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Oxidation-assisted creep damage in a wrought nickel-based superalloy: Experiments and modelling

E. Chateau [1], L. Rémy *

Centre des Matériaux, Mines Paris - Paristech, UMR CNRS 7633, BP87 F-91003 Evry, France

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ABSTRACT

Creep damage investigation was carried out in wrought nickel-based superalloy Udimet 720LI in air at 850 °C using multiple cross-sections specimens in order to be able to make interrupted tests. In all tests conducted on this material, creep curves showed only tertiary stage and the surface connected intergranular cracking was found to be dominant in creep fracture. It was shown that γ' precipitate coarsening occurs in the bulk of the specimens and obeys the LSW kinetics. Metallographic analysis led to the conclusion that creep does not alter oxidation, except at grain boundaries, where oxide spikes can be developed under creep. Therefore grain boundary oxidation was found to be creep strain-assisted.

A constitutive model accounting for precipitate coarsening was proposed. The oxidation-assisted intergranular damage and the oxidation embrittlement of the microstructure elements phenomena were successfully described using the continuum damage mechanics and the local ductility exhaustion laws, respectively. Creep rupture and elongation curves were taken into account by the model with suitable accuracy, as well. The model was found able to figure the specimen's geometry variations effects on lifetime and creep elongation curves.

1. Introduction

Nickel-based superalloys are widely used for components operating at high temperature, such as gas turbine discs, for high-pressure stages. Such rotating components are primarily submitted to creep and creep-fatigue loading due to the simultaneous occurrence of high centrifugal loads as well as high temperature. The microstructure of these alloys consists of a solid solution matrix γ with a face centred cubic structure and intermetallic precipitates γ' basically Ni_3 (Ti, Al). Wrought superalloys's creep and creep-fatigue resistance has been increased over the years by modifying the alloys's composition, in order to increase the volume fraction of γ' precipitates, the strength of these precipitates and that of the matrix [1,2]. This has been achieved by first increasing Al and Ti contents and then, by increasing Mo, W and Nb contents. However, when the volume fraction of γ' precipitates is increased up to levels about 0.4, the extreme alloy strength caused difficulties on forging [2]. Further increases in precipitate content can only be achieved using different processing routes, such as powder metallurgy [2,3].

Wrought alloys show a good resistance to creep-fatigue up to 650 °C [1]. However the latest development in gas turbine technology requires that parts could work at higher temperatures, ranging from 700 to 900 °C. At such temperature levels, environment effect can be a major issue in material's damage [4]. The importance of oxidation in low cycle fatigue and creep of superalloys has been known for a long time since the pioneer's work of Coffin in the 70s [4–6] in various wrought and cast superalloys [7–12]. The interaction of oxidation with creep-fatigue has been reported in our group for cobalt-based and nickel-based superalloys, in conventionally cast, single crystal directionally solidified or powder metallurgy alloys [8–15].

Creep damage is usually associated with mechanisms occurring in the bulk of specimens or components [16–18], such as cavities growth at grain boundaries intersections, which are among the most widely reported mechanisms [18,19]. The microstructure degradation due to the dissolution or coarsening of precipitate particles can also occur [20].

As superalloy components often operate under highly oxidizing conditions and eventually with superimposed corrosion, their oxidation behaviour has been the object of numerous investigations, either in commercial systems or in simplified compositions used to model the behaviour of complex alloys [see for instance 21–23]. The interaction of straining and oxidation has been mostly investigated from the standpoint of oxidation mechanisms [24–26]. Nevertheless oxidation effects on the mechanical behaviour have

* Corresponding author. Tel.: +33 1 60 76 30 47; fax: +33 1 60 76 31 60.
E-mail address: luc.remy@mat.ensmp.fr (L. Rémy).
[1] Now with ELENGY, GDF Suez, Service Technique, Courcellor 1, 2 rue Curnonsky, 75017 Paris, France.

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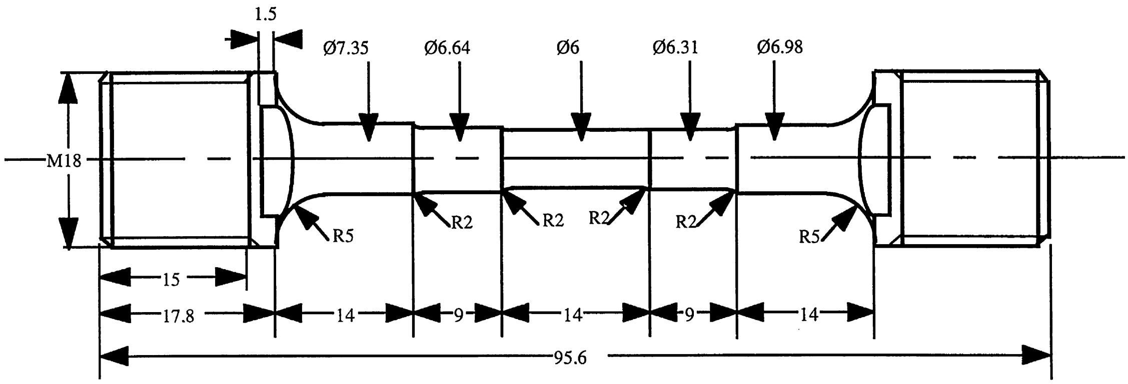

Fig. 1. Geometry of the multiple sections specimen used for creep tests.

been investigated for fatigue, creep-fatigue or thermal fatigue in steels and superalloys [see for instance review 4].

The interaction with environment can cause significant damage under creep [27]. Cane and Manning [28] have shown that oxide spallation in low alloy ferritic steels can reduce the load bearing section and thus increase the stress experienced and reduce creep life. High temperature exposure in air and oxygen is shown to reduce the creep resistance of pure nickel, as well [29]: in fact, the carbon dioxide gas bubbles development at grain boundaries is found to be responsible of this resistance degradation due to the presence of carbon atoms in the nickel structure [30]. Other creep-oxidation interaction consequences such as embrittlement is reported too in IN738 [31] and in X750 [32] alloys.

The present study aim is to investigate the high temperature creep behaviour of Udimet 720 LI, a nickel-base wrought superalloy, the properties of which have been optimized by Turbomeca. Thus, creep tests are carried out in laboratory air at 850 °C up to failure. Applied creep stresses are below the macroscopic yield stress with no plasticity on initial loading. Extensive observations of specimen sections near the surface and in the bulk are made to quantify the extent of surface damage induced by oxidation as well as the microstructure degradation due to high temperature exposure in the bulk.

The purpose of this investigation is to identify the major damage mechanisms occurring during tertiary creep, and to propose a damage model that could account for the observed behaviour. Some results of this study have been partly presented at several conferences [33–35]. The damage model uses the same framework previously proposed to describe oxidation effects in low cycle fatigue and thermal fatigue in poly-crystals [12,14] and more recently in single crystals [14,15].

Therefore, this paper reports creep test results and microstructural observations to quantify damage induced by oxidation near the surface and microstructure degradation in the bulk, due to the evolution of γ' precipitate distribution. Consequently, a new damage model is proposed using a constitutive equation derived from previous works on creep as well as damage rate equations deduced from measurements. The prediction capability of the model is illustrated.

2. Material and experimental procedure

The material studied is Udimet 720 LI, with a low interstitial content that has been optimized by Turbomeca. Its chemical composition in wt% is Ni–15.95Cr–2.99Mo–1.15W–2.58Al–14.66Co–5.08Ti with 0.01C, 0.02B, and very low content in impurities (S, P, N, O).

For the thermal–mechanical treatment and heat-treated condition used, the grain size is about 150 μm. The volume fraction of γ' strengthening precipitates is about 0.41 and the distribution in size is composed of several populations. The yield strength at 850 °C is 798 MPa for usual strain rate levels.

Original tensile smooth specimens featuring five different cross-sections (varying according to geometric series) (Fig. 1), are designed to identify material behaviour and damage mechanisms [35]. The creep tests are conducted in air at 850 °C using a 4 lamps bulb furnace until the minimum section of each specimen failed, while the larger sections remain unbroken. Accordingly, each test provides four unbroken sections of each specimen presenting various damage states for different stress levels, and one elongation versus time curve and one lifetime evaluation on specimen section having the smallest radius. Strain in the minimal section of the sample is measured with an axial extensometer using a creep-fatigue test facility that ensures a careful control of specimen loading. The gauge length is about 10 mm and the maximum measurable displacement is around 0.5 μm. Only one test is carried out under 5×10^{-3} Pa vacuum at 850 °C using a vacuum chamber designed in our laboratory.

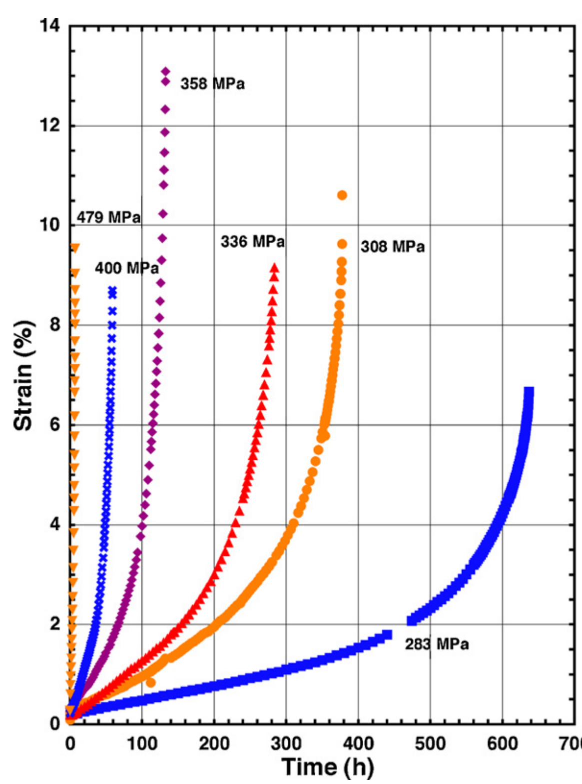

Fig. 2. Creep curves (strain versus time) obtained for different stress levels in air at 850 °C.