AUTOMATION OF THE DATA ANALYSIS SYSTEM
USED IN
PROCESS MODELING APPLICATIONS

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

In Partial Fulfillment of
The Requirements for the Degree of
Master of Science

by
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June 1986
ABSTRACT

At the present time, great emphasis is being placed on efforts to increase part quality and productivity. This is true of most engineering components, especially those which are formed to net shape for ensuring high quality service performance as well as for reducing material and energy consumption. In order to achieve this goal, modern factories are implementing CAE/CAD/CAM technology.

To achieve near net shapes in metal forming processes, it is very important to select the controlling process parameters which will produce a uniform microstructure and the desired mechanical properties in the finished shape. This objective makes process modeling an important stage in the manufacture of parts with minimum defects on a repetitive basis with reduced lead times.

A group of control parameters like strain rate sensitivity (m), efficiency of power dissipation (n), J co-content, etc. have been systematically developed already by making use of the foundations of continuum thermodynamics and extremum principles. These parameters have been used as the basis for determining the intrinsic workability of the material in temperature-strain rate space at various strain values.

Hence, the main objective of this thesis is to automate
this methodology which will aid the design engineer in (1) Selecting proper process parameters and (2) Obtaining an optimal solution for analysis of the process.

Material modeling involves conversion of experimentally obtained compression test data consisting of flow stress measurements as a function of strain, temperature and strain rate into constitutive equations which describe material behavior during deformation processes. These results can be graphically displayed using three-dimensional surfaces and temperature-strain rate processing maps (contours), which delineate regions for optimal operation.

As an illustration of this automation, three-dimensional surface plots and processing maps have been developed for a few typical engineering materials like Al-4Mg and Al-5Si alloys. These results have been substantiated by comparison with previous experimental work and microstructural analysis.
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<td>$\sigma$</td>
<td>Flow Stress of the Material at any particular temperature, strain and strain rate</td>
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<td>$\varepsilon$</td>
<td>Strain</td>
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<tr>
<td>$\dot{\varepsilon}$</td>
<td>Strain Rate</td>
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<td>$G$</td>
<td>The power content derived from the kinetic energy portion of the total energy</td>
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<tr>
<td>$J$</td>
<td>The power co-content derived from the potential energy portion of the total energy</td>
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<td>$J_{\text{max}}$</td>
<td>The maximum possible value of $J$</td>
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<td>$P$</td>
<td>Total instantaneous power input into the system</td>
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<tr>
<td>$K$</td>
<td>Constant</td>
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<td>$m$</td>
<td>Strain rate sensitivity index of a material at a particular strain, strain rate and temperature</td>
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<tr>
<td>$n$</td>
<td>Efficiency of power dissipation of the material at a particular strain, strain rate and temperature</td>
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<td>$Q$</td>
<td>Working Heat of the body</td>
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<td>$T$</td>
<td>Temperature (Absolute) of the body</td>
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<td>$\dot{S}_0$</td>
<td>Nominal entropy rate of the system</td>
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<td>$\dot{S}$</td>
<td>Total entropy rate of the system</td>
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<td>$\delta \dot{S}$</td>
<td>First order variation of the entropy rate</td>
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<td>$\delta^2 \dot{S}$</td>
<td>Second order variation of the entropy rate</td>
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<td>$\Delta$</td>
<td>Portion of energy generated by the system which is zero when the system is reversible</td>
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<td>$\dot{S}_{\text{sys}}$</td>
<td>Rate of entropy production by the system</td>
</tr>
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<td>$\dot{S}_{\text{app}}$</td>
<td>Applied rate of entropy input equal to $P/T$</td>
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<td>$s$</td>
<td>Ratio of $\dot{S}<em>{\text{sys}}$ to $\dot{S}</em>{\text{app}}$.</td>
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ACKNOWLEDGEMENTS

I wish to express my sincere thanks to my advisor Dr. J. S. Gunasekera, for his valuable advice and help during the course of this thesis.

I also wish to express my deep gratitude to Dr. Sokka M. Doraivelu for his constant help and advice in completing this thesis and for providing me with the information necessary to validate the results of this thesis.

Finally, I wish to thank my parents for their constant encouragement and patience.

June 1986

Srivats Gopinath
CHAPTER I
INTRODUCTION

The Air Force Wright Aeronautical Laboratories/Materials Laboratory is currently investigating numerous high temperature materials for application in future aircraft systems [1]. These materials include metal alloys, metal-matrix composites, and high-strength polymeric materials. These materials are being developed for specific applications and hence, processing is done under special conditions in order to achieve the theoretically desired mechanical properties. Also, part quality and savings in material and energy consumption during material processing are important objectives. Hence, precision manufacturing operations such as Net-Shape and Near-Net-Shape processes have been used to fabricate these parts to ensure superior quality while reducing material and energy consumption.

Currently, costly "build-and-test" methods are in use for selection of process variables, viz. temperature and strain rate (ram velocity). This implies high cost of tooling and setup resulting in longer lead times prior to production which is detrimental to efficient operation of the factory. Besides, build-and-test methods are based on previous experience and consequently depend on having previous experience available. To overcome these problems, it is becoming increasingly important to use the Computer-
Aided-Engineering approach which involves analysis of material flow for process simulation. Hence, process modeling plays an important role in the manufacture of parts with minimum defects on a repetitive basis with reduced lead times. Substantial progress has been made in recent years, using finite element methods, in the computer aided modeling of metalforming processes. Of special mention are powerful software tools like the rigid-viscoplastic finite element analysis package ALPID [11] and the die design package STREAM [10]. In order to develop usable predictive models for a deformation process, it is necessary to determine quantitative relationships which describe the behavior of an engineering material under processing conditions. In other words, it means development of constitutive equations which describe material behavior during deformation. These constitutive equations relate the flow stress to the strain, strain rate and temperature.

The rigid-viscoplastic finite element package ALPID which was developed under the Processing Science Program is presently capable of simulating two-dimensional plane-strain and axisymmetric metalforming problems under isothermal or hot-die-working conditions. The analysis gives several admissible solutions to a given plasticity problem, but it is often desirable to arrive at a unique or optimum solution. This in turn, depends on the method for optimizing the
material-flow process and die design procedures. This leads to a need to develop a "Dynamic Material Model" using an approach that would include (1) Material modeling during deformation, and (2) Criteria for optimization of material flow variables and die design procedures.

The development of a dynamic material model requires the choice of state variables which describe the current state of the material at any instant of time. In this thesis, the state variables which are relevant are the temperature (T), stored elastic energy (W), internal energy (E), working heat (Q), entropy (S), entropy production rate (Ṡ), logarithm of the flow stress (log σ), and logarithm of the strain rate (log ε). These state variables are sufficient to describe a system which contains both reversible and irreversible components. They also make it possible to specify inequalities or constraints for optimizing finite element analysis solutions of metal-forming operations. These inequalities involving stability criteria which provide a means of determining the "intrinsic workability" of the workpiece material have been incorporated into the automated data analysis system which was developed as the major objective of this thesis. The allowable temperature and strain rate ranges are determined from temperature-strain rate maps (processing maps) which describe material behavior during deformation processes. These processing maps define processing variable
regions which result in stable material flow. For the first time, it is possible to demarcate stable regions for processing. This will prove to be an extremely valuable design aid to the processing engineer. In effect, the entire process of dynamic material modeling and selection of optimum process parameters will become automatic and routine, and thus, will be less prone to errors in human judgement. Ultimately, this project is aimed at automating the design methodology which has been developed for controlling microstructure and properties in a net shape product.
CHAPTER 2
DYNAMIC MATERIAL BEHAVIOR MODELING

2.1 Development of material modeling criteria

In reviews of various criteria used for determining the intrinsic workability of the material, Malas [1] refers to work done by Dieter which mentions that workability is a material property and should be independent of changes in geometry, die design, press characteristics and lubrication conditions. However, by observing center burst phenomena, Malas notes that although these phenomena during extrusion observed for one set of conditions suggest poor material workability, this phenomenon is not observed for the same material and die geometry for a different set of processing conditions. Therefore, the present modeling approach uses a new and quantitative definition of material workability properly defined in terms of the dependence of material properties on process variables and based on the ability of a material to dissipate power by favorable metallurgical mechanisms.

The modeling approach adopted here is based on the rigid-viscoplastic finite element method formulation developed by Lee and Kobayashi [3]. Here, although elastic strains are neglected, this method offers definite economic advantages over elastic-plastic finite element methods. This
method has been used in the development of the ALPID code [11] and subsequent analysis of various problems such as solid-cylinder upsetting, extrusion, rolling, etc.

2.2 Development of Stability Criteria

In related previous work done by Prasad and others [6], a unifying theme for modeling of physical systems, as developed by Wellstead has been used for establishing stability criteria. The results involve the definition of a control parameter which describes the efficiency of power dissipation by a workpiece material through metallurgical processes and development of processing maps based on this control parameter.

In this thesis, these results, along with additional thermodynamic principles considered by Malas, have been incorporated. Here, another control parameter which directly relates to the rate of entropy production has been used to define stable regions for processing. In this approach, the metal processing system is considered as being made up of the metal working equipment and the workpiece. The metal working equipment consisting of tools, driving motors and controls, are considered as "sources" and "stores" of energy, while the workpiece is the basic device for dissipating energy. Thus, the system is viewed as an energy manipulator, and the most important criterion used in optimization
of process control is the intrinsic ability of the material to dissipate power.

2.3 Assumptions [1]

(1) Materials under hot-working conditions are considered to be isotropic and homogeneous; thus simplified yield criteria, flow rules and thermodynamic principles are applicable.

(2) A material system under processing conditions is considered to be dynamic because it satisfies the following conditions:

* Time is an independent variable and enters the analysis through integration of strain rate imposed on the workpiece material; it always marches forward.

* Initial conditions cannot be precisely specified when a strain rate is imposed on the system, i.e. the dynamic (actual) path taken by the material to attain the final condition cannot be specified a priori.

* The workpiece material behavior is stochastic, since it is impossible to predict occurrences such as fracture, cavitation and shear localization which lead to workpiece failure.

(3) The metal processing system is considered to be open
with respect to the surroundings but is closed with respect to exchanging matter.

(4) Material deformation can be divided into elastic and plastic deformation. Elastic deformation is recoverable and is neglected here since we are mainly concerned with the irreversible part of the plastically deforming system. Plastic deformation of the material is considered to be irreversible — no matter how small the plastic strain.

2.4 Development of Control Parameters [1]

In the dynamic material model, the workpiece material is considered to be a dissipator of power, while other components of the metal working equipment are "sources" and "stores" of power. The constitutive equation for the workpiece material is an analytical relationship describing the variation of flow stress with process variables, namely, temperature and strain rate. This equation is an intrinsic characteristic of the workpiece material and describes the manner in which the energy is converted at any instant into a form — usually thermal or microstructural — which is not recoverable by the system. Thus, hot working is modeled in terms of management of several irreversible thermodynamic processes which are controlled by the rate of energy input and subsequent dissipation of that energy by dynamic metall-
When a workpiece is deformed at a given temperature and strain rate, the instantaneous power absorbed by the workpiece is $\sigma \dot{\varepsilon}$. A typical constitutive relation for a simple dissipator is schematically represented in Fig. 1(a) in the form of flow stress variation with strain rate at constant temperature and strain.

The instantaneous power can be written as

$$\sigma \dot{\varepsilon} = \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} + \int_0^\sigma \dot{\varepsilon} \, d\sigma \quad \text{(1a)}$$

or

$$P = G + J \quad \text{(1b)}$$

In Fig. 1(a), the area below the curve is:

$$G = \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} \quad \text{which is the dissipator content}$$

And the area above the curve is:

$$J = \int_0^\sigma \dot{\varepsilon} \, d\sigma \quad \text{which is the dissipator co-content}$$

The G-content is derived fundamentally from the kinetic energy part of the total energy. The kinetic energy part of the system is converted into heat; therefore, the G-content represents the heat that is dissipated during the course of deformation. This portion does not affect any metallurgical phenomena occurring within the workpiece.

The J co-content is derived from the potential energy
Fig. 1. Schematic Description of Constitutive Relation of Material System as Energy Converter (Dissipator)
(a) Material System as Nonlinear Energy Dissipator (General Case)
(b) Material System as Linear Energy Dissipator (Special Case)
portion of the total energy of the system. It is this portion of the energy that is responsible for dissipation of power in the form of dynamic metallurgical changes within the workpiece.

The parameter which determines the partition between $G$ and $J$ is the strain rate sensitivity index $m$. It is also a function of temperature and strain rate. From equation (1), it follows that the partition of power between $G$ and $J$ at any particular temperature and strain is given by:

$$\frac{\partial J}{\partial G} |_{T,\varepsilon} = \frac{\partial (\ln \sigma)}{\partial (\ln \dot{\varepsilon})} |_{T,\varepsilon}$$

$\partial (\log \sigma)/\partial (\log \dot{\varepsilon})$ is simply the strain rate sensitivity of the material. From equation (2), it can also be seen that the constitutive equation is of the type:

$$\sigma = K \varepsilon^m$$

In the hot working range for pure metals, $m$ is independent of temperature and strain rate; but in the case of complicated alloy systems, it has been shown to vary with temperature and strain rate.

The $J$ co-content may be evaluated as follows:

From equation (3), the constitutive equation may be rewritten as:

$$\dot{\varepsilon} = K_1 \sigma^{1/m}$$

where $K_1$ is a constant. $J$ can be evaluated for any temperature and strain as follows:
Thus, \( J = \int_0^\sigma \dot{\varepsilon} \cdot d\sigma = \int_0^\sigma k \sigma^{m/l} d\sigma \).

Thus,

\[
J = \frac{k \sigma^{(m+1)/m}}{(m+1)/m} \quad \text{-----------------------------}(6)
\]

The maximum value which \( m \) can attain under stable flow conditions is 1. This limitation on the value of \( m \) is based on theoretical stability analysis [1]. At this value of \( m \), \( J \) will reach its maximum such that the workpiece now becomes a linear dissipator. Thus, we have the following expression:

\[
J_{\text{max}} = \frac{\sigma \cdot \dot{\varepsilon}}{2} \quad \text{-----------------------------}(7)
\]

Here, one-half the total power is dissipated as material flow and the other half is dissipated as heat as shown in Fig.1(b). \( J_{\text{max}} \) is the theoretical maximum which is attainable by a material. The behavior of superplastic materials approaches this extreme. Superplastic behavior occurs theoretically when the rate of increase of elastic stored energy is balanced by the rate of dissipation. The other extreme occurs for materials which are strain rate insensitive and those which do not flow. In these cases, \( J \) is zero. Most engineering materials under hot processing conditions fall in between these two limits. The effect of \( J \) on material flow is more clearly revealed if the power dissipation capacity is normalized with respect to the idealized linear dissipator. Thus, we define the efficiency of power dissipa-
tion as follows:

\[ n = \frac{J}{J_{\text{max}}} \]  

\[ n = \frac{J}{J_{\text{max}}} = \frac{2m}{(m+1)} \]  

(8) \quad (9)

From equations (6), (7) and (8), we have

It has been proved by Ziegler and others [1] that \( m \) must be greater than zero to achieve stable flow. Since the efficiency \( n = \frac{2m}{(m+1)} \), it automatically follows that \( n \) should be positive for mechanical stability. The upper limit can also be determined as \( m = 1 \) for which the efficiency reaches 100%. This is the case when \( J \) becomes equal to \( J_{\text{max}} \) and the material exhibits superplastic behavior. Thus, on the basis of numerical evaluation, experimental determination and the use of theoretical stability criteria, it has been established that the range of \( m \)-values for stable material flow is given by:

\[ 0 < m < 1 \]  

(10)

This relationship can also be seen from equation (9), for \( n \) to lie between 0 to 100%. Hence, we see that for material processing under hot working conditions, it is most desirable to have processing regions in the regions which provide the highest value of \( J \), which in turn means the highest efficiency value. This is consistent with the intent of maximizing the \( J \) co-content since this portion of the power input directly contributes to dynamic metallurgical
changes within the workpiece.

2.5 Material Stability [1]

To establish proper stability criteria for metalforming applications, Liapunov functions have been formulated in terms of the process variables. The Liapunov function is a quantity associated with the Liapunov function stability criteria which is one of the most accepted methods in engineering design.

The entropy production rate of a system for stable processes increases for irreversible processes. In fact, only irreversible processes in a thermodynamic system contribute to the production of entropy.

If the total rate of entropy is denoted by $\dot{S}$, a Taylor's series expansion yields the following expression:

$$\dot{S} = \dot{S}_0 + \delta\dot{S} + \delta^2\dot{S}/2$$  \hspace{1cm} (11)

Also, $\dot{S} = Q/T + \Delta$  \hspace{1cm} (12)

Where $Q =$ Working heat of the body  
$T =$ Temperature of the body  
$\dot{S}_0 =$ Nominal rate of entropy  
$\delta\dot{S} =$ First order variation of entropy rate  
$\delta^2\dot{S} =$ Second order variation of entropy rate

Here, $\Delta$ is that portion of the entropy rate generated by the system which is zero when the system is reversible. Thus, the linear terms in equation (11) are equal to $Q/T$ when the
system is reversible and it is the higher order term which contributes to entropy production when the system is plastically deformed and is irreversible.

Since the higher order term in equation (11) contributes to entropy production, stability of the system is given by this term. Prigogine [1] proved that the second order term in equation (11) is a Liapunov function with the state variable as log \( \dot{\varepsilon} \). Hence if a Liapunov function is formulated in terms of the expression \( \delta^2 \dot{S}/2 \) and the state variable log \( \dot{\varepsilon} \), we have the following condition for stability:

\[
\frac{\partial}{\partial (\log \dot{\varepsilon})} \left( \frac{\delta^2 \dot{S}/2}{\delta} \right) < 0 \tag{13}
\]

Liapunov function stability criteria requires the system to lower the total energy of the system continuously. Since \( m > 0 \) is itself a condition for stability, we can formulate Liapunov functions in terms of the state variables \( m \) and log \( \dot{\varepsilon} \). In such a case, \( \partial m / \partial (\log \dot{\varepsilon}) \) should be less than zero in the stable region. At this point, an analogy may be drawn with the maxima-minima concept in calculus which requires the second derivative of a function to be less than zero to reach a maximum value. This is similar to the condition \( \partial m / \partial (\log \dot{\varepsilon}) < 0 \) for stability. This quantity is also the second partial derivative of log \( \sigma \) with respect to log \( \dot{\varepsilon} \). Physically, it may be said that within the stable region,
the strain rate sensitivity will decrease with increase in strain rate at any temperature. The change in \( m \)-values implies that although the actual values of \( m \) may be high within a stable region (suggesting improved workability), the change in these values could be such that the partial derivative becomes negative. It can also be said on the lines of the maximum value of a function that the stability will reach a maximum at a point within the stable region. From equation (12), the following expression may be written:

\[
\Delta = \left. \frac{\partial P}{\partial T} \right|_{\epsilon, \dot{\epsilon}} - \left. \frac{\partial (ST)}{\partial T} \right|_{\epsilon, \dot{\epsilon}} \quad \text{(14)}
\]

Thus, \( \Delta = \dot{S}_{sys} \quad \text{(15)} \)

where \( \dot{S}_{sys} \) = Rate of entropy production by the system

\( T \) = Absolute temperature of the workpiece at any instant of time

\( P \) = Instantaneous power input into the workpiece

Further, the entropy production rate by the system can be written as the partial derivative of the instantaneous power input with respect to the absolute temperature at that instant. Thus, the following expression may be written:

\[
\Delta = \left. \frac{\partial P}{\partial T} \right|_{\epsilon, \dot{\epsilon}} = - \frac{P}{T} \left. \frac{\partial (\log P)}{\partial (1/T)} \right|_{\epsilon, \dot{\epsilon}} \quad \text{(16)}
\]

\[
= \frac{P}{T} \left[ - \frac{\partial (\log P)}{T \partial (1/T)} \right] \quad \text{(17)}
\]
Now, \[
\frac{\delta \log P}{T \delta \left( \frac{1}{T} \right)} \frac{\delta \log \sigma}{\dot{\varepsilon} \cdot \dot{\varepsilon}} = \frac{\delta \log \sigma}{T \delta \left( \frac{1}{T} \right)} \frac{\delta \log \sigma}{\dot{\varepsilon} \cdot \dot{\varepsilon}}
\] \hspace{1cm} \text{-------(18)}

Thus, we define a new coefficient \( s \) such that
\[
s = \frac{1}{T} \frac{\delta \log \sigma}{\delta \left( \frac{1}{T} \right)} \frac{\delta \log \sigma}{\dot{\varepsilon} \cdot \dot{\varepsilon}}
\] \hspace{1cm} \text{-------(19)}

From equation (17), we get
\[
\Delta = - \frac{P}{T} s
\] \hspace{1cm} \text{-------(20)}

If \( P/T \) is written as \( \dot{S}_{\text{app}} \), where \( \dot{S}_{\text{app}} \) is the applied rate of entropy input, we can write
\[
\Delta = - \dot{S}_{\text{app}} \cdot s
\] \hspace{1cm} \text{-------(21)}

From equation (15), we get
\[
s = \dot{S}_{\text{sys}} / \dot{S}_{\text{app}}
\] \hspace{1cm} \text{-------(22)}

According to the Second Law of Thermodynamics, \( s \) should be greater than one for stable material flow. In other words, the rate of entropy production by the system should be at least as fast as the rate of entropy applied externally to the system in order to have a stable system. Therefore, if \( s \) is also treated as a Liapunov function, \( \dot{s}/\delta \log \dot{\varepsilon} \) should also be less than zero to satisfy stability requirements. The same could be said of \( s \) as was previously mentioned for \( m \) regarding stability criteria. Within the stable region, \( s \) values could be higher, suggesting increased rate of dissipation by the workpiece which will ultimately result in improved microstructural properties. However, the change in \( s \) values could be such that the partial derivative becomes
negative. This is also analogous to the maxima-minima concept, since it can be said that the stability will reach a maximum point within the stable region.

Thus, two conditions are used in the dynamic modeling approach for stability criteria:

\[
\frac{\delta m}{\delta (\log \dot{\varepsilon})} < 0 \quad ; \quad \frac{\delta s}{\delta (\log \dot{\varepsilon})} < 0 \quad (23)
\]

These two conditions are used in the development of processing maps. Several dynamic models have also been included in this report to illustrate the validity of this analysis and these are further supplemented by reference to previous microstructural studies which confirm the conclusions that can be drawn on basis of the model alone, prior to actual testing of the material.
CHAPTER 3

EXPERIMENTAL DATA ACQUISITION

Dynamic material behavior during processing can be accurately described using the following methods:

(1) Constitutive equations which relate the flow stress to strain rate, temperature and strain.

(2) Three dimensional surfaces relating the efficiency of power dissipation and strain rate sensitivity to strain rate and temperature at any given strain.

(3) Contour plots (processing maps) of strain rate sensitivity, efficiency of power dissipation and stability over a range of temperatures and strain rates at any given strain.

The basic data required to develop the above mentioned processing maps and surfaces are:

(i) Flow stress as a function of strain rate and temperature over a wide range.

(ii) Strain rate sensitivity as a function of strain rate and temperature over a wide range.

3.1 Experimental Techniques [2]

Several experimental techniques available for obtaining
material data under hot working conditions have been reviewed previously, as noted by Barker, Doraivelu, et al [2]. These include:

(1) Hot tensile testing
(2) Hot compression testing
(3) Hot torsion testing
(4) Laboratory scale testing using any metalworking process such as rolling, extrusion, or forging.

Among these possible methods, it is noted that the hot compression test has several advantages over the other methods since:

(a) It is simple to conduct under isothermal conditions
(b) It closely resembles direct compression processes such as forging and extrusion
(c) It is possible to reach reasonably large strains without the acute onset of plastic instability (barreling)
(d) The specimen geometry is a simple cylinder and is therefore, easy to fabricate

At this stage, it may also be mentioned that the plane strain compression test may also be chosen as an alternative to hot compression of a cylindrical specimen. This method involves compression of a rectangular strip of the material to be tested between two plattens under plane strain conditions. This method has an added advantage over the cylindri-
cal compression test specimen that the effect of barreling is totally eliminated. However, the cylindrical test specimen is described here owing to the reason that most of the materials tested at the Air Force Wright Aeronautical Laboratories have been tested using this method. Owing to the above mentioned reasons, the hot compression test is preferred for obtaining the required material property data. Therefore, the experimental setup and methodology described below is applicable to a laboratory scale test.

3.2 Experimental Arrangement for Hot Compression Testing

The experimental setup for hot compression testing is shown schematically in Fig. 2. A cylindrical specimen is compressed between flat plattens which are well lubricated. The lubricant at the material-platten interface plays an important role in controlling the heat transfer from the die to the workpiece and the gradients within the deforming metal. It also influences friction conditions. The ultimate effect is to change the velocity fields or metal flow in the deformation zone and to influence the limiting strain. Besides, lubricants directly influence factors such as part surface quality, metal flow, grain structure, mechanical properties, dimensional consistency and load and energy requirements. Further, the lubricants also promote longer die life.
HOT COMPRESSION TEST SET-UP

Fig. 2. Schematic Diagram of Hot Compression Test Setup
Referring to Fig. 2 again, the pushrods are layered with insulating material to reduce conductive heat losses. The velocity of the crosshead is controlled by an exponential decay circuit to maintain a constant true strain rate throughout the test. The normal testing range is in between $10^{-4}$ and $10^2$ sec$^{-1}$. The three zone resistance furnace used for specimen heating is driven by a temperature controller which monitors and controls each zone independently. The temperature is also measured adjacent to the specimen by two thermocouples which run alongside the pushrods. Data is collected by means of Computer-Aided Data Acquisition as well as by strip chart recorders which provide a visual display of load versus time during the test and also serves as a backup to the Computer-Aided Data Acquisition System.

3.3 Computer Aided Data Acquisition

The Data Acquisition System senses and records the load cell voltage on magnetic tape. The sampling rate, i.e. the rate at which data is measured, can be set as desired. The collected flow stress data at a typical strain value and strain rate setting is then used as input to data analysis and subsequent dynamic material modeling. A similar procedure is repeated at different temperatures and strains.
4.1 Development of Constitutive Equations

The software package which has been developed using the previously mentioned modeling criteria has been named MIS (Material Information System). The computations involved follow the modeling methodology discussed in the previous chapters. The first step towards modeling the material is the development of a set of constitutive equations for the material over the measured range of temperature and strain rate. A schematic diagram of the Dynamic Material Modeling process is shown in Fig. 3.

Flow stress and strain rate values which have been previously obtained by experiment are converted into log $\sigma$ and log$\dot{e}$ values and the constitutive relationship is obtained by fitting data points to piecewise quadratic equations [4]. Quadratic equations are selected to ensure that the values of $m$ and $s$ stay within the prescribed limits in accordance with the physical laws of thermodynamics and stability criteria. At the points of intersection of the two equations, log $\sigma$ and the slopes are matched to obtain a smooth transition from one equation to another. In the regions where two successive curves overlap, the values obtained by the two equations are averaged out. In this
Fig. 3. Schematic Diagram of the Dynamic Material Modeling Process
fashion, numerous intermediate points are generated for log σ versus log Ė curves at each temperature. Then, a similar process is repeated for generation of intermediate points for the log σ versus 1/T curves at each value of strain rate. Then, values of m, s, \( \frac{\partial m}{\partial (\log \dot{\varepsilon})} \) and \( \frac{\partial s}{\partial (\log \dot{\varepsilon})} \) are obtained by taking the finite difference between two successive points located close to each other. Further, note that the temperature axis is represented as the reciprocal of the absolute temperature (1/T) since the physical laws based on which the modeling has been carried out are more evident in the graphical output rather than if T were to be used in representation of the Z-axis.

4.2 Calculation of m and n values

These values are calculated by taking the finite difference between two successive points located close to each other which have been generated by the piecewise averaging method described above. The relationship used here is:

\[
m = \frac{\delta(\log \sigma)}{\delta(\log \dot{\varepsilon})} \bigg|_{T, \varepsilon} = \frac{\log \sigma_{\varepsilon} - \log \sigma_{E}}{\log \dot{\varepsilon}_{\varepsilon} - \log \dot{\varepsilon}_{E}}\bigg|_{T, \varepsilon}
\]

Then, the values of the efficiency of power dissipation n are calculated using the relationship \( n = \frac{2m}{m + 1} \)

4.3 Calculation of \( \frac{\partial m}{\partial (\log \dot{\varepsilon})} \) values

Using the values of m generated as mentioned above, the
values of $\frac{\delta m}{\delta (\log \dot{e})}$ are calculated by again taking the finite difference between two successive points.

$$\frac{\delta m}{\delta (\log \dot{e})} \bigg|_{T, \dot{e}} = \frac{m_1 - m_2}{\log \dot{e}_1 - \log \dot{e}_2} \tag{25}$$

4.4 Calculation of $s$ values

These are calculated making use of the values obtained for the $\log \sigma$ versus $(1/T)$ curves obtained as mentioned previously. The relationship used is:

$$s = \frac{\delta (\log \sigma)}{T \ \delta (1/T)} \bigg|_{\epsilon, \dot{\epsilon}} = \frac{\log \sigma_1 - \log \sigma_2}{[T_1 + T_2] \left[ \frac{1}{T_1} - \frac{1}{T_2} \right]} \bigg|_{\epsilon, \dot{\epsilon}} \tag{26}$$

4.5 Calculation of $\frac{\delta s}{\delta (\log \dot{e})}$ values

Using the values of $s$ generated as mentioned above, $\frac{\delta s}{\delta (\log \dot{e})}$ is calculated using the relationship:

$$\frac{\delta s}{\delta (\log \dot{e})} \bigg|_{T, \dot{e}} = \frac{s_1 - s_2}{\log \dot{e}_1 - \log \dot{e}_2} \bigg|_{T, \epsilon} \tag{27}$$

4.6 Determination of Stable Region for Processing

Once the values of $\frac{\delta m}{\delta (\log \dot{e})}$ and $\frac{\delta s}{\delta (\log \dot{e})}$ have been calculated, each grid point is examined to determine if both values are less than zero at that point or not. If both values happen be to zero at a particular grid point, that point is said to lie within the stable region. Otherwise,
the point lies outside the stable region. Hence, the logic used is as follows:

(a) Initially, a stability flag is set at the numerical value zero.

(b) If the values of $\frac{d}{d}(\log \dot{e})$ and $\frac{d}{d}(\log \dot{e})$ are both found to be less than zero, the value of the stability flag is changed to the numerical value 1.

Hence, we essentially have a binary logic to determine the stable region. In form of a graphical output using contour plots, the point at which the 0.5 contour line passes through would be the stable boundary [5]. This is clear from the fact that if two neighboring points exist such that the value of the flag is 0 at one point and 1 at the other, it means that these points lie in the unstable and stable region respectively. Hence, it can be reasonably assumed that the stable boundary at which the system is marginally stable, passes half-way in between two such neighboring points. This, in effect is the contour line with the value 0.5. Thus, the 0.5 contour line is used to delineate the stable and unstable regions.

The above data is then utilized by the program which generates a datafile compatible with the popular graphics display package MOVIE.BYU. Using this package, output is then obtained in the following forms:

(a) Three dimensional surface plots
(b) Two dimensional contour plots (processing maps)

4.7 Data Analysis by MIS (Material Information System)

MIS is an extremely userfriendly and interactive program which has been developed to perform the task of dynamic material behavior modeling. It is not necessary for the user to have any extensive knowledge of computers and/or dynamic material behavior modeling in order to use this package.

The package is userfriendly and interactive in the sense that it performs error checking at all stages of data input and does not accept erroneous data. It is entirely menu driven and it is very easy to select the desired options. A typical session with MIS would involve the following stages:

1. The user selects the desired input format in which he wishes to provide data input. The options available are either interactive data input or input from a datafile.

2. The user now inputs the flow stress-strain rate data at various temperature values. This is accomplished by answering a series of interactive questions. Alternatively, if the user has chosen to input data through a datafile, the name of that datafile has to be specified. It is important to note that the datafile has to be created prior to running MIS [Appendices A and C].
(3) The user may check his input values before the program begins computation. Hence, if it is desired to change any particular value, or if an incorrect value has been input, it can easily be changed by selecting the value to be changed from a table of values which is displayed on the screen for review, and replacing it with the new value.

(4) MIS then fits a series of piecewise quadratic functions over the whole range of values in a manner described previously in Section 4.1. Then a whole set of intermediate points are generated by interpolating in between the points at which testing has been carried out. Then, values of $m, s, \frac{\partial m}{\partial (\log \dot{\varepsilon})}, \frac{\partial s}{\partial (\log \dot{\varepsilon})}$ and stability flags are generated at each interpolated grid point.

(5) The user can select the desired graphical output display format. MIS can generate data for displaying three-dimensional surfaces of flow stress, strain rate sensitivity or efficiency of power dissipation as a function of strain rate and the reciprocal of the temperature in degrees Kelvin. Alternatively, data for generation of contour plots (processing maps) of strain rate sensitivity, efficiency of power dissipation, $\frac{\partial m}{\partial (\log \dot{\varepsilon})}$, $\frac{\partial s}{\partial (\log \dot{\varepsilon})}$ and stability can be generated. Scaling of the grid and axis system for three-dimensional surface plots and contour plots is also performed by MIS.
(6) The data generated is formatted for direct use with the graphics display package MOVIE.BYU. MIS has also been interfaced with the MOVIE system character generation modules. Consequently, the user can also generate character titles of his choice along the X, Y and Z axes if desired.

The principal menus in MIS are shown in Fig. 4.
Fig. 4. Main Menus Available in the Material Information System (MIS)
CHAPTER 5
MODELING OF TWO MATERIALS
AND THEIR VERIFICATION

Using the modeling methodology described in the previous chapters, several materials have been modeled using MIS. Here, for illustration and verification purposes, two typical materials will be considered: Al-4Mg and Al-5Si alloy materials. To illustrate the capabilities of this package, several surface plots and processing maps have been shown in Figs. 5-12 for the Al-4Mg alloy, and Figs. 13-20 for the Al-5Si alloy. Stability plots are generated primarily by assigning a scalar quantity 0 to points which lie in the unstable range and a value of 1 to points which lie in the stable range. Hence, if two neighboring points are considered each of which lie in the stable and unstable range, then the point with a scalar value of 0.5 will lie on the stable boundary. Hence, the 0.5 contour line will represent the stable boundary for processing. In other words, the 0.5 contour line is the upper limit of the plastic strain rate and temperature ranges below which stable material processes exist. Along this boundary, the system is considered to be marginally stable. Any point which lies in the region where either $\delta m/\delta (\log \dot{\varepsilon})$ or $\delta s/\delta (\log \dot{\varepsilon})$ are greater than zero, instability exists in the form of unfavorable processes which produce defects, fracture, or plastic instabilities.
5.1 Mechanical Property Correlation in Upset Product [8]

The mechanical properties of the product depend to a large extent on the microstructure of the starting material since this controls the structural damage caused during deformation processing. The three damage mechanisms that have been identified to be most important in materials containing hard particles are:

1. Cavity formation at matrix particles which is important at low temperatures and high strain rates.

2. Wedge type micro-cracking at the grain boundary triple junctions which is important at low strain rates and high temperatures.

3. Flow localization due to adiabatic heating which is important at very high strain rates.

A fourth mechanism involving dynamic recrystallization was later considered to be often beneficial, for example in grain refinement. The structural damage by any of the above mechanisms will be reflected in the form of reduced ductility of the product.

Once stable regions for processing a given material have been identified with the help of these processing maps, the next step is to determine the optimum processing condition to obtain maximum intrinsic workability of the material. It has been found by experimentation performed on a large
Fig. 5. Three Dimensional Plot of Log FLow Stress of Al-4Mg Alloy at 0.6 Strain
Fig. 6. Three Dimensional Plot of Strain Rate Sensitivity of Al-4Mg Alloy at 0.6 Strain
Fig. 7. Three Dimensional Plot of Efficiency of Power Dissipation of Al-4Mg Alloy at 0.6 Strain
Fig. 8. Contour Plot (Processing Map) of Strain Rate Sensitivity of Al-4Mg Alloy at 0.6 Strain
Fig. 9. Contour Plot (Processing Map) of Efficiency of Power Dissipation of Al-4Mg Alloy at 0.6 Strain
Fig. 10. Contour Plot (Processing Map) of $\frac{\Delta m}{\Delta (\log \dot{\varepsilon})}$ of Al-4Mg Alloy at 0.6 Strain
Fig. 11. Contour Plot (Processing Map) of $\partial s/\partial (\log \dot{\varepsilon})$ of Al-4Mg Alloy at 0.6 Strain
Fig. 12. Stability Map Showing Safe Processing Regions for Al-4Mg Alloy at 0.6 Strain
number of different materials that strain hardening occurs at low values of efficiency \( n < 5\% \), while dynamic recovery takes place between 10-15\%, ductile fracture and wedge cracking occur at values greater than 35\% \([7]\). Hence, one would typically prefer the 10-25\% efficiency range, where mechanisms of dynamic recovery exist. This would result in refined grain size in the microstructure of the product.

5.2 Interpretation of the Processing Map for Al-4Mg alloy

According to the considerations mentioned above, it is possible to interpret the processing map in the physical sense. Fig. 12 shows the stability map for the Al-4Mg alloy. The 0.5 value contour line is the stable boundary along which the system is marginally stable. The shaded region corresponds to the condition when \( \delta m/\delta (\log \dot{\varepsilon}) \) and \( \delta s/\delta (\log \dot{\varepsilon}) \) are both less than zero. This stability map can be interpreted as follows:

The system is unstable in the low strain rate region below 350 K. However, stable processing may be carried out above this temperature. If hammer forging is to be used, the high strain rate region should be selected for processing. However, if it is desired to use a press, the low strain rate region should be considered for selection of process parameters. Typically, in these regions, one would prefer processing conditions where the efficiency of power dissipation is appropriate for the desired microstructure. On this
basis, processing conditions in the region of 300–500 K and 40–200 sec\(^{-1}\) strain rate would be preferred for hammer forging where efficiency is in the range of 2–14%. As previously mentioned, on basis of previous experimental observation and verification on other materials, it could be said that in the 2–5% range, strain hardening would occur, while in the 10–15% range, dynamic recovery is the dominant mechanism. For processing by using a press, one would select processing conditions in the region of 450–600 K, but in a strain rate range of 0.02 sec\(^{-1}\) to 1 sec\(^{-1}\) where the efficiency ranges from 10–30%.

5.3 Verification of the Model by Microstructural Analysis of Al-4Mg alloy

In order to verify the predictions that were made regarding the behavior of the Al-4Mg alloy, the actual microstructures were examined at various temperatures and strain rates [8]. The microstructure of the Al-4Mg alloy which was used as the starting material for testing showed the presence of large second phase particles present at the grain boundaries and fine particles (undissolved impurities) in the grain interior.

The microstructures of the specimens processed at different temperatures and strain rates were further analyzed and it was found that the microstructure of the Al-4Mg alloy
Fig. 13. Three Dimensional Plot of Log Flow Stress of Al-5Si Alloy at 0.6 Strain
Fig. 14. Three Dimensional Plot of Strain Rate Sensitivity of Al-5Si Alloy at 0.6 Strain
Fig. 15. Three Dimensional Plot of Efficiency of Power Dissipation of Al-5Si Alloy at 0.6 Strain
Fig. 16. Contour Plot (Processing Map) of Strain Rate Sensitivity of Al-5Si Alloy at 0.6 Strain
Fig. 17. Contour Plot (Processing Map) of Efficiency of Power Dissipation of Al-5Si Alloy at 0.6 Strain
Fig. 18. Contour Plot (Processing Map) of $\frac{\Delta m}{\Delta (\log \dot{\varepsilon})}$ of Al-5Si Alloy at 0.6 Strain
Fig. 19. Contour Plot (Processing Map) of $\frac{\partial s}{\partial \left(\log \varepsilon\right)}$ of Al-5Si Alloy at 0.6 Strain
Fig. 20. Stability Map Showing Safe Processing Regions for Al-5Si Alloy at 0.6 Strain
upset at higher temperatures did not exhibit recrystallized grain structure, and that the microstructures obtained after processing were quite similar to that of the starting material, as far as the nature was concerned.

In related previous work done by Rao [8], it was observed that in the low temperature-high strain rate range (upto about 100 sec⁻¹), the ductility started to decrease appreciably as the temperature, indicating the possibility of cavity formation at the matrix particles. This was confirmed by fracture tests conducted on the alloy in this region. This seems to agree fairly well with the stable boundary which has been drawn by MIS. The material is stable over most of the region. This can be attributed to the fact that the size of the matrix particles present in the alloy is relatively smaller and that the mechanism of cavitation damage or wedge-cracking is quite sensitive to the matrix-particle size. This is consistent with the existence of narrow unstable regions predicted by the MIS package.

5.4 Interpretation of the Processing Map for Al-5Si alloy

In Fig. 20, the stable boundaries for the Al-5Si material have been drawn using MIS. The 0.5 value contour line is the stable boundary along which the system is marginally stable. Contour values lower than 0.5 lie in the unstable region while values greater than 0.5 lie in the stable
region. Accordingly, the stability map may be interpreted as follows:

There exists an unstable region in the temperature range of 300-475 K corresponding to the strain rate range of 0.02 sec⁻¹, except for a narrow stable band between 375 and 400 K. Processing in this unstable region could result in cavity damage at the grain boundaries. The other major unstable region is in the high temperature-high strain rate region. This region ranges from 500-800 K in the strain rate range of about 1 to 200 sec⁻¹. Thus, processing at higher temperatures cannot be done in this strain rate range. Hence, processing at higher temperatures should be done at low strain rates only. This is possible by using a press for processing. But there is another unstable region in the low strain rate-high temperature regime. At temperatures ranging from 725 to 800 K and strain rates from 0.02 to 0.09 sec⁻¹, instability has been detected. Unfavorable mechanisms like wedge cracking could exist in this processing range.

5.5 Verification of the Model by Microstructural Analysis of Al-5Si alloy

The possible behavior of the Al-5Si material as predicted by MIS is now compared with actual microstructural analysis carried out and analyzed by Rao [8].

The microstructure of the Al-5Si alloy exhibited the
presence of large Silicon particles at the grain boundaries in the as-cast form. The microstructure of the forged-annealed Al-5Si alloy (starting material) showed large Silicon particles essentially at the grain boundaries of the Al-5Si solid solution matrix and a fine precipitation of Silicon particles in the grain interior. This was very similar to the as-cast form of the material.

Later, the microstructures of the specimens processed at different temperatures and strain rates were further analyzed. The micrographs of the specimen deformed at 300 K and 0.02 sec\(^{-1}\) had features similar to that of the starting material: large particles at the grain boundaries and fine precipitates in the interior. The specimen structure remained nearly the same up to about 550 K. Above this temperature, the precipitates in the grain interior were found to be dissolving in the matrix. At very high temperatures (above 700 K), the microstructure also showed the presence of recrystallized grains.

As regards the material properties, there was a reduction in the ductility of the material at high temperatures, which was found to be caused by wedge cracking at the grain boundary triple junctions. Further, fracture studies conducted on the material showed that fracture at low temperatures was ductile in nature. Specimens processed at high temperatures and low strain rates (0.02 and 0.2 sec\(^{-1}\)) show
features of grain boundary separations or cracks. These findings agree quite well with the stability map constructed by MIS, which further confirms the validity of the stability approach.

In conclusion of this chapter, it can be said that the Liapunov function stability criteria used here has proved to be a realistic and valid approach for determining safe regions for processing so that acceptable and stable microstructures can be obtained. This can be said on basis of the fact that the Al-4Mg and Al-5Si alloys were modeled by this package and the predictions were verified by comparison with actual experimental studies conducted on the material in the past.
CHAPTER 6
OPTIMIZATION AND SCOPE FOR FUTURE WORK

Essentially, optimization of process design involves incorporating the design constraints into the finite element simulation which is performed after material modeling. This involves selection of optimum processing parameters to be input as process variables into the finite element simulation. This makes the simulation model a realistic one.

In the past, finite element simulations have been carried out by designers to study specific problems by systematically varying design parameters. In such a case, optimizing design parameters is entirely dependent on the past experience of the engineer. This kind of computer simulation is analogous to the "build-and-test" methods used on the shop floor. Hence, this is not a very efficient way of performing realistic finite element simulation. Therefore, a need exists to optimize the input design parameters such that the simulation is realistic as well as optimal.

The most important part of process design is to select those processing parameters which will ensure the desired microstructure and mechanical properties in the finished part. The material behavior constraints and design methodology involving stability criteria provides a proper way of optimizing process parameters. It is to be noted that the
rigid viscoplastic finite element package ALPID is not a design package but an analysis package. Material behavior constraints are not built into it, hence such a basis can be provided using MIS to select processing conditions. It is also possible to incorporate behavioral constraints directly into the ALPID package by modification of the code, as was done for process modeling of a Ti-6242 forged compressor disk [1].

The various stages in process design are:

(1) Selection of ram velocity, temperature and load

(2) Die design

(3) Preform design

6.1 Refining and Developing the Algorithm

At present, piecewise quadratic fits are used to determine the constitutive behavior of the material. Although this is sufficient to satisfy physical requirements, there is no way of checking whether the input data points are correct or not. For example, if one of the readings obtained at a particular temperature and strain rate is inconsistent with the other data, the curves fitted are forced to pass through this bad data point. Hence, this would result in erroneous values of m and s. Consequently, the model developed would not be entirely correct. Hence, other curve fitting techniques could be examined, like B-splines, which would not directly pass through these bad data points, but
would blend smoothly in between. The result of this is the reduction of the error involved. It is also possible to constrain the first order and second order derivatives to suit the physical requirements of the system.

Alternatively, a statistical technique could be adopted which would eliminate the bad data points and then resume computation. If the number of points remaining after data reduction is less, the system should be capable of informing the user that testing needs to be carried out again, or that more points are needed for modeling of the system.

6.2 Incorporating Material Behavior into CAD/CAM of Dies

In designing and manufacturing extrusion and forging dies, two methodologies can be used. In the first method, the design of the die is obtained by making use of the Computer-Aided-Engineering (CAE) systems approach. This approach [9] integrates dynamic material behavior modeling, geometric modeling, analytical process modeling, CAD/CAM of dies and process control as illustrated in Fig. 21. Advanced process modeling is the essence of this approach and the understanding of dynamic material behavior in a quantitative way for all materials - composite materials, metals, alloys, polymers and ceramics - makes this integration possible and generic. One of the results of integrating material behavior modeling and geometric modeling with advanced process
Fig. 21. The Computer-Aided-Engineering Approach
modeling is CAD/CAM of dies.

In the second method, well established empirical rules are used for arriving at an acceptable design alternative. At present, both these procedures follow a trial and error approach to achieve the required goal. Either process used by itself is time consuming and expensive. The CAE systems approach lacks empirical design aids during the selection of an initial design and the experience based method lacks analytical aids for verification of the final design. The optimum die design procedure would be to utilize both of these methods.

Prior to attempting to accomplish the above mentioned task, MIS can be used by the interactive die design package STREAM. Currently, STREAM can perform load and stress calculations for only about four materials. Each material has a constitutive equation which is used in calculating the flow stress. Besides, these constitutive equations at present are incapable of accounting for temperature effects during deformation. Hence, the material data generated by MIS can be used to determine the flow stress at various temperatures and constant updates can be performed. Consequently, STREAM would then become capable of designing dies for any material.
6.3 Software Integration for Expert System Development

The various software tools like ALPID, STREAM and MIS have been developed using fundamental and powerful scientific analytical techniques. Although these packages are valuable design aids, they are not integrated into a closely connected sequence such as that shown in Fig. 22 for interpretation of results and finding optimum solutions to complex problems.

The third step, namely preform shape design, is an important stage in process design. The preform shape is generally determined either by the experience of the process engineer or by an Expert System which is based on the CAE systems approach and rules derived from past experience. At present, there is no such Expert System available. However, research is currently under way as part of the Manufacturing Science Program towards developing an Intelligent Apprentice System for process simulation [9]. Such an Expert System will allow the user to focus on the design problem rather than worry about how the various software tools interact. The Expert System would aid and prompt engineers not fully familiar with CAE tools in solving complex design problems in an almost routine fashion. This CAE/CAD/CAM methodology for dynamic material modeling embraces constitutive equations, stable and unstable regions and optimization of processing parameters and ultimately helps in forming a
Fig. 22. Proposed Integration of Existing Software Tools
connected sequence of steps beginning with material modeling and ending with processing of the material under optimum or near-optimum conditions.
CHAPTER 7
CONCLUSIONS

This thesis has succeeded in effectively automating the thermodynamic and continuum mechanics criteria used in dynamic material behavior modeling which will ultimately aid in optimization of process design and eliminate costly "build-and-test" methods of selecting process variables.

For the first time, stable regions for processing have been mapped out using stability criteria. Now, a comprehensive package exists which will provide information relating to different process parameters which are of prime importance in optimum process design.

A process simulation model takes into account the influence of material properties on the stress and strain distribution during deformation. Thus, to achieve a realistic process modeling capability, accurate and reliable material behavior models need to be developed. The development of the MIS software package has greatly contributed to fulfilling such a need. The Material Information System (MIS) will provide a powerful tool and material database for the processing engineer. This software package will greatly reduce the time and effort involved in materials characterization required for modeling of metalworking processes.
The need has already been felt for a materials test data analysis system which can quickly and reliably generate three-dimensional plots and two-dimensional contour maps of important material parameters and provide quick visual references relating to stability information using Dynamic Material Modeling. It is earnestly hoped that the Material Information System (MIS) package will satisfy a need for such quick data analysis and generation of a materials database.
REFERENCES


APPENDIX A

PREPARATION OF INPUT DATA

(I)

CARD 1 [ Free format ]

Variable(s)                                Entry
MATR                                      Name of the material which will
                                          be modeled by the user.

(II)

CARD 1 [Free format ]

Variable(s)                                Entry
NUMPT                                     Number of strain rate flow
                                          stress data which have been
                                          collected at a particular tem­
                                          perature. This program can only
                                          handle the case when there are
                                          equal number of data available
                                          at each temperature.

NUMTEM                                    Number of temperatures at which
                                          data have been collected.

(III) Temperature data :

CARD 1 [ Free format ]

Variable(s)                                Entry
TEMP(NUMTEM)                               Value of the various tempera­
                                          tures at which data have been
collected. Note that the number of values input at this stage should be exactly equal to NUMTEM input earlier.

(IV) Flow stress, strain rate data:

<table>
<thead>
<tr>
<th>Variable(s)</th>
<th>Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARD 1: STRESS(1,NUMPT)</td>
<td>Flow stress data at TEMP(1)</td>
</tr>
<tr>
<td>CARD 2: STRATE(1,NUMPT)</td>
<td>Strain rate data at TEMP(1)</td>
</tr>
<tr>
<td>CARD 3: STRESS(2,NUMPT)</td>
<td>Flow stress data at TEMP(2)</td>
</tr>
<tr>
<td>CARD 4: STRATE(2,NUMPT)</td>
<td>Strain rate data at TEMP(2)</td>
</tr>
</tbody>
</table>

and so on. Thus, in this deck, the number of STRESS and STRATE data will be equal to NUMTEM. It should also be noted that the number of values on each card should be exactly equal to NUMPT input earlier.
APPENDIX B

SAMPLE RUN USING INTERACTIVE DATA INPUT
RUN MIS

Specify whether you wish to input data interactively or read from a datafile

I : For interactive data input
D : For data input from a datafile

Enter option accordingly >>> I

Specify the name of the material which is to be modeled dynamically >>> AL-55I

Specify the number of points at which test data has been obtained at a particular temperature >>> 4

Indicate the number of various temperatures at which test data have been recorded >>> 11

Now input the values of the various temperatures at which data have been recorded >>> 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800

For 300.0 degrees, input flow stress values >>> 173, 192, 233, 259

Now input the corresponding values of strain rate >>> 0.02, 0.2, 8, 200

For 350.0 degrees, input flow stress values >>> 164, 183, 223, 254

Now input the corresponding values of strain rate >>> 0.02, 0.2, 8, 200
For 40.0 degrees, input the following stress values: 150, 171, 210, 250

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200

For 45.0 degrees, input the following stress values: 125, 145, 192, 243

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200

For 50.0 degrees, input the following stress values: 88, 117, 168, 228

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200

For 55.0 degrees, input the following stress values: 58, 88, 132, 206

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200

For 60.0 degrees, input the following stress values: 39, 58, 97, 177

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200

For 65.0 degrees, input the following stress values: 26, 40, 70, 135

Now input the corresponding values of strain rate: 0.02, 0.2, 8, 200
For 700.0 degrees, input flow stress values >>>> 18, 29, 53, 101

Now input the corresponding values of strain rate >>>> 0.02, 0.2, 8, 200

For 750.0 degrees, input flow stress values >>>> 13, 21, 40, 77

Now input the corresponding values of strain rate >>>> 0.02, 0.2, 8, 200

For 800.0 degrees, input flow stress values >>>> 10, 16, 32, 62

Now input the corresponding values of strain rate >>>> 0.02, 0.2, 8, 200

Do you wish to check your input values before proceeding with the computation? (Y/N) >>>> N

Specify whether the temperature units are in degrees Kelvin or degrees Fahrenheit

K : For temperature in degrees Kelvin
F : For temperature in degrees Fahrenheit

Enter option accordingly >>>> K
Do you want an output of the curve fit coefficients? (Y/N) >>> N

Select the desired option:

1: Obtain 3-D surface plots
2: Obtain contour plots
3: Quit and exit from the system

Enter your option accordingly >>> 1

Select the desired option:

1: Generate display file for flow stress values
2: Generate display file for strain rate sensitivity
3: Generate display file for efficiency values
4: Return to main display menu
5: Quit and exit from the program

Enter your option accordingly >>> 3

Input the name of the movie-compatible datafile into which you would like to store your generated coordinates (DEV:[UIC]NAME.EXT) >>> EFFIC.DAT

Do you wish to generate titles along the X, Y and Z axes? (Y/N) >>> N

Select the desired option:

1: Return to 3-D plot menu
2: Return to contour plot menu
3: Quit and exit from the program

Enter option accordingly >>> 3

Successful execution of program

$
APPENDIX C

SAMPLE RUN USING DATA FILE AS INPUT
Specify whether you wish to input data interactively or read from a datafile

I: For interactive data input
D: For data input from a datafile

Enter option accordingly >>>> D

Input the name of the datafile from which the data is to be read >>>> ALL5SI

Do you wish to check your input values before proceeding with the computation? (Y/N) >>>> N

Specify whether the temperature units are in degrees Kelvin or degrees Fahrenheit

K: For temperature in degrees Kelvin
F: For temperature in degrees Fahrenheit

Enter option accordingly >>>> K

Do you want an output of the curve fit coefficients? (Y/N) >>>> N

Select the desired option:

1: Obtain 3-D surface plots
2: Obtain contour plots
3: Quit and exit from the system

Enter your option accordingly >>>> 2
Select the desired option:

1: Generate contour values for strain rate sensitivity
2: Generate contour values for efficiency of dissipation
3: Generate contour values for \( \frac{dm}{d(\log\text{strain rate})} \)
4: Generate contour values for \( \frac{ds}{d(\log\text{strain rate})} \)
5: Generate contour values for stability maps
6: Return to main display menu
7: Quit and exit from the program

Enter your option accordingly >>>> 2

Input the name of the movie-compatible datafile into which you would like to store your generated coordinates (DEV:[UIC]NAME.EXT) >>>> CNTEFF.DAT

Do you wish to generate titles along the X and Y axes? (Y/N) >>>> N

Input the name of the datafile into which you want the function values to be written into >>>> FNEFF.DAT

Select the desired option:

1: Return to 3-D plot menu
2: Return to contour plot menu
3: Quit and exit from the program

Enter option accordingly >>>> 3

Successful execution of program
Specify whether you wish to input data interactively or read from a datafile

I : For interactive data input
D : For data input from a datafile

Enter option accordingly >>>> D

Input the name of the datafile from which the data is to be read >>>> ALL5SI

Do you wish to check your input values before proceeding with the computation? (Y/N) >>>> N

Specify whether the temperature units are in degrees Kelvin or degrees Fahrenheit

K : For temperature in degrees Kelvin
F : For temperature in degrees Fahrenheit

Enter option accordingly >>>> K

Do you want an output of the curve fit coefficients? (Y/N) >>>> Y

Do you want coefficient values displayed on the terminal or output to a datafile?
T : For display on the terminal
D : For output to a datafile

Enter option accordingly >>>> T
<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0.27715E-02</td>
<td>0.51901E-01</td>
<td>0.23182E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.65337E-02</td>
<td>0.53800E-01</td>
<td>0.23241E+01</td>
</tr>
</tbody>
</table>

Temperature = 350.0 degrees Kelvin

Log(stress) = A * Log(strain rate)**2 + B * Log(strain rate) + C

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0.22990E-02</td>
<td>0.53120E-01</td>
<td>0.22985E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.43841E-02</td>
<td>0.54484E-01</td>
<td>0.23027E+01</td>
</tr>
</tbody>
</table>

Temperature = 400.0 degrees Kelvin

Log(stress) = A * Log(strain rate)**2 + B * Log(strain rate) + C

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.46584E-03</td>
<td>0.55788E-01</td>
<td>0.22722E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.50900E-03</td>
<td>0.55797E-01</td>
<td>0.22722E+01</td>
</tr>
</tbody>
</table>

Temperature = 450.0 degrees Kelvin
Temperature = 500.0 degrees Kelvin

\[
\log(\text{stress}) = A \cdot \log(\text{strain rate})^2 + B \cdot \log(\text{strain rate}) + C
\]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>0.44781E-02</td>
<td>0.75196E-01</td>
<td>0.22117E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.97585E-03</td>
<td>0.76309E-01</td>
<td>0.22152E+01</td>
</tr>
</tbody>
</table>

Temperature = 550.0 degrees Kelvin

\[
\log(\text{stress}) = A \cdot \log(\text{strain rate})^2 + B \cdot \log(\text{strain rate}) + C
\]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.98488E-02</td>
<td>0.10009E+00</td>
<td>0.21436E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.10679E-02</td>
<td>0.98294E-01</td>
<td>0.21374E+01</td>
</tr>
</tbody>
</table>

Temperature = 600.0 degrees Kelvin

\[
\log(\text{stress}) = A \cdot \log(\text{strain rate})^2 + B \cdot \log(\text{strain rate}) + C
\]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.27340E-01</td>
<td>0.11550E+00</td>
<td>0.20386E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>0.94515E-02</td>
<td>0.10799E+00</td>
<td>0.20153E+01</td>
</tr>
</tbody>
</table>
Temperature = 650.0 degrees Kelvin

\[
\log(\text{stress}) = A \times \log(\text{strain rate})^2 + B \times \log(\text{strain rate}) + C
\]

\[
\text{POINTS : COEFFICIENT A : COEFFICIENT B : COEFFICIENT C :}
\]

\[
1-3 : -0.12664E-01 : 0.14200E+00 : 0.18689E+01
\]

\[
2-4 : 0.15812E-01 : 0.13618E+00 : 0.18509E+01
\]

Temperature = 700.0 degrees Kelvin

\[
\log(\text{stress}) = A \times \log(\text{strain rate})^2 + B \times \log(\text{strain rate}) + C
\]

\[
\text{POINTS : COEFFICIENT A : COEFFICIENT B : COEFFICIENT C :}
\]

\[
1-3 : -0.13598E-01 : 0.15448E+00 : 0.17167E+01
\]

\[
2-4 : 0.17445E-01 : 0.14814E+00 : 0.16971E+01
\]

Temperature = 750.0 degrees Kelvin

\[
\log(\text{stress}) = A \times \log(\text{strain rate})^2 + B \times \log(\text{strain rate}) + C
\]

\[
\text{POINTS : COEFFICIENT A : COEFFICIENT B : COEFFICIENT C :}
\]

\[
1-3 : -0.16780E-01 : 0.16689E+00 : 0.15872E+01
\]

\[
2-4 : 0.12288E-01 : 0.16095E+00 : 0.15689E+01
\]
Temperature = 800.0 degrees Kelvin

\[ \log(\text{stress}) = A \cdot \log(\text{strain rate})^2 + B \cdot \log(\text{strain rate}) + C \]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT A</th>
<th>COEFFICIENT B</th>
<th>COEFFICIENT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.62329E-02</td>
<td>0.18917E+00</td>
<td>0.13394E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>0.58577E-02</td>
<td>0.18671E+00</td>
<td>0.13318E+01</td>
</tr>
</tbody>
</table>

Strain rate = 0.20000E-01

\[ \log(\text{stress}) = D \cdot (1.0/\text{Temperature})^2 + E \cdot (1.0/\text{Temperature}) + F \]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.71735E+05</td>
<td>0.49282E+03</td>
<td>0.13924E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.27006E+06</td>
<td>0.15981E+04</td>
<td>-0.81301E-01</td>
</tr>
<tr>
<td>3-5</td>
<td>-0.80175E+06</td>
<td>0.40711E+04</td>
<td>-0.29906E+01</td>
</tr>
<tr>
<td>4-6</td>
<td>-0.76966E+06</td>
<td>0.39242E+04</td>
<td>-0.28360E+01</td>
</tr>
<tr>
<td>5-7</td>
<td>-0.42537E+06</td>
<td>0.26201E+04</td>
<td>-0.15942E+01</td>
</tr>
<tr>
<td>6-8</td>
<td>-0.84334E+06</td>
<td>0.40764E+04</td>
<td>-0.28605E+01</td>
</tr>
<tr>
<td>7-9</td>
<td>-0.33507E+06</td>
<td>0.24474E+04</td>
<td>-0.15572E+01</td>
</tr>
<tr>
<td>8-10</td>
<td>-0.14956E+06</td>
<td>0.18970E+04</td>
<td>-0.11494E+01</td>
</tr>
<tr>
<td>9-11</td>
<td>0.65308E+06</td>
<td>-0.31994E+03</td>
<td>0.37925E+00</td>
</tr>
</tbody>
</table>
Strain rate = 0.50238E-01

\[ \text{Log(stress)} = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F \]
Strain rate = 0.79621E-01

Log(stress) = D \times (1.0/Temperature)^2 + E \times (1.0/Temperature) + F

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.54603E+05</td>
<td>0.38356E+03</td>
<td>0.15927E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.28662E+06</td>
<td>0.16265E+04</td>
<td>0.64539E-01</td>
</tr>
<tr>
<td>3-5</td>
<td>-0.47497E+06</td>
<td>0.25159E+04</td>
<td>0.11106E+01</td>
</tr>
<tr>
<td>4-6</td>
<td>-0.67561E+06</td>
<td>0.33630E+04</td>
<td>0.20026E+01</td>
</tr>
<tr>
<td>5-7</td>
<td>-0.12354E+07</td>
<td>0.55007E+04</td>
<td>0.40385E+01</td>
</tr>
<tr>
<td>6-8</td>
<td>-0.38465E+06</td>
<td>0.25355E+04</td>
<td>0.14600E+01</td>
</tr>
<tr>
<td>7-9</td>
<td>-0.14306E+06</td>
<td>0.17614E+04</td>
<td>0.84083E+00</td>
</tr>
<tr>
<td>8-10</td>
<td>-0.72900E+06</td>
<td>0.35000E+04</td>
<td>0.21286E+01</td>
</tr>
<tr>
<td>9-11</td>
<td>0.39184E+06</td>
<td>0.40419E+03</td>
<td>0.62469E-02</td>
</tr>
</tbody>
</table>
Strain rate = $0.12619E+00$

Log(stress) = $D \times (1.0/Temperature)^2 + E \times (1.0/Temperature) + F$

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>$-0.50192E+05$</td>
<td>$0.35533E+03$</td>
<td>$0.16471E+01$</td>
</tr>
<tr>
<td>2-4</td>
<td>$-0.28304E+06$</td>
<td>$0.16027E+04$</td>
<td>$-0.16131E-01$</td>
</tr>
<tr>
<td>3-5</td>
<td>$-0.39236E+06$</td>
<td>$0.21189E+04$</td>
<td>$-0.62340E+00$</td>
</tr>
<tr>
<td>4-6</td>
<td>$-0.65771E+06$</td>
<td>$0.32393E+04$</td>
<td>$-0.18028E+01$</td>
</tr>
<tr>
<td>5-7</td>
<td>$-0.14128E+07$</td>
<td>$0.61224E+04$</td>
<td>$-0.45485E+01$</td>
</tr>
<tr>
<td>6-8</td>
<td>$-0.29130E+06$</td>
<td>$0.22140E+04$</td>
<td>$-0.11499E+01$</td>
</tr>
<tr>
<td>7-9</td>
<td>$-0.93566E+05$</td>
<td>$0.15005E+04$</td>
<td>$-0.64322E+00$</td>
</tr>
<tr>
<td>8-10</td>
<td>$-0.86789E+06$</td>
<td>$0.38779E+04$</td>
<td>$-0.23449E+01$</td>
</tr>
<tr>
<td>9-11</td>
<td>$0.34013E+06$</td>
<td>$0.54113E+03$</td>
<td>$-0.43787E-01$</td>
</tr>
</tbody>
</table>

Strain rate = $0.20000E+00$

Log(stress) = $D \times (1.0/Temperature)^2 + E \times (1.0/Temperature) + F$

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>$-0.46426E+05$</td>
<td>$0.33118E+03$</td>
<td>$0.16952E+01$</td>
</tr>
<tr>
<td>2-4</td>
<td>$-0.27625E+06$</td>
<td>$0.15623E+04$</td>
<td>$0.53759E-01$</td>
</tr>
</tbody>
</table>
Strain rate = 0.41826E+00

\[
\text{Log(stress)} = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F
\]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.44969E+05</td>
<td>0.32211E+03</td>
<td>0.17268E+01</td>
</tr>
<tr>
<td>2-4</td>
<td>-0.24633E+06</td>
<td>0.14008E+04</td>
<td>0.28854E+00</td>
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<tr>
<td>3-5</td>
<td>-0.27341E+06</td>
<td>0.15287E+04</td>
<td>0.13808E+00</td>
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<tr>
<td>4-6</td>
<td>-0.68634E+06</td>
<td>0.32722E+04</td>
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<tr>
<td>5-7</td>
<td>-0.15284E+07</td>
<td>0.64875E+04</td>
<td>-0.47595E+01</td>
</tr>
<tr>
<td>6-8</td>
<td>-0.24303E+06</td>
<td>0.20078E+04</td>
<td>-0.86405E+00</td>
</tr>
<tr>
<td>7-9</td>
<td>0.33696E+05</td>
<td>0.11212E+04</td>
<td>-0.15476E+00</td>
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<tr>
<td>8-10</td>
<td>-0.10512E+07</td>
<td>0.43403E+04</td>
<td>-0.25392E+01</td>
</tr>
</tbody>
</table>
Strain rate $= 0.87469\times 10^0$

Log(stress) = $D \times (1.0/Temperature)^2 + E \times (1.0/Temperature) + F$

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.43560E+05</td>
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<td>0.39340E+00</td>
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<td>-0.17368E+01</td>
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<tr>
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<td>-0.44229E+01</td>
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<tr>
<td>6-8</td>
<td>-0.30714E+06</td>
<td>0.21834E+04</td>
<td>-0.93420E+00</td>
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<td>7-9</td>
<td>0.83670E+05</td>
<td>0.93067E+03</td>
<td>0.68226E-01</td>
</tr>
<tr>
<td>8-10</td>
<td>-0.10787E+07</td>
<td>0.43795E+04</td>
<td>-0.24864E+01</td>
</tr>
<tr>
<td>9-11</td>
<td>0.41361E+06</td>
<td>0.25754E+03</td>
<td>0.35620E+00</td>
</tr>
</tbody>
</table>

Strain rate $= 0.18292E+01$

Log(stress) = $D \times (1.0/Temperature)^2 + E \times (1.0/Temperature) + F$

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
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</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.42202E+05</td>
<td>0.30363E+03</td>
<td>0.17910E+01</td>
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</table>
Strain rate = 0.38254E+01

\[ \log(\text{stress}) = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F \]

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
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<tr>
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<td>0.35160E+04</td>
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<td>-0.31816E+01</td>
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<tr>
<td>6- 8</td>
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<td>0.30035E+04</td>
<td>-0.14467E+01</td>
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<tr>
<td>7- 9</td>
<td>0.78577E+05</td>
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<td>8- 10</td>
<td>-0.10011E+07</td>
<td>0.40883E+04</td>
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</table>
Strain rate = 0.80000E+01

Log(stress) = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
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<tr>
<td>3-5</td>
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<td>0.12815E+04</td>
<td>0.62916E+00</td>
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<tr>
<td>4-6</td>
<td>-0.77984E+06</td>
<td>0.35536E+04</td>
<td>-0.17625E+01</td>
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<tr>
<td>5-7</td>
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<td>7-9</td>
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<td>9-11</td>
<td>0.67376E+06</td>
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<td>0.11746E+01</td>
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</tbody>
</table>

Strain rate = 0.15229E+02

Log(stress) = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-0.34454E+05</td>
<td>0.25025E+03</td>
<td>0.19273E+01</td>
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</tbody>
</table>
### Strain Rate

\[ \text{Strain rate} = 0.28931 \times 10^2 \]

### Log(stress) equation

\[ \log(\text{stress}) = D \times (\frac{1}{\text{Temperature}})^2 + E \times (\frac{1}{\text{Temperature}}) + F \]

#### Points

<table>
<thead>
<tr>
<th>Points</th>
<th>Coefficient D</th>
<th>Coefficient E</th>
<th>Coefficient F</th>
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<td>3-5</td>
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<td>0.10942E+04</td>
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<td>-0.10323E+01</td>
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<tr>
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<td>-0.25076E+01</td>
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<tr>
<td>7-9</td>
<td>-0.25340E+06</td>
<td>0.18480E+04</td>
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Strain rate = 0.55189E+02

Log(stress) = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F

<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
</tr>
</thead>
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<tr>
<td>3-5</td>
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<td>0.10853E+01</td>
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<tr>
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<tr>
<td>5-7</td>
<td>-0.69272E+06</td>
<td>0.30479E+04</td>
<td>-0.10195E+01</td>
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<tr>
<td>6-8</td>
<td>-0.13037E+07</td>
<td>0.51768E+04</td>
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<tr>
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<td>-0.68310E+00</td>
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<tr>
<td>8-10</td>
<td>-0.66584E+06</td>
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<td>-0.11564E+01</td>
</tr>
<tr>
<td>9-11</td>
<td>0.67616E+06</td>
<td>-0.62507E+03</td>
<td>0.13993E+01</td>
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</table>

Strain rate = 0.10506E+03

Log(stress) = D \times (1.0/\text{Temperature})^2 + E \times (1.0/\text{Temperature}) + F
<table>
<thead>
<tr>
<th>POINTS</th>
<th>COEFFICIENT D</th>
<th>COEFFICIENT E</th>
<th>COEFFICIENT F</th>
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<tbody>
<tr>
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<td>0.20673E+01</td>
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<tr>
<td>3- 5</td>
<td>-0.16024E+06</td>
<td>0.80108E+03</td>
<td>0.13968E+01</td>
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<tr>
<td>4- 6</td>
<td>-0.29169E+06</td>
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<td>-0.22724E+00</td>
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<td>6- 8</td>
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<td>0.64479E+04</td>
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</tr>
<tr>
<td>7- 9</td>
<td>-0.96236E+06</td>
<td>0.40021E+04</td>
<td>-0.17490E+01</td>
</tr>
</tbody>
</table>

Strain rate = 0.20000E+03

\[
\text{Log(stress)} = D \times (1.0/\text{Temperature})^{2} + E \times (1.0/\text{Temperature}) + F
\]
\begin{verbatim}
Select the desired option:

1 : Obtain 3-D surface plots
2 : Obtain contour plots
3 : Quit and exit from the system

Enter your option accordingly >>>> 1

Select the desired option:

1 : Generate display file for flow stress values
2 : Generate display file for strain rate sensitivity
3 : Generate display file for efficiency values
4 : Return to main display menu
5 : Quit and exit from the program

Enter your option accordingly >>>> 3

Input the name of the movie-compatible datafile into which you would like to store your generated coordinates (DEV:\[UIC\]NAME.EXT) >>>> EFFIC.DAT

Do you wish to generate titles along the X, Y and Z axes ? (Y/N) >>>> N

Select the desired option:

1 : Return to 3-D plot menu
2 : Return to contour plot menu
3 : Quit and exit from the program

Enter option accordingly >>>> 3

Successful execution of program
\end{verbatim}
APPENDIX D

SAMPLE INPUT DATA FILE
TYPE ALLSSI.DAT
ALSSI
4, 11
300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800
173, 192, 233, 259
0. 02, 0. 2, 8, 200
164, 183, 223, 254
0. 02, 0. 2, 8, 200
150, 171, 210, 250
0. 02, 0. 2, 8, 200
125, 145, 192, 243
0. 02, 0. 2, 8, 200
88, 117, 168, 228
0. 02, 0. 2, 8, 200
58, 88, 132, 206
0. 02, 0. 2, 8, 200
39, 58, 97, 177
0. 02, 0. 2, 8, 200
26, 40, 70, 135
0. 02, 0. 2, 8, 200
18, 29, 53, 101
0. 02, 0. 2, 8, 200
13, 21, 40, 77
0. 02, 0. 2, 8, 200
10, 16, 32, 62
0. 02, 0. 2, 8, 200
$
APPENDIX E

SAMPLE RUN USING MOVIE.BYU FOR SURFACE PLOTS
RUN COMMAND

<MOVIE SYSTEM DISPLAY>
<READ GEOM FILE> EFFIC.DAT
<READ: 4 PARTS; 641 COORDINATES; 554 ELEMENTS.>
<READ DISP FILE>
<READ FUNC FILE>
<PREVIOUS RANGE:>
< -1.699 <X> 3.634 0.628 <Y> 5.961 2.400 <Z> 6.800>
<ORIGIN MOVED TO: 0.968 3.295 4.600>
<DISTANCE TO ORIGIN: 18.67, ANGLE: 28.00, ZMIN: 0.10, ZMAX: 37.33>
<4 PARTS WITH ELEMENT LIMITS:>
  1 450 451 466 467 510 511 554

>> ROTATE
<AXIS, ANGLE> Y, -45
>> ROTATE
<AXIS, ANGLE> X, 30
>> VIEW
APPENDIX F

SAMPLE RUN USING MOVIE.BYU FOR CONTOUR PLOTS
RUN COMMAND
<MOVIE SYSTEM DISPLAY>
<READ GEOM FILE> CNTEFF.DAT
<READ: 1 PARTS; 496 COORDINATES; 450 ELEMENTS.>
<READ DISP FILE>
<READ FUNC FILE> FNEFF.DAT
<PREVIOUS RANGE:>
<  2.400 <X<  6.400  -1.699 <Y<  2.301  0.000 <Z<  0.000>
<  4.96212E+00 <SCALAR FUNCTION<  3.65719E+01>
<ORIGIN MOVED TO:  4.400  0.301  0.000>
<DISTANCE TO ORIGIN:  14.00 , ANGLE:  28.00 , ZMIN:  0.10 , ZMAX:  28.00>
< 1 PARTS WITH ELEMENT LIMITS:>
  1 450

>> FAST
<MIXED DATA?>
<POOR MAN'S PROCEDURE?> Y
<PARTS I1/I2 IMMUNE TO POOR MAN'S PROCEDURE>
  >>> 1
  >>>
<PARTS I1/I2 WITH CLOCKWISE ORDERING>
  >>>
  >> FEATURE
<FEATURE ANGLE ( 0.00)> 1
  >> CONTOUR
<NUMBER OF CONTOURS, LABEL SPACING> 21, 6
<RANGE (X1, X2)> 0, 40
  >> VIEW