MATEC Web of Conferences **7**, 01007 (2013)
DOI: 10.1051/matecconf/20130701007
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On the influence of microstructural gradients in the fatigue lifetime estimation of a railway axle

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Abstract. This study aims at characterizing the influence of gradients at different scales (loading, geometry, microstructure...) on fatigue strength through a multi-scale finite element modeling associated to several high cycle fatigue criteria. This is a necessary step in the perspective of conducting a relevant experimental campaign on notched specimen exhibiting a gradient of mechanical properties.

INTRODUCTION

In the case of forged railway axles fatigue lifetime estimation, a consistent fatigue criterion has to take into account the fact that the axle is subjected to a global stress gradient as it undergoes rotatory bending, superimposed in the most critical zones to a local geometrical stress concentration due to the presence of notches (Fig. 1). It has been shown [1]–[2], that classical multiaxial fatigue criteria fail to account for such gradient effects. Macroscopic gradients are also superimposed to microstructural ones coming from mechanical properties gradients associated to the manufacturing processes. For the considered axles, the local forging of the wheel seats induces several changes in the surrounding microstructure. Micrographic observations have confirmed that the grain size is no more homogeneous in the thickness of the axle. The slight anisotropy induced by rolling also seems to have disappeared in the forged sections. To try and evaluate the fatigue phenomena that can arise because of these modifications, a numerical investigation on representative notched specimen is described in the next sections.

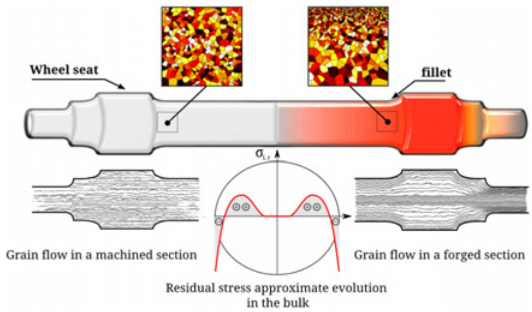

Figure 1. Summary of the influence of forging.

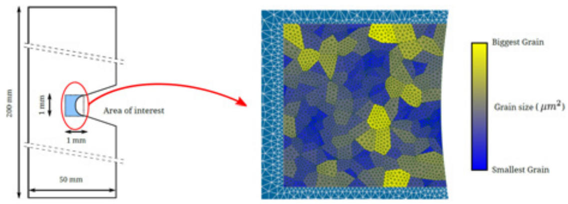

Figure 2. Numerical multi-scale model.

NUMERICAL MODEL DESCRIPTION

The main observable modification induced by forging under the wheel seats being grain size heterogeneity, as a first step a model allowing the study of the influence of grain size and geometry has been developed. This model is constituted of a notched specimen, into which a polycrystalline aggregate has been inserted to take explicitly into account the microstructure at the notch tip (Fig. 2). As a first step, and to facilitate statistical considerations over the aggregates, the microstructure there is approximated by Voronoi polyhedra, generated through the neper software [3].

LOCAL CONSTITUTIVE LAWS

In the present paper, and in the voluntary framework of considering the grain local size as the main modifier of mechanical behaviour, the material local constitutive law is chosen as an Armstrong-Frederick law (as identified by [4] for this particular steel) where the initial yield stress is chosen according to the Hall-Petch law:

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}}. \quad (1)$$

This choice allows a good representation of the ferritic part of the microstructure. A proposition for approximating grain orientation inspired by [5] is then made. Comparison with computations made with crystalline constitutive laws is under way.

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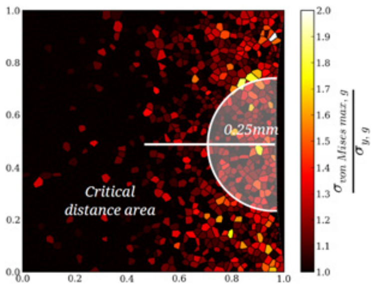

Figure 3. Plasticity in an aggregate with homogeneous grain size during cyclic loading.

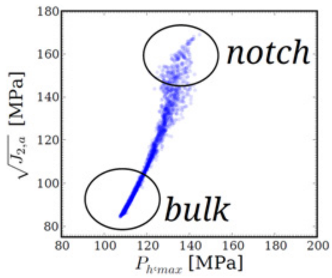

Figure 4. Crossland criterion in each grain for the same cyclic loading.

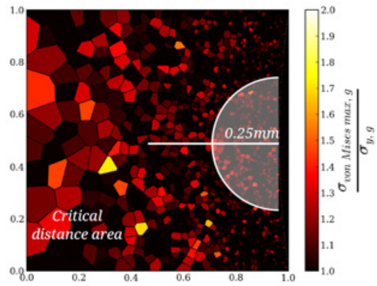

Figure 5. Plasticity in an aggregate with non-homogeneous grain size during cyclic loading.

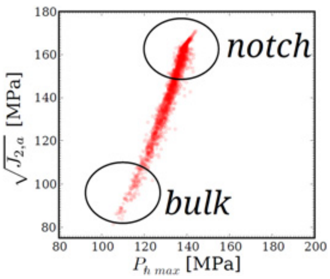

Figure 6. Crossland criterion in each grain for the same cyclic loading.

COMPUTATIONS DESCRIPTION

Preliminary simulations have shown that in the vicinity of the notch, for a given maximum stress at the notch tip the specimen is not very sensitive to the nature of the global loading (bending or tension), so cyclic tensile test with a R ratio of (-1) are simulated, as these tests will then be slightly simpler to perform experimentally. The loading is chosen so that it induces plasticity in some grains while living most of them in an elastic state, so it is significantly higher than the material real fatigue limit. In the current framework however, it is not such a setback as we are looking for qualitative considerations over the effects of various microstructural gradients.

RESULTS

In order to evaluate the criticality of different loading paths, geometries and microstructural gradients, cyclic loadings are numerically performed on the notched specimen presented earlier, once for an aggregate with a homogeneous grain size, and once for an aggregate characterised by a microstructural evolution between its inner and outer layers. The results of this computation are presented on the following figures.

The analysis of Figs. 3 and 4 confirms the expectations one would have for a homogeneous material: the most critical grains with respect to the Crossland criterion are also the most critical ones in the sense of plasticity.

When a microstructural gradient is present however, the critical grains yielded by the Crossland criterion and the most critical ones in the sense of plasticity are quite different (Figs. 5, 6). This is important because fatigue crack nucleation is likely to initiate significantly below the surface in the second case. It is also interesting to note that a critical distance approach, as described in [6], does not directly allow to discriminate results in the case of microstructural gradients.

CONCLUSION

An experimental campaign is being done at the moment to try and use full-field measurements to validate the strong assupmptions made on the mechanical local behaviour made in the first part.

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