Fracture Toughness of Neutron-Irradiated CuCrZr

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Introduction

- Precipitation-hardened CuCrZr is a prime candidate for high heat flux applications in the ITER first wall and divertor components.The fracture toughness and the effect of neutron damage in CuCrZr are of great interest for ITER design and safety considerations.

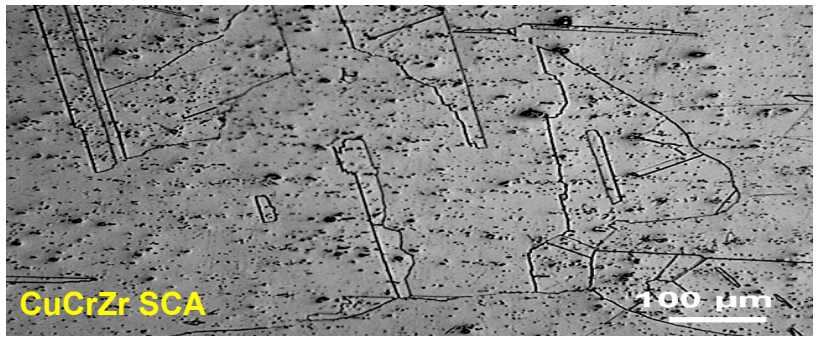
- **Previous studies**:
  - Limited fracture toughness data with large scatter
  - Irradiated fracture toughness data only up to 0.3 dpa.
  - Properties of CuCrZr are sensitive to heat treatments

- **This study:**
  - **Extend fracture toughness data to 1.5 dpa**
  - **Evaluate effect of heat treatments on fracture toughness**:
    - **p**rime **a**ged (PA)
    - **s**low-**c**ooled and **a**ged (SCA)

Experiment

Material:

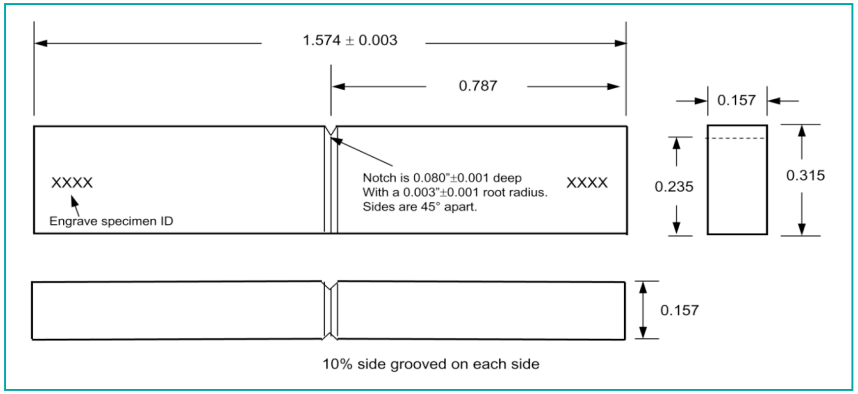
- Elbrodur® G CuCrZr 98.97wt%Cu – 0.84wt%Cr – 0.14wt%Zr
- Two heat treatments:
  - **CuCrZr PA:** solution-annealed and **p**rime **a**ged
  - **CuCrZr SCA:** HIPped at 1040°C/2 h at 140 MPa + solutionized at 980°C/0.5 h with a **s**low **c**ooling rate of 50-80°C/min + **a**ged at 560°C/2 h



•Specimens:

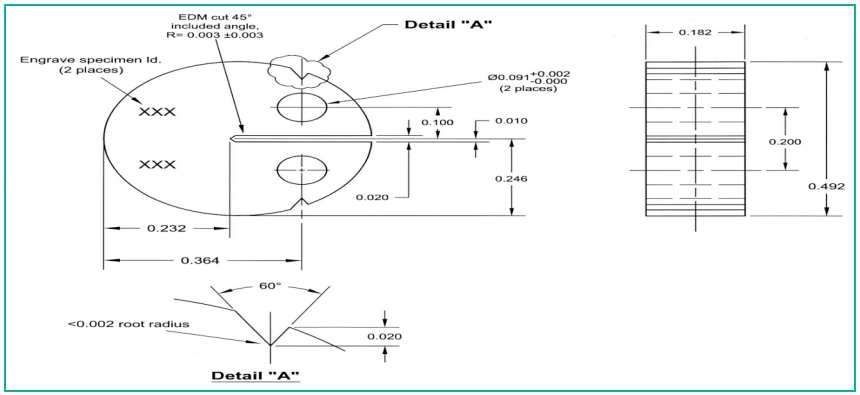
•Single edge-notched bend (SE(B)) specimens (for both unirradiated & irradiated testing) :

- 40×8×4 mm
- T-L orientation
- Fatigue precracked
- 20% side-grooved

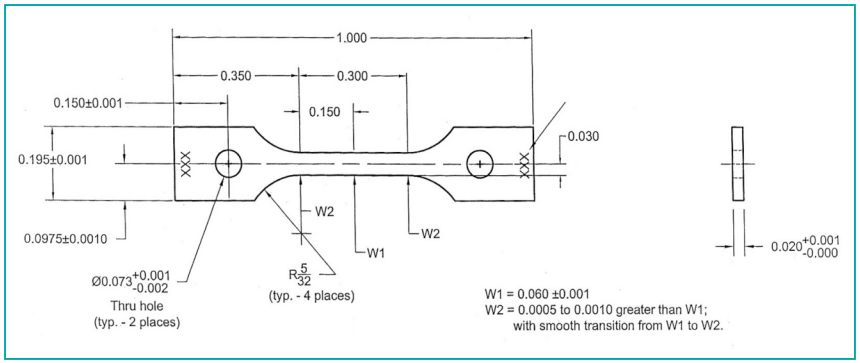


•0.18T disk compact tension (DCT) specimens (for unirradiated testing) :

- ϕ = 12.5 mm ; t = 4.62 mm
- T-L orientation
- Fatigue precracked
- 20% side-grooved



•Type SS-3 sheet tensile specimens (gauge 7.62×1.52×0.5 mm)



Irradiation:

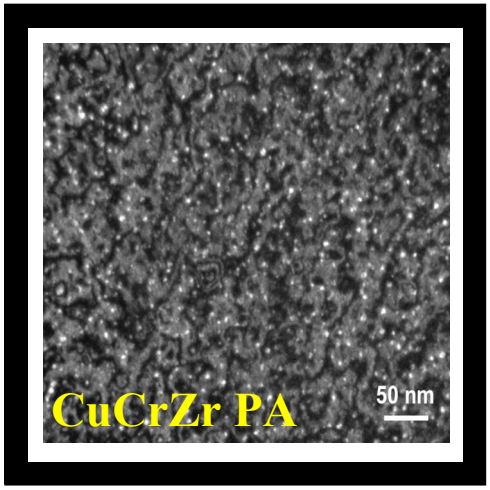
- Irradiations in HFIR HT tube facility using perforated capsules
- Irradiation temperature: ~80°C
- Irradiation doses: 0.15 and 1.5 dpa
- Specimens were coated with a thin film of high purity Al, and vacuum-sealed in Al foil to prevent corrosion

Post-irradiation examination:

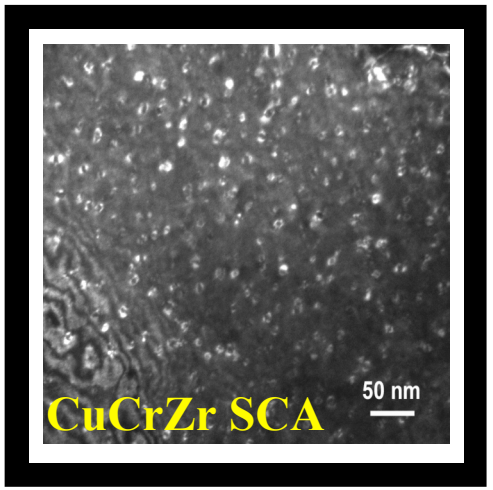
- Fracture toughness testing at room temperature
  - J-R tests
  - Crack growth monitored by unloading compliance technique
- Tensile testing at room temperature and 1x10-3 /s
- TEM examinations on unirradiated specimens
- SEM fractography on unirradiated specimens

Results

Unirradiated microstructure of PA and SCA:



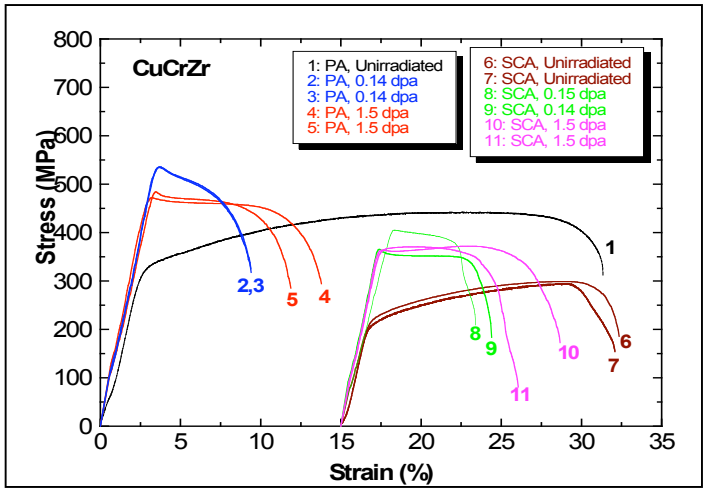
Precipitate density: ~4.3×10^{22} /m^3
Precipitate size: ~3 nm

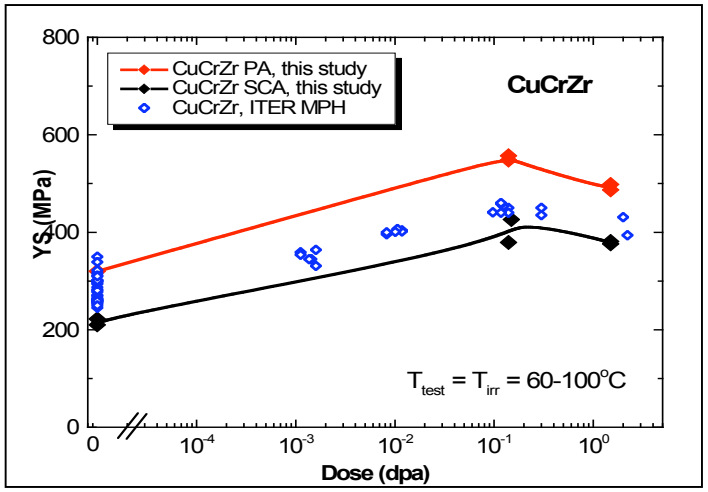


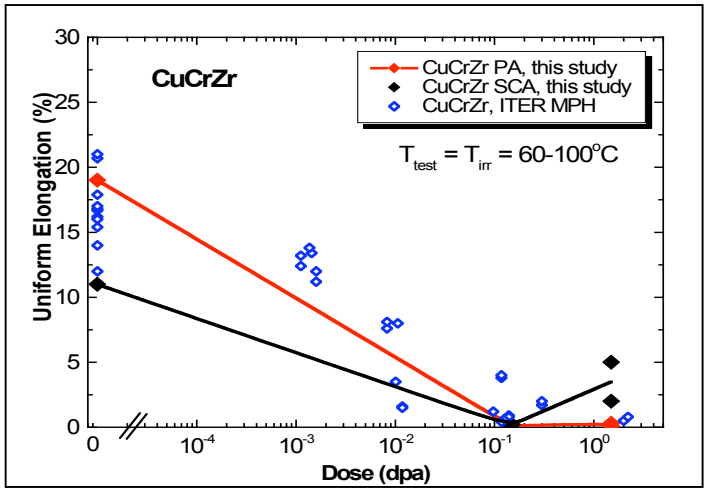
Precipitate density: ~1.9×10^{22} /m^3
Precipitate size: ~9 nm

Tensile properties after irradiation:

- Yield stress increases with increasing dose; saturation dose is ~0.1 dpa
- Uniform elongation decreases significantly with increasing dose; plastic instability at yield occurred at ~0.1 dpa
- CuCrZr SCA has much lower strength than CuCrZr PA



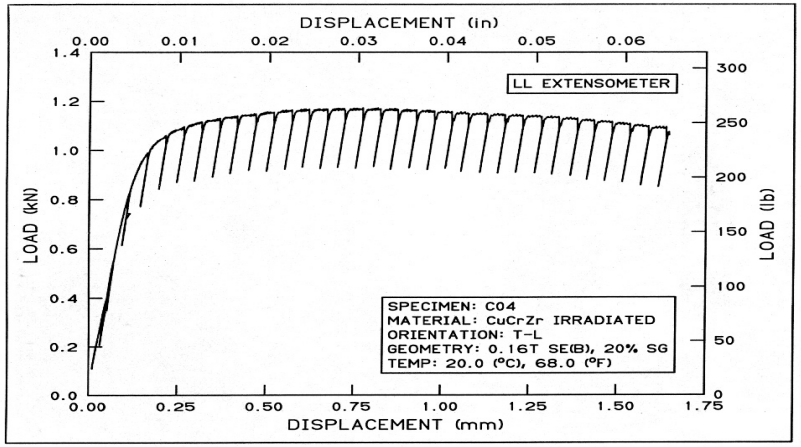


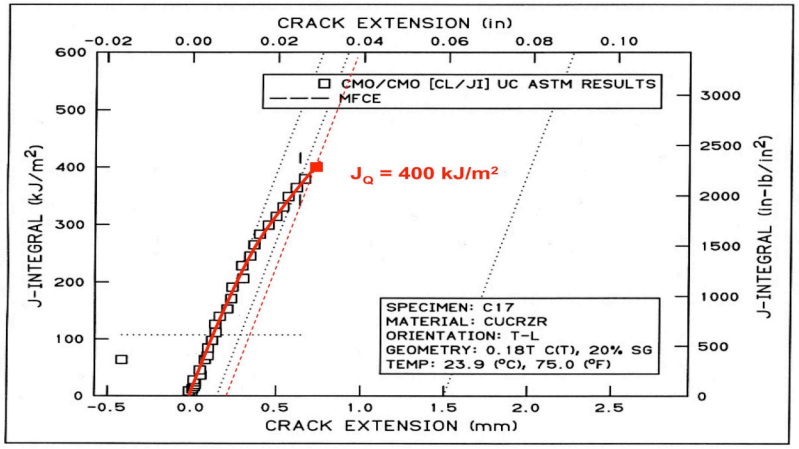


Fracture toughness results:

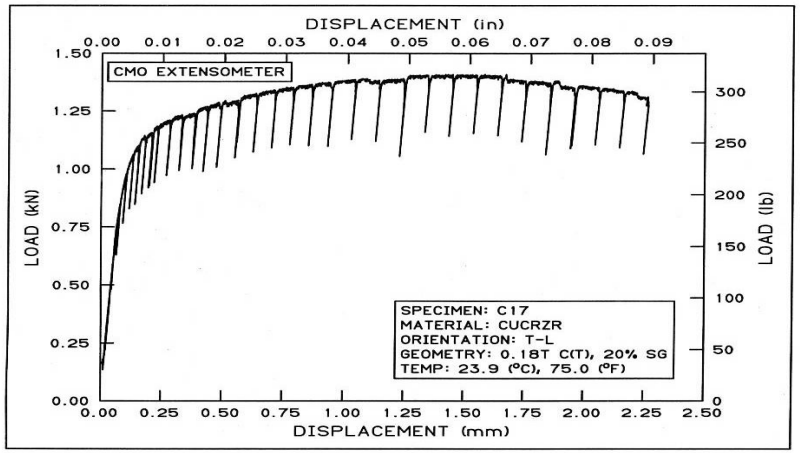
J-R curves and definition of JQ and Jmax:

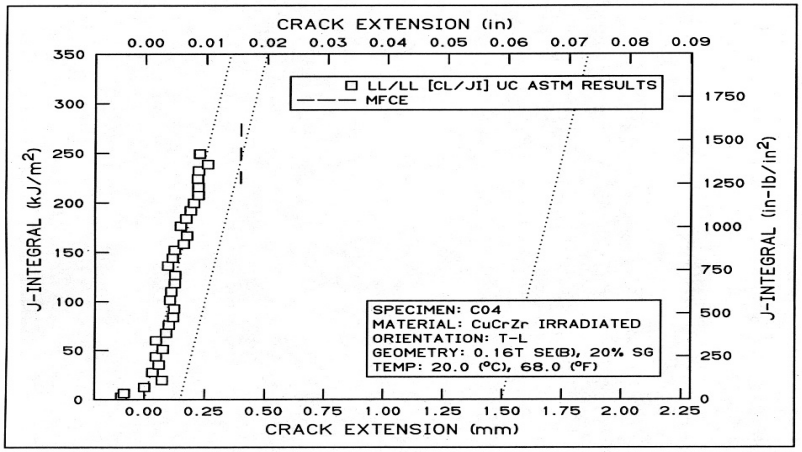
- All SE(B) and DCT specimens were tested to a load line displacement limit without failure; significant plasticity was observed
  - All DCT specimens showed some stable crack extension
  - Some SE(B) specimens showed a small amount of crack extension, while some showed no crack extension at all





For the tests exhibiting some crack extension, the JQ values were estimated from the J-R curves by the intersection of the regression line with the 0.2-mm offset line.

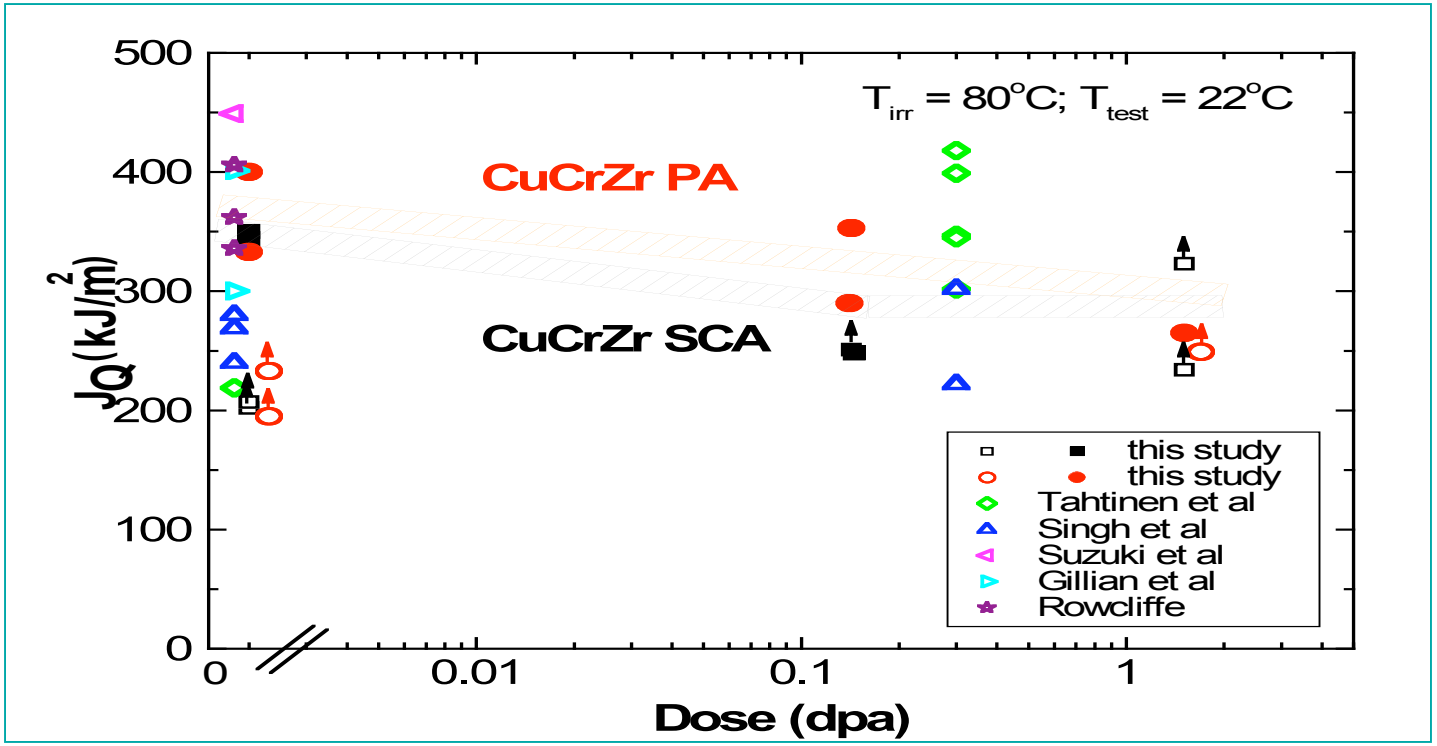




For the tests that did not show any crack extension, the maximum J- value was reported, and in this case, $J_{max} < J_Q$

Effect of neutron irradiation on fracture toughness:

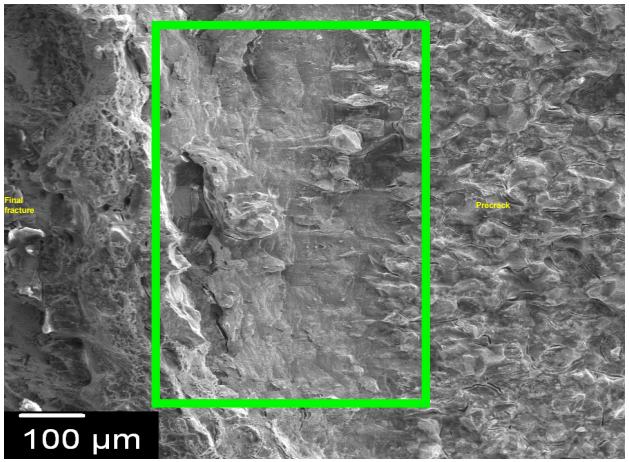
- Neutron irradiation slightly reduced toughness for both CuCrZr PA and CuCrZr SCA heat treatment conditions
- The J_Q value is still high, >~200 kJ/m^2 (equivalent to K_Q 171 MPa√m) up to 1.5 dpa
- Effect of heat treatment is insignificant

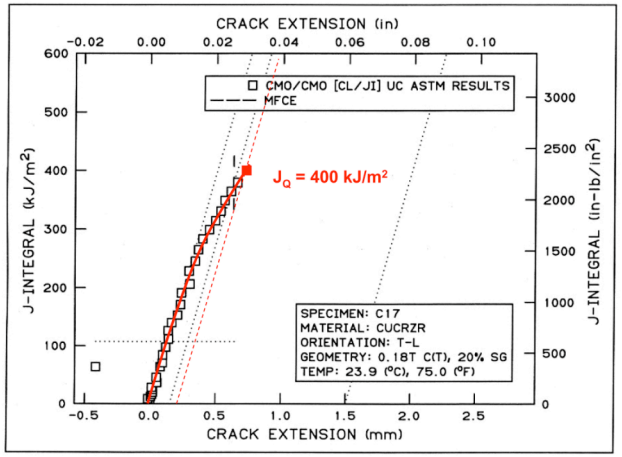


Large scatter data in the literature could be due to differences in heat treatment, specimen geometry, or testing methods

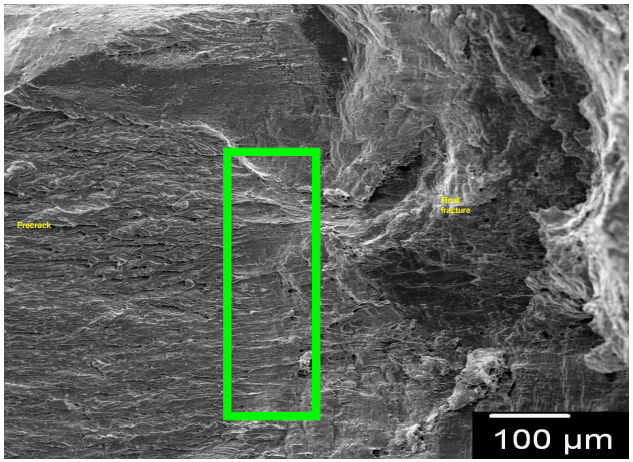
Results

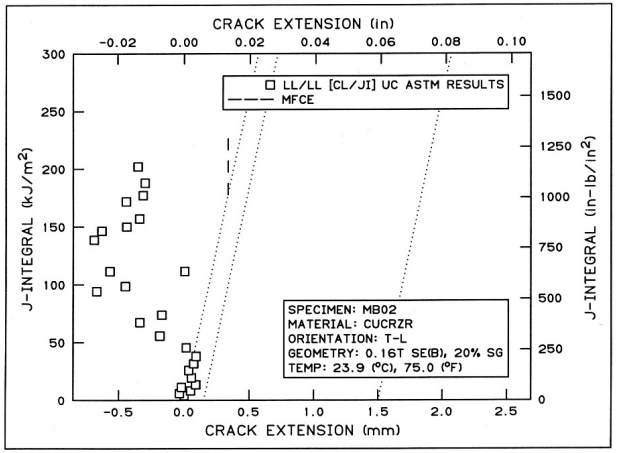
SEM Fractography:





Crack extension was confirmed by SEM.





No crack extension was observed by SEM.

Conclusions

- The strength of CuCrZr SCA is significantly lower than that of CuCrZr PA. For both heat treatments, yield stress increased with increasing dose with a saturation dose ~0.1 dpa. Plastic instability at yield and complete loss of uniform elongation occurred at ~0.1 dpa.

- The heat treatments had no significant influence on fracture toughness of CuCrZr in the unirradiated condition.

- There was a slight decrease in fracture toughness for both CuCrZr PA and SCA after irradiation. The fracture toughness remained high up to ~1.5 dpa.