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Characterization of hot deformation behavior of alloy 617 through kinetic analysis, dynamic material modeling and microstructural studies

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ABSTRACT

The hot deformation behavior of alloy 617 has been studied by performing hot compression in a range of temperatures (1173–1473 K) and strain rates (0.001–10 s^{-1}). The peak flow stress found to increase with Zener–Hollomon parameter (Z) following a hyperbolic-sine function relationship whereas peak strain followed power-law type relationship with Z. The average activation energy for the entire hot deformation domain was estimated to be 481 kJ mol^{-1}. The experimental stress-strain data has been used to develop processing map employing dynamic material model. The material exhibits a wide stable domain below 0.1 s^{-1} spanning over 1250–1473 K, with a peak efficiency of ~45%. Based on the processing map and subsequent microstructural observation, the optimum hot deformation domain of alloy 617 is identified as 1323–1423 K and 0.001–0.1 s^{-1}. Furthermore, microstructural observation alone has revealed that a significant DRX with grain refinement could also be obtained at high temperature (> 1373 K) and high strain rate (> 1 s^{-1}) domain although processing map has marked this region as unstable domain.

1. Introduction

Alloy 617, a Ni-base superalloy which exhibits an exceptional combination of high temperature strength and good oxidation resistance is an attractive material for applications under corrosive environments, such as ducting, combustion cans of gas turbine, catalyst-grid supports in chemical industries etc. It also has wide applications in oil, marine and nuclear industries [1]. The desired components are manufactured by various thermo-mechanical processing (TMP) routes such as forging, rolling, extrusion etc. Mechanical properties of materials depend on the microstructure which, in turn, can be controlled by varying processing parameters (like strain, strain rate and temperature) during TMP [2,3]. Workability can be improved by the proper selection of hot working parameters in Ni-based superalloys [4–9]. At optimum temperatures and strain rates, the workability is enhanced through dynamic recovery (DRV) or dynamic recrystallization (DRX). Processing at non-optimum conditions significantly reduces workability due to severe plastic instabilities resulting in adiabatic shear band or wedge cracking [8,9]. Attention, therefore, needs to be focused on correlating the microstructure with flow behavior and optimizing process parameters of the alloy 617.

Processing map based on dynamic material modeling (DMM) is an excellent tool for the optimization of the process parameters for hot deformation [10,11]. The DMM is popular because of two reasons. Firstly, it consumes minimum time and effort. Secondly, it is well validated and has been applied to a range of materials such as steels [12–15], superalloys [4–9,16], Mg alloys [17–18], Al alloys [19–20], Ti alloys [21,22], Zr alloys [23] and intermetallic compounds [24,25]. The processing map using DMM considers hot deformation as a process of power dissipation and the work-piece is acting as a dissipater of power. For mathematical analysis, the total power dissipated (by work piece) P is divided into two complimentary parts G and J given as [11,26],

$$P = G + J \tag{1}$$

Total power dissipated can also be represented as,

$$P = \sigma\dot{\varepsilon} = \int_0^{\dot{\varepsilon}} \sigma.\, d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon}.\, d\sigma \tag{2}$$

where σ is the plastic stress and $\dot{\varepsilon}$ is the strain rate. G content $\left(\int_0^{\dot{\varepsilon}} ,\sigma.\, d\dot{\varepsilon}\right)$ is attributed to the power dissipation through plastic

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deformation whereas J content ($\int_0^{\sigma} \dot{\varepsilon}.d\sigma$) is attributed to power dissipation through metallurgical changes. The ratio of power attributed to metallurgical changes to total plastic deformation is referred to as strain rate sensitivity index (m),

$$\text{i e.} \left(\frac{dJ}{dG}\right)_{T,\varepsilon} = \left(\frac{\partial \ln\sigma}{\partial \ln\dot{\varepsilon}}\right)_{T,\varepsilon} = m \tag{3}$$

where T and ε are the temperature and strains at which deformation is taking place. The power dissipated by the microstructure is generally represented in efficiency of power dissipation. The efficiency (η) of power dissipation is a function of strain rate sensitivity (m) and could be derived as:

$$\eta = \frac{J}{J_{max}} = \frac{2m}{(m+1)} \tag{4}$$

where J_{max} is the theoretically maximum power that can be absorbed by the microstructure during the deformation. The variation of the efficiency with temperature and strain rate is called the power dissipation map or efficiency map. However, the efficiency parameter alone is not sufficient enough to delineate the safe domains from the unsafe ones. For this purpose, a flow instability criterion is used. As proposed by Ziegler [27], during hot deformation, flow localization or instability occurs when the rate of entropy generation by the material under deformation is not able to match the rate of entropy imposed on it. The instability criterion $\xi(\dot{\varepsilon})$ for plastic flow proposed by Ziegler [27], s given as,

$$\xi(\dot{\varepsilon}) = \frac{\partial log\left(\frac{m}{m+1}\right)}{\partial log(\dot{\varepsilon})} + m \leq 0 \tag{5}$$

While efficiency of power dissipation gives an idea about microstructural mechanisms at each forming condition, instability data could provide information regarding the forming feasibility in that domain. The region is considered as unsafe for processing if it is satisfying instability criteria ($\xi(\dot{\varepsilon}) \leq 0$).

In the past, processing maps of various Ni-base superalloys such as Ni-Cr-W alloy [4], Inconel 690 [5], 704 H [7], Haynes 230 [9], Inconel 718 [16, 28–30], have been developed. It has been suggested that DRX could occur at certain strain rates and temperatures which reduces forming loads, increases efficiency of power dissipation and results in a homogeneous microstructure. Limited work has been carried out in the area of processing map development for hot deformation of solid solution strengthened Ni-base superalloys, specifically in Ni-Cr-Mo system like alloy 617 [31]. The present study is carried out to understand the hot deformation behavior of alloy 617 as a function of strain, strain rate and temperature with an objective to optimize the processing parameters for hot deformation. Towards this, hot compression tests have been performed in the temperature and strain rate range of 1173–1473 K and 0.001–10 s^{-1} respectively. The experimental flow stress data have been subsequently used for kinetic analysis as well as to develop the processing map. The processing map domains have been validated through extensive microstructural studies.

2. Experimental procedure

2.1. Hot compression

The alloy 617 used in the present investigation was received from VDM Metals GmbH, Germany, solution annealed at 1448 K and quenched with water (abbreviated hereafter as AR specimen). The chemical composition of the alloy is given in Table 1. The isothermal uni-axial compression tests were carried out on cylindrical specimens of 10 mm diameter and 15 mm height using a thermomechanical simulator (model Gleeble 3800). The uniaxial compression tests were performed in the temperature ranges of 1173–1473 K (in steps of 50 K) at nominal strain rates of 0.001, 0.01, 0.1, 1 and 10 s^{-1}. Chemically pure Ni and high quality graphite were used between specimens and the platens to minimize the friction during deformation. Before imparting the deformation, each specimen was heated at a rate of 5 K s^{-1} to the desired deformation temperature, and was held for 2 min. at that temperature to achieve homogeneous temperature distribution throughout the body. At the specified test conditions, the specimens were subjected to 50% height reduction. With the help of spray nozzles equipped in hot deformation chamber of the machine, the hot deformed specimens were quenched in water within 1–2 s after the deformation to freeze the microstructure. Standard equations were used to convert the load-stroke data to true stress-true strain data. The elastic strains were subtracted from the true stress-strain curves to get true stress-true plastic strain curves [32]. It is to be noted here that no significant barreling of the specimen was observed following compression deformation.

Table 1
Chemical composition (in wt%) of alloy 617 used in this study.

Element	Ni	Cr	Co	Mo	Al	Ti	Mn	Fe	C
wt%	55	21.8	11.5	8.7	1.07	0.38	0.08	1.02	0.06

2.2. Electron Back Scatter Diffraction (EBSD) characterization

The specimens for EBSD investigation were prepared using the standard metallographic polishing procedure. The microstructures were examined in the uniform deformation zone of the specimens. EBSD scans were performed on all processed samples using a TSL-OIM system attached to field emission scanning electron microscope (model INSPECT F manufactured by FEI, USA) operating at 30 kV. EBSD maps were collected from the processed samples using a step size of 0.25–0.5 μm depending on the grain size using a hexagonal grid. In addition to this, high resolution (at much finer step size of 0.1 μm) EBSD maps were taken in some selected specimens where fine grain sizes are present. The data collected by EBSD was analyzed using TSL OIM (version 7.2) software. Standard clean-up procedure (grain dilation for single iteration) was applied before analyzing the EBSD data. The EBSD data was analyzed to calculate the average grain sizes, area fractions of DRX (f_{DRX}) and local misorientation. To calculate the DRX fraction, the DRX grains were partitioned out employing the grain orientation spread (GOS)[1] approach. In our earlier work it was shown that GOS with a 'cut off' of 1° is a suitable criterion to partition DRX grains from the deformed matrix [33]. A similar observation has been made for the present alloy as well and thereby GOS with a 'cut off' of 1° was used to calculate the DRX fraction from all the hot-deformed specimens. To ensure statistical significance, the data in each specimen is analyzed from at least three maps (area of each map $\sim 500 \times 500$ μm^2) obtained from different locations of the uniform deformation zone of the specimens (at center of the cylindrical cross section of specimen). The microstructure/data reported in this study is a representative microstructure /average of the values obtained from these maps.

[1] The GOS is average difference in orientation between the average grain orientation and all measurements in a grain [33].