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## Fatigue behavior of innovative alloys at elevated temperature

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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 and 40CrMoV13.9 specimens. Two geometries are considered: hourglass shaped (both materials), 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 works on these alloys under high-temperature fatigue are available in the literature and no results deal with notched components.

In the present contribution, after a brief review of the recent papers, material properties and experimental procedure are described. The new data from un-notched and notched specimens are summarized in the corresponding fatigue curves. The Cu-Be specimens fatigue data are re-analysed in terms of the mean value of the Strain Energy Density (SED). The approach, successfully used by the same authors to summarise fatigue data from notched specimens made of different materials tested at room temperature, is extended here for the first time to high-temperature fatigue. In the plates with central holes the SED is evaluated over a finite size control volume surrounding the highly stressed zone at the hole edge. A value of the radius equal to 0.6 mm seems to be appropriate to summarize all fatigue data in a quite narrow scatter-band. Thanks to the SED approach it is possible to summarise in a single scatter-band all the fatigue data, independent of the specimen geometry.

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*Keywords:* high-temperature fatigue; copper-cobalt-beryllium alloy; fatigue strength; notched specimens; 40CrMoV.

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## 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 (Lu et al. 2006, Caron 2001, Davis 2001).

At the current state of the art, relatively few papers are available in the literature dealing with the fatigue strength of copper alloys (both at room and high-temperature). Worth mentioning is a 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. In another newsworthy paper by Kwofie (2006), the cyclic creep behavior of copper, which usually accompanies low cycle fatigue under tensile mean stress, was investigated. While the fatigue strength problem at high temperature has been investigated in a number of papers and books such as Prasad et al. (2013), Ko and Kim (2012), Liu et al. (2013), no papers discuss the fatigue behavior at elevated temperature of notched specimens made of Cu-Be alloys. Only a recent work by Berto et al. (2013) presents a complete characterization of this alloy at high temperature, considering smooth and notched specimens.

Another material which is commonly employed for hot-rolling of metals is 40CrMoV13.9 steel. It is usually subjected to a combination of mechanical and thermal loadings. High temperature fatigue strength of different steels has been studied in the literature. In Krukemyer et al. (1994) an experimental investigation was conducted on 22Cr-20Ni-18Co-Fe alloy at 871 °C using un-notched specimens. Cyclic deformation properties of the tested material were obtained from the data, and three fatigue models were applied. Dealing with the 1.25Cr0.5Mo steel, high-temperature stress controlled tests were carried out at by Fan et al. (2007) at different loading conditions to investigate the fatigue–creep interaction. Fully reversed axial fatigue tests have been performed by Uematsu et al. (2008) by testing smooth specimens of 18Cr–2Mo ferritic stainless steel (type 444) at room temperature, 673 K and 773 K in laboratory air, with the aim to investigate the effect of temperature on high cycle fatigue behavior.

At the best of authors knowledge the recent and past literature lacks of data from plain and notched specimens made of 40CrMoV13.9 and Cu-Be at high temperature. To fill this gap, the present paper investigates the behavior of these alloys at temperatures ranging from room temperature up to 650°C. Two geometries are considered: hourglass shaped (both materials), plates weakened by a central hole (Cu-Be alloy).

The paper describes the experimental procedure adopted during the tests. 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-analyzed 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.

The 40CrMoV13.9 has the chemical composition shown in Table 3 (mass %). The data-sheet reports the following mechanical properties at room temperature (25°C): elastic modulus E equal to 206 GPa, tensile strength equal to 1158 MPa and a yield strength of 1034 MPa with a percent of elongation of 15%.

Table 1. Chemical composition of the Cu-Be alloy under investigation.

Copper Alloy	Cu (%)	Co (%)	Be (%)	Ni (%)	Fe (%)	Zr (%)	Si (%)	Al (%)
UNS No. C17410	99.5 min	0.35-0.6	0.15-0.50	/	0.20 max	/	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

Table 3. Chemical composition of 40CrMoV13.9 steel under investigation.

C	Si	Mn	P	S	Cr	Mo	V
0.36-0.43	Max 0.4	0.4-0.7	0.025	Max 0.035	3-3.5	0.8-1.1	0.15-0.25

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 different temperatures and more precisely: the hour-glass shaped specimens made of 40CrMoV13.9 were tested at room temperature, 360°C and 650°C; the Cu-Be specimens, instead, were tested at room temperature and 650 °C.

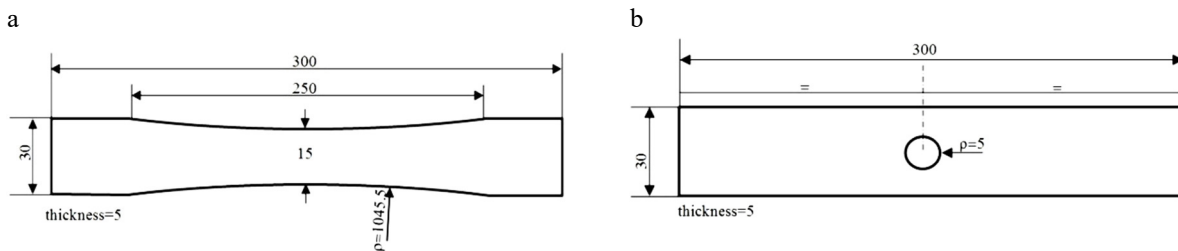


Fig. 1. (a) hour-glass shaped specimen; (b) plate with central hole.

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 data of the Cu-Be hourglass specimens and plates weakened by

central holes. 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, with  $T_{\Delta\sigma} = 1.32$  for smooth specimens and  $T_{\Delta\sigma} = 1.28$  for notched specimens. During the tests, both for un-notched and notched specimens no signs of plasticity were detected. Due to the large radius of the hole (5 mm), it was natural to think that the fatigue strength reduction factor  $K_f$  could assume a value equal to the theoretical stress concentration factor  $K_t$ , which is 2.30 (with reference to the net area). By assuming a priori  $K_f$  numerically equal to  $K_t$ , i.e. by considering a full notch sensitivity, the expected maximum stress range at two million cycles for the plate with central holes can be compared with the experimental data. 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.

Regarding the 40CrMoV13.9 steel, in Fig. 3 the fatigue data from hourglass shaped specimens are plotted at different temperatures, including ambient temperature. It is evident that no differences in terms of fatigue strength can be identified within ambient temperature and 360°C, while a substantial reduction of fatigue strength can be noted between ambient temperature (or 360°C) and 650°C. The reduction in fatigue strength at two million cycles is quantified in 84%.

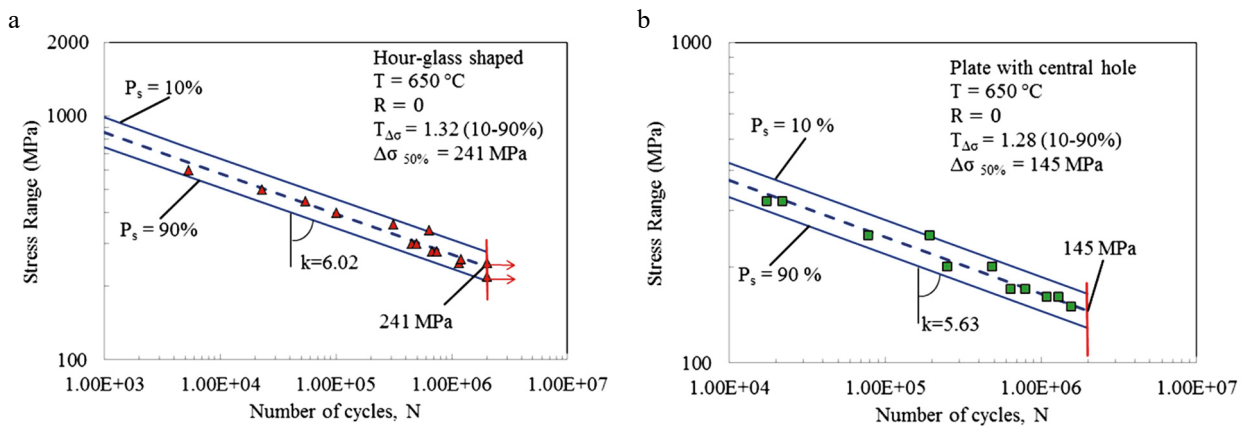


Fig. 2. Cu-Be fatigue data: (a) hour-glass shaped specimens; (b) plate with central hole specimens.

### 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 et al. (2010; 2008), Lazzarin and Berto (2005), Lazzarin and Zambardi (2001). A review of the method has been presented in Berto and Lazzarin (2014).

In order to re-analyse the high temperature fatigue data in terms of strain energy density, it is necessary to determine the critical radius  $R_c$  that defines the size of the volume over which the energy was averaged (see Fig. 4-b). As widely described in the above mentioned references, the control radius depends on plain specimen fatigue limit and on the threshold behavior  $\Delta K_{th}$  in the case of metallic materials under high-cycle fatigue loads. Since high temperature data from the cracked material under investigation were not available (e.g.  $\Delta K_{th}$ ), the critical radius has been estimated for this case by equating the values of the critical SED at  $2 \times 10^6$  cycles as determined from the plain and the notched specimens.

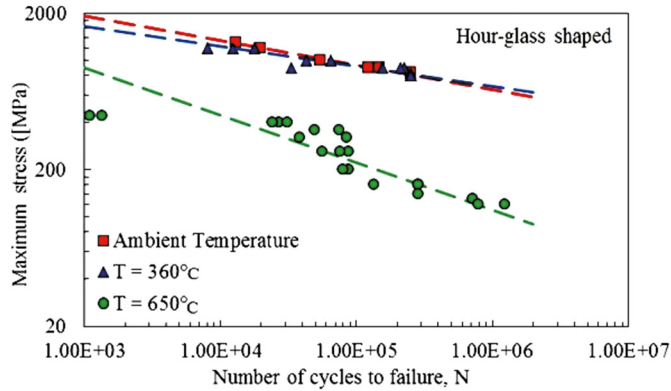


Fig. 3. 40CrMoV13.9 fatigue data, hour-glass shaped specimens.

In the high cycle fatigue regime the critical SED range for un-notched specimens can be simply evaluated by using the following expression:

$$\Delta W_c = \Delta \sigma^2 / 2E$$

At  $2 \times 10^6$  cycles, by using the mean value of the stress range from plain specimens (241 MPa), the SED range is  $0.22 \text{ MJ/m}^3$ . In parallel, the averaged SED for plates with central holes have been calculated by means of Ansys code modelling one quarter of the plate and taking advantages of the double symmetry. The radius of the control volume has been varied to match the SED value previously determined from the un-notched specimens at  $2 \times 10^6$  cycles. The material has been assumed isotropic and linear elastic with the Young's modulus  $E = 133000 \text{ MPa}$  (which is typical of CuBe alloy under investigation) and the Poisson's ratio  $\nu = 0.3$ . The 8-nodes iso-parametric element plane 82, with plane strain key-option has been selected.

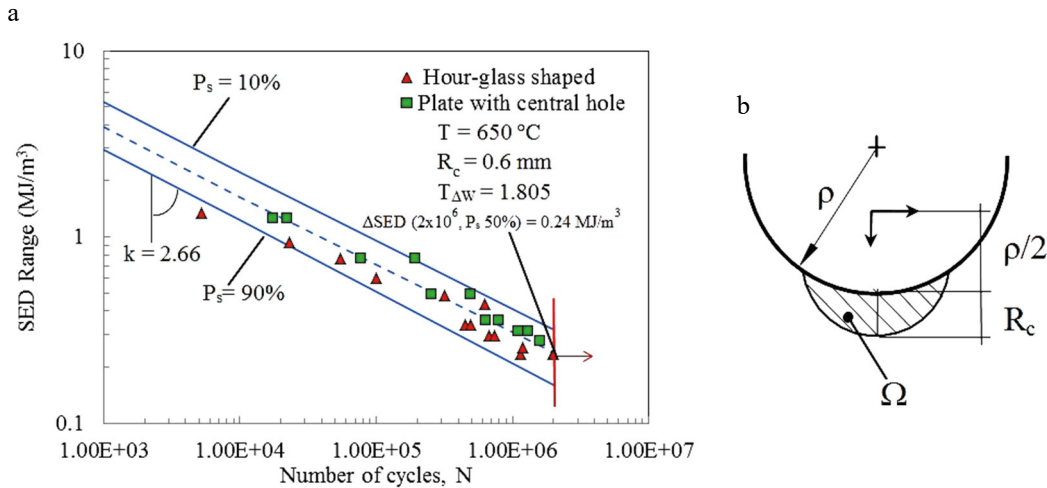


Fig. 4 (a) synthesis of Cu-Be fatigue data by means of local SED; (b) critical volume of plate with central hole.

The simulation has been repeated for different values of  $R_c$ , 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; 2008). For the plates with the central hole, the lower deviation with respect to the reference values ( $0.22 \text{ MJ/m}^3$ ) has been obtained considering a control radius  $R_c = 0.6 \text{ mm}$ . For this value, in fact, the SED range has been found to be  $0.24 \text{ MJ/m}^3$ , which is very close to that of un-notched specimens. The fatigue data are plotted in terms of

averaged SED range over a control volume in Fig. 4, considering the aforementioned critical radius. It is possible to observe that the scatter band is narrow, being the scatter index  $T_{\Delta w} = 1.805$ , equal to 1.34 when reconverted to an equivalent local stress range.

## Conclusions

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 summarize 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.

Dealing with 40CrMoV13.9 some preliminary results are summarized in the paper dealing with un-notched specimens. Future developments will be devoted to investigate the behavior of the same notched material to understand the temperature transition between fatigue and creep.

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