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Study of the fracture behavior of a CuCrZr alloy

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Abstract

A previous study concerning the characterization of a CuCrZr alloy, considered as a possible candidate for the construction of passive satellites while highlighting some critical issues such as low hardness and elastic modulus, showed very interesting characteristics of toughness evaluated with preliminary tests on Charpy specimens and tensile tests. Considering that this alloy finds applications within the ITER project, an international program of great interest, it seems important to characterize many aspects of the alloy. For this reason, fatigue crack propagation rate (da/dn vs ΔK) and K_{IC} measurements were performed, too.

KEYWORDS

fatigue, fracture resistance, toughness

1 | INTRODUCTION

CuCrZr alloys have good castability and good machinability. Moreover, the CuCrZr alloys have an excellent combination of strength, electrical conductivity, and thermal conductivity.[1,2] These properties make these alloys an interesting candidate also for dissipating for example heat generated by nuclear fusion experiments. They are frequently used as engineering materials in various electric and electronic devices.

CuCrZr alloys have high strength and electrical conductivity resulting from precipitation of dispersed particles.[3,4] In fact, these alloys are age-hardenable: heat treatment, constituted by solution treatment followed by quenching and aging, provides a significant strength increase. Aged CuCrZr alloys possess high electric conductivity due to negligible electron scattering on solutes. 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.[5,6] Although precipitation from liquid of Cr and Zr phases decreases the mechanical properties of the alloy, a considerable strengthening of these alloys can be achieved by means of precipitation of secondary phases and thermo-mechanical processing. Plastic deformation can be performed by rolling, drawing, etc. CuCrZr alloys are studied also because they are used for high heat flux applications in components of the ITER[7] burning plasma device. CuCrZr is an interesting material for ITER because it exhibits high thermal conductivity, high strength, good ductility, radiation resistance, commercial availability, and low cost. However, to investigate the fracture behaviour of Cu-based alloys is very important.[8]

In this work, based on the results obtained in a previous work,[9] we analysed the toughness and fatigue properties of a CuCrZr alloy especially produced for evaluating its potential applications.

Toughness measurement tests have been carried out, both with CT and Charpy specimens for the determination of K_{IC}, impact strength, and crack propagation rate. The fracture surfaces have been carefully examined with both qualitative and quantitative methods by performing fractographic analyses of specimens subjected to fatigue tests.

2 | EXPERIMENTAL METHODS

CuCrZr was manufactured and provided by Società Metallurgica Minotti. The nominal composition was 98.9 wt% Cu, 1 wt% Cr, and 0.1 wt% Zr. The as-received material was forged and aged.

The Charpy Impact Test was carried out by using ASTM E 23 standards for a Type A specimen. Tensile tests were carried out for determining tensile strength, elongation, and modulus. Copper alloy specimens for Standard Charpy-V tests, with a 2-mm-deep 45° notch, for the determination of K_{IC} (ASTM E 399) and crack propagation rate (ASTM 647), were obtained from the as-received material that was forged and aged.

The fatigue tests were performed on standard CT specimens (as ASTM E647 indications) by using an hydraulic testing machine working at 30 Hz. The tests are performed using two load ratios at constant ΔP and sinusoidal wave form. The main parameters have been R = 0.1 and ΔP = 2500 N, and R = 0.7 and ΔP = 900 N.

The fracture surfaces of the CT and Charpy specimens were observed and characterized by using scanning electron microscope (SEM). Microstructural analyses were carried out by means of SEM and optical microscope on specimens etched by using ferric chloride reagent. Microanalyses were carried out by means of energy dispersion spectroscopy (EDS).

3 | RESULTS AND DISCUSSION

CuCrZr alloy is a PH copper alloy (heat-treatable alloy). Cr content must be lower than 1.5 wt% to avoid the formation of coarse Cr particles. Zr, whose concentration is lower than 0.25 wt%, increases the alloy hardness due to the formation of precipitates and increases the alloy ductility avoiding intergranular fracture.

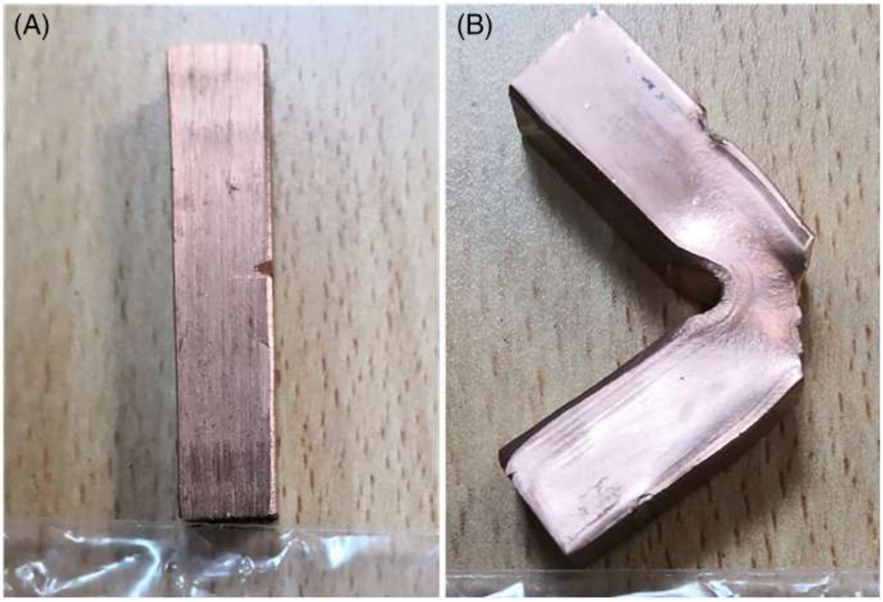

FIGURE 1 Charpy specimen before (A) and after (B) the test

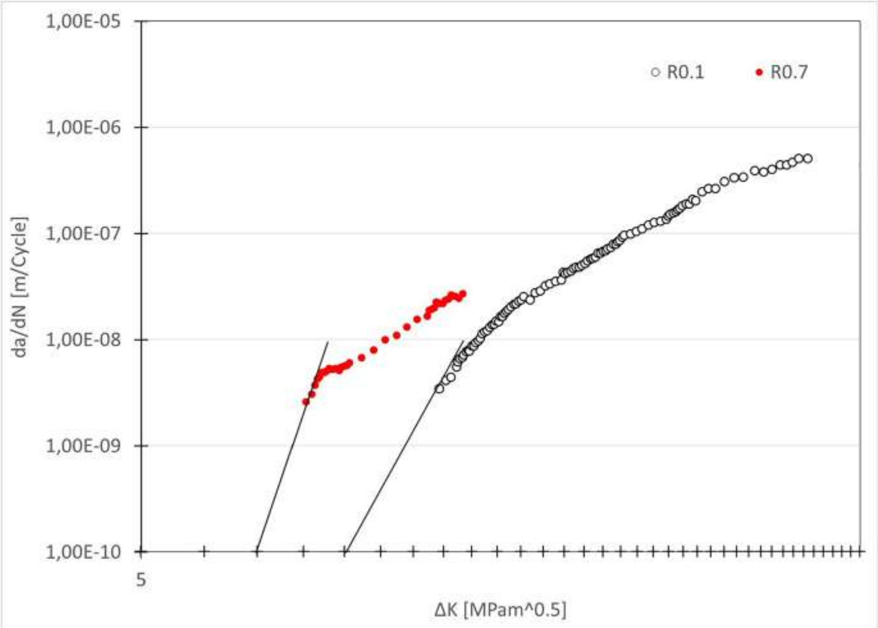

FIGURE 2 Fatigue crack propagation rate vs ΔK of two representative tests

Specimens of the as-received alloy have been analyzed by means of EDS. Several analyses carried out on different specimens highlighted that, although they are not homogeneous, the actual composition is about 99.12 wt% Cu, 0.8 wt% Cr, and 0.08 wt% Zr. SEM and optical microscope analyses of CuCrZr alloys revealed that the grain size is about 50 μm and that there is a phase distributed throughout the material that is a Cr rich phase.[9] 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 is 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, formation of primary precipitates can occur with consequent strength decrease of the alloy.

The tested specimens had a hardness of about 130 HV10. Tensile tests gave the following values of the mechanical properties: UTS 394 MPa, σ_y 180 MPa, and E% 32.5.

One of the main requirements for this alloy is that it needs to possess a good fracture toughness. Three specimens of the as-received alloy have been subjected to Charpy impact tests, and none of them broke as it can be seen from Figure 1. Tests highlighted that the alloy fracture toughness is higher than 290 Joule and then that the tested alloy is very tough as already mentioned in literature.[10] A preliminary test made for measuring K_{IC} gave a value equal to 49 MPa $m^{0.5}$.

Figure 2 shows the experimental values of crack propagation rate da/dn vs ΔK for R 0.1 and 0.7. This figure, that shows the curves that interpolate the first points, allows determining the values of ΔKth obtained for crack propagation rates of about 10^{-10} m/cycle. The ΔKth varies over

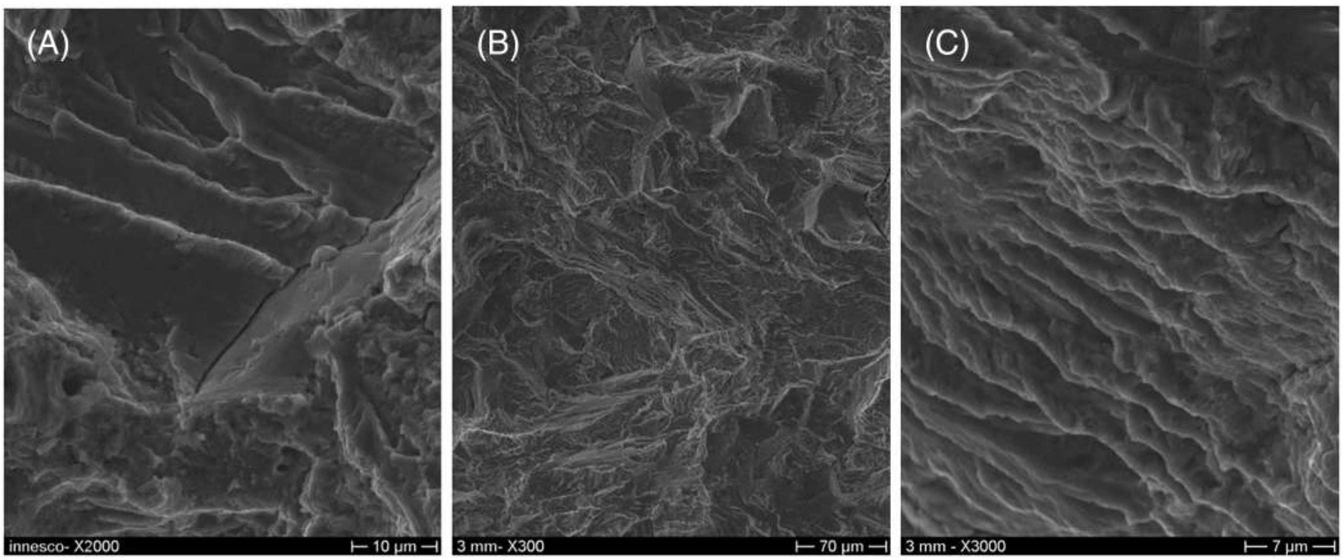

FIGURE 3 SEM micrograph showing the fracture surfaces in correspondence of crack initiation (A) and at 3 mm from crack initiation (B). (C) Specimen tested with *R* = 0.1

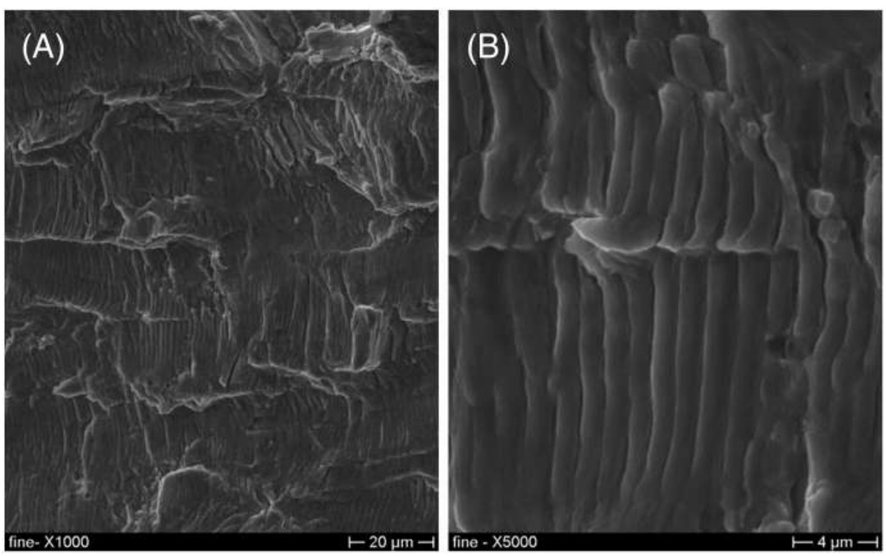

FIGURE 4 SEM micrograph showing fatigue striations in the final part of the fracture surface. Specimen tested with R = 0.1

the range 7 to 9 MPa $m^{0.5}$. Clearly, the values of ΔKth are very close in the case of ΔKeff which generally are almost coincident with the values of ΔK for high values of R (in our case $R = 0.7$). In the case of $R = 0.1$, there is a higher value of ΔKth (around 9) due to the crack closure effects. As far as the Paris regime is concerned, the trend lines converge towards the static fracture mode regime. However, in stage III it is clear that the accelerations are reduced. This is well evidenced by the considerable material plasticization at the crack tip during the propagation stage. Moreover, the curves move to the right as R decreases, indicating a marked closure effect for this alloy. The calculated maximum value of K is 38 MPa $m^{0.5}$ at $R = 0.7$ and 41 MPa $m^{0.5}$ at $R = 0.1$. This confirms the measured value of K_{IC}.

Although the examination of fracture surfaces after Charpy impact tests shows that, even at higher load application rates, the alloy behavior is always very ductile, fatigue fracture propagation proceeds in a brittle mode. By observing SEM micrographs reported in Figure 3, it is apparent that fracture of specimens tested with $R = 0.1$ propagates in a transcrystalline way. Brittle fatigue fracture propagated on cleavage planes, and at high magnification blunt striations can be easily seen (Figure 3C). In the final zone of the fatigue crack, the approximately 1-μm striations can be easily seen (Figure 4).

By observing fracture surfaces of specimens tested with $R = 0.7$, it can be highlighted that even in this case the fatigue fracture proceeded in a brittle made. In fact, Figure 5 shows a cleavage-like fracture and, only in the final zone of the fracture, distinctive fatigue striations can be seen together with cleavage planes.

SEM observation of the fracture surface in the static fracture mode regime highlights that the fracture is characterized by plastic deformation as it can be seen in Figure 6A. By comparing the micrograph reported in this figure with the one of the fracture surface after tensile test (Figure 6B) and

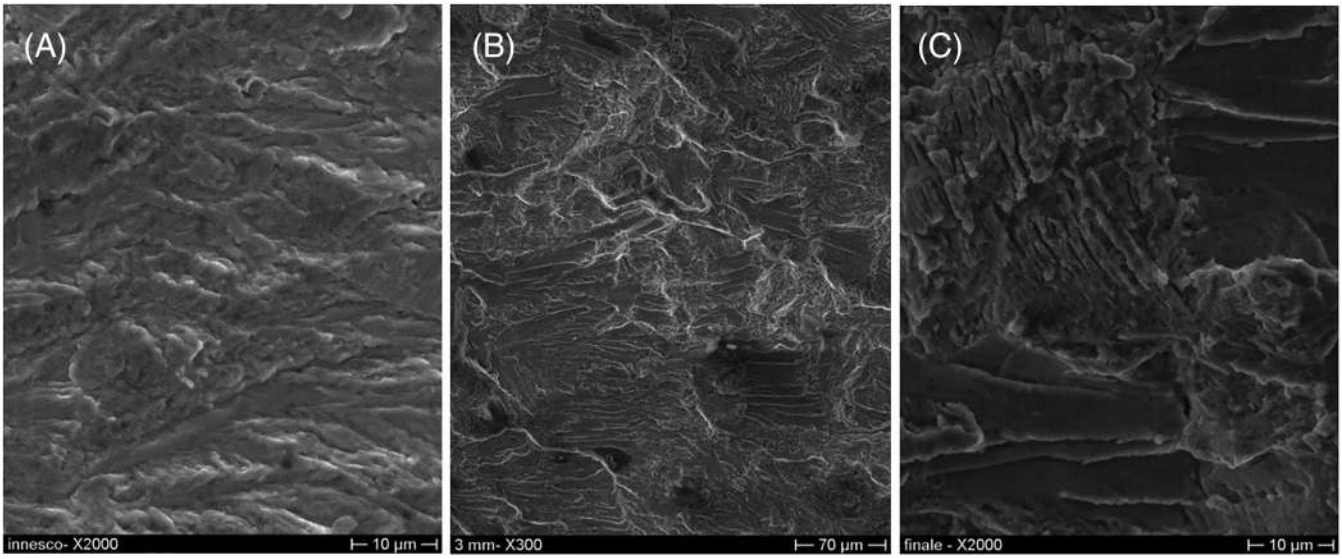

FIGURE 5 SEM micrograph showing the fracture surfaces in correspondence of crack initiation (A) and at 3 mm from crack initiation (B) and in the final part (C). Specimen tested with $R = 0.7$

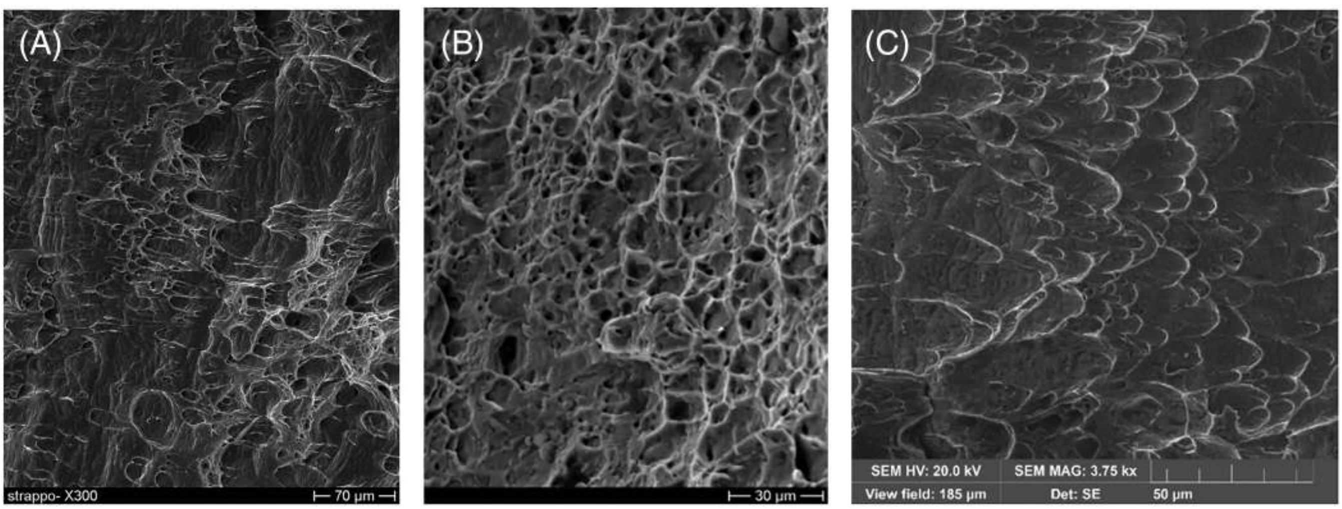

FIGURE 6 SEM micrographs showing the fracture surfaces of the CT specimen in the last stage (A), of the tensile specimen (B) and of the Charpy specimen (C)

with the one of the Charpy specimen (Figure 6C) it is apparent that, independently on the type of applied load, the studied alloy shows a ductile fracture. This alloy, before separation, has an intensive local extension and necking down. The studied material does not show, even after impact tests, mixed mode of cleavage and dimpled fracture. Moreover, there is not intergranular fracture, and this confirms the effect of Zr that avoids intergranular fracture. By observing fracture surfaces, the coarse Cr particles do not seem to affect the fracture behavior of the alloy.

4 | CONCLUSIONS

In this work, a complete characterization of an important copper-based alloy used in ITER (International Thermonuclear Experimental Reactor) is presented.

The main interesting properties are evaluated performing different mechanical tests. Obtained fracture surfaces are observed by using a SEM in order to determine the main fracture micromechanisms.

KIC tests and Charpy impact tests highlight that the alloy toughness is high. The fatigue tests, performed at low and high load ratios, show that the alloy is strongly influenced by the load conditions, mainly in terms of ΔK_{th}. Furthermore, the third stage of the da/dN curves slope decreases in ΔK due to the high tendency of the alloy to the plasticization, as observed in the Charpy tests, too. From fracture surface observations, the fatigue crack propagation in the second stage shows traditional striations, characterized by a step compatible with the measured propagation rate.

AUTHOR'S CONTRIBUTIONS

A.P. and C.P. planned the tests and provided the specimens. F.I, C.B. and V.D.C. performed fatigue tests. A.B., F. F. and D.P.performed metallurgical analyses. All the authors discussed and interpreted the results and gave their contribution to the conception and the writing of the paper.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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