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Effect of specimen type and size on fracture resistance curve determination for CuCrZr alloy

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Abstract

The precipitation hardened copper alloy CuCrZr is one of the candidate materials for the first wall and divertor components of ITER. In order to validate the applicability of copper alloys in the structural components of ITER, the effect of neutron irradiation on the fracture toughness behaviour has to be studied. Fracture toughness testing of irradiated materials requires the use of miniaturised specimens and the verification of specimen size effects on fracture toughness test results. In the present study the effects of specimen type, size as well as temperature on the ductile tearing fracture resistance behaviour of CuCrZr alloy will be shown. The applicability of miniaturised specimens for fracture resistance curve determination is considered by studying the allowable crack extension with which the miniaturised specimens still have similar fracture resistance curves as full-size specimens. The crack length and *J*-integral values will be compared to ASTM standard requirements for the maximum allowable crack extension and *J*-integral values in the fracture resistance test.

1. Introduction

A material's ability to resist ductile fracture is characterised by the fracture resistance that is plotted as a function of crack extension. Ideally, a fracture resistance curve unambiguously describes the material's ability to resist ductile fracture, and, therefore, it is considered as a material parameter. In the case of ductile fracture, elastic plastic parameters, i.e. either the *J*-integral (*J*) or the crack opening displacement (δ) are used as a parameter to describe fracture resistance. Experimental procedures for measuring the fracture resistance curve includes monotonously increasing loading of precracked specimens with a known geometry.

The valid specimen size for fracture resistance testing depends on the crack tip stress and strain behaviour. Requirements in testing standards stand for assuring that a *J* controlled stress strain state prevails close to the crack tip [1]. In a test specimen, *J* controlled conditions exist at the tip of a stationary crack when the plastic zone at the crack tip is small compared to in-plane dimensions of the cracked specimen ligament or thickness. Stable crack growth may, cause a situation where *J* does not characterise the crack tip conditions anymore. In a stable crack growth situation, the fracture is *J* controlled as long as the elastic unloading and the nonproportional plastic loading at crack tip are embedded within the zone of *J* dominance. When the crack grows out of the zone of *J* dominance, the measured fracture resistance curve is no longer uniquely characterised by the *J*-integral [2].

In practice, various factors have been found to have an effect on the fracture resistance curve. These factors are loading mode, geometry and size of the test specimen, crack length to specimen with ratio and side grooving of the specimen [3–7]. All these factors affect the constraint at the crack tip. A high constraint occurs at a crack tip when the plastic deformation near the crack tip is hindered due to the surrounding elastic material and a three dimensional stress state develops.

The present study is restricted to test specimens having a high constraint at the crack tip e.g. compact tension CT and single edge bend SEB specimens with an initial crack length to a specimen with ratio of 0.5.

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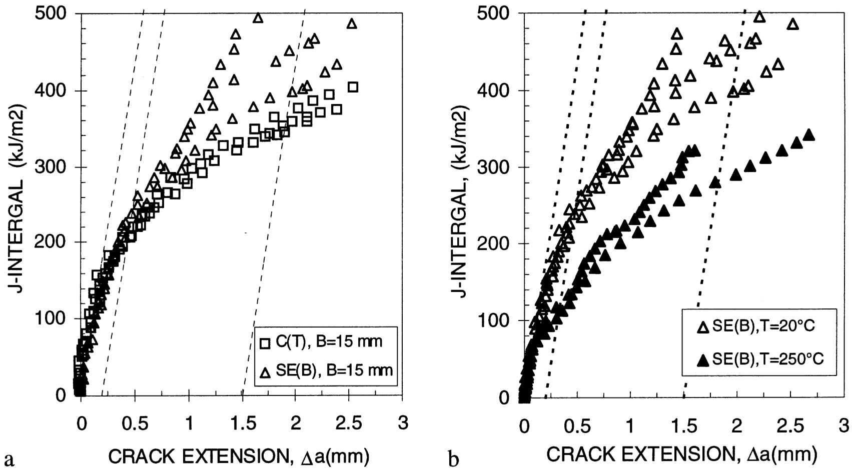

Fig. 1. Fracture resistance curves of CuCrZr alloy: (a) 15 mm CT and SEB specimens at room temperature; (b) 15 mm SEB specimen at room temperature and at 250°C.

2. Experimental

The fracture resistance of a CuCrZr alloy (produced by Outokumpu Oy) was determined using two different specimen types and several specimen sizes, see Table 1. The CuCrZr alloy was in the fully hardened condition e.g. cold rolled about 60% after solution anneal at 960°C for 1 h and subsequently precipitation heat treated at 460°C for 2 h. Fracture resistance curves (*J–R* curves) were determined according to the standard ASTM E1737-96 at room temperature as well as at 250°C. SEB specimens for three point bend testing and pin-loaded CT specimens for tensile testing were used. The SEB specimens with the thickness of 3, 10 and 15 mm and CT specimens with the thickness of 15 mm were tested.

All specimens were precracked to the initial crack length to a specimen width ratio of about 0.5 using a loading ratio $R = 0.1$ during precracking. After precracking, the specimens were 20% side grooved. The crack length during the fracture resistance test was measured using the unloading compliance method with the exception of those tests performed with 3 mm thick SEB specimens. In that case, the direct current potential drop (DCPD) method was used for crack length measurements. All tests were performed under displacement control.

3. Results

The effect of the specimen type and of temperature on fracture resistance for CuCrZr alloy is shown in Fig. 1. The specimen type does not seem to have any major effect on the fracture resistance curve. The fracture resistance curves determined using 15 mm compact CT and 15 mm SEB specimens are very similar yielding *J*-integral values for the onset of the ductile crack growth, $J_{0.2BL}$, of about 230 kJ m^{-2}. The effect of the test temperature on the fracture resistance of CuCrZr alloy is notable. At the temperature of 250°C the *J*-integral value for the onset of the ductile crack growth, $J_{0.2BL}$, is about 115 kJm^{-2} and is about 50% of the corresponding room temperature value. The ductile tearing resistance, d*J*/d*a*, was similar at room temperature and at 250°C.

The effects of specimen type and size on fracture resistance curves are summarised in Fig. 2. The effect of the specimen size on the fracture resistance of CuCrZr alloy seems to be negligible when the crack extension is less than about 25–30% of the initial ligament length. At low *J*-integral values fracture resistance curves are similar and only the curve determined using $3 \times 4 \times 27$ mm^3 SEB specimen differs slightly from the others. The reason for this might be that the DCPD crack length measurement method, which was used only for the 3 mm

Table 1
Specimen types and sizes used in fracture resistance (*J–R*) tests

Test method	Specimen type	Specimen dimensions ($B \times W \times L$ mm^3)	T_{test} (°C)
Tensile	CT	$15 \times 30 \times 31.25$	20
Three point bend	SEB	$15 \times 30 \times 160$	20,250
Three point bend	SEB	$10 \times 10 \times 55$	20
Three point bend	SEB	$3 \times 4 \times 27$	20,250

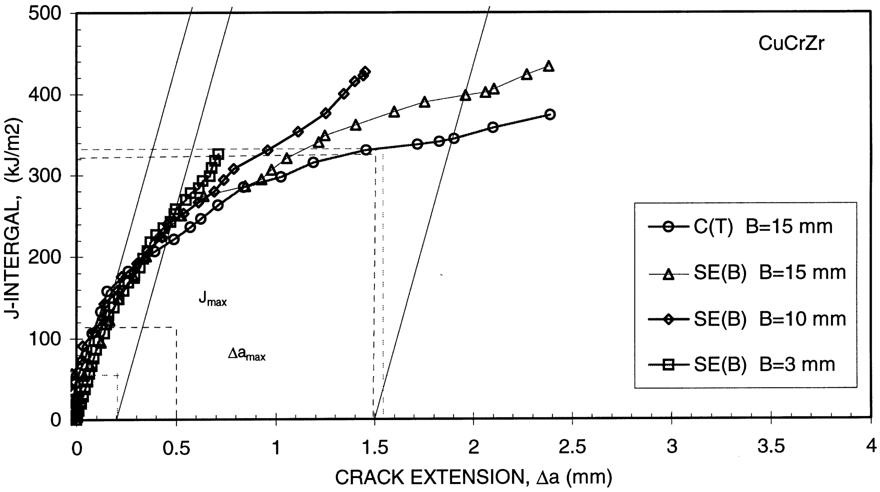

Fig. 2. Specimen type and size effects on fracture resistance curves of CuCrZr alloy.

thick SEB specimens, overestimates the measured crack length in the beginning of the fracture resistance test. The extension of the plastically deformed area at the crack tip in the beginning of the fracture resistance test and the crack tip blunting contribute to the measured DCPD signal without actual crack propagation.

4. Discussion

The standard ASTM E1737-96 states that allowable crack extension Δa_{max} and J-integral value J_{max} should not exceed the following limitations related to specimen dimensions:

$$\Delta a_{max} = 0.1\, b_0,$$
$$J_{max} = (b_0\, \sigma_Y)/M \quad \text{or} \quad J_{max} = (B\, \sigma_Y)/M.$$

The constant M is defined to ensure the constraint at the crack tip in all test specimen types and loading modes covered by the standards. For the studied CuCrZr alloy the flow stress (σ_Y) at room temperature is 435 MPa and the initial ligament (b_0) and the thickness (B) varies with the specimen size. According to the fracture resistance standard the constant M is limited to 20. Δa_{max} and J_{max} values calculated by using the initial ligament lengths for the 15 mm CT and SEB specimens as well as for the 10 and 3 mm SEB specimens are 1.5 mm and 326 kJm^{-2}, 0.5 mm and 109 kJm^{-2} and 0.2 mm and 44 kJm^{-2}, respectively. The limitations presented in the standard are shown in Fig. 2.

Both the 15 mm thick CT and SEB types of test specimens with an initial crack length to specimen width of 0.5 have similar fracture resistance curves. When comparing these curves to fracture resistance curves determined with 10 and 3 mm thick SEB specimens, the fracture resistance curves are the same until the crack extension exceeds 25–30% of the initial ligament.

The allowable J-integral value denotes the maximum measuring capacity of the test specimen by ensuring the crack tip constraint and three-dimensional stress state. In the case of brittle fracture the testing standards [8,9] limits the value of the constant M to $M \geqslant 30$–50 by ensuring linear elastic or elastic plastic behaviour at the crack tip. However, in ductile fracture the standards apply the less restricting criterion with $M = 20$ because of plastic behaviour. When comparing the process zones in brittle and ductile fractures, it can be concluded that the process zone in ductile failure is about one-fifth smaller than the process zone in brittle fracture and consequently also the constant M for ductile fracture can be expected to be about one-fifth of that defined for brittle fracture. Moreover, ductile tearing has the tendency to increase and maintain the constraint at the crack tip together with a high initial crack length to specimen width ratio and side grooving. Based on the results presented above, the restriction for a maximum crack extension and allowable J-integral value as presented in the standard ASTM E1737-96 seems to be conservative for the side grooved high constraint type of 10 and 3 mm thick SEB test specimens.

5. Conclusions

Fracture resistance curves determined for the CuCrZr alloy according to the ASTM standard testing procedure with 15 mm CT or 15 mm SEB specimens are similar. No specimen type effect can be observed.

Different size SEB specimens give similar fracture resistance curves for the CuCrZr alloy when crack extension does not exceed 25–30% of the initial ligament size. The results suggest that the ASTM standard requirements for allowable crack extension and *J*-integral values are conservative for the side grooved high constraint type of 10 and 3 mm thick SEB test specimens.

The fracture resistance of the CuCrZr alloy is significantly lower at the temperature of 250°C compared to that at room temperature. The *J*-integral value for the onset of the ductile crack growth, $J_{0.2BL}$, decreased from 230 kJ m^{-2} at room temperature to 115 kJ m^{-2} at the temperature of 250°C.

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