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Extension of linear elastic strain energy density approach to high temperature fatigue and a synthesis of Cu-Be alloy experimental tests

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ABSTRACT

The present paper summarizes the results from uniaxial-tension stress-controlled fatigue tests performed at different temperatures up to 650°C on Cu-Be specimens. Two geometries are considered: hourglass shaped and plates weakened by a central hole (Cu-Be alloy). The motivation of the present work is that, at the best of authors' knowledge, only a limited number of papers on these alloys under high-temperature fatigue are available in the literature and no results deal with notched components. The Cu-Be specimens fatigue data are re-analyzed in terms of the mean value of the Strain Energy Density (SED) averaged over a control volume. Thanks to the SED approach it is possible to summarize in a single scatter-band all the fatigue data, independently of the specimen geometry.

1. Introduction

In recent years, the interest on fatigue assessment of steels and different alloys at high temperature has increased continuously. In fact, high-temperature applications have become ever more important in different engineering fields, e.g. turbine blades of jet engine, nuclear power plant, molds for the continuous casting of steel, hot rolling of metals.

Among the traditional alloys available for this kind of applications, Cu-Be alloys surely stand out and fall within the most interesting materials suitable not only for high-temperature applications, thanks to their excellent compromise between thermal conductivity and mechanical properties over a wide range of temperatures (Caron, 2001; Davis, 2001; Lu et al., 2006).

In recent years, the interest on fatigue assessment of steels and different alloys at high temperature has increased continuously. In fact, high-temperature applications have become ever more important in different engineering fields, e.g. turbine blades of jet engine, nuclear power plant, molds for the continuous casting of steel, hot rolling of metals. In parallel, in order to bear mechanical loadings

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combined with critical conditions at high temperature, the development and testing of innovative materials has progressed substantially (Reardon, 2011). Among the traditional alloys available for this kind of applications, Cu-Be alloys surely stand out and fall within the most interesting materials suitable not only for high-temperature applications. In fact, they are also commonly adopted for magnet applications, thanks to their excellent compromise between thermal conductivity and mechanical properties over a wide range of temperatures (Caron, 2001; Constantinescu et al., 1996; Davis, 2001; Lu et al., 2006; Ratka and Spiegelberg, 1994; Zhou et al., 2008). In the above mentioned usages, cyclic mechanical loadings are usually combined with extreme heat flux, leading to the well-known conditions of high-temperature fatigue.

Despite that the required mechanical properties of Cu alloys have been gradually increased, at the current state of the art, relatively few papers are available in the literature dealing with the role played by a small amount of Cu on static properties of different steels (Alaneme et al., 2010; Bose and Klassen, 2009; Gonzalez et al., 2003; Kar et al., 2007; Maji and Krishnan, 2013). On the other hand, the number of scientific works on the fatigue strength of copper alloys (both at room and high-temperature) reduces drastically. Worth mentioning is contribution by Li et al. (2004), who reviewed some expressions able to quantify the thermal creep and fatigue life time of various copper alloys, including Cu-Ni-Be alloy. Fatigue experiments on bimetallic copper/stainless steel plates up to 500°C were performed in order to simulate the behavior of the first wall of the ITER (International Thermonuclear Experimental Reactor) (Li et al., 2000, 2004). The fatigue lifetime was given in terms of total strain amplitude and the specimens were designed for the specific application.

In another newsworthy paper (Kwofie, 2006), the cyclic creep behavior of copper, which usually accompanies low cycle fatigue under tensile mean stress, was investigated. Starting from a previously proposed exponential mean-stress function that accounts for the effect of the mean stress on cyclic loading behavior at room temperature, an empirical relationship was proposed for cyclic creep as an extension to high-temperature applications. The relationship involves the imposed stress amplitude and the mean stress value (Kwofie, 2006).

Other authors analyzed the fatigue-creep behavior of single crystals and bycristals copper under fatigue at elevated and room temperature, paying attention to microstructural aspects. For example, in Miura et al. (2004), the temperature dependence on the cyclic creep behavior of Cu–SiO2 bi-crystals of different but controlled misorientation angles was investigated at 400°C. In Yang et al. (2005) the deformation and dislocation microstructure of a [0 1 3] double-slip-oriented copper single crystal, under a symmetric tension–compression cyclic load, was studied at room temperature, in open-air and in a neutral 0.5M NaCl aqueous solution, respectively.

Hot compression tests were carried out in Shen et al. (2009) to study the static properties and microstructure of dispersion strengthened copper alloy deformed at high temperatures. With reference to the static properties, a new method of carrying out high-strain-rate tests at elevated temperatures on beryllium copper was proposed in Quinlan and Hillery (2004). In this work some equations correlating the ultimate tensile strength to the strain rate and the temperature were provided as well as some relationships linking elongation at fracture and strain rate (Quinlan & Hillery, 2004).

While the fatigue strength problem at low and high temperature has been investigated in a number of papers and books (Ko & Kim, 2012; Liu et al., 2013; Prasad et al., 2013, Torabi & Aliha, 2013) (see also References reported therein) as well as the modeling of materials subjected to high temperature inelastic behavior has been studied in recent contributions, the number of works dealing with copper alloys is limited and, in particular, no papers discuss the fatigue behavior at elevate temperature of notched specimens made of Cu-Be alloys.

The authors recently presented a complete characterization of this alloy and 40CrMoV13.9 steel at high temperature, considering smooth and notched specimens (Berto et al., 2014, 2013; Gallo et al., 2014). To the best of authors' knowledge, the recent and past literature lacks of data from plain and notched specimens made of Cu-Be at high temperature. To fill this gap, the present paper investigates the behavior of this alloy at temperatures ranging from room temperature up to 650°C. Two geometries are considered: hourglass shaped and plates weakened by a central hole. The obtained fatigue curves are discussed with emphasis on the reduction of stress concentration effects. Finally, the fatigue data of Cu-Be alloy are re-analysed in terms of the averaged Strain Energy Density approach, applied to a control volume surrounding the most stressed region at the notch edge

2. Experimental details

2.1 Material

The Cu-Be alloy under investigation belongs to high conductivity class usually used for production of shells for hot rolling. The spark emission spectroscopy analysis gave the composition reported in Table 1. In the same Table a comparison between the present alloy and the copper alloy UNS Number C17410 is carried out. This is a specific alloy belonging to the above mentioned high conductivity class but characterized by a very low concentration of alloying elements. However it is the most close to the material under investigation in the present paper. The tensile properties of the material at 650°C, obtained through tensile tests on un-notched specimens, are listed in Table 2.

Table 1. Chemical composition of the Cu-Be alloy under investigation; *min. value, °max. value.

Alloy	Cu (%)	Co (%)	Be (%)	Ni (%)	Fe (%)	Zr (%)	Si (%)	Al (%)
C17410	99.5*	0.35-0.6	0.15-0.50	/	0.20°	/	0.20	0.20
Specimen	98.6	0.88	0.215	0.0052	0.0197	>0.12	0.0019	/

Table 2. Static properties of the investigated Cu-Be alloy at 650°C

Test No.	Ultimate stress (MPa)	Yield stress (MPa)	Percentage elongation (%)
1	673	410	15.6
2	676	413	18.3
3	660	403	20.1

2.2 Procedure

The fatigue tests are conducted on a servo-hydraulic MTS 810 test system with a load cell capacity of 250 kN. The system is provided with a MTS Model 653 High Temperature Furnace. The furnace includes the MTS digital PID Temperature Control System and is controlled through high precision thermocouples. The furnace nominal temperature ranges from 100°C to 1400°C and the control point stability is about ± 1°C. The specimen was heated to reach the desired temperature and after a short waiting period (20 minutes) necessary to assure a uniform temperature, the test was started. The temperature was maintained constant until specimen failures thank to the PID temperature control system. The uniaxial tensile fatigue tests were carried out over a range of cyclic stresses at 5 Hz; the load ratio R was kept constant and equal to 0.01. The considered geometries are depicted in detail in Fig. 1. The concerned fatigue tests were carried out at room temperature and 650 °C.

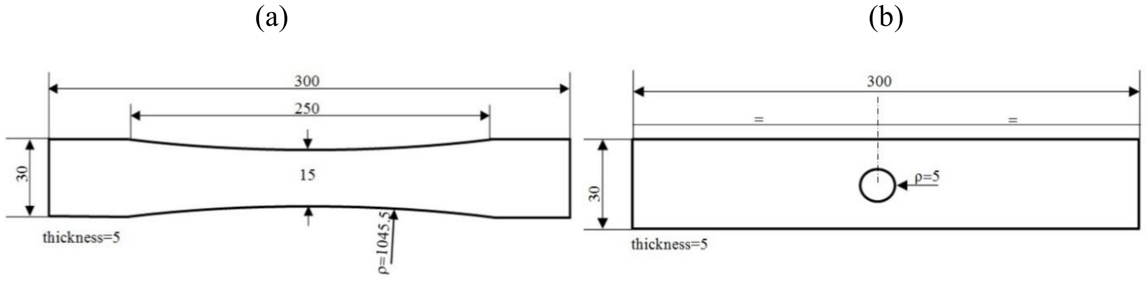

Fig. 1. (a) hour-glass shaped specimen; (b) plate with central hole; all dimensions in mm

3. Results and discussion

3.1 Fatigue test results

The fatigue data were statistically elaborated by using a log-normal distribution and are plotted in a double log scale. All stress ranges are referred to the net area. The run-out samples, over two million cycles, were not included in the statistical analysis and are marked with a horizontal arrow. A vertical line indicates the values corresponding to two million cycles.

Fig. 2 shows the fatigue obtained fatigue data. By comparing the results from notched and un-notched specimens, a reduction of 39% of the mean value of the stress range at two million cycles can be observed. In both cases the scatter index is limited. It is evident that the temperature has reduced the notch sensitivity of the material, indeed the actual K_f is equal to 1.66 whereas the expected value was 2.3.

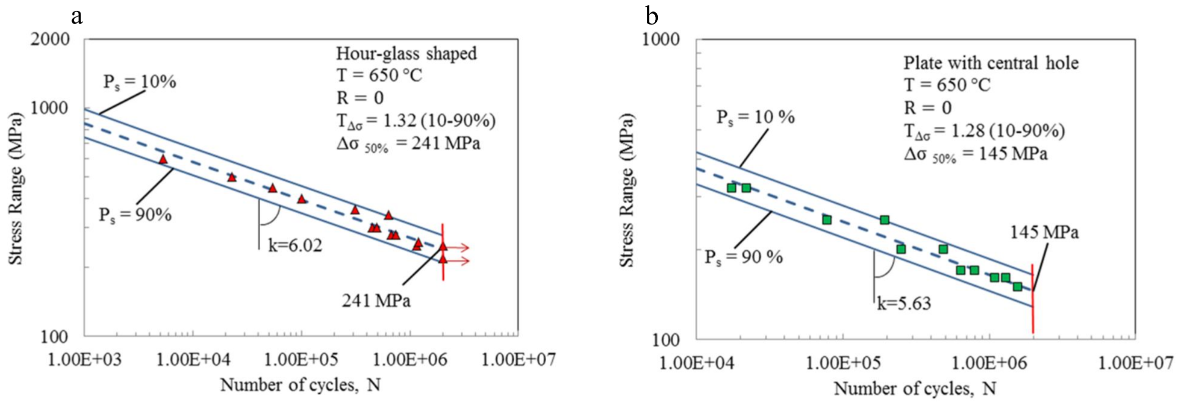

Fig. 2. Cu-Be fatigue data: (a) hour-glass shaped specimens; (b) plate with central hole specimens

3.2 A synthesis in terms of linear elastic SED averaged over a control volume

The averaged strain energy density criterion (SED) states that brittle failure occurs when the mean value of the strain energy density over a given control volume is equal to a critical value W_c. Such a method has been extensively used in the literature and its power, especially when dealing with fatigue of notched components, has been largely proofed, e.g. by (Lazzarin and Berto, 2005; Lazzarin et al., 2010, 2008, 2001; Torabi, 2013a, 2013b, 2013c). A review of the method has been presented in (Berto and Lazzarin, 2014).

In order to re-analyze the high temperature fatigue data in terms of strain energy density, it is necessary to determine the critical radius Rc that defines the size of the volume over which the energy was averaged (see Fig. 3-b). Since high temperature data from the cracked material under investigation were not available (e.g. ΔK_{th}), the critical radius has been estimated by equating the values of the critical SED at $2x10^6$ cycles as determined from the plain and the notched specimens. In the high cycle fatigue regime the critical SED range for un-notched specimens can be simply evaluated by using the following expression:

$$\Delta W_c = \Delta\sigma^2 / 2E \tag{1}$$

At $2x10^6$ cycles, by using the mean value of the stress range from plain specimens (241 MPa), the SED range is 0.22 MJ/m^3. In parallel, the averaged SED for plates with central holes have been calculated by means of ANSYS code. The material has been assumed isotropic and linear elastic with the Young's modulus E = 133000 MPa (which is typical of Cu-Be alloy under investigation) and the Poisson's ratio $\nu = 0.3$. The simulation has been repeated for different values of Rc, ranging from 0.2 to 0.9 mm (with a step of 0.1 mm). Coarse meshes have been used because the SED value is independent of the mesh pattern as documented in Lazzarin et al. (2010). For the plates with the central hole, the lower deviation with respect to the reference values (0.22 MJ/m^3) has been obtained considering a control radius $R_c = 0.6$ mm that returns a SED range of 0.24 MJ/m^3. The fatigue data are plotted in terms of averaged SED range over a control volume in Fig. 3.

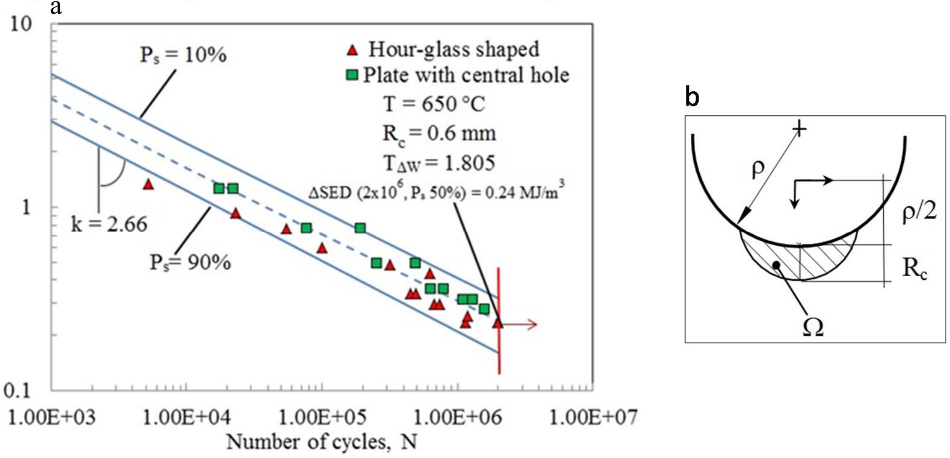

Fig. 3. (a) synthesis of Cu-Be fatigue data by means of local SED ; (b) critical volume of plate with central hole

4. Conclusion

The fatigue tests presented in this paper have shown that although the notched specimens have a less fatigue strength in absolute terms, they are characterized by a lower sensitivity to the high temperature with respect to hourglass-shaped specimens. This aspect is highlighted by the comparison between the fatigue strength reduction factors of the considered geometries.

Thanks to the SED approach, which is extended here for the first time to high-temperature fatigue, it is possible to summarise in a single scatter-band all the fatigue data from Cu-Be alloy, independent of the specimen geometry. The suitable control radius for this material has been found to be equal to 0.6 mm.

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