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# Effect of neutron irradiation on fracture toughness behaviour of copper alloys

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**Abstract**

One of the most important factors in deciding about the applicability of materials in the structural components of ITER, is the effect of neutron irradiation on the fracture toughness behaviour of these materials. In the present work, the fracture toughness properties of two candidate materials for the first wall and divertor components of ITER, namely precipitation hardened CuCrZr and dispersion hardened CuAl25 alloys, have been studied in the unirradiated and irradiated conditions. In parallel, tensile properties of these alloys have been also investigated in the unirradiated and irradiated conditions. 

## 1. Introduction

The current design for ITER utilizes copper alloys in the first wall and divertor structures. The function of the copper alloy in the first wall is mainly to dissipate heat produced by plasma disruptions and therefore the copper alloy is not designed to provide structural support for the first wall. However, the copper alloy for the divertor is designed for heat dissipation and for structural support of the divertor cassette. The anticipated range of operating temperature for copper alloys in the first wall and divertor cassette is from 100°C to 350°C.

On the basis of the currently available data, the dispersion strengthened CuAl25 alloy is being considered as the primary candidate alloy. The precipitation hardened CuCrZr alloy has been chosen as one of the backup alloys. Within the frame work of the ITER technology programme, screening experiments are being carried out to determine the effect of irradiation on physical and mechanical properties of these alloys [1–3]. Experimental results on these alloys have been reviewed by Fabritsiev et al. [4]. Recently, some results on the effect of irradiation on the low cycle fatigue behaviour of these alloys have also become available [5,6]. As regards the effect of irradiation on the fracture toughness behaviour of these alloys, practically nothing has been reported in the open literature. Recently this problem has been investigated and the results on the effect of irradiation on tensile as well as fracture toughness behaviour of CuAl25 IG0 and CuCrZr alloys are reported in the present paper.

## 2. Experimental

Two types of copper alloys, namely CuCrZr (produced by Outokumpu Oy) and GlidCop® CuAl25 IG0 produced by OM6 (formerly SCM Metals) were studied. Main alloying elements in CuCrZr alloy were 0.78 wt% Cr and 0.13 wt% Zr. The CuCrZr alloy plate (40 mm thick) was in hot rolled condition. The plate was heat treated (F) at 960°C for 1 h followed by water quench and precipitation heat treatment at 460°C for 2 h followed by air cooling. The grain size was about 200 μm. The CuAl25 IG0 alloy plate (20 mm thick) was in cross rolled condition with final heat treatment (D) at 980°C for 2 h. The grain size was about 1 μm.

Both unirradiated and irradiated tensile specimens of CuCrZr and CuAl25 IG0 were tested in an INSTRON machine at a strain rate of $1.3 \times 10^{-3}$ $s^{-1}$. Tensile testing at elevated temperatures was carried out in a vacuum of $10^{-5}$ Torr. Single edge bend SE(B) fracture toughness

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specimens of dimensions 3 × 4 × 27 $mm^3$ were machined from the plates of the above described copper alloys. The notch and the 20% side grooves were machined by applying electric wire discharged machining. The applied prefatigued crack length to specimen width was about 0.5. Fracture resistance curves were determined using the displacement controlled three point bend testing with a constant displacement rate of $1.5 \times 10^{-2}$ mm/min. Fracture resistance testing at elevated temperatures was carried out in a silicon oil bath. Load, displacement and crack length measured using the DC-PD method were recorded during the testing and the fracture resistance curves were determined following the ASTM E1737-96 standard procedure.

Both tensile and fracture toughness specimens of CuCrZr and CuAl25 IG0 were irradiated with fission neutrons in the DR-3 reactor at Risø National Laboratory at temperatures in the range of 50–350°C to a neutron fluence of $1.5 \times 10^{24}$ n/$m^2$ ($E$ > 1 MeV) corresponding to a displacement dose of 0.3 dpa (NRT). Irradiations were carried out with a neutron flux of $2.5 \times 10^{17}$ n/$m^2$ s corresponding to a damage rate of $5 \times 10^{-8}$ dpa (NRT)/s. Irradiations were performed in the atmosphere of helium or a mixture of helium and argon. Irradiations at 200°C and 350°C were carried out in a temperature controlled rig where the irradiation temperature was monitored, controlled and recorded continuously throughout the whole irradiation period.

## 3. Results

### 3.1. Tensile test results

Tensile test results for the unirradiated CuCrZr and CuAl25 IG0 alloys tested at 22°C, 200°C and 350°C are quoted in Table 1. Table 1 also contains the results for CuCrZr and CuAl25 IG0 alloys irradiated at 200°C and 350°C to a displacement dose level of 0.3 dpa and tensile tested (in vacuum) at the irradiation temperature. It should be pointed out that the $\sigma_{0.2}$ yield stress for CuCrZr increases significantly due to irradiation at 200°C whereas the irradiation at 350°C causes a noticeable softening in CuCrZr alloy. It should be also mentioned that the CuCrZr alloy irradiated and tested at 200°C does not exhibit any work hardening; on the contrary, it has a tendency to work soften. The specimen irradiated at 350°C, on the other hand, shows significant amount of work hardening when tested at 350°C.

### 3.2. Fracture toughness test results

Fig. 1 shows the typical fracture resistance curves of CuCrZr and CuAl25 IG0 alloys as a function of test temperature. Crack initiation and stable crack growth were observed for CuAl25 IG0 alloy at all studied temperatures and specimen orientation. However, for CuCrZr alloy extensive crack tip blunting occurred and clear stable crack growth was observed only at the elevated temperatures of 200°C and 350°C. Both initiation fracture toughness, $J_{0.2BL}$, for stable crack growth and tearing resistance values were higher for CuCrZr alloy than that for CuAl25 IG0 alloy. The effect of temperature and specimen orientation on the initiation fracture toughness for copper alloys is shown in Fig. 2. For CuAl25 IG0 alloy the initiation fracture toughness was higher in L–T orientation than in T–L orientation whereas the fracture toughness of CuCrZr alloy showed only moderate orientation dependence. The anisotropy in the initiation fracture toughness decreased with increasing temperature in both copper alloys. The initiation fracture toughness of CuAl25 IG0 alloy was relatively high at room temperature, average 98 kJ/$m^2$, and decreased continuously with increasing temperature to about 6 kJ/$m^2$ at the temperature of 350°C. A minimum in $J_{0.2BL}$ was not observed. At room temperature the initiation fracture toughness of CuCrZr alloy was about 240 kJ/$m^2$ and decreased first to about 130 kJ/$m^2$ at

Table 1
Tensile properties of unirradiated and irradiated CuCrZr and CuAl25 IG0 alloys

| Material | Orientation | Dose (dpa) | $T_{irr}$ (°C) | $T_{test}$ (°C) | Heat Treat. | $\sigma_{0.2}$ (MPa) | $\sigma_{max}$ (MPa) | $\varepsilon_t$ (%) | $\varepsilon_u$ (%) | $\varepsilon_u^p$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| CuCrZr | TL | – | – | 22 | F | 265 | 370 | 22.0 | 21.0 | 19.8 |
| | TL | – | – | 200 | F | 223 | 290 | 18.6 | 17.5 | 16.5 |
| | TL | – | – | 350 | F | 213 | 263 | 17.5 | 15.8 | 14.9 |
| | TL | 0.3 | 200 | 200 | F | 349 | 349 | 6.3 | 1.8 | 0.7 |
| | TL | 0.3 | 350 | 350 | F | 187 | 233 | 19.0 | 16.1 | 14.5 |
| CuAl25 IG0 | TL | – | – | 22 | D | 356 | 426 | 20.0 | 15.0 | 14.5 |
| | TL | – | – | 200 | D | 272 | 290 | 17.0 | 8.0 | 6.8 |
| | TL | – | – | 350 | D | 228 | 238 | 43.0 | 4.0 | 2.5 |
| | TL | 0.3 | 200 | 200 | D | 343 | 375 | 14.4 | 3.8 | 1.3 |
| | TL | 0.3 | 350 | 350 | D | 189 | 203 | 10.6 | 5.3 | 3.8 |

$\varepsilon_t$: total elongation; $\varepsilon_u$: uniform elongation; $\varepsilon_u^p$: plastic part of uniform elongation.

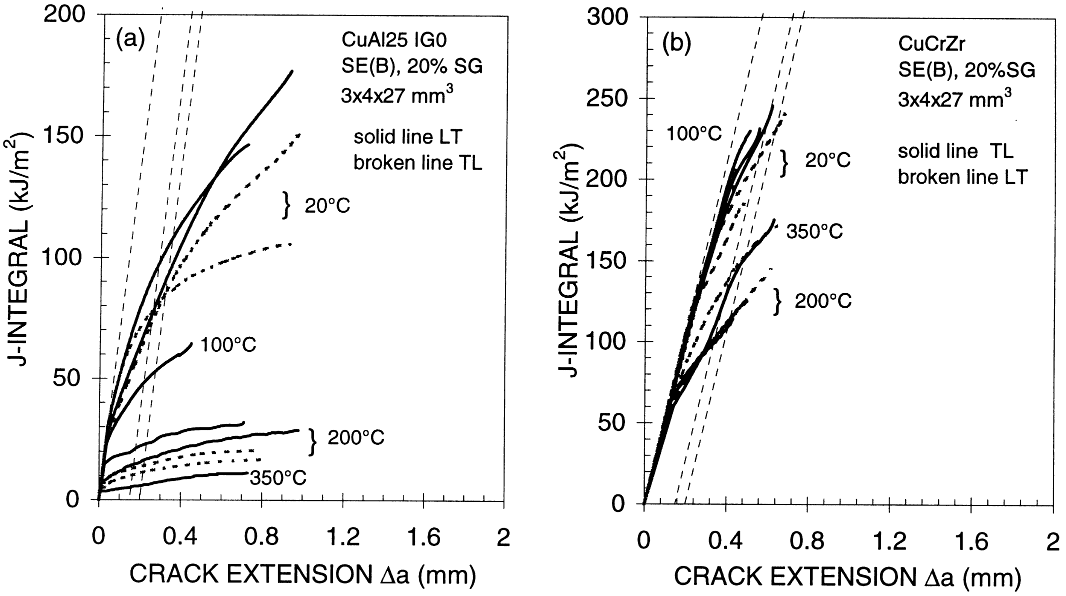


Fig. 1. Effect of temperature on fracture resistance curves of unirradiated (a) CuAl25 IG0 and (b) CuCrZr alloys.

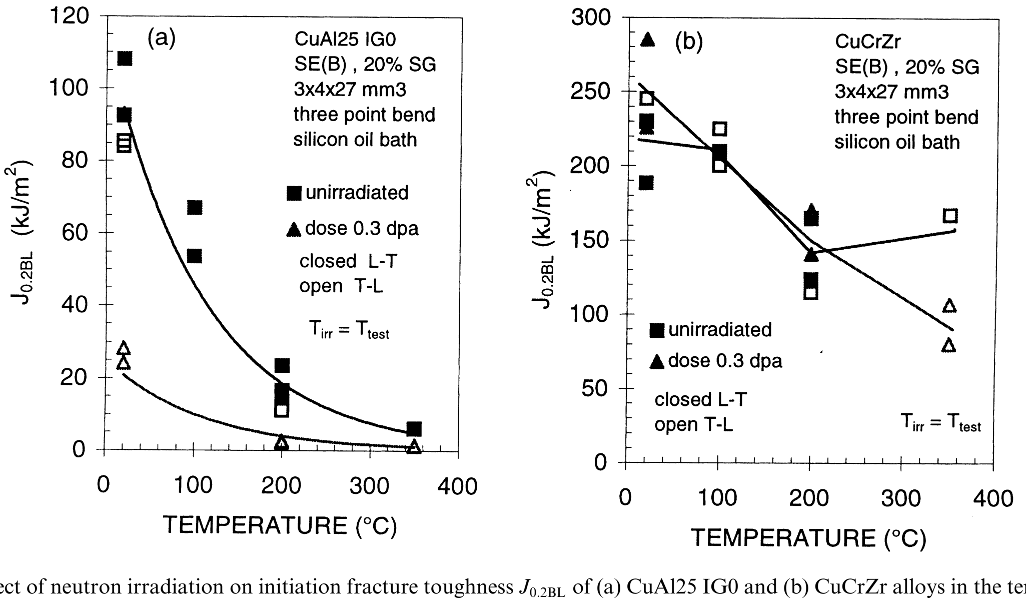


Fig. 2. Effect of neutron irradiation on initiation fracture toughness $J_{0.2BL}$ of (a) CuAl25 IG0 and (b) CuCrZr alloys in the temperature range from 20°C to 350°C.

temperature of 200°C and remained at about 150 kJ/m$^2$ at temperature of 350°C.

Fig. 2 also shows the effect of neutron irradiation on initiation fracture toughness of CuAl25 IG0 and CuCrZr alloys. A marked decrease in fracture toughness of CuAl25 IG0 alloy due to neutron irradiation to the dose level of 0.3 dpa was observed at temperatures in the range from 20°C to 200°C. However, no significant effect of neutron irradiation was observed in the fracture toughness of CuCrZr alloy at or below 200°C but an indication of a decrease in fracture toughness was observed at the irradiation and test temperature of 350°C.

## 4. Discussion

The fracture toughness of the ultra fine grain size powder metallurgical CuAl25 IG0 alloy is more sensitive to temperature increase than that of the conventionally produced hot rolled CuCrZr alloy. The present fracture toughness results are in good accord with the reported values in literature [8,9] as shown in Fig. 3.

In order to understand the factors controlling temperature dependent changes in fracture toughness micromechanical modeling coupled with macroscopic continuum mechanics can be applied [7]. Stress modified critical strain criterion is based on the idea that microvoids nucleate when local crack tip strain exceeds a critical plastic strain over a characteristic distance. The local crack tip strain distribution can be roughly described by modulus, work hardening exponent and yield strength. However, these parameters describing the crack tip strain distribution have similar temperature dependence in both copper alloys as estimated from the tensile test results and therefore cannot explain the different fracture toughness behaviour with temperature increase of these alloys. Local conditions of fracture in the crack tip vicinity are governed by critical plastic strain over characteristic distance. It should be emphasized that the critical plastic strain in the characteristic distance plays significant role in determining the temperature dependent fracture toughness behaviour. Characteristic distance which is comparable with a mean spacing of the void nucleating particles is expected to be a constant value if the deformation mechanisms and microstructure remain unchanged over the studied temperature range. The crack initiation occurs when the local plastic strain exceed a critical value specific to the relevant stress state. Although local critical plastic strain is not directly related to tensile elongation values, it can be expected from the observed decrease in uniform elongation values in tensile tests that it is smaller and decreases more rapidly with temperature for CuAl25 IG0 than that for CuCrZr alloy. The ultra fine grain size together with dislocation interactions with dispersoids and grain boundaries and apparent heterogeneity in particle distribution are expected to favour low work hardening ability and leading to strain localization and early increase in the local plastic strain in CuAl25 IG0 alloy in contrast to CuCrZr alloy with a larger grain size.

Neutron irradiation induces lattice defects in the form of clusters, loops and tetrahedra [2] which result in hardening and loss of tensile ductility in both copper alloys. The hardening was most pronounced at low temperatures below recovery stage V (~$0.3T_m$) and almost no hardening or even softening in tensile test results was observed at temperature of 350°C in both copper alloys. The irradiation induced clusters and loops are believed to pin the dislocations. This results in hardening and loss of tensile ductility at low temperatures. At high temperatures where irradiation defects are able to recover also hardening reduces and tensile ductility increases. In ultra fine grain size CuAl25 IG0 alloy irradiation defects are expected to further retard work hardening ability leading to more extensive strain localization and lower fracture toughness values compared to properties of non irradiated copper alloy. In the CuCrZr alloy, on the other hand, the fracture toughness seems to be almost unaffected at low temperatures. However, at 350°C a significant decrease was observed in the fracture toughness of the CuCrZr alloy. In view of the tensile results, this decrease is unexpected. It is

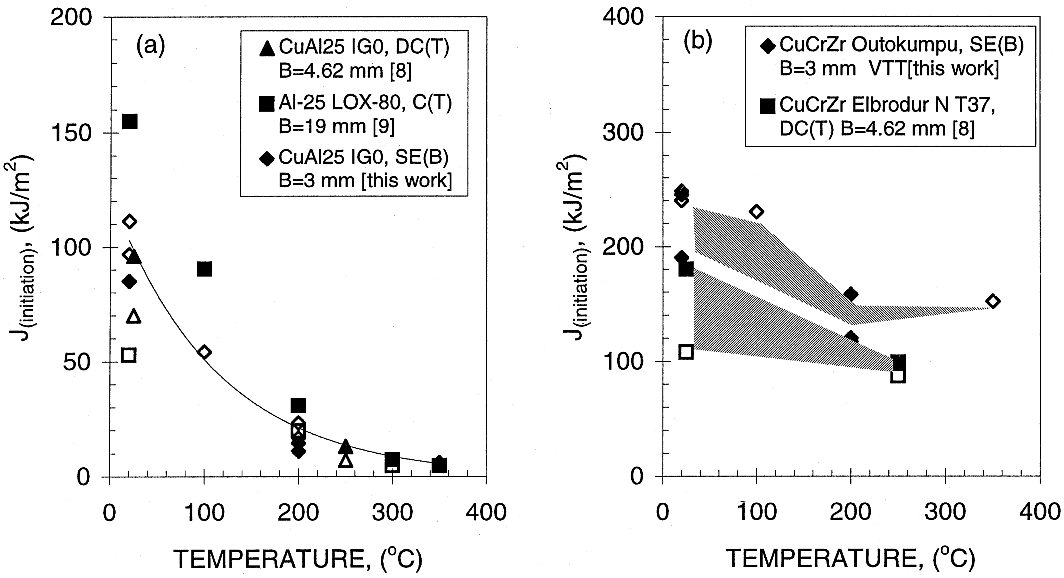


Fig. 3. Initiation fracture toughness values as a function of temperature for unirradiated (a) CuAl25 IG0 and (b) CuCrZr alloys. Open and closed symbols indicate T–L and L–T specimen orientations, respectively.

expected that due to relatively large grain size dislocation cells and tangles responsible for work hardening may form to some extent in the vicinity of the crack tip in irradiated CuCrZr alloy resulting in relatively high fracture toughness values at temperatures below 200°C. At higher temperatures irradiation induced coarsening of precipitates in CuCrZr alloy [1] may also be partly responsible for the observed reduction in tensile strength and also affect the fracture toughness behaviour. The effect of irradiation on tensile and fracture toughness behaviour of copper alloys are complicated and more experimental studies are needed to explain the observed temperature dependence of the fracture toughness.

## 5. Conclusions

1. The tensile strength and ductility of unirradiated CuAl25 IG0 and CuCrZr alloys decreased continuously with increasing temperature up to 350°C.
2. Fracture toughness of CuCrZr alloy was higher than that of CuAl25 IG0 alloy at temperatures in the range 20–350°C both in unirradiated and irradiated (0.3 dpa) state.
3. Fracture toughness of unirradiated CuAl25 IG0 alloy decreased with increasing temperature from 20°C to 350°C, whereas the fracture toughness of unirradiated CuCrZr alloy remained almost constant at temperatures up to 100°C and decreased significantly at 200°C and slightly increased at 350°C.
4. Neutron irradiation to a dose level of 0.3 dpa resulted in hardening and reduction in uniform elongation to about 2–4% at temperature of 200°C in both copper alloys. At higher temperatures softening was observed and uniform elongation increased to about 5% and 16% for CuAl25 IG0 and CuCrZr alloys, respectively.
5. Fracture toughness of CuAl25 IG0 alloy reduced markedly due to neutron irradiation to dose level of 0.3 dpa at the temperatures in the range from 20°C to 350°C. The fracture toughness of the irradiated CuCrZr alloy also decreased in the range from 20°C to 350°C, although it remained almost unaffected at temperatures below 200°C and decreased significantly at a temperature of 350°C when compared with fracture toughness of unirradiated CuCrZr alloy.

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