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A microstructural based creep model applied to alloy 718

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ABSTRACT

In this work a creep model based on the microstructural evolution of precipitation strengthening metals is presented. The model describes the influence of precipitates on the threshold stress as well as the power-law and the exponential creep rates depending on the aging condition. To show the predictive capabilities of this model, it was applied to the nickel based superalloy Alloy 718. This alloy is precipitation strengthened by the γ′ and γ″ phases. Thermo-kinetic simulations based on a calibrated MatCalc routine were performed to determine the evolution of the volume fraction and mean radius of the precipitates. In addition, sequential creep and tensile tests were performed to characterize the mechanical material behavior. The simulated microstructural evolution and the corresponding measured mechanical properties were used to parametrize the creep model. Finally, the fully parametrized model was applied to simulate deformation mechanism diagrams for different aging conditions. From these diagrams the purely elastic, the power-law and the exponential deformation regimes can be estimated depending on the precipitate volume fraction and mean precipitate radius.

1. Introduction

The macroscopic behavior of metals is governed by their structure at the micro- and nanometer scales. The increasing understanding of the underlying microstructure has led to improved multi-scale constitutive models, which have become applicable for component design with today's computing power and continuing advances in numerical methods like the well established Finite Element (FE) method (Groh et al., 2009; Horstemeyer and Bammann, 2010). However, microstructure-based modeling remains challenging by considering microstructural factors such as volume fraction, mean distance or number densities of precipitates (Kassner et al., 2007; Morra et al., 2009; Basirat et al., 2012; Le Graverend et al., 2014; Fisk et al., 2014). In many material models parameters are introduced to describe microstructural evolutions, without requiring an intensive microstructural analysis. Parameters are estimated by fitting them to experimental results. For a comprehensive review of existing microstructure-based models the interested reader is referred to the articles by Kim et al. (2016) and Ahmadi et al. (2014). In the present context, it should be noted that most microstructurally based creep models in the literature are usually limited to the description of the power-law creep regime (Blaizot et al., 2016; Zhao et al., 2015; Dyson, 2009).

In this contribution a semi-empirical creep model is derived. It is able to describe the influence of precipitates on the steady state creep rates for long as well as short time aging processes and a wide range of loading conditions. Evolution equations for the threshold stress and for the power-law breakdown are proposed.

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Table 1
Chemical composition of Alloy 718.

	Cr	Fe	Nb	Ti	Al	Mo	Co	Ni
wt. %	18.0	17.6	5.4	1.0	0.5	3.0	0.1	Balanced

To test the predictive capabilities of the model, it is applied to Alloy 718. This alloy is part of the nickel-based superalloys, which are used for a wide range of high temperature applications whenever corrosion resistance and high strength at elevated temperatures are needed. The microstructure, which is responsible for these outstanding properties, consists of four phases. During aging in the intermediate temperature range between 850 °C and 600 °C (Drexler et al., 2015) two kinds of precipitates nucleate in the matrix phase γ: thermodynamically stable $Ni_3(Al,Ti)$ γ' ($L1_2$ structure) and thermodynamically metastable Ni_3Nb γ'' ($D0_{22}$ structure) precipitates (Miller, 2001). During long-term aging operations in the high temperature range above 850 °C the γ'' phase starts to dissolve to the advantage of the stable orthorhombic Ni_3Nb δ phase ($D0_a$ structure) (W. Liu et al., 1999).

The thermo-kinetic simulation software MatCalc was used to compute the evolution of the precipitate volume fraction and mean radii (Drexler et al., 2015; Saunders et al., 2004). Furthermore, sequential creep and tensile tests were performed to parametrize and validate the creep model in the full temperature range. Finally, deformation mechanism diagrams for different aging conditions are obtained from these simulations.

The microstructurally based creep model developed in the present work can be included in a straightforward manner into unified constitutive models such as they exist already for Alloy 718. The numerical implementation is well described in the work by Becker and Hackenberg (2011).

2. Material and methods

2.1. Sample material

Samples for the mechanical characterization of Alloy 718 were cut out of the middle section of a forged and direct aged cylinder with the chemical composition given in Table 1. The cylinder had a diameter of 360 mm and a height of 55 mm. The direct aging heat treatment process consists of natural air-cooling from forging temperature (approximately 1000 °C) to room temperature. The cooling rates were small enough to form nano-dispersed γ′ and γ'' precipitates. The total volume fraction was about 20%. The homogeneity of the microstructure was investigated by measuring hardness, grain size and volume fraction of the δ precipitates. The grain size was determined using the mean linear intercept technique. The area fraction of the δ precipitates was measured by a combination of digital image editing and energy dispersive X-ray spectroscopy (EDX) (see Fig. 1). This was done in a Zeiss Evo 50 scanning electron microscope at 15 kV acceleration voltage after standard sample grinding and polishing. The measurement results are summarized in Table 2; they reveal a homogeneous distribution in the middle section of the forged and heat treated cylinder.

2.2. Thermo-kinetic simulations

The thermo-kinetic simulations were performed with the commercial solid-state transformation kinetics software MatCalc (MatCalc software documentation, 1.12.2016). The databases and MatCalc version used in this contribution are summarized in

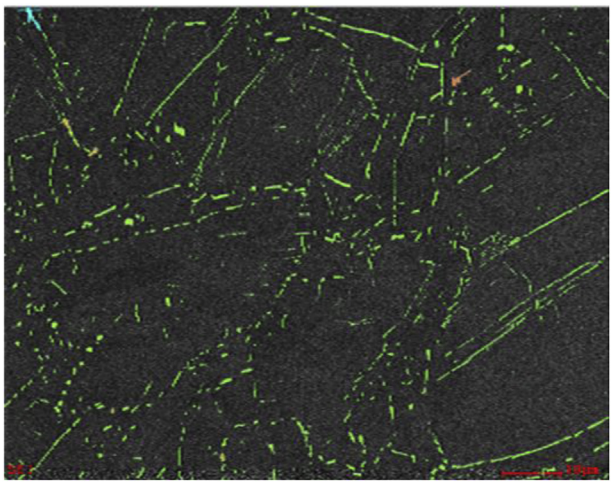

Fig. 1. Digital image editing of an electron backscatter picture in combination with energy dispersive X-ray spectroscopy (EDX) to measure the area fraction of the δ precipitates in the base material.