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Axial-torsional high-cycle fatigue of both coarse-grained and nanostructured metals: A 3D cohesive finite element model with uncertainty characteristics

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ABSTRACT

In this study the combined axial–torsional fatigue life and damage evolution of both coarse-grained (CG) and nanostructured metals are modeled by a 3D cohesive finite element method with uncertainty characteristics. To account for the random nature of metal fatigue, we combine the Monte Carlo simulation with the three-parameter Weibull statistical distribution function. For both CG and nanostructured metals, we find that the axial load levels have greater effects than random fields on the amplitude of specimen rotation. Compared with the CG metals, the nanostructured metals are found to exhibit an improved fatigue resistance, for the reason that their damage process initiates from the subsurface beneath the nanograined layer and then extends to the exterior surface. Good agreements between the numerical results and experimental data are also observed. It shows the applicability of the 3D cohesive finite element method for the analysis of damage evolution and prediction of fatigue life in these two classes of metals.

1. Introduction

The fatigue behavior of structural components is known to be strongly influenced by uncertainties. Nominally identical specimens under the same load can have extensive scatter in their fatigue life. The scatter of fatigue results can be attributed to the internal defects of the specimens, unavoidable wear, and machining errors, etc. In order to effectively simulate the scatter of fatigue results, the uncertainty factors should be taken into account in a quantitative manner.

In most cases, probabilistic models can be invoked to consider multiple sources of randomness. Monte Carlo simulation (MCS), a widely-accepted probabilistic method, directly takes into consideration the statistical distribution and can be used in the situation with a large number of random variables. Based on the probability density function, it is able to simulate the randomness of material parameters and establish statistical models. For instance, Beaurepaire and Schuëller performed the MCS to study the variability of material parameters of aluminum alloy [1] and Bahloul et al. conducted the MCS to evaluate the effects of geometric parameters on reliability in fatigue [2].

Based on the weakest-link theory, Weibull proposed an empirical distribution regarded as Weibull distribution [3], which was

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widely used to study the strength of fiber [4], ceramics [5], concrete [6], cast alloy [7], and the fatigue life of metals [8]. Its cumulative probability function is expressed as follows:

$$P(\sigma) = 1-\exp\left[-\frac{V}{V_0}\left(\frac{\sigma-\sigma_u}{\sigma_0}\right)^m\right] \quad \text{for } \sigma > \sigma_u \qquad \text{and}$$
$$P(\sigma) = 0 \quad \text{for } \sigma \leqslant \sigma_u \tag{1}$$

where σ_0 is the scale parameter and m is the Weibull modulus, and σ_u is the threshold stress below which no specimen is expected to fail. V and V_0 are the sample volume and the reference volume, respectively. The mean and variance of the Weibull distribution can be determined by σ_0, σ_u, and m. The Weibull distribution can be introduced into MCS to obtain the scatter of fatigue results and/or the description of material parameters. For instance, Yi et al. have employed it to study the effects of pore population upon the fatigue scatter, and showed that the simulated results were in a good agreement with the experiments [9]. The influence of the critical stress scatter on the regularity of crack arrest front was similarly investigated [10]. These studies have demonstrated that, although MCS needs intensive simulations due to the existence of numerous finite elements, it is an effective approach to the study of fatigue scatter and the randomness of material parameters.

The two-parameter Weibull distribution is identical to the three-parameter one with $\sigma_u = 0$. But if the two-parameter distribution is used, there is a probability that the fracture stress of metals is smaller than the yield strength. This is not a desirable feature as the specimen should deform plastically beyond the yield strength [11]. To alleviate this shortcoming, the three-parameter Weibull distribution will be employed and σ_u is taken as the yield strength σ_y in this paper.

In addition to the scatter of fatigue results, it is important to effectively simulate the fatigue damage evolution. At present, extensive experiments are being conducted [12–14], and various numerical methods are being proposed to simulate the fatigue damage evolution. The virtual crack closure technique (VCCT) is also employed to simulate the fatigue crack growth [15,16]. This technique requires the crack to be preset in the specimen, which restricts VCCT from simulating the initiation of the fatigue crack. Additionally, the extended finite element method (XFEM) is also recognized in the simulation of fatigue crack propagation [17,18]. This method requires the additional degree of freedom to represent the discontinuities and singularities on the crack surface so that there is no need to update the mesh. However, there are some limitations in XFEM applications. For instance, it is generally used in the crack tip and at present it is not able to deal well with the problems of multiple cracks [19,20].

The cohesive finite element method (CFEM) is a versatile one. It does not have the limitations of most of the traditional fracture approaches [21–30]. For instance, Dai et al. successfully used it to study the influence of microstructural characteristics on the fracture behavior of 316LN [30]. Not only is it widely useful to the study of fracture process, it is also effective to the simulation of fatigue damage evolution [31–33]. Along this line, Yamaguchi et al. have used it to predict the fatigue damage progress in fiber-metal laminates and provided good consistency with experimental data [31]. In addition, Chen et al. also employed it to analyze the progressive failure of fiber-metal laminates [32]. However, none of these studies has considered the scatter of fatigue results. This limitation can be removed, as mentioned above, through the introduction of MCS. In this context, we note that, combined with 2D CFEM, the MCS has been used to model fatigue crack initiation and propagation [1]. Based on such a combination, He et al. has considered the uncertainty parameters to simulate the fatigue crack path and fatigue life under mixed mode [34]. Bahloul et al. also integrated the MCS with 2D FEM to predict the fatigue life of the cracked structures after repair [2]. It is fair to say that, due to its simplicity, the 2D model has been employed by most researchers so far. But 3D model is a more precise approach to simulate the complex damage initiation and evolution processes of real structural components. For this reason, we will combine the 3D CFEM with the MCS to investigate the fatigue damage evolution of the metals.

The metallic specimen to be considered is depicted in Fig. 1. It shows the geometry of the fatigue specimen in our laboratory. The combined axial-torsional loads with both stress ratios -1 have been applied with an in-phase sinusoidal waveform under the frequency of 1 Hz. 304 stainless steel (SS) is chosen as the material of the CG specimens. Its wide application in engineering is due to its good corrosion and oxidation resistance. However, its application is limited by its low mechanical strength. The nanograined layer (NGL) was created by surface mechanical attrition treatment (SMAT). As a novel severe plastic deformation process, it can realize self-nanocrystallization on the metal surface [35]. For instance, Bahl et al. fabricated nanocrystalline surface on 316L SS by SMAT and found the increased corrosion fatigue strength [36]. Gradient structure generated by the SMAT in Cu and 304SS exhibited good uniform elongation and high yield strength simultaneously [37,38]. In addition, the SMATed specimens were found to have other superior properties [39–41]. Due to the improved mechanical properties of the SMATed metals, the SMAT has been used as our

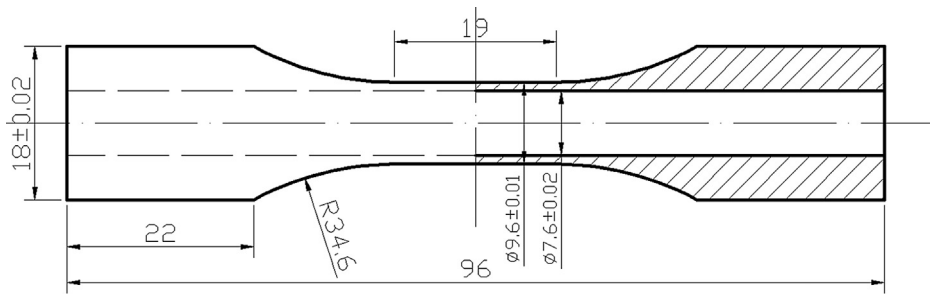

Fig. 1. The geometry of the experimental specimen.