Instability Maps: An Aid to Tool Design

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The properties of metals and their alloys depend strongly on their processing history. For example, the distributions of phases, grain structure, alloy compositional segregation, and defects in final commercial products depend strongly on the conditions under which the materials are fabricated. These microstructural changes during processing are crucial in determining properties such as strength, ductility, homogeneity, conductivity, and others that are important for industrial applications. Research all over the world is focusing on development of predictive models needed by industry for tailoring materials properties for particular applications. The present paper discusses the development of various models for microstructural control during processing for a 15Cr-15Ni-Titanium modified austenitic stainless steel. This is known as alloy D9 in nuclear industry and bears technological significance as a candidate material for in-core applications of fast breeder reactors as clad and wrapper tubes. To begin with, a material model that clearly identifies a processing window is developed for this alloy. Subsequently, the concept of activation energy maps to identify the instability domain is used to find the processing window. A process simulation model was used to design the process and the tooling for hot extrusion of this alloy. In the process simulation a general-purpose finite element package is used to simulate the extrusion process, and the results are compared with the domains of the processing window to design the process.

Keywords alloy D9, dynamic materials model, dynamic recrystallization, FEM simulation, flow instabilities, hot extrusion, tool design

1. Introduction

Austenitic stainless steels, primarily AISI 316 and its modifications, have been selected worldwide as prime candidate materials for fuel cladding and subassembly wrapper tubes of fast breeder reactors. A 15Cr-15Ni-2.2Mo-0.3Ti austenitic stainless steel has been developed indigenously for applications as in-core material for the prototype fast breeder reactor program in India.[1] This conforms to ASTM A771 UNS 38660 and is commonly referred to as alloy D9. This material is a candidate material for in-core applications as fuel cladding tube and hexagonal subassembly wrapper. Considering the critical application of this alloy, it is necessary to process this material to produce defect free products with controlled microstructure. Thus the constitutive behavior of this material needs to be understood to arrive at the optimum processing parameters. Based on dynamic materials modeling (DMM),[2] the processing maps are generated for this alloy and the "safe" and "unsafe" domains have been identified.[3] Extensive microstructural characterisation was carried out to find out various mechanisms in the various domains of the processing map. Rolling and forging tests were also performed to validate the predictions of the processing map of this alloy and reported that the predictions of the processing map are accurate.[4]

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2. Instability Maps of Alloy D9

In DMM, the efficiency of power dissipation through microstructural changes, given by $\eta = 2m/(m + 1)$, where m is the strain rate sensitivity, is plotted as a function of temperature and strain rate to obtain a processing map. The different domains exhibited by the map are correlated with specific microstructural processes occurring during hot working. The domain of dynamic recrystallization (DRX) and dynamic recovery (DRY) are identified as the best regions to process the material. However, in some alloy systems these domains occur at very low strain rates and the productivity would be drastically affected if processed at such low strain rates. Hence a safe domain at higher strain rates that increases productivity is better to use for processing. The "instability" domain needs to be found and ensured during the process the processing parameters are always in the processing window. The DMM has its basis in the extremum principles of irreversible thermodynamics as applied to large plastic flow described by Ziegler.[5] Kumar[6] and Prasad[7] developed a continuum criterion combining these principles with those of separability of power dissipation and have shown that flow instability will occur during hot deformation if $\xi(\dot{\varepsilon}) = \{\partial \ln[m/(m + 1)]/\partial \ln \dot{\varepsilon}\} + m < 0$. Where $\dot{\varepsilon}$, is strain rate. The variation of the instability parameter with temperature and strain rate constitutes an instability map, which may be superimposed on the processing map for delineating the regimes of flow instability.

Figure 1 gives the processing map developed based on DMM criterion and the safe and unsafe domains are identified in the diagram.[3] At lower temperatures and higher strain rates, flow localization is found to occur. The instability map (Fig. 2) exhibited unsafe domains at lower temperatures and higher strain rates. The microstructural features revealed flow localization as instabilities. A different approach to identifying the

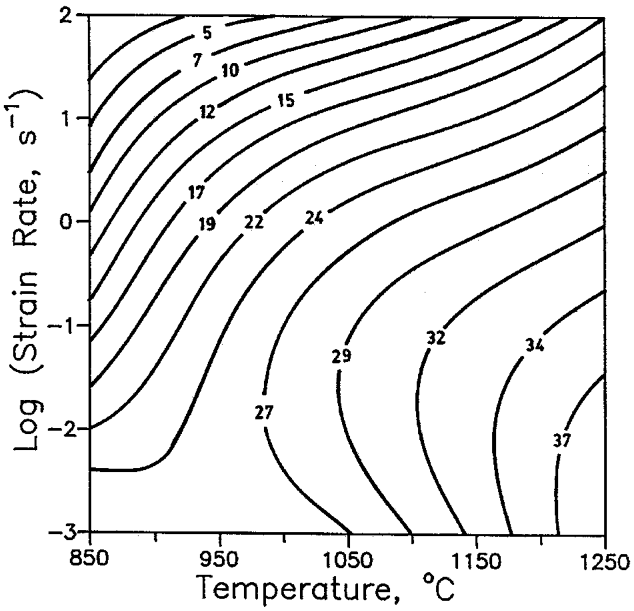

Fig. 1 Contour map representing iso-efficiency contours {$\eta = [2m/(m+1)]$, marked as percent}, at a strain of 0.4

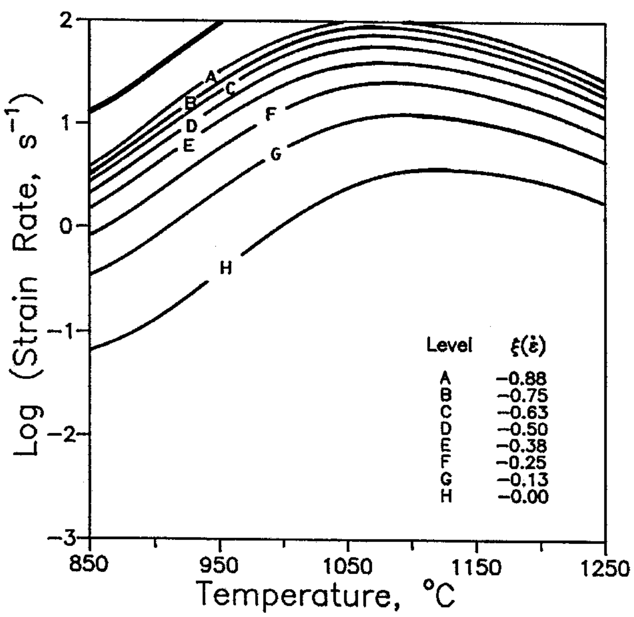

Fig. 2 Contour map representing instability parameter marked as percent for alloy D9 at a strain of 0.4

safe and unsafe domains is based on the apparent activation energy maps discussed below.

The operating mechanisms in high temperature deformation can be identified based on the values of Q, the apparent activation energy. Gegel et al.[8] have suggested the following equation to calculate Q as

$$Q = 2.3\,\mathrm{k}\left(\frac{\delta \log \dot{\varepsilon}}{\delta \log \sigma}\right)\left(\frac{\delta \log \sigma}{\delta (1/T)}\right),$$

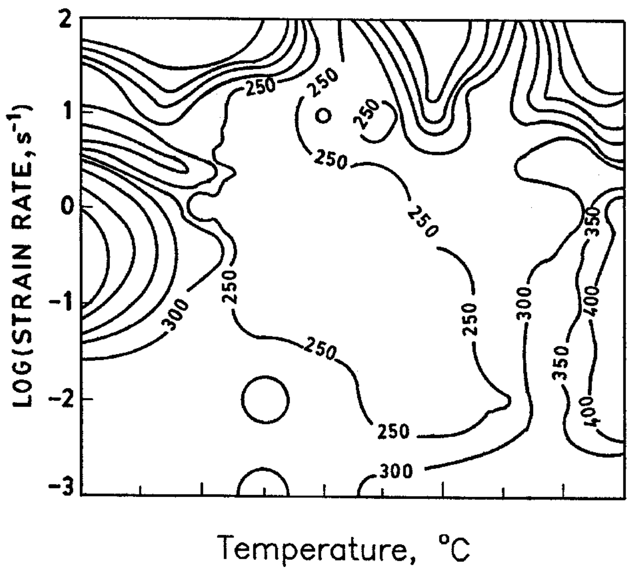

Fig. 3 Contour map representing activation energy in kJ/mol for alloy D9

where k and T have their usual meanings. Lagneborg[9] has shown that correct values of activation energy can also be obtained from continuous tests rather than more often used strain rate change or temperature change tests. According to the DMM theory, Malas and Seetharaman[10] suggested that stable processing windows should correspond to "stable" Q regimes, i.e., where a plateau of Q exists. Long and Rack[11] have used this concept in identifying the unsafe domains for Ti-26Al-10Nb-3V-1Mo alloy. The values of activation energy were computed based on the equation explained above for alloy D9, and the variation of activation energy as a function of temperature and strain rate is given in Fig. 3 as a contour map. The values of activation energy in kJ/mol are indicated in the map as iso-activation energy contours. It can be seen from Fig. 3 that at low temperatures and high strain rates, the contours are very close when compared with the high temperatures and low strain rates regimen. The stable Q regimen identified on the basis of activation energy maps is in very good agreement with the unsafe domains identified based on instability parameter $\xi(\dot{\varepsilon})$. During processing these unsafe domains need to be avoided.

3. Process Design Using Instability Maps

The instability maps are generated using closed loop servo-hydraulic system under controlled conditions of temperature and strain rate. However, in any manufacturing process, the material will be subjected to a range of strain rates depending on the geometry of the deformation zone. As the processes in industry are non-isothermal, there will be temperature gradients from the surface to interior of the work piece. Since the dissipative microstructures occurring in the work piece are dependent on temperature and strain rate as decided by the constitutive behavior of the work piece, there will be microstructural inhomogenities in the work piece. Therefore, the

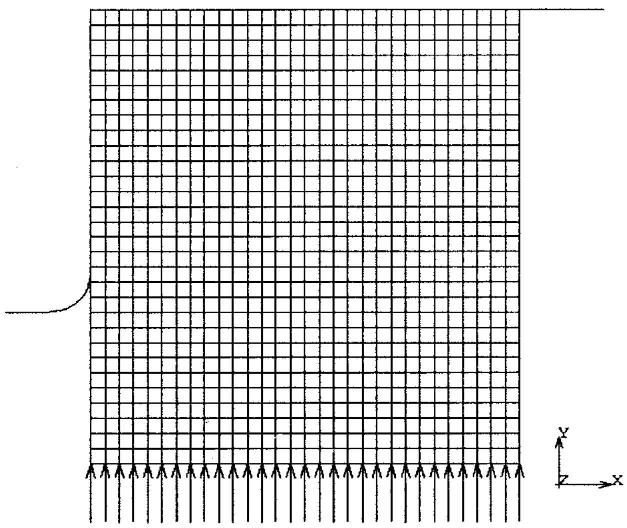

Fig. 4 Initial finite element configuration for the extrusion trials

simulation of a manufacturing process is necessary to understand the variation of process parameters in the deformation zone to decide the processing schedule. An extrusion process is simulated to know the process parameters in the deformation zone to understand the microstructure developed during deformation. Since the billets of alloy D9 are coated with glass lubricant prior to extrusion and the extrusion die is preheated, isothermal conditions were assumed to simulate the material flow in the deformation zone. The simulation is carried out for a circular billet to circular rod forward extrusion. Hence the problem simplifies to a 2D axisymmetric case.

4. Simulation Procedure

Since plastic strains outweigh elastic strains in most of the metal forming processes, the idealization of rigid-plastic behavior could be assumed. This allows larger increments of deformation and reduces computational time with reasonable amount of accuracy of the solution. The constitutive equation used was of the type $\sigma = K\dot{\varepsilon}^m$ where σ is the flow stress and $\dot{\varepsilon}$ is the strain rate. The constants were obtained as $K = 99.8$ and $m = 0.192$ using the flow stress data at 1200 °C of this material, with a correlation coefficient of 0.99.[3] The initial configuration of the mesh is shown in Fig. 4 for the billet size of 120 mm diameter with the die opening of 40 mm diameter. Due to symmetry, half of the billet is simulated for extrusion. Axisymmetric elements type 10 of Marc library[12] were used in this simulation. Since the elements would become severely distorted during the deformation, the automatic re-meshing of Marc was used to overcome this problem. The simulation was carried out for the ram speeds of 4, 80, 200, and 300 mm/s.

5. Results and Discussion

The simulation without periodic re-meshing resulted in a badly distorted mesh and penetration of the metal into the die. To overcome these problems, the re-mesh option of Marc was used. Due to the intermediate re-meshing, there was no observed penetration of the metal into the die. The strain rate contour plots were obtained for various ram speeds of 4, 80, 200, and 300 mm/s. Figure 5 shows the strain rate contours for a ram speed of 80 mm/s. The maximum strain rate is noticed near the die entrance. At all other regions of the billet, the strain rate experienced by the material is very much lower. It was observed that as the ram speeds increased, the strain rates in the deformation zone progressively increased. Table 1 gives the maximum strain rates observed for various ram speeds.

The various domains identified based on DMM and extensive microstructural studies, hot ductility measurements are explained below[3]:

1) DRX occurs in the temperature range 1000-1200 °C, and strain rates are in the range 0.001-1 s^{-1}.
2) Flow instabilities occur at high temperatures and at strain rates above 7 s^{-1}. At lower temperatures they are manifested at lower strain rates. In different regions, these are manifested as dynamic strain ageing, adiabatic shear deformation, and flow localization.

Among all the processes DRX is the most preferred process since the intrinsic workability of the material is enhanced by the reconstitution of strain free grains. Also the regions of flow instability need to be avoided during processing. Generally hot extrusion of steel is carried out with glass as lubricant with the preheating of dies. The pre heating temperature is in the order of 300 °C. During the extrusion, the billets will also be heated up due to the heat generated as the result of deformation. The heat balance for the extrusion process has been studied and found that the temperature loss to the material during extrusion would be of the order of 50 °C, and hence isothermal extrusion is considered in the current study. Since the temperature for safe processing widow for this material is in the range from 1050 to 1250 °C, this assumption may not introduce any significant error. The extrusion carried out at 1200 °C with the ram speed of 4 mm/swould result in very low strain rates (of the order of 10^{-2} s^{-1}) in the deformation zone and might lead to grain growth. Even though this region is in the safe zone of the processing map, this is not preferred since productivity of the plant is severely affected. A ram speed of 300 mm/s (Table 1) resulted in the maximum strain rates in the range 40-45 s^{-1} near the die entrance. The strain rates in the deformation zone were in the range 15-25 s^{-1}. If the extrusion were carried out at 300 mm/s at a temperature of 1200 °C, the strain rates seen by the material during extrusion would appear in the flow localization domain. Such processing parameters that use the "unsafe" domain of the processing map are not favored, and the ram speed of 300 mm/s needs to be avoided.

The strain rates are in the range 1-2 s^{-1} in the deformation zone for the ram speed of 80 mm/s (Fig. 4) with the maximum strain rates of 7-9 near the die entry. All these strain rates are within the safe domain of the processing map, and the strain rates of 1 s^{-1} are in DRX domain. Hence this is the ideal ram speed for extruding this material at a temperature of 1200 °C. The strain rates observed in the deformation zone of the extrusion with the ram speed of 200 mm/s (Fig. 5) falls in both the safe and unsafe domains of the processing map. Since some of the unsafe domain is used during processing, there would be

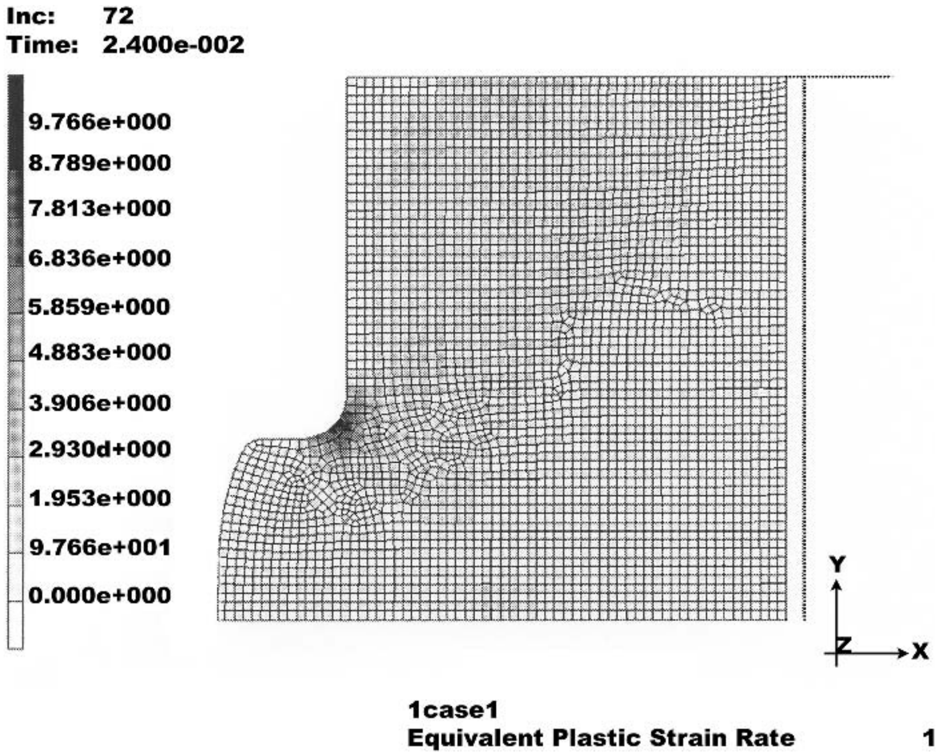

Fig. 5 Final finite element configuration after remeshing at a ram speed of 80 mm/s

Table 1 Maximum Strain Rate Observed at Various Ram Speeds During Extrusion

Ram Speed, mm/s	Max. Strain Rate, s^{-1}
4	0.02-0.04
80	7-9
200	20-25
300	40-45

likelihood of some microstructural defects and hence such processing conditions need to be avoided or examined carefully before selecting these processing parameters.

6. Conclusions

Based on the finite element simulation of the extrusion process and comparing the results with a processing map of type 304L material, the following conclusions are drawn:

- A ram speed of 80 mm/s is optimum for extruding this material where the strain rates in the deformation zone coincide with the DRX domain of the processing map.
- Even though a ram speed of 4 mm/s is in the safe domain of the processing map, considering the productivity of the plant, this ram speed need not be selected.
- Ram speeds of both 200 and 300 mm/s result in the strain rates that fall in the unsafe domain of the processing map and need to be avoided.
- It is illustrated that the output of a processing map could be used with the results of a finite element simulation to design a metal forming process to obtain favorable microstructures of the product.

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