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Grain boundary–slip bands interactions: Impact on the fatigue crack initiation in a polycrystalline forged Ni-based superalloy

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ABSTRACT

Low cycle fatigue properties of polycrystalline γ–γ' Ni-based superalloys are dependent on many factors such as temperature, environment, grain size and distribution of the strengthening phases. Under LCF conditions, an intergranular crack initiation is often observed. The local conditions favoring such a damage mode are analyzed in this paper considering the high strength cast and wrought Udimet™ 720Li alloy tested at room temperature. Tensile and fatigue tests were performed on samples having two different microstructures with various γ' precipitates distributions. The objective is to focus on the plasticity and damage processes developed near grain boundaries. A special attention was paid on the slip transfer between neighboring grains taking into account the local crystallographic orientations. In some specific crystallographic configurations (linked to geometrical considerations between slip planes activated on both side of the grain boundary), a localized crystallographic rotation was detected within very small volumes confined at the tip of slip bands developed in the neighboring grain. Although limited in size ($\sim$30 μm^3), these micro-volumes are associated to an intense elastic/plastic activity resulting from very high local stresses due to the elastic rotations. The development of such specific zones was investigated at different stages of the monotonic and cyclic behavior at room temperature and was identified as favoring micro-cracks initiation.

1. Introduction

Because of their good balance of mechanical properties, microstructure stability and corrosion resistance at high temperatures, as well as their workability, polycrystalline nickel-based superalloys are the most suitable material class to manufacture aeroengines high pressure turbine disks [1]. These components are submitted to a wide range of design criteria that concern the resistance to disk burst, the resistance to creep deformation and dwell-fatigue crack growth for the rim part and in the same time, the resistance to low cycle fatigue (LCF) for the bore sections [2]. In this field, many studies published over the last decades often refer to an intergranular crack initiation mode for a wide range of temperature and cycling frequency [3], including low cycle fatigue [4], ultrasonic fatigue [5] and dwell-fatigue [6]. For high temperatures, the damage processes that develop at the grain boundaries are mainly associated to complex interactions between strain and environmental effects. Intergranular cracking due to oxidation was mentioned for example in Udimet™ 720Li alloy [7,8] and in other Ni-based superalloys [9]. Sliding at grain boundaries could also contribute to deformation and damage processes at high temperatures [10]. On the contrary, for low and intermediate temperatures (up to $\approx$500 °C), the oxidation process as well as grain boundary sliding could not be active enough to directly generate cracks. However intergranular fatigue crack initiation is often mentioned in this temperature range, for nickel-based superalloys as for other pure metals and alloys [11]. The origin of such damage processes is generally related to the development of plasticity mechanisms closed to (or through grain boundaries) and to the strain incompatibilities between surrounding grains. In this field, the interactions between grain/twin boundaries and persistent slip bands active at least in one of the neighboring grains have been identified to be a key point for the grain boundary cracking at room temperature (on pure Ni [12], 316L austenitic stainless steel [12,13], pure Cu [14], α-iron [15]) and intermediate temperature (on Ni based superalloys [5]). In a previous work, the authors have studied how plasticity develops locally near grain boundaries in the Udimet 720Li alloy deformed at room temperature under monotonic tensile loading. This study focused on the early stages

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of plasticity in a strain amplitude range compatible with fatigue applications. A special attention was paid to the local crystallographic configurations that favor or not the slip bands transmission from one grain to its neighbor [16]. The contrast in terms of active plasticity between neighboring grains appeared in these past experiments as a key factor. When the development of slip bands is greatly favored in each grain, no strain incompatibility at the grain boundary appears. Two configurations can be observed: as a first one, the direct transmission of intense slip bands could be easy between slip systems already activated in both grains; as a second configuration, the generation of new slip bands in one side of the grain boundary could also be promoted by the local stress field induced at the tip of each slip band active in the opposite side of the grain boundary. If it is difficult to distinguish both cases one from the other, both mechanisms correspond to the great majority of the configurations of plasticity development near grain boundaries. However, in a few cases, the slip bands transmission through grain boundaries appeared clearly more difficult and even sometimes impossible. The corresponding local microstructure generally associates a grain well oriented to favor the production of intense slip bands and another one for which plasticity could not be activated, essentially due to a too low level of Schmid factor. In such a type of configuration it has been observed the development of a specific deformation mechanisms confined in highly localized zones that we have called "micro-volumes" [16]. This phenomenon corresponds to a crystalline local elastic rotation that takes place in the non deformed grain, from the grain boundary, directly in correspondence with the tip of slip bands formed in the neighboring grain. Fig. 1 illustrates this phenomenon for a local configuration particularly contrasted in terms of Schmid factor (Fig. 1(a)). For this case, the "non-deformed" grain presents an orientation near <1 1 1> according to the loading direction with a very low Schmid factor ($\mu = 0.292$) for the possible slip systems, and the slip bands produced in the deformed grain correspond to a high value of Schmid factor ($\mu = 0.497$). Electron backscattered diffraction (EBSD) analyses performed in such zones have shown that the crystalline rotation increases progressively, from the tip of the slip band to the bulk of the grain, with a maximum amplitude that could reach 10–12° (Fig. 1(d) and (f)). To compute the local strain/stress field in the micro-volumes an EBSD patterns cross correlation approach was adopted using the cross court CC3 software. This recently developed technique (also called high resolution HR-EBSD) allows the evaluation of small crystalline rotations from EBSD patterns with an improved angular resolution up to 0.02° [17–19]. More details on that point can be found in [16,34]. It was relatively easy to define a reference point in the central part of each grain far away from slip bands and micro-volumes since very low plastic strain amplitude were investigated. However the quantitative interpretation of strains evaluated by such a method remains very complex in the presence of a large plastic deformation and a high degree of rotation that generally lead to an overestimation of the local stress fields in the micro-volumes [20,21]. Local stresses much higher than the conventional yield stress (defined at 0.2% of plastic deformation) have been evaluated by this approach, result that could not be completely realistic. A recalculation of local strain and stress fields by a more appropriate method will be performed in a further work. Nevertheless, qualitative information could be obtained from conventional and HR-EBSD measurements, especially concerning the spatial extent of the "micro-volumes" and the form of the associated local strain and stress tensors. Moreover, careful SEM observations have shown the evidence of slip traces developed specifically inside the micro-volumes in coherence with the evolution of the local Schmid factor due to the crystalline rotation (Fig. 1(e)). This evidences the fact that high local stresses, above the actual local yield strength, were induced inside the micro-volumes leading to the development of a local slip activity.

The aim of the present paper is to analyze the influence of the high local stresses and of the micro-plasticity mechanisms developed in these micro-volumes as a possible origin for crack

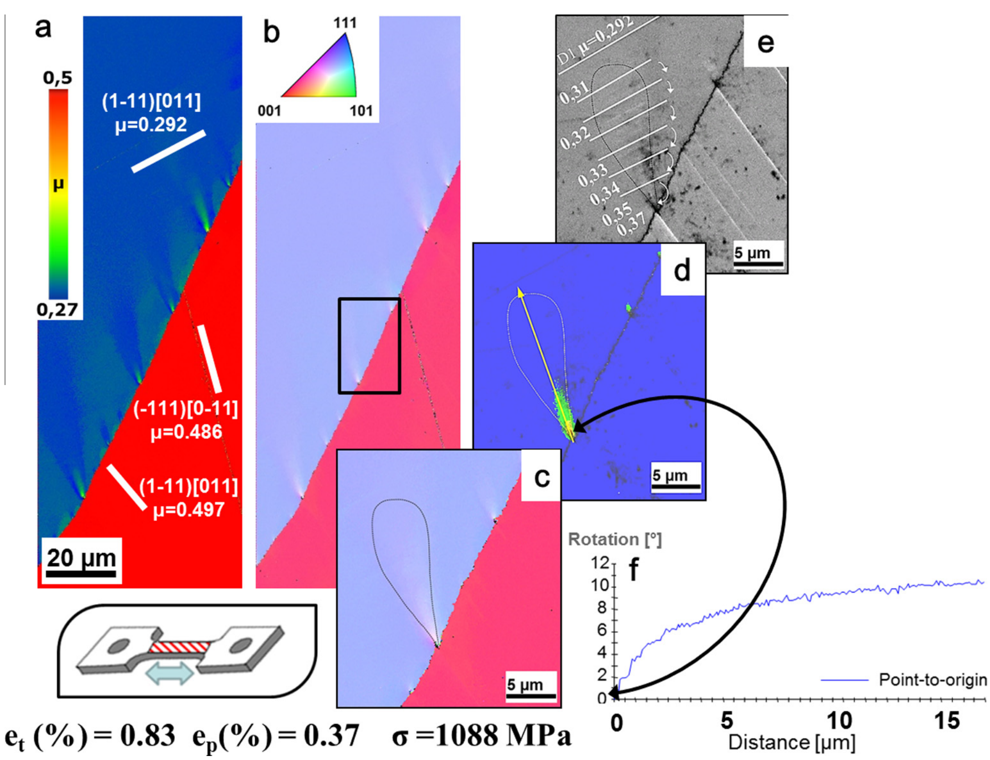

Fig. 1. Schmid factor (a) and inverse pole figure (b) maps of a grain boundary developing micro-volumes under a tensile test. In (c–e) maps are respectively inverse pole figure (c) misorientation (d) and Image Quality (IQ) image (e) maps focused on a micro-volume nucleated from that grain boundary and highlighted in (b). (f) is the corresponding misorientation profile along the axis plotted in (d) [16].