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Fatigue crack propagation mechanisms in C70250 and CuCrZr copper alloys

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Abstract

A previous study concerning the characterization of CuNiSi (C70250) and CuCrZr alloys showed very interesting characteristics of toughness evaluated with tensile tests and preliminary tests on Charpy specimens. These alloys could have interesting applications such as devices used for energy production, particle physics and aerospace. These alloys are used in the ITER (International Thermonuclear Experimental Reactor) project, an international program of great interest. For this reason, it seems important to characterize the mechanical properties of these alloys. In particular, fatigue crack propagation rate (da/dn vs ΔK) measurements were performed.

Keywords: Copper alloys; CuCrZr alloy; 70250 alloy; fatigue; fracture behavior.

1. Introduction

Among the commercial copper-based alloys, the most used alloys are the Cu–Be alloys because of their excellent mechanical behaviour. However, because of the high toxicity of beryllium, studying novel interesting copper alloys could be really important for many applications (Paolozzi et al. 2019). Among several alloys, CuNiSi and CuCrZr alloys appear promising because they couple high strength and hardness, due to the fact that they are precipitation

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hardenable, with good thermal and electrical conductivities. CuNiSi alloys are used for producing electric and electronic components, in which the precipitation of the intermetallic compound Ni_2Si increases the mechanical properties. In literature, many studies have been devoted to the study of phase precipitation (Liao et al. 2019; Lei et al. 2017), and more recently to the mechanical properties and fracture behaviour of these alloys (Saadouki et al. 2018; Goto et al. 2016; Felli et al. 2018; Gholami et al. 2017). Other interesting alloys are CuCrZr alloys. They have good castability and good machinability. Moreover, the CuCrZr alloys have an excellent combination of strength, electrical conductivity and thermal conductivity (Li et al. 2009; Morozova et al. 2018). For this reason, they are good candidates also for dissipating heat generated by nuclear fusion experiments. They are frequently used as engineering materials in various electric and electronic devices. The high strength of CuCrZr alloys is due to the precipitation of dispersed particles (Zhang et al. 2017; Chbihi et al. 2012). Because of the low solubility of Cr and Zr in Cu, the optimal contents of Cr and Zr in CuCrZr alloys are limited to 0.67 and 0.12 wt.%, respectively (Bochvar et al. 2007; Liu et al. 2017). CuCrZr is an interesting material for ITER (International Thermonuclear Experimental Reactor) project because it exhibits high thermal conductivity, high strength, good ductility, radiation resistance, commercial availability and low cost. Because of its unique properties, some studies have been carried out for determining its mechanical properties such as fatigue resistance (Nishi and Enoeda 2011, Wu et al. 2007; Brotzu et al. 2019a).

In this work, based also on the results obtained in a previous work (Brotzu et al. 2019b), the fatigue behaviour of the C70250 alloy was analysed compared with that of a CuCrZr alloy especially produced for evaluating its potential applications. The fracture surfaces have been carefully examined with the aim of understanding the fracture behaviour of these alloys.

2. Materials and methods

In this work, two aged Cu based alloys, the C70250 and the CuCrZr, characterized by the chemical compositions shown in Table 1 and in Table 2, respectively, have been used to perform high-stress ratio fatigue crack growth tests. The results have been compared to highlight the different behaviour of the two selected alloys. Microstructural analyses were carried out by means of optical microscope on specimens etched by using ferric chloride reagent. Microanalyses were carried out by means of EDS (Energy Dispersion Spectroscopy) in the aged condition. Both the investigated alloys have been optimized by a study of the hardness obtained in different aging conditions.

Fatigue crack propagation tests were performed in air according to ASTM E647 standard, using CT (Compact Type) 10 mm thick specimens, reported in Fig. 1a, and considering a high stress ratio value (R = Pmin/Pmax = 0.7). Tests were performed using a computer-controlled servo-hydraulic machine, visible in Fig. 1b, in constant load amplitude conditions, with 30 Hz loading frequency, a sinusoidal waveform and laboratory conditions. Crack length measurements were performed by means of a compliance method using a double cantilever mouth gage and controlled using an optical microscope (x40). The fracture surfaces of the CT specimens were observed and characterized by using scanning electron microscope (SEM).

3. Result and discussion

The C70250 alloy, produced in a vacuum induction furnace, is characterized by an actual composition slightly different from the nominal one, as shown in Table 1, mainly in terms of Ni and Si content. The alloy has been solubilized at 1000 °C in a vacuum furnace before being quenched in water. Then the alloy has been aged at 500 °C for 8 h. The aging time has been selected by taking into account the results of a previous experimental work (Felli et al., 2018).

Table 1. Nominal composition of C70250 alloy in comparison with the composition of the experimental alloy

	Ni	Si	Mg	Mn	Fe	Zn	Pb	Cu
Nominal composition	2.2-4.2	0.25-1.2	0.05-0.3	0-0.1	0-0.2	0-1.0	0-0.05	Bal.
Actual composition	5	10	0.6	0.01	0.3	0.1	0	Bal.

Table 2. CuCrZr alloy nominal chemical composition

	Cr	Zr	Cu
Nominal composition	1	0.1	Bal.
Actual composition	0.8	0.08	Bal.

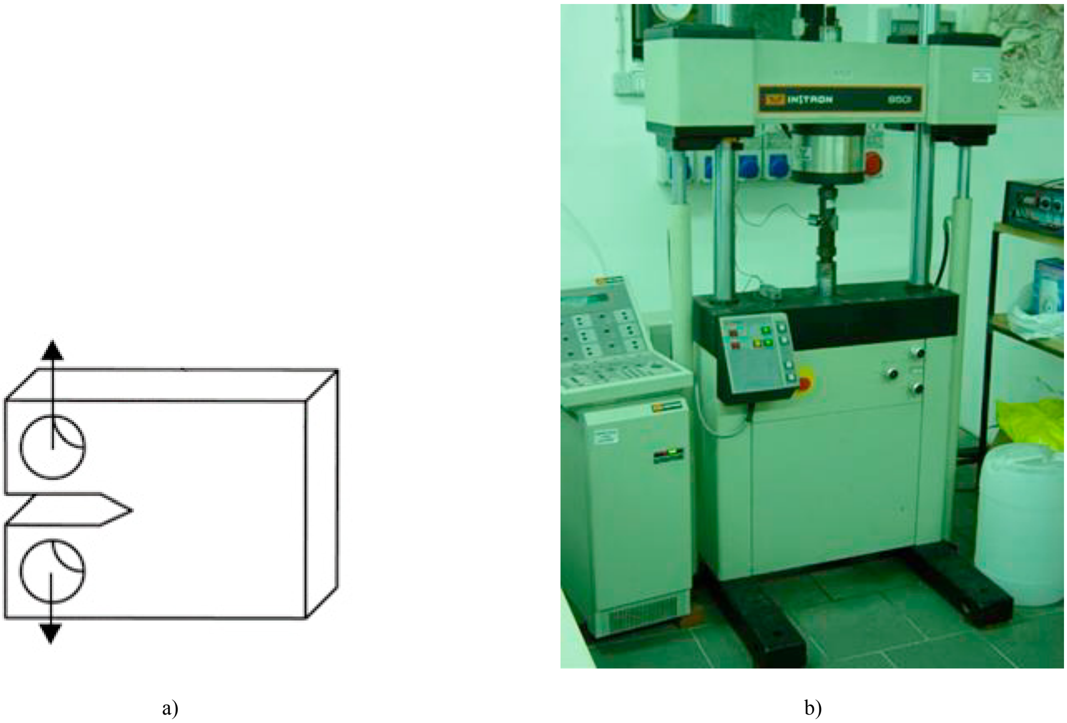


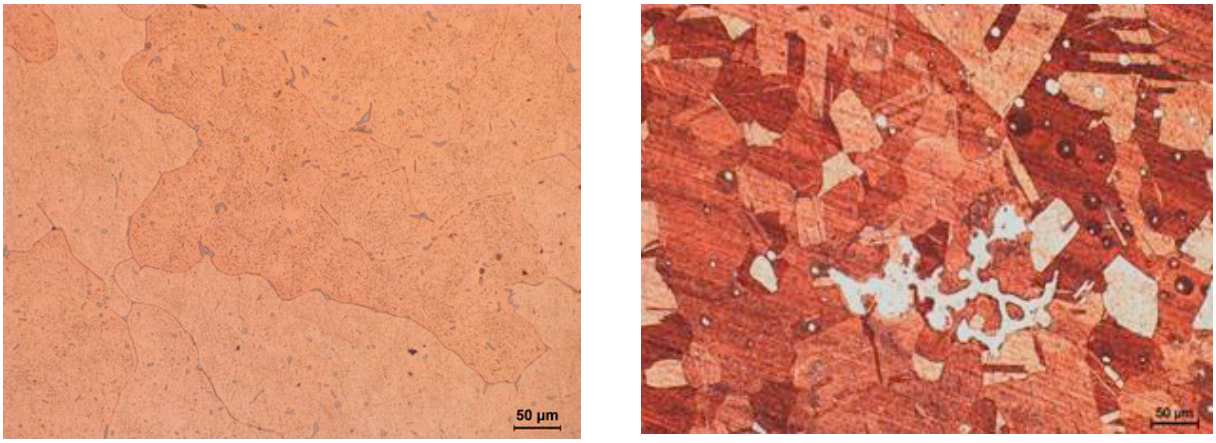
Fig. 1. Fatigue test equipment: a) CT specimens sketch, b) servo-hydraulic machine

CuCrZr alloy is a PH copper alloy (heat-treatable alloy) that has been subjected to forging. Cr content must be lower than 1.5wt% to avoid the formation of coarse Cr particles. Zr, whose concentration is lower than 0.25wt%, increases the alloy hardness due to the formation of precipitates and it increases the alloy ductility avoiding intergranular fracture. By observing Table 2, it is apparent that the content of alloying elements must be kept low: this is due to their low solubility in copper. In fact, it must be stressed that the highest equilibrium solubility of Cr in Cu is 0.71 wt.% at 1070 °C. Rapid solidification or severe plastic deformation are required to obtain a Cu-Cr supersaturated solid solution. On the other hand, the Zr solubility is very small (0.1 wt.%) even at a temperature close to the melting point. On the ground of these considerations, concentrations of Cr and Zr in CuCrZr alloys are usually limited to 0.67 and 0.12 wt.%, respectively. Obviously, if the solidification stage is not properly controlled, the formation of primary precipitates can occur with a consequent decrease of the alloy strength. In order to perform the tests, the CuCrZr alloy has been solubilized at 1000 °C and quenched in fresh water. In a previous work (Brotzu et al., 2019b) two different aging temperatures have been investigated (450 °C and 500 °C) and, on the ground of the obtained results, in this work specimens have been aged at 500 °C for 1.5 h.

The micrographs reported in Fig. 2 show the microstructure of the C70250 alloy, characterized by the presence of a fine and dispersed Ni_2Si phase (grey phase in Fig. 2a), and the microstructure of the CuCrZr alloy, where the Cr-rich phase formed during solidification is well visible (bright phase in Fig. 2b).

Both the alloys used in the characterization tests have been aged by selecting aging time and temperature that allow obtaining for each material the highest strength.

Fatigue crack propagation tests have been carried out by using a high-stress ratio (R=0.7) in order to evaluate the fatigue behaviour reducing the closure effect. The results are shown in Fig. 3.



a) b)

Fig. 2. Micrographs showing the microstructure of a) C70250 and b) CuCrZr.

The C70250 shows the lower ΔKth and a high crack growth rate for low ΔK. The Paris stage is not so evident, like in the case of the CuCrZr alloy, and a well-developed third stage can be observed in a range of ΔK starting from around 6 MPa $m^{0.5}$ up to critical ΔK (about 7 MPa $m^{0.5}$).

CuCrZr alloy is characterized by a range of ΔK greater than the C70250 one, and an extensive Paris stage starts at 8.5 MPa $m^{0.5}$ up to 14 MPa $m^{0.5}$. The ΔKth can be assumed to be 7 MPa $m^{0.5}$. Both the alloys show a maximum crack growth rate of less than 10^{-7}m/cycle.

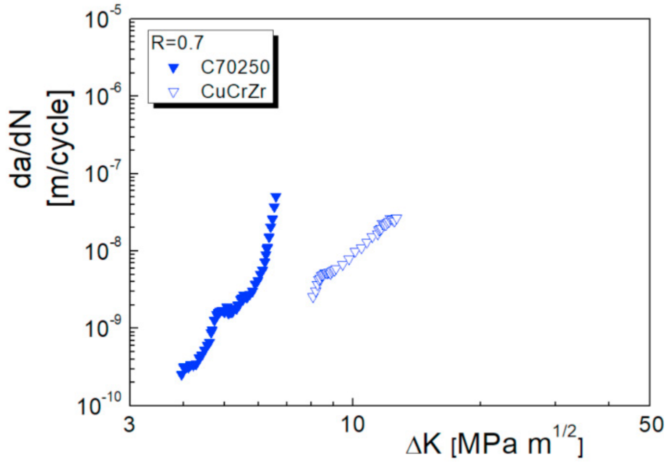


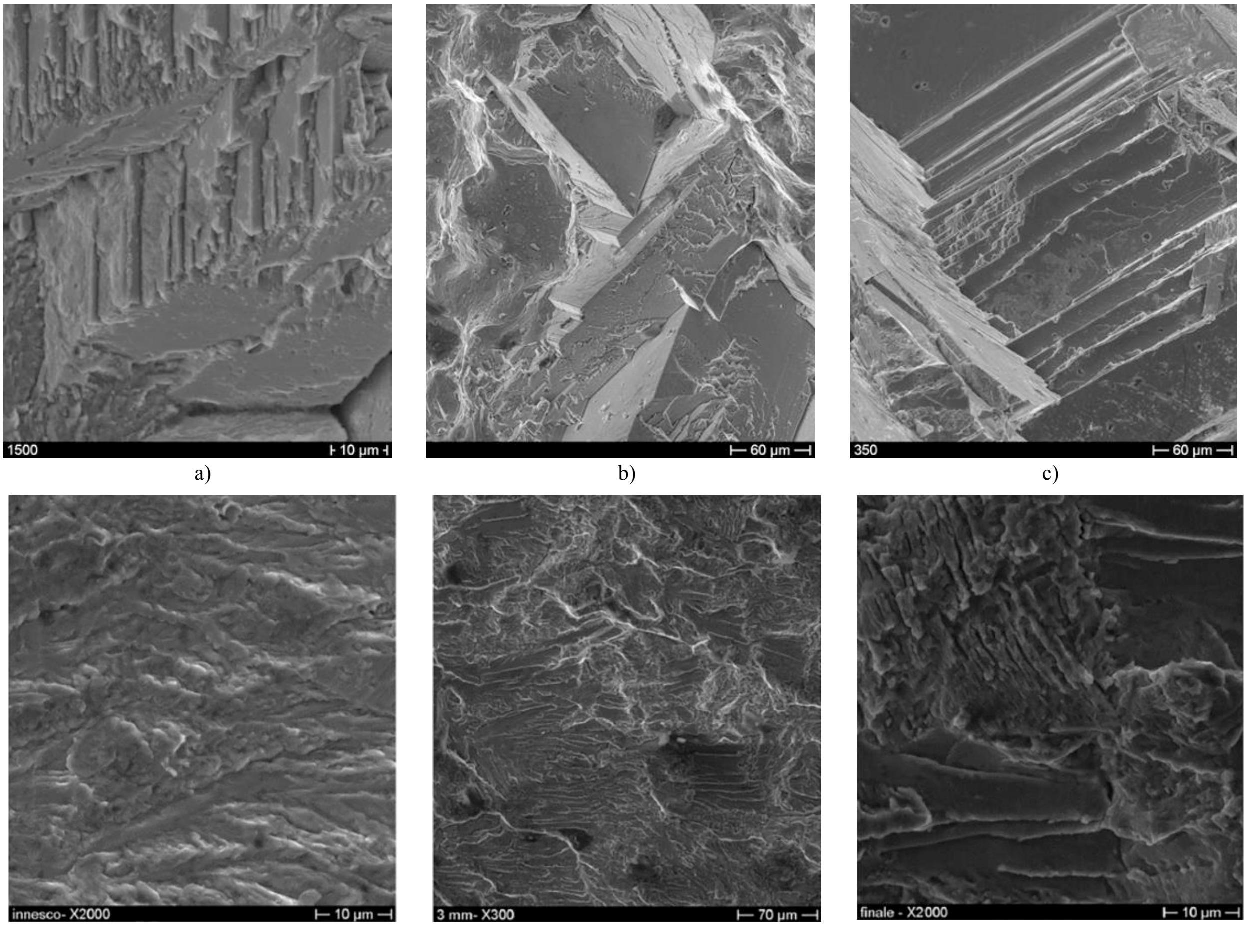
Figure 3. Fatigue crack propagation rate vs. ΔK of C70250 alloy, compared with CuCrZr alloy.

In terms of fracture micromechanisms, C70250 alloy shows a behaviour that is more brittle in comparison with that of CuCrZr alloy as shown in the SEM micrographs reported in Fig. 4. In particular, at low ΔK (Figure 4a) an intergranular propagation is observed with cleavage mainly in the crack propagation direction. At medium ΔK (Figure 4b) the cleavage is more evident in intergranular crack propagation, with short striations on grain boundaries, close to the edges. Also, at high ΔK (Figure 4c) the cleavage is evident and the striations on the boundary grains are oriented in the crack propagation direction.

The CuCrZr alloy is characterized by a ductile behaviour with cleavage fracture at low ΔK (Figure 4d). For intermediate values of ΔK (Figure 4e) cleavage micromechanisms are visible. Cleavage fracture is more evident for high values of ΔK (Figure 4f). For high ΔK the cleavage direction follows the main crack propagation direction. In all conditions, the CuCrZr alloy fracture surface shows fatigue striations in transgranular propagation.

The fracture analysis confirms the behaviour observed in fatigue crack propagation results (Fig. 3) where the CuCrZr shows a better fatigue behaviour.

It must be highlighted that the C70250 alloy, in contrast to CuCrZr alloy that was forged before aging, has an as-cast microstructure that determines a worst fatigue behaviour and the formation of a very irregular fracture surface with changing in some areas of the fracture mode. For high values of the stress ratio, the closure effect is negligible, but it is probable that by decreasing the stress ratio the closure effect could increase and the position of the two curves in the dA/dN vs. ΔK diagram could invert.



a) b) c)

d) e) f)

Fig. 4. Fatigue fracture surface analysis of 70250 (a, b and c) and CuCrZr (d, e and f) alloys: a) and d) at low ΔK corresponding to the crack initiation, b) and e) at Paris stage, c) and f) observations corresponding to the failure conditions.

4. Conclusions

In this work, the C70250 alloy, in the as-cast conditions and optimized in terms of aging parameters, has been investigated comparing its high-stress ratio fatigue behaviour with the behaviour of a forged and optimized CuCrZr alloy. A high value of the stress ratio (R=0.7) has been selected to avoid closure effects.

The da/dN-ΔK curves show a better fatigue crack propagation behaviour of the CuCrZr alloy. For all investigated ΔK, the C70250 shows crack micromechanisms characterized by a brittle morphology, starting from the near ΔKth conditions up to failure condition. The main crack propagation micro-mechanisms observed by SEM are always transgranular with the presence of few areas characterized by intergranular fracture. The CuCrZr alloy shows a more ductile behaviour and the fracture surface morphology is always transgranular and highlights fatigue striations.

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