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Extremely-low-cycle fatigue behaviors of Cu and Cu–Al alloys: Damage mechanisms and life prediction

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Abstract—The extremely-low-cycle fatigue (ELCF) behaviors of pure Cu and Cu–Al alloys are comprehensively studied following the cyclic push–pull loading tests with extremely high strain amplitudes (up to ±9.5%). Compared with the common low-cycle fatigue (LCF) region, several unique features in the ELCF regime can be noticed, including the deviations of fatigue life from the Coffin–Manson law, the non-negligible proportion occupied by the cyclic hardening stage of the whole fatigue life, special microstructures formed by cyclic loading containing deformation twins, shear bands and ultra-fine grains and the transformation of fatigue cracking modes. All these characteristics indicate the existence of special interior fatigue damage mechanisms of ELCF. To help discover the new damage mechanisms under ELCF, a model of fatigue life prediction with a hysteresis energy-based criterion is proposed. Based on the analysis of the experimental and modeling results, two intrinsic factors determining the ELCF properties were concluded: the capacity of ELCF damage, and the defusing and dispersion ability of the external mechanical work. The former can be evaluated by a parameter of the model called the intrinsic fatigue toughness W_0, which is related to the microstructure evolution condition, the cyclic hardening ability, the deformation homogeneity and possibly the static toughness. The latter can be represented by the damage transition exponent β, which can be enhanced by improving the planarity, reversibility and uniformity of plastic deformation, reflecting the decline in the degree of surface damage and the dispersion of fatigue cracks. For Cu–Al alloys with increasing Al content, cooperation between an increasing damage capacity and a decreasing damage accumulation rate leads to a comprehensive improvement in the ELCF properties.

Keywords: Extremely-low-cycle fatigue; Cyclic hardening; Fatigue crack; Hysteresis energy; Damage mechanism

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1. Introduction

Nowadays, the fatigue properties of engineering materials are commonly considered in most cases of structure design, to predict and prevent possible failure under cyclic loads [1]. Among these cases, one special circumstance has attracted attention in recent years: the cyclic loading condition with extremely large strain amplitude, such as earthquakes [2]. Under this condition, materials normally fail in fewer than 100 cycles, and perform differently from common low-cycle fatigue (LCF) behaviors. To distinguish this very-low-cycle regime from larger cycle parts of the LCF region, the fatigue process with a life of fewer than 100 cycles is termed extremely-low-cycle fatigue (ELCF) [3]. As an indispensable factor for seismic design, it is of great necessity to obtain a comprehensive and in-depth understanding of the ELCF behaviors of materials.

Several notable features make ELCF a special instance that needs to be re-recognized based on the classical LCF theory [4–6], which has been well developed since the 1950s:

(i) Microstructure evolution: the extremely large strain amplitude and relatively huge accumulated plastic strain during the ELCF tests could lead to special plastic deformation behavior followed by special microstructure evolution processes obviously different from the common LCF conditions.

(ii) Cyclic hardening/softening behavior: changes occurring in plastic deformation and microstructure evolution are always related to the transformation of cyclic hardening/softening behaviors, resulting in higher hardening/softening rates, larger saturation stress amplitudes, etc. Moreover, the extremely short cyclic life changed the proportion of stabilized cycles: this shrinks with the decrease of fatigue life, even completely disappearing under some extreme conditions as specimens fail before reaching the cyclic stabilization (cyclic hardening/softening saturation) [7–10]. Hence fatigue models based on the hypothesis of cyclic stabilization are unable to make accurate predictions of lifetime in the ELCF regime [11,12].

(iii) Mode of fracture and failure: according to previous research, the failure modes between ELCF and common LCF are significantly different [7,13–15]. For instance, in several push–pull fatigue tests, the

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fracture in the ELCF range often occurs in the interior of the specimen, while in the common LCF regime, the fatigue crack often starts from the surface [7]. Similar to (ii), the very short fatigue life changed the proportion of crack initiation, propagation and final fracture: due to the fast initiation of fatigue cracks in the ELCF regime, the stage of crack propagation becomes a main section of the whole fatigue life. This condition, together with the fracture mode transition [14,15] mentioned above, greatly changed the fatigue fractography [7,9], as well as the variation tendency of cyclic life [8].

These three aspects help distinguish ELCF clearly from common LCF, and make it another important category of fatigue.

Based on the distinctions between common LCF and ELCF, two main research tasks of ELCF can be summarized here: one is the foundation of new theories of ELCF damage mechanisms and cracking behaviors; the other is the building of new models for ELCF life prediction. On the one hand, the special behaviors of microstructure evolution, cyclic hardening/softening [7–10] and fracture mode [7,13–15] indicate a series of new underlying fatigue damage mechanisms, which need to be considered differently to those in common LCF conditions. On the other hand, the transformation of those internal mechanisms essentially causes deviation from the Coffin–Manson law in predicting the ELCF life [2,8,9,11,12], making life prediction an unsolved problem in ELCF investigation. Due to these analyses, damage mechanism and the life prediction model are considered as two main aspects in this study.

For the first aspect, pure Cu and a single-phase Cu–Al alloy system were chosen to conduct the ELCF tests and following observations, rather than the steels and other typical engineering materials mostly studied in previous ELCF research [2,7,10]. Compared with practical engineering materials, the pure Cu and Cu–Al alloys possess certain advantages for ELCF investigation as follows. Firstly, the pure Cu and Cu–Al alloys with different Al content can cover almost all the basic mechanisms of plastic deformation, making these a good choice for a comprehensive investigation of ELCF behavior, as the plastic deformation and microstructure evolution are considered the primary problem during the ELCF procedure. According to many studies [16–20], with increasing Al content, the single-phase Cu–Al alloys experience the transition of plastic deformation mechanisms from a typical wavy-slip manner (for pure Cu and alloys with low Al content) to a planar-slip manner (for alloys with more Al) and finally to the formation of stacking faults and deformation twins (for alloys with a relatively high Al content). The diversity of plastic deformation mechanisms for Cu–Al alloys is beneficial for achieving an integrated understanding of typical microstructure evolution behaviors and corresponding damage mechanisms. Secondly, a comprehensive improvement of mechanical properties is found in this alloy system with increasing Al content, including the synchronous improvement of strength and plasticity [21,22], the enhanced work-hardening ability [18,23,24] and the extended fatigue life in regimes of both HCF and common LCF [25,26]. Therefore, it is possible to extend this highly useful trend to the ELCF region, and previous mechanical research into this alloy system is of great reference value for the investigation of ELCF properties. Moreover, both the pure metal and alloys we chose share the simplest single phase; without the interference of the second phase or complicated elements, observation and analysis are greatly simplified. This factor, together with the concise binary components, makes the Cu–Al alloy system an ideal model material for the investigations of ELCF behaviors.

For the second aspect, the hysteresis energy is chosen to evaluate the ELCF damage by building a life prediction model, to replace the strain amplitude used in the Coffin–Manson law, which has been widely accepted in the study of the common LCF region. Corresponding background information will be introduced in detail at the beginning of Section 4.

In this study, the ELCF properties of pure Cu and a single-phase Cu–Al alloy system are comprehensively studied by cyclic push–pull loading tests with extremely high strain amplitudes. Several ELCF damage mechanisms are then carefully investigated, including the plastic deformation mechanism, microstructure evolution process, cyclic hardening behavior, crack distributions and fracture modes. A fatigue life prediction model with a hysteresis energy-based criterion is proposed, to evaluate the ELCF damage and build a relationship between microscopic damage mechanisms and macroscopic fatigue properties.

2. Experimental procedures

Pure Cu of 99.97% purity and Cu–Al alloys of three different Al contents (Cu–5 at.% Al, Cu–8 at.% Al, Cu–16 at.% Al) were investigated in this study. The pure Cu and Cu–Al alloys were cold-rolled and then annealed at 800 °C for 2 h to obtain highly homogeneous microstructures with an average grain size of ~150 μm. Push–pull strain-controlled fatigue tests were then carried out on an Instron 8850–250 kN testing machine with a strain ratio of −1 and a strain rate of $1 \times 10^{-2}\ \mathrm{s}^{-1}$ in ambient air at room temperature. Due to our focus on the ELCF behaviors, relative large strain amplitudes ($\Delta\varepsilon = 4\%, 8\%, 12\%, 16\%, 19\%$) were chosen, in an attempt to limit the fatigue life below 100. Correspondingly, a round bar shape with gauge dimensions of 10 mm (diameter) × 12 mm was designed for the fatigue specimens, to ensure the cyclic deformation is as stable as possible. After fatigue tests, surface deformation and damage morphologies (including fractured surfaces) of specimens were observed by scanning electron microscopy (SEM) with a LEO Supra 35 field emission scanning electron microscope. The deformed microstructures were characterized by transmission electron microscopy (TEM) with an FEI Tecnai F20 microscope, operated at 200 kV. Thin foils for TEM observations were firstly cut from the fatigue specimens parallel to the loading axis by a wire cutting machine, with an original thickness of 300 μm. Then they were mechanically reduced to ~50 μm thick, followed by a twin-jet polishing method in a solution of H_3PO_4:C_2H_5OH: H_2O = 1:1:2 (vol.) with a voltage of 8–10 V at −6 °C. Modeling and calculations were conducted by Matlab software.

3. Experimental results

3.1. Fatigue life

The data for fatigue life for pure Cu and Cu–Al alloys at different strain amplitudes are listed in Table 1. For each metal or alloy, fatigue life decreases with increasing strain