COMPUTER SIMULATION OF THE
HAMMER FORGING PROCESS

A Thesis Presented to
The Faculty of The College of Engineering and Technology
Ohio University

In Partial Fulfillment
of The Requirement for The Degree of
Master of Science

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— June 1986

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CHAPTER I

INTRODUCTION

Drop forging can be produced on various machinery such as mechanical presses, screw presses, hydraulic presses, and hammers. Among them, hammers are the most commonly used type of machine in the drop forging industry.

Hammers are preferred for small or medium batch sizes because of quicker tool set-up and lower overheads [1]. Moreover, they have often been used to produce forgings of elongated or branched shapes, since hammer blocks provide wide die areas to accommodate several preform dies. Forgings made from difficult-to-forge material that require forging energy beyond the capability of available presses, can also be transferred to hammers so that the required energy can be built up by repeated blows [2].

The basic fact involved is that metal subjected to external pressures tends to flow in the directions of the least resistance. This movement of metal is defined as plastic flow. In hammer forging processes, this plastic flow of metal is controlled under impact load until it fills dies of predetermined shape. The impact energy in hammer forging causes compressive strain to take place below the area subjected to the blow. The quickness of the impact
tends to localize this effect and confine most of the metal working to the exterior [2]. This results in directional material structure of the hammer-forged part. The hammer forging compacts the metal fibers and improves the material properties.

The capacity of a mechanical hammer is defined in terms of the maximum energy that the machine can generate for the deformation of workpiece. However, the capacity of the hammer which is defined by the maximum deformation energy is only one of the factors determining the type of work for which a particular machine is suitable [1]. Dugdale investigated the efficiency of mechanical hammers for operations where the forging forces are high. He assumed that the ram could be essentially represented by two cylindrical rods and that the forging force was constant throughout the operation [1]. With this assumption, he found that no work could be done on the workpiece, unless the impact velocity of the ram exceeded a certain minimum value. The analysis of hammer forging is more complex than the simplified model assumed by Dugdale since he had no information about the effect of the geometry of ram and anvil on the dynamic load conditions [4]. The present thesis provides an approach to correlate the dynamic characteristics of the hammer and the dynamic behavior of materials.
A computer program A.L.P.I.D. (Analysis of Large Plastic Increment Deformation) 1.41 version developed by Battelle Laboratories in Columbus, Ohio has been modified for the simulation of hammer forging, applicable to the following two kinds of hammer forging processes:

1. Gravity Drop Hammer Forging
2. Power Drop Hammer Forging

Also, the important features of the A.L.P.I.D. 1.41 version include:

1. Use of high order elements such as linear, quadratic and cubic elements of serendipity and lagrangian families,
2. a general description of die and automation of die boundary condition which enable the user to use any number of arbitrary shaped dies of different types and friction coefficient,
3. automatic initial guess generation by which input data requirements are reduced to a level for simple analysis and improves remarkably, the solution efficiencies.

Two example solutions (one is drop hammer forging and the other is power drop hammer forging) have been supplied in chapter 4 to demonstrate the feasibility and flexibility of the program. The modification of A.L.P.I.D. 1.41
version for the hammer forging simulation is based on the empirical relationships and other literature surveys regarding hammer forging analysis.

As a basic and essential approach toward the analysis of hammer forging, the rigid-viscoplastic finite element formulation suggested by Oh, Rebelo, and Kobayashi [5] has been used. For the estimation of die velocity during the hammer forging process, three possible methodologies have been suggested. Among them, the energy balance method based on the force exerted on dies has been adopted.

The runs of the modified A.L.P.I.D. 1.41 will provide users with information for the proper design and control of the hammer forging process.
CHAPTER II

GENERAL FEASIBILITY STUDY FOR THE HAMMER FORGING PROCESS

Hammer forging is carried out in a succession of die impressions on the workpiece using repeated blows. The action of this process is repeated the kneading and forming of the workpiece with predetermined die shapes. Intermittent, impact pressure of the hammer blows refines and improves the physical properties of the workpiece. This improvement can be obtained in any metal that is worked through successive forging stages from preform operations to attainment of final geometric shape of dies. The work materials of the process include any of the malleable compositions of metal such as iron, steel, alloy steel, stainless steel, brass, aluminium, and titanium. The hammer forging sequence consists of preforming, blocking, and finishing, which is followed by the trimming process. Large quantities of high-quality forgings of an identical kind can be rapidly and economically produced with hammer forging. The quantities, however, are not restricted to large volume only. The hammer forging process is preferred for even small quantities of products when the chief purpose of forging is not only to impart shape to the product but also to obtain the improvement of its physical properties to satisfy service requirements.
2-1 THE ADVANTAGES OF THE HAMMER FORGING PROCESS

The selection of the hammer forging process to produce a desired part is based on one or a number of essential factors, which can be enumerated as follows [6]:

1. Greater strength
2. Ability to withstand unpredictable loads
3. Minimum of machine finishing
4. Saving in material
5. Elimination of internal defects

Concerning factor 1, a part which is drop-forged is substantially stronger than a casting of the same cross-sectional area. Because of this fact, the hammer forging process is preferred for saving on the amount of material required and reducing the cost of parts.

Concerning factor 2, when a part is forged, the metal flow can be controlled for the rearrangement of fiber structure of workpiece in the direction most desirable for the requirements of service conditions. The hammer-forged grain structure can be controlled as to the density and the orientation of slip planes of the grains in such a manner that a hammer-forged part can withstand at unpredictable load conditions.

Concerning factor 3, comparing a hammer-forged part
with a casting of the same part, it is found that tolerances of the hammer-forged part are in much closer limits than that of a sand casting of the same size. In hammer forging, no allowance needs to be made for warpage, but must be allowed for in casting.

Concerning factor 4, hammer forging requires less finishing, compared to sand casting since the allowance is in such a low limits

Concerning factor 5, hammer forgings are usually made on solid metal bars which eliminates the blow holes in the workpiece.

2-2 HAMMER FORGING EQUIPMENTS

Hammer forging is a forging process characterized by kinetic energy of ram assembly. During a moving ram stroke, the deformation proceeds until the effective kinetic energy of ram assembly is converted into plastic deformation energy of the workpiece and frictional energy during the deformation process. Therefore, it is natural to classify the hammer forging process depending on how the kinetic energy of ram assembly is generated. Also it is natural to rate the capacity of the hammer forging equipment in terms of energy, i.e. foot-pounds, meter-kilogram or meter-tons.
2-2-1 GRAVITY DROP HAMMER FORGING

In a simple gravity drop hammer, the upper ram is positively connected to a board (board drop hammer), a belt (belt drop hammer), a chain (chain drop hammer), or a piston (oil, air, or steam-lift drop hammer) as in Figure 1. The ram is lifted to a certain height and then dropped on the

Figure 1. Principles of Various Types of Gravity Drop Hammers [1]
workpiece which is placed on the anvil. During the
downstroke, the ram is accelerated by gravity. The
upstroke takes place immediately after the blow.

The force necessary to ensure the quick lift-up of the
ram can be equal to 3 to 5 times the ram weight. The
essential features of the construction of a common board
hammer is shown in Figure 2 together with schematic
diagrams of the operation of the lifting rolls. The force
of the blow can be varied within limits by adjusting the
height of the fall.

Board hammers are rated on the basis of the weight of
the ram assembly. Of recent design is a hammer forging
which is similar in performance to the board hammer, but
it uses compressed air or steam and a piston as a means of
raising the moveable small piston rod. Air pressure is
used only to lift the ram and not to apply any force on the
downstroke. The details of construction and operation are
shown in Figure 3.
Figure 2. Details of Board Drop Hammer [6]
Figure 3. Air Piston Lift Gravity Drop Hammers [6]
2-2-2 POWER DROP HAMMER FORGING

The operating principle of a power drop hammer is illustrated in Figure 4. During downstroke, the ram is accelerated by either steam or cold air or hot air pressure in addition to gravity. In this type of hammer, the ram is lifted with oil pressure against an air cushion. The compressed air slows down the upstroke of the ram and contributes to its acceleration during the downstroke blow. The outline and operation are shown in Figure 4.

Figure 4. Sequence of Operation of U.S. Industry Machine:
(a) Safe Position  (b) Charge Position
(c) Triggering    (d) Impact Position [21]
2-3 CAPABILITIES AND APPLICATIONS OF HAMMER FORGING

Basically, hammer forging can be classified into two types. One is gravity drop hammer forging and the other is power drop hammer forging. Detailed discussion of hammer forging follows.

The ratings of capabilities for hammers in U.S. are defined in view of ram weight, which is not very meaningful to users. Furthermore, the blow efficiency is not a good parameter for the representation of hammer capability. In the European forging society, the usual range of hammer capabilities is illustrated in Figure 5 [1].

![Figure 5 Approximate Range of Application for Gravity Drop, Power Drop, and Counter-Blow Hammers in Europe [1]](image-url)
To obtain a higher blow efficiency, the ratio of anvil to ram weight is suggested to be around 20 to 1 or 25 to 1. Additionally, the installation of a large hammer foundation is recommended to reduce the vibrational energy loss and increase blow efficiency. To meet these requirements economically, hammer forging designers usually construct the anvil and the frame in one piece. The other approach to foundation design for better efficiency is a spring-like mounting system. The mounting system includes the anvil being bolted to a concrete base resting on springs which are mounted to the concrete floor as shown in Figure 6.

Figure 6. Schematic Diagram of Foundation Design for Reducing Hammer Forging [1]
Also, one of the modern designs which is available up to 60,000 foot-pound capacity is illustrated in Figure 7. In this system, the ram is accelerated downward with air pressure while the hydraulic fluid that is forced through the distributor into the cylinder at the base of the hammer accelerates the anvil and frame upward. Through adequate design of the hydraulic system, a small upward motion of the anvil provides a counterblow effect and vibrational losses are reduced.

Figure 7 Hydraulic Anvil Hammer Design Using Counterblow Principle to Reduce Ground Vibration [1]
CHAPTER III

THEORETICAL ANALYSIS OF THE HAMMER FORGING PROCESS

The objective of this thesis is to review the finite element formulation for the analysis of large plastic deformation of rate sensitive materials where the velocities of dies change with time. A typical example of such a process is hammer forging. The behavior of material is characterized as rigid-viscoplastic. The following steps are introduced to obtain a solution for the problem of hammer forging.

Firstly, an approach to the development of constitutive equations for the rigid viscoplastic material is presented.

Secondly, an approach to establish the continuously changing velocity field based upon the analysis of blow load and energy characteristics is described.
3-1. RELEVANT PREVIOUS WORKS ON THE MODELING OF HAMMER FORGING

The development of high-velocity metal working in recent years has stimulated research into the hammer forging process. Generally acceptable assumptions have been suggested by C.E.N. Sturgess and M.G. Jones [7] and have been widely adopted in most analyses of hammer forging processes. With those assumptions, the nominal deformation energy can be calculated from the calculated impact velocity, \( v = \sqrt{2gh} \), where \( h \) is the vertical height of the fall. This calculated impact was compared with the measured impact velocity with the help of accelerometer impulses and the variation in results was found to be only \( \pm 2 \) percent. Furthermore, from the measured values, it was noted that the percentage loss of energy at impact situation is not always negligible. This total amount of loss is the sum of the losses due to elastic rebounding of the tup assembly, friction and the guides and energy transmitted to the anvil, etc [4]. To take this energy loss into consideration, an idea for the determination of blow efficiency was suggested by T. Altan, F.W. Boulger, J.R. Becker, and N. Akgermann [1]. For a successful forging, the kinetic energy of the hammer at impact should exceed the work required [8].

Two of the three methods suggested in this thesis for
estimation of the hammer forging velocity function are based upon energy balance analysis. An energy balance method based on the kinetic energy of the ram assembly and the force exerted on the dies was suggested by S.I. Oh, N. Rebelo, and S. Kobayashi [5]. In this approach to solve the non-steady-state deformation problem, the assumption of a quasi-static process is justified for die velocities[4]. For this method, calculation of the ram assembly kinetic energy has been suggested by many authors[1,8,9]. The other method is also based upon an internal energy balance. The kinetic energy of the ram assembly is assumed to be converted into deformation and frictional energy. At every step of the deformation process, this total energy can be calculated by summing the contributions from all the elements and the interfaces between the workpiece and dies. Then, for estimation of the ram velocity at the next step, the new kinetic energy of the ram assembly can be calculated by subtracting deformation energy and frictional energy from the ram assembly kinetic energy. An the approach for calculating deformation and friction energy has been suggested by many authors [10-15].

The dynamic force analysis method is based on the analysis of forces including internal forces and those due to the elastic deflection of the dies. The differential equation based on the force balance can be solved by using
separation of variables. Solving this differential equation, using the initial values of deformation strain, strain-rates, and flow stress, and knowing the workpiece dimensions and friction conditions, the forging load can be obtained [16].

3-2. CONSTITUTIVE EQUATION FOR RATE-SENSITIVE PLASTIC MATERIAL

3-2-1 PHYSICAL FOUNDATION

Often, experimental results from dynamic loading conditions can be obtained accurately but their interpretation gives rise to doubt. The dynamic phenomena occurring in a test piece during the impact process are influenced by a number of factors, which makes the selection of the dominant one very difficult. Often a phenomenon is determined simultaneously by several factors of equal importance[16]. Metals having a well-defined yield limit are particularly sensitive to strain-rate.

Most of the plastic stress-strain laws in practical use are based on the assumption that a unique relation exists between $\dot{\sigma}$ and $\dot{\varepsilon}$. Thus the physical relationship for the one-dimensional problem can describe the general material behavior under various loading conditions.

With regard to this, the following equation was
suggested by H.G. Hopkins [20].

$$\sigma = \phi(\varepsilon^p, \dot{\varepsilon}^p)$$ \hspace{1cm} (1)

where $\sigma$ is the nominal tensile stress and $\varepsilon^p$ and $\dot{\varepsilon}^p$ are the nominal plastic strain and strain-rate, respectively.

A physical law was suggested L.E. Malvern which can be expressed by the equation [38]:

$$\dot{\varepsilon} = \dot{\varepsilon}/E + \langle \bar{\varepsilon} \rangle \left[ \sigma - f(\varepsilon) \right]$$ \hspace{1cm} (2)

where $\varepsilon$ denotes total nominal strain, $E$ denotes Young's Modulus and $\sigma = f(\varepsilon)$ is the static relation between simple tension and compression. Here, $\langle \bar{\varepsilon} \rangle$ has been defined as follows:

$$\langle \bar{\varepsilon} \rangle = \bar{\varepsilon} \quad \text{if} \quad \sigma > f(\varepsilon)$$

$$\langle \bar{\varepsilon} \rangle = 0 \quad \text{if} \quad \sigma < \text{or} = f(\varepsilon) \hspace{1cm} (3)$$

L.E. Malvern discussed in detail two cases.

$$\bar{\varepsilon} = a \ast \{ \exp b[\sigma - f(\varepsilon)] - 1 \}$$ \hspace{1cm} (4)

and the linear function

$$\bar{\varepsilon} = c \ast [\sigma - f(\varepsilon)]$$ \hspace{1cm} (5)

where $a$, $b$, and $c$ are constants depending on the material.

For the solution of the problem of the propagation of plasticstress waves in a bar a more general physical
relation was used by L.E. Malvern, namely:

\[ \dot{\varepsilon} = \frac{\dot{\sigma}}{E} + < g(\sigma, \varepsilon) > \]  

(6)

where the function \( g(\sigma, \varepsilon) \) is determined by experiment.

3-2-2. CONSTITUTIVE EQUATION

The traditional equation for strain rate is as follows:

\[ \dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^e + \dot{\varepsilon}_{ij}^p \]  

(7)

However, in the rigid-viscoplastic concept, \( \dot{\varepsilon}_{ij}^p \) can be neglected. The constitutive equation for work-hardening and rate-sensitive plastic material can take the following form.

\[ \dot{\varepsilon}_{ij} = \frac{1}{2\mu} \dot{\sigma}_{ij} + \frac{1 - 2\nu}{E} \dot{\sigma}_{ij} S_{ij} + \nu' < \Psi(F) > \ast \frac{\partial F}{\partial \sigma_{ij}} \]  

(8)

where \( S_{ij} \) is Kronecker delta, \( \nu' = \nu / K \) denotes a defined as follows:

\[ < \Psi(F) > = \begin{cases} 0 & \text{for } F < \sigma = 0 \\ \Psi(F) & \text{for } F > 0 \end{cases} \]  

(9)

The function \( \Psi(F) \) is chosen to represent the results of
test on the behaviour of metals under dynamic loading.

\[ F(\sigma_{ij}, \varepsilon_{\text{pl}}^p) = \frac{f(\sigma_{ij}, \varepsilon_{\text{pl}}^p)}{K} - 1 \]  

(10)

where the function \( F(\sigma_{ij}, \varepsilon_{\text{pl}}^p) \) is the general static function and the function \( f(\sigma_{ij}, \varepsilon_{\text{pl}}^p) \) depends on the state of stress \( \sigma_{ij} \) and the state of plastic strain \( \varepsilon_{\text{pl}}^p \). The parameter \( K \) is defined by the expression

\[ K = K(\psi_p) = K(\int_0^{\varepsilon_{\text{pl}}^p} \sigma_{ij} d\varepsilon_{\text{pl}}^p) \]  

(11)

This quantity is called the strain hardening parameter. It is much more convenient to write the constitutive equation (8) in a slightly different form as follows:

\[ \dot{\varepsilon}_{ij} = \frac{1}{2\mu} \sigma_{ij} + \frac{1 - 2\nu}{E} \dot{\sigma}_{ij} \sigma_{ij} + \nu^p \varepsilon_{EF} (F) \frac{\partial f}{\partial \sigma_{ij}} \]  

(12)

where \( \nu^p = \nu / K \) denotes a viscosity constant of material. Equation (12) includes the assumption that the rate of increase of the inelastic components of the strain tensor is a function of the excess stress over the static yield criterion. This function of the excess of stress above the static yield criterion generates an inelastic strain-rate according to a viscosity law of the Maxwell type. The plastic part of relation (12) is
\[ \dot{\varepsilon}_{ij}^p = u \overrightarrow{F} \frac{\partial f}{\partial \sigma_{ij}} \] (13)

By denoting \( I_2 \), the invariant of the inelastic strain-rate tensor is

\[ ( I_2 ) = u \overrightarrow{F} \left( \frac{1}{2} \dot{\sigma}_{ij} * \dot{\sigma}_{ij} \right) \] (14)

According to (14) and (10), we have

\[ f(\sigma_{ij}, \varepsilon_{ij}^p) = K(\overrightarrow{W}) \left\{ 1 + \overrightarrow{H} \left[ \frac{I_2}{2} \right] \left( \frac{1}{2} \dot{\sigma}_{ij} * \dot{\sigma}_{ij} \right) \right\} \]

(15)

This expression implicitly represents the dynamic yield condition for an elastic / viscoplastic work-hardening material and describes the dependence of the yield criterion on the strain rate. The change of the yield surface during the deformation process is caused by isotropic and anisotropic work-hardening effects and by the strain rate effects. Assuming isotropic (and isotropic work-hardening), incompressibility, and the Huber-Mises yield criterion, we have

\[ f = ( J_2 )^{\frac{1}{2}} \] (16)
where \( J_2 = \frac{1}{2} \frac{\partial}{\partial t} \delta_{ij} \delta_{ij} \) is the second invariant of the derivative stress tensor. Then equation (13) becomes

\[
\dot{\varepsilon}_{ij} = \nu \langle \Phi ( \frac{J_2}{K} - 1 ) \rangle \rangle \frac{\delta_{ij}}{J_2} 
\]

(17)

Squaring both sides

\[
\dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij} = \nu \langle \Phi ( \frac{J_2}{K} - 1 ) \rangle \rangle ^2 \frac{\delta_{ij} \delta_{ij}}{4 J_2} 
\]

(18)

We obtain

\[
I_\frac{1}{2} = \frac{\nu}{2} \langle \Phi ( \frac{J_2}{K} - 1 ) \rangle \rangle 
\]

(19)

\( I = \frac{1}{2} \frac{\dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}}{\rho} \) is the second invariant of the strain-rate tensor. Substituting equation (16) into equation (15), we can get

\[
\dot{\varepsilon}_{ij} = \frac{I_\frac{1}{2}}{J_2} \delta_{ij} \delta_{ij}^{\dot{\sigma}} \quad \text{or using effective stress and strain instead of } J_\frac{1}{2} \text{ and } I_\frac{1}{2}.
\]

(20)

From equation (15), the dynamic yield criterion is

\[
J_2 \frac{1}{2} = K( W_p ) * [ 1 + \Phi( \frac{I_\frac{1}{2}}{\nu} ) ]
\]

(21)

For one-dimensional states, the equation (21) now gives

\[
\sigma = \rho( \dot{\varepsilon}^p ) * [ 1 + \Phi( \frac{\dot{\varepsilon}^p}{\nu^*} ) ]
\]

(22)
where \( u^* = \left( \frac{2}{\sqrt{3}} \right) \eta \), \( \phi (\dot{\varepsilon}^p) = \sqrt{3} \cdot K \cdot \dot{W}_p \)

For metal forming, (22) can be represented in the form:

\[
\sigma = Y \left[ 1 + \left( \frac{\dot{\varepsilon}}{\nu} \right)^n \right]
\]  \hspace{1cm} (23)

where \( Y = Y(\varepsilon) \) is the static yield stress.

Then from (20)

\[
\sigma_{ij}^* = \frac{2}{3} Y \left[ 1 + \left( \frac{\dot{\varepsilon}}{\nu} \right)^n \right] \frac{\dot{\varepsilon}_{ij}}{\dot{\varepsilon}}
\]  \hspace{1cm} (24)

In this particular case, by applying (19) and (22) to uniaxial stress, the form of \( \phi \) can be shown to be

\[
\phi (X) = X^{\nu} \quad \text{and} \quad \sqrt{3} \cdot K = Y
\]  \hspace{1cm} (25)

3-3. RIGID VISCOPLASTIC FINITE ELEMENT FORMULATION

The rigid viscoplastic material is an idealization of the actual one, obtained by neglecting the elastic response. However, in many cases, this idealized analysis shows good agreement with the actual large plastic increment deformation \([8,9]\).

Two fundamental assumptions are usually made in plastic analyses, one regarding the yield criterion and the other one regarding the stress - strain relation \([7]\).
Firstly, for the yield criterion, the hypothesis of Von Mises seems to be invariably accepted, i.e. that yielding starts when the effective or equivalent stress

\[
\bar{\sigma} = \sqrt{\frac{1}{2} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right)}
\]

(26)

reaches the yield point or more precisely, when there is no longer a linear relationship between equivalent stress and equivalent strain. The equivalent strain may be written

\[
\bar{\varepsilon} = \sqrt{\frac{2}{9} \left( (\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right)}
\]

(27)

At equation (26) and (27), \(\sigma_1, \varepsilon_1\) are principle stress and strain components.

Secondly, most of the plastic stress-strain laws in practical use are based on the assumption that a unique relation exists between \(\bar{\sigma}\) and \(\bar{\varepsilon}\) (i.e. if one of the two is specified, the other is determined).

The rigid viscoplastic material for the analytical convenience supplies a simplified solution procedure with excellent solution accuracies due to the negligible effect of elastic response at large strain in actual metal forming.
processes. In this section a finite element formulation associated with boundary value problems is described.

3-3-1. EXTREMUM PRINCIPLE

The analysis of the deformation process of the rigid viscoplastic material is concerned with the associated boundary value problems. Even in the process of quasi-static deformation, the geometry of the billet and dies, the state of inhomogeneity and the desired values of the material parameters are supposed to be specified or to have been determined already at a generic stage. The velocity vector, \( \mathbf{v} \) is prescribed on a part of the surface, \( S_v \); together with the tractional force, \( \mathbf{f} \), on the remainder of the surface, \( S_f \). Also, equilibrium and compatibility equations are supposed to be satisfied by the stress and velocity field solution. With regard to this, the extremum principle derived by Hill [19] needs to be invoked to solve such boundary value problems.

Among all possible constitutive equations, attention will be restricted to the case where there exists the work function \( E(\dot{\varepsilon}_{ij}) \), such as

\[
\sigma_{ij} = \frac{\partial E}{\partial \dot{\varepsilon}_{ij}}
\]  

(28)
and where $E$ is convex. The existence of the work function $E(\dot{\varepsilon}_{ij})$ can be ensured, if $\mathcal{C}'$ is a single-valued function of $\dot{\varepsilon}$, satisfying

$$\frac{\partial \mathcal{C}'}{\partial \dot{\varepsilon}_{ij}} = \frac{\partial \mathcal{E}}{\partial \dot{\varepsilon}_{ij}}$$  \hfill (29)

Also, $E$ is a convex function, if

$$E(\dot{\varepsilon}^*) - E(\dot{\varepsilon}) > (\dot{\varepsilon}^*_{ij} - \dot{\varepsilon}_{ij}) \cdot \frac{\partial E}{\partial \dot{\varepsilon}_{ij}}$$  \hfill (30)

With this restriction, the following relationship can be obtained without consideration of the body force:

$$\int_V E(\dot{\varepsilon}^*) \, dV - \int_{S_F} F \cdot \dot{\mathcal{V}} \, dS_F > \text{or} = \int_V E(\dot{\varepsilon}) \, dV - \int_{S_F} F \cdot \dot{\mathcal{V}} \, dS_F$$  \hfill (31)

where $\dot{\varepsilon}$, $\mathcal{V}$ are actual quantities and the starred quantities are kinematically admissible ones. It can be shown that the solution is uniquely determined at points of the body where $E$ is strictly convex but not necessarily in all respects elsewhere. It can also be proved that a relation (31) holds even for a deformation process in which a rigid zone is involved, although equation (28) is not defined at the origin of the strain-rate surface.
3-3-2. IMPLEMENTATION OF BOUNDARY CONDITION

The implementation of boundary conditions on $S_F$ or $S_V$, both of which have already been mentioned in section 2-1, is straightforward and can be referred to elsewhere. The particular attention must be paid to the boundary condition in the analysis of plasticity using the F.E.M. (Finite Element Method). Also the effect of frictional stress is very important in metal forming processes. It can alter the position of the neutral point in the workpiece and it may cause to bulge the billet during deformation. Among various friction laws, the constant shear law is adopted in this section, which is a common assumption for metal forming. The die boundary conditions along curved die-workpiece interface have been mainly considered in the framework of F.E.M..

At the initial stage, consider a curved die surface which is in contact with a billet, as shown in Figure 8.

Now, the boundary condition can be written as

$$V_n = V_D \times n \quad \text{(32)}$$

$$f_S = -mK \frac{\Delta V_S}{\Delta t} = -\frac{2}{\pi} mK \tan^{-1} \left( \frac{\Delta V_S}{U_v} \right) \Delta t \quad \text{(33)}$$

where $n$ is the unit normal vector as shown in the figure and the subscripts $n$ and $s$ denote the normal and tangential
Figure 8. Schematic Diagram of Curved Die and Workpiece [10]

directions to the interface, respectively. The expression of \( f_5 \) in equation (33) has been used for the smooth transition of frictional stress near the neutral point of the flat die surface. Here, \( \Delta V_5 \) is the slipping velocity, \( m \) the friction factor, \( K \) the local flow stress in shear, and \( U_0 \) is a very small positive number compared to \( \Delta V_5 \). However, in most cases, the die surface does not coincide with the billet surface defined by the F.E.M. approximation. These discrepancies are shown in Figure 8(b). Because of the discrepancy in geometry, the necessary quantities in equation (33) are not well defined at the contact node.
Thus, to minimize errors caused by this factor, elements of billet in the F.E.M. approximation should be meshed as intensively as possible along the surface of the curved interface. Moreover, to overcome these difficulties, the boundary condition normal to the surface is enforced at the contacting node and is given by:

\[ V_n = V_0 \times n(i) \quad (34) \]

where \( n(i) \) is the unit normal to the die surface, rather than to the element surface, at node \( i \). It is assumed that the slipping velocity \( V \) can be approximated by:

\[ \Delta V_S = \sum_i H_i \Delta U_{S_i} = \sum_i H_i (v_{S_i} - v_0 \times S(i)) \quad (35) \]

Here, \( H_i \) is the F.E.M. shape function on the surface, \( v_{S_i} \) the tangential velocity of the \( i \)-th node and \( S(i) \) the unit tangent to the die surface at the contact node \( i \). By substituting equation (35) into the expression for \( \Delta V_S \), the integrand of the die boundary term is

\[ \int_{f_S} v_S \, dV_S = \int v_S - \sum_{i,j} \frac{2}{\pi} m K_j \tan^{-1} \left( \frac{v_{S_i} - v_0 \times S(i)}{U_0} \right) ] dv_{S_j} \quad (36) \]
3-3-3. FINITE ELEMENT FORMULATION

Deformation of the billet is characterized by the following equations and it can be extended to rigid-viscoplastic F.E.M.. As was defined by equations (26) and (27), and are defined by \( \sqrt[3]{3/2} \dot{\varepsilon}_{ij} \) and \( \sqrt[2]{2/3} \dot{\varepsilon}_{ij} \) respectively and also as defined by equation (24), the constitutive equation is

\[
\dot{\varepsilon}_{ij} = \frac{2}{3} \frac{\mathbf{S}}{\varepsilon} \cdot \dot{\varepsilon}_{ij}
\]

Moreover, the strain-rate equation can be defined as

\[
\dot{\varepsilon}_{ij} = \frac{1}{2} \left( V_{i,j} + V_{j,i} \right)
\]

where \( \dot{\varepsilon}_{ij} \) and \( V_{ij} \) are strain-rate and velocity components, respectively and " , " denotes differentiation. According to the extremum principle mentioned in section (2-1), the minimum of the functional

\[
\pi = \int_{\Omega} E( \dot{\varepsilon} ) \, dv - \int_{\partial F} \dot{\varepsilon} \, \mathbf{v} \, dS_{F} (38)
\]

with respect to the admissible velocity field, \( \mathbf{v} \), with incompressible constraint, is searched for. By introducing a Lagrangian multiplier, this problem can be changed to the stationary value problem without constraints [10].

\[
\pi = \int_{\Omega} E( \dot{\varepsilon} ) \, dv - \int_{\partial F} \dot{\varepsilon} \, \mathbf{v} \, dS_{F} + \int_{\Omega} \lambda \dot{\varepsilon}_{ij} \, dv (39)
\]
Here, the Lagrangean multiplier $\lambda$ can be shown to be equal to the hydro-static stress component. Also, by introducing an interface frictional integrand, equation (39) can be modified into

$$\pi = \int_V E(\dot{\epsilon}) \, dV + \int_V \lambda \dot{\epsilon} \, dV - \int_{S_F} F \, V \, dS_F - \int_{S_C} \left[ \int_{S_C} \frac{1}{2} \dot{\epsilon} \, dV \right] \, dS_C$$

where $S_C$ is the interface boundary condition where frictional stresses occur and

$$E(\dot{\epsilon}) = \int_{\Sigma_C} \frac{1}{2} \dot{\epsilon} \, d\Sigma$$

For discretization of the functional (40), the distribution function $H_i$, which is assigned to each node is introduced such that

$$U(X) = \sum_i H_i(X) \, U_i$$
$$V(X) = \sum_i H_i(X) \, V_i$$

where $U(X)$ and $V(X)$ are velocity components in the $X_1$ and $X_2$ directions, respectively, $U_i$ and $V_i$ are those at nodal points, and the summations are made over nodal points. Applying the stationary condition, the following set of algebraic nonlinear equations in $U$ and $\lambda$ can be obtained

$$\frac{\partial \pi}{\partial U_i} (U_i, \cdots, U_{2M}) = 0 \quad i = 1, \cdots, 2M$$
$$\frac{\partial \pi}{\partial \lambda} = 0$$

(43)
By the Newton-Raphson method, the solution of the highly nonlinear algebraic simultaneous equation can be obtained. Using the first two terms of a Taylor expression near the assumed velocity field \( U_o \), (relation 43) becomes

\[
\begin{align*}
\left[ \frac{2 \pi}{2 U_i} \right]_{u = U_o} + \left[ \frac{\partial^2 \pi}{2 U_j U_i} \right]_{u = U_o} \Delta U_j &= 0 \\
\left[ \frac{\partial \pi}{\partial \lambda} \right]_{u = U_o} + \left[ \frac{\partial^2 \pi}{\partial \lambda \partial U_i} \right]_{u = U_o} \Delta U_j &= 0
\end{align*}
\]

Equation (44) becomes

\[
\begin{align*}
\sigma_{ij} &= \frac{2}{3} Y \left( 1 + \frac{\dot{\varepsilon}_e}{\dot{\varepsilon}_o} \right) \dot{\varepsilon}_{ij} \\
\text{and equations (44) are accordingly modified. For all}
\end{align*}
\]
practical purposes, any element can be considered to be rigid if \( \dot{\varepsilon} < \dot{\varepsilon}_o \).

3-4. THEORETICAL ANALYSIS OF DIE VELOCITY FUNCTION FOR HAMMER FORGING PROCESS

The theoretical analysis considered is based upon following assumptions with regard to the impact situation.

(1) The moving platen of the machine is in free
flight prior to impact.

(2) The forging dies are assumed to be rigid.

(3) The billet material is homogeneous, isotropic, incompressible, rigid-viscoplastic, and obeys the Von Mises yield criterion.

(4) Plastic wave propagation effects are ignored.

Assumption (3) implies that elastic strain can be ignored and that the surface shear stress has no influence on yielding.

Plastic wave propagation effects are ignored, since in general the process time can be assumed to be much longer than the transmission times for plastic waves passing through billets.

Incorporating these assumptions, three alternative approaches are possible for the modeling of the hammer forging velocity function. Detailed considerations are referred to in subsequent sections.

3-4-1. DYNAMIC FORCE ANALYSIS

As previous research has shown, the dynamic forces in forging are deeply influenced by process variables such as material characteristics, geometries of dies, workpiece temperature, dies and workpiece interface friction
conditions, initial ram impact velocity and the effective mass of the hammer. To sort out this complex situation, a typical process model for impact forging is selected and for simplicity, impact forging with an anvil hammer can be considered as two rigid bodies colliding against a massless, rigid plastic workpiece. Consideration of the free body diagram of Figure 11 at impact leads to the following equations of motion.

\[ M_r \ddot{h} - F(h, \dot{h}) = M_r \ddot{\alpha}_r \]  \hspace{1cm} (46-a)

\[ M_\omega \ddot{h} + F(h, \dot{h}) - F_s = M_\omega \ddot{\alpha}_\omega \]  \hspace{1cm} (46-b)

where

- \( M_r \) = ram mass
- \( F(h, \dot{h}) \) = Collision Force
- \( \ddot{\alpha}_r \) = ram acceleration
- \( M_\omega \) = anvil mass
- \( \ddot{\alpha}_\omega \) = anvil acceleration
- \( F_s \) = anvil spring force.
- \( G \) = gravity acceleration

By combining \( W_\omega - F_s \) and with mathematical manipulation, following relation can be obtained where \( W = M \cdot G \):

\[ M \ddot{h} + F(h, \dot{h}) = 0 \]  \hspace{1cm} (47)

where

- \( M \) = effective mass = \( M_\omega \cdot M_r / M_\omega + M_r \)
- \( \dot{h} \) = time rate of change of the deformation rate
  \[ = \ddot{\alpha}_r - \ddot{\alpha}_\omega \].
The force $F(h, \dot{h})$ can be determined with knowledge of the material flow stress $\sigma_0$, the flow constraint from friction $Q_F$ and the workpiece volume $V$, as follows:

$$F(h, \dot{h}) = Q_F \sigma_0 \frac{V}{h} \quad (48)$$

On assuming the constitutive equation $\sigma = K \dot{\varepsilon}^m \varepsilon = C(\varepsilon) \dot{\varepsilon}^m$. 

Figure 11. Free Body Diagram For Impact Forging With An Anvil [16]
substituting into equation (48) and combining with equation (47) the following relation can be obtained:

\[ M \ddot{h} + Q_\tau C V (1/h)^n \dot{h} = 0 \quad (49) \]

The solution of (49) can be obtained by the method of separation variables. At the generic stage, values of strain and strain-rates, flow stress and forging load can be obtained by knowing the ram velocity on impact, the workpiece dimensions and new values of the strain and strain-rate, flow stress and forging load are calculated with updated values of the workpiece diameter and \( Q_\tau \). When the deformation rate, \( \dot{h} \), becomes equal to zero, the forging blow is completed (the ram and anvil achieve the same velocity).

This force balance method includes the inertial effect of the hammer forging impact. However, this analysis is an idealization of the actual process where the workpiece mass is neglected. The other idealization in this analysis is the assumption that anvil spring force is constant all through the deformation process which is not true in actual process. Thus for a proper analysis, these two considerations need to be included.
This method is based on analysis of the total energy balance in the forging system. Basically, the kinetic energy of the moving ram assembly is supposed to be transformed into deformation energy of the workpiece and frictional energy. This energy will contribute to the rise of workpiece temperature during deformation. Experimentally, it is found that about 90% of the energy supplied to effect plastic compression reappears as heat and causes a rise in temperature of the workpiece.

For the analysis of energy balance during deformation process, the quasi-static concept needs to be considered. For the justification of the quasi-static process, the deformation in height at each deformation step should be less than 1% of the workpiece height. Considering small deformations at each step, this process can be assumed to be quasi-linear step-by-step.

At each step of the deformation process, the total energy generated by the moving ram can be calculated by summing the relevant energies in the workpiece. After that, by subtracting the total energy from the kinetic energy of the moving ram assembly, estimation of the new velocity of die for the next step can be provided. This procedure is repeated until the moving ram velocity reaches zero or the minimum velocity to overcome the resistance of
material against the deformation.

3-4-2-1. DETERMINATION OF WORKPIECE DEFORMATION ENERGY

The workpiece deformation energy can be calculated from the strain-rate components and the time increment for each deformation step.

\[ d \vec{\varepsilon} = \dot{\vec{\varepsilon}} \Delta t \]

\[ W_p = \int \int \int \int \overline{\sigma} \ d\vec{\varepsilon} \ dV \]  

(50)

where \( \overline{\sigma} \) is the effective or equivalent stress as shown in equation (26), \( \Delta t \) is the time increment at each step and \( d\vec{\varepsilon} \) is

\[ d \vec{\varepsilon} = \sqrt{\frac{2}{9} \left( (d \varepsilon_1 - d \varepsilon_2)^2 + (d \varepsilon_2 - d \varepsilon_3)^2 + (d \varepsilon_3 - d \varepsilon_1)^2 \right)} \]

(51)

since the plastic strain increment is identical with the total strain increment.

Further, in the special case where the principal axes of successive strain increment do not rotate relative to the element, these strain increment components stand in a constant ratio one to another during each deformation step, and putting

\[ \frac{d \varepsilon_2}{d \varepsilon_1} = x \quad , \quad \frac{d \varepsilon_3}{d \varepsilon_1} = y \]

(52)
\[ d \varepsilon_1 + d \varepsilon_2 + d \varepsilon_3 = 0 \]

and since

\[ X + Y + 1 = 0 \text{ or } Y = -(1 + X) \tag{53} \]

Thus \[ d \varepsilon = \frac{2}{3} d \varepsilon(1 + X^2 + Y^2) \]

or \[ d \varepsilon = \frac{2}{\sqrt{3}} (1 + X + X^2)^{1/2} \ d \varepsilon_1 \tag{54} \]

By putting (54) to (50)

\[ W_p = \int \int \varepsilon \ \frac{2}{\sqrt{3}} (1 + X + X^2)^{1/2} \ d \varepsilon_1 \ dV \tag{55} \]

By considering the whole die geometry deformation after each step, the values of \( X \) and \( d \varepsilon \) can be obtained. Thus, in this particular case, equation (55) can define the deformation energy of the workpiece at each step.

3-4-2-2. DETERMINATION OF FRICTIONAL ENERGY DISSIPATION

Observation of the radial components of the velocity vector that exist at the interface between the workpiece and the dies, the workpiece slides against the dies. As was referred to [20], uniform deformation velocity field needs to be considered. For simplicity, the uniform velocity field of the disk shown in Figure 12 can be described as follows:
\[ V_\theta = 0 \]
\[ V_y = -\frac{Y}{T_o} V \]
\[ V_x = \frac{1}{2} \frac{R}{T_o} V \]

where \( V \) is the velocity of the moving ram and the velocity component \( V_\theta = 0 \) is defined due to axi-symmetry.

Figure 12. The disk, the platens, and the coordinate system [8]
The velocity field of equation (56) implies \( \theta \) - independence of all components of the velocity vector due to cylindrical symmetry. The component \( V_\phi \) varies linearly from zero at \( y = 0 \) to \(-V\) at the top of the workpiece, where \( y = T_o \). This component of the \( R \)-coordinate, indicates that planes perpendicular to the axis of symmetry move uniformly and remain plane through the deformation process; these planes, however, expand radially. The velocity component \( V_R \) varies linearly with respect to the \( R \)-coordinate and independent of the \( y \)-coordinate. This indicates that all points on a cylinder at the distance \( R \) from the axis of symmetry move outwardly at a uniform speed. The velocity field of equation (56) is called a uniform homogeneous velocity field. As was revealed in equation (33)

\[
f_s = -m \cdot K \frac{\Delta V_y}{|\Delta V_y|} \Delta t = -\frac{2}{\pi} m K \tan^{-1}\left( \frac{\Delta V_y}{V_c} \right) \Delta t
\]

\[
W = \int_{S_c} \int f_s dV_y \ dS_c
\]

where \( S_c \) is the surface over which the frictional forces occur. For the simplest case in Figure 5, \( dV_y \) is:

\[
dV_y = \frac{dr}{2T_o} V
\]

Thus, the frictional dissipation energy can be calculated
effectively. As an approximate approach to calculate frictional dissipation energy, the uniform-homogeneous-deformation velocity field can be assumed.

Considering all these factors and concepts about internal energy balance approach, the following relation can be suggested for estimation of the new velocity after each step of deformation.

\[
\frac{1}{2} m V^i = \frac{1}{2} m V^* + W_p + W_f
\]

\[
\frac{1}{2} m V^* = \frac{1}{2} m V^i - W_p - W_f
\]

\[
V = \sqrt{\frac{2}{m} \left( \frac{1}{2} m V^i - W_p - W_f \right)}
\]

(58)

where \( m \) is the mass of the moving ram assembly and \( W_p \) and \( W_f \) has already been defined by equations (55) and (57) respectively. Therefore, as mentioned at the beginning of this section, the above calculation needs to be done iteratively until the new ram die velocity reaches zero or the minimum velocity to overcome the resistance of material against the deformation. Also the moving ram die velocity should be updated for the next iteration after each deformation step.

In this approach, the inertial effect at impact has been neglected. However, when the weight of ram is far
greater than that of the workpiece, this approach still stands with good accuracy. For the estimation of the die velocity in hammer forging, the new portion of the computer program to calculate the deformation and frictional energies should be coded and interfaced with the source file of A.L.P.I.D..

3-4-3. ENERGY BALANCE APPROACH - BASED ON
THE FORCE EXERTED ON THE DIES

Basically, this method is the same as method (B) in view of the energy balance approach. However, the approach to calculate the energy absorbed by workpiece is simplified. Instead of calculating the internal deformation of the workpiece and the frictional energy dissipation at the interfaces between workpiece and dies, the kinetic impact energy during any time increment, which is the force exerted on the die during each step multiplied by the velocity of die, needs to be calculated for estimation of the new velocity after each deformation step. As was the case of the second method the quasi-static process is assumed during each step deformation. For justification of the quasi-static process at each step, the reduction in height at each step needs to be adjusted as 1% or less. With this concept, the non-steady-state deformation problem can be analyzed in a step-by-step quasi-linear manner during
deformation step. Accordingly, the calculated work done by the contact force at die and workpiece interface is subtracted from the kinetic energy of the moving ram and the updated die velocity for the subsequent deformation step can be estimated. For simulation of the whole hammer forging process, this calculation should be repeated until new die velocity reaches zero.

3-4-3-1. ANALYSIS OF FORGING ENERGY CHARACTERISTICS

In gravity drop hammer, the total impact blow energy is equal to the kinetic energy of the ram, and the calculated impact velocity \( V_1 \) is \( V_1 = \sqrt{2gH} \) where \( H \) is the vertical height of the ram fall. Therefore, the kinetic energy at the moment of impact is:

\[
E_T = \frac{1}{2} m_1 V_1^2 = \frac{1}{2} \frac{W}{g} V_1^2 = W_1 H \tag{59}
\]

where
- \( m_1 \) = mass of the dropping ram
- \( V_1 \) = velocity of the ram at the start of deformation
- \( W_1 \) = weight of ram assembly
- \( g \) = gravity acceleration
- \( H \) = vertical height of ram drop

In a power drop hammer, the total-blow energy is generated by the free-fall of the ram and by the pressure
acting on the ram cylinder. Therefore the total blow energy is

\[
E_T = \frac{1}{2} m_i v_i^2 + P A H
\]  

(60)

where, in addition to the symbol definitions above

\[P = \text{air, steam, or oil pressure acting on ram cylinder in downstroke}\]

\[A = \text{surface area of ram cylinder where pressure is exerted.}\]

Thus, \(E_T\) can be defined as a following simplified form :

\[
E_T = (W_i + P A) H
\]  

(61)

3-4-3-2. ANALYSIS OF THE BLOW EFFICIENCY

During the working stroke after impact, the total nominal energy (\(E_T\)) of a hammer is not entirely converted into useful energy available for deformation (\(E_u\)). Some small amount of initial kinetic energy is supposed to be lost in overcoming friction of the guides and a significant portion is lost in the form of noise and vibration to the environment. In anvil hammers including power drop hammers, the blow efficiency is defined by :

\[
\psi = \frac{E_A}{E_T} = \frac{1 - \frac{K}{W_i}}{1 + \left( \frac{W_R}{W_i} \right)}
\]  

(62)

where \(E_T = \text{total nominal energy}\)
\[ EA = \text{actual energy available for forging} \]
\[ K = \text{coefficient of impact} \]
\[ W_R = \text{ram weight including die half} \]
\[ W_A = \text{anvil weight including die half} \]

Equation (62) shows that the blow efficiency increases with increasing anvil weight \((W_A)\). Therefore, usually a large anvil-to-ram-weight ratio is desirable. As an economical compromise, the ratio varies between 10 to 1 and 25 to 1. The value of \(K\) is 0.6 to 0.8 for soft blow and 0.1 to 0.3 for hard blows. Thus, the blow efficiency varies between 0.8 to 0.9 for soft blows and 0.3 to 0.6 for hard blows.

Experimental studies conducted on hammer forging indicate that \(\gamma\) decreases with increasing forging load (hard-blows) and that \(\gamma\) decreases with increasing off-center loading toward front and back (usually hammer guides are on right and left). In addition, \(\gamma\) is independent of the ratio of the weight in case of counterblow hammers.

3-4-3-3. ANALYSIS OF FORGING LOAD

The transformation of kinetic energy into deformation energy during a working blow is supposed to develop a large force at the interface between dies and workpiece. For instance, consider a forging blow where the load \((P)\) varies from \(P/3\) at start to \(P\) at the end of the stroke \((h)\). The
developed deformation energy \( (E_A) \) is the surface area under the solid-load stroke curve in Figure 13.

\[
E_A = \frac{P}{3} + P + \frac{4Ph}{6}
\]  \( (63) \)
Considering a hammer with total initial kinetic energy \( E_T \) and blow efficiency \( \varphi \), \( E_A = \varphi * E_T \). Thus equation (63), gives the following relation:

\[
P = \frac{6 E_A}{4 h} = \frac{3 \varphi E_T}{2 h}
\]  

(64)

Further, by considering the smaller increment in the die stroke, a better approximation to the available deformation energy can be generated. As mentioned at the beginning of this section, by considering that the load \( (P) \) increases quasi-linearly at each deformation step, the available deformation energy \( (E_A) \) can be calculated as follows:

\[
E = P_i \Delta h
\]  

(65)

where \( P_i \) is varying from \( P/3 \) to \( P \) and \( \Delta h \) is approximately \( h * (1/100) \).

3-4-3-4. ESTIMATION FOR UPDATED DIE VELOCITY AFTER EACH DEFORMATION STEP

The fundamental principles for this approach have already been revealed. Basically, the principle of total energy balance during any deformation process should be maintained. By considering equations (59), (60), (61), and
the following relation can be used for estimation of the new velocity after each deformation step:

\[ V_i = \sqrt{\frac{2}{m_i} (\zeta E_r - P_i \Delta h)} \]  

where \( P_i \) is force exerted on dies, 
\( E_r \) follows either equation (59) or (60), 
\( E_A \) is the deformation energy of workpiece 
\( E_A' \) is the die force energy which is die force times reduction in height at each deformation step (\( \Delta h \))

\( \zeta \) is blow efficiency

and after 1-st step deformation, 
\( \zeta \) should be 1., (100 %) and \( E_r \) should be kinetic energy of ram assembly, since there is no impact situation.
As in the second method, inertial effect during impact was neglected. But adopting the quasi-static deformation concept, the accuracy has been improved greatly. By calculating the impact energy of the workpiece instead of workpiece deformation and frictional energy, the analysis to determine the estimation of the die velocity has been simplified while proper accuracy. For an improved analysis, the inertial effect may be considered.
CHAPTER IV

SIMULATION OF THE HAMMER FORGING PROCESS

BY COMPUTER PROGRAM

4-1 INTRODUCTION TO THE PROGRAM

The program developed is based on the rate sensitive rigid-viscoplastic F.E.M. (Finite Element Method) and is coded in FORTRAN-77. The theoretical detail has already been discussed in chapter 3.

The program A.L.P.I.D.H. (Analysis of Large Plastic Increment Deformation for Hammer Forging) has been modified from A.L.P.I.D. 1.41 version developed by Battelle Laboratories in Columbus, Ohio.

The program A.L.P.I.D.H. can handle analysis of both the normal hydraulic forging and the hammer forging processes. Accordingly, in the program A.L.P.I.D.H., the following two types of hammer forging processes can be analyzed:

1. Gravity Drop Hammer Forging
2. Power Drop Hammer Forging

By looking into the result of A.L.P.I.D.H. hammer forging simulation, the following estimation for the proper design of the hammer forging process can be accomplished:
1. Vertical height between ram and anvil assembly in gravity drop hammer and power drop hammer
2. The weight of the ram assembly including half of die
3. The required pressure and area where the pressure is impinged
4. Metal flow during forging
5. Strain, strain-rate, and stress distribution in workpiece during deformation
6. Proper preform design of the die shape and forging condition

Furthermore, a preprocessor FORTRAN program called "HMINP" for the preparation of the hammer forging input data file has been developed for the users' convenience in using A.L.P.I.D.H.. HMINP can also be used for the preparation of the normal hydraulic forging input file. Typical input files for the hammer forging simulation are illustrated in Appendix I. While running HMINP for the preparation of the input file, the program allows users to review and to change the values of input variables.

In subsequent sections, the detailed features of the program A.L.P.I.D.H. and HMINP will be discussed.
4-2 FEATURES OF THE PROGRAM HMINP AND A.L.P.I.D.H.

The present section discussed some features of the program concerned with the input and output. The preprocessor program for the preparation of the input file of the A.L.P.I.D.H., has been developed and the preprocessor program HMINP can be initiated and executed with the command @HMINP. While going through HMINP to prepare the input file, users can review the input variables line-by-line. By reviewing input variables, users can check the variables and can change any inconsistent variables.

Generally, the input file structure of hammer forging simulation is very similar to the input file structure of a normal hydraulic forging simulation. However, for the hammer forging simulation, some additional input variables need to be specified. Regarding all variables except the additional variables for hammer forging simulation, users may refer to users's manual of A.L.P.I.D. 1.41 version. Therefore, in this section, only additional variables for hammer forging simulation has been discussed one-by-one.

While running the preprocessor program HMINP, users are supposed to reach master control card 4 to input the value of NINOUT(7) which defines the types of the forging process simulation. Users's option at NINOUT(7) is as
follows:

<table>
<thead>
<tr>
<th>NINOUT(7)</th>
<th>Type of Forging Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal Hydraulic Forging</td>
</tr>
<tr>
<td>3</td>
<td>Hammer Forging</td>
</tr>
</tbody>
</table>

In case of normal hydraulic forging option, all consequential input variables for the hammer forging simulation need not be specified. Accordingly, all concerned execution of the A.L.P.I.D.H. for the hammer forging simulation can be excluded. In case of the hammer forging simulation option, depending on the consequential input variables on master card-9, the simulation can be either the gravity drop hammer forging or power drop hammer forging.

At master control card-5, users need to input the value of TMP which is average working temperature of the forging process. To decide the proper value of the average working temperature, the users’ past experience in forging industry is very important and essential.

As a variation to the previous A.L.P.I.D. 1.4l version concerning master control card-6, users need not specify the value of the maximum time increment per step.
(DTMAX), since A.L.P.I.D.H. will generate DTMAX automatically. The value of DTMAX controls the deformation height during each deformation step. In the hammer forging simulation, the die velocity is changing continuously after each deformation step and the automatically generated value of DTMAX controls the deformation height during each step to be 0.01 of billet height under deformation.

Also at master control card-6, it is recommended that the total number of steps (NSTEP) to be executed by A.L.P.I.D.H. needs to specified as a large number such as 50 or 100. Whatever large value of NSTEP might be specified, the hammer forging simulation by A.L.P.I.D.H. will be terminated when the velocity of die reaches zero or the minimum velocity to overcome the resistance of workpiece against the deformation.

At master control card-7, the values of conversion parameters of mass (ICONM) and length (ICONL) need to be specified. Here, the unit of mass is related with the mass of the ram and the anvil assemblies and the unit of the length is related with the initial vertical height between the anvil and the ram assemblies, and the grid coordinates. By the conversion process of the program with these conversion parameters, whatever the input units of mass and the length might be, the output units of A.L.P.I.D.H. will
be in English units. When users decide the values of ICONM and ICONL, it is recommended that all units of lengths and all units of masses be unified. The users's options in parameters for unit conversion are as follows:

<table>
<thead>
<tr>
<th>Input Length Unit</th>
<th>Values of Conversion parameters (ICONL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter</td>
<td>1</td>
</tr>
<tr>
<td>Centimeter</td>
<td>2</td>
</tr>
<tr>
<td>Millimeter</td>
<td>3</td>
</tr>
<tr>
<td>Foot</td>
<td>4</td>
</tr>
<tr>
<td>Inch</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input Mass Unit</th>
<th>Values of Conversion Parameter (ICONM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ton / Ounce</td>
<td>1</td>
</tr>
<tr>
<td>Kilogram / Pound</td>
<td>2</td>
</tr>
<tr>
<td>Gram / Grain</td>
<td>3</td>
</tr>
</tbody>
</table>

At master control card-9, the values of six variables each of which has direct relevance to the hammer forging simulation, need to be specified.

First, the value of the blow efficiency coefficient
(COF) defines the energy transformation efficiency from the kinetic energy of ram assembly to the workpiece deformation energy. In the hammer forging simulation by A.L.P.I.D.H., this variable (COF) characterizes the actual efficiency of the hammer forging equipment. The general estimation for this value can be defined as equation (62) which is:

\[ \eta = \frac{1 - K^2}{1 + \frac{W_R}{W_A}} \]

where

- \( K \) is the coefficient of impact
- \( W_R \) is the ram weight including half of die
- \( W_A \) is the anvil weight including half of die

Also in the hammer forging process, the foundation of the equipment is very influential and the basic design criteria regarding the foundation of the hammer forging equipment has been discussed in section 2-6. For the proper determination of this coefficient, the user's past experience with their forging equipment, processes and knowledge about workpiece material characteristics are the most dominating factors.

Second, the value of the gravity acceleration (GR) needs to be specified in accordance with the unit conversion parameter of length (ICONL).
Third, the value of mass of the ram assembly (AMAS) including half of the die needs to be specified in accordance with the unit conversion parameter of the mass (ICONM).

Fourth, the vertical fall height (DHGT) between the ram and the anvil assembly needs to be specified in accordance with the unit conversion parameter of length (ICONL).

Fifth, in case of the power hammer forging simulation, the power pressure of equipment exerted on the ram assembly (PRS) needs to be input. However, in case of the gravity drop hammer forging simulation, this power pressure does not have to be specified.

Sixth, the total cumulative area (AREA) where the power pressure of the forging equipment is impinged, has to be specified in accordance with the unit conversion parameter of length (ICONL). Also for PRS, AREA does not have to be specified in the gravity drop hammer forging simulation.

At the master control card-10, users have to input a parameter which deeply influences the solution convergence of A.L.P.I.D.H. at each deformation step. It is the initial vertical height of the workpiece (BHGT). For the solution convergence of A.L.P.I.D.H. at each deformation step, a new initial guess at each step has to be generated since the die velocity is changing continuously step-by-step which is
contrary to the A.L.P.I.D. 1.41 version. For proper initial guess generation, the solution convergence parameters are very important factors to obtain the solution convergences for velocity function and tractional force within iteration limit. Thus in A.L.P.I.D.H., new solution convergence parameters and the new, proper, initial guess at each step are generated at each deformation step. For the generation of new solution convergence parameters, the value of BHGT is one of the essential parameters. In the normal hydraulic hammer forging simulation with A.L.P.I.D. 1.41 version, the die velocity is constant until the workpiece is deformed into the final geometric shape. However, in the hammer forging simulation, the die velocity is changing continuously after each deformation step. Therefore, the updated initial guess for the solution convergence of the velocity function and tractional force has to be generated at the beginning of each deformation step and the values of the parameters influencing the solution convergences should be renewed step-by-step.

The other important scheme to be considered for the better accuracy in the hammer forging simulation is the control of the workpiece height reduction at each deformation step. Having been mentioned in section 3-3, the workpiece height reduction at each deformation step has to be adjusted so small that the quasi-linear deformation
concept can be justified. For this purpose, the program A.L.P.I.D.H. allows the workpiece deformation height during each step to be only 1 percent of the workpiece height of the previous step. Thus, the workpiece deformation height reduction per step is as follows:

<table>
<thead>
<tr>
<th>Step</th>
<th>Calculation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>$H$</td>
<td>$H$</td>
</tr>
<tr>
<td>1-st</td>
<td>$0.01 \times H$</td>
<td>$0.01 \times H$</td>
</tr>
<tr>
<td>2-nd</td>
<td>$(1 - 0.01) \times H$</td>
<td>$9.9 \times 10^{-1} \times H$</td>
</tr>
<tr>
<td>3-rd</td>
<td>$(1 - 0.01 - 9.9 \times 10^{-1}) \times 0.01 \times H$</td>
<td></td>
</tr>
</tbody>
</table>

With regards to all concepts for the hammer forging simulation, one example input file has been provided in Appendix I to help users' better understanding.

The output of the program developed will provide users with better understanding of the hammer forging process and with sound guidelines regarding die and preform design. For a given workpiece, the actual forging process includes several die try-outs and preform development trials. Also, the process simulation with the program developed will enable the users to modify the die and preform geometry on the computer to obtain the proper metal flow before the dies are actually manufactured and the
preforms are determined. The benefit of the computer simulation is that the amount of trial and error experimentation necessary for the process development can be reduced to a minimum. Therefore, the result is reduced manufacturing cost and lead time. The computer simulation by the program developed will give the information regarding metal flow, local strain, strain-rate, stress distribution, the time required for the process, the force exerted on the dies, etc. Also by looking into data at various friction conditions, users can find out the most suitable lubrication condition for the actual forging process.

For users' reference, the flow chart of the program "HMINP" and the typical execution procedure of "HMINP" have been supplied at Appendix 2 and 3 respectively.

4-3. VALIDATION OF PROGRAM A.L.P.I.D.H. OUTPUT

4-3-1. COMPARISION BETWEEN THE A.L.P.I.D.H. OUTPUT AND CALCULATION WITH SLAB METHOD

Die forging load obtained from program A.L.P.I.D.H. output was compared with the calculation by slab method which is an approximate method for analyzing plastic deformation.

Among various cases, the simple compression deformation process shown in Figure 14 was considered. In this case,
neutral neutral axis is the geometric center of the workpiece. Thus the flow stress distribution is the same as shown in Figure 14. For outward flow, using the symbols given in Figure 14, axial forging stress is given by:

\[
\bar{\sigma}_x = \frac{2 R}{H} \left( R - r \right) + \bar{\sigma}
\]  

(67)

where \( \bar{\sigma} \) is the flow stress of the forged material, 
\( f \) is friction factor,
\[ \gamma = f \bar{\sigma} \]

By assuming an incompressible and rigid-viscoplastic material, the forging load \( P \) is given by:

\[
P = 2 \left[ - \frac{2 h \sqrt{h_i}}{h} r_i^2 + \left( \frac{2 \sqrt{h_i}}{h} r_i + \bar{\sigma} \right) \frac{1}{2} \frac{h_i}{h} r_i^2 \right]
\]

(68)

where \( h_i \) is initial height of workpiece
\( r_i \) is initial radius of workpiece
\( h \) is height of workpiece under deformation

The variation of forging load during deformation determined by A.L.P.I.D.H. and the slab method calculation are shown in Figure 15.
Friction stress \( \sigma_z = \frac{2r}{H} (R-r) + \sigma \)

Figure 14. Distribution of Forging Stress \( \sigma_z \) In Upset Forging of A Large Flat Part [1]
4-3-2. COMPARISON OF THE FORGING LOAD BETWEEN HAMMER FORGING AND HYDRAULIC FORGING

As shown in Figure 15, hammer forging can generate greater forging than hydraulic forging. The other typical difference in the forging load curve is that the forging load is decreasing around the end of hammer forging. The two fold reasoning behind the behaviour is first the hammer forging die velocity is decreasing continuously and second strain-rate, which is a dominating factor in the determination of the forging load, is decreasing continuously. Contrary to hammer forging, the die forging load in hydraulic forging is increasing continuously since the strain-rate is increasing continuously.
Figure 15. Forging Load Distribution Comparison Between A.L.P.I.D.H. (Hammer Forging and Hydraulic Forging) and Slab Method
### Case Study: 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Gravity drop forging</td>
</tr>
<tr>
<td>Initial billet height</td>
<td>57.2 MM</td>
</tr>
<tr>
<td>Upper ram fall height</td>
<td>1000 MM</td>
</tr>
<tr>
<td>Upper ram mass</td>
<td>30 Kilogram</td>
</tr>
<tr>
<td>Blow efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Friction factor</td>
<td>0.06</td>
</tr>
<tr>
<td>Number of die</td>
<td>2</td>
</tr>
</tbody>
</table>

From the simulation with the above input parameters, the following output parameters can be obtained:

<table>
<thead>
<tr>
<th>Total stroke</th>
<th>0.2293 E+02 MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load (Die I)</td>
<td>0.4714 E+04 Pounds</td>
</tr>
<tr>
<td>Step number</td>
<td>from 1 to 51</td>
</tr>
</tbody>
</table>

Aluminium is a less stiff material than AISI-4337. By comparing input parameters of gravity drop forging simulations of Aluminium and AISI-4337 workpiece in connection with output parameters in subsequent section, users can find that in case of Aluminium, less weight and less initial fall height of the ram assembly are required to deform the workpiece than in case of AISI-4337.
Figure 16 CASE 1 - Die force distribution at various steps
Figure 17  CASE 1 - Initial grid - step 0
Figure 18 CASE 1 - Grid distortion - step 10
Figure 19  CASE 1 - Grid distortion - step 30
Figure 20  CASE 1 - Grid distortion - step 50
Figure 21  CASE 1 - Stress contour - step 10
Figure 22  CASE 1 - Stress contour - step 30
Figure 23  CASE 1 - Stress contour  - step 50
Figure 24  CASE 1 - Strain-rate contour - step 10
Figure 25 CASE 1 - Strain-rate contour - step 30
Figure 26  CASE 1 - Strain-rate contour - step 50
Figure 27 CASE 1 - Strain contour - step 10
Figure 28  CASE 1 - Strain contour - step 30
Figure 29  CASE 1 - Strain contour  - step 50
### 4-5 CASE STUDY: 2

<table>
<thead>
<tr>
<th>Material</th>
<th>AISI-4337</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Power drop forging</td>
</tr>
<tr>
<td>Initial billet height</td>
<td>57.2 MM</td>
</tr>
<tr>
<td>Upper ram fall height</td>
<td>2000 MM</td>
</tr>
<tr>
<td>Upper ram mass</td>
<td>200 Kilogram</td>
</tr>
<tr>
<td>Blow efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Friction factor</td>
<td>0.06</td>
</tr>
<tr>
<td>Number of dies</td>
<td>2</td>
</tr>
</tbody>
</table>

From the simulation with the above input parameters, the following output parameters can be obtained:

- Total stroke (Die I): $0.1815 \times 10^2$
- Maximum load (Die I): $0.5872 \times 10^5$
- Step number: from 1 to 38
Figure 30  CASE 2 - Die force distribution at various steps
Figure 31  CASE 2 - Initial grid - step 0
Figure 32  CASE 2 - Grid distortion - step 10
Figure 33  CASE 2 - Grid distortion - step 30
Figure 34  CASE 2 - Grid distortion - step 38
Figure 35  CASE 2 - Stress contour  - step 10
Figure 36  CASE 2 - Stress contour - step 30
Figure 37 CASE 2 - Stress contour - step 38
Figure 38  CASE 2 - Strain-rate contour - step 10
Figure 39  CASE 2 - Strain-rate contour - step 30
Figure 40  CASE 2 - Strain-rate contour - step 38
Figure 41  CASE 2 - Strain contour - step 10
Figure 42  CASE 2 - Strain contour  - step 30
Figure 43  CASE 2 - Strain contour - step 38
CHAPTER V

SUGGESTIONS FOR FURTHER STUDY IN THE HAMMER FORGING SIMULATION

Based on the research that has been presented in this thesis, followings approaches can be suggested for more successful simulation of hammer forging:

1. A.L.P.I.D. 1.41 version can be executed in connection with a temperature input file for the forging process simulation in temperature variance. Presently, for this simulation, all of the dies and workpiece have to be meshed which is not necessary in the isothermal simulation and the A.L.P.I.D. simulation has to be stopped after each deformation step. After one step deformation, the workpiece and dies should be remeshed in the way the nodes along the interfaces between dies and workpiece match consistently one by one. Only after this remeshing done, the next step simulation can be executed which is a tedious, time-consuming procedure. Thus if the automatic remeshing capability to solve this problem can be supplied with the A.L.P.I.D., the hammer forging simulation in working temperature variance can be accomplished effectively.

2. For better accuracy of the hammer forging simulation, proper subroutines for the determination of flow stress of materials at dynamic loading conditions need to be
developed. For this accomplishment, sound experimental data regarding characteristics of materials at the impact loading conditions need to be investigated and based on the analysis in section 3-2, a empirical relation among stress, strain, strain-rate, and temperature can be obtained.

3. One of the disadvantages of the program A.L.P.I.D. is found that when too many nodes are in contact with dies during deformation step, A.L.P.I.D. gives the error message which is "Solution does not converge within iteration limit." Thus, it can be suggested that proper approach for the implementation of boundary condition at the interfaces between dies and workpiece needs to be developed.

4. When the moving die velocity is small, the inertial effect can be neglected. But in the hammer forging analysis, this inertial effect is not always negligible. Thus for the more proper analysis of hammer forging, consideration for inertial effects may be included.
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Of Plastic Deformation in A Bar of Material Exhibiting
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### APPENDIX 1 EXAMPLE INPUT FILE OF THE HAMMER FORGING SIMULATION

POWER DROP FORGING SIMULATION (TYPATNIUM 6242 : H/R =2.25)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>25</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

1

3 0

0 1 1 1 0 1 3

900.

100 20 0.000000

3 2

0.050000 275000.0000 0.2000000 0.70000 110.1000000

0.85 200.0 980.0 1500. 100.0 1

57.200

6 1

0.000000 0.000000 0.000000 0.000000

0.000000 65.000000 0.0000000

7.500000 65.000000 0.0000000

9.500000 61.250020 8.700000

30.000000 56.025000 2.5000000

30.000000 45.673000 8.0000000

70.600000 45.673000 0.0000000

5 1

0.000000 0.000000 0.000000 0.000000

7.0 15.673000 0.0000000

32.00000 15.673000 12.0000000

30.00000 1.4800000 4.0000000

25.40000 0.0000000 0.0000000

0.000000 0.0000000 0.0000000

1 0.000000 0.0000000

2 3.175000 0.0000000

3 6.350000 0.0000000

4 9.525000 0.0000000

5 12.700000 0.0000000

6 15.875000 0.0000000

7 19.050000 0.0000000

8 22.225000 0.0000000

9 25.400000 0.0000000

10 0.000000 7.1500000

11 3.175000 7.1500000

12 6.350000 7.1500000
<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
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APPENDIX II

FLOW CHART OF PROGRAM "HMINP"

PREPROCESSOR PROGRAM "HMINP"
START
@HMINP

INPUT FILE NAME WHERE DATA WILL BE STORED

REVIEW INPUT FILE NAME

OPTION TO CHANGE FILE NAME

YES

NO

INPUT MASTER CONTROL DATA CARDS

DETERMINATION OF SIMULATION TYPE at NONOUT(7)

HYDRAULIC FORGING

HAMMER FORGING

A

B
INPUT ADDITIONAL VARIABLES FOR THE HAMMER FORGING SIMULATION

REVIEW MASTER CONTROL DATA CARDS

SELECTIONS OF VARIABLES TO BE CHANGED

OPTIONS TO CHANGE INPUT VARIABLES

YES

NO

INPUT DIE DESCRIPTION DATA CARDS

OPTION TO USE NASTRAN PREPROCESSOR FILE FOR THE DIE DESCRIPTION

REVIEW DIE DESCRIPTION DATA
OPTIONS TO
CHANGE DIE DESCRIPTION DATA

SELECTIONS OF VARIABLES TO BE CHANGED

YES

NO

OPTION TO USE NASTRAN PREPROCESSOR FILE FOR THE NODAL COORDinates AND CONNECTIVITIES OF WORKPIECE

INPUT THE NODAL COORDINATES AND CONNECTIVITIES WITH HAND TYPING

USE NASTRAN PREPROCESSOR FILE GENERATED WITH "FEM" SOFTWARE OF INTERGRAPH

INPUT ELEMENT DATA CARDS

INPUT BOUNDARY NODES DATA CARDS

FORTRAN STOP
APPENDIX 3 TYPICAL RUN OF "HMINP"

@HMINP

********************************************************
* THIS IS A SOFTWARE PACKAGE IN FORTRAN - 77 *
* WHICH IS A PREPROCESSOR TO ALPHAM (ANALYSIS *
* OF LARGE PLASTIC INCREMENTAL DEFORMATIONS *
* FOR HAMMER FORGING ANALYSIS ) *
* THIS IS AN INTERACTIVE AND USER-FRIENDLY *
* PROGRAM WHICH ASKS QUESTIONS TO THE USER AT *
* EACH STAGE OF DATA INPUT AND REFORMATS THE *
* SPECIFIED DATA INTO ALPID COMPATIBLE INPUT *
* AND STORES THE DATA INTO A DATA FILE NAMED *
* BY THE USER *
********************************************************

PRESS "RETURN" KEY TO CONTINUE

ENTER FILE NAME (MAXIMUM 11 CHARACTERS)
-------> EXAMPL.OAT

YOUR DATA WILL BE STORED UNDER THE FILE NAME:

EXAMPL.OAT

DO YOU WISH TO CHANGE THE FILE NAME ? (Y/N)
-------> N

PLEASE ENTER TITLE (MAXIMUM 80 CHARACTERS)
-------> HAMMER FORGING SIMULATION (ALUMINIUM)
THE TITLE OF YOUR SIMULATION RUN IS:
HAMMER FORGING SIMULATION (ALUMINIUM)
DO YOU WISH TO CHANGE THE TITLE? (Y/N)
------> N

MASTER CONTROL DATA INPUT BEGINS

NUMBER OF NODES (IS)
------> 60

NUMBER OF ELEMENTS (IS)
------> 45

TOTAL NUMBER OF ELEMENT GROUPS (IS)
------> 1

DEGREES OF FREEDOM PER NODE (2 FOR ALPID VERSION 1.4)
------> 2

NUMBER OF NODES REQUIRING FORCE CALCULATION (IS)
------> 6

NUMBER OF DIES (IS)
------> 2

MAXIMUM NUMBER OF POINTS TO DESCRIBE A DIE (IS)
------> 6

AXISYMMETRIC OR PLANE STRAIN? (ENTER 1 OR 2)
------> 1

RIGID PLASTIC OR RIGID VISCOPLASTIC
3: RIGID PLASTIC OR RIGID VISCOPLASTIC.
THIS IS THE ONLY OPTION ALLOWED
IN THIS VERSION OF ALPID (VERSION 1.4) (IS)
-------) 3
IS THE MODE OF SOLUTION COUPLED WITH FEMTEM (ENTER: 1) OR ALPID 1.41 ISOTHERMAL
(ENTER: 0) ? (IS)
0

THE CURRENT VALUES OF MASTER CONTROL DATA CARD, LINES 1, 2 AND 3 ARE:

0  QUIT PARAMETER REVIEW
1  NUMBER OF NODES          60
2  NUMBER OF ELEMENTS        45
3  TOTAL NUMBER OF ELEMENT GROUPS 1
4  NO. OF NODES REQ-FORCE CALCUL. 6
5  NUMBER OF DIES            2
6  MAX. NO. OF PTS TO DESCRIBE DIE 6
7  AXISYMMETRIC OR PLANE STRAIN 1
8  RIGID- PLASTIC OR VISCOPLASTIC 0

ENTER NUMBER OF THE VARIABLE TO BE CHANGED
-------) 0

0  NO INPUT INFORMATION PRINTED
1  INPUT INFORMATION IS PRINTED
-------) 0

0  ITERATION INFORMATION NOT PRINTED
1  ITERATION INFORMATION IS PRINTED
-------) 1

0  RESULTS NOT PRINTED
N  EVERY NTH SOLUTION IS PRINTED
-------) 5

0  SOLUTIONS NOT WRITTEN TO TAPE3
N  EVERY NTH STEP SOLUTION IS WRITTEN TO TAPE3
-------) 5
0  INPUT FROM FILE ; INITIAL RUN
1  INPUT FROM TAPE3 ; CONTINUING RUN
2  INPUT CODED ; STRAIN DATA ; AFTER REMESHING

-----> 0

0  INITIAL GUESS FROM INPUT
1  GENERATE INITIAL GUESS

-----> 1

1  NORMAL FORGING ANALYSIS
3  ANVIL HAMMER FORGING ANALYSIS

-----> 3

THE CURRENT VALUES OF MASTER CONTROL DATA CARD - LINE 4 :

0  QUIT PARAMETER REVIEW
1  NINOUT(1)   0
2  NINOUT(2)   1
3  NINOUT(3)   5
4  NINOUT(4)   5
5  NINOUT(5)   0
6  NINOUT(6)   1
7  NINOUT(7)   3

ENTER NUMBER OF THE VARIABLE TO BE CHANGED

-----> 0

ENTER AVERAGE WORKING TEMPERATURE (F15.7)

-----> 900.

CURRENT VALUE OF PARAMETER IN MASTER CONTROL CARD-5

0  QUIT PARAMETER REVIEW
1  AVERAGE WORKING TEMPERATURE   900.0000

0

NUMBER OF SOLUTION STEPS TO BE CALCULATED IN RUN (IS)

-----> 30
MAXIMUM NUMBER OF ITERATIONS PER STEP (IS)  
------> 20

MAXIMUM TIME INCREMENT BETWEEN SOLUTION STEPS (FIS.7)  
------> 0.0

MAXIMUM EFFECTIVE STRAIN INCREMENT BETWEEN SOLUTION STEPS (FIS.7)  
------> 0.0

THE CURRENT VALUES OF MASTER CONTROL DATA CARD - LINE 6

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ENTER NUMBER OF THE VARIABLE TO BE CHANGED  
------> 0

ENTER INPUT LENGTH UNIT CONVERSION PARAMETER (FIS.7)

<table>
<thead>
<tr>
<th>INPUT LENGTH UNIT</th>
<th>CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>METER</td>
<td>1</td>
</tr>
<tr>
<td>CENTI METER</td>
<td>2</td>
</tr>
<tr>
<td>MILI METER</td>
<td>3</td>
</tr>
<tr>
<td>FEET</td>
<td>4</td>
</tr>
<tr>
<td>INCH</td>
<td>5</td>
</tr>
</tbody>
</table>

------> 3

ENTER INPUT MASS UNIT CONVERSION PARAMETER (FIS.7)
INPUT MASS UNIT : ICONM
TON/OUNCE         1
KG/POUND          2
GRAM/GRAIN        3

CURRENT VALUES OF PARAMETERS IN MASTER CONTROL CARD- LINE 7

0 QUIT PARAMETER REVIEW
1 ICONNL          3
2 ICONNM          2

ENTER NUMBER OF PARAMETER TO BE CHANGED
0

RELATIVE ERROR LIMIT FOR ITERATION CONVERGENCE (F15.7)
-----> 0.001

PENALTY CONSTANT (F15.7)
-----> 10000.0

DECELERATION COEFFICIENT FOR NEWTON-RAPHSON PROCESS (F15.7)
-----> 1.0

EFFECTIVE STRAIN RATE BELOW WHICH MATERIAL IS RIGID (F15.7)
-----> 0.4

APPROXIMATE AVERAGE STRAIN RATE (F15.7)
-----> 10.5

THE CURRENT VALUES OF MASTER CONTROL CARD - LINE 7/8(HAMMER FORGING)

0 QUIT PARAMETER REVIEW
1 RELATIVE ERROR LIMIT      1.000000E-03
2 PENALTY CONSTANT          10000.00
3 DECELERATION COEFFICIENT  1.000000
4 EFFECTIVE STRAIN RATE     0.400000
5 APPROX. AVG. STRAIN RATE 10.50000

ENTER NUMBER OF VARIABLE TO BE CHANGED

------> 0

COEFFICIENT WHICH DEFINES THE EFFICIENCY OF TRANSFORM FROM KINETIC ENERGY OF HAMMER TO DEFORMATION & ENERGY (F15.7)

------> 0.85

GRAVITY ACCELERATION (F15.7)

------> 9800.

MASS OF HAMMER (F15.7)

------> 200.

INITIAL VERTICAL HEIGHT BETWEEN HAMMER AND ANVIL (F15.7)

------> 2000.

PRESSURE OF POWER HAMMER FORGING EQUIPMENT (F15.7)

------> 10000.

AREA WHERE POWER PRESSURE TO HAMMER IS IMPINGED (F15.7)

------> 50

VERTICAL HEIGHT OF INITIAL BILLET (F15.7)

------> 57.2

SOLUTION CONVERGENCE PARAMETER (F15.7)

CURRENT VALUES OF MASTER CONTROL CARDS (8 & 9) FOR ANALYSIS OF HAMMER FORGING

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>QUIT PARAMETER REVIEW</td>
</tr>
<tr>
<td>1</td>
<td>COF</td>
</tr>
<tr>
<td>2</td>
<td>AMAS</td>
</tr>
</tbody>
</table>
3  GR  9800.000
4  DHGT  2000.000
5  PRS  10000.00
6  AREA  50.00000
7  BHGT  57.20000

ENTER NUMBER OF VARIABLES TO BE CHANGED
------> 0
*********************************************************************************************

START DIE DESCRIPTION DATA

*********************************************************************************************

FOR DIE NUMBER  1
NUMBER OF CORNER POINTS TO DESCRIBE THE DIE SHAPE (IS)
------> 3

TYPE OF FRICTION
  1  CONSTANT SHEAR FACTOR FRICTION
  2  COULOMB FRICTION
------> 1

FRICTION COEFFICIENT (F15.7)
------> 0.08

VELOCITY OF DIE (F15.7)

X1 COMPONENT OF DIE VELOCITY
------> 0.0

X2 COMPONENT OF DIE VELOCITY
------> 0.0

INITIAL DIE STROKE IN X1 DIRECTION (F15.7)
------> 0.0

INITIAL DIE STROKE IN X2 DIRECTION (F15.7)
------> 0.0

FOR DIE NUMBER  2
NUMBER OF CORNER POINTS TO DESCRIBE THE DIE SHAPE (IS) ------→ 2

TYPE OF FRICTION
1 CONSTANT SHEAR FACTOR FRICTION
2 COULOMB FRICTION
------→ 1

FRICITION COEFFICIENT (F15.7) ------→ 0.08

VELOCITY OF DIE (F15.7)
X1 COMPONENT OF DIE VELOCITY ------→ 0.0

X2 COMPONENT OF DIE VELOCITY ------→ 0.0

INITIAL DIE STROKE IN X1 DIRECTION (F15.7) ------→ 0.0

INITIAL DIE STROKE IN X2 DIRECTION (F15.7) ------→ 0.0

DO YOU HAVE A NASTRAN PREPROCESSOR FILE FOR DIE DESCRIPTION? (Y OR N) N

ENTER DIE CORNER POINT COORDINATES AND RADIUS (F15.7)

X1 COORDINATE
------→ 0.0

X2 COORDINATE
------→ 23.1

RADIUS
------→ 0.0

X1 COORDINATE
------→ 7.51
X2 COORDINATE
------> 23.1

RADIUS
------> 0.0

X1 COORDINATE
------> 9.5

X2 COORDINATE
------> 8.0

RADIUS
------> 12.7

ENTER DIE CORNER POINT COORDINATES AND RADIUS (F15.7)

X1 COORDINATE
------> 50.8

X2 COORDINATE
------> 22.22

RADIUS
------> 0.0

X1 COORDINATE
------> 25.4

X2 COORDINATE
------> 0.0

RADIUS
------> 0.0

I  NDP  NFTP  FRCFAC  YD1  YD2  STROK1  STROK2
DO YOU WISH TO CHANGE ANY PARAMETERS FROM ABOVE? (Y/N)

--------> N

<table>
<thead>
<tr>
<th>I</th>
<th>J</th>
<th>X1</th>
<th>X2</th>
<th>CORNER RAD.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.000000</td>
<td>23.100004</td>
<td>0.000000</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>7.500000</td>
<td>23.100004</td>
<td>0.000000</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>9.500000</td>
<td>0.000000</td>
<td>12.699998</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>50.799992</td>
<td>2.220000</td>
<td>0.000000</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>25.399996</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

DO YOU WISH TO CHANGE ANY DIE COORDINATES? (Y/N)

--------> N
DO YOU HAVE A NASTRAN PREPROCESSOR OUTPUT FILE FOR BILLET NODAL COORDINATES AND ELEMENT CONNECTIVITY? (Y OR N) 

Y

WHAT IS THE NAME OF NASTRAN PREPROCESSOR FILE NAME, TYPE & VERSION NUMBER (FN.FT;V/N)?

FEM.DAT;3

INPUT TOTAL NUMBER OF BOUNDARY NODES.

5

WHAT IS BOUNDARY NODE NUMBER (I5)?

1

WHAT IS BOUNDARY CONDITION IN X1-DIRECTION FOR NODE 1 (0 OR 1: NUMBER OF DIE) (I5)?

0

WHAT IS BOUNDARY CONDITION IN X2-DIRECTION FOR NODE 1 (0, 1, OR -N: NUMBER OF DIE) (I5)?

1

HOW MANY VELOCITIES MUST BE SPECIFIED FOR THIS NODE (IF NO SPECIFICATION REQUIRE 0, TYPE 0)?

0

WHAT IS BOUNDARY NODE NUMBER (I5)?

2

WHAT IS BOUNDARY CONDITION IN X1-DIRECTION FOR NODE 2 (0 OR 1: NUMBER OF DIE) (I5)?

0

WHAT IS BOUNDARY CONDITION IN X2-DIRECTION FOR NODE 2 (0, 1, OR -N: NUMBER OF DIE) (I5)?

1

HOW MANY VELOCITIES MUST BE SPECIFIED FOR THIS NODE (IF NO SPECIFICATION REQUIRE 0, TYPE 0)?

0

WHAT IS BOUNDARY NODE NUMBER (I5)?

3

WHAT IS BOUNDARY CONDITION IN X1-DIRECTION FOR NODE 3 (0 OR 1: NUMBER OF DIE) (I5)?

0

WHAT IS BOUNDARY CONDITION IN X2-DIRECTION FOR NODE 3 (0, 1, OR -N: NUMBER OF DIE)
E) (15)?
0
WHAT IS BOUNDARY NODE NUMBER (15)?
4
WHAT IS BOUNDARY CONDITION IN X1-DIRECTION FOR NODE 4(0 OR 1: NUMBER OF DIE)
(IS)?
0
WHAT IS BOUNDARY CONDITION IN X2-DIRECTION FOR NODE 4(0, 1, OR -N: NUMBER OF DIE)
(E) (15)?
1
HOW MANY VELOCITIES MUST BE SPECIFIED FOR THIS NODE(IF NO SPECIFICATION REQUIRE
0, TYPE 0)?
0
WHAT IS BOUNDARY NODE NUMBER (15)?
5
WHAT IS BOUNDARY CONDITION IN X1-DIRECTION FOR NODE 5(0 OR 1: NUMBER OF DIE)
(IS)?
0
WHAT IS BOUNDARY CONDITION IN X2-DIRECTION FOR NODE 5(0, 1, OR -N: NUMBER OF DIE)
(E) (15)?
0
HOW MANY VELOCITIES MUST BE SPECIFIED FOR THIS NODE(IF NO SPECIFICATION REQUIRE
0, TYPE 0)?
0
ELEMENT GROUP NUMBER
1
TYPE OF ELEMENT
1 LINEAR RECTANGULAR ELEMENT
2 QUADRATIC RECTANGULAR ELEMENT
3 CUBIC RECTANGULAR ELEMENT
NUMBER OF NODES PER ELEMENT
4
RIGID PLASTIC OR VISCOPLASTIC MATERIAL
(THE ONLY OPTION IS 1 FOR ALPID VERSION 1.4)
MATERIAL NUMBER
1 SIMPLE FLOW STRESS BEHAVIOR
(ALPID TO USE PREPROGRAMMED ROUTINE)
2, 10 FLOW STRESS BEHAVIOR IS DEFINED BY
SUBROUTINE WITH THE SAME NUMBER
------> 1

ELEMENT SOLUTION FLAG
0 ELEMENT SOLUTION PRINTED
1 ELEMENT SOLUTION NOT PRINTED
------> 1

COORDINATES OF STRESS OUTPUT POINTS
0 PRINTED
1 NOT PRINTED
------> 1

0 STRESSES ARE PRINTED
1 STRESSES ARE NOT PRINTED
-1 STRESSES OUTLINE INCLUDES PRINCIPAL STRESSES
------> 0

0 STRAINS OR STRAIN RATES TO BE PRINTED
1 STRAINS OR STRAIN RATES ARE NOT TO BE PRINTED
------> 0

ENTER PARAMETERS IN EQUATION
STRESS = CKST*(STRAIN**EN)*(STRAIN RATE**EM) + YCOUNT
MATERIAL CONSTANT CKST (F15.7)
------> 12.1

STRAIN HARDENING INDEX EN (F15.7)
------> 0

STRAIN RATE HARDENING SENSITIVITY INDEX EM (F15.7)
------> 0.15

WHAT IS A CONSTANT TO DESCRIBE FLOW STRESS (F15.7)?
0
INPUT OF BOUNDARY NODE DATA

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) ------) 4
ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) ------) 0.0
ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) ------) 0.0
ANGLE IN DEGREES, OF COORDINATE ROTATION FOR NODAL POINT FORCE OR VELOCITY (F15.7) ------) 0.0

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) ------) 5
ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) ------) 0.0
ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) ------) 0.0
ANGLE IN DEGREES, OF COORDINATE ROTATION FOR NODAL POINT FORCE OR VELOCITY (F15.7) ------) 0.0

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) ------) 6
ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) ------) 0.0
ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) 
------> 0.0

ANGLE IN DEGREES, OF COORDINATE ROTATION 
FOR NODAL POINT FORCE OR VELOCITY (F15.7) 
------> 0.0

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) 
------> 7

ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) 
------> 0.0

ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) 
------> 0.0

ANGLE IN DEGREES, OF COORDINATE ROTATION 
FOR NODAL POINT FORCE OR VELOCITY (F15.7) 
------> 0.0

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) 
------> 8

ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) 
------> 0.0

ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) 
------> 0.0

ANGLE IN DEGREES, OF COORDINATE ROTATION 
FOR NODAL POINT FORCE OR VELOCITY (F15.7) 
------> 0.0

ENTER NODAL POINT NUMBER OF BOUNDARY NODE (IS) 
------> 9

ENTER NODAL POINT FORCE IN X1 DIRECTION (F15.7) 
------> 0.0

ENTER NODAL POINT FORCE IN X2 DIRECTION (F15.7) 
------> 0.0
-----) 0.0

ANGLE IN DEGREES, OF COORDINATE ROTATION
FOR NODEAL POINT FORCE OR VELOCITY (F15.7)
-----) 0.0

YOUR DATA HAS BEEN WRITTEN INTO THE FILE
EXAMPLE.DAT

FORTRAN STOP
$
ABSTRACT

The A.L.P.I.D. 1.41 (Analysis of Large Plastic Increment Deformation) version based on rigid-viscoplasticity and finite element method has been modified for the simulation of hammer forging. As a theoretical background for this modification, three methodologies have been suggested and among them, energy balance method based on the force exerted on dies has been adopted. Also preprocessor program called 'HMINP' for the easy preparation of the input file to run A.L.P.I.D.H. has been developed and a command file to run A.L.P.I.D.H. has been developed.