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Processing Maps: A Status Report

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In the last two decades, processing maps have been developed on a wide variety of materials including metals and alloys, metal matrix composites, and aluminides, and applied to optimizing hot workability of materials and for process design in bulk metal working. Processing maps consist of a superimposition of efficiency of power dissipation and the instability maps, the former revealing the "safe" domain for processing and the latter setting the limits for avoiding undesirable microstructures. The dynamic materials model, which forms the basis for processing maps, is discussed in relation to other materials models. The application of dynamical systems principles to understanding of deterministic chaos in the system will help in achieving a greater degree of microstructural control during processing. The patterns in the hot working behavior as revealed by the processing maps of several classes of alloys relevant to technology are reviewed briefly. Processing maps have also been applied to analyze several industrial problems including process optimization, product property control, and defect avoidance, and a few examples are listed. With the processing maps reaching a matured stage as an effective tool for optimizing materials workability, expert systems and artificial neural network models are being developed to aid and prompt novice engineers to design and optimize metal processing without the immediate availability of a domain expert, and the directions of research in this area are outlined.

Keywords aluminides, metal matrix composites, processing maps

1. Introduction

Several materials models are currently popular for characterizing the hot working behavior of metals and alloys; these include the kinetic model,[1] atomistic model,[2] and dynamic materials model and its variants.[3-6] Details of these models are discussed in a recent review.[7] The processing map is a product of the dynamic material model that was developed in 1984,[3] for two primary reasons: (1) To evaluate the explicit microstructural response of the material to the processing parameters from the constitutive equation that relates the flow stress to temperature, strain rate and strain, and (2) to integrate the materials behavior with the finite element model that simulates metal-working processes using mechanics of large plastic flow. At the end, such integration is expected to result in a reliable and robust simulation tool that will help the metal working industry in solving the problems related to workability and microstructural control in commercial materials. In this paper, the results obtained on the processing maps over the past two decades will be reviewed in light of the above expectations, and the present status of this research will be presented.

2. Basis for Processing Maps

The processing maps are developed on the basis of the principles of dynamic material model, which were discussed earlier literature.[7] The physical basis for the processing maps is interdisciplinary and is contained in the concepts of physical systems modeling,[8] mechanics of large plastic flow,[9] and deterministic chaos in dynamical systems.[10,11] The extremum principles of irreversible thermodynamics of the quasi-static processes of large plastic deformation are particularly helpful. Ziegler[9] has shown that the behavior of such a system follows the principle of maximum rate of entropy production, which is equivalent to the principles of least irreversible force or least velocity corresponding to the velocity and force spaces, respectively. At a given temperature in the hot-working regime, the rate of dissipation work (power) is directly proportional to the rate of internal entropy production,[9] which is always positive since the process is irreversible:

$$P = \bar{\sigma} \cdot \dot{\bar{\varepsilon}} = \theta \frac{d^{(i)}S}{dt} \geq 0, \qquad \text{(Eq 1)}$$

where $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain rate, θ is the temperature and $\frac{d^{(i)}S}{dt}$ is the rate of internal entropy production. The total rate of entropy production consists of two complementary parts.[12] The first part (generally larger) consists of "conduction entropy," which is due to the conduction of heat from where it is generated (due to plastic flow) to the colder parts of the body. The second part is due to a microstructural dissipation, which lowers the flow stress for plastic flow (dislocation movement). Ziegler[9] represented these two in terms of dissipative functions in the velocity and force space and showed that the instantaneously dissipated total power ($\bar{\sigma} \cdot \dot{\bar{\varepsilon}}$) is given by:

$$P = \int_0^{\dot{\bar{\varepsilon}}} \bar{\sigma} \cdot d\dot{\bar{\varepsilon}} + \int_0^{\bar{\sigma}} \dot{\bar{\varepsilon}} \cdot d\bar{\sigma} = G + J, \qquad \text{(Eq 2)}$$

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where $\overline{\sigma}$ is the effective stress and $\dot{\varepsilon}$ is the effective strain rate. In terms of physical systems terminology,[8] the first integral is called G content and the second one a J co-content since it is a complementary part of G content. The constitutive equation decides the relative values of power dissipation through the heat conduction and microstructural dissipation since the origin of viscoplasticity is in the microstructural dissipation. For plastically deforming materials, the power law:

$$\overline{\sigma} = K\,(T,\overline{\varepsilon},\dot{\varepsilon})\dot{\varepsilon}^{\mathrm{m}(\mathrm{T},\varepsilon\dot{\varepsilon})} \qquad \text{(Eq 3)}$$

is widely used to define a constitutive relation. In Eq 3, T is the temperature and $\overline{\varepsilon}$ is the effective strain. For fixed values of T and $\overline{\varepsilon}$ we are interested in studying ($\Delta J/\Delta G$) and ($\Delta J/\Delta \mathrm{P}$) for small variations of $\dot{\varepsilon}$, to obtain an indicator of changes in the dissipative mechanism. Assuming that dependence of K, m on $\dot{\varepsilon}$ is weak (not necessarily zero) over a narrow range, the instantaneous values of ΔJ, ΔG, and ΔP are given by the following integrals:

$$\Delta J \approx \int_{\overline{\sigma}}^{\overline{\sigma}+\Delta\overline{\sigma}} \dot{\varepsilon}\,\mathrm{d}\overline{\sigma} \qquad \text{(Eq 4)}$$

$$\Delta G \approx \int_{\dot{\varepsilon}_0}^{\dot{\varepsilon}_0+\Delta\dot{\varepsilon}_0} \overline{\sigma}\,\mathrm{d}\dot{\varepsilon} \qquad \text{(Eq 5)}$$

$$\Delta P \approx K\,(\dot{\varepsilon} + \Delta\dot{\varepsilon})^{\mathrm{m}+1} \qquad \text{(Eq 6)}$$

and

$$\Delta J/\Delta G = m \qquad \text{(Eq 7)}$$

$$\Delta J/\Delta P = m/(m+1) \qquad \text{(Eq 8)}$$

We further define the "efficiency of power dissipation (η) with respect to a linear dissipator ($m = 1$) to be

$$\frac{\Delta J/\Delta P}{(\Delta J/\Delta P)_{\mathrm{linear}}} = \frac{m/(m+1)}{1/2} = \frac{2m}{m+1} \equiv \eta. \qquad \text{(Eq 9)}$$

From this analysis, we see that m is the key parameter defining the relative (not absolute) partitioning of power between heat generation and microstructural change. The value of m for stable flow in a viscoplastic solid is between 0 and 1[9] and as the value of m increases, the microstructural dissipation will increase. The value of m less than one (commonly known as negative strain rate sensitivity) is observed for the process of dynamic strain aging where moving dislocations are repeatedly locked and unlocked by faster moving solute atoms. Deforming solids in which m is more than one are described as "locking solids" in continuum mechanics.[13] Both the above extremes represent flow instabilities.

Processing maps consist of superimposition of two distinct maps: the power dissipation maps and the instability maps. These are described in Fig. 1.

The power dissipation map represents the three-dimensional variation of the efficiency of power dissipation (Eq 9) as a function of temperature and strain rate, which may be conveniently viewed as an isoefficiency contour map. As discussed above, it developed by exploring the viscoplastic nature of the material deforming at elevated temperature and by giving a physical interpretation to the strain rate sensitivity (of flow stress) parameter (m) as a power partitioning factor that permits explicit evaluation of the power dissipation through microstructural changes. Such a concept finds support in thermomechanics[9,12] in terms of complementary functions that represent the rate of entropy production occurring by heat conduction and internal entropy changes caused by microstructural processes. Others have contested saying that such a power-partitioning concept[14] does not have any basis in continuum mechanics. Notwithstanding this criticism, it is clear that the key factor that decides the dynamic behavior of the material in hot working is the strain rate sensitivity of flow stress which, in simple physical terms, decides the mechanism (or path) that the material constitutively chooses under a given set of hot working conditions (e.g., temperature and strain rate). This will be the "shortest" path that will dissipate energy in the most efficient way, which may not always be a "safe" mechanism from microstructural viewpoint. Thus the most efficient power dissipation mechanisms are not necessarily the best for hot workability since these could be cracking or damage mechanisms. Also, depending on the imposed hot working conditions, the system can choose a single mechanism (deterministic) or a combination of two or more mechanisms (probabilistic) that have a characteristic m value. The processing map is obtained at a constant strain, and its dependence on strain is generally not significant under hot working conditions. If the dissipation maps are drawn as a function of strain, they serve as snapshots showing the development of the microstructural processes with deformation. However, the changes occur within about 20% of deformation beyond which the flow reaches a steady state unless the material is cracking. In such a case, the state of stress will have a significant effect.

Domains or windows representing various microstructural mechanisms are identified in the processing maps, and these have characteristic features.[7] The "safe" mechanisms include dynamic recovery, dynamic recrystallization (DRX), and superplastic deformation while the microstructural "damage" mechanisms include void formation, wedge cracking, intercrystalline cracking, and other types of cracking processes. After establishing that the domain is "safe" (e.g., dynamic recrystallization), information about the optimum process parameters (temperature and strain rate corresponding to the peak efficiency in the domain), and the ranges of the processing parameters (widths of the domain in temperature and strain rate axes) may be obtained from the processing map. Such information may also be used for process design like the starting and finishing temperatures, the speed of the machine and the type of process (isothermal or nonisothermal) without resorting to expensive and time-consuming trial and error methods.

Instability maps are developed on the basis of an instability criterion derived on the basis of the extremum principles of irreversible thermodynamic as applied to continuum mechanics of large plastic flow.[9] While the instability criterion is derived, the power partitioning principle similar to that used for dissipation maps is applied so that flow instabilities caused by microstructural processes will be revealed by these maps. The criterion is given by the dimensionless parameter ξ:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln[m/(m+1)]}{\partial \ln\dot{\varepsilon}} + m \leqq 0 \qquad \text{(Eq 10)}$$

for flow instability.[7] The temperature and strain rate regimes where ξ is negative exhibit flow instabilities that are generally manifest in the form of adiabatic shear bands or flow localizations in the microstructure. There are also other criteria developed to reveal flow instabilities in processing, and these are based on phenomenological parameters,[15] Lyapounov functions,[4] and mathematical modifications of the criterion given in Eq 10.[6] However, the above criterion (Eq 10) is extensively validated with respect to its consistency. It may be mentioned that the application of the instability maps to process design is probably more relevant to industrial processing than the power dissipation maps are. This is because for high productivity reasons industrial processing is done at the highest possible speed than the optimum dictated by the workability domain, and the limiting factor is the onset of the flow instability. The second reason is that processing at higher speeds results in finer grain sizes, which is often desirable in the product.

3. Deterministic Chaos

The seemingly simple system of a material undergoing hot deformation is considerably complex due to the following characteristics:

- Dynamic and nonlinear: the response of the system (flow stress) is nonlinearly dependent on the dynamical variables (strain rate, temperature and strain).
- Irreversibility: A large plastic strain is applied in a relatively short time. The microstructural change associated with large plastic is irreversible, and the rate of entropy production in the system is positive.
- Dissipation of power: During hot working, the material essentially dissipates energy at a rate that depends on the applied strain rate and the temperature. The power dissipation occurs through two complementary modes: temperature rise and microstructural change.
- Sensitivity to initial conditions: Small changes in the chemistry, initial microstructure, applied temperature; strain rate, and strain can cause a large change in the response of the system or lead to different mechanisms of deformation.

In view of the nonlinearity and sensitivity to initial conditions, the materials system exhibits deterministic chaos, which is responsible for making it complex and unpredictable similar to that occurring in other dissipative systems.[16-19] The nonlinear dynamics of the materials system and the deterministic chaos occurring during hot working have been characterized using a dynamical system approach.[20] For a materials system with a given chemistry (composition) and processing "history," the state (or phase) space variables for hot working are (1) temperature of deformation, (2) strain rate, (3) strain, and (4) dissipative state of the microstructure. Since the power dissipation and the rate of entropy production are directly related (Eq 1), the efficiency parameter (Eq 9) describes the relative rate of entropy production occurring during hot deformation and represents the rate of microstructural change in the system. It can thus be used as a state space parameter for tracking the microstructural evolution in the system. It may be noted that a higher efficiency of power dissipation corresponds to a lower dissipative energy state of the material.

In other physical systems like lasers, electronics, flight dynamics, etc.,[16,17] differential equations are formulated for relating the response of the system to each of the state space variables and solved to evaluate its state at any given time during its evolution. In nonlinear systems, these equations are very complex and need sophisticated numerical techniques to solve them. In materials systems, the very formulation of the equations is difficult, if not impossible, since the atomistic mechanisms that could occur are not known *a priori*, and many of the mathematical terms involved in describing the microstructural changes accurately are yet to be established. In view of this difficulty, it is necessary to use a topological approach to describe the nonlinear dynamics, which requires accurate experimental data on the material behavior. The processing map is one such approach and is similar to a "Poincare map" in dynamical systems. The changes that occur in the processing map with strain describe the microstructural evolution of the system during hot deformation.

3.1 Consequences of the Dissipative Nature

The general dynamic characteristics of a material in hot working are described below using the processing maps obtained on a nickel aluminide alloy.[21] The processing maps are shown in Fig. 1(a-d) as contour maps, which correspond to strains of 0.1, 0.2, 0.3, and 0.5, respectively. It may be noticed that these are similar to the "Poincare" sections of the microstructural evolution of the system, as mentioned earlier. The contours represent constant efficiency of power dissipation, which is directly related to the relative rate of entropy production in the system caused by a change in the microstructure. In other words, it represents the rate of microstructural change occurring due to hot deformation, and the contours may be termed as microstructural "trajectories."

3.1.1 Transients. At the start of plastic deformation, the different temperature-strain rate combinations generate a random spectrum of dissipative energy states, which may be depicted as a "cloud" of points in the plane of temperature-strain rate. With increasing strain, the stable microstructural trajectories go through transients until a group settles down or decays into an attracting set or space, which occupies zero volume in the state space. A very common process that occurs during this transient stage of hot deformation is the dynamic recovery. The dynamic recovery process is not highly dissipative since it only annihilates some dislocations and retains or stores considerable elastic energy. The process, however, is responsible for the nucleation of attractors like dynamic recrystallization. If the material does not have good workability, cracking processes occur very early in the deformation and these have very short transients. The trajectories will form basins of attraction right from the start of deformation since cracking is probably the most favored process for dissipating the energy. With reference to the map at a strain of 0.1 given in Fig. 1(a), the domains occurring at 1100 °C/0.001 s^{-1}, 1100 °C/10 s^{-1}, and

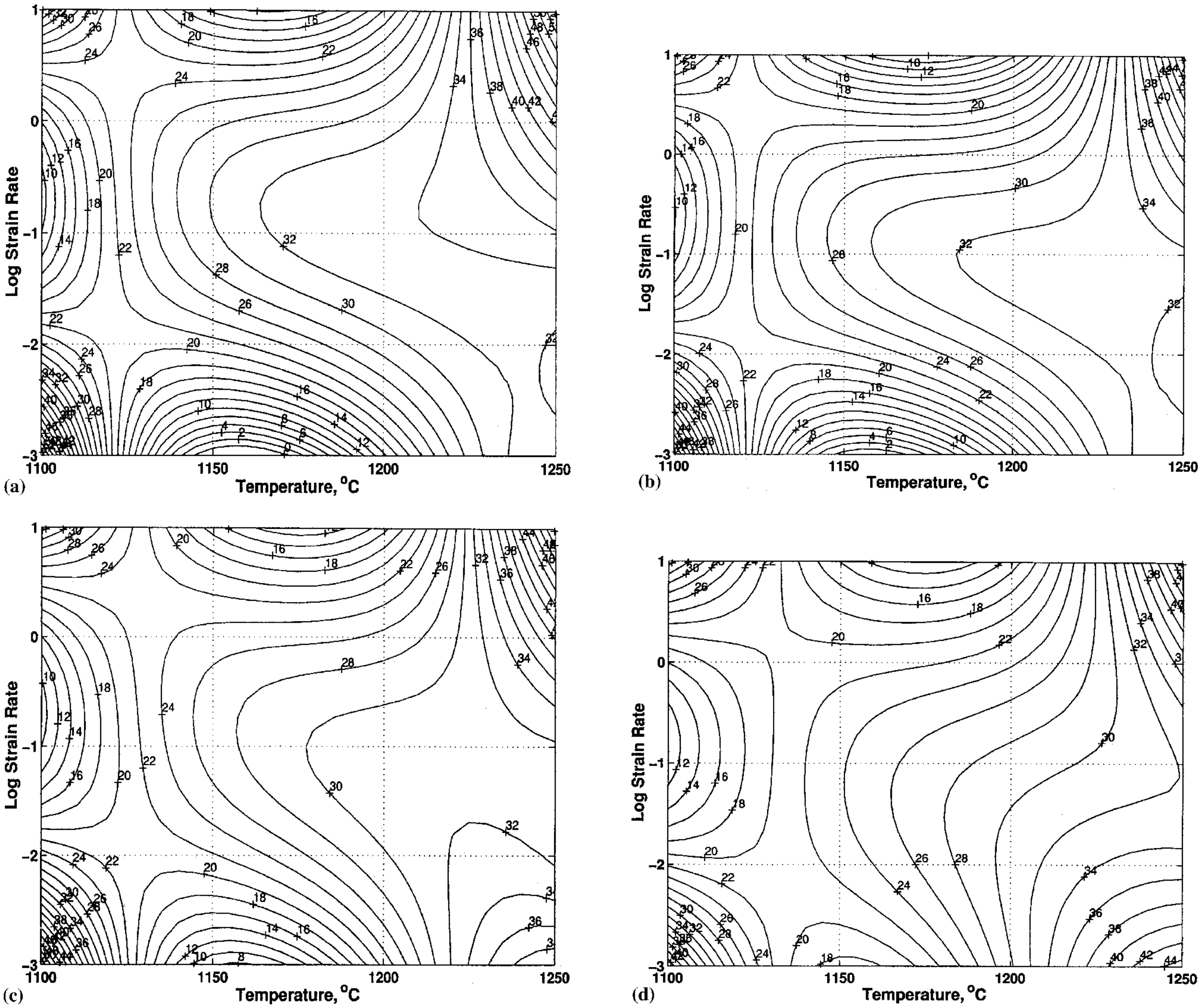

Fig. 1 Processing maps for nickel aluminide alloy at different strains: **(a)** 0.1, **(b)** 0.2, **(c)** 0.3, and **(d)** 0.5. The contours represent efficiency of power dissipation marked as percent.

1250 °C/10 s^{-1} represent cracking processes and are confirmed[21] to represent grain boundary cracking, cracking at γ colonies in a γ' matrix, and intercrystalline cracking in disordered nickel aluminide, respectively. From this map, it may be noted that the trajectories in the temperature range 1125-1200 °C and strain rate range 0.01-1.0 s^{-1} represent transient deformation associated with dynamic recovery.

3.1.2 Attractors. As the material is deformed to strains higher than 0.1, the topology of the map changes as seen in Fig. 1(b-d). While the cracking domains described above do not significantly change with strain, a new domain of attraction develops at 1250 °C/0.001 s^{-1}, the critical change occurring after a strain of 0.2. Microstructural observations have confirmed that this domain represents dynamic recrystallization of the nickel aluminide alloy. From the spacing of contours, it is obvious that the efficiency hill represented by this domain is less steep than the other three damage processes. Dynamic recrystallization imparts excellent hot workability to the material and is a preferred process for hot working most of the materials. The shape of this attractor may be constructed from the change in the trajectories in this regime of the map, and it is easy to see that this has a wineglass shape, although it is not so symmetrical in cross section.

3.2 Lyapounov Exponent

From the maps, the chaotic nature of the material behavior in hot working can be confirmed by establishing the Lyapounov exponent, which is the most important dynamic invariant of an attractor that quantifies its sensitivity to initial conditions.[22] It measures the average rate of divergence (or separation) of neighboring trajectories in phase space, averaged over the initial conditions spread over the trajectory. Let us consider the behavior of the nickel aluminide alloy at the strain

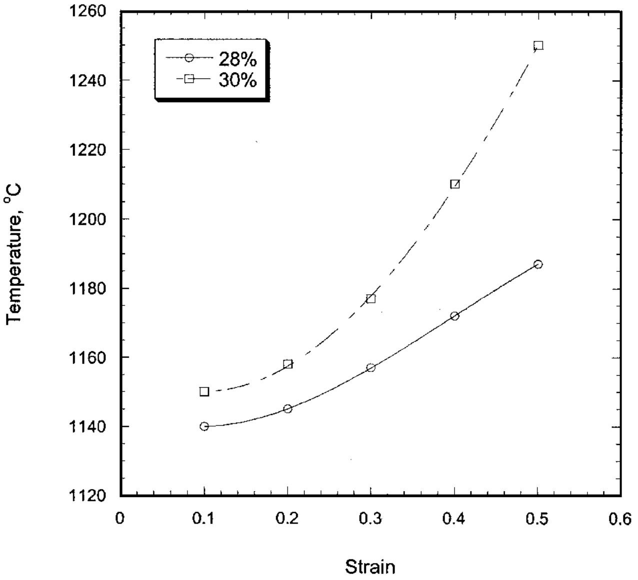

Fig. 2 Divergence of neighboring trajectories with 28% abd 30% efficiency at a strain rate of 0.1 s^{-1}

rate of 0.1 s^{-1} and a trajectory with an efficiency of power dissipation of about 32% (Fig. 1). The temperature of this trajectory moves to higher values as the strain increases as shown in Fig. 2. The neighboring trajectory has an efficiency of 30%, and its position simultaneously moves to higher temperatures but at a much faster rate than the trajectory with 28% efficiency. Their temperature divergence can be expressed in the form of an exponential equation:

$$\Delta T = \Delta T_0 \exp(\lambda \varepsilon) \quad \text{(Eq 11)}$$

where ΔT_0 is the temperature difference at a strain of 0.1, λ is the Lyapounov exponent, and ε is the strain. From the data given in Fig. 2, the value of λ is estimated to be about 4. This clearly establishes that there is deterministic chaos in the system.

3.3 Bifurcations

A bifurcation is a qualitative change in the systems dynamics as a control parameter is varied.[11,22] This change will be associated with a change in the topology of the attractor-basin phase portrait or processing maps. On the basis of the changes in the processing maps (Fig. 1a-d), a bifurcation diagram may be built at a temperature of 1250 °C by following the change in the strain rate for the contour with 34% efficiency of power dissipation and is shown in Fig. 3. Up to a strain of 0.2, this trajectory just appeared at a strain rate of about 0.04 s^{-1}, and at higher strains, it bifurcates as shown in Fig. 3. This bifurcation separates the intercrystalline cracking domain at higher strain rates and the dynamic recrystallization domain at lower strain rates. All the strain rates within the strain rate limits of the bifurcation will result in a chaotic behavior and will cause microstructural instabilities.

In conclusion, the above analysis shows that the dynamic systems approach describes the systems behavior very well and has the potential to become a powerful tool in achieving microstructural control in hot working of materials.

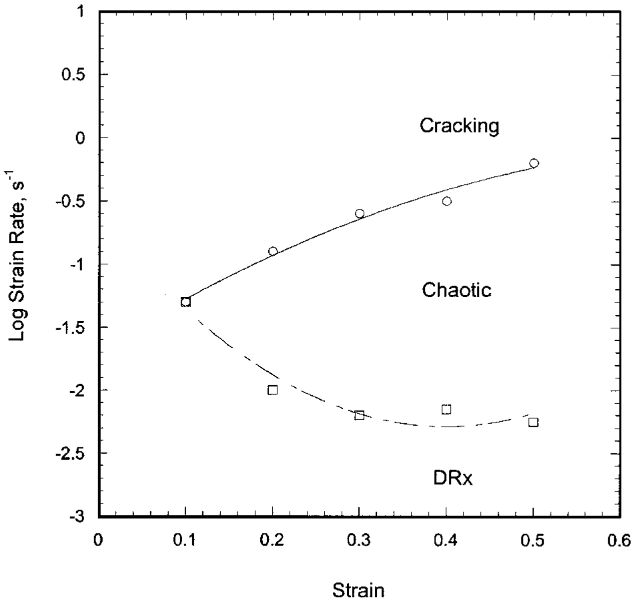

Fig. 3 Bifurcation diagram at 1250 °C for trajectory with 34% efficiency

4. Processing Map as a Process Design Tool

The information from processing maps may be effectively integrated with the design and optimization of metal working processes. While the temperature and strain rate at the peak efficiency in the DRX domain are chosen as optimum process parameters, the process should be controlled such that the local values of temperature and strain rate do not enter the undesirable regimes like flow instability or cracking. Further, the choice of the machine may be done on the basis the strain rate range for the DRX; the highest strain rate limit is set by that which initiates the flow instabilities. Also, if the range of temperature for the DRX domain is narrow (e.g., about 50 °C) and/or the strain rate is lower than about 0.01 s^{-1}, it is necessary to choose an isothermal process. Another important aspect is the grain size control in processing. It is often required that the product has a fine grain size, and process schedules may be designed to achieve this, provided the relationship between the grain size and the process parameters is known. For this purpose, the kinetic analysis of the flow stress data within the DRX window will be useful. It is a standard practice[1] to apply the kinetic rate equation for the strain rate:

$$\dot{\varepsilon} = A\,\sigma^n \exp[-Q/RT], \quad \text{(Eq 12)}$$

where A is a constant, n is the stress exponent, σ is the flow stress, Q is the activation energy, R is the gas constant, and T is temperature. From this analysis, the apparent activation energy is estimated and the temperature compensated strain rate parameter (Zener-Hollomon) Z, given by:

$$Z = \dot{\varepsilon} \exp[Q/RT] \qquad \text{(Eq 13)}$$

is evaluated. Since the Z parameter correlates well with grain size in the DRX domain, it can be used effectively for grain size control in a component as long as the local temperatures and strain rates fall within the DRX domain. It must be emphasized here that the kinetic analysis is valid only within a deterministic domain.

5. Critical Aspects in Developing Processing Maps

Since the processing maps are only as good as the data input, considerable care has to be exercised in generating the experimental data. For example, testing has to be done under constant true strain rate conditions, and the correction for the adiabatic temperature rise has to be incorporated while arriving at the flow stress values. Another important aspect is the characterization of the processing history, prior heat treatment, and initial microstructure. In the case of as-cast materials, homogenization treatment has a significant impact on the processing map and so do the differences in the initial microstructure like cast (dendritic or cellular) versus wrought, powder metallurgy compacts, and lamellar versus equiaxed microstructures in the case of some two-phase materials. It is also useful to have knowledge of solutionizing temperature, particle precipitation, transformation temperature, and other metallurgical effects since these will be reflected in the map in terms of inflexions in the contours, and ending or expanding of domains and their movement with respect to the strain rate axis. Prior knowledge of physical metallurgy of the system offers a good way to cross check with the features of the map and often some new effects caused by the dynamics of deformation are revealed. Furthermore, the dissipative microstructures respond to the post-deformation heat treatments differently and may result in a new set of innovative microstructures. The maps of materials that exhibit very low intrinsic workability (extensive cracking regimes) are less accurate since in put flow stress data itself will not be accurate, and so extra care must be exercised during their interpretation. Finally, it must be emphasized that the domains and instability regimes exhibited in a map should be validated by detailed microstructural examination before the results are implemented.

6. Hot-Working Behavior of Materials

Over the past two decades, processing maps have been developed on more than 200 materials including pure metals, binary and ternary alloys, metal matrix composites, and aluminides. These have been compiled in the form of a compendium of processing maps, which serves as a hot-working guide[23] and also resulted in more than 100 publications. These researches have revealed some general patterns of material behavior in hot working and few important results are outlined below:

- The controversy regarding the occurrence of DRX in pure aluminum is put to rest since the maps obtained on aluminum of different purities not only revealed a domain of DRX but also responded to the effect of impurities which influence the rate of grain boundary migration. DRX in aluminum does not exhibit the so-called critical strain since it has a high rate of nucleation and occurs right from the start of plastic flow.
- In copper, the processing maps brought out the important effect of interstitial oxygen which can change the rate controlling mechanism at high temperatures from one of dislocation core diffusion in oxygen free copper to another of lattice self diffusion.
- In nickel, the effect of Curie temperature (354 °C) on its stacking fault energy is reflected in its hot-working behavior, which is similar to that of a low stacking fault energy metal like copper although its room-temperature stacking fault energy is closer to aluminum. In nickel-based superalloys, the maps have recorded the important effects of γ' and carbides on the workability window.
- The possibility of producing novel microstructures in alloy steels by post deformation cooling of dissipative structures is revealed while in stainless steel the various regimes of flow instabilities and their manifestations have been established.
- In magnesium and alloys, the importance of slow speed forging, rolling, and extrusion at higher temperatures in avoiding the flow localization is brought out in addition to the need to homogenize the alloys and use connected processing schedules.
- In titanium alloys, the response of lamellar versus equiaxed starting microstructures to hot working as well as the role of oxygen content is revealed.
- In Zn alloys, the advantage of using high speed forming at warm temperatures is brought out.
- In metal-matrix composites, although the behavior of the matrix phase is modified by the dispersoid, the basic mechanism of hot deformation is not significantly changed.
- The basic hot deformation mechanisms like DRX, large grained superplasticity and globularization of lamellar structures that occur in metallic materials, also occur in aluminides and these can be used for optimizing hot workability and controlling microstructures in this special class of materials.[21,24,25]

7. Applications to Solve Industrial Problems

Processing maps have been used to solve the workability problems in the industry and few of the examples are discussed in the *Hot Working Guide*.[23] A brief list includes the following:

- Forging of metal matrix composite 6063 Al with SiC particulates
- Extrusion of 2124 Al with SiC whiskers
- Optimization of impact extrusion of Zn alloy for battery cans
- Connected processing schedule for Mg alloy plate manufacture
- Upset forging of as-cast Ni-Ti shape memory alloy

- Strain induced porosity in ELI grade Ti-6Al-4V cogging process[26]

In general, in the analysis of industrial workability problems using processing maps, the emphasis was more on exploiting the limiting conditions for the flow instability than using the optimum parameters for the workability domain. The obvious driving force is to maximize the productivity by pushing the speed as high as possible but without the onset of flow instability. Very often, the modification of the processing history in the prior processing step will help in expanding the workability window and permit faster processing. Thus in designing such connected processing steps, processing maps developed after each stage of processing will be of immense help to optimize the next step and so on.

8. Development of AI Techniques and Expert Systems

The availability of large amount of data and information on materials regarding their hot workability has prompted the development of expert systems and artificial intelligence techniques like artificial neural networks for the purpose of encouraging and aiding a novice in this area to use it for process design and control. The recently developed expert system[27] for forging called FORGEX is probably the first one of its kind that would address the materials workability issues directly. This system uses the database for optimum conditions of workability and a knowledge base for machines, lubricants, and die materials to deliver forging solutions for a given material. In addition, it gives information about the metallurgical aspects like grain size and alert regimes for flow instability as well as conducts an analysis of forging defects. Artificial neural network models are developed by training the system to recognize the patterns of behavior in DRX domain and the instability regimen, and these models may be used to interpret the processing maps in the absence of an expert.

9. Conclusions

The concept of processing maps has reached a mature stage and may be used as an effective tool for optimization of hot workability and control of microstructure in a wide range of materials. It may be integrated with any finite element code for large plastic flow in the form of constitutive equations as well as in mapping the microstructural features in a component being hot worked. It is also effective in designing processes from the materials workability viewpoint and in analyzing the formation of both micro and macro defects in metal working processes. Application of the concept of deterministic chaos will lead into the synthesis of novel microstructures and in developing control systems for achieving stable microstructures in hot worked products.

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