Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys

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ABSTRACT

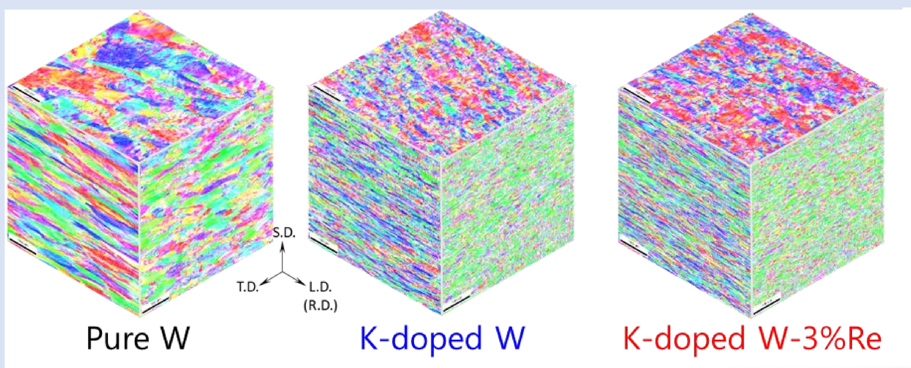
This contribution reviews the efforts done towards the assessment of the irradiation effects and operational temperature window performed over the last several years in the frame of the European fusion programme focusing on the armour and heat sink materials.

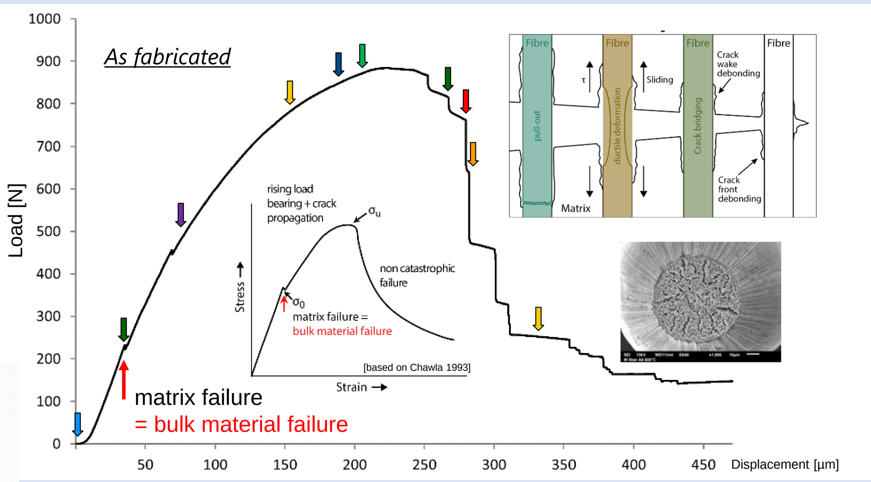
Driven by the technological priorities, the irradiation tests campaigns were arranged in two waves. The first one involved baseline materials focusing on delivery of the engineering design data and the second one targeted screening irradiation of the advanced materials. Execution of the irradiation programmes was realized in Europe on BR2 reactor, while other reactors were involved for the irradiation of RAFM steels.

Extraction of the properties of the neutron exposed materials involved extensive post irradiation examination (PIE) campaigns. Unique nuclearized facilities in Germany, Belgium, and Greece were involved to deliver thorough information on the performance of the neutron exposed materials in terms of: mechanical, microstructural, chemical and physical properties. The most important results signifying our current understanding of the operational limits are reported in this contribution. The performance of the advanced materials is also assessed and presented, which already at this stage allows drawing some important conclusions. In summary, we provide an outlook for continuation of the research programmes involving irradiation facilities as well as technological and research material matrices within next 5 years.

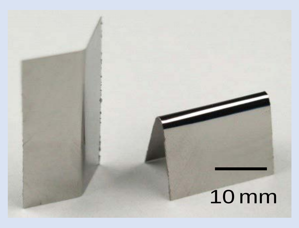
BACKGROUND

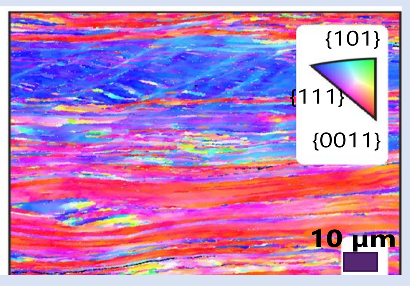
- Five different tungsten (W) grades and five different Cu-based grades were investigated under neutron irradiation.





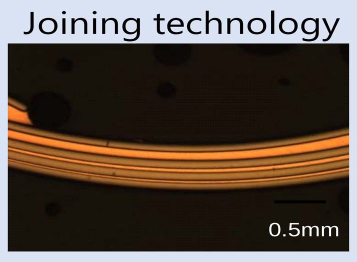
Ductile W thin foil



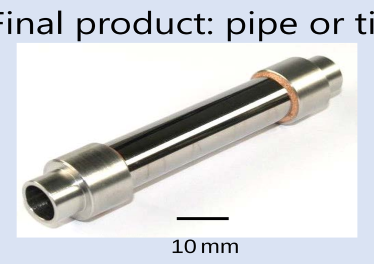


Main criteria for selection: cost/up-scale potential, enhanced ductility, resistance against recrystallization, formability.

Joining technology



Final product: pipe or tile



Main results

Pure tungsten of ITER specification, see Figure 1 and 2.

Large shift in Ductile to Brittle Transition Temperature

ΔDBTT = 600-625°C

Irradiation below 800°C embrittles W

Advanced tungsten materials, see Figure 3 and 4

ΔDBTT of rolled plates is lower by 50-150°C than in ITER spec. W

At T_{irr}=1100°C, ΔDBTT is ~250-400°C for rolled and forged W plates

At T_{ir}r=600°C, Re alloying increases DBTT shift

Advanced Cu-based materials, see Figure 5-9

W-fiber composites: reduction in total elongation & hardening

W-Cu Laminates: strong impact on ductility (= embrittlement)

W-particle composite: reduction of elongation, minor hardening/softening

V-alloyed CuCrZr: softening after irradiation at 450°C

ODS-CuCrZr: reduction of uniform & total elongation

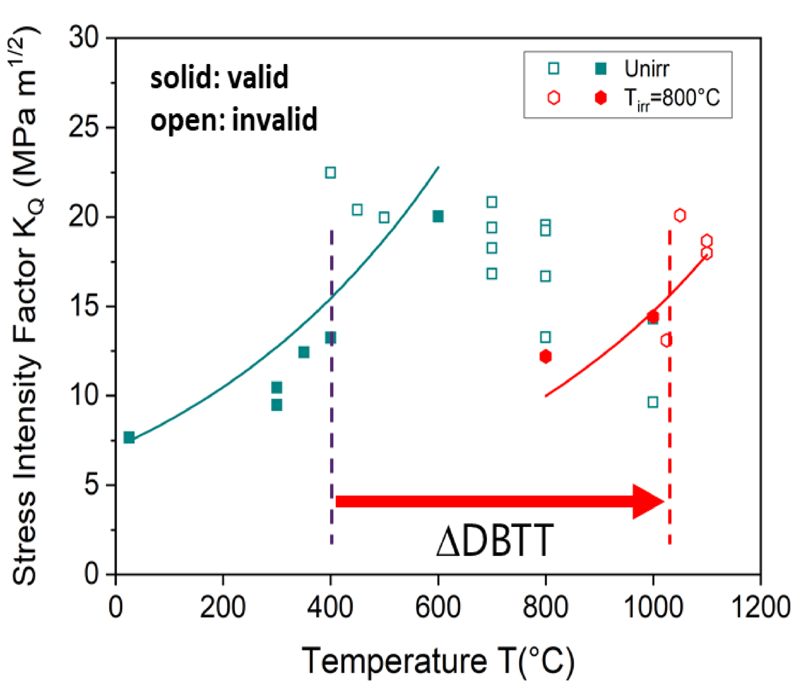


Fig.1 Fracture toughness of tungsten after neutron irradiation up to 1 dpa

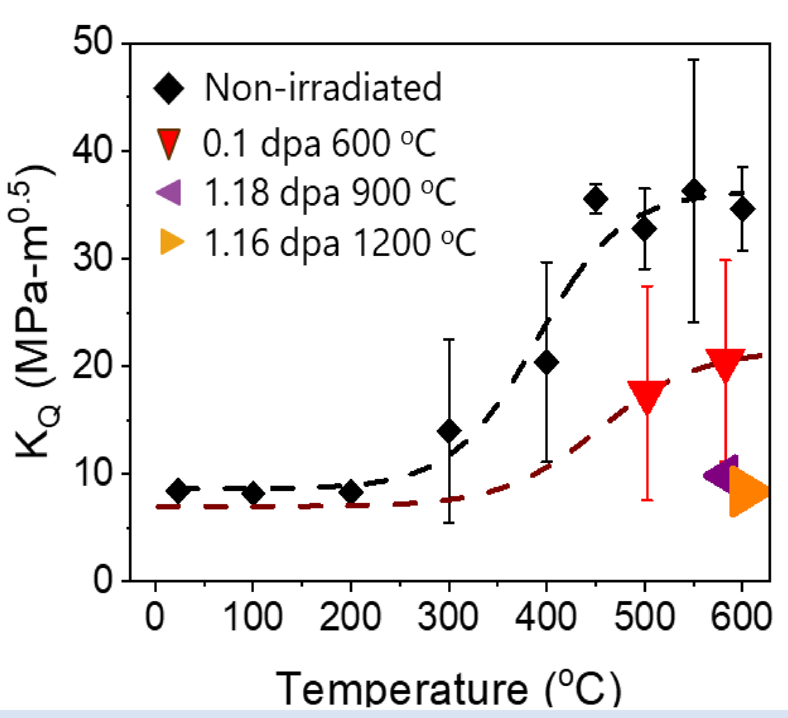


Fig.2 Fracture toughness of tungsten after neutron irradiation up to 0.1-1 dpa

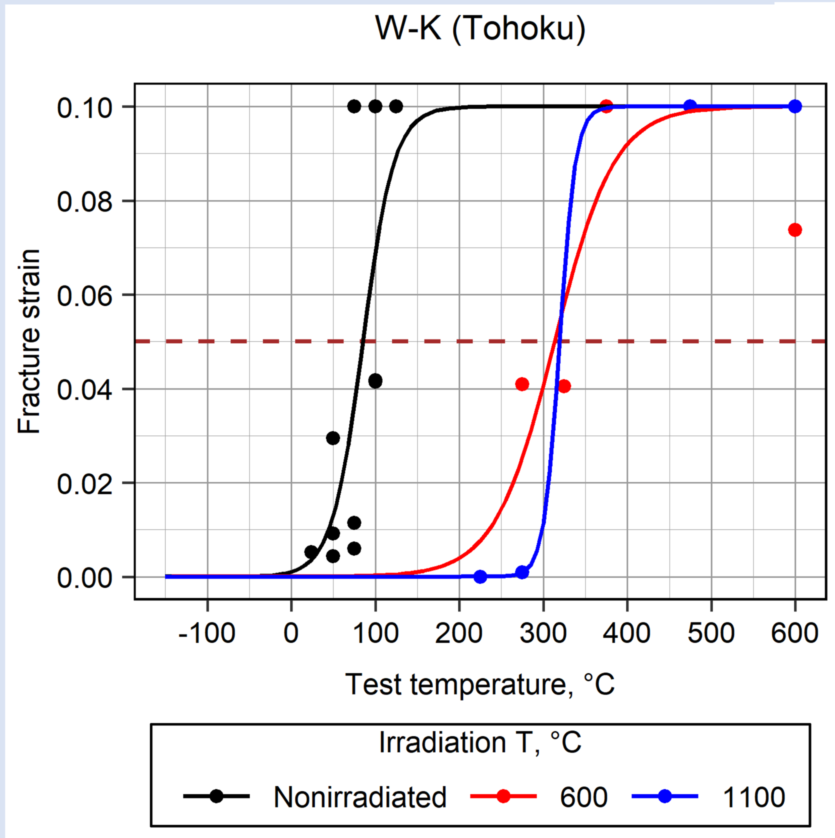


Figure 3. Determination of DBTT in K-doped W plate at 1 dpa Ti_{rr}=600 or 1100 °C.

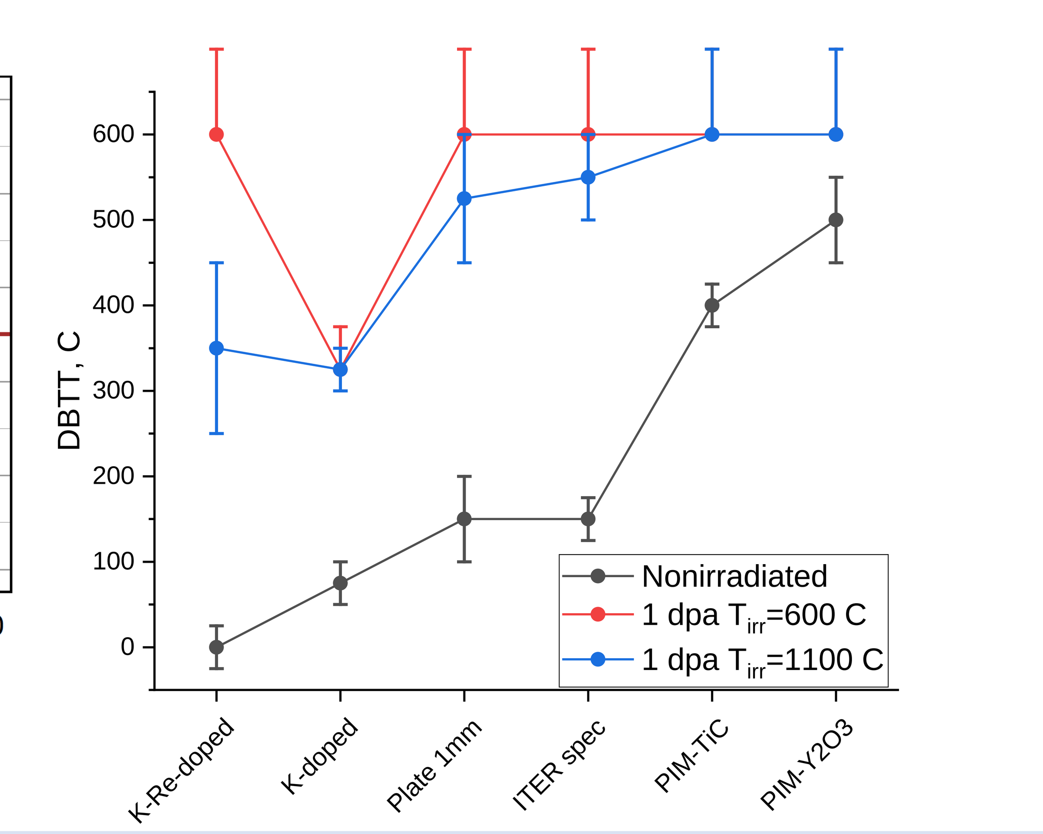
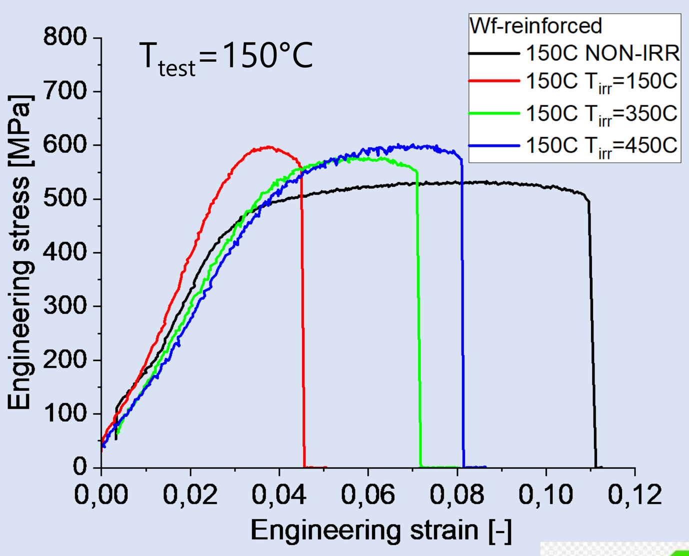


Figure 4. DBTT at 1 dpa for a number of advanced W materials

- W-fiber composites:
  - Some fibers fracture brittle
  - Matrix remains ductile



Promising results

Figure 5. Stress-strain response of CuCrZr reinforced by W fiber at 2.5 dpa.

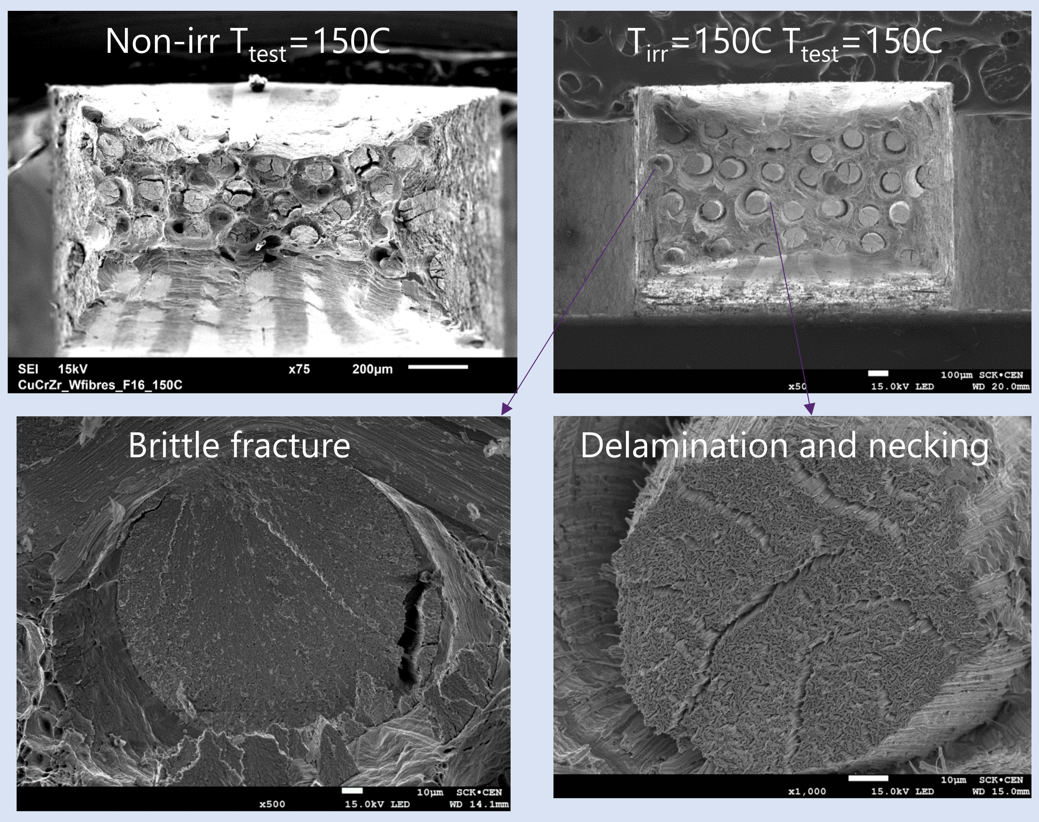
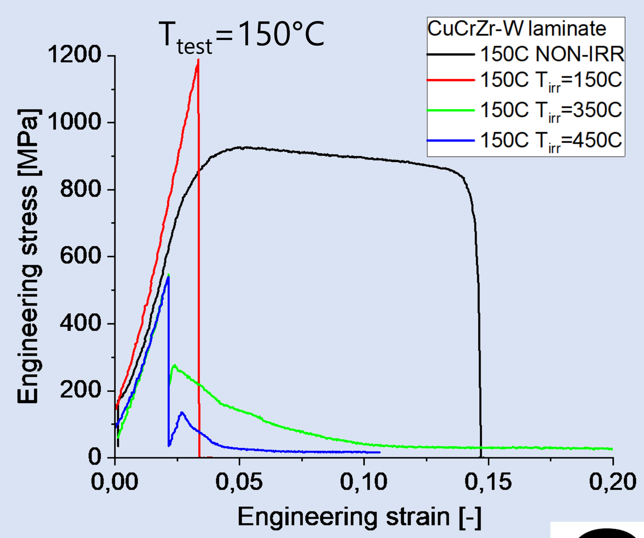


Figure 6. Fracture surface of the tensile samples and fibers after the irradiation.

- W-Cu laminates:
  - Fully brittle fracture
  - Cracks initiate near interfaces



Unexpected results

Figure 7. Stress-strain response of CuCrZr reinforced by W fiber at 2.5 dpa.

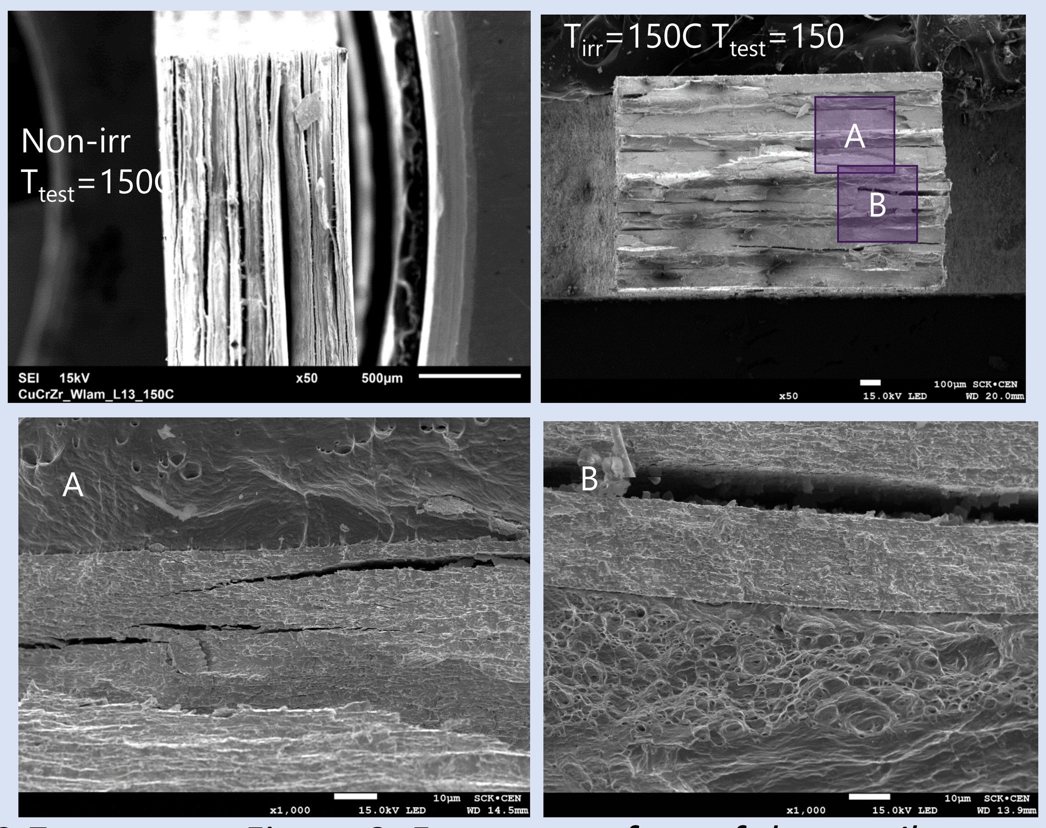
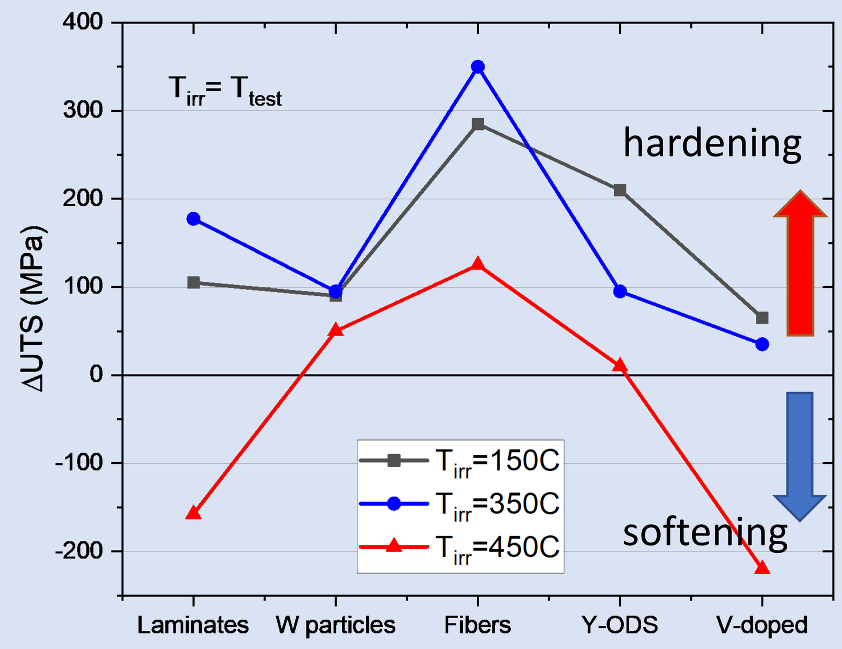


Figure 8. Fracture surface of the tensile samples and fibers after the irradiation.



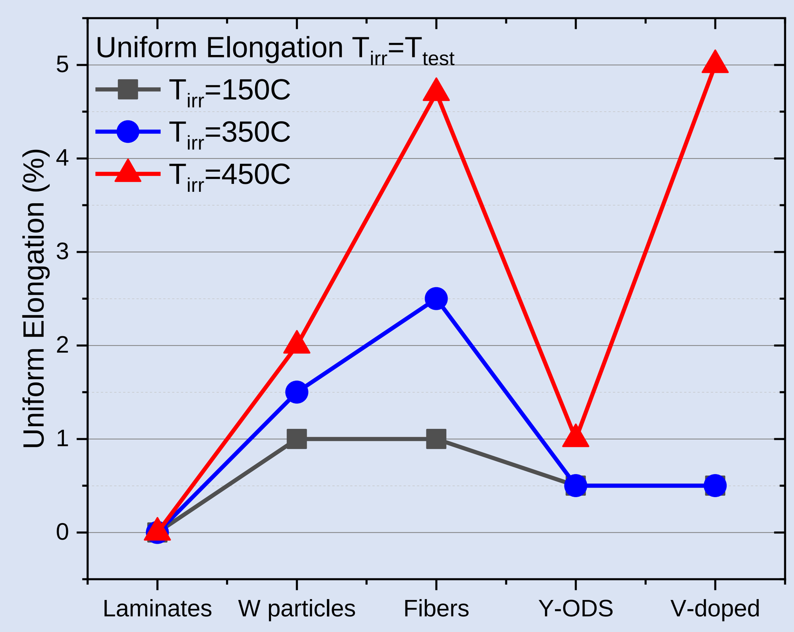


Figure 9. Change of the Ultimate Tensile Strength (left) and uniform elongation (right)

CONCLUSION

- ITER specification W irradiated at ~1 dpa has DBTT range of 900-1100°C
- Advanced W-alloys irradiated at ~1 dpa (W) exhibit DBTT below 600°C
- Application rolling/forging reduces DBTT and irradiation embrittlement
- Unexpected embrittlement of W-Cu laminates is observed
- Irradiation softening of V-alloyed CuCrZr occurs above 350°C
- Promising results for fiber-reinforced composites: potential extension of application window up to 450°C

ACKNOWLEDGEMENTS / REFERENCES

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