ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right] \]  

(2.9)

where \( v_i \) and \( v_j \) are the components of velocity. It should be noticed that the engineering shear strain rate is double the tensor component of shear strain rate, that is

\[ \gamma_{xy} = \dot{\varepsilon}_{xy} + \dot{\varepsilon}_{yx} = 2 \dot{\varepsilon}_{xy} \]

\[ \gamma_{xz} = \dot{\varepsilon}_{xz} + \dot{\varepsilon}_{zx} = 2 \dot{\varepsilon}_{xz} \]

\[ \gamma_{yz} = \dot{\varepsilon}_{yz} + \dot{\varepsilon}_{zy} = 2 \dot{\varepsilon}_{yz} \]  

(2.10)

In the most analyses of metal forming problems, the material is assumed to follow von Mises' yield criterion:

\[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy} \tau_{yz} + \tau_{zx}) = 2\bar{\sigma}^2 \]  

(2.11)

where \( \bar{\sigma} \) is the yield, or flow stress.

Mises' yield criterion when expressed in terms of deviatoric stress tensor is:

\[ 3 \sigma'_{ij} \sigma'_{ij} = 2\bar{\sigma}^2 \]  

(2.12)
When the materials are assumed to be rigid-plastic, the elastic deformation is neglected, and the relation between deviatoric strain rate and stress components is given by Levy-Mises equation as:

\[
\dot{\varepsilon}_{ij} = \frac{3}{2} \frac{\dot{\varepsilon}}{\sigma} \sigma'_{ij}
\]

(2.13)

where \( \dot{\varepsilon} \) is the equivalent strain rate.

The equivalent strain is obtained by integrating the equivalent strain rate with respect to time, therefore:

\[
\varepsilon = \int \dot{\varepsilon} \, dt
\]

(2.14)

In the elastic-plastic behavior, the relation between the strain rate and stress rate is given by Prandtl-Reuss' equation and strain rate components are expressed in terms of elastic strain rate which is related to stress rate by Hook's law.

\[
\dot{\varepsilon}_{ij} = \frac{\dot{\sigma}'}{2G} + \delta_{ij} \frac{\dot{\sigma}_m}{3K} + \frac{3\dot{\varepsilon}}{2\sigma} \sigma'_{ij}
\]

(2.15)

\[
= \frac{\dot{\sigma}'}{2G} + \delta_{ij} \frac{\dot{\sigma}_m}{3K} + \frac{3\dot{\sigma}}{2\sigma H'} \sigma'_{ij}
\]

where \( H' = \frac{d\sigma}{d\dot{\varepsilon}} \)
The plastic work per unit volume up to an equivalent strain $\bar{\varepsilon}$ is given by:

$$w = \int_0^{\bar{\varepsilon}_1} \sigma d\bar{\varepsilon}$$  \hspace{1cm} (2.17)

This corresponds to the area under the flow curve shown in Figure 2.2.

![Flow curve diagram](image)

**Figure 2.2 Flow curve**

On the other hand, the work done by the hydrostatic pressure, $P$, to extrude a billet of length $l_b$ and cross-sectional area $A_b$ is given by:

$$W_{\text{pressure}} = Pl_bA_b$$  \hspace{1cm} (2.18)

If it is assumed that all of this work is dissipated in
plastic deformation and has caused an equivalent strain $\varepsilon_1$ in the product, then

$$W_{\text{deformation}} = l_b b \int_0^{\varepsilon_1} \sigma d\varepsilon$$  \hspace{1cm} (2.19)

Comparing equations (2.18) and (2.19) reveals that the relation between the extrusion pressure and the strain, $\varepsilon$, in the product is given by:

$$p = \int_0^{\varepsilon_1} \sigma d\varepsilon$$  \hspace{1cm} (2.20)

The fact is that not all of the extrusion pressure is spent on uniform deformation. This pressure consists of three components: 1) the pressure to overcome the frictional force between the billet and the die, 2) the pressure for uniform deformation of the material, and 3) the pressure for redundant deformation. The frictional force depends on the contact area between the die and the billet, therefore, for a given extrusion ratio and a constant coefficient of friction, the pressure required to overcome this force increases as the die angle decreases. The uniform deformation is the minimum deformation necessary to change the outside dimension of the billet and the pressure required to cause such deformation increases with an increase in the extrusion ratio and die angle.
Finally, the redundant deformation, which increases with the die angle, is the additional internal shearing that occurs in the product. Figure 2.3 is a schematic comparison of ideal and actual deformation.

![Homogeneous deformation](image1)

![Redundant deformation](image2)

**Figure 2.3 Comparison of ideal and actual deformation**

Theoretical estimation of hydrostatic extrusion pressure ranges from the ideal extrusion pressure, derived from the equation [13]:

\[ P_{\text{ideal}} = \int_{0}^{\ln R} \overline{\sigma} d\overline{\varepsilon} \]  \hspace{1cm} (2.21)

to the empirical expression [12] of:

\[ P = a + b \ln R \]  \hspace{1cm} (2.22)
where $R$ is the extrusion ratio, and $a$ and $b$ are constants. In extrusions with large ratios and small die angles, the value of $a$ is small compared with $b \ln R$, therefore, the above equation may be approximated by [14]:

$$P = c \ln R$$

(2.23)

where $c$ is a constant for a given material.

2.1.3 Product Augmented Hydrostatic Extrusion

Product augmented hydrostatic extrusion, which can reduce the pressure required in extrusion process by the addition of a tensile pull on the product, was originally described by Robertson in his patent [15] and later suggested by Bridgman [16] and Low et al [17].

Theoretical analysis of fluid-to-fluid hydrostatic extrusion, which can predict the required pressure of either product or billet augmented extrusion, was derived by Avitzur [18]. Limiting conditions for the cases of billet and product augmentation have been considered by Thompson [19].
2.2 Prevailing Theories

2.2.1 Analytical Approaches

Among all the factors which are concerned in a metal working process, the required externally-applied load is the major one, and the load is generally unpredictable. However, by employing pertinent assumptions, several techniques have been developed to approximate the required load.

2.2.1.1 Energy Method

The deformation energy method is the simplest method to predict the external load, in which it is assumed that all of the external load is used to cause deformation only.

Consider the element $\Delta l$ of the billet as shown in Figure 2.4. The initial diameter of the billet is $D_0$ and the final diameter is $D_1$. Due to the incompressibility of the material when it is extruded through the die, a volume of metal $A_0 \Delta l$ must exit as $A_1 \Delta l_1$ and the total external work done by the pressure is:

$$ W = P_e A_0 \Delta l $$

(2.24)
The deformation energy required in deforming the volume $A\Delta l$ to a strain $\varepsilon$ is given by:

$$E_d = \left( \int_0^\varepsilon \sigma d\varepsilon \right) A_0 \Delta l$$ \hspace{1cm} (2.25)

Since the mean flow stress $\sigma_{ave}$ is defined as:

$$\sigma_{ave} = \frac{1}{\varepsilon_1} \int_0^\varepsilon \sigma d\varepsilon$$ \hspace{1cm} (2.26)

hence:

$$E_d = (\sigma_{ave} \varepsilon) A_0 \Delta l$$ \hspace{1cm} (2.27)
Also, since the deformation is assumed to be ideally uniform, the equivalent strain is:

$$\varepsilon_{\text{ideal}} = \ln R$$ \hspace{1cm} (2.28)

Therefore,

$$E_d = (\sigma_{\text{ave}} \ln R) \Delta l$$ \hspace{1cm} (2.29)

By equating the external work to the energy expended in deforming the billet, we find:

$$P_e = \sigma_{\text{ave}} \ln R$$ \hspace{1cm} (2.30)

This equation relates the external pressure to the extrusion ratio and average flow stress; however, the friction has been neglected.

2.2.1.2 Slab Method

The slab method, or free body equilibrium approach, was developed to calculate the external load by integrating the differential equation of equilibrium of stress state. The two major assumptions in the slab analysis are that the planar sections remain planar and surface friction does not influence the internal distortion.

The slab method has been applied to many forming processes for its simplicity. Osakada and Mellor [20] showed that the required pressure to extrude a material
with yield stress \( \sigma_y \) through a conical die of an included angle \( \alpha \) at an extrusion ratio \( R \) is given by:

\[
P = \sigma_y \left(1 + \frac{1}{\mu \cot \alpha} \right) (R - 1) + \frac{4\alpha}{3\sqrt{3}}
\]  

(2.31)

where \( \mu \) is the friction coefficient between the die and the workpiece.

The slab analysis of product augmented hydrostatic extrusion will be discussed in next chapter.

2.2.1.3 Lower Bound Analysis

Prager and Hodge [21] presented the lower bound analysis to direct extrusion as:

"Among all statically admissible stress fields, the actual one maximizes the expression:

\[
I = \int_{s_v} T_i v_i ds
\]

(2.32)

where \( I \) is the computed power supplied by the tool over surfaces over which velocity is prescribed."

In the equation listed above, \( T_i \) are the normal components of surface traction over which velocity is prescribed and \( v_i \) is the ram velocity.
2.2.1.4 Upper Bound Analysis

The upper bound analysis was developed to predict a load that is at least equal to or greater than the exact load needed to cause plastic flow. And, the method focuses on satisfying a yield criterion by assuming that the velocity field is kinematically admissible.

Avitzur [22] assumed a special velocity field of the material within the die flowing toward the apex and derived equations for the load in direct extrusion as following:

\[ P = \sigma_y \left\{ \left[ f(\alpha) + \frac{m}{\sqrt{3}} \cot \alpha \right] \ln R + \frac{2}{\sqrt{3}} \frac{\alpha}{\sin^2 \alpha} \right\} \quad (2.33) \]

where \( \sigma_y \) is the effective flow stress of the material, \( \alpha \) the semi-cone angle, and \( f(\alpha) \):

\[
 f(\alpha) = \frac{1}{\sin^2 \alpha} \left( 1 - \cos \alpha \sqrt{1 - \frac{11}{12} \sin^2 \alpha} + \frac{1}{\sqrt{132}} \ln \frac{1 + \sqrt{11/12}}{\sqrt{11/12} \cos \alpha + \sqrt{1 - (11/12)} \sin^2 \alpha} \right) \quad (2.34)
\]

Avitzur also proposed a theory which can apply to fluid-to-fluid extrusion by:

\[ P = P_b + P_f + S + T \quad (2.35) \]
where \( P \) is the effective extrusion pressure, \( P_b \) fluid pressure surrounding the billet, \( P_f \) fluid pressure surrounding the product, \( S \) compressive stress superimposed on the billet, and \( T \) tensile stress superimposed on the product.

2.2.2 Numerical Approaches

Numerical approaches of the metal forming analysis are relatively new techniques which have made great progress by the development of electronic machines. The finite element method, for example, solves the problem of metalforming by dividing the continuum into an assemblage of discrete, quadrilateral regions called elements. Several finite element packages have been coded and applied to solve problems successfully, one of them, called NIKE2D, will be introduced later.
3.1 The Slab Method

3.1.1 Introduction

As mentioned in the previous chapter, the slab method has been applied to the analyses of many forming processes since its simplicity. By assuming that planar sections remain planar and the deformation is homogeneous, we can calculate the stresses and loads by integrating the differential equation of equilibrium under a simplified stress state. The assumptions also include that surface friction will not influence the internal distortion of the material or of the orientation of principal directions.

Even though all of these assumptions deviate in real cases, the slab method still can support the users some information, if applied to product augmented hydrostatic extrusion.

3.1.2 Nomenclature

\[ D_p : \text{diameter of product} \]
\[ D_b : \text{diameter of billet} \]
\[ R : \text{extrusion ratio} \]
\[ \alpha : \text{semicone die angle} \]
3.1.3 Theory

By assuming that the pressure within the container is the same at all points across any transverse plane and considering the free body diagram of the slab-shaped element shown in Figure 3.1, the force equilibrium equation in axial (Z) direction is:

\[
\sum F_z = P_z \frac{\pi D^2}{4} - (P_z + dP_z) \frac{\pi}{4} (D + dD)^2 + P_\alpha \pi D ds \sin \alpha
\]

\[\mu P_\alpha \pi D ds \cos \alpha = 0 \quad (3.1)\]

and,

\[\frac{ds \sin \alpha}{dz} = \frac{d(D/2)}{\tan \alpha} \quad (3.2)\]

\[\frac{ds \cos \alpha}{dz} = \frac{d(D/2)}{\tan \alpha} \quad (3.3)\]
For small $\alpha$ and $\mu$, the stresses distribution of the element is close to spherical, that is, $\sigma_r \approx \sigma_\theta$. The stresses acting on the element and Mohr's circle are described in Figure 3.2.

According to Tresca criterion, the billet will be extruded through the die when:

$$ Y = \sigma_z - \sigma_r = P_z - P_r $$

(3.4)
and for a spherical slab, $P_\alpha = P_r = P_\theta$
hence,

$$P_\alpha = P_z + Y$$  \hspace{1cm} (3.5)

Substituting equations (3.2), (3.3) and (3.5) into (3.1),
and let

$$\beta = \mu \cot \alpha$$

$$\frac{d P_z}{\beta P_z + (1+\beta) Y} = \frac{2 \, dD}{D}$$  \hspace{1cm} (3.6)

If $\mu \neq 0$, $\alpha \neq 0$ and $Y = \text{constant}$

$$\frac{1}{\beta} \ln \left( \beta P_z + (1+\beta) Y \right) = 2 \ln D + \ln C$$

or,

$$\left( \beta P_z + (1+\beta) Y \right)^{1/\beta} = D^2 C$$  \hspace{1cm} (3.7)

where $D$ and $C$ are constants.

![Diagram showing stresses distribution and Mohr's circle](image)

Figure 3.2 Stresses distribution and Mohr's circle
Consider boundary conditions: $D = D_p$, $P_z = -P_1$
and equation (3.7) becomes:

$$\left[ - \beta P_1 + (1+\beta) Y \right]^{1/\alpha} = D_p^2 C$$

hence

$$C = \frac{\left[ - \beta P_1 + (1+\beta) Y \right]^{1/\alpha}}{D_p^2} \quad (3.8)$$

Substituting equation (3.8) into (3.7), after simplifying, we obtain:

$$P_z = (\frac{D}{D_p})^{2\alpha} \left[ - P_1 + \left( \frac{1+\beta}{\beta} \right) Y \right] - \left( \frac{1+\beta}{\beta} \right) Y \quad (3.9)$$

The extrusion ratio is defined by:

$$R = \left( \frac{D_b}{D_p} \right)^2 \quad (3.10)$$

Substituting equation (3.10) into (3.9), the extrusion pressure required is:

$$P_z = R^\alpha \left[ - P_1 + \left( \frac{1+\beta}{\beta} \right) Y \right] - \left( \frac{1+\beta}{\beta} \right) Y \quad (3.11)$$

3.1.4 The Slab Method Program

A Fortran program of slab analysis of product augmented hydrostatic extrusion was written as following:
C PROGRAM SLAB METHOD
C THIS PROGRAM IS AIMED TO SIMULATE THE BEHAVIOR OF
C PRODUCT AUGMENTED HYDROSTATIC EXTRUSION BY SLAB
C METHOD. FOR GIVEN EXTRUSION RATIO, DIE ANGLE,
C LUBRICATING CONDITION AND YIELD STRESS OF THE
C MATERIAL, FIND THE RELATION BETWEEN PULLING STRESS
C AND HYDROSTATIC PRESSURE.
C VARIABLES

REAL A, U, Y, P1, P, R
C A : SEMICONE DIE ANGLE (DEGREE)
C U : FRICTION COEFFICIENT BETWEEN BILLET AND
C DIE
C Y : YIELD STRESS OF MATERIAL (PSI)
C P1 : PULLING STRESS (PSI)
C P : HYDROSTATIC PRESSURE (PSI)
C R : EXTRUSION RATIO

REAL B
CHARACTER*1 MAYBE
C CONSTANTS

REAL PI
PARAMETER (PI=3.141593)
C BEGIN

WRITE(4,*) 'INPUT DATA.'
C LOOP
10 CONTINUE
C INPUT EXTRUSION CONDITIONS
WRITE(3,*) 'ENTER THE EXTRUSION RATIO'
READ(5,*) R
WRITE(6,20) R

20 FORMAT(//,2X,'THE EXTRUSION RATION IS',2X,F7.4)
WRITE(4,*) 'R = ',R
WRITE(3,*) 'ENTER THE SEMICONE DIE ANGLE (DEGREE)'
READ(5,*) A
WRITE(6,30) A

30 FORMAT(//,2X,'THE SEMICONE DIE ANGLE IS',2X,F5.2,
+2X,'DEGREES')
WRITE(3,*) 'ENTER THE FRICTION COEFFICIENT BETWEEN
+BILLET AND DIE'
READ(5,*) U
WRITE(6,40) U

40 FORMAT(//,2X,'THE FRICTION COEFFICIENT BETWEEN BILL
+ET AND DIE',2X,F6.4)
WRITE(3,*) 'ENTER THE YIELD STRESS OF MATERIAL
+(PSI)'
READ(5,*) Y
WRITE(6,50) Y

50 FORMAT(//,2X,'THE YIELD STRESS OF MATERIAL IS',
+2X,F8.2,2X,'PSI')

C LOOP

P1 = -1000.
DO 80 I=1,50
    P1 = P1 + 1000.
C EXIT WHEN (P1 .GE. Y)
   IF (P1 .GE. Y) GO TO 90
C CALCULATE THE HYDROSTATIC PRESSURE
   B = U / TAN(A*PI/180.)
   P = R**B * (((1+B)/B * Y - P1) - (1+B) / B * Y
   IF (P .LE. 0) THEN
      P = 0.
      P1 = (((1+B)/B) * Y * ( 1 - R**B )
      WRITE(6,60) P1
      WRITE(6,70) P
   GO TO 90
ENDIF
WRITE(6,60) P1
60 FORMAT(//,2X,'WHEN THE PULLING STRESS IS',2X,
   F9+1,2X,'PSI')
WRITE(6,70) P
70 FORMAT(//,2X,'THE HYDROSTATIC PRESSURE IS',2X,
   F12+.5,2X,'PSI')
   WRITE(4,*) P1,P
80 CONTINUE
90 WRITE(3,*') 'CHANGE EXTRUSION CONDITIONS? (Y/N)'
   READ(5,100) MAYBE
A computer package TELL-A-GRAF was used to create Figure forms of the results.

3.1.5 Simulation Parameters

In the simulation of product augmented hydrostatic extrusion by the slab method, four extrusion ratios of 4, 6, 10 and 15 in conjunction with three die angles of 30°, 45° and 60° were used. Three coefficients of friction of 0.03, 0.05, 0.1 and 0.5 were assumed and the yield stress of aluminum was taken to be 20,000 psi.

3.2 The Finite Element Analysis

3.2.1 Introduction

The idea of the finite element method is that any continuous quantity can be approximated by a set of piecewise continuous functions defined over a number of
components assembled to represent the quantity. In fact, the concept of the finite element analysis was conceived in the early 1940s by McHenry [23], Hrenikoff [24] and Newmark [25].

The method had its birth in the early 1950s by the publication of Turner, Clough, Martin and Topp [26] and Clough [27] was the first person to use the term "finite element." Later, Wilson and Nickell [28] showed the application of the finite element method to heat transfer problem.

Today finite element technique has advanced from a procedure for solving structure problems to a general numerical method for solving a differential equation or systems of differential equations. Several general purpose finite element programs are available which are capable of handling problems of any engineering discipline. In this investigation, an implicit, static and dynamic, finite-deformation, finite element computer program, NIKE2D [29], has been used to simulate the product augmented hydrostatic extrusion.

3.2.2 Theory

In the analysis of metal forming, there are two schemes of the finite element method: the rigid-plastic
analysis and the elastic-plastic analysis. In the former, assuming that elastic deformations are neglected and the strain or strain rate components are only plastic ones, is not feasible for the analysis of large metal deformation which is elastic-plastic in nature. Lee and McMeeking [30] showed that in most cases of metal deformation, the elastic response is essentially unchanged by plastic deformation, and the two behaviors can be considered uncoupled.

3.2.2.1 Basic Mechanics

3.2.2.1.1 Displacements

In any continuum mechanics problem, the analyst concerns the initial shape of the body and its deformation throughout the history of loading. The particle initially located at position $x$ will move to a new position $z$, as shown in Figure 3.3.

Assuming conservation of the material, there will be a one-to-one correspondence between $x$ and $z$, and the history of the position of a particle can be written as:

$$z = z(x,t) \quad (3.11)$$

This relationship can be inverted. Therefore,

$$x_i = x_i(z_1,z_2,z_3,t) \quad i = 1,2,3 \quad (3.12)$$
and \[ z_i = z_i(x_1, x_2, x_3, t) \quad i = 1, 2, 3 \] (3.13)

Depending on whether or not the displacement vector is associated with a point in the original or deformed configuration, the components of the displacement vector are given by:

\[ u_i(x_1, x_2, x_3) = z_i(x_1, x_2, x_3) - x_i \] (3.14)

\[ u_i(x_1, x_2, x_3) = z_i - x_i(z_1, z_2, z_3) \] (3.15)

The velocity vector of the material is the time derivative of the displacement vector; thus,

\[ v_i = \frac{\partial u_i(x, t)}{\partial t} \quad i = 1, 2, 3 \] (3.16)

Figure 3.3 Coordinate systems and description of displacement
3.2.2.1.2 Strain Measures

The description of strain is the key to the analysis of deformation. Considering an infinitesimal line segment connecting two neighboring particles which located at \( x \) (\( P^0 \)) and \( x+dx \) (\( P' \)) in the initial configuration, as seen in Figure 3.4, we have,

\[
\text{dx}_i = \frac{\partial x_i}{\partial z_j} \text{dz}_j \tag{3.17}
\]

and

\[
\text{dz}_i = \frac{\partial z_i}{\partial x_j} \text{dx}_j \tag{3.18}
\]

Also,

\[
\text{ds}_0^2 = \text{dx}_1^2 + \text{dx}_2^2 + \text{dx}_3^2 \tag{3.19}
\]

\[
\text{ds}^2 = \text{dz}_1^2 + \text{dz}_2^2 + \text{dz}_3^2 \tag{3.20}
\]

When strain motion is considered, we may rewrite equations (3.19) and (3.20), using the Kronecker delta, as:

\[
\text{ds}_0 = \delta_{ij} \text{dx}_i \text{dx}_j = \delta_{ij} \frac{\partial x_i}{\partial z_r} \frac{\partial x_j}{\partial z_s} \text{dz}_r \text{dz}_s \tag{3.21}
\]

and

\[
\text{ds} = \delta_{ij} \text{dz}_i \text{dz}_j = \delta_{ij} \frac{\partial z_i}{\partial x_r} \frac{\partial z_j}{\partial x_s} \text{dx}_r \text{dx}_s \tag{3.22}
\]

Subtracting the expressions (3.19) and (3.20) from one another, we obtain:
\[ ds^2 - ds_0^2 = (\delta_{rs} \frac{\partial z_r}{\partial x_i} \frac{\partial z_s}{\partial x_j} - \delta_{ij}) \, dx_i dx_j \]  
(3.23)

and
\[ ds^2 - ds_0^2 = (\delta_{ij} - \delta_{rs} \frac{\partial x_r}{\partial z_i} \frac{\partial x_s}{\partial z_j}) \, dz_i dz_j \]  
(3.24)

Defining the strain tensors as:
\[
e_{ij} = \frac{1}{2} (\delta_{rs} \frac{\partial z_r}{\partial x_i} \frac{\partial z_s}{\partial x_j} - \delta_{ij})
\]  
(3.25)

and
\[
h_{ij} = \frac{1}{2} (\delta_{ij} - \delta_{rs} \frac{\partial x_r}{\partial z_i} \frac{\partial x_s}{\partial z_j})
\]  
(3.26)

equations (3.23) and (3.24) can be expresses by:
\[ ds^2 - ds_0^2 = 2e_{ij} \, dx_i dx_j \]  
(3.27)

and
\[ ds^2 - ds_0^2 = 2h_{ij} \, dz_i dz_j \]  
(3.28)

Figure 3.4 Deformation of a continuum
3.2.2.1.3 Strain Rates

The material strain rate tensor is defined as:

\[
.e_{ij} = \frac{\partial e_{ij}}{\partial t} = \frac{1}{2} \left[ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right]
\]  \hspace{1cm} (3.29)

where:

\[
\frac{D}{Dt} (ds^2 - ds_0^2) = 2e_{ij} \, dx_i dx_j
\]  \hspace{1cm} (3.30)

Similarly, the spatial strain rate tensor is expressed by:

\[
.h_{ij} = \frac{\partial h_{ij}}{\partial t} = \frac{1}{2} \left[ \frac{\partial v_i}{\partial z_j} + \frac{\partial v_j}{\partial z_i} \right]
\]  \hspace{1cm} (3.31)

where:

\[
\frac{D}{Dt} (ds^2 - ds_0^2) = 2h_{ij} \, dz_i dz_j
\]  \hspace{1cm} (3.32)

The material and spatial strain rate tensors are related by the expression:

\[
.e_{ij} = h_{ij} \frac{\partial z_k}{\partial x_i} \frac{\partial z_l}{\partial x_j}
\]  \hspace{1cm} (3.33)

3.2.2.1.4 Stress Measures and Stress Rates

As described in Figure 3.5, the stress vector \( P_{(n)} \), defined as the surface force per unit area in the undeformed body, may be expressed in terms of \( t_{(n)} \) as:
\[ P(n) = t(n) \frac{dA}{dA_0} \] (3.34)

where \( P(n) \) acts on an area element whose unit normal in the initial state is \( n_0 \).

The material, or Piola-Kirchhoff, stress tensor is defined as:

\[ S_{AB} = \sigma_{ij} \frac{\partial x_A}{\partial z_i} \frac{\partial x_B}{\partial z_j} \] (3.35)

where \( \sigma_{ij} \) is the Cauchy stress tensor.

Figure 3.5 Stress principle
The material stress rate tensor is the time derivative of the stress tensor rate, hence:

\[ S_{AB} = \frac{\partial S_{AB}}{\partial t} \quad (3.36) \]

3.2.2.2 Governing Equations for Elasto-plastic Deformation

The basic equation which described the mechanics of elasto-plastic deformation is the Lagrangean description of the rate equation given by the expression

\[
\int_{v_0}^{v} S_{ij} \frac{\partial v_i}{\partial x_i} dv = \int_{s_0}^{s} f_i \partial v_i ds + \int_{v_0}^{v} b_i \partial v_i dv \quad (3.37)
\]

where \( [S] \) is the material rate of the unsymmetric nominal stress tensor or the first Piolo-Kirchhoff stress tensor; \{b\}, the body force intensity vector; and \{f\}, the surface traction vector. In the equation expressed above, all integrations are performed in the reference configuration. In the Eulerian description of the deformation; however, the motion is described in terms of true stress and true strain, both of which are defined with respect to an Eulerian or current reference frame. This is a more appropriate way of stating the rate equation since the laws
of plasticity are usually formulated with reference to the current configuration [31].

The scheme that is most popular among the researchers in the field of large incremental metal deformation is the "updated Lagrangean" scheme, in which the state at a time \( t \) is taken as the reference for displacements that occur at time \( t+\Delta t \). This updated Lagrangean description of equation (3.37), as formulated by McMeeking and Rice [32], is given as:

\[
\int_v \left[ \tau_0^{ij} \delta \varepsilon_{ij} + \sigma_{ij} \delta (\varepsilon_{ik} \varepsilon_{kj} - V_k, i V_k, j / 2) \right] dv
= \int_s f_i \partial v_i ds + \int_v b_i \partial v_i dv \tag{3.38}
\]

where the suffix \( ,j \) refers to partial differentiation with respect to the spatial variables \( x \) and summation is implied with respect to repeated suffixes. In the above equation, \( [\tau^0] \) is the Jaumann rate of the Kirchhoff stress tensor and is expressed as:

\[
\tau^0_{ij} = \tau_{ij} - W_{ik} \tau_{kj} + \tau_{ik} W_{kj} \tag{3.39}
\]

\( \tau^0_{ij} \) is also related to \( [S_{ij}] \) through the expression:

\[
\tau^0_{ij} = S_{ij} + \sigma_{kj} \varepsilon_{ki} + \sigma_{ik} \varepsilon_{kj} - \sigma_{ik} V_j, k \tag{3.40}
\]
In the above equation, \([\sigma_{ij}]\) is the Cauchy stress tensor and is related to the Kirchhoff stress tensor \(\tau_{ij}^0\) by the equation

\[
\tau_{ij}^0 = (\beta^0/\beta)\sigma_{ij}
\]  

(3.41)

where \(\beta^0\) and \(\beta\) are the material densities in the reference and current configurations. The rate of deformation tensor \(\dot{\epsilon}_{ij}\) is given by:

\[
\dot{\epsilon}_{ij} = (v_{i,j} + v_{j,i})/2
\]  

(3.42)

and the spin tensor, \([W]\), by

\[
W_{ij} = (v_{i,j} - v_{j,i})/2
\]  

(3.43)

Equation (3.43) is the well-known formulation of McMeeking and Rice. In NIKE2D, modification has been made by using the Green-Naghdi rate in stead of the Jaumann rate [33].

3.2.2.3 Constitutive Equations

Various metals are used in the metal deformation processes, and each of them has a range of constitutive model. The one used in this study, aluminum, exhibits elastic response as well as plastic behavior.

The finite element program used in this work, NIKE2D, considers the elastic-plastic material model in two
methods. In the first one, when isotropic, kinematic, or a combination of isotropic and kinematic properties are concerned, hardening may be specified by varying hardening parameter $\beta$ between 0 and 1, as shown in Figure 3.6. The other method is using a variable hardening law by defining an effective stress-effective plastic strain curve [34], in which effective stress is given by:

$$
\bar{\sigma} = \left( -\frac{3}{2} S_{ij} S_{ij} \right)^{1/2}
$$

(3.44)

where

$$
S_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \phi_{ij}
$$

(3.45)

and $\sigma_{ij}$ is the Cauchy stress tensor.

Figure 3.6 Elastic-plastic behavior with isotropic and kinematic hardening, where $l_0$ and $l$ are the undeformed and deformed length of a uniaxial tension specimen.
Effective plastic strain is given by:

\[ \varepsilon_P = \int_0^t d\varepsilon_P \]  \hspace{1cm} (3.46)

where \( t \) denotes time and

\[ d\varepsilon_P = \left( \frac{2}{3} \varepsilon_{ij}^p \varepsilon_{ij}^p \right)^{1/2} \]  \hspace{1cm} (3.47)

### 3.2.3 The Finite Element Program

The finite element program used in this investigation, NIKE2D, is a fully vectorized, implicit, finite-deformation, large strain, finite element code for analyzing the response of two-dimensional axisymmetric, plane strain, and plane stress solids. A variety of loading conditions can be handled including traction boundary conditions, displacement boundary conditions, concentrated nodal point loads, body force loads due to base accelerations, and body force loads due to spinning. Elastic, orthotropic-elastic, elastic-plastic, thermo-elastic-plastic, soil and crushable foam, linear viscoelastic, thermo-orthotropic elastic, elastic-creep, and strain rate dependent material models are implemented [35]. The Green-Naghdi rate and automated step size control with the quasi-Newton schemes are used in the code.
3.2.4 Simulation Parameters

The problem was treated axisymmetrically and therefore, half of the meridian planes of the billets were discretized as the domain of the problem, as shown in Figure 3.7. Two extrusion ratios of 4 and 6 in conjunction with one die angles of 45° were simulated.

The domain was divided into a 8 x 40 grid. Coefficient of friction of 0.05 was used at the die-billet interface, and uniform pressure boundary conditions were imposed on the exposed surfaces of the billets to simulate the hydrostatic fluid pressure with five different pulling stresses 1000 psi, 3000 psi, 5000 psi, 7000 psi and 9000 psi. The yield stress of the material used, aluminum, was assumed to be 20000 psi.
Figure 3.7  Finite element discretization of the domain
CHAPTER FOUR RESULTS AND DISCUSSION

4.1 Simulation Results of the Slab Method

Presented in this section are the results of cases of die angle of 45 degrees, frictional coefficient of 0.05 and four extrusion ratios, namely 4, 6, 10 and 15. All of the extrusion simulations are augmented with different pulling stresses. The results of cases with different die angles (30, 45 and 60 degrees), extrusion ratios (4, 6, 10 and 15) and friction coefficients (0.03, 0.05, 0.1 and 0.15) are given in Appendix A.

As shown in Figure 4.1, in the case of pure extrusion, the hydrostatic pressure required to extrude the billet increases as the extrusion ratio increases. In fact, this pressure is proportional to the natural logarithm of the extrusion ratio. In every case, when the augmented pressure was imposed on the product, the required hydrostatic pressure decreased. As the Figure indicates, the relationship between the pulling stress and the hydrostatic pressure is linear in the range of analysis.

Another important observation is the fact that for the same die angle, the required pressure increases with increase in frictional coefficient. This relation is given in equation (3.11). Furthermore, for a given coefficient of friction, the required pressure decreases as the die
angles increase. This is due to the fact that the contact area between the work piece and the die land increases as the die angles increase.

4.2 Simulation Results of the Finite Element Method

As mentioned before, NIKE2D, a finite element analysis code with large deformation simulation capabilities was used to numerically investigate the problem at hand. The results presented in this section, therefore, are those of the program for extrusion ratios of 4 and 6 in conjunction with die angle of 45 degrees. Five different augmentation loads of 1000, 3000, 5000, 7000 and 9000 psi were imposed on the product during the extrusion process. In all cases, simulations were started with the front end of the billet in the die. This was accomplished by designing the geometry of the leading end of the billets to match that of the die for the particular die angle under the investigation. This effect is shown in Figure 4.2 which shows the domain of the finite element problem for the extrusion ratio of 4 and die angle of 45 degrees.

Figure 4.3 is the corresponding deformed configuration of the original mesh. The Figure shows the steady state behavior of the material in which the flow patterns indicate a tendency of a material element to move through the die faster the farther it is from the die. In
addition, the deformed geometry shows less deformation of the elements near the leading end of the billet. This is due to the fact that the leading elements have gone through smaller extrusion ratio than the rest of the billet. Consequently, these elements have been less deformed than the rest of the billet.

Figures 4.4, 4.5 and 4.6 give the distribution of axial, radial and hoop stresses, respectively. In Figure 4.4, the region of the leading end of the billet is under tensile stresses, however, near the die, compressive stresses prevailed. This is of course due to the fact that tensile augmented stress is still applied and the material in the die is subjected to compressive loading in the deforming zone. The same conditions of stress distribution happens in the radial and hoop stresses.

The foregoing presentations of the results were of those of extrusion ratio of 4 and die angle of 45 degrees with pulling stress of 5000 psi. Similar sets of results have been obtained for all cases of simulations mentioned earlier and are presented in Appendix B.

In the simulation of the extrusion problem, the fluid pressure of the actual press were simulated as pressure boundary conditions on the back end and top of the billet. The augmentation loads were also simulated as negative pressure boundary conditions applied on the leading end of the billets. As the extrusion proceeded, the simulation
process was stopped in due time to remove the loads from that portion of the billet which had entered the die. In continuing the process, the cycle was repeated until the steady state was reached. In all cases of simulation, buckling of the billets occurred when high stress rates were simulated.

Figure 4.7 shows the relation between the steady state hydrostatic pressure and the pulling stress as a function of time. These results correspond to a stress rate of 250 psi/sec. Figure 4.7 also indicates the fact that higher augmentation load reduces the required hydrostatic pressure. From the results obtained, for every additional 2000 psi of augmentation pressure there is a decrease of 4500 psi in hydrostatic pressure requirement. It is obvious that the pulling stress does help in reducing the hydrostatic pressure before up to the limiting condition of yielding stress of the product. Figure 4.8 shows the comparison of extrusion ratios of 4 and 6, with the same frictional coefficient (0.05). The required hydrostatic pressure increases as extrusion ratio increases and decreases linearly with increase in pulling stress. Using the empirical expression (2.22), we found a value of 33368.26 psi for the slope \(a\) and 15784.34 psi for the \(y\) intercept \(b\).
4.3 Comparison of the Results of Slab Method and Finite Element Technique

Figures 4.9 and 4.10 show the results of the slab method and NIKE2D for different extrusion ratios. The hydrostatic pressure results obtained by the slab method are noticeably smaller than those of the finite element simulation. This is due to the fact that in the slab analysis technique, it is assumed that the surface friction does not influence the internal distortion of the material. This is of course not the case with the numerical simulation of the process in which the boundary conditions have significant effect on the material.
Figure 4.1 Simulation results of the slab method

(Die angle: 45 degrees, frictional coefficient: 0.05)
Figure 4.2 Domain of the finite element problem

(Die angle: 45 degrees, extrusion ratio: 4)
Figure 4.3  Deformed configuration

(Die angle: 45 degrees, extrusion ratio: 4)
Figure 4.4 Contours of axial stress

(Die angle: 45 degrees, extrusion ratio: 4)
Figure 4.5  Contours of radial stress

(Die angle: 45 degrees, extrusion ratio: 4)
Figure 4.6  Contours of hoop stress

(Die angle: 45 degrees, extrusion ratio: 4)
Figure 4.7: Relation between pulling stresses and hydrostatic pressures (extrusion ratio: 4)
Figure 4.8  Comparison of pressure requirements for extrusion ratios of 4 and 6
(Die angle: 45 degrees, frictional coefficient: 0.05)
Figure 4.9  Comparison of pressure requirements  
(Slab and FEM method)
Figure 4.10  Comparison of pressure requirements
(Slab and FEM method)
1. Extrusion pressure during the process of augmented hydrostatic extrusion is significantly reduced as the augmentation load is increased. The relationship between augmentation pressure and the hydrostatic pressure is linear in the range of this investigation.

2. Extrusion pressure during the process of hydrostatic extrusion increases as the extrusion ratio is increased. Moreover, this increase is a linear function of natural logarithm of extrusion ratio, without any consideration of augmentation loads. That is to say that the extrusion ratio increases as linear function of extrusion ratio with or without any augmentation.

3. Extrusion pressure is directly proportional to the amount of friction between the billet and the die. This effect is found to be minimal, however, since low coefficient of friction is inherent to the nature of hydrostatic extrusion process.

4. Extrusion pressure is also a function of die angle. As die angle increases, there is an increase in the pressure requirements to successfully extrude the billet.
The above conclusions on pressure requirements indicate that there is a reverse effect on extrusion pressure due to the die angle and extrusion ratio. As the die angle is increased, the pressure requirement drops, due to the fact that more homogenous material deformation is taken place and, therefore, there is less of redundant work involved. On the other hand, however, with decrease in die angle, there is an increase in contact area between the die and the billet. This in turn will result in more frictional force. This increase in friction will require more pressure. Hence, there must be an optimum die angle for the process. A substantial amount of data is needed for optimizing the die angle for a given set of operating parameters.

The above conclusion also point out to a number of facts by means of which the extrusion pressure can be lowered. Lower extrusion pressure means lower fluctuating stresses in the extrusion chamber. This is an important consideration for design of extrusion presses since fatigue life is substantially improved for a given chamber subjected to smaller stress magnitudes. In the view of economics, it means that the cost of the extrusion container and the press can be reduced. However, since this investigation didn't consider the design of the extrusion equipment such as the size of container, pressure generator and die sets, still a great deal of work is
needed to be done in this area. Also, experimental work to compare the results of this investigation are of significant value.

In short, augmented hydrostatic extrusion is a feasible method of production. It is earnestly hoped that this investigation will be helpful in future study of augmented hydrostatic extrusion.
REFERENCES


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34. Hallquist, John O., Ibid., p. 77-78.


Die angle: 30 degrees, frictional coefficient: 0.03
Die angle: 30 degrees, frictional coefficient: 0.05
Die angle: 30 degrees, frictional coefficient: 0.1
Die angle: 30 degrees, frictional coefficient: 0.15
Die angle: 45 degrees, frictional coefficient: 0.03
Die angle: 45 degrees, frictional coefficient: 0.1
Die angle: 45 degrees, frictional coefficient: 0.15
Die angle: 60 degrees, frictional coefficient: 0.03

AL - 60 - 0.03

Legend
- □ R = 4
- □ R = 5
- □ R = 10
- ◼ R = 15
Die angle: 60 degrees, frictional coefficient: 0.05
Die angle: 60 degrees, frictional coefficient: 0.1
Die angle: 60 degrees, frictional coefficient: 0.15
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 1000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 1000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 4

Frictional coefficient: 0.05, pulling stress: 3000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 4

Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 3000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 7000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 7000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 9000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 4
Frictional coefficient: 0.05, pulling stress: 9000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 1000 psi
AL-45-6-1000
TIME = 0.63259E+03
DSF = 0.10000E+01

Deformed configuration

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 6

Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 1000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 1000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 3000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 3000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 3000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 6

Frictional coefficient: 0.05, pulling stress: 5000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 5000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 6

Frictional coefficient: 0.05, pulling stress: 5000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 5000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 5000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 7000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 7000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 7000 psi
Domain of the finite element problem

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 9000 psi
Deformed configuration

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of axial stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of radial stress

Die angle: 45 degrees, extrusion ratio: 6

Frictional coefficient: 0.05, pulling stress: 9000 psi
Contours of hoop stress

Die angle: 45 degrees, extrusion ratio: 6
Frictional coefficient: 0.05, pulling stress: 9000 psi
APPENDIX C NIKE2D IN INTERACTIVE GRAPHICS SYSTEM

NIKE2D is a fully vectorized, implicit, finite-deformation, large strain, finite element code for analyzing the response of two-dimensional axisymmetric, plane strain, and plane stress solids. The procedures of running NIKE2D in Interactive Graphics System as available in Ohio University will be discussed in detail in this appendix.

C.1 Pre-processor: MAZE

C.1.1 Introduction

MAZE, which has three phases, is an interactive program that has been developed as an input generator for NIKE2D, DYNA2D, and possibly other codes through the standard grid link file, SGLF [36]. In the first phase, lines and parts are defined. In the second phase, boundary conditions may be specified, slidelines may be defined, parts may be merged to eliminate nodes along common interfaces, boundary nodes may be moved for graded zoning, the mesh may be smoothed, and load curves may be defined. In the third phase, material properties may be defined.
C.1.2 Procedures

To invoke MAZE, having an account in UDA2, which was linked to a Micro-VAX in Stocker room 247, is necessary. After logging on the system, key in the command "RUN UDA2:[51,2] MAZE," the terminal should reply as following:

DEFAULT FILE NAMES :
O=MAZOUT  M=MAZSAV
PLEASE DEFINE INPUT FILE NAMES (IF ANY) OR CHANGE DEFAULTS :

For the first run, hit the RETURN (or ENTER) key only. The terminal will prompt:

MAZE (VERSION I) COMPILED 04/29/85

BOX #:

Key in any number you prefer, for example, 1. The terminal prompts as:

Device 1 is VT100/RetroGraphics
Device 2 is Tek. 4014
Device 3 is Tek. 4025
Device 4 is HP 2648
Device 5 is RAMTEK 9400
Device 6 is LASER_WIDE
Device 7 is LASER_LONG
Device 8 is REMOTE 4014
Device 9 is Tek. 4105
Device 10 is Tek. 4017 AND 4109
Device 11 is Tek. 4010 & GraphOn
Device 12 is HP7475_LONG
Device 13 is HP7475_TALL
Device 14 is Tek. 4115
Device 15 is Digital VT240
Device 16 is Lexidata
Device 17 is Visual 550

Graphics device number?

For using Interpro 32, key in 10. For using Interact Work Station, key in 2.

After these procedures, MAZE is ready for using and user is in phase 1 in which lines and parts are defined. To define a line, "LD" and "LP" commands are needed, for example,

LD 1 LP 2 0 0 1 0

It means that line number 1 has two points, the first point at (0,0) and the second point at (1,0), where the first index indicates the r coordinate, and the second index indicates the z coordinate, as shown in Figure C.1.

After several lines have been defined, "PART" command is used to form a part, for example,

PART 5 6 7 8 2 5 20

It means lines 5, 6, 7 and 8 form a part with material definition 2, which will be defined in phase 3, and the part is divided into a 5 x 20 grid, as seen in Figure C.2.
After defining lines and parts, command "ASSM" is used to assemble mesh from all previously defined parts and end phase 1.

In phase 2, load curves may be defined, boundary conditions may be specified and slidelines may be defined. To define a load curve, "LCD" command is used, for example,

```
LCD 1 4 0 0 100 5000 220 5000 240 0
```

It means that load curve number 1 is defined by four points, which are (0,0), (100,5000), (220,5000) and (240,0), where the first index indicates the time scale and the second index indicates the load scale.

Slideline types are defined by "SLN" command as:

```
SLN n k (if k=1,2,3)
```

or

```
SLN n k f (if k=4)
```

where k=1 for sliding only, k=2 for tied wall, and k=3 for frictionless sliding with voids. When k=4, for frictional sliding with voids, Coulomb frictional constant f is defined. For example,

```
SLN 1 4 0.05
```

means slideline 1 is type 4 with Coulomb frictional constant 0.05.

"P n B" command is used to display the boundary nodes number of part n, for example

```
P 2 B
```

as shown in Figure C.3.
"MSR" and "SLV" commands are used to define master and slave sides. Boundary conditions are defined by "NBCS s c" command, in which s indicates the side number and c=0 for no constraint, c=1 for r-constraint, c=2 for z-constraint, and c=3 for r and z constraints. For example,

```
NBCS 3 1
```

means side number 3 with r-constraint only.

Pressure boundary condition can be defined by "PBC" command, for example

```
PBC 252 279 2 1 1
```

and it indicates boundary nodes 252 to 279 (counterclockwise) have a pressure loading applied that varies in time according to load curve 2. The scale factor on load curve 2 varies linearly from 1 at boundary node 252 to 1 at boundary node 279.

Command "TITLE" is to define title. "TERM" is to set terminal time. "NSTEP" can set the number of desired time steps. "PRTI" is used for node and element data dump interval for printer. "PLTI" is for node and element data dump interval for plotter.

User can choose analysis type by "ANAL n" command, where n=0 for static analysis, n=1 for dynamic analysis with lumped mass matrix, and n=2 for dynamic analysis with static solution at time = 0. Bandwidth minimization option is also available by "BWMO n" command. If n=1, control flag is set for NIKE2D to minimize bandwidth. If n=2,
control flag is set for NIKE2D to read destination vector from MAZE generated input file.

"WBCD NIKE2D" is used to end phase 2 and begin phase 3. In phase 3, material properties are defined. According to the material type, user can select one from ten material types which NIKE2D supports. Finally, "END" is used to end MAZE.
Figure C.1 Define a line
MAZE VERSION I  (COMPILED 04/29/85)  COMMAND : PART

Figure C.2 Define a part
Figure C.3 Display boundary nodes number
After finishing all the procedures stated above, two files, MAZSAV and MAZOUT, are created. MAZSAV is the data file that user just key in, which can be modified to remesh. And in the later run of MAZE, user can change the default file name as:

C=MAZSAV

MAZOUT is the data generated by MAZE for using in running NIKE2D. Listing C.1 and C.2 are typical data files of MAZSAV and MAZOUT.

1
10
LD 1 LP 2 0 0 1 0
LD 2 LP 3 1 0 1 3.7929 0.5 5
LD 3 LP 2 0.5 5 0 5
LD 4 LP 2 0 5 0 0
PART 1 2 3 4 1 10 50
Y
LD 5 LP 2 1 3.7929 1.5 3.7929
LD 6 LP 2 1.5 3.7929 1.5 5.5
LD 7 LP 2 1.5 5.5 0.5 5.5
LD 8 LP 2 0.5 5.5 0.5 5 LAT 0.5 5 1 3.7929 0.1
PART 5 6 7 8 2 5 20
Y
ASSM
LCD 1 4 0 0 100 5000 220 5000 240 0
LCD 2 4 0 0 143 35750 153.5 35750 155 0
LCD 3 4 0 0 160 40000 165 40000 167 0
LCD 4 4 0 0 200 50000 220 50000 240 0
SLN 1 4 0.05
SLNP 1.0
P 2 B
MSR 682 562
P 1 B
SLV 11 561
P 2 B
NBCS 1 3.0
P 1 B
NBCS 3 1.0
P 1 B
PBC 561 551 1 -1 -1
PBC 363 418 2 1 1
Listing C.1  Data file of MAZSAV

PRODUCT AUGMENTED HYDROSTATIC EXTRUSION
N 2  687  600  400.6000E+01  40  0  1  50  21  0
 4  4  0  55  0  0  0  0  1  0  1  0  1  1  10  150.1  E-020.1000E-01  0
 1  30.9700E-01
ALUMINUM
 0.100E+08  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.300E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.200E+05  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.100E-01  0.100E+01  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 2  10.2830E+00
STEEL
 0.300E+08  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.300E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
SLIDELINE NUMBER 1

LOAD CURVE # 1

MASS DISTRIBUTION VOLUMES MASSES RMASS-CENTER ZMASS-CENTER
1.41260E+01 1.37022E+00 0.00000E+00 2.26751E+00
9.46070E+00 2.67738E+00 0.00000E+00 4.70986E+00
TOTALS 2.35846E+01 4.04760E+00 0.00000E+00 3.88305E+00

MASS MOMENTS
IRR IZZ
2.74786E+00 6.45676E-01
Listing C.2 Data file of MAZOUT

C.2 Procedures of running NIKE2D

Although the terminal time and desired steps number were defined in MAZE, automatic step size control by NIKE2D is possible. By typing "AUTO" on columns 53 to 56 in the first line of the output file of MAZOUT, NIKE2D will adjust the step size using quasi-Newton schemes.

To invoke NIKE2D, key in "RUN UDA2:[51,2]NIKE2D." The terminal will prompt as:

DEFAULT FILE NAMES:
O=N2HSP  G=N2PLOT  D=N2DUMP

PLEASE DEFINE INPUT FILE NAMES OR CHANGE DEFAULTS

The user should key in "I=MAZOUT" after these messages and hit the "RETURN" key. The terminal will reply as:

NIKE2D (VERSION 0) COMPLIED 11/08/86

ON VAX COMPUTER NOTE THE FOLLOWING CHANGE:
CTRL-C INTERRUPTS NIKE2D AND PROMPTS FOR A SENSE SWITCH

TYPE THE DESIRED SENSE SWITCH: SW1.,SW2.,ETC. TO CONTINUE THE EXECUTION. NIKE2D WILL RESPOND AS EXPLAINED IN THE USERS MANUAL.
And several iteration parameters including the title name will show later as:

**PRODUCT AUGMENTED HYDROSTATIC EXTRUSION**

**CPS BANDWIDTH/PROFILE MINIMIZATION ATTEMPTED**

BANDWIDTH (PROFILE) BEFORE MINIMIZATION = 1115 (11443)

BANDWIDTH (PROFILE) AFTER MINIMIZATION = 1115 (11443)

NUMBER OF ELEMENTS PER GROUP = 600

AVAILABLE WORKING SPACE FOR EQUATION SOLVER = 35834

WORKING SPACE USED = 35834

NUMBER OF WORDS IN STIFFNESS MATRIX = 34552

MAXIMUM COLUMN HEIGHT IN STIFFNESS MATRIX = 276

AVERAGE COLUMN HEIGHT IN STIFFNESS MATRIX = 25

NUMBER OF BLOCKS IN OUT-OF-CORE SOLUTION = 1

After these messages, the user should hit the "CONTROL" and "C" key at the same time, and the terminal will prompt as:

CANCEL

ENTER SENSE SWITCH:

The user can select one of six sense switch controls to use. The six sense switch controls are listed as follows.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1.</td>
<td>A restart file is written and KIKE2D terminates.</td>
</tr>
<tr>
<td>SW2.</td>
<td>NIKE2D responds with time and cycle number.</td>
</tr>
<tr>
<td>SW3.</td>
<td>NIKE2D responds every cycle with time, cycle number, and convergence behavior until SW3. is retyped.</td>
</tr>
<tr>
<td>SW4.</td>
<td>A restart file is written and NIKE2D continues calculation.</td>
</tr>
<tr>
<td>SW5.</td>
<td>Enter interactive graphics and rezoning phase.</td>
</tr>
<tr>
<td>SW6.</td>
<td>Requests user to input a new time step value.</td>
</tr>
</tbody>
</table>

Listed C.3 Terminal sense switch controls

After NIKE2D terminating, three files, N2HSP, N2PLOT and N2DUMP, are created. N2HSP is the output file of NIKE2D which includes all the input file from MAZE and the iteration parameters. N2PLOT is a binary plotting file for graphics which will be used in ORION -- postprocessor of NIKE2D. And N2DUMP is the dump file for restarting.

C.3 Post-processor: ORION

C.3.1 Introduction

ORION is the interactive post-processor for NIKE2D, DYNA2D, TACO2D, TOPAZ and GEM2D. ORION reads the binary
plot files generated by two-dimensional finite element codes. Contour and color fringe plots of a large number of quantities may be display on meshes consisting of triangular and quadrilateral elements. ORION can compute strain measures, interface pressures along slide lines, reaction forces along constrained boundaries, and momentum [37].

C.3.2 Procedures

To invoke ORION, the user should key in the command "RUN UDA2:[51,2]ORION." The terminal will prompt as:

DEFAULT OUTPUT FILE NAMES :
T=ORNOUT S=ORNSAV
PLEASE DEFINE INPUT FILE NAMES OR CHANGE DEFAULTS :
>

The user then key in, for example

G=N2PLOT

The terminal will reply as following in which title and terminal parameters are included.

ORION (VERSION A) COMPLIED 08/05/86
HELP PACKAGE IS NOW AVAILABLE: TYPE "HELP"
OR "HELP/COMMANDNAME" FOR A COMMAND DESCRIPTION
PRODUCT AUGMENTED HYDROSTATIC EXTRUSION
LAST STATE IS STATE # 25 AT TIME= 0.24000E+03
NUMBER OF MATERIALS = 2
Now the user should key in any number, for example 1, and the terminal will ask the user to select the device as in MAZE. After the procedures, the phase 1 is ready for using. In phase 1, deformations are display according to the desired state or time. To display the deformation of a specified state, "STATE n GO" command is used. Figure C.4 shows a typical display of "STATE" command. To display the deformation of a specified time, "TIME t GO" is available.

Contours of stress distribution are very important in the analysis of deformation and are available by "CONTOUR" command. By "CONTOUR c n m₁ m₂ . . . mₙ," contour component number c on n materials including materials m₁, m₂, . . . , mₙ is plotted. The component number c is listed on page 18 of the reference [37]. Figure C.5 shows a typical plot of "CONTOUR" command.

"PHS2" is used to proceed to phase 2. In phase 2, time history plots and prints of stress and strain components are possible. To print the plotted time history data, "PRINT" and "COLUMN" are used before any plots. An example of getting plots is listed below:

NODES 1 369
GATHER
NTIME 2 1 369

In this example, the time history of one node, 369, is requested. "GATHER" command is used to read through the plot files and store the time histories for all the variables specified previously. "NTIME 2" command is used to plot the axial displacement. A plot of this example is shown in Figure C.6.

Finally, "END" or "T" command is used to terminate ORION. After these procedures, two files, ORNOUT and ORNSAV, are created. ORNSAV is the data file which includes all the commands that user keyed in. ORNOUT is the output file that includes all the plotting data.
Figure C.4 Display of "STATE n GO" command
Figure C.5 Plot of "CONTOUR" command
Figure C.6 Plot of component 2 node 369