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Evaluation of size effect on strain-controlled fatigue behavior of a quench and tempered rotor steel: Experimental and numerical study

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ABSTRACT

Combining the weakest-link theory with fatigue crack growth modeling, this study presents a mechanical-probabilistic modeling of specimen size effect for 30NiCrMoV12 steel in a low cycle fatigue (LCF) regime. Particularly, the influence of specimen size on fatigue life is quantified by experiments in strain-controlled fatigue and crack propagation. Experimental results from replica tests with three geometrical specimens indicate that nearly all of its fatigue life consists of multiple surface cracking with mutual interactions and coalescences. A probabilistic procedure for multiple surface fracture simulation is then established by incorporating random processes of crack formation, propagation and coalescence between dispersed surface cracks. Moreover, an evaluation of surface damage evolution is elaborated based on statistical physics for different structural sizes/volumes, which showed good agreement between analytical life distributions and test results.

1. Introduction

Fatigue and fracture tests are normally conducted on small test specimens of structural materials used for aircraft engines, nuclear power plants, and high-speed trains. More specifically, to satisfy safety demands, accurate assessment of fatigue life is required in structural integrity design and assessment. However, due to various factors, including specimen size, heat treatment, microstructure, and load conditions (temperature and frequency), a comprehensive understanding of fatigue and fracture behavior has not yet been attained [1]. In practice engineering, combinations of these factors usually contribute to a significant scatter in the fatigue life data or performance, which is one of the most critical factors for designing structure [2–4]. For the 30NiCrMoV12 as-quenched and tempered steel of research interest, which was developed for aerospace application and then adopted as high performance solution for railway axles due to its excellent mechanical properties, its heat treatment process has been optimized for the required strength and toughness through appropriate microstructure (martensite packets, blocks and laths) and carbide precipitates. Specifically, Zheng et al. [5] investigated the influence of austenitizing temperature and martensitic microstructure on carbide precipitates and mechanical properties during tempering in as-quenched and tempered 30NiCrMoV12 alloy steel. In addition, quantification of the size effect, i.e. how to extrapolate from test specimens to real components with different volumes, is critically important for ensuring structural integrity when designing structural/mechanical components.

In predicting the fatigue life of full scale components or structures, such as engine hot section components and high-speed train railway axles [6,7], the specimen size effect is critical when utilizing the laboratory testing of small standard specimens as the reference basis. In other words, fatigue testing on large specimens for those structures is not always possible due to financial/technical considerations (availability of testing equipment, test costs and time). Therefore, characterizing the influence of specimen size on fatigue life is needed and corresponding methods are lacking, especially a robust probabilistic method for quantifying the specimen size effect.

Until now, most conventional methods treated the effect of specimen size on fatigue life as a negative one, namely this effect reduces fatigue strength/life for an increase of specimen size [8–11]. From the viewpoint of defect-induced fatigue, the size of the most dangerous defect generally increases with the size/scale of engineering structure/component [12]. However, few guidelines, recommendations or mandatory regulations have launched well on the strength assessment of structures with different sizes/volumes under different loadings. Among them, the treatment of size effect by the German FKM guideline is purely empirical, which is determined from empirical design curves/formulas [10,13,14]. The application of the specimen size effect to other cross-sectional shapes/volumes and stress distribution conditions

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Nomenclature

a	Crack length
b	Fatigue strength exponent
d	Crack tip distance
α	Weibull scale parameter
n	Number of loading cycles
β	Weibull shape parameter
n'	Cyclic strain hardening exponent
D_0	Diameter of cross section
$\Delta\sigma_{eff}$	Effective stress range
$\Delta\varepsilon_{p,eff}$	Effective plastic strain range
K'	Cyclic strength coefficient
λ	Crack density
ε_a	Strain amplitude
N_f	Number of cycles to failure
$\gamma_{standard}$	Scale factor for standard specimen from the reference small specimen
a_i, a_f	Initial and final crack length
c	Fatigue ductility exponent
E	Elastic modulus
σ_y	Yield strength
R	Stress ratio
P_f	Failure probability
σ_f'	Fatigue strength coefficient
ε_f'	Fatigue ductility coefficient
L_0	Gauge length
ν	Poisson's ratio
ΔJ_{eff}	Effective cyclic J-integral
$\Delta\varepsilon_t$,$\Delta\varepsilon_e$, ε_p	Total, elastic and plastic strain range
$\Delta\sigma$	Stress range
r_p	Diameter of plastic deformation zone
γ_{large}	Scale factor for large specimen from the reference small specimen

is often not explained as well as the robustness of the low cycle fatigue (LCF) resistance against specimen size [15]. One of the commonly-used way to characterize the size effect by means of the weakest-link theory and the statistics of extremes. Recently, by combining the theory of critical distance with the volumetric approaches, Wang et al. [16] explored statistical size effect of TA19 titanium alloy for different scales of test sections with central circular holes, and pointed out that both the geometrical and statistical size effect should be taken into account for analyzing the combined effect of size and notch in practice. By interpreting the Coffin-Manson parameters as geometry-independent parameters, Schmitz et al. [17] developed a probabilistic fatigue model to consider the effects of specimen size and inhomogeneous strain fields of polycrystalline metals. Later, they [18,19] calibrated the geometry-independent model parameters from the hazard density approach and the surface integration over the FEA stress, then elaborated a probabilistic procedure to predict the fatigue crack initiation life distribution of arbitrarily shaped parts by considering the combined size and notch support effect. Blasón et al. [20] investigated the transferability of fatigue properties of 42CrMoS4 steel alloy with different sizes, and quantified the twofold scale effects for the statistical interpretation of cracking behavior. However, a probabilistic interpretation between the propagation crack growth rate and the fatigue failure lifetime is lacking. Therefore, to explain the specimen size effect toward increasing reliability of fatigue critical components, metallurgical and mechanical details must be considered in fatigue modeling and life assessment.

Note from [21,22] that fatigue life of ductile steels is generally dominated by crack propagation life rather than crack initiation life, which also agrees well with the experimental observations of current study (see Section 2). Namely, the influence of specimen size on the fatigue crack propagation rate, particularly on the scatter in small fatigue crack growth, has been viewed as the main factor influencing the fatigue life. Specifically, the influence of specimen size on mechanical properties varies from the type and local features of the component/structure, while the effect of inclusion can be neglected [21]. The challenge will be to use not only the governing factors, such as local microstructure, local stress/strain, surface conditions and damage physics, but also statistical approaches to understand the size effect in a LCF regime. Among them, surface microcracks, which describe the fatigue damage from the viewpoint of random damage events, have been studied recently to fully understand the fatigue failure mechanism [23–31], which is essential for fatigue life prediction and inspection routines for the development of cracks or defects. These cracks usually initiate at the specimen surface during the initial stage of fatigue tests and then extend to failure with accelerated crack growth rates through coalescence under high crack density. For life assessment of engineering designs with different sizes, lifing procedures based on Monte Carlo simulation have shown advantages on accounting for the statistical scatter of experimental life of materials with different microstructures [29,32].

In this regard, this paper attempts to quantify the influence of specimen size on fatigue life of 30NiCrMoV12 steel from the viewpoint of mechanical-probabilistic modeling and numerical simulation of surface cracking behavior. In particular, an alternative procedure for practical fatigue design by considering size effect will be critically investigated. This paper contains the following parts. In Section 2, strain-controlled fatigue experiments are carried out on three geometries of specimens to investigate the specimen size effect. Moreover, its cyclic response and surface cracking behavior are explored. Section 3 elaborates a mechanical-probabilistic prediction of specimen size effect on total fatigue life through combining the weakest-link theory and crack propagation modeling in a LCF regime, which quantifies the specimen size effect by summing the effect of statistical defects and that of crack propagation. Combining analytical with experimental studies, Section 4 presents and validates a numerical procedure for multiple fracture evaluation by considering the effects of crack initiation, crack propagation and crack coalescence under different specimen geometries. Section 5 compares the present work with other studies and elaborates consequences for fatigue design with and/or without defects. Section 6 summarizes the theoretical and experimental results of the current work.

2. Experimental program

2.1. Material

Low cycle fatigue tests have been conducted on specimens with three different geometries of similar shape, which are designed according to ASTM standard E606 [33], E739 [34] and prepared by electro-chemical polishing [35]. Fig. 1 shows the geometry of standard specimen used in the strain-controlled fatigue tests. Three different specimen geometries have been manufactured to study statistical size effects. The diameter (D_0) and the gauge length (L_0) of the three specimens as well as the number of tested specimens are listed in Table 1. Particularly, the minimum number of specimens required in $S-N$ testing was determined according to the ASTM standard E739, in which the replication index is calculated as 86.67%. The specimens were made of 30NiCrMoV12 steel grade (according to UNI 6787 [36]). This alloyed steel grade comes from a very selected scrap that is melt in an Electric Arc Furnace (EAF) then refined in a Ladle Heating Furnace (LHF), and finally vacuum degassed and poured into ingots. Its heat treatment includes normalization at 900℃ for structure levelling and grain size