Probabilistic reliability assessment of a component in the presence of internal defects

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Metallic components and structures usually contain metallurgical defects as an inevitable result of any fusion welding or manufacturing process. Typical examples of defects are pores, non-metallic inclusions, cavities, lack of fusion or corrosion pits. Such discontinuities act as stress raisers (notches) and lead to premature crack formation in the early stages of fatigue life. Fatigue cracks are prone to initiate and grow from the small metallurgical defects not only on the surface but also in the interior of a component. Therefore, reliability and fatigue performance of metallic structures is determined by the distribution of defects contained in the most highly stressed volume. In this regard, fatigue life assessment of engineering structures in the presence of defects population has become of paramount concern from practical viewpoint. The need for accurate lifetime predictions is additionally supported by modern requirements on weight efficiency and minimizing fuel consumption, which should make the fatigue design less conservative without losses in the overall safety.

Effect of surface defects and roughness on the fatigue behavior has been extensively studied over the last 50 years. However, the nature of internal fatigue crack initiation and growth, the mechanisms of the fish-eye formation and the conditions responsible for the subsurface crack nucleation are not fully elucidated yet. This is related to a great complexity associated with the experimental determination of internal crack growth and to the fact that surface notches normally overshadow the internal defects in terms of their notch severity. Nevertheless, the topic of internal defects has recently become of great importance because some advanced manufacturing and material processing technologies have emerged over the last decades. A common attribute of these technologies is that the manufactured parts consistently show internal crack origins from various types of metallurgical defects in regions of high cycles (HCF) [1] and very high cycles (VHCF) [2]. Laser-assisted material processing techniques like laser beam welding (LBW) [3], laser metal deposition (LMD) [4] and selective laser melting (SLM) [5] are typical examples of the abovementioned technologies characterized by the inherent subsurface crack initiation. Parts produced by additive manufacturing possess some unique features with regard to the surface roughness, microstructure and defect distribution. Under these circumstances, both surface and internal defects may be responsible for fatigue failure. The crack origin position is always determined by a tradeoff between the surface roughness and the population of internal defects. However, if an additional post-processing technique is applied, e.g. laser surface remelting [6] or laser shock peening (LSP) [7], fatigue cracks inevitably originate from the subsurface discontinuities and, in some cases, even from microstructural inhomogeneities. Hence, the fatigue life of these components is entirely controlled by the growth of cracks initiated from internal defects, and the scatter in fatigue life is related to the scatter of defect size. Therefore, a quantitative characterization and probabilistic modelling of the fatigue life are needed in order to ensure the in-service security.

Traditional fatigue assessment of engineering structures with defects is based on the S-N curves with safety factors and is deterministic in nature. In this work, we propose a fatigue life assessment model for internally flawed materials based on the fracture mechanics approach which takes into account the size distribution of defects as well as their spatial distribution, influence of a vacuum-like environment at the crack tip of internal cracks, short crack behavior and some other relevant aspects. A methodology for simulating the scatter of fatigue life based on the statistical distributions of defect density and defect size is presented [1]. One of the major challenges in this regard is the definition of the most critical defect that initiates the worst-case fatigue crack. In contrast to conventional assessment procedures using the assumption that the largest defect initiates a dominant crack, in this work, two random variables – pore diameter and depth – are considered to identify the life-controlling defect. The evidence for this approach has been justified by experiments, i.e. very often, the crack-initiating pore is smaller than the largest pore in a specimen but it is located in a more critical location, e.g. closer to a free surface. Thus, the crack initiating capability of a defect relies on several factors, including its depth under the surface and also the local microstructure.

The global fatigue assessment model consists of several interdependent subroutines including the crack-growth module and the probabilistic module for generation of defects distribution in a specimen. The life-controlling defects are selected by the statistics of extremes for a given geometry, stress state and randomly distributed defects in a component. Crack initiation in the sense of nucleation of microstructurally short cracks is normally neglected. The most critical defect is identified by considering the shortest fatigue life among the defects. The applied crack-growth model predicts the fatigue life on the basis of the growth of a single crack from a given material defect. The model of physically short cracks based on the cyclic R-curve is used to quantify the accelerated growth of cracks in the near-threshold region. Finally, the probability of failure of a component is calculated as a product of statistical analysis of multiple random input data.

For the purpose of investigating the effect of defects on fatigue life, specimens have been manufactured from Ti-6Al-4V by LBW. A defocused laser subsequently treated the welded joints in order to smoothen the surface to promote internal crack initiation. The weldment can be regarded as a single layer of material in an additively manufactured part. The overall process of additive manufacturing can be considered as a cumulative laser welding process, where the defects of each layer are integrated in a big population for a final part. From the practical viewpoint, however, it is easier and cheaper to produce a weld with relatively simple geometry, thus, excluding other factors. Moreover, the defect size and distribution is not affected significantly by additional thermal cycles. Another factor to be considered is the required amount of statistics that is needed for the model validation. In this regard, due to its simplicity, the LBW process does not impose any restrictions on the number of specimens thus enabling to produce a large number of specimens to account for the large inherent scatter of fatigue testing. 2D maps (diameter-depth) of defects were measured by X-Ray analysis of the specimens. Fatigue testing was followed by thorough fractographical analysis of the broken specimens. The size- and spatial distributions of defects were subsequently considered in the model to predict the life-controlling defect in the specimens. Furthermore, LSP as a post-processing technique for the fatigue life extension is investigated.

Figure 1. Schematic illustration of the probabilistic modelling for assessment of the lifetime scatter.

The model development demonstrated that accurate lifetime assessment relies on careful consideration of the crack growth rates in vacuum and the short crack effect. The size distribution of the crack initiating defects differs from the overall defect population in a volume. On average, the life-controlling pores are slightly larger than the pores initially present before testing. Moreover, under reasonable assumptions, this shift can be predicted with good agreement. Random defect analysis can successfully predict the scatter of fatigue life and probability of failure, based on the given defect population (see Figure 1). A key role in the probabilistic modelling plays a criterion of a critical pore, i.e. a pore that initiates the dominant crack. An assumption based on the shortest fatigue life supported by the fractographical observations shows reasonable agreement with experiments.

Keywords: internal defects, fracture mechanics, probabilistic modelling, laser welding, additive manufacturing.

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