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Plastic deformation modeling of AL-6XN stainless steel at low and high strain rates and temperatures using a combination of bcc and fcc mechanisms of metals

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Dedicated to Dr. Kirk Valanis for his seminal work in Mechanics

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Abstract

Combination of physically based constitutive models for body centered cubic (bcc) and face centered cubic (fcc) metals developed recently by the authors [Voyiadjis, G.Z., Abed, F.H., 2005. Microstructural based models for bcc and fcc metals with temperature and strain rate dependency. Mech. Mater. 37, 355–378] are used in modeling the plastic deformation of AL-6XN stainless steel over a wide range of strain rates between 0.001 and 8300 s^{-1} at temperatures from 77 to 1000 K. The concept of thermal activation analysis as well as the dislocation interaction mechanism is used in developing the plastic flow model for both the isothermal and adiabatic plastic deformation. In addition, the experimental observations of AL-6XN conducted by Nemat-Nasser et al. [Nemat-Nasser, S., Guo, W., Kihl, D., 2001. Thermomechanical response of AL-6XN stainless steel over a wide range of strain rates and temperatures, J. Mech. Phys. Solids 49, 1823–1846] are utilized in understanding the underlying deformation mechanisms. The plastic flow is considered in the range of temperatures and strain rates where diffusion and creep are not dominant, i.e., the plastic deformation is attributed to the motion of dislocations only.

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The modeling of the true stress–true strain curves for AL-6XN stainless steel is achieved using the classical secant modulus for the case of unidirectional deformation. The model parameters are obtained using the experimental results of three strain rates (0.001, 0.1, and 3500 s^{-1}). Good agreement is obtained between the experimental results and the model predictions. Moreover, the independency of the present model to the experiments used in the modeling is verified by comparing the theoretical results to an independent set of experimental data at the strain rate of 8300 s^{-1} and various initial temperatures. Good correlation is observed between the model predictions and the experimental observations.

Keywords: Constitutive modeling; Flow stress; Dislocation density; Strain rate and temperature effect; Activation energy; Stainless steel; Classical secant method, Plasticity

1. Introduction

Two physically based constitutive models were developed by Voyiadjis and Abed (2005) to simulate the plastic deformation behavior for two different crystal structures of metals; body centered cubic (bcc) and face centered cubic (fcc) that is subjected to high strain rates and temperatures. The two constitutive models were derived based on the concept of thermal activation analysis and the dislocation interaction mechanisms as well as the additive decomposition of the thermal and athermal stresses. Both models were successfully applied to several bcc metals (Tantalum, Molybdenum, Niobium, and Vanadium) and fcc metals (OFHC Copper) over a wide range of temperatures (77–1000 K) and strain rates (0.001–8500 s^{-1}). The deformation mechanism of bcc metals is generally attributed to the resistance of the dislocation motion by the Peierls barriers (short-range barriers) provided by the lattice itself. Thus, the behavior of bcc metals shows a strong dependence of the thermal yield stress on the strain rate and temperature whereas, the plastic hardening is hardly influenced by either the strain rate or the temperature and therefore, it contributes to the athermal part of the flow stress. In fcc metals, on the other hand, the emergence and evolution of a heterogeneous microstructure of dislocations as well as the long-range intersections between dislocations dominates and controls the mechanisms of thermal activation analysis behavior. Thus, the thermal activation is strongly dependent on the plastic strain, consequently, the increase in the yield point with a decrease in temperature is highly dependent on the strain-hardened states. Moreover, there is no strain rate and temperature effect on the initial yield stress, which implies that when the plastic strain is zero, the stress–strain curves at different temperatures and strain rates, will have the same starting point.

In this paper, both bcc and fcc models are utilized in modeling the plastic deformation behavior of AL-6XN stainless steel under low and high strain rates and temperatures. In addition to iron (bcc), the microstructure of AL_6XN stainless steel is composed mainly of 23.84% of nickel (Ni) (fcc metal) and 20.56% and 6.21% of chromium (Cr) and molybdenum (Mo) (bcc metals), respectively. Table 1 shows