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A holistic approach to thermomechanical processing of alloys

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Abstract. New process design and control methods are needed for significantly improving productivity and reducing costs of thermomechanical processes such as hot metal forging. Current practices for accomplishing basic design tasks such as selecting the number of forming steps and specifying the processing conditions for each thermomechanical operation produce feasible solutions that are often far from optimal. Substantial improvements in effectiveness and efficiency can be realized through holistic approaches that optimize the whole system performance and not just individual subsystems such as workpiece material behavior, material flow in dies, and equipment responses. Recent progress in the application of dynamical modelling and process design techniques using ideal forming concepts and trajectory optimization are discussed. Monitoring methods for the on-line monitoring of the process and an intelligent forging system has been proposed.

Keywords. Stainless steel; dynamic material modelling; intelligent forming.

1. Introduction

Manufacturers are forever striving to reduce the cost of production and raw materials (Stallkamp 2001; Seybold 2001). Price slashing is becoming so dominant that quality is often sacrificed for other considerations. In order to deal with quality issues, industries need to use more effective design practices and adopt upstream design processes that enable them to deliver customized services and products at relatively lower cost. Historically, the design of metal-forming processes is based on expensive trial and error techniques. The geometry of the piece and the capability of the machine are the main considerations, while behaviour of the materials is often ignored. This trial and error method is unsuitable for the production of small batches and newer materials, which has restricted work involving forming. It is to be emphasised that our Indian industries often handle small batches and newer materials. Hence, any scientific methodology explored and employed to optimise processing parameters to produce quality products at low cost is a significant research contribution to the area of manufacturing engineering.

An optimisation procedure has been proposed by Venugopal (1981) for the selection of safe temperature zone for processing based on various technical parameters as given in figure 1a. This procedure involves establishing the relationships between various process variables and properties of billet and tool materials. The process variables are optimised using

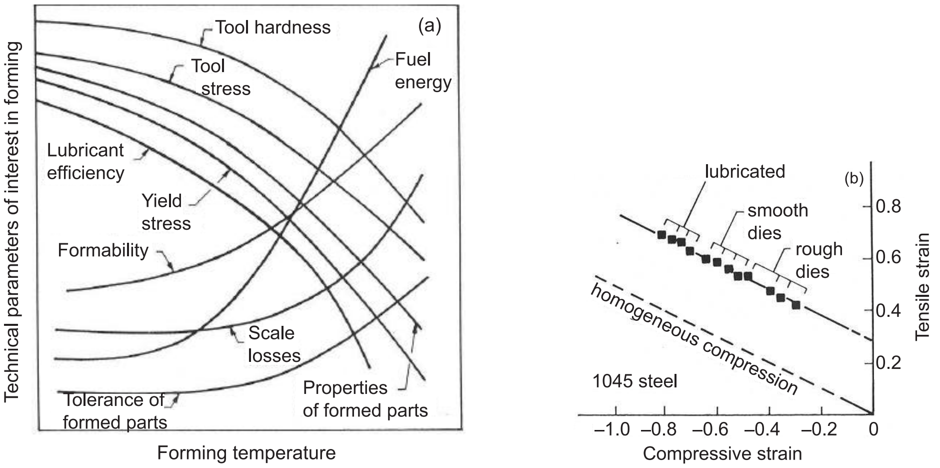

Figure 1. **(a)** Consolidated concepts involved in selecting optimal temperature in metal forming (Venugopal 1981) **(b)** Optimisation of cold workability using locus of surface strains at fracture (Khun 1973).

the above correlation. Empirical criteria and fracture models are proposed for the optimisation of workability (Khun *et al* 1973), in particular cold workability. In this approach, compression tests are performed for establishing experimental fracture criteria for bulk-forming processes. Compression test specimens are provided with small grid markings at the mid-height of the cylindrical surface. Measurements of the grid displacements at various stages of the test permit calculation of principal strains and stress histories. The test should be performed by compressing a series of identical specimens in sequence to progressively larger reductions until fracture occurs. The locus of principal surface strains at fracture gives the limit for safe working. An example is given in figure 1b for cold deformation of 1045 steel. The straight-line relationship between principal compressive and tensile surface strains at fracture is a characteristic result of the ductile fracture process, and the line can be treated as a fracture criterion representing the workability of the material. Though these methods are better than the trial and error technique, they are tedious and expensive.

Optimisation of workability requires an understanding of the constitutive behaviour of the material under processing conditions. Earlier, attempts have been made by Ashby (Frost & Ashby 1982) and Raj (1981) to understand the effects of strain, strain rate, temperature and microstructure on the flow behaviour of metals during deformation processing. They have developed maps that describe the deformation and fracture modes which occur during processing.

In the Ashby maps normalised shear stress is plotted against absolute temperature. Figure 2 gives a typical example of an Ashby Map. The maps are divided into regimes, within each of which a particular mechanism is dominant. The regime boundaries are the loci of the points at which two mechanisms contribute equally to the overall strain rate. The contours of constant strain rate are superimposed on the fields and they show the net strain rate that a given combination of stress and temperature will produce. There are other kinds of maps also with different axes like: (i) Shear strain rate and normalised shear stress with contours of temperature, (ii) axes of strain rate and temperature (or reciprocal temperature) with contours of

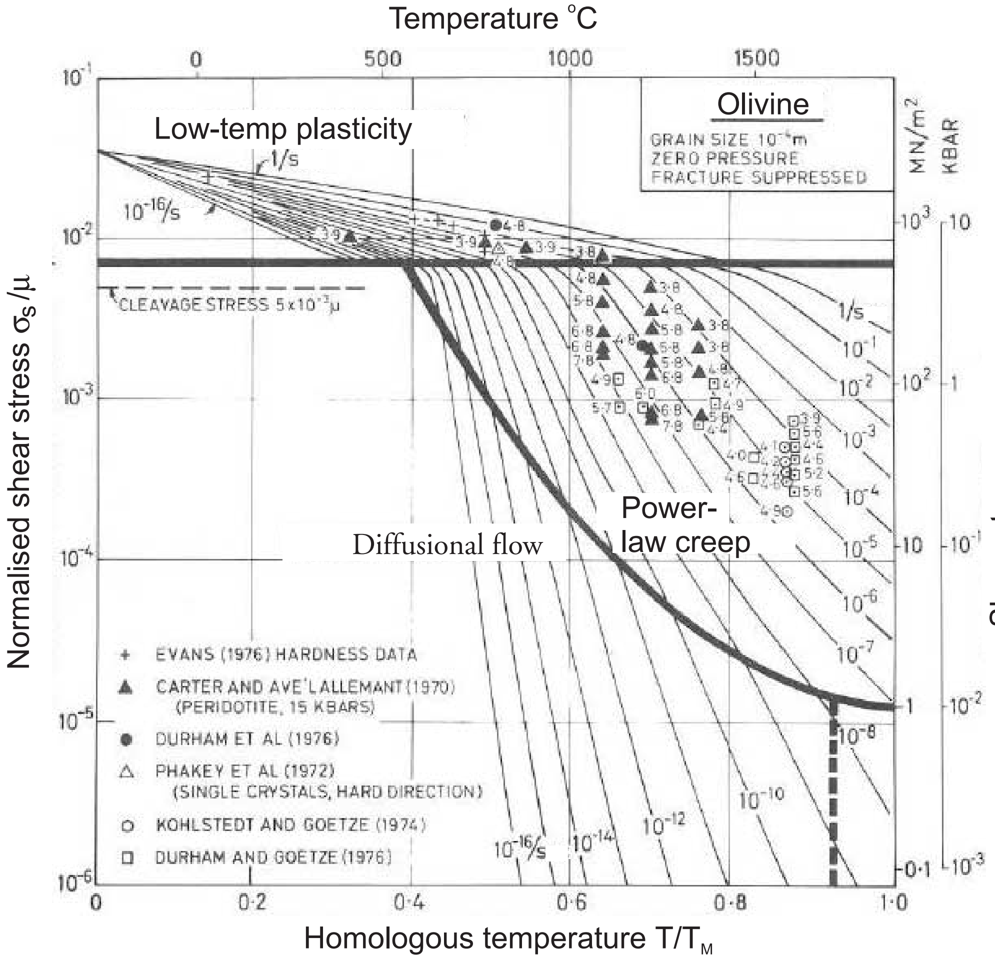

Figure 2. Typical Ashby's map (Frost & Ashby 1982).

constant stress. These maps can theoretically be constructed for any polycrystalline material, showing the area of dominance of each flow mechanism. Ashby and co-workers developed similar maps, which give domains of various fracture processes.

Raj maps are developed considering the failure mechanisms that can operate in a material over ranges of strain rate and temperature. These maps are useful for processing in the sense that they define the regions in which it is "safe" to process the workpiece material and avoid defect nucleation. Raj Map for austenitic stainless steel is shown in figure 3.

Both Ashby and Raj maps are deterministic since they use shear strain rate equations, which are valid for steady states. The equations depend on a number of basic atomic processes such as dislocation motion, diffusion, grain boundary sliding, twinning and phase transformations. Both the maps are limited to simple systems and cannot be applied to complex commercial alloys since in these materials it is not always possible to identify the atomistic mechanisms unequivocally. As the maps are based on the atomistic theory, it is difficult to integrate them with continuum approaches. Also, process optimisation is difficult to achieve, using these atomistic approaches. Though these developments have lead to the understanding of the

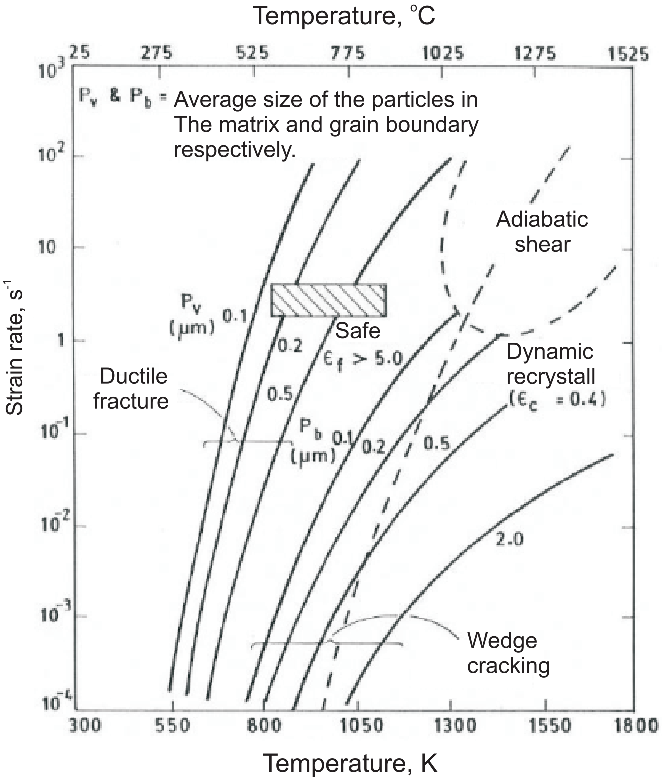

Figure 3. Typical Raj maps for austenitic stainless steel type AISI 316.

mechanisms of hot deformation, it is difficult to use them directly for the design of deformation processes. A continuum approach has been therefore developed by Prasad *et al* (1984) and is briefly described below.

1.1 *Dynamic material model*

Dynamic material model processing maps (Prasad & Seshacharyulu 1998) have shown potential for direct industrial application in arriving at optimum processing parameters. In this model, the workpiece is considered to be a dissipator of power. The constitutive equation describes the manner in which the power is converted at any instant into two forms: thermal and microstructural, which are not recoverable by the system. The dissipator element is considered to be nonlinear, dynamic and irreversible. At any instant, the total power dissipated consists of two complementary parts: G-content representing the temperature increase and J-co-content representing the dissipation occurring through microstructural processes. The power partitioning between G and J is decided by the strain rate sensitivity (m) of the flow stress (σ). At a given temperature and strain rate J co-content is given by:

$$J = [m/(m+1)]\sigma\dot{\varepsilon}, \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate. The J co-content of the workpiece, being a nonlinear dissipator, is normalised with that of an ideal dissipator ($m = 1$) to obtain a dimensionless parameter η

called the efficiency of power dissipation:

$$\eta = (J/J_{\max}) = 2m/(m+1). \tag{2}$$

The variation of η with temperature and strain rate constitutes a processing map. The various domains in the map may be correlated with specific microstructural processes and applied for microstructural control. The dynamic material model has its basis in the extremum principles of irreversible thermodynamics as applied to large plastic flow described by Ziegler (1983). According to the principle of maximum rate of entropy production, a system undergoing large plastic deformation will be unstable, if

$$\mathrm{d}D/\mathrm{d}\dot{\varepsilon} < D(\dot{\varepsilon})/\dot{\varepsilon} \tag{3}$$

where $D(\dot{\varepsilon})$ is the dissipation function characteristic of the constitutive behaviour of the workpiece. Prasad & Seshacharyulu (1998) applied the principle of separability of the rate of entropy production into the conduction entropy (heat generation) and internal entropy (microstructural changes) and considered the dissipation function corresponding to the microstructural changes (J-co-content) for deriving a criterion for instability as:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln [m/(m+1)]}{\partial \ln \dot{\varepsilon}} + m < 0. \tag{4}$$

The variation of $\xi(\dot{\varepsilon})$ with temperature and strain rate constitutes an instability map. The instability map delineates instability regions where $\xi(\dot{\varepsilon})$ is negative and these instability regions could be avoided in processing. These instability maps are superimposed on the processing maps and the safe working regions for processing (i.e., the region where the efficiency of power dissipation is high and the instability parameter is positive) are predicted. A typical processing and instability map for stainless steel type AISI 316 L is given in figure 4 (Venugopal 1993).

1.2 *Multidiscipline process design and optimisation*

Recently Malas (Malas *et al* 2001) and his co-workers have proposed a new technique namely, multidiscipline process design and optimization technique (MPDO), which drives part quality, delivery time and cost. MPDO is a technique that links tools from different environments, while providing a framework for automating, optimizing and integrating the engineering design processes (Skelton 1988; Chung & Richmond 1993, 1994; Malas & Frazier 1999), with the help of computers. In this framework, a connection exists between various interacting components of the metalworking process, which includes models for the workpiece, lubrication, tooling, metalworking equipment, inspection tools and analysis.

Each component of the manufacturing system is represented by a set of relations, called *state equations*, that describe the time evolution of internal variables and *input–output* relationships. When these state equations and input-output relationships are viewed as a whole, they provide a complete system description (Malas & Frazier 1999). This systems approach to process design, when linked to computer-aided optimization models for design and analysis, allows simplified forming models to be used, irrespective of the shape of the component (Wagoner & Chenot 2001).

Industrial process design and optimization demand consideration of data needs and how data is to be gathered? The type of material model depends on the existence of a cost-effective and efficient method for obtaining material parameters that must be measured

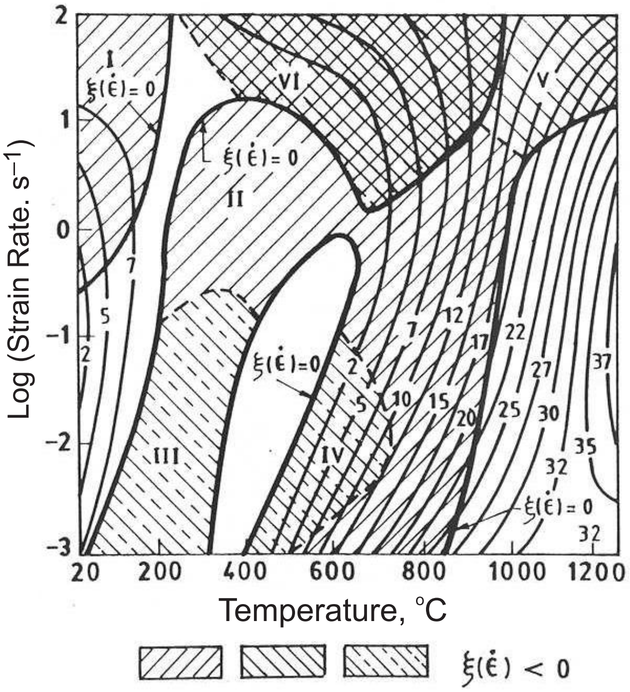

Figure 4. Typical DMM processing map for stainless steel type AISI 316L. The contours represent the values of iso-efficiency of power dissipation and the values are marked as percentages (Venugopal 1993).

(Prasad *et al* 1984; Skelton 1988; Gegel *et al* 1988; Gegel 1988; Chung & Richmond 1993; Prasad *et al* 2000). If the material information, for example, includes material parameters measured from an extensive amount of electron and optical microscopy studies done with respect to a matrix of key process parameters, a microstructure evolution model based on these parameters may not be affordable. The type of material model created for industrial process simulation depends on two issues: (1) the existence of an industrially sensible method for obtaining the needed material parameters, and (2) the danger that the parameters so measured imply nothing about the value for a slightly different prior thermomechanical history. Several reasons why material properties may be capricious (Gegel 1988) are as follows:

- Engineering alloys of similar composition can have lot-to-lot variations in properties due to their *dynamical* nature, making it also impossible to precisely describe the conditions needed for the material model. The capricious nature of some engineering alloys may affect the value of the measured parameters, and, in turn, influence the end state of the workpiece. Every engineering alloy system possesses multiple mechanisms for providing the degrees of freedom needed for dissipating energy while undergoing forced dissipative flow during deformation processing. Some of the dissipation mechanisms include the following: lamellar kinking, adiabatic shearing, grain boundary cracking, dynamic grain growth, grain boundary diffusion, dynamic recrystallization and dynamic recovery (Prasad 2000; Cebron & Ashby 2000; Malas 1985; Venugopal 1993; Tamirisakandala *et al* 2000). These mechanisms may operate either in series or in parallel and at unpredictable times. Thus, the stochastic nature of an engineering alloy can produce erratic results, especially when material stability is path dependent.

- Processing predominantly in a region of material stability can reduce the sensitivity of an alloy to stochastic events. A stable processing space is a region defined by temperature, effective strain-rate and time, where the desired microstructures and associated properties evolve in a stable fashion regardless of the state of stress. In contrast, instability is defined as any set of conditions during processing that cause plastic instabilities as flow localization, fracture, grain boundary cavitations, dynamic grain growth, etc., to occur. The occurrences of these defects are strongly *material path* or *trajectory* (Malas & Frazier 1999) dependent when processing occurs outside the limits for stable material flow.

The concept of material stability is akin to the idea of workability (*trajectory*) (Malas & Frazier 1999; Gegel *et al* 1988), and it can be expressed in terms of key process parameters, temperature and effective strain-rate ranges as a function of time, where microstructures and mechanical properties evolve without forming deleterious structures regardless of the state of stress. Also, the variations of material parameters that evolve under stable conditions are minimal, and the process is robust. These ranges, where plastic and structural instabilities are absent, can be incorporated easily in the simulation model as nonholonomic constraints (Gegel 1988). These stability limits are the constraints needed for designing preform and other intermediate product shapes, which are required for optimizing metalworking processes used to produce components with complex shapes.

A strategy for systematically calculating near optimal control parameters for hot deformation processes is presented. The objective is to show a system design approach that holds promise for substantially reducing manufacturing cost, risk and delivery time to a customer, while resulting in an improved product that satisfies customer requirements and expectations. Critical issues such as efficient material flow and the sensitivity of the variation of finished part properties to small changes in key process parameters will be addressed using lumped-parameter models of microstructure evolution and optimization techniques for controlling microstructure during thermomechanical processing.

2. Optimal process design

Figure 5 describes the steps involved in the new methodology, namely two stage approach proposed by Venugopal *et al* (1997). The microstructure development optimisation determines

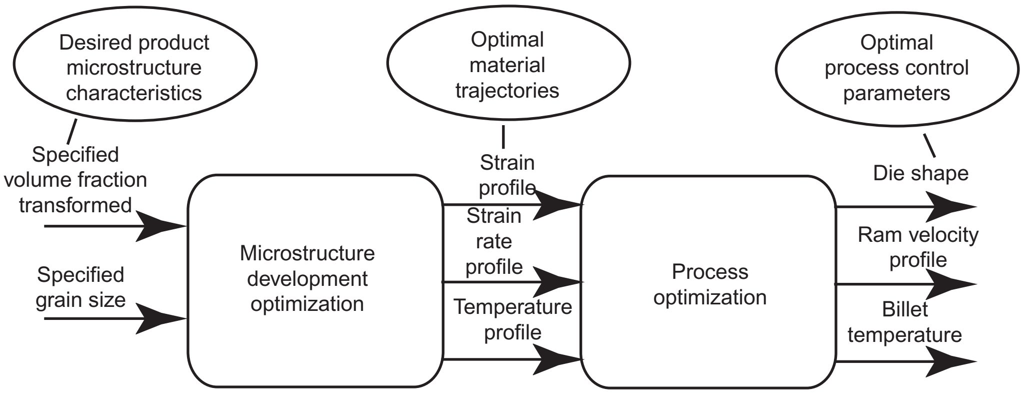

Figure 5. A schematic of the two-stage approach (Venugopal *et al* 1997).

optimal trajectories of strain, strain rate, and temperature. From these optimal trajectories, the process optimisation stage determines optimal process control parameters, namely the die shape, the ram velocity profile and billet temperature. Goals of the first stage are to achieve enhanced workability and prescribed microstructural parameters. In the second stage, a primary goal is to achieve the thermo-mechanical conditions obtained from stage one for predetermined regions of the deforming workpiece.

In the first stage, material behaviour models that describe the kinetics of primary metallurgical mechanisms such as dynamic recovery, dynamic recrystallisation, and grain growth during hot working are required for analysis and optimisation of material system dynamics. These mechanisms have been studied extensively, and relationships for describing particular microstructural processes have been developed for a variety of materials. Constraints may be in the form of acceptable ranges of temperature and strain rate over which the materials exhibit "safe" processing window. The "safe" processing window may be identified using any of the proven methodologies.

2.1 *Thermomechanical processing systems*

A metalworking manufacturing enterprise for the purpose of this discussion consists of a sequence of thermomechanical processing steps to produce a component. Each unit process, such as forging, heat treatment, material removal and nondestructive evaluation (NDE), can be decomposed into sub-subsystems, i.e., the workpiece material, tooling, equipment, control system etc., which can be decomposed further. A typical block diagram for a hot forging equipment system is shown in figure 6.

Manufacturing processes can be mathematically modeled as nonlinear dynamical systems using a state-variable formulation, i.e. a system of coupled, first-order nonlinear differential equations. Symbolically this is often written in the form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{5}$$

where **x** and **u** are vectors of the system's state and control variables respectively. The function **f** defines the relationship among the current state of the system, the current control variables, and the rate of change of the state. The important point concerning dynamical models is that they are valid for a broad range of control signals, unlike algebraic models, which are only valid for a particular class of process controls, such as constant temperature and strain-rate.

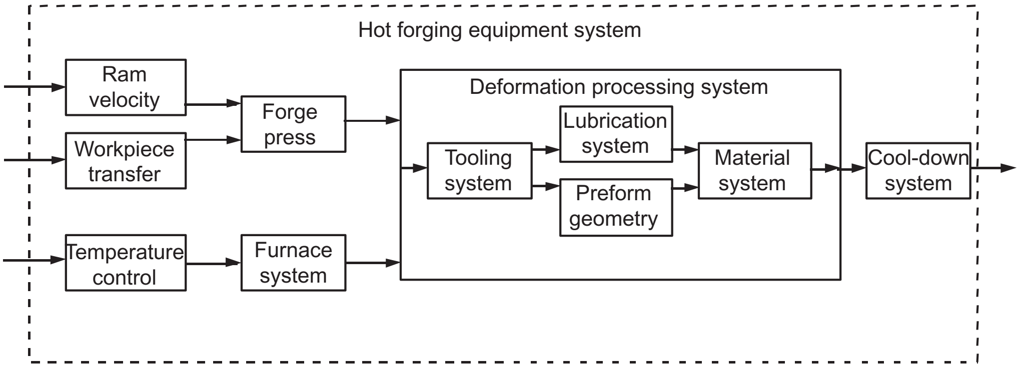

Figure 6. Block diagram of a metal forging system (Gegel *et al* 2001).

The use of dynamical models provides greater predictive capability over algebraic models and more degrees of freedom in the time domain for optimal process design.

Dynamical models of material behaviour are especially important because of the time-varying behavior of quantities such as microstructure, flow stress, and defect formation. Figure 7 illustrates how the microstructure and flow stress of a γ-TiAl alloy responds to different transient processing conditions (Gegel *et al* 2001). In this example, the material responses under constant strain rate conditions versus increasing step-changes in strain-rate are compared. Because several different processing histories (trajectories) can lead to nearly the same end result, it is important to be able to find the best trajectory to realize the desired objectives. Consequently, models and design techniques for controlling microstructure during thermomechanical processing have been developed to address critical issues such as stability, transient and steady state response, and robustness of *material trajectories*.

Considerable attention is paid to material stability criteria, constitutive laws, and physical insight about the materials processes for modelling. Stability analysis tools such as the

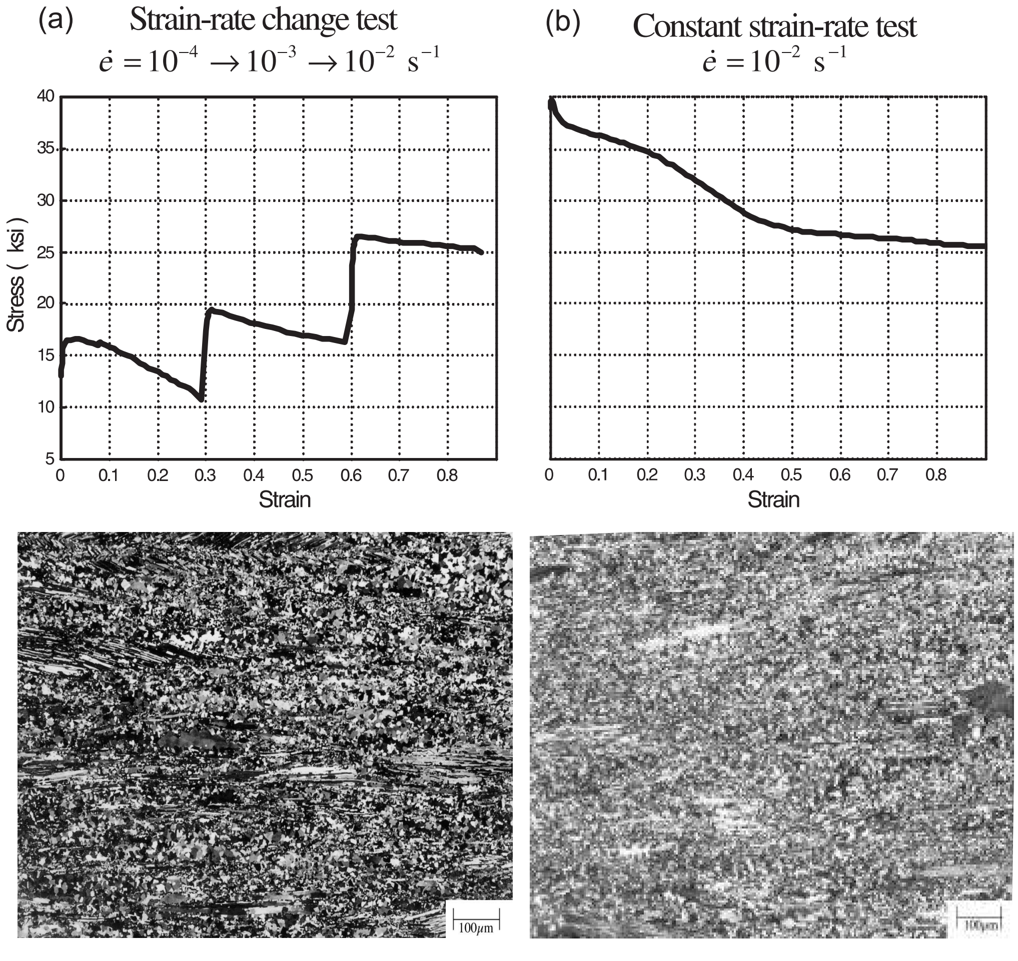

Figure 7. Illustration of dynamic effects in microstructure evolution: Final average grain size **(a)** 10 μm and **(b)** 8 μm (Gegel *et al* 2001).

dynamic material model (DMM) (Prasad *et al* 1984; Gegel 1988; Gegel *et al* 1988; Malas & Seetharaman 1992; Prasad *et al* 2000) are used to efficiently identify desirable processing regimes in temperature, effective strain-rate and time space. Malas (1991) and Venugopal & Mannan (1998) suggested that the following dynamic material model (DMM) stability criteria can be used to identify the stable regime for 'safe' processing of the materials.

$$0 < m \leq 1, \tag{6}$$

$$\dot{m} < 0, \tag{7}$$

$$s \geq 1, \tag{8}$$

$$\dot{s} < 0, \tag{9}$$

where $m = \partial\sigma/\partial \ln \dot{\varepsilon}, \dot{m} = \partial m/\partial \ln \dot{\varepsilon}, s = \partial \log \sigma/\partial [1/T], \dot{s} = \partial s/\partial \log \dot{\varepsilon}, \sigma =$ flow stress, $T =$ temperature and $\dot{\varepsilon} =$ strain rate.
The apparent activation energy,

$$Q = sRT/m, \tag{10}$$

where $R =$ gas constant, should be constant in the stable region. In this method, the reasonable "safe" processing range corresponds to the processing condition where a desirable and fairly constant value of activation energy is operative. The variation of above stability parameters in the strain rate and temperature space constitutes the DMM stability map.

Process design windows are easily identified using the DMM map, which can have contours of activation energy, power dissipation and strain-rate sensitivity superimposed on the stability limits to guide in the selection of a suitable process design window. Other empirical information such as dissipative microstructures can be superimposed on the map to aid in selecting the appropriate stability region. All differential equations contain parameters whose values must be determined prior to solving the equations such as boundary conditions and material behavior. Since these parameters are the source of all nonlinearly in the model, how the modelling team chooses to deal with these parameters can profoundly influence material process model development and its use in design and optimization. Figure 8 is a stability map for 316L stainless steel (Gegel 2001), and a stability map with apparent activation energy contours for 316L stainless steel is shown in figure 9 (Venugopal & Mannan 1998).

A process design window is shown that encompasses a stable region where the activation energy is relatively low with respect to an unstable region frequently characterized by apparent activation energy about one order of magnitude larger than the stable region, which is designated as the process design window for this particular case. This processing window defines the process variable constraints needed for precise microstructure control and reduced sensitivity to process parameter, P, variation. Using this processing window, the variations of measured grain size for several processing temperatures within and outside the process design window are shown. The variation in grain size inside the design window is minimal and practically constant, but large grain size variations are seen when the material is processed outside the constraints for material process stability. *Thus, within these desirable design windows, dynamical state variable models of microstructure evolution can be developed and used to identify precise material trajectories for achieving a wanted microstructure* (Malas *et al* 1997).

The stable dynamical regions in this map are represented by the + symbol. These stability regions have relative low values for the apparent activation as was shown for the case in figure 9. These regions, where the activation energy is relatively low, are the locations where the

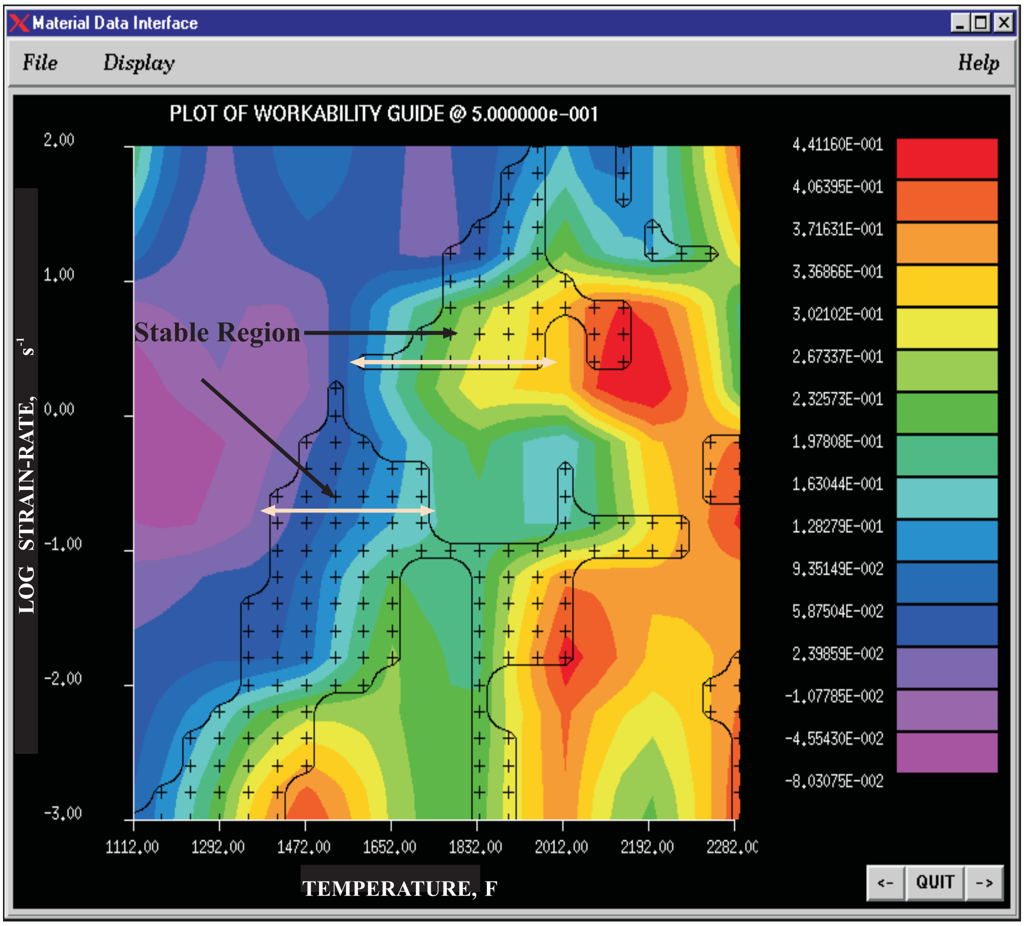

Figure 8. DMM stability map for 316L stainless steel. The colour shade indicates the values of the parameter m (Gegel *et al* 2001).

rate of free energy reduction for the material system is relatively fast. Two stability parameters for function arguments that correspond to mechanical and structural dynamic stability were used to construct the DMM stability map, and they were the strain-rate sensitivity parameter and the rate of generation of entropy parameter respectively. The ratio of these two parameters, $(s/m) = Q/RT$, will give the activation energy Q (Venugopal & Mannan 1998). In this ratio, s is the entropy production rate parameter (microstructure stability argument), m is the strain-rate sensitivity parameter (mechanical stability argument), R is the universal gas constant, and T is the absolute temperature. These parameters are readily assessable from the constitutive equation data needed for process modelling whether the analysis is a lumped parameter or a full FEM model. The stability map boundaries are the loci of all singularities, which can include first-order phase transformations, dynamic grain growth, shear band formations, fracture mechanisms, etc. When the workpiece material is processed in one of the stable regions, it will flow in a stable fashion regardless of the state of stress. Therefore, the idea of workability should contain the concept of material stability (Gegel *et al* 1988; Prasad *et al* 1984; Gegel 1988).

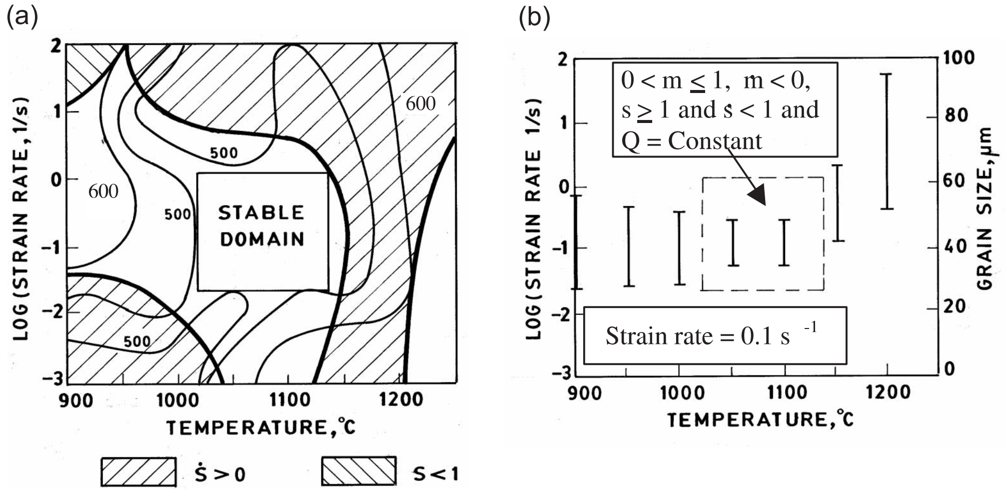

Figure 9. DMM stability map with design window and measured grain size showing the effect of hot working 316L within the design window (Venugopal & Mannan 1998).

A microstructure and a set of mechanical properties will evolve continuously in the material stability regions and possess a unique set of properties. Consistency of material properties arises because the workpiece's dissipation mechanisms are operating in an extremum condition, where the activation energy is a minimum and the rate of energy dissipation is maximum (Malas 1991). Under this set of conditions, the time, temperature and deformation path is insensitive to external perturbations in the key process parameters. To illustrate the robustness of the material process, Figure 10 shows the grain size variance of 316L stainless steel after it has been deformed at different temperatures and at a constant strain-rate within the temperature range for material stability.

The tensile strength for 316L Stainless forged at a strain-rate of $0{\cdot}15\,\mathrm{s}^{-1}$ is presented in figure 11, and it exhibits little variance change as a function of the forging temperature within the stable region, i.e., $[\partial P/\partial T]_{\dot{\varepsilon}} \cong 0$, where P is the tensile strength in this case. For most engineering alloys, consistent properties can be obtained by designing admissible preform shapes such that the workpiece material will remain within an appropriate material stability domain during processing.

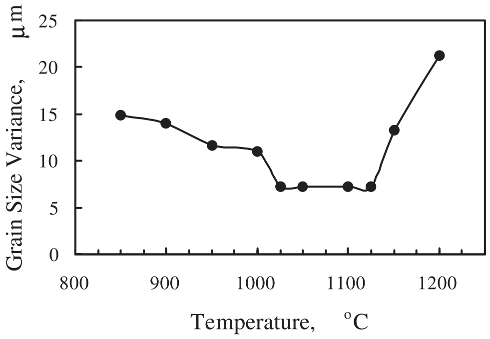

Figure 10. Grain size variance in stainless steel 316L as a function of processing temperature at a nominal strain-rate of $0{\cdot}15\,\mathrm{s}^{-1}$.

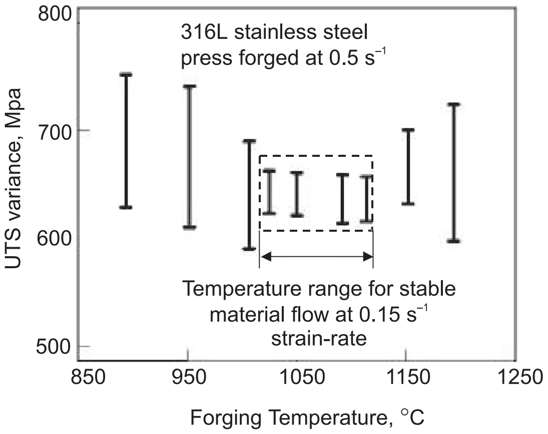

Figure 11. UTS variation for 316L stainless steel as a function of press forging temperature.

Full-scale plate rolling studies were done by the authors using 304L Stainless Steel to show these design principles (Venugopal *et al* 2000). Plates of 304L stainless steel were rolled to a reduction of about 20% in a single pass at near isothermal conditions and at two different strain-rates of 2·22 s^{-1} and 3·44 s^{-1}. The plates were immediately quenched after rolling and the grain sizes were measured as a function of the rolling temperature. The grain size of the different plate products, shown in figure 12, was practically constant when the rolling was done in the material stability region shown by the material stability map in figure 13. However, processing outside the material stability limits for the rolling temperature shows that the microstructure parameter becomes highly sensitive to changes in the key process parameters. Similar observations have been made on a wide range of other materials as P/M nickel base alloys, aluminum metal matrix alloys, and titanium base alloys (Malas 1991). These material stability phenomena are significant material characteristics, and they must be seriously considered during material process design. This concept has important economic and quality benefits when systematically incorporated in the process model as constraints. The DMM processing maps shown by figure 8 and figure 13 for 316L and 304L AISI Stainless Steel alloys, respectively, contain process design windows for robust microstructure and property control. *It is only within these key material process parameter regimes that dynamical state space*

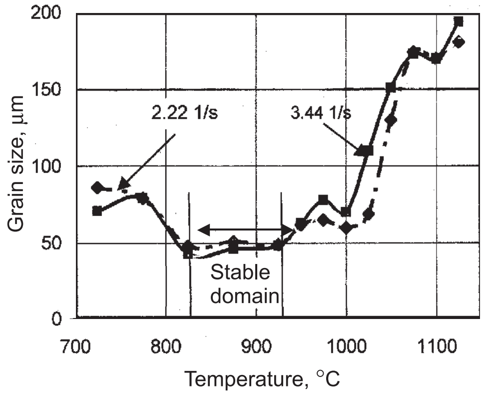

Figure 12. Grain size for 304 stainless steel.

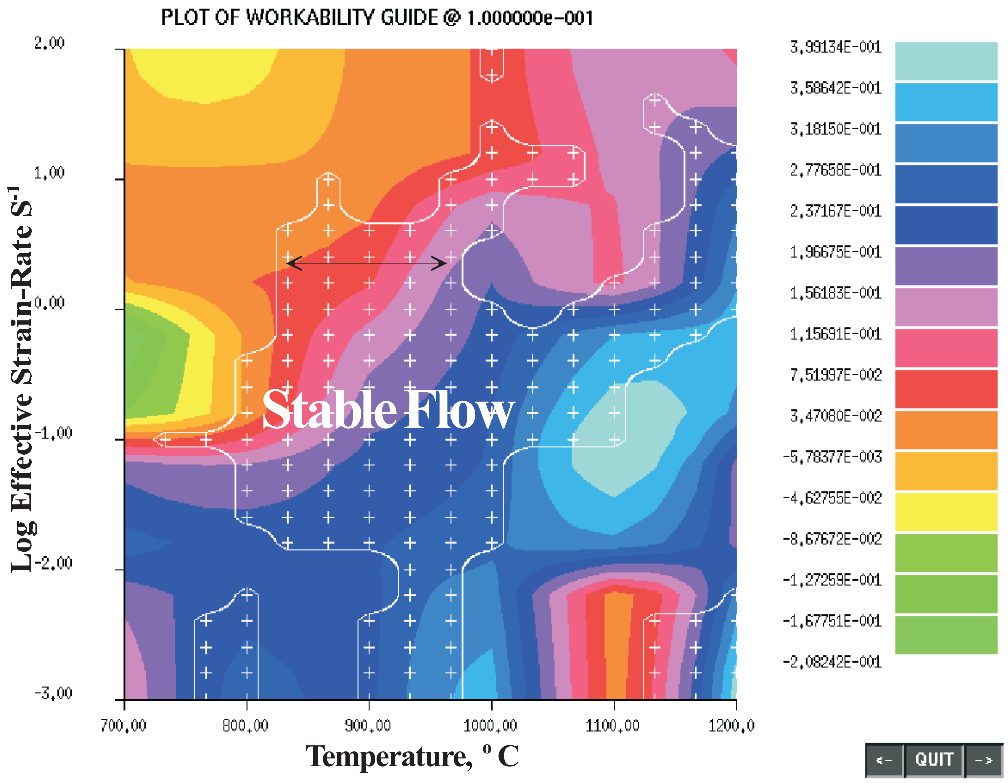

Figure 13. DMM stability map for 304L stainless steel. The colour shade indicates the variation of the parameter *m* (Gegel *et al* 2001).

models of microstructure evolution can be developed and used to identify precise material trajectories for achieving the design objectives of finished shapes (Venugopal *et al* 1997).

The goal of achieving more efficient material flow and better control of the spatial distribution of microstructure can be achieved using state space material process models and geometry mapping relationships between starting and finished shapes (Malas 1985). The concept of shape simplification, also called *ideal forming*, defines an idealized process that the actual process should approximate as closely as possible. However, when shape or volume becomes a relevant factor, meshed based numerical solutions that are appropriate for specific types of equation structure and boundary conditions may be necessary. Also, a given material process may require all types of solutions to solve different aspects of a single problem. This discussion of near optimal process design places focus on a new kind of process design concept that emphasizes ideal forming models, material stability analysis and geometry mapping between the initial and final states to predict important process parameters.

3. Shape change mapping

A new kind of process model is emerging based predominantly on ideal forming concepts and geometrical mapping relationships between the initial and final states (Frazier 1997;

Frazier *et al* 1998). In this approach, strong emphasis is placed on geometry mapping and the use of simplified models to predict key process parameters. The extrusion process is an example of a steady state process that can be effectively modeled using this method of analysis. For this material process case, material flow occurs predominantly along an axial direction, and interface friction can be appreciable. High interface friction factors will have an effect on the load and can cause heterogeneous deformation along the radius. In this class of problem, microstructure evolution is influenced by the flow pattern, the rate of energy input and the ability of the workpiece material to dissipate this energy by stable and desirable microstructure creating mechanisms.

Figure 14 is an example of process modelling by means of shape-change mapping starting with an initial billet geometry and proceeding through a preform state and then to a finish state. This illustration is for an axisymmetric integral blade and rotor forging, where the material flow is predominantly in the radial direction for most of the process. The material flow process does not become three dimensional until the final stages of the finish forging operation. The top die shown in figure 14 is considered to be a preform die, which is subsequently replaced by another top die for finish forging after the top-preforming die has reached an appropriate displacement. The bottom die is commonly a finisher die, which is not changed at any time during the forging process.

Dynamic models of equipment systems are also useful and essential for determining the desired adjustable parameter settings for coincident tracking of the equipment response with optimized commands. In general, furnaces and forming machinery possess a range of time-varying performance capabilities that can be tuned to satisfy the needs of a given process. An example using a high fidelity dynamical model of a 1000-ton hydraulic forge press is described elsewhere in a published paper (Frazier *et al* 1997).

4. Trajectory optimization

For processes modeled by dynamical relationships, the optimization of time-varying rather than stationary quantities is required. This leads to the notion of trajectory optimization,

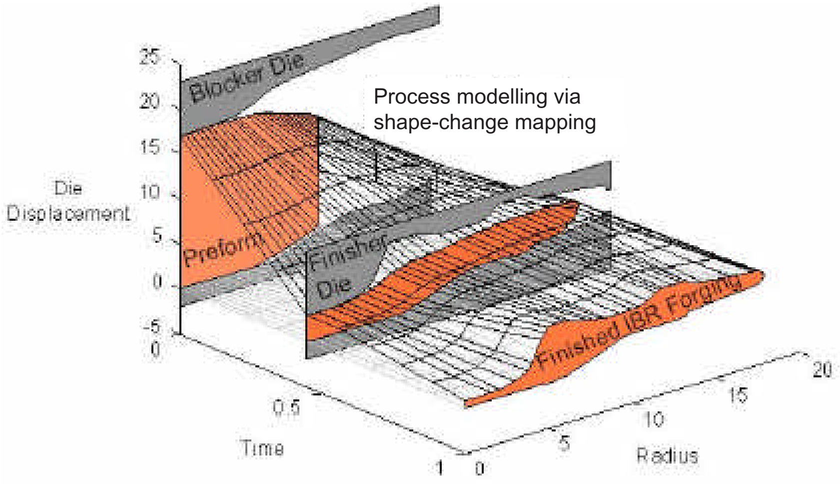

Figure 14. Shape-change mapping for a two-step forging sequence (Gegel *et al* 2001).

i.e. the calculation of the best path for some quantity to follow over time. A mathematical description of this type of problem is

$$\min J = \sum_{j=0}^{N_h-1} h_j(\mathbf{x}(t_j)) + \sum_{i=}^{N_g-1} \int_{t_i}^{t_{i+1}} g_i(\mathbf{x}(t), \mathbf{u}(t))\mathrm{d}t, \tag{11}$$

subject to the constraints

$$\begin{aligned} &c_i(\mathbf{x}(t_i), \mathbf{u}(t_i)) \leq 0, \quad i = 1 \text{ to } N_c, \\ &d_i(\mathbf{x}(t), \mathbf{u}(t)) \leq 0, \quad t \in [t_1, t_u]_i, \quad i = 1 \text{ to } N_d, \end{aligned}$$

and the material and process models

$$\begin{aligned} \dot{\mathbf{x}}^w &= \mathbf{f}_j^w(\mathbf{x}_j^p, \mathbf{x}^w, \mathbf{u}_j), \quad j = 1 \text{ to } N_f, \\ \dot{\mathbf{x}}_j^p &= \mathbf{f}_j^p(\mathbf{x}_j^p, \mathbf{x}^w, \mathbf{u}_j), \quad j = 1 \text{ to } N_f, \end{aligned} \tag{12}$$

where

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}^w \\ \mathbf{x}_1^p \\ \vdots \\ \mathbf{x}_{N_f}^p \end{bmatrix} \quad \text{and} \quad \mathbf{u} = \begin{bmatrix} \mathbf{u}_1 \\ \vdots \\ \mathbf{u}_{N_f} \end{bmatrix}. \tag{13}$$

A block diagram illustrating the model for the case of 3 sequential processes is shown in figure 15. An explanation of quantities is given below.

J	overall design objective (a targeted goal),
h_j	objective terms defined at a point in time: often used for final workpiece objectives such as microstructure,
g_i	integrand of objective terms defined on a time interval: energy required, processing cost, processing time etc,
c_i	constraints defined at a point in time: often final value constraints such as strain, cross head travel limit etc,
d_i	constraints defined over a time interval: temperature limits, strain-rate limits, load limits of equipment etc,

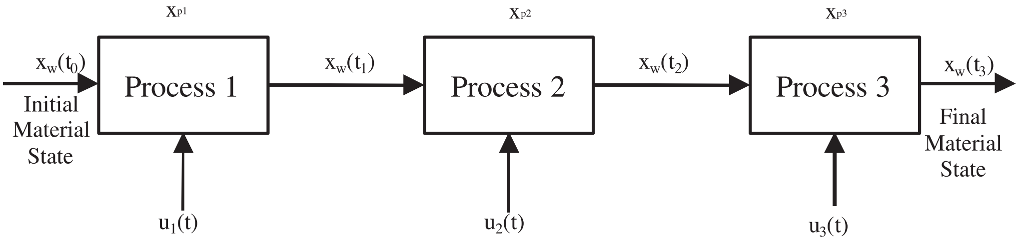

Figure 15. Block diagram of a three-stage material processing system.

$\mathbf{x}^w$ vector of workpiece states: dislocation density, average grain size, fraction transformed etc.

$\mathbf{x}_j^p$ vectors of process states: ram speed, pressure, ambient temperature etc.

$\mathbf{u}_j$ vectors of process controls, desired ram speed, desired pressure, desired temperature etc.

N_f, N_c, N_d, N_g, N_h number of discrete processes, pointwise constraints, interval constraints, pointwise objective terms, and interval objective terms, respectively.

The subscript j in the quantities $\mathbf{x}_j^p$ and $\mathbf{u}_j$ refers to a particular thermomechanical process such as forging, extrusion, heat treatment etc.

4.1 *Illustration on trajectory optimisation*

The above approach is applied for controlling microstructure (in the present case grain size) during hot extrusion of stainless steel type AISI 304L. The optimum ram velocity and die profile for extruding 304L to obtain a final grain size of 35 μm have been determined using the above two-stage approach. An empirical model for 304L has been developed for this purpose in the temperature range of 950°C to 1250°C and strain rate range of $0{\cdot}1\,\mathrm{s}^{-1}$ to $20\,\mathrm{s}^{-1}$, which are normally envisaged in an extrusion process. Compression tests were performed on 304L in the above temperature and strain rate range to generate the model. The effects of strain, strain rate and temperature on microstructural evolution of this material during hot working are as below.

Volume fraction recrystallised:

$$\chi = 1 - \exp\left[\ln(2)((\varepsilon - \varepsilon_c)/\varepsilon_{0\cdot5})^2\right], \tag{14}$$

critical strain,

$$\varepsilon_c = 5{\cdot}32 \times 10^{-4} e^{8700/T}, \tag{15}$$

plastic strain for 50% vol. recrystallisation,

$$\varepsilon_{0\cdot5} = 1{\cdot}264 \times 10^{-5} d_o^{0\cdot31} \dot{\varepsilon}^{0\cdot05} e^{6000/T}, \tag{16}$$

and average recrystallised grain size,

$$d = 20560 \dot{\varepsilon}^{-0\cdot3} e^{-0\cdot25(Q/RT)}, \tag{17}$$

where $Q = 310$ kJ/mol and $R = 8{\cdot}314 \times 10^{-3}$ kJ/mol-K. Using the above model and flow stress data (for estimating the rate of change of temperature due to deformation) the state-space model for microstructural evolution has been generated.

4.1a *Optimisation of the microstructural trajectories:* In the present case, a tube extrusion from OD 137 mm: ID 40 mm to tube dia. of 48 mm: 6 mm wall thickness (true strain = 3·46) is considered. The desired final grain size in the product is 35 μm. For the above case, the following optimality criterion was chosen:

$$J = 10(\varepsilon(t_f) - 3{\cdot}46)^2 + \int_0^{t_f} (\mathrm{d}(t) - 35)^2\,\mathrm{d}t, \tag{18}$$

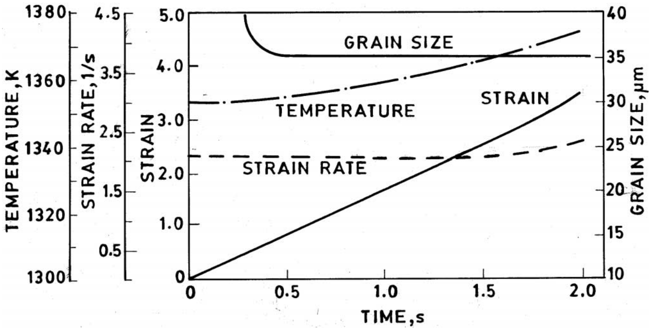

Figure 16. Trajectories of strain, strain rate, temperature and grain size for achieving the desired final grain size of 35 μm.

where a desired final strain of 3·46, with a weighing factor of 10, and a desired grain size of 35 μm have been specified. The optimal strain, strain rate and temperature trajectories has been obtained using the above criteria and microstructural model. The optimal strain, strain rate and temperature trajectories are given in figure 16.

4.1b *Optimisation of the process parameters:* Using the following relationships (Eqns. (19) and (20)) the shape of the extrusion die for extruding the material has been obtained.

$$V_{ram} = L \Big/ \int_{t=0}^{t_f} e^{\varepsilon(t)}\, \mathrm{d}t, \tag{19}$$

$$r(t) = r_o e^{-\varepsilon(t)/2}, \qquad y(t) = V_{ram} \int_0^t e^{\varepsilon(\tau)}\, \mathrm{d}\tau, \tag{20}$$

where r_o is the die entrance radius (equal to the billet radius), L is the die length, and $\varepsilon(t)$ is the required strain trajectory, t is the time interval, V_{ram} is the ram velocity, r is the die radius and y is the axial distance (die throat length). Figure 17 gives the optimum die profile for achieving final grain size of 35 μm obtained by using this approach. The optimum ram velocity for achieving the above grain size is found to be 160 mm/s and billet temperature is 1353 K.

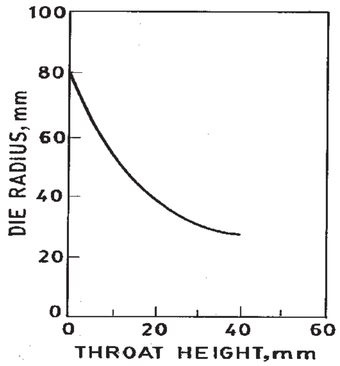

Figure 17. Optimum die profile for achieving a final grain size of 35 μm.

4.1c *Experimental verification:* The design methodology was verified in an industrial environment by means of detailed extrusion experiments with the die having optimal profile, obtained in this investigation. The extrusion test was performed at optimal conditions of temperature and ram velocity. The billet material was AISI 304L. The outer diameter, inner diameter and length of the billet were 137 mm, 48 mm and 500 mm respectively. The final outer diameter of the tube was 48 mm and wall thickness 6 mm. The ambient temperature of the die, container and follower block was 623 K and soak temperature of the billet 1353 K. Molten glass was used as lubricant during extrusion. The extruded tube was ejected into a water tank immediately after the completion of the extrusion. The extruded piece was cut along its longitudinal axis, polished and etched for microstructural investigation. Microstructural examination carried out along the entire length of the tube revealed that there is no variation in microstructure along the length. Grain size measurements were done using Hyen intercept method. Histograms were made to find the grain size distribution and the average grain diameter. The measured average grain size was 38 μm, which is close to the designed value.

Optimization is just one method for performing a process design. Whether the resulting design is the best design depends entirely on the criteria specified by the product designer. As illustrated above, optimization techniques require the specification of two types of criteria: objectives (wants) and constraints (needs). To achieve the desired goals, the designer must specify all relevant criteria and must carefully determine the criteria that are objectives and the criteria that are constraints.

As an example, it may be desired to minimize the production costs (objective) while maintaining specified product quality standards (constraint). On the other hand, the opposite scenario may be desired, i.e. maximize the product quality (objective) while not exceeding a specified cost (constraint). Effective optimization strategies consider the entire processing design problem, not just some parts, thereby avoiding over-optimization of parts of the process at the expense of the whole manufacturing enterprise.

5. Using ideal forming concepts

Ideal forming concepts are based upon the notion that ideal deformation conditions can be defined for a material and or a process only if there is a limited set or class of boundary condition restrictions. In addition, the boundary conditions associated with simplified process analysis models are often consistent with the assumptions used in ideal forming concepts. Therefore, the simplifying assumptions built into simplified models actually provide good design criteria. It follows that since simpler, not simplistic, design solutions are known to be better than complex ones; it is desirable to find design solutions for which a simplified analysis is valid. For example, it is generally desirable to simplify a 3-D metal deformation process to be predominantly a 2·5-D forming process.

The idealized optimization approach to process design is a stark contrast to the traditional philosophy that a more predictive capability for material process models leads to better design solutions. Some designers run detailed finite element simulations looking for trends in the behavior of certain key process field parameters as the material flow pattern and how they are affected by different values of die velocity, die temperature and workpiece temperature. This *ad hoc* approach to material process design is frequently but mistakenly called process optimization. It is very labor intense and costly, and the ad hoc approach seldom leads to an optimal solution. Effective optimization strategies consider the entire material processing design problem, not just some parts of the process at the expense of the whole manufacturing enterprise.

6. Process control using intelligent control techniques

It has been shown that the trajectory optimisation method (i.e., the open-loop control method) can be successfully used in deformation processing for producing quality products. This open-loop control method uses empirical microstructure development models to determine the optimum deformation path for achieving the desired microstructure and a process model to calculate the processing parameters necessary for achieving the optimum deformation path. The required processing parameters are utilised to set-up and regulate the metalworking equipment used to produce the part. Feedback improvements between the metalworking equipment system and the process model are not considered in the open-loop control system method. Since the process is carried out in the region where the process is robust in nature, the feed back control system can be incorporated to control the process. Moreover the open loop control approach requires that the process model be accurate enough in predicting all aspects of the deformation process or that the process model be empirically calibrated. In some applications, the former is not computationally feasible, and the latter is difficult to consistently achieve. For this reason, some type of process monitoring or sensing is needed for real-time feedback control compensation as indicated in figure 18.

Parameters such as temperature of the billet, strain experienced by the billet and speed of the press slide can easily be measured and controlled effectively during the process. Since the process is robust, these parameters are need not be measured and controlled with the great degree of accuracy. The microstructural state of the billet can be assessed through ultrasonic sensors. The microstructural state of the billet can also be determined indirectly from the values of strain, strain rate and temperature using the models describing the evolution of microstructure during working. The online determination of grain size during rolling has been attempted and proved to be successful.

Acoustic emission (AE) is a well-known nondestructive evaluation (NDE) technique. Proponents of AE have long suggested that the technique may be suitable for real-time process monitoring for a variety of forming process. AE has been used extensively to study deformation and fracture (Mullins *et al* 1997). Recent studies indicate that a good correlation exists between the AE data and various metallurgical processes that are occurring during forming. For metal deformation, the occurrence of AE events at different points in the deformation path is well correlated with deformation and fracture mechanisms. Another significant source of AE is the fracture of inclusions and the propagation of existing cracks (Mullins *et al* 1997). Friction is a common source of AE energy emission. The material flow in the die-cavity and the event of die-closure can also give rise to AE energy emission. Hence, the important phe-

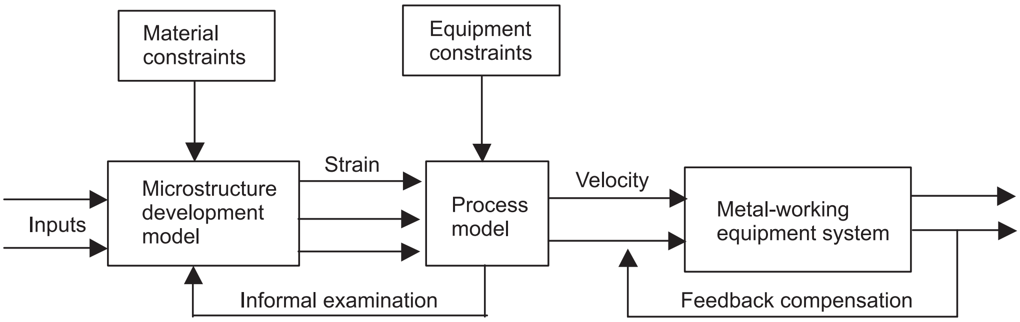

Figure 18. A block diagram illustrating the multi-step, closed loop design methodology.

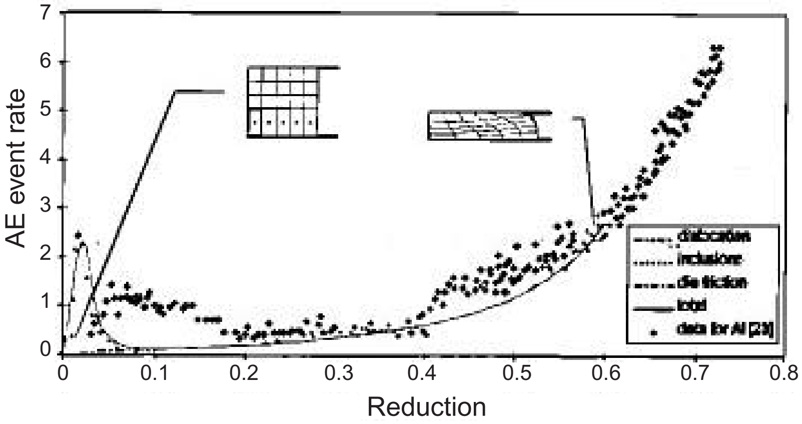

Figure 19. AE during upsetting operation (Mullins *et al* 1997).

nomena such as deformation, cracking, lubricant break down, material flow in the die-cavity and die-closure can be monitored by using AE technique. The authors have carried out some preliminary investigations to examine the feasibility of using AE technique for monitoring forging operation. The authors have predicted AE using simulation technique and compared with that of the experimental investigations. Figure 19 indicates that the predictions based on simulation studies are corroborated well with that of the experimental results. Figure 20 shows the AE recorded at varied friction conditions during open-die forging. Figure 21 shows the predicted AE in case of a disk forging (Mullins *et al* 1997). These results indicate that the cracking of the billet, abnormal rise in friction coefficient due to lubricant break down and the improper filling up of the die cavity by the deforming metal during forging can be inferred by AE. Hence, by monitoring of the process one can predict the quality of the parts during forging and apply corrective action during the operation if the quality of the product is not meeting the specification.

The foregoing discussions indicate that using reliable database, customised software and good monitoring technique quality parts can be produced economically. With the above objective in mind an intelligent forging system consisting of built in knowledge base system for the

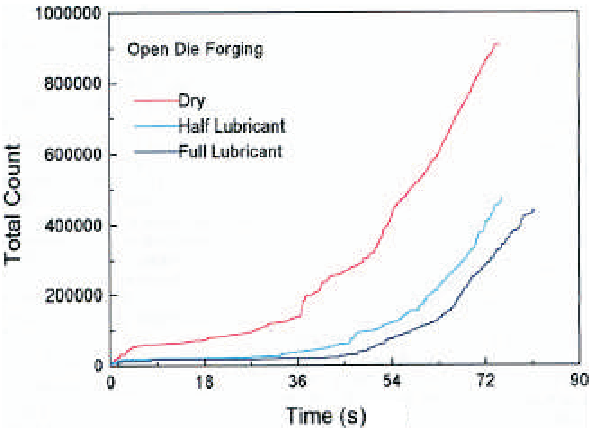

Figure 20. AE at different friction conditions.

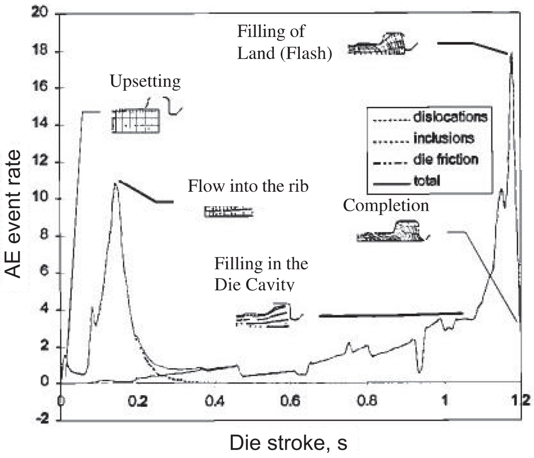

Figure 21. Calculated AE during disk-forging operation (Mullins *et al* 1997).

design and control of metal forging operation, monitoring tools for the measurement of billet temperature, ram velocity, deformation ratio, friction, to assess the cracking and die fill, and enhanced visualisation features an intelligent forging system has been proposed as shown in

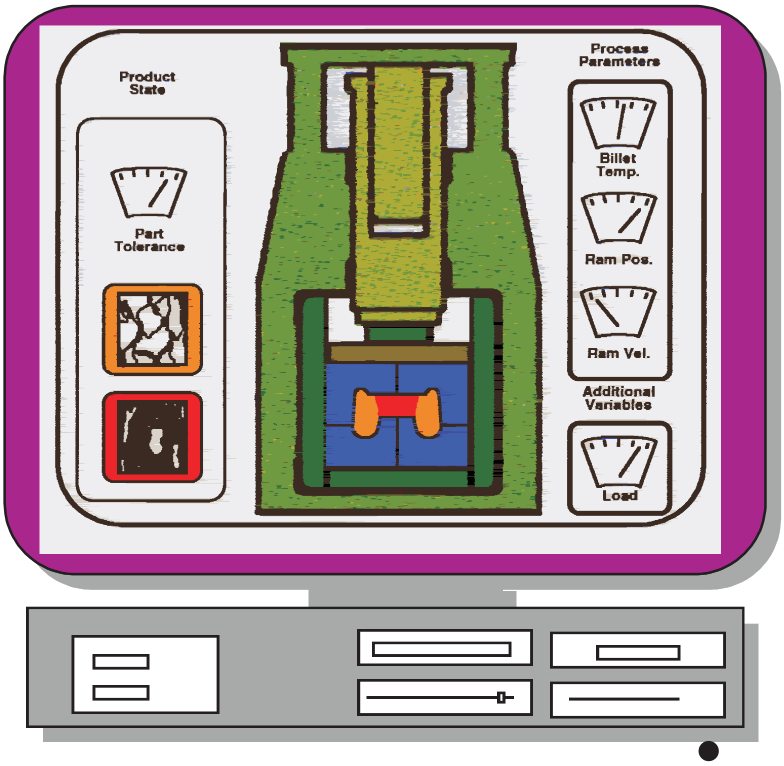

Figure 22. Intelligent forging system for monitoring and controlling microstructure in the component during forging.

figure 22. This system should be capable of predicting the microstructural state of the billet at various locations using appropriate models during forging and adjusting the process parameters with controllers to correct the deviations if any.

7. Summary

Design engineers work under considerable time pressure, and they need to have easy-to-use tools to speed the design of manufacturing processes. It is increasingly important to adopt upstream technical and business processes that enable them to deliver customized services and products at relatively low costs and deliver them with the expected quality when the customer expects the parts to be delivered. Multidiscipline process design and optimization (MPDO) strategies drive part quality, delivery time and cost. It is a set of tools and standards that form an infrastructure to link data and tools from different environments. By means of a MPDO infrastructure based upon commercial software, the design process can be integrated, automated and accelerated.

The benefits of MPDO are measured in terms of the ways it helps process design teams do their job. MPDO helps the design team to achieve the following:

1. Create innovative design alternatives.
2. Manage the dynamical and material stability effects in the design of thermomechanical material processes.
3. Handle explicitly design objectives and constraints on workpiece materials, processing equipment and tooling.
4. Improve product design.
5. Reduce cost and time-to-market
6. Use simplified models and concepts in a cost-effective manner to identify optimal workpiece material trajectories.

The use of the state space method provides considerable insight into the controllability of metalworking processes. It is a constrained optimization method, where the overall design is specified as constraints and objectives to accommodate multiple physical and economical requirements. This approach identifies optimal workpiece material trajectories that are generally needed for achieving customer product specifications.

The ideal forming concepts are based upon the notion that ideal deformation conditions can be visualized and defined for a material and process only if there is a limited set of boundary condition restrictions. These concepts are based also on meaningful material stability conditions and expressing them in the form of nonholonomic (inequality) constraints. The capricious nature of material behaviour can be managed by designing the material process to operate primarily in the material stability regions of process parameter space. The deleterious stochastic events are dampened in these regions and the apparent activation energies that correspond to beneficial energy dissipation mechanisms are relatively low compared to material failure mechanisms.

Most importantly, the analytic microstructure evolution models are only reliable when applied in the stable regions, where microstructure and mechanical property parameter variance is not sensitive to material path trajectory. Whether an ideal design concept approach is sufficient for material process optimization is based in part on the design objectives for the finished part and the fundamental thermophysical properties of the workpiece material.

A menu of process analysis methods is available to industrial process design teams to handle almost any material process design problem. It is possible to use ideal design concepts using mesh based models that have few if any restrictions on geometry. The simplified finite element method (SFEM), for example, corresponds to analysis methods such as the SLAB and upper bound (UB) methods with respect to computation time and the analysis of a typical step of the forming process. Appropriate analysis methods, lead to the ideal forming concept for optimizing different types of material process operations.

Methods for monitoring the process to attempt for on-line process control have been discussed. The AE technique has proved to be a successful for assessing the lubricant condition and die filling. An intelligent system for the control of the process has been proposed.

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