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Constitutive modeling of nitrogen-alloyed austenitic stainless steel at low and high strain rates and temperatures

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ABSTRACT

In this paper, microstructures-based constitutive relations are introduced to simulate the thermo-mechanical response of two nitrogen-alloyed austenitic stainless steels; Nitronic-50 and Uranus-B66, under static and dynamic loadings. The simulation of the flow stress is developed based on a combined approach of two different principal mechanisms; the cutting of dislocation forests and the overcoming of Peierls–Nabarro barriers. The experimental observations for Nitronic-50 and Uranus-B66 conducted by Guo and Nemat-Nasser (2006) and Fréchard et al. (2008), respectively, over a wide range of temperatures and strain rates are also utilized in understanding the underlying deformation mechanisms. Results for the two stainless steels reveal that both the initial yielding and strain hardening are strongly dependent on the coupling effect of temperatures and strain rates. The methodology of obtaining the material parameters and their physical interpretation are presented thoroughly. The present model predicts results that compare very well with the experimental data for both stainless steels at initial temperature range of 77–1000 K and strain rates between 0.001 and 8000 s^{-1}. The effect of the physical quantities at the microstructures on the overall flow stress is also investigated. The evolution of dislocation density along with the initial dislocation density contribution plays a crucial role in determining the thermal stresses. It was observed that the thermal yield stress component is more affected by the presence of initial dislocations and decreases with the increase of the originated (initial) dislocation density.

1. Introduction

Steel alloys are of great significance in a wide range of structural, naval, nuclear, and aerospace applications. Over the years, several new types of steels have been developed to satisfy the growing need for high performance materials necessary to withstand extreme loadings. High strength steels are an important example as they demonstrate a high capability of absorbing energy. This property makes high strength steels preferred in military applications where impacts and explosions are involved. Among the different types of high strength steels, stainless steels are of great importance. Stainless steels show high corrosion resistance due to the high% of chromium content, and also demonstrate an excellent mechanical performance in terms of stiffness and strength retentions compared to the carbon steels (Lai et al., 2012). Steel alloys can be classified into three main categories, ferritic, austenitic, and martensitic. Among these categories, austenitic stainless steel is considered to be the largest group as it forms almost 70% of the total production of stainless steel (Rusinek et al., 2009). Austenitic stainless steels exhibit outstanding mechanical properties such as high strain

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hardening and large ductility. These properties are associated with the low stacking fault energy (SFE) inducing the twining effect which increases the strain hardening in the material (Bouaziz and Guelton, 2001; Bouaziz et al., 2008). Many types of austenitic stainless steels have been developed to enhance the mechanical properties and to lower the production cost. Recently, there has been a trend to replace the expensive nickel and carbon contents in the austenitic stainless steels with the low cost nitrogen without compromising on the desired mechanical properties. The addition of nitrogen enhances the austenite stability, corrosion resistance, and the mechanical properties such as work hardening, strength, toughness, and ductility (Simmons, 1996). Thus, there have been several experimental studies, in the recent past, on nitrogen-alloyed stainless steels regarding their chemical and mechanical properties, the microstructure and uses in different applications (e.g., Kim et al. (2004), Guo and Nemat-Nasser (2006), Fréchard et al. (2006), Rotnik et al. (2006), Li et al. (2007), Wang et al. (2008). On the contrary, the constitutive modeling of nitrogen-alloyed stainless steel is still at its nascent stage.

Constitutive modeling of pure metals and alloys has been a topic of great interest for decades as it enables simulating the static and dynamic behavior of the materials. Over decades, several empirical and semi-empirical constitutive models have been introduced to describe the thermo-mechanical behavior of pure metals and alloys (e.g., Johnson and Cook (1983)). Despite the success and simplicity of these models, they do not present a good understanding of the materials' mechanical behavior as the models parameters are not physically justifiable. Physically-based constitutive models offer a good understanding and a better simulation of the mechanical behavior of the materials. Zerilli and Armstrong (ZA) (1987) proposed a semi-physically based model to describe the behavior of body-centered cubic (bcc) and face-centered cubic (fcc) metals. Unfortunately, the ZA model shows inconsistencies in the definitions of the material parameters due to the approximations used in its derivation which caused a deviation from the actual mechanical response particularly at elevated temperatures (Abed and Voyiadjis, 2005a). Voyiadjis and Abed (VA) (2005a) and Voyiadjis and Abed (2005b) derived microstructures-based and consistent constitutive relations to define the flow stress for pure metals with different crystal structures for static and dynamic applications. The VA models were then extended to simulate the plastic deformation of AL-6XN stainless steel (Abed and Voyiadjis, 2005b) and to capture the thermo-mechanical response of high strength ferrite steels (Abed, 2010), over a wide range of strain rates and temperatures.

Very few attempts were made to describe the complex mechanical response of nitrogen-alloyed austenitic stainless over a wide coupling of temperatures and strain rates. Guo and Nemat-Nasser (2006) introduced empirical definitions for the strain hardening components in order to be able to simulate the experimental results and capture the coupling effect of temperatures and strain rate for a nitrogen-alloyed stainless steel. A similar approach was attempted by the RK model (Rusinek et al., 2009) to predict the thermo-mechanical response of some nitrogen-alloyed stainless steels. However, the true stress–true strain results failed to compare well with experimental results at several combinations of temperatures and strain rates. The main objective of this paper is, therefore, to develop a physically-based constitutive relation capable of capturing the complex behavior of nitrogen-alloyed austenitic stainless steels at different loading conditions. The different failure mechanisms encountered at the microstructure level as well as the experimental observations will be considered in deriving the new model. The constitutive relation will be utilized to describe the plastic deformation of two nitrogen-alloyed austenitic stainless steels; Nitronic-50 and Uranus-D66 over a wide range of temperatures and strain rates.

2. Nitrogen-alloyed stainless steels

The addition of nitrogen, which is a strong austenite-forming and stabilizing element, to steel improves its resistance to corrosion. It also increases the tensile strength of austenitic stainless steel, without a reduction in ductility or toughness. Two Nitrogen-alloyed austenite stainless steels, Nitronic-50 and Uranus-B66, are considered in the constitutive modeling presented in this paper. The experimental results presented by Guo and Nemat-Nasser (2006) for Nitronic-50 and Fréchard et al. (2008) for Uranus-B66 will be utilized in understanding the thermo-mechanical behavior. The chemical compositions for the two alloys, which consist of mainly bcc (Fe, Cr, Mo) and fcc (Ni) elements are listed in Table 1. The high chromium and molybdenum content of these two alloys enhances their corrosion resistance when compared to other stainless steels (e.g., grades 316 and 316L). Both materials are of great importance as they are widely used in industry and construction for a variety of applications. It is, therefore, necessary to develop a constitutive model capable of accurately describing the thermo-mechanical response, so that it can be implemented in finite element codes for design purposes.

2.1. Nitronic-50

Nitronic-50 is a structural stainless steel used in a wide range of applications such as naval construction, pumps, fittings, cables, and heat exchangers. It provides a combination of corrosion resistance and strength, and has very good mechanical properties at both elevated and very low temperatures. It also displays good ductility at high strain rates even at very low temperatures. Guo and Nemat-Nasser (2006) conducted static and dynamic experimental tests on Nitronic-50 stainless steel at a range of temperatures between 77 and 1000 K. The stress–strain

Table 1
Chemical composition for Nitronic-50 (Guo and Nemat-Nasser, 2006) and Uranus-B66 (Fréchard et al., 2008).

	Cr	Ni	Mn	Mo	Si	N	C	Fe
Nitronic-50	22	12.5	5	2.25	1.0	0.3	–	Bal.
Uranus-B66	23.8	21.2	3.7	5.5	–	0.47	0.01	Bal.