The hot working behavior of 304L stainless steel is characterized using processing maps developed on the basis of the Dynamic Materials Model and hot compression data in the temperature range of 700 °C to 1200 °C and strain-rate range of 0.001 to 100 s⁻¹. The material exhibits a dynamic recrystallization (DRX) domain in the temperature range of 1000 °C to 1200 °C and strain-rate range of 0.01 to 5 s⁻¹. Optimum hot workability occurs at 1150 °C and 0.1 s⁻¹, which corresponds to a peak efficiency of 33 pct in the DRX domain. Finer grain sizes are obtained at the lower end of the DRX domain (1000 °C and 0.1 s⁻¹). The material exhibits a dynamic recovery domain in the temperature range of 750 °C to 950 °C and at 0.001 s⁻¹. Flow instabilities occur in the entire region above the dynamic recovery and recrystallization domains. Flow localization occurs in the regions of instability at temperatures lower than 1000 °C, and ferrite formation is responsible for the instability at higher temperatures.

I. INTRODUCTION

The hot working characteristics of austenitic stainless steels have been studied extensively using torsion, tension, and compression techniques, and the influence of hot deformation parameters on the hot workability and the development of microstructure has been reported. [1-4] The hot ductility is higher in the regime of dynamic recrystallization (DRX), which occurs in the temperature range of 1100 °C to 1200 °C and torsional strain-rate range of 0.1 to 5 s⁻¹. The apparent activation energy for hot deformation was estimated to be in the range of 347 to 508 kJ/mol. Although these studies have led to the understanding of the mechanisms of hot deformation, they cannot be directly used for the optimization of hot workability. The aim of the present investigation is to develop a processing map for hot working of 304L stainless steel and use it for the optimization of hot workability and controlling the microstructure. The constitutive behavior of 304L stainless steel has been studied in detail by Semiatin and Holbrook [5] using hot torsion and hot compression. The material undergoes flow localization at higher strain rates and lower temperatures, while DRX occurs above 1000 °C. The influence of forging speed on the microstructure of 304L has been investigated by Mataya et al., [6] and processing-property maps have been generated. Dynamic recovery occurred at lower forging temperature, while softening due to recrystallization was seen at higher strain rates and temperatures.

The processing maps are developed on the basis of the principles of the Dynamic Materials Model, [7] which is reviewed by Gegel et al., [8] and Alexander. [9] In this model, the workpiece under hot working conditions is considered to be a dissipator of power. At any instant, the power dissipation occurs through a temperature rise ($G$ content) and a microstructural change ($J_{co}$ content), and the power partitioning between these two is decided by the strain-rate sensitivity ($m$) of flow stress ($\sigma$). At a given temperature and strain, the $J_{co}$ content is given by

$$J = \frac{m}{m + 1} \sigma \dot{\varepsilon}$$

where $\dot{\varepsilon}$ is the strain rate. The $J_{co}$ content of the workpiece, which is a nonlinear dissipator, is normalized with that of an ideal linear dissipator ($m = 1$) to obtain a dimensionless parameter called efficiency of power dissipation:

$$\eta = \frac{J}{J_{max}} = \frac{2m}{m + 1}$$

The variation of $\eta$ 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 Materials Model has its basis in the extremum principles of irreversible thermodynamics as applied to large plastic flow described by Ziegler. [10] Kumar [11] and Prasad [12] 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

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln (m/m + 1)}{\partial \ln \dot{\varepsilon}} + m < 0$$

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 regions of flow instability.
II. EXPERIMENTAL

Stainless steel of type AISI 304L of the following composition (weight percent) was used in this investigation: 0.02C, 0.005S, 0.035P, 10.3Ni, 18.6Cr, 1.7Mn, 0.58Si, 0.07Mo, balance Fe. The starting material was in the form of 25-mm hot-rolled rods in solutionized condition. The rods were cold swaged to 12-mm diameter and annealed at 1050 °C for 30 minutes. The resulting average grain diameter was 110 μm. Cylindrical specimens of 10-mm diameter and 15-mm height were machined for hot compression testing. During machining, it was ensured that the edges of the specimen were chamfered to avoid foldover in the initial stages of compression. Also, concentric grooves were provided on the faces of the specimens to ensure effective lubrication during compression. Borosilicate glass was used as a lubricant. The temperature of the specimen was monitored with a thermocouple embedded in a 0.8-mm diameter hole drilled at half the height of the specimen. This thermocouple was also used for the measurement of the adiabatic temperature rise in the specimen during deformation. A computer-controlled servohydraulic machine (DARTEC, Stourbridge, West Midlands, United Kingdom) was used for conducting the hot compression tests. This machine was equipped with an exponential decay of the actuator speed so that constant true strain rates in the range of 0.001 to 100 s⁻¹ could be imposed on the specimen. Isothermal tests were conducted by surrounding the specimen, platen, and push rods with a resistance furnace with silicon carbide heating elements. The temperature was controlled within ±2 °C. The adiabatic temperature rise was recorded with the help of a Nicolet transient recorder. The tests were conducted over a temperature range of 700 °C to 1200 °C at intervals of 50 °C at different true strain rates ranging from 0.001 to 100 s⁻¹. In each case, the specimens were compressed to about half their height, and the load-displacement data were obtained. The deformed specimens were water quenched and examined using standard metallographic techniques.

The procedure for obtaining power dissipation maps was as follows: The load-stroke curves obtained in compression at a constant temperature and true strain rate were converted into true stress—true plastic strain curves using standard equations. The flow stress data as a function of temperature, strain rate, and strain were obtained from the above curves and used for constructing the power dissipation maps. The log flow stress vs log strain rate data were fitted using a cubic spline, and the strain-rate sensitivity (m) was calculated as a function of strain rate. This was repeated at different temperatures. The efficiency of power dissipation through microstructural changes [η = 2m/(m + 1)] was then calculated as a function of temperature and strain rate and plotted as a three-dimensional map and an isoefficiency contour map. The data were also used to evaluate the instability parameter ξ(ε) (Eq. [3]) as a function of temperature and strain rate and to obtain an instability map.

The ductility in hot torsion was measured in the temperature range of 700 °C to 1200 °C and effective strain-rate range of 0.1 to 100 s⁻¹. Hot torsion tests were performed on a microprocessor-controlled machine which has the facility for torsional speed regulation within 1 pct and angular twist measurement within ±1 deg. The effective fracture strain for each test condition was measured from the angle of twist data and was taken as a measure of hot ductility.

III. RESULTS

The microstructure of the starting material is shown in Figure 1, which reveals equiaxed grain structure. True stress—true strain curves (typical of the behaviors at temperatures lower than about 1000 °C) are shown in Figure 2 for 800 °C. These curves show that the material exhibits work hardening, and the work hardening rate is lower at lower strain rates. The stress-strain curves at temperatures higher than 1000 °C and strain rates lower than 1 s⁻¹ revealed that the material exhibits flow softening. (Typical curves at 1200 °C are shown in Figure 3.) It is observed that the material exhibits flow...