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Emrittlement Effects of LBE on Ferritic/Martensitic Steels After Irradiation in SINQ Targets

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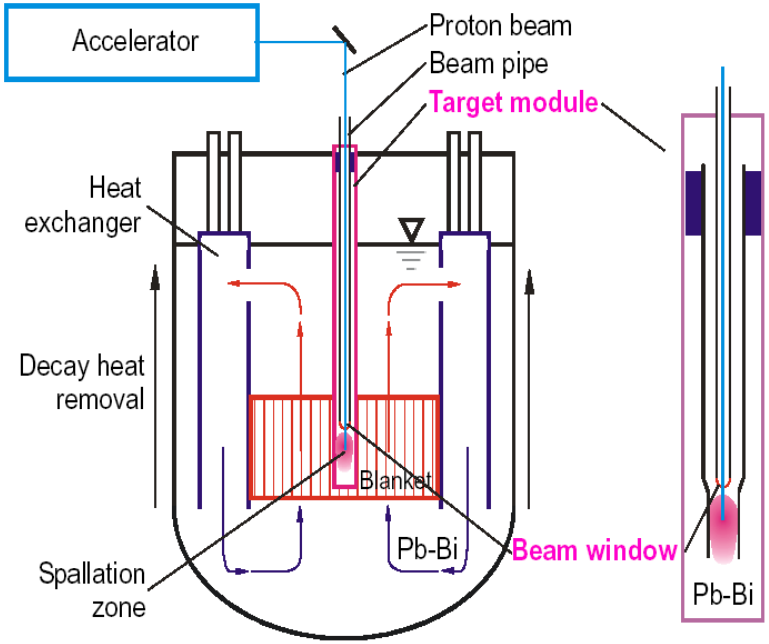
Introduction

- **LBE (lead-bismuth eutectic) is selected as target and coolant material for the targets of the spallation sources and the accelerator driven system (ADS) -for example MEGAPIE;**
- **The T91 FM (ferritic/martensitic) steel is the main candidate structural material**

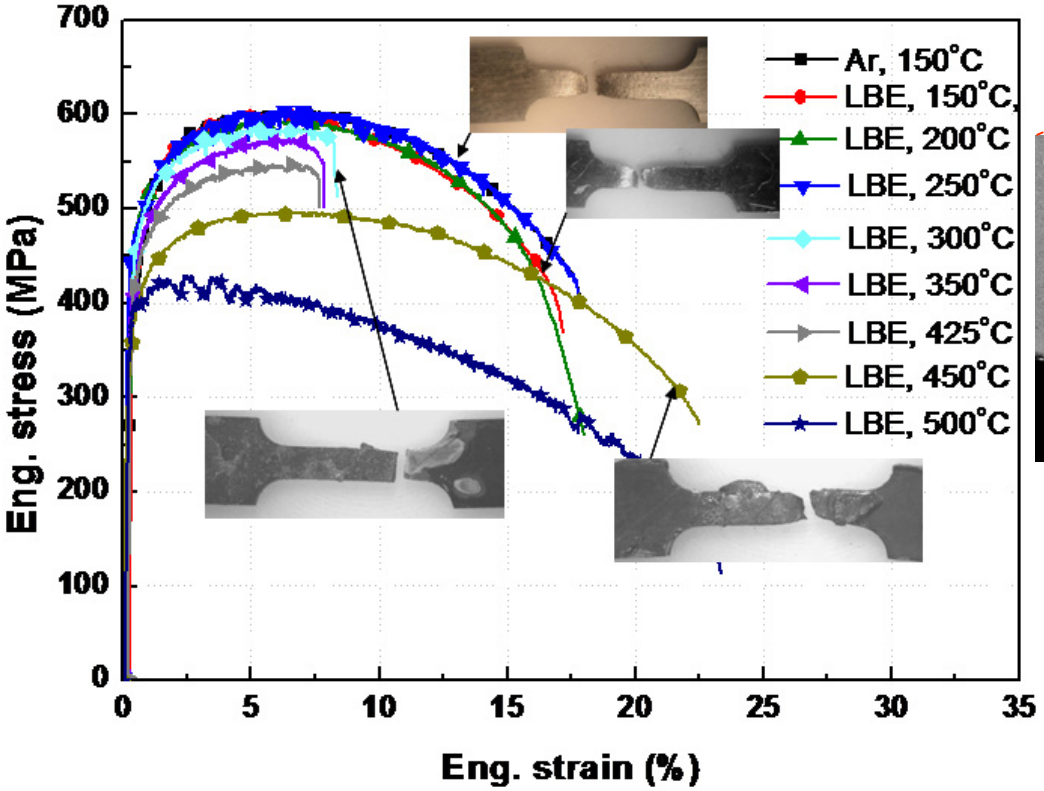


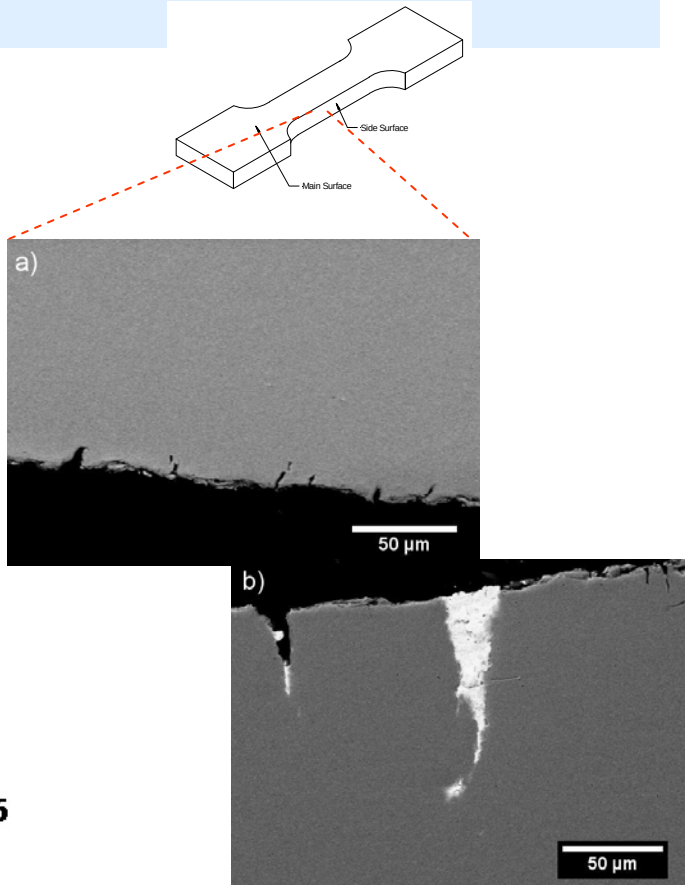
curtsy to Dr. W. Wagner

Introduction

- **Our previous studies demonstrated that**

  a) The steel could sensitive to the LBE embrittlement effects when there were cracks or flows on the surfaces of specimens;





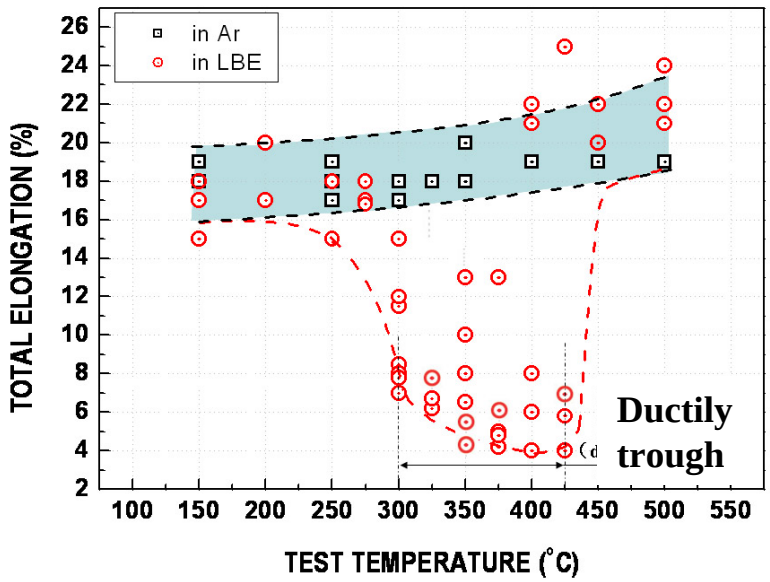
Y.Dai, B.Long and F.Groeschel, J.Nucl.Mater,356(2006),222.

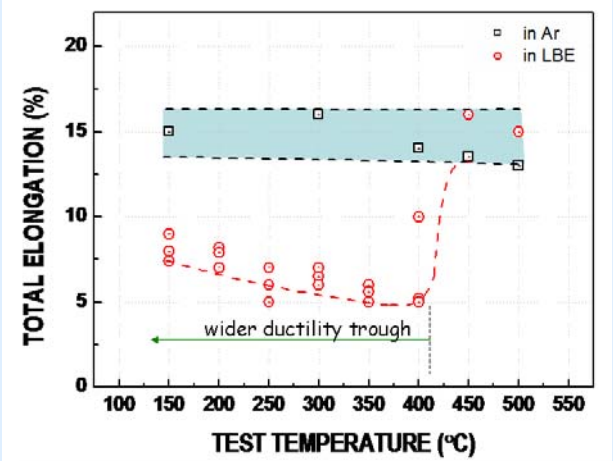
Introduction

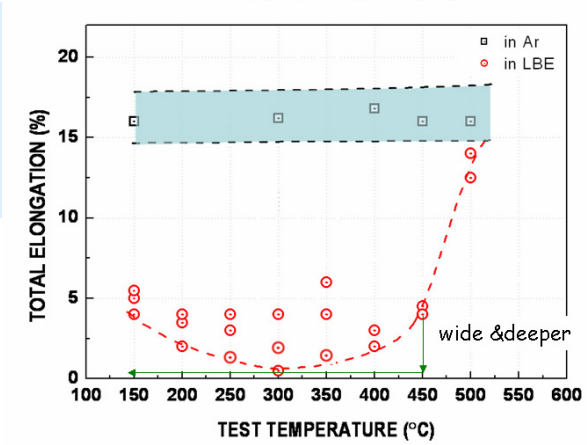
- **Our previous studies demonstrated that**

  b) The LBE embrittlement effects can be strongly enhanced by the hardening of the steels

Standard heat-treatment T91







tempered T91

B. Long, Y. Dai, *J. Nucl. Mater.*, *376 (2008) 341-345*

Materials

Heat treatment: to simulate radiation hardening

- **HT760 (T91): normalized at 1040°C for 1h, tempered at 760°C for 2h**
  Microhardness HV0.05 = 220 :standard metallurgical state
- **HT600 (T91): normalized at 1040°C for 1h, tempered at 600°C for 2h**
  Microhardness HV0.05 = 350
- **HT500 (T91): normalized at 1040°C for 1h, tempered at 500°C for 2h**
  Microhardness HV0.05 = 450

Material	Cr	Ni	Mn	Mo	Ti	V	Si	P	Nb	W	Ta	C
T91[1]	8.76	0.10	0.60	0.86	-	0.19	0.32	0.019	0.07	---	----	0.09
F82H	7.65	0.02	0.10	0.003	0.004	0.19	0.07	0.003	0.002	1.98	0.03	0.09

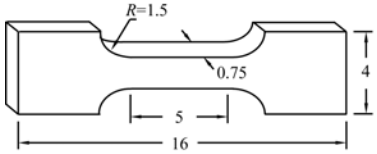
1. Heat-A387, from INDUSTEEL for MEGAPIE project

Materials and specimens

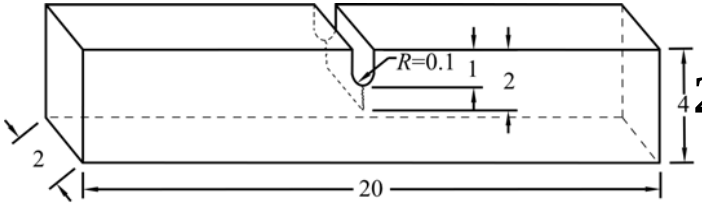
Specimen for irradiation

specimens

- For tensile test
- For 3-p bending test
- For TEM and small punch

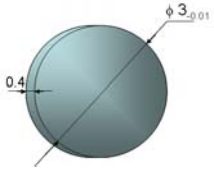


16×4×0.75 *mm* with a gauge section of 5×1.5×0.75 *mm*



20×4×2 mm and with a notch of 1 mm in depth

$a_0/w \sim 0.5$



disc with ϕ 3 and 0.4mm thickness

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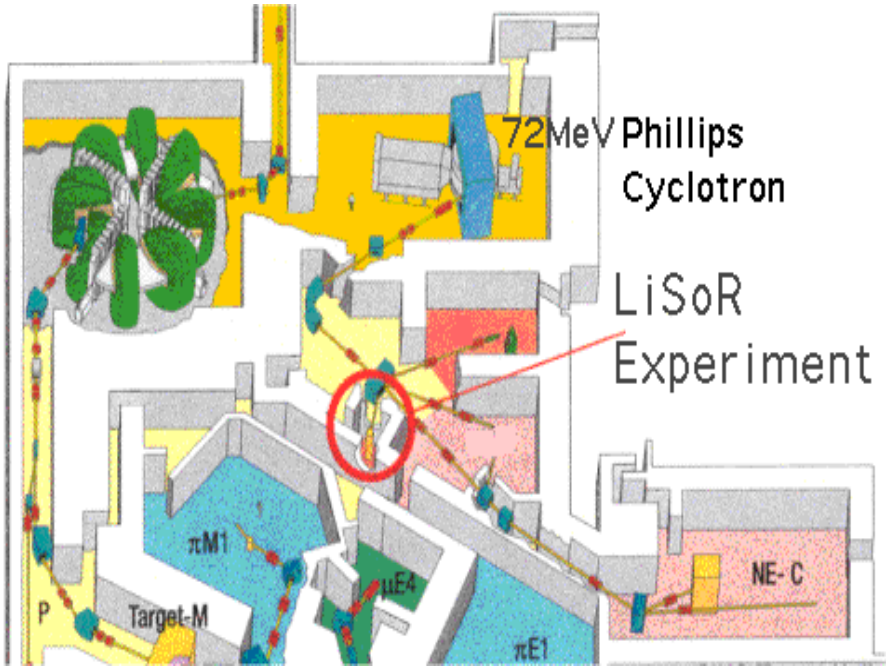
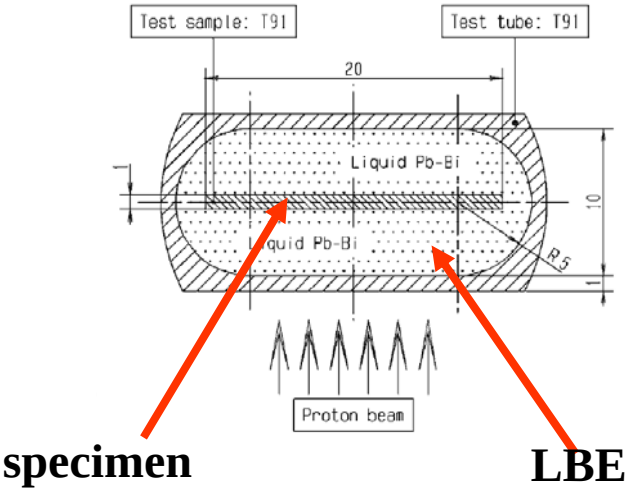
LiSoR loop



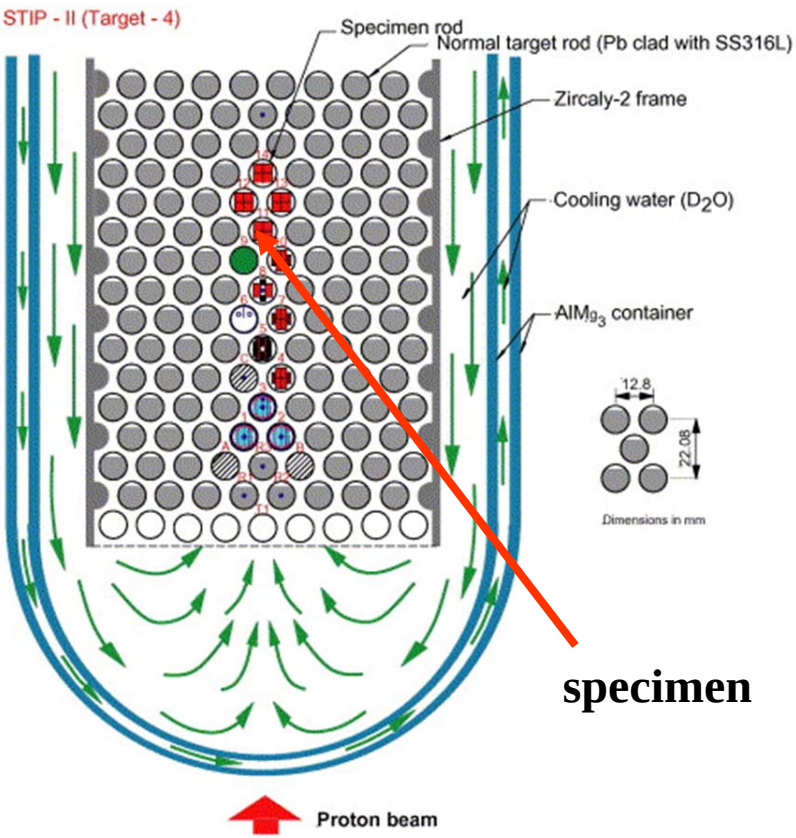
from PSI website



Irradiation parameters:

- **Beam energy: 72 MeV**
- **Inlet LBE temperature: 300°C**
- **Irradiation temperature: 325 – 525 °C**
- **Irradiation dose: max. 0.48 dpa (displacement per atom)**
- **Oxygen concentration in LBE: saturated**

Irradiations at SINQ (STIPs)



STIP program is aiming at studying radiation damage in structural materials under a mixed spectrum of high-energy protons plus spallation neutrons.

Irradiation parameters:

- **beam energy: ~ 570MeV**
- **irradiation temperature: 100 – 500 °C**
- **irradiation dose: max. 20 dpa**
- **He concentration: max. 1790 appm**

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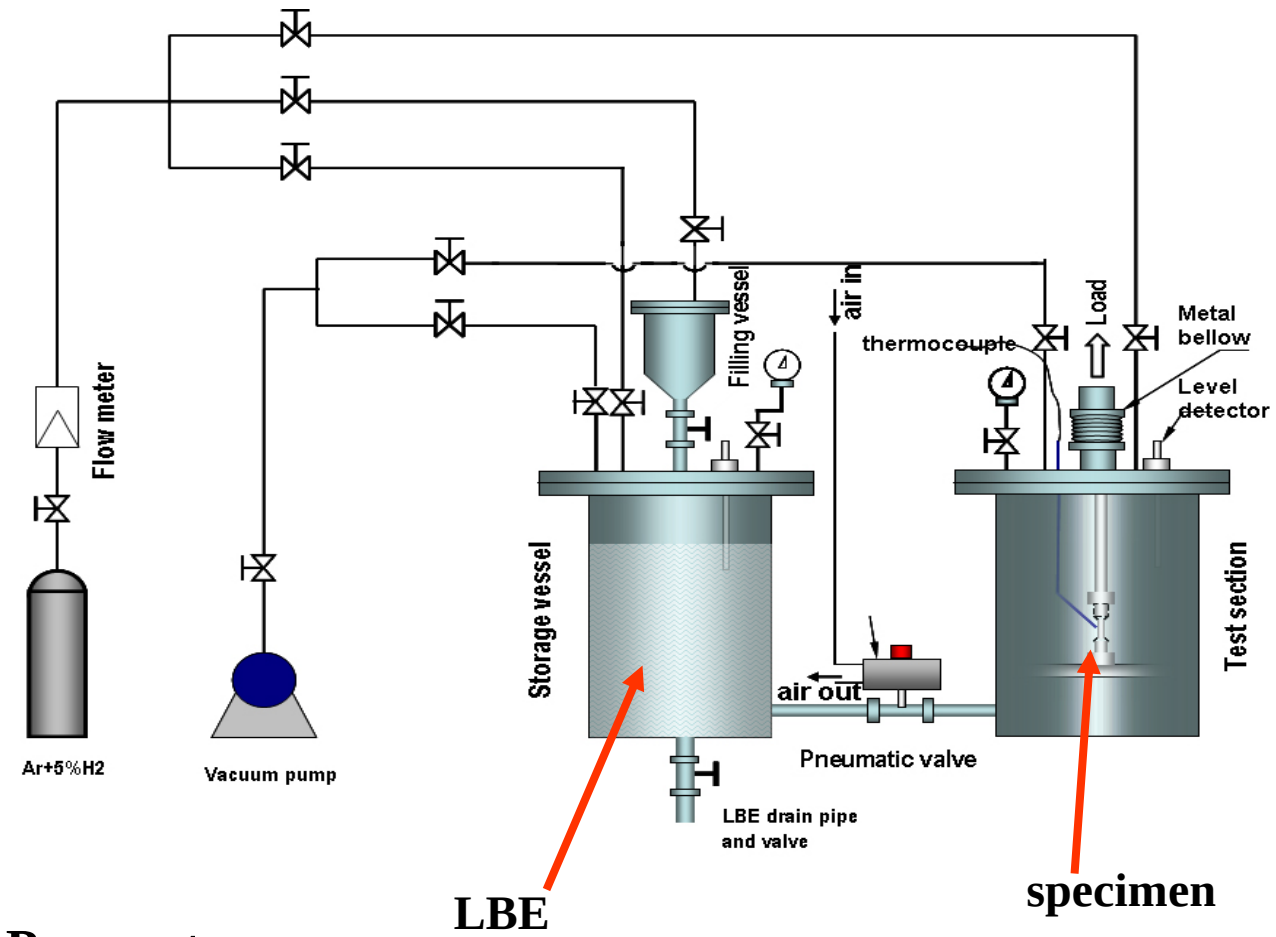
LME test facility

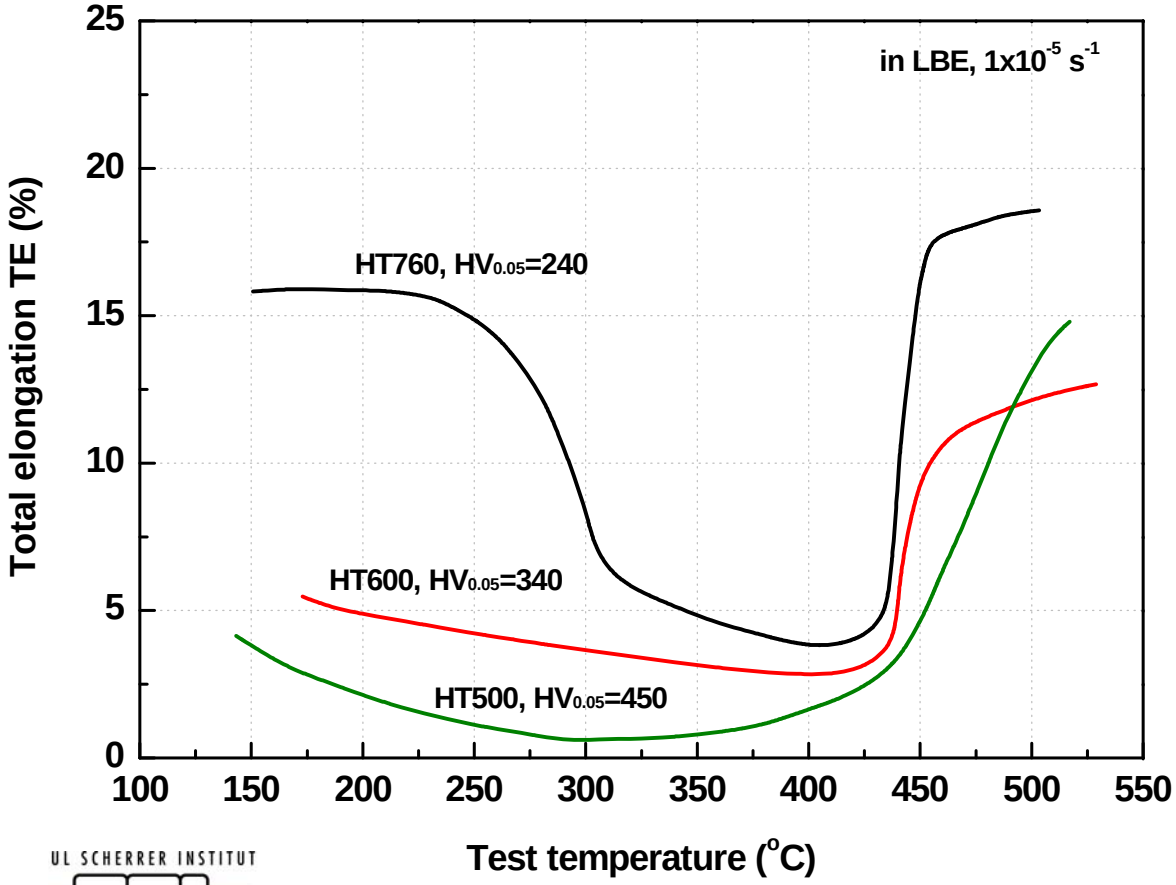


Parameters:

- **test temperature: 150 to 500 °C**
- **oxygen concentration in LBE: $1x10^{-6}$ wt.%**

Comparison of SSRT tests results on HT760, HT600 and HT500

- The "ductility trough" of HT760 is 300-425°C
- The "ductility troughs" of HT600 and HT500 cover a wider temperature range
- LBE embrittlement effects on tensile properties of FM steels can be strongly enhanced by the hardening of the steels (high strength → high risk to LME)



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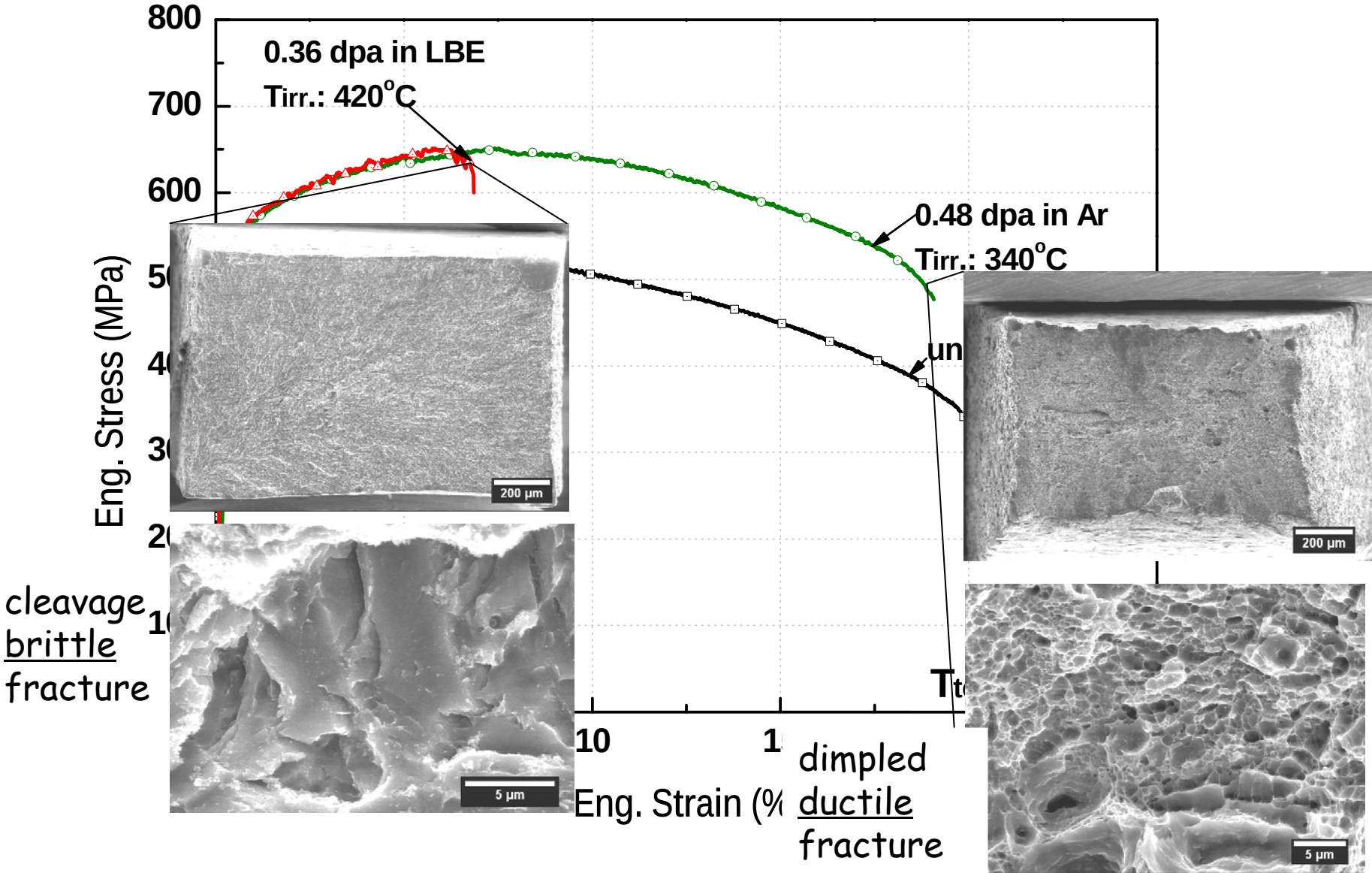
SSRT on irradiated T91

(LiSoR-3 and -4)

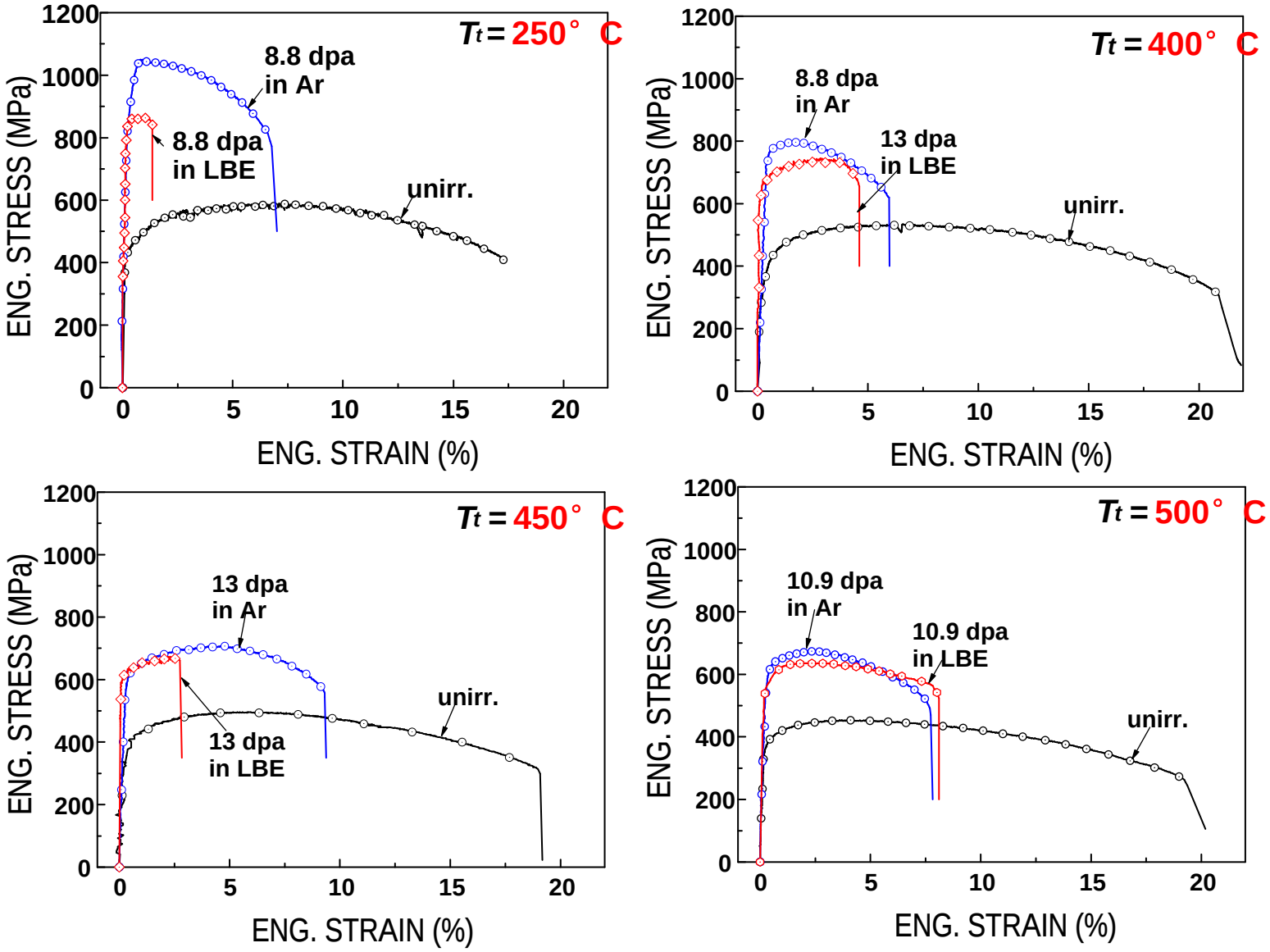
▲ **In Ar: irradiation-induced hardening; In LBE: LBE-induced embrittlement**



Irradiated T91

(STIP-3)

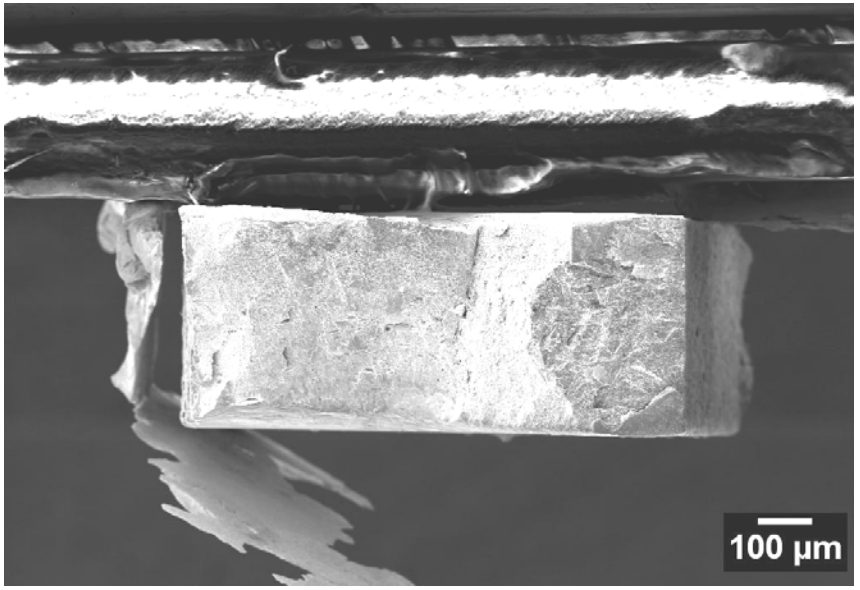
- LBE-induced embrittlement occurs in the temperature range of 250-450°C

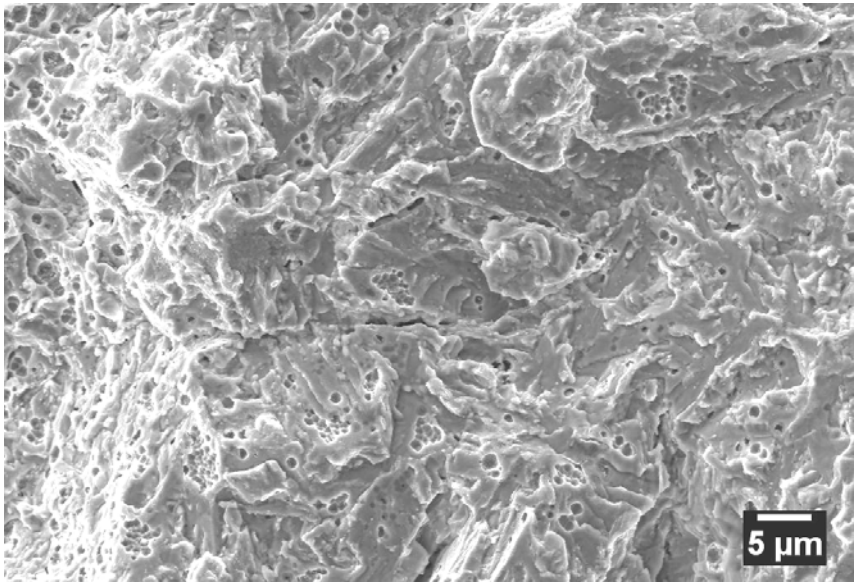


Irradiated T91

(STIP-3)

13.0 dpa/451°C in LBE at 450°C



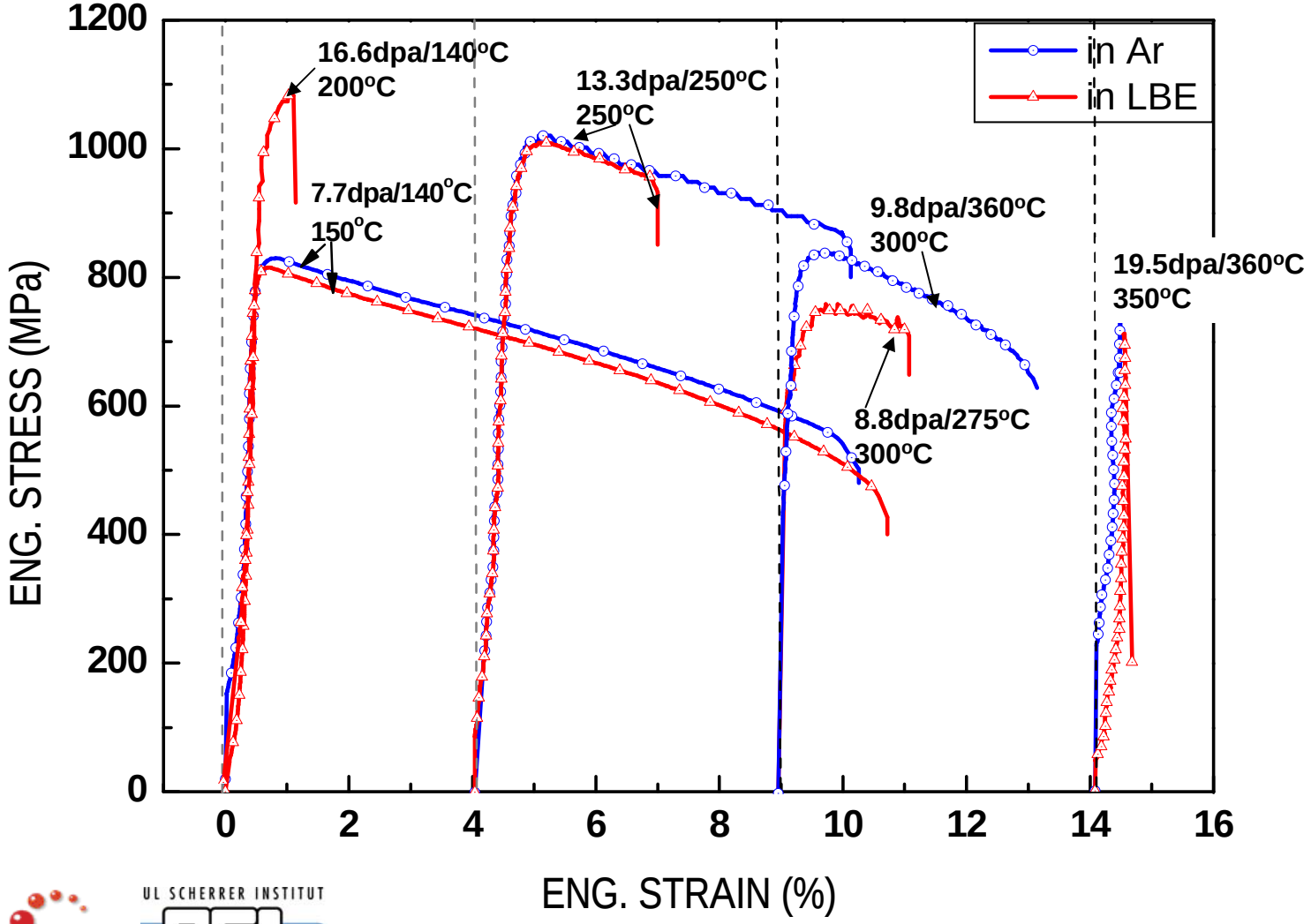


cleavage brittle fracture

SSRT on irradiated F82H

(STIP-2 and -3)

▲ **LBE-induced embrittlement : 200 – 350°C**



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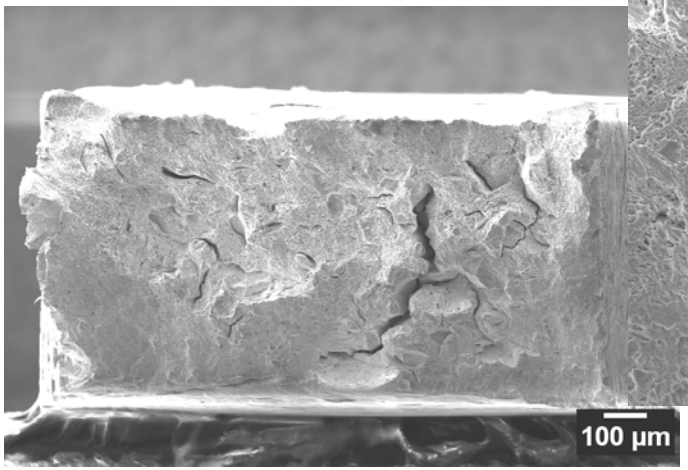
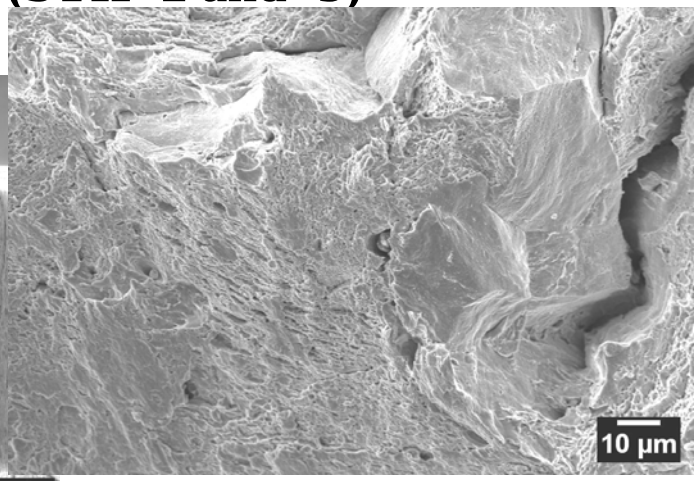
Irradiated F82H

(STIP-2 and -3)

13.3dpa/250°C

in Ar at 250°C

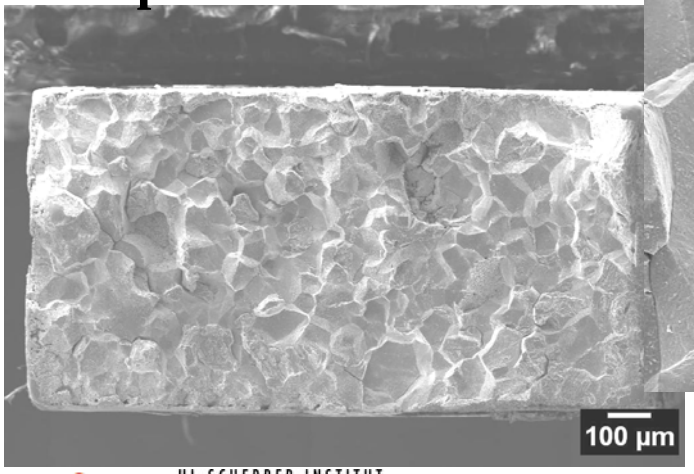


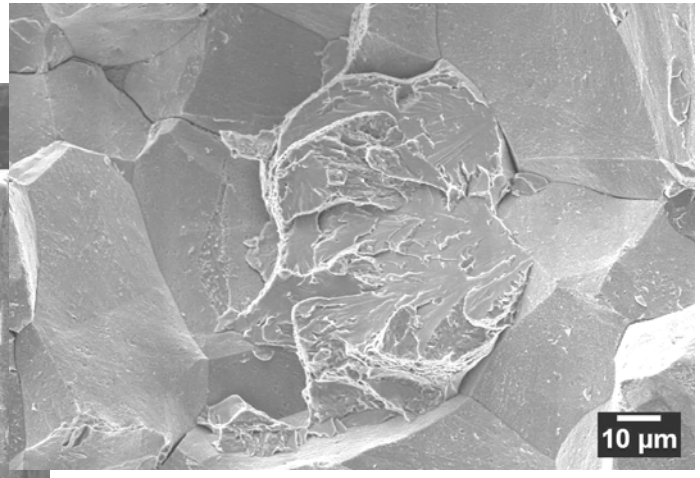


mixed <u>ductile &</u> <u>brittle</u> fracture

13.3dpa/250°C

in LBE at 250°C





cleavage & intergranular <u>brittle</u> fracture

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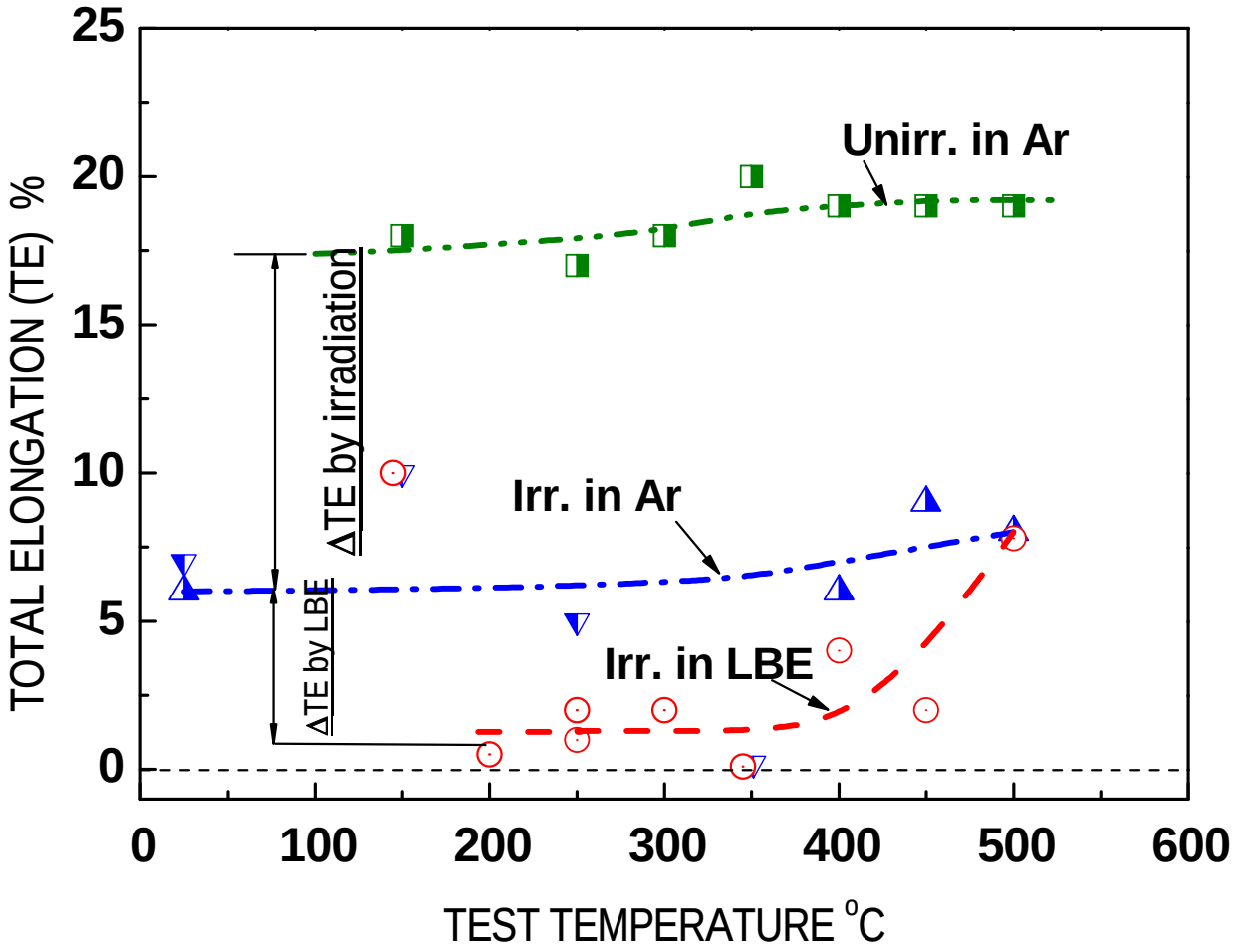
Comparison of SSRT tests results on irradiated specimens

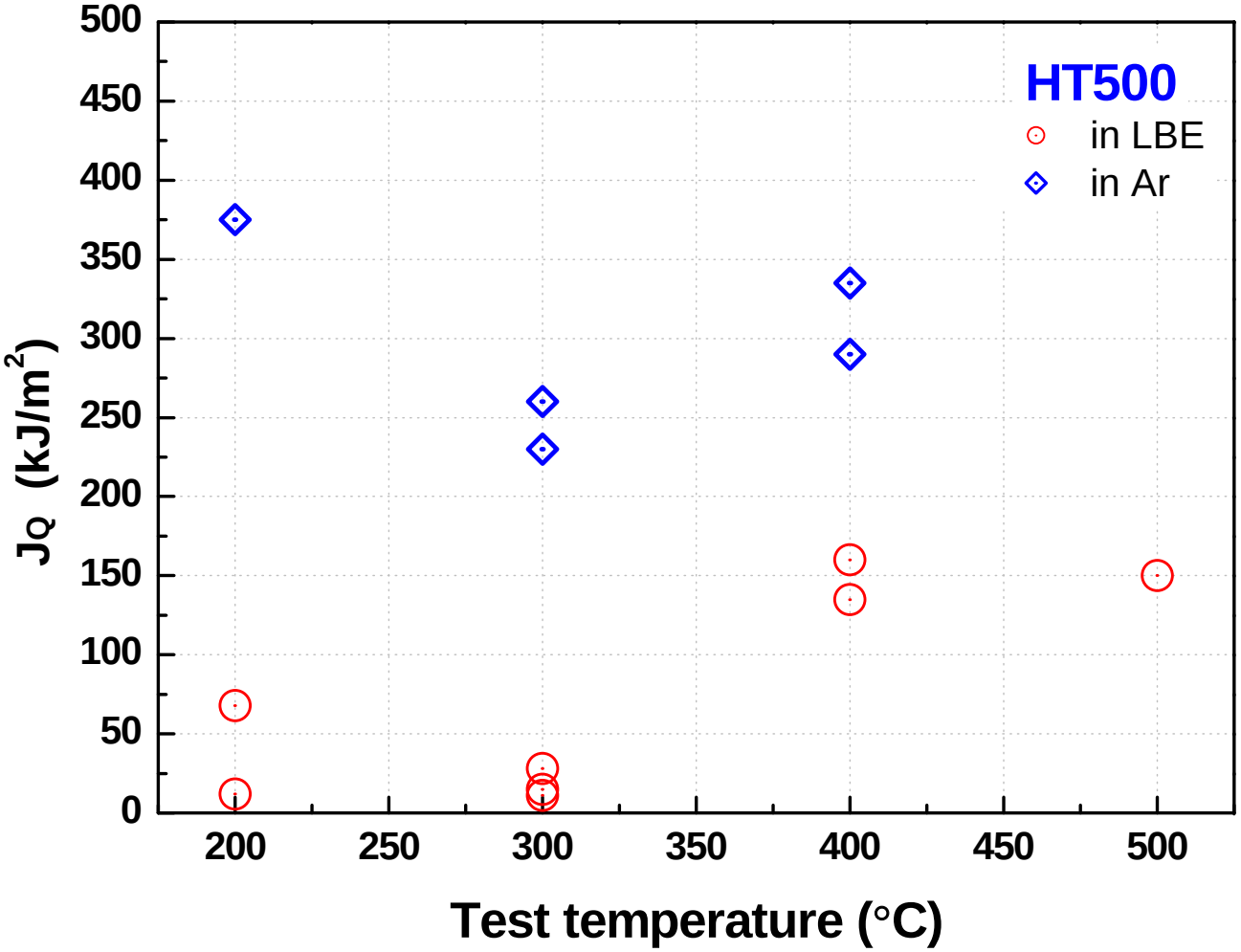
- Irradiated specimens suffer a drastic loss of ductility due to irradiation -induced embrittlement effect
- Most irradiated specimens tested in LBE undergo a further reduction in ductility



3P bending tests on HT500

(tempering at 500°C)

- **Fracture toughness is strongly reduced in LBE environment: only about 12 kJ/m² at T = 300°C**

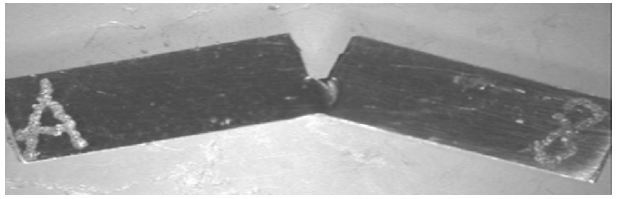


HT500

(tempering at 500°C)

in Ar

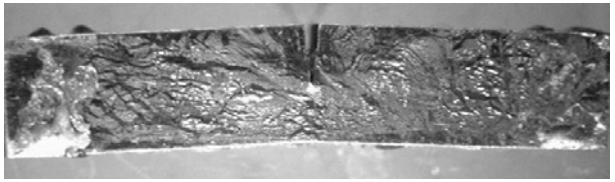
300° C



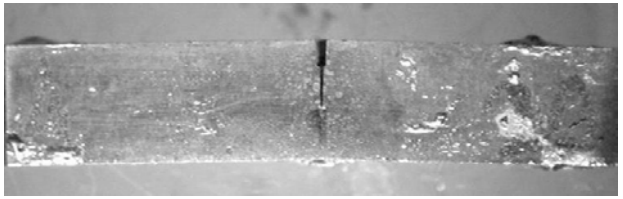
a large bending deformation

in LBE

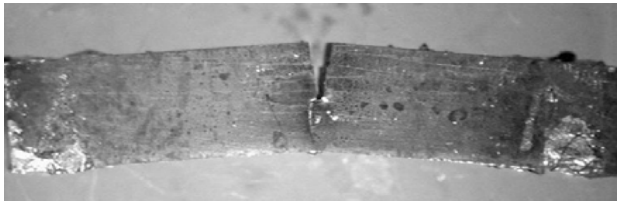
200° C



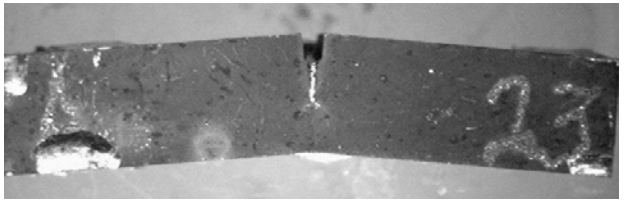
300° C



400° C



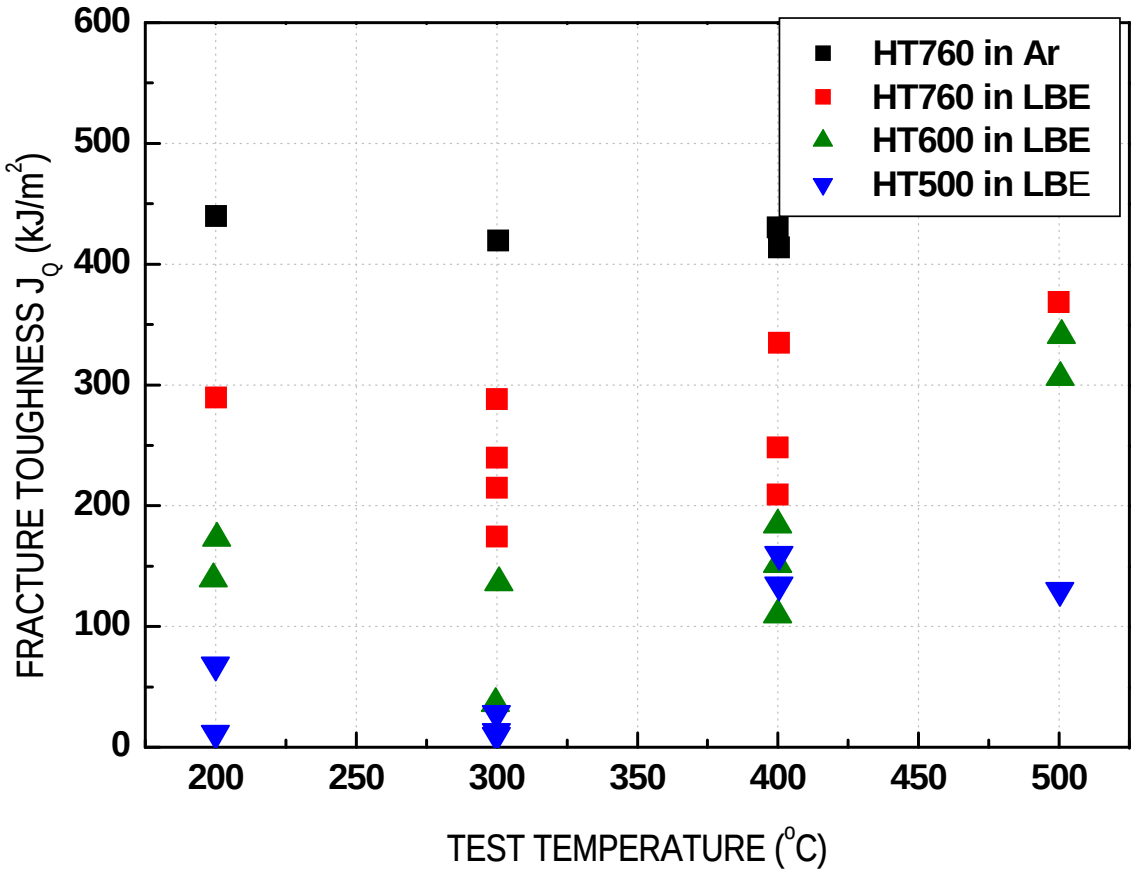
500° C



a slight bending defromation

Comparison of 3-p bending tests results on HT760, HT600 and HT500

- HT760: fracture toughness is reduced in LBE as compared to Ar
- HT600 and HT500: fracture toughness is further reduced in LBE
- LBE embrittlement effects on fracture toughness of FM steels can be strongly enhanced by the hardening of the steels (higher strength → higher risk to LME)



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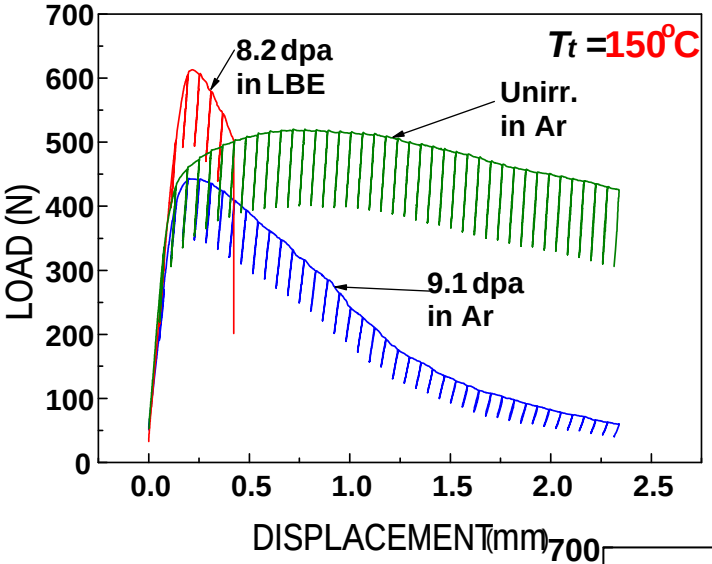
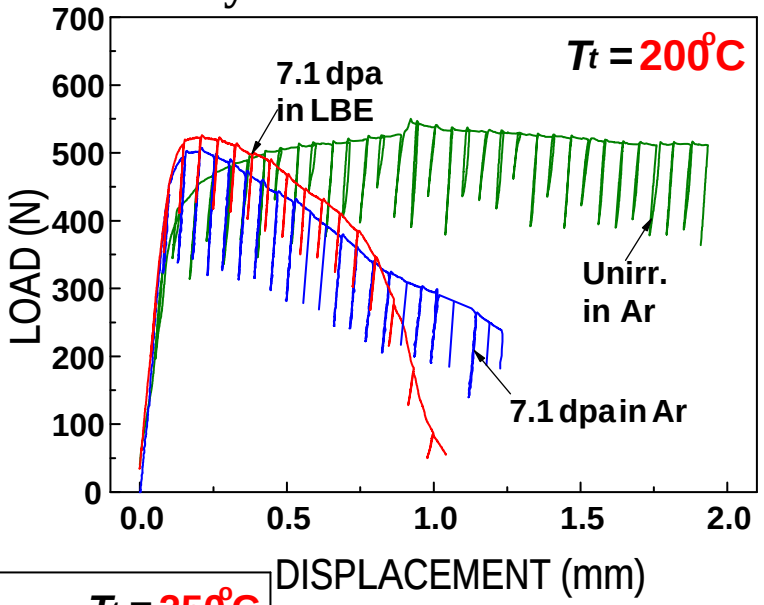
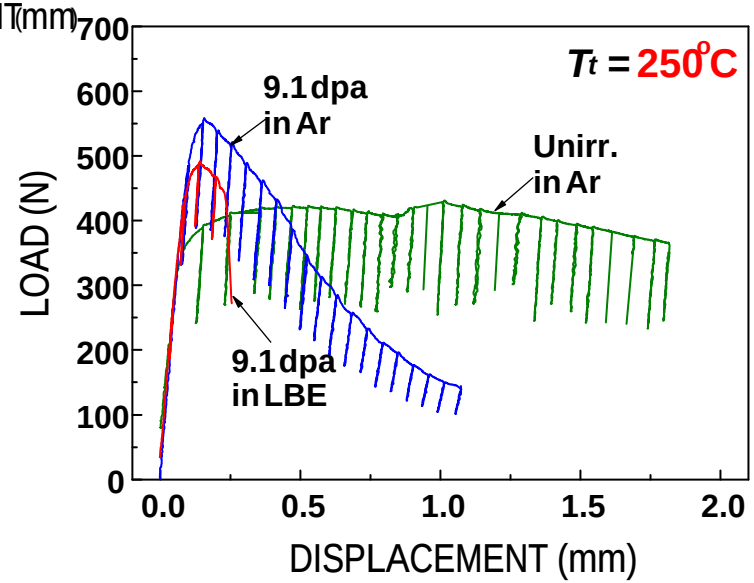
3-p bending test on irradiated T91

(STIP-1 and -3)

- Tested in Ar: irradiation induced embrittlement effect
- Tested in LBE: a further embrittlement effect by LBE is observed

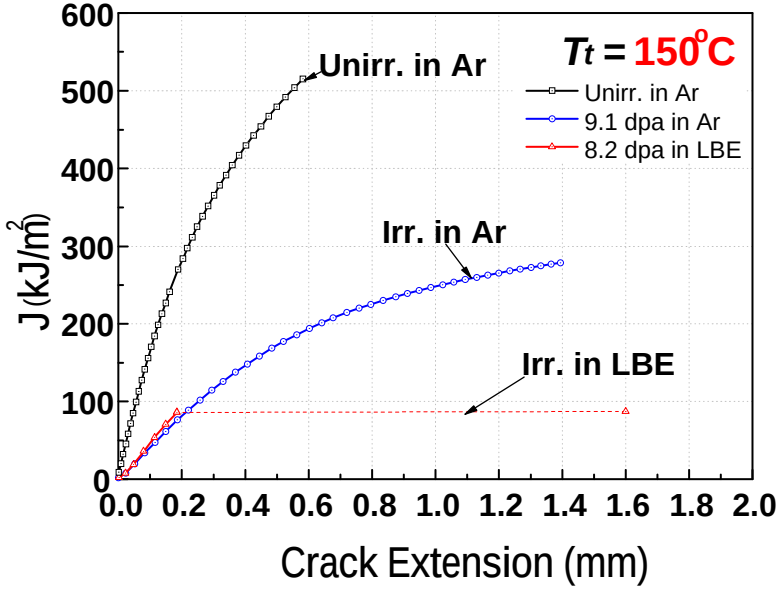


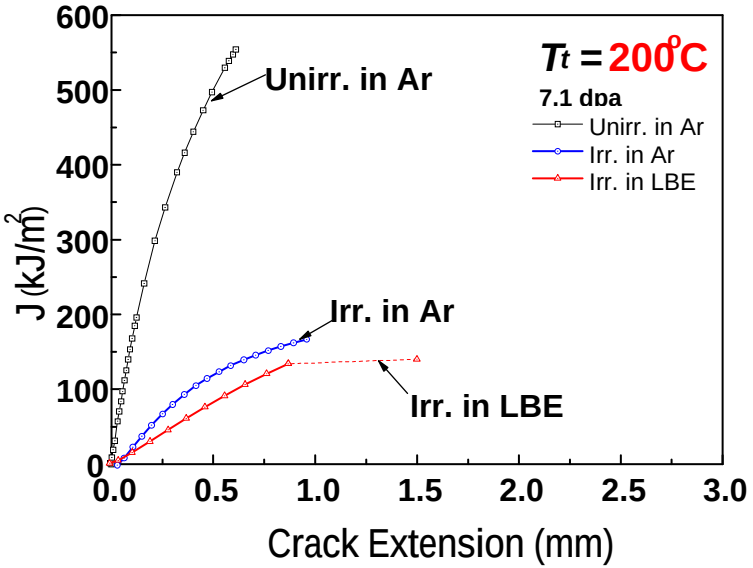




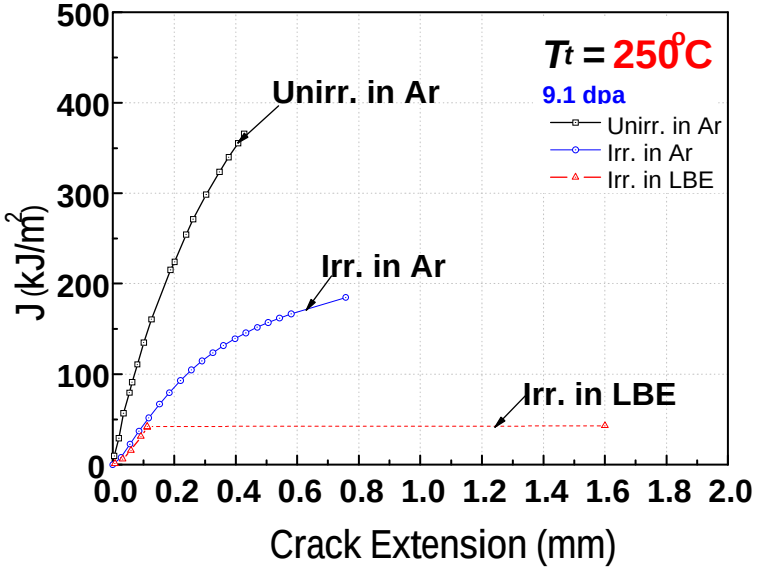
Irradiated T91 (STIP-1 and -3)

J-R curves



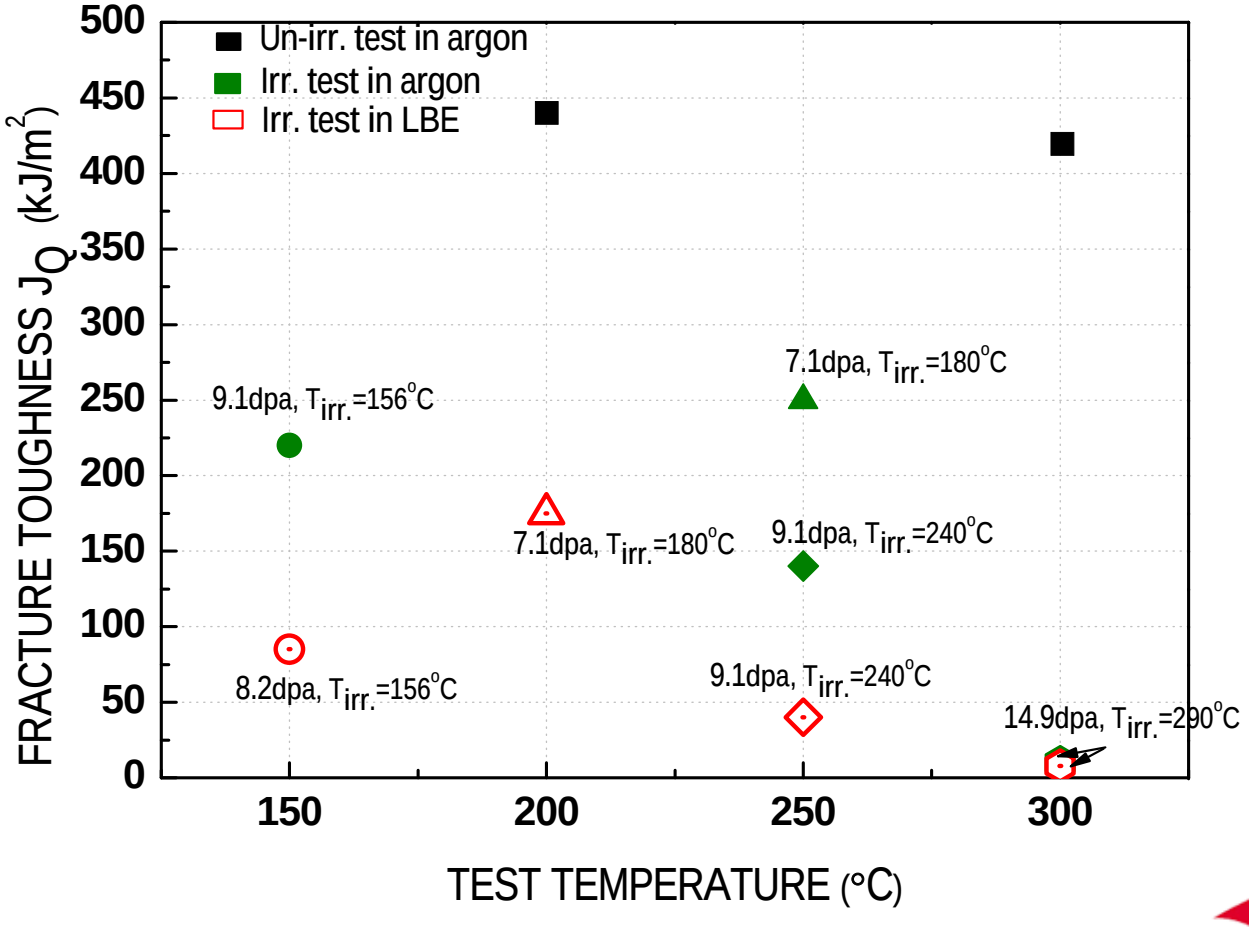


- J values of irradiated specimens are much lower than those of unirradiated ones
- J values are further reduced by LBE



Comparison of 3-p bending tests results on irradiated specimens

- The fracture toughness of irradiated specimens is reduced by irradiation-induced embrittlement
- The fracture toughness of irradiated specimens decreases further as a result from exposure to liquid LBE



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Conclusions

- The ductility trough of the T91 FM steel in the standard heat treatment state is 300-425°C. For tue first time, the ductility trough of the T91 steel in LBE is determined.

- The LBE embrittlement effects can be strongly enhanced by the hardening of the steels

- The combination of irradiation-induced embrittlement with LBE-induced embrittlement may give rise to unexpected premature failure. Therefore, it should deserve a great attention.

Acknowledgments

- To my supervisors Dr. Yong Dai and Prof. Nadine Baluc
- To Drs Freiderich Groeschel, Heike Glasbrenner and Werner Wagner of ASQ (PSI), to Dr.Thierry Auger (France), Dr. Jours Van de Bosch (Belgium), Dr. Peter Hosemann (USA)
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Proposed mechanism