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Effects of microstructure in high temperature fatigue: Lifetime to crack initiation of a single crystal superalloy in high temperature low cycle fatigue

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ABSTRACT

Single crystal superalloys are now the best alloys to make blades and vanes in aero-engines and gas turbines due to their temperature capability, their creep and fatigue resistance. Their composition and microstructure are optimised by heat treatments but low cycle fatigue resistance is mostly controlled by the initiation and early growth of micro-cracks at casting pores. An enriched engineering damage model is proposed to describe micro-crack growth from pores with a process zone concept. Damage equations use summation of contributions on all slip systems as the constitutive model. Oxidation can play a significant role that can be described through embrittled material ahead of micro-crack tip. To investigate the behaviour under small scale yielding at finer scale, experiments were carried out using sharp notches. Early growth of cracks in the notch vicinity was studied at two temperatures 650 °C and 950 °C. While at the lower temperature the notch can be analysed as a crack, anomalous crack growth rates are observed at the higher temperature. Using finite element computations and a damage model, this behaviour is attributed to local viscoplastic strain concentrations, and oxidation effects. Effects of strain concentration are attenuated since only a small volume of material is highly strained at the notch vicinity.

1. Introduction

The efficiency of gas turbines for aero-engines relies in part on the temperature capability of turbine blade and vane materials. Both types of components are exposed to severe thermal and mechanical loadings in hot combustion gases. Most of these components are usually made of conventionally cast nickel base superalloys [1].

The thermal fatigue review of Woodford and Mowbray [2] has pointed out at the influence of grain boundary and deleterious behaviour of phases that form at inter-dendritic areas such as primary γ–γ'eutectic, eutectic carbides often MC carbides which often show a chinese script form [3]. This has been confirmed by several works, in isothermal low cycle fatigue [4–9], under thermal fatigue [10], or thermal mechanical fatigue [11]. Mechanical properties are often correlated with the size secondary dendrite arms. Thermal fatigue life can be shown to decrease drastically when the secondary dendrite size increases in superalloys, and this has been associated with a drastic increase of early crack growth as illustrated in Fig. 1 [3]. However this effect is not primarily a strength effect but this reflects the increase in oxidation kinetics along inter-dendritic areas with increasing secondary dendrite arm size, i.e. with increasing segregation of elements.

As the major stress arises along blade or vane height, directional solidification was first developed [12] to avoid maximum stress normal to grain boundaries that are usually quite weak regions in cast materials. Thus such components show higher creep rupture life and ductility than conventional castings. But the main advantage is that dendrite growth occurs along the [001] direction of the face-centred cubic (fcc) lattice that corresponds to minimum Young's modulus, typically about 30% lower than that of conventionally cast alloys. This yields under elastic conditions a considerable reduction of thermal stresses and improvement in thermal fatigue resistance.

The temperature capability can be further increased using solidification into single crystal form. The minor alloying elements used to strengthen grain boundaries are no longer necessary and then alloys with higher incipient melting temperatures can be developed and avoiding the formation of undesirable phases [12,13]. Thus different "generations" alloys were designed using different alloying elements that have a large heat treatment window [13,14], which means a large difference between incipient melting temperature and γ' solvus temperature. This allows to make a solution treatment to dissolve most eutectic phases and completely gamma prime without incipient melting.

Then combinations of heat treatments were designed mostly to optimise creep and tensile strength. A usual size of γ' secondary cube precipitates around 0.4–0.5 μm was thus shown to give the better strength [15]. This has been confirmed in different studies

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in LCF [16–18]. In the industrial practice, however, solution treatments are usually too short to achieve complete homogenisation of the alloy since they contain heavy elements such as Ta, W, Re, Ru. Therefore the size of the precipitates is usually larger in the inter-dendritic areas than in the core of the dendrites (see e.g. [16,17,19,20].

The dendrite growth controls the refinement of the casting microstructure. The density of primary dendrites depends on thermal gradient G and withdrawal rate V according to a $G^{1/2}$ $V^{1/4}$ variation as proposed by Kurz and Fisher [21] and it is influenced by composition and phase formation (see e.g. [13]). The variation of secondary dendrite size was reported to vary as $(GV)^{1/3}$ in work on Rene N4 [22]. However in industrial casting conditions, primary dendrite size is usually in the range 0.3–0.5 mm and secondary dendrite size in the range 0.05–0.09 mm (see e.g. [13,23]).

The heat treatment duration to full solutioning of the eutectic phases is directly related to the size of the dendrites in the single crystal superalloy. Typically a 3–4 h treatment at 1315 °C is necessary for CMSX2 superalloy solidified in a low temperature gradient typical of industrial conditions which gives rise to a primary dendrite size of 0.45 mm. In a high temperature gradient the primary dendrite size reduces to 0.15 mm and a 30 min hold at the same temperature is sufficient [24].

The porosity is affected in the same way: the porosity is about 0.5% in the low gradient conditions and the pore size can reach 80 μm in crystal rods. It decreases to 0.1% in a high gradient condition with a maximum pore size about 10 μm [24].

Low cycle fatigue (LCF) of superalloys, which are high strength alloys, occurs in conditions where the elastic strains are larger than plastic strains at the macroscopic level (see [19,20]). Therefore even the LCF life of single crystal superalloys is controlled by defect density, as usually for high cycle fatigue. Defects are concentrated at inter-dendritic areas and consist of carbides depending upon the carbon in the alloy, sometimes remnant eutectic phases and mostly casting pores [19,20] as reported earlier in high cycle fatigue for MarM200 single crystals [25,26]. As a consequence the fatigue life of CMSX2 ⟨001⟩ smooth specimens solidified under high thermal gradient conditions (primary dendrite spacing 0.15 mm, porosity 0.1%) is longer than for industrial low thermal gradient conditions (primary dendrite spacing 0.45 mm, porosity 0.5%). The difference in fatigue lives increases with decreasing the stress range: at 760 °C at 0.33 Hz, a factor of 3–5 can be observed for a stress range of 1250 MPa [24].

At medium and at high temperature oxidation interacts with fatigue but casting pores are at the origin of surface cracks or can favour internal cracking (often in the subsurface region) depending upon test frequency and temperature [19,20].

A few authors have investigated the orientation dependence of fatigue life at medium and high temperature [27–29]. In particular uniaxial low cycle fatigue under total mechanical strain control was conducted for AM1 specimens with ⟨001⟩, ⟨111⟩, ⟨101⟩ and ⟨123⟩ loading axis at medium frequency 0.05 Hz with number of cycles to failure ranging from 100 to a few 10^5 cycles [20]. Orientation dependence was found with ⟨001⟩ specimens leading to longer lives, and ⟨111⟩ specimens exhibiting shorter lives. This orientation dependence of uniaxial low cycle fatigue life is mainly due to the orientation dependence of Young's modulus, since elastic strains tend to be larger than plastic strains except at high mechanical strain ranges. For a given frequency this orientation dependence almost vanishes when the uniaxial stress range is used instead of mechanical strain range [20] as shown for other alloys [19,30]. A similar conclusion applies to thermal–mechanical fatigue (TMF) tests when comparing tests using a single TMF strain versus temperature cycle [31]. Examinations of the fracture surfaces show that cracks initiate at pores and subsurface mostly. Early crack growth occurs in a mode I cracking governed by maximum normal stress whatever the orientation of the loading axis leading to multiple slip, duplex or single slip at a macroscopic scale, i.e. in an opening mode. This is opposite to the usual behaviour in poly-crystals where initiation occurs along one slip plane in one or a few grains giving early crack growth in shear mode and then crack growth normal to principal stress. In single crystal superalloys, transition to stage I cracking along crystallographic planes usually octahedral {111} planes occurs only in the final stage of cracking at medium temperatures [19,20,31].

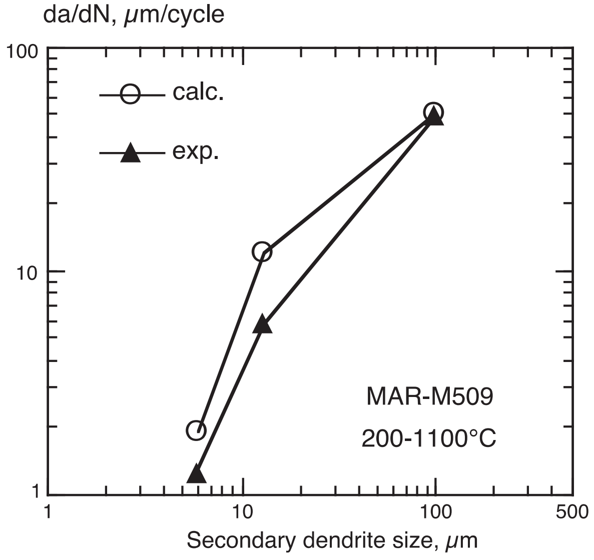

Fig. 1. Variation of the crack growth rate in the vicinity of the thin edge (*da*/*dN*) of wedge specimens of MAR-M509 submitted to thermal shock (200 ⇔ 1100 °C) as a function of the secondary dendrite size (after François and Rémy [3]).

Cailletaud and coworkers [32,33] have proposed for anisotropic single crystal superalloys a crystallographic constitutive model that uses viscoplastic phenomenological equations like those proposed by Chaboche at the macroscopic level [34,35], but at the level of slip systems. This model was enriched to describe the stress–strain field under creep-fatigue loading [36]. A more detailed model was recently proposed to account for finer physical details of superalloy deformation mechanisms [37,38] but increasing the computing cost for structures. The main feature is however that the stress–strain behaviour parameters of cyclic behaviour are strongly dependent upon the temperature in superalloy single crystals, with a strong localisation in slip bands at low and medium temperatures and a more homogenous deformation at higher temperatures (above about 800 °C).

Since defects and casting pores are frequent in high strength single crystal superalloy, they constitute a material feature. They have to be included in a life prediction model to be used at the element scale. An example of scatter in fatigue life is recalled first with the use of fatigue crack growth data at medium temperatures analysed using linear elastic fracture mechanics. As the life prediction model is used as a post-processor of the stress analysis, the crystallographic constitutive model is recalled secondly. Then an enriched engineering damage model is described to predict the LCF lifetime. Finally to simulate the local situation at a pore, the growth of micro-cracks at sharp notches is investigated using experiments under small scale yielding at two temperatures with little (650 °C) and significant viscoplasticity (950 °C) respectively. The results are discussed using a finite element analysis and the crystallographic constitutive model.