JOURNAL OF MATERIALS SCIENCE **39** (2004) 5557–5560 LETTERS

Strategy for the design of thermomechanical processes for AISI type 304L stainless steel using dynamic materials model (DMM) stability criteria and model for the evolution of microstructure

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The dynamic materials model (DMM) [1] is a proven technique for studying constitutive behavior of materials. In this model, 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 DMM processing map. The different domains exhibited by the map are correlated with specific microstructural processes occurring during hot working. Prasad [1] has 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 the strain rate. The variation of the instability parameter, $\xi(\dot{\varepsilon})$ with temperature and strain rate, constitutes an instability map, which may be superimposed on the processing map for delineating the regimes of flow instability.

The optimal domains predicted by the DMM processing maps are quite wide. In practice, in a wide domain it is very difficult to control the microstructure of the product. Hence, some refining procedure needs to be established for the precise control of the microstructure during working. Malas and Seetharaman [2] proposed stability criteria based on DMM. According to them the optimal processing windows for safe working are: $0 < m \leq 1$, $\dot{m} < 0$, $s \geq 1$, and $\dot{s} < 0$, where $\dot{m} = \partial m/\partial \ln \dot{\varepsilon}$, $s = \partial \log \sigma/\partial(1/T)$, $\dot{s} = \partial s/\partial \log \dot{\varepsilon}$ and T = temperature in K. The apparent activation energy $Q = sRT/m$, where R = gas constant. In this methodology the reasonable "safe" processing range corresponds to the processing condition where a desirable and fairly constant value of Q is operative. These criteria can be used to refine the safe processing window to achieve better microstructural control during processing.

In order to control the development of microstructure during hot working, a new strategy for systematically calculating near-optimal control parameters for hot deformation process has been proposed [3]. This approach involves developing state-space models from available material behavior and hot deformation process models. The control system design consists of two basic stages, and analysis and optimization are critical in both stages. In the first stage, the kinetics of certain dynamic microstructural behavior and intrinsic hot workability of the material are used, along with an approximately chosen optimality criterion, to calculate the optimum strain ($\varepsilon(t)$), strain-rate ($\dot{\varepsilon}(t)$), and temperature ($T(t)$) trajectories for processing. A suitable process simulation model is then used in the second stage to calculate process control parameters, such as ram velocity, die profiles, and billet temperature, which approximately achieve the strain, strain-rate, and temperature trajectories calculated in the first stage. This process design approach treats the deforming material as a dynamic system and involves developing state-space models from available material behavior and hot deformation process models. The design approach requires three basic components for defining and setting up the optimization problem: (1) a dynamic system model, (2) physical constraints, and (3) an optimality criterion. The system models of interest are material behavior and deformation process models. Constraints include the hot workability of the workpiece and the limitations of the forming equipment. Optimality criteria could be related to achieving a particular final microstructure (grain size), regulating temperature, and/or maximising deformation speeds. Fig. 1 describes the steps involved in the proposed new approach [3]. The microstructure development optimization determines optimal trajectories of strain, strain rate, and temperature. From these optimal trajectories, the process optimization 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, models of material behavior that describe the kinetics of primary metallurgical mechanisms such as dynamic recovery, dynamic recrystallization, and grain growth during hot working are required for analysis and optimization of material system dynamics. The objective is to define the acceptable ranges of temperature and strain rate over which the material exhibits a "safe" processing window. The complete details of this approach are available elsewhere [3].

The aim of the present investigation is to evaluate the constitutive flow behavior of austenitic stainless steel

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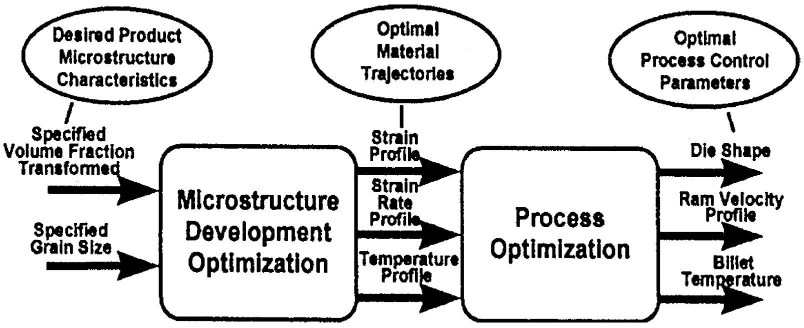
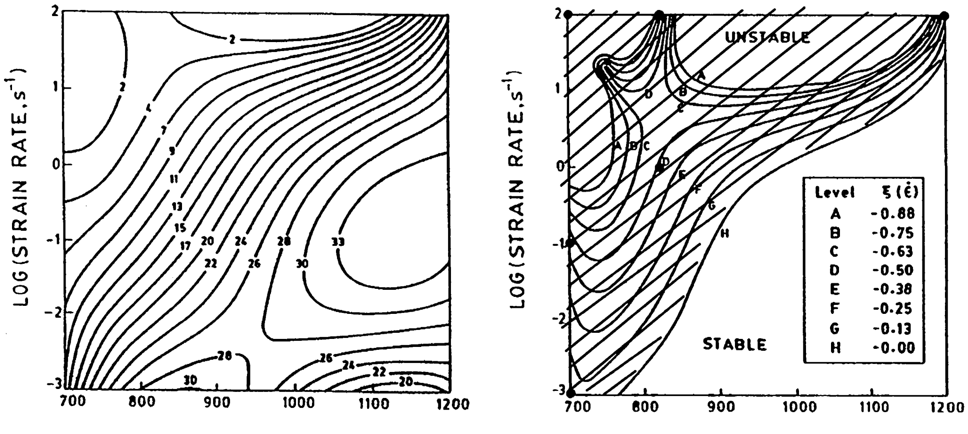


Figure 1 A schematic of the two-stage approach [3].



(a) (b)

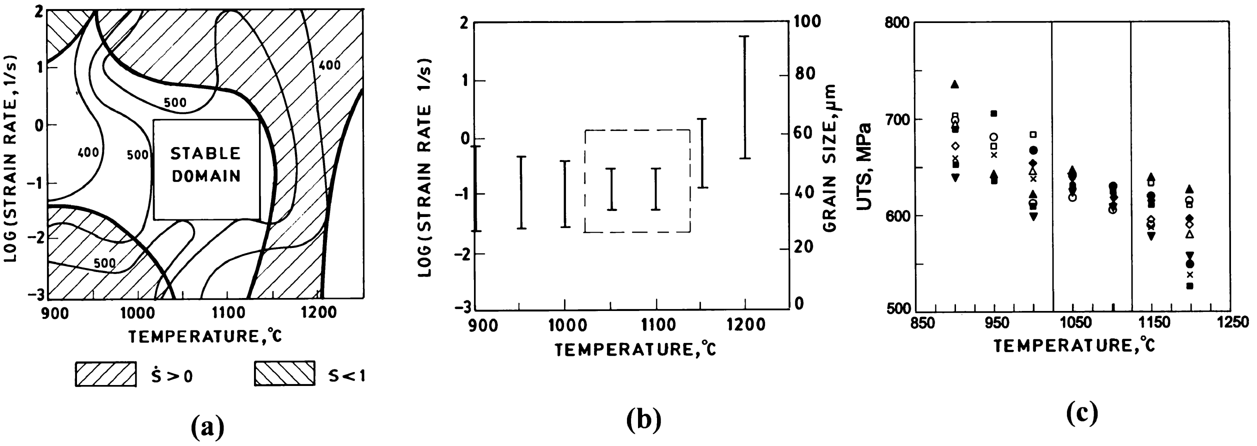
Figure 2 (a) Processing map representing iso-efficiency contours (marked as pct.) and (b) instability map representing the variation of $\xi(\dot{\varepsilon})$ parameter for stainless steel type AISI 304L.

type AISI 304L in order to generate DMM processing maps for the purpose of identifying optimum parameters for hot working. These processing maps are further refined using the parameters m, $\dot{m}$, s, $\dot{s}$ and Q. Further, models for the evolution of microstructure are developed in the 'refined window' for controlling the development of microstructure during hot working. An extrusion process has been designed using the new two-stage methodology for stainless steel, type AISI 304L, in order to obtain a desired grain size at 35 μm in the product. In order to validate the usefulness of the refining procedure, extrusion trials were conducted at optimum conditions.

Stainless steel of type AISI 304L was used in this investigation and the details of the experimental procedure and the procedure for obtaining processing maps are available elsewhere [4]. The power dissipation map obtained at a strain of 0.5 for stainless steel AISI 304L is shown in Fig. 2a. The map reveals a favourable domain occurring in the temperature range of 1000 to 1200 °C and strain-rate range of 0.01 to 5 s^{-1} with a peak efficiency of about 33 pct at 1150 °C and 0.1 s^{-1}. It has been proved that this domain represents the process of dynamic recrystalization (DRX) [4].

The variation of the instability parameter $\xi(\dot{\varepsilon})$ with temperature and strain rate at a strain of 0.5 is shown in Fig. 2b. According to this criterion, the regimes of the map where $\xi(\dot{\varepsilon})$ is negative will represent unstable flow and are above by contour H, indicated as hatched area in Fig. 2b. The phenomena responsible for the unstable flow are identified as flow localization and dynamic strain aging [4].

The values of m, $\dot{m}$, s, $\dot{s}$ and Q have been calculated and contour maps have been generated for stainless steel type 304L and 316L. A typical contour map of the above parameters at a strain of 0.5 for 316L is given in Fig. 3. The stable domain, where Q = constant is marked in the figure, which is a refined window for processing. The results of the press forging trials carried out at industrial scale on SS 316L in the temperature range 900 to 1200 °C have demonstrated the potential of this refining procedure in process optimization. The grain size and the room temperature mechanical properties of the forged products were evaluated. The measured grain size as a function of forging temperature is given in Fig. 3b. Fig. 3b shows that the variance in the grain size of the samples deformed in the stable domain is small. The above feature implies that a small variation in temperature will not cause a change in grain size in the product. Hence, the control of microstructure in the product is precise if the material is processed in the stable regime. The values of UTS of the forged products as a function of forging temperature are given in Fig. 3c. Fig. 3c shows that the variance in UTS values is much less in the products forged in the stable region whereas the scatter is large in the products that are forged in the unstable regions. The same feature is observed in the values of YS and ductility. When the



(a) (b) (c)

Figure 3 (a) DMM stability map for stainless steel 316L; the values of activation energy are represented as contours in kJ/mol and variation of (b) grain size of the rolled products of 316L as a function of rolling temperature and (c) UTS of the forged products of 316L (deformed at 0.15 s^{-1}) as a function of forging temperature.

material is processed within the stable region, metallurgical and mechanical properties have low sensitivity to small variations in external stimuli, and these properties are not sensitive to the path [5]. It is not sensitive to path because the process is operating in an 'extremum' (a region of low and nearly constant activation energy). In the unstable regions, an infinite number of paths can exist, which are sensitive to small variations in external stimuli such as temperature and strain-rate fluctuations. The process is robust in nature in this refined domain. A change in the temperature and strain rate during processing will not cause significant changes in the microstructure and properties of the product. In industrial conditions, the robust process is preferred in order to control the process effectively. For stainless steel type, AISI 304L, a region in the temperature and strain rate envelope of 1020 to 1120 °C and 0.1 to 5 s^{-1} respectively, is found to be the 'safe' processing window using the refining procedure.

The two-stage (Fig. 1) 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 mentioned two-stage approach. An empirical model for the DRX process in 304L has been developed for this purpose in the 'refined window.' The effects of strain, strain rate, and temperature, on microstructural evolution of this material in this refined window are:

volume fraction recrystallized,

$$\chi = 1 - \exp\left[\ln(2)\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{0.5}}\right)^2\right] \tag{1}$$

critical strain,

$$\varepsilon_c = 5.32 \times 10^{-4} e^{8700/T} \tag{2}$$

plastic strain for 50% vol. recrystallization,

$$\varepsilon_{0.5} = 1.264 \times 10^{-5}\, d_0^{0.31}\, \varepsilon^{0.05}\, e^{6000/T} \tag{3}$$

and average recrystallized grain size,

$$d = 20560\dot{\varepsilon}^{-0.3} e^{-0.25\left(\frac{Q}{RT}\right)} \tag{4}$$

where, d_0 = initial grain diameter, ε = strain, T = temperature in K, d = grain diameter μm, $Q = 310$ kJ/mol and $R = 8.314 \times 10^{-3}$ 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.

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) will be considered. The desired final grain size in the product is 35 μm. For the above case, the following optimality criterion was chosen:

$$J = 10(\varepsilon(t_f) - 3.46)^2 + \int_0^{t_f} (d(t) - 35)^2 \mathrm{d}t \tag{5}$$

where a desired final strain of 3.46, a weight factor of 10, and a desired grain size of 35 μm have been specified. The optimal strain, strain rate, and temperature trajectories have been obtained using the above criteria and microstructural model. The optimal strain, strain rate, and temperature trajectories are given in Fig. 4a. Using the following relationships (Equations 6 and 7) the shape of the extrusion die for extruding the material has been obtained.

$$V_{\mathrm{ram}} = \frac{L}{\int_{t=0}^{f_t} e^{\varepsilon(t)} \mathrm{d}t} \tag{6}$$

$$r(t) = r_0 e^{-\varepsilon(t)/2}, \quad y(t) = V_{\mathrm{ram}} \int_0^t e^{\varepsilon(t)} \mathrm{d}t. \tag{7}$$

where r_0 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). Fig. 4b gives the optimum die profile for achieving a 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 when billet temperature is 1080 °C.

The extrusion test was performed at optimum conditions of temperature and ram velocity with the die having the optimum profile. The extruded tube was ejected

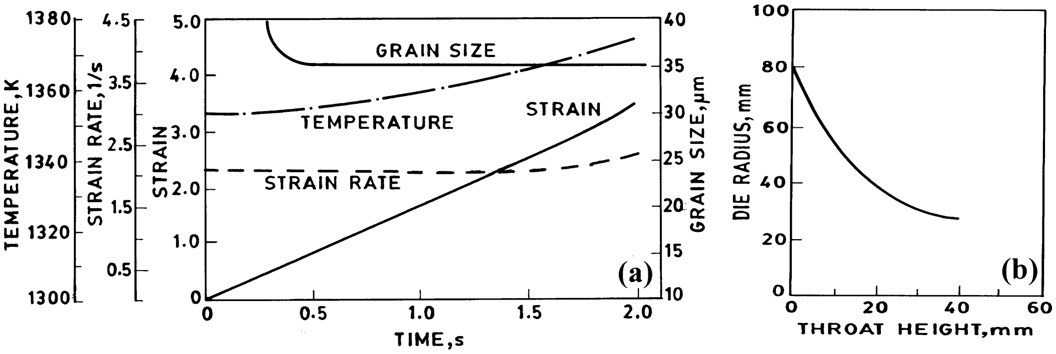


Figure 4 (a) Trajectories of strain, strain rate, temperature and grain size and (b) Optimum die profile for achieving a final grain size of 35 μm in 304L.

into a water tank immediately after the completion of the extrusion. Microstructural examination carried out along the entire length of the tube revealed that there was no variation in microstructure along the length. The measured average grain size was 38 μm, very close to the designed value.

The constitutive flow behavior of stainless steel type AISI 304L was studied in the temperature range 600 to 1200 °C and strain rate range 0.001 to 100 s^{-1}, with a view to optimising the hot workability. The process parameters for the optimum workability in 304L stainless steel were 1150 °C and 0.1 s^{-1}, and the temperature and strain rate ranges for obtaining DRX microstructure were: 1000 to 1200 °C and 0.01 to 10 s^{-1} respectively. New methodologies to refine the safe processing window and for better microstructural control have been presented. The validity of the proposed methodologies for refining the processing window and for controlling the development of microstructure during hot working has been demonstrated with an extrusion trial on an industrial scale.

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Received 6 February 2003
and accepted 16 April 2004