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ScienceDirect

Procedia Engineering 74 (2014) 210 – 217

Procedia Engineering

www.elsevier.com/locate/procedia

XVII International Colloquium on Mechanical Fatigue of Metals (ICMFM17)

Influence of microstructure and micro notches on the fatigue limit

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Abstract

To achieve a high fatigue limit the most common approach is to increase the static strength and hardness of a material. This is realized mostly by decreasing microstructural dimensions as the grain size or the spacing between phases in more phase materials. According to the Hall-Petch-relationship the static strength is increased by that way. Simultaneously, the fatigue limit, which is defined by the non-propagation of cracks, increases with decreasing microstructural dimensions. The reason is that microstructurally small cracks are stopped at microstructural barriers so that smaller distances between neighboring barriers reduce the length of non-propagating cracks and increase the intrinsic fatigue limit. But this increase of the fatigue limit is confined by the dimensions of the flaws within the material, such as non-metallic inclusions or geometrical notches, which reduce the fatigue limit of high strength materials significantly.

The trade-off between small microstructural dimensions and the dimensions of the flaws will be discussed on the basis of experimental results in three examples. Firstly, commercial pure titanium shows a distinct change of the fatigue limit not before the notches are larger than the grain sizes, although the stress intensity at the notches is significant [1]. Secondly, micro notches in high strength materials always result in a huge decrease of the fatigue limit [2]. Thirdly, as bulk metallic glasses do not possess microstructural barriers like grain boundaries notches are a crucial factor in this class of materials [3].

On the basis of these examples and the modified Kitagawa-Takahashi diagram [4] a new approach to explain the microstructure and notch influence on the fatigue limit will be presented. This could be the basis for future developments to increase the fatigue limit of metals.

Selection and peer-review under responsibility of the Politecnico di Milano, Dipartimento di Meccanica

Keywords: fatigue limit, microstructure, micro notch, artificial defects, titanium, high-strength steel, bulk metallic glasses

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Selection and peer-review under responsibility of the Politecnico di Milano, Dipartimento di Meccanica
doi:10.1016/j.proeng.2014.06.251

1. Introduction

The demand to customise properties of materials is continuously rising. New functions of parts have to be achieved simultaneously with good mechanical properties. Unfortunately, the requirement for new functions and the need to secure good mechanical properties are conflicting. For instance small cavities at the surface of parts could have beneficial effect as reservoirs for lubricants during tribological loadings but they would also act as small notches, which are often harmful during fatigue loadings. Therefore the paper deals with the particularity of small notches to have an influence on the fatigue limit of parts in relation to the influence of the microstructure on the fatigue limit.

Approaches to increase the fatigue limit by increasing the static strength are discussed in the light of the effect of small notches or defects on the fatigue limit. The question will be whether there is a maximum possible fatigue limit like the theoretical strength by avoiding any notches or flaws.

Nomenclature

a	crack length
σ_a	stress amplitude $(\sigma_{max}-\sigma_{min})/2$
σ_e	fatigue limit
σ_{min}	minimum value of applied stress
σ_{max}	maximum value of applied stress
K_f	fatigue reduction factor
K_t	stress concentration factor
K_{th}	threshold value for long cracks
R	load ratio $\sigma_{min}/\sigma_{max}$

1.1. Influence of microstructure on the fatigue limit

It is well known that the static strength of a material is determined by the hardening mechanisms [5]. For low and medium strength metals the fatigue limit corresponds to the static strength or hardness linearly. However with increasing hardness the fatigue limit becomes lower than expected from linearity [6] because the failure mechanism changes from intrinsic flaws to inherent and/or processing flaws [7]. This is because the size of inherent or process flaws becomes larger than the size of the microstructural dimensions like spacing between grain boundaries in high strength metals, whereas such flaws are significantly smaller than the microstructural dimensions in low and medium strength metals. It follows that a crack which is initiated at the surface or at a flaw is stopped at least at the next microstructural barrier when the applied load is below the fatigue limit [8]. In the following the term “intrinsic fatigue limit” will be used when a fatigue crack was initiated without inherent or process flaws. If the crack was initiated by an inherent or a process flaw the fatigue limit will be called “inherent” or “process fatigue limit”, respectively. In any case, Navarro and de los Rios derived an approximation of the fatigue limit which depends on the critical shear stress to activate a dislocation source behind the microstructural barrier at which the crack is stopped and has a Hall-Petch-like grain size dependence [9].

1.2. Influence of micro notches on the fatigue limit

The investigation of the influence of notches on the fatigue limit has a fairly long history [10]. It has been shown that there is a decrease of the fatigue limit of a notched specimen by a factor of K_f ($< K_t$) compared with the fatigue limit of an unnotched specimen [11]. Yet, most considerations regarding notches are focused on notches on a macroscale whereas new manufacturing techniques enable the production of functionalized surfaces with very small notches with dimensions on the microscale [12]. Such small notches might behave differently than macro notches because the dimensions of the micro notches are in the same order as the microstructural dimensions. As yet, only a