Effect of micro-alloying and heat treatment on the neutron irradiation behavior of EUROFER type steels

M. Rieth[1], E. Simondon[1],. Pintsuk[2], G. Aiello3, J. Henry[2]4, D. Terentyev[2]5, A. Puype[6], N. De Wispelaere[6], C. Cristalli[7], L. Pilloni[8], O. Tassa[9], M. Klimenkov[1], H.-C. Schneider[1], P. Fernandez[10], T. Gräning[11], X. Chen[11], A. Bhattacharya[11], J. Reed[11], J.W. Geringer[11], M. Sokolov[11], Y. Katoh[11], L. Snead[12]

Presentation #1079

INSTITUTE FOR APPLIED MATERIALS – APPLIED MATERIALS PHYSICS

[1]Karlsruhe Institute of Technology, IAM-AWP, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[2]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, 52425 Jülich, Germany
[3]EUROfusion, PPPT, 85748 Garching, Germany
[4]Université Paris-Saclay, CEA, Service de Recherches Métallurgiques Appliquées, 91191, Gif-sur-Yvette, France
[5]Belgian Nuclear Research Centre, SCK•CEN, Mol, 2400, Belgium
[6]OCAS NV, Pres. J.F. Kennedylaan 3, 9060 Zelzate, Belgium
[7]ENEA, Brasimone, Camugnano, BO 40032, Italy
[8]ENEA CR CASACCIA, Via Anguillarese 301, 00123 Rome, Italy
[9]Centro Sviluppo Materiali S.p.A., Via di Castel Romano 100, 00128 Roma, Italy
[10]National Fusion Laboratory, CIEMAT. Avenida Complutense, 40., Madrid, Spain
[11]Oak Ridge National Laboratory, Oak Ridge, TN 37831-6115, USA
[12]Irradiation Materials Sciences Consulting (IMSC), 206 S. Country Road, Bellport NY 11713, USA

Chemical composition

wt.%	E	H	I	P	J	K	L	O
Cr	**8.83**	8.70	8.73	8.70	9.00	7.84	9.14	8.8
C	**0.107**	0.058	0.110	0.105	0.107	0.017	0.106	0.06
Mn	**0.53**	0.02	0.02	0.02	0.39	<0.03	0.54	0.50
V	**0.20**	0.35	0.35	0.20	0.22	0.22	0.20	0.3
N	**0.019**	0.047	0.042	0.045	0.022	0.022	0.038	0.07
W	**1.08**	1.07	1.08	1.14	1.10	0.99	1.11	0.97
Ta	**0.12**	0.10	0.09	0.09	0.11	0.13	0.12	0.05
Si	**0.04**	0.04	0.04	0.03	<0.04	<0.04	0.03	0.15
Prov.	KIT				SCK.CEN		CEA	ENEA

⊖ Mn ⇨ enables higher tempering temperature & ⊖ dislocation loop formation

⊖ C ⇨ ⊖ Coarse $M_{23}C_6$

⊕ V, N ⇨ ⊕ MX-type precipitates

Materials processing

‘Technological’ HT

High austenitization T
Low tempering T

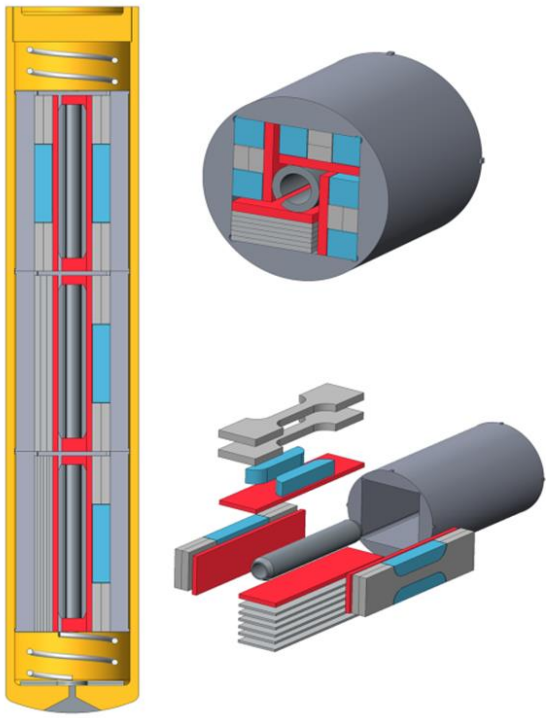
	E	H	I	P	J	K	L	O
TMT	TMT + Technological HT (980°C + slow AC)	**1150°C**/1h 8 steps of HR down to 900°C + WQ			**1250°C**/1h 6 steps of HR down to **850°C** +AC		TMT	**1080°C**/1h + HR at **650°C**
Heat treatment After TMT	**980°C** 0.5h	**1000°C** 0.5h	**1000°C** 0.5h	**1000°C** 0.5h	**880°C** 0.5h	**1050°C** 15min	**1150°C** 0.5h	
	+ AQ	+ WQ	+ WQ	+ WQ	+ WQ	+ WQ	+ AQ	
	+ **760°C**	+ **820°C**	+ **820°C**	+ **820°C**	+ **750°C** 2h	+ **675°C** 1.5h	+ **700°C**	**760°C** 1h
	+ AC	+ AC	+ AC	+ AC	+ AC	+ AC	+ AC	+ AC
Prov.	KIT				SCK.CEN		CEA	ENEA

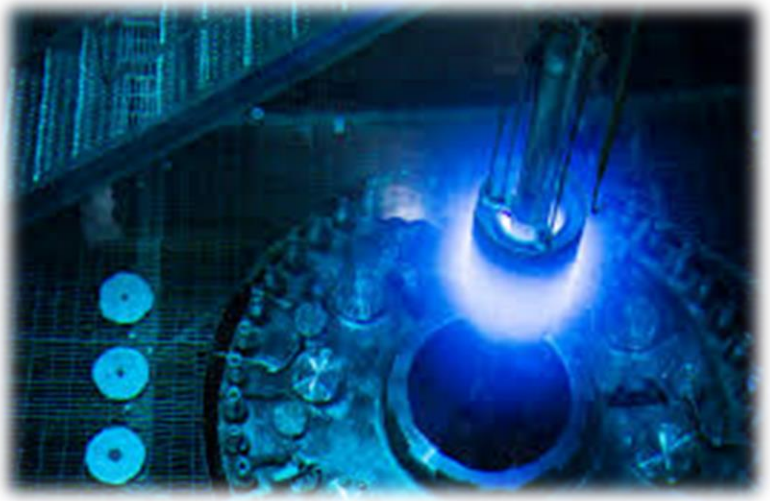
High tempering T

AQ= Air Quench
WQ = Water Quench
AC = Air Cooling
HR = Hot Rolling

Irradiation specifications

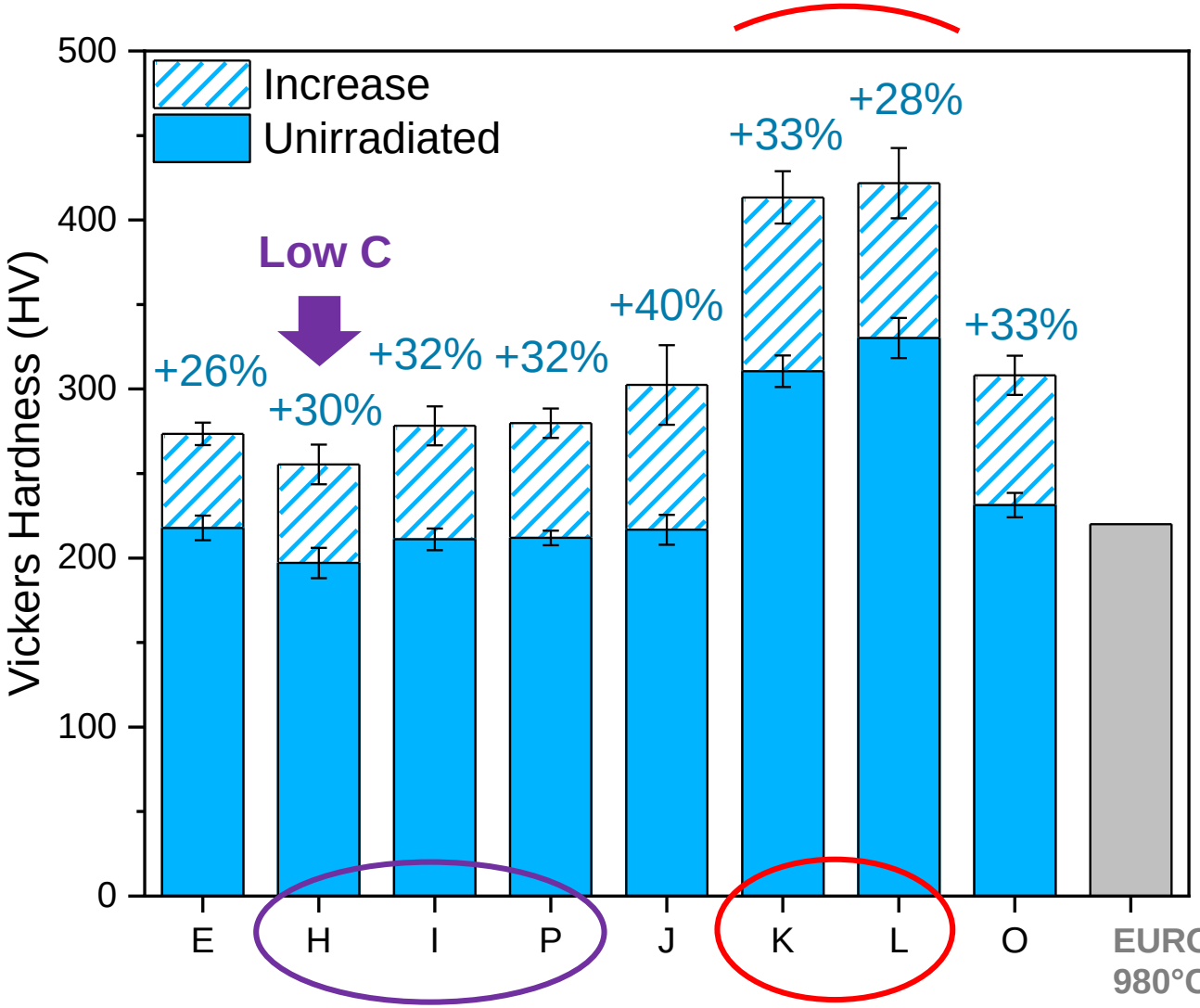
- Neutron irradiation in 85 MW High Flux Isotope Reactor (HFIR)
- Target dose of **2.5 dpa ± 0.38 dpa**





- Target temperature of **300 °C**
- Tensile & bend bar test samples

Vickers microhardness

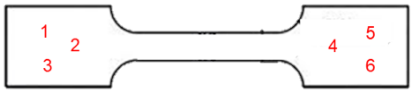


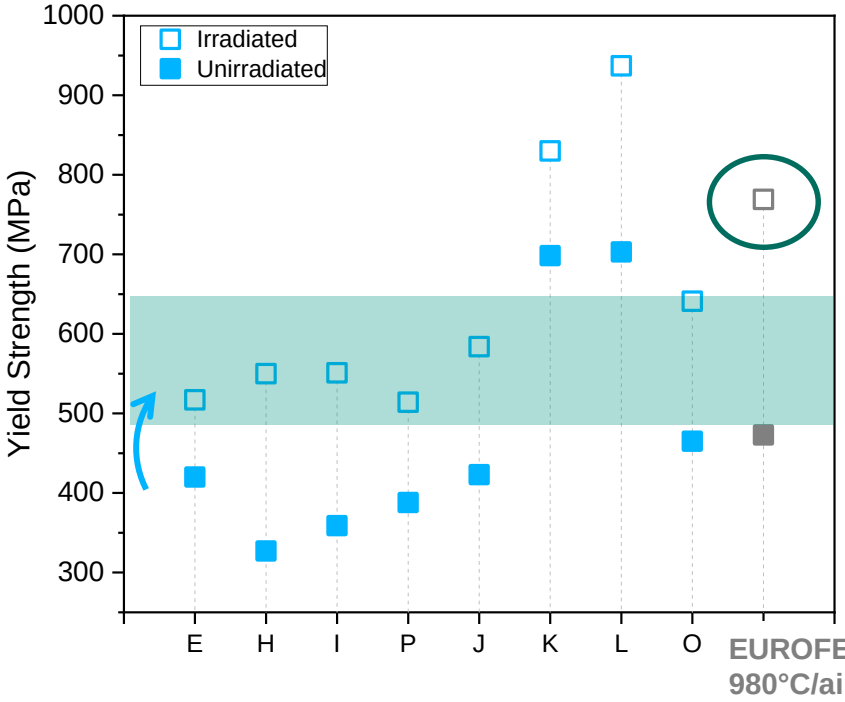
- Most grades are in the range of EUROFER97/2 before irradiation
- K & L show higher strength
- Every alloy shows hardening

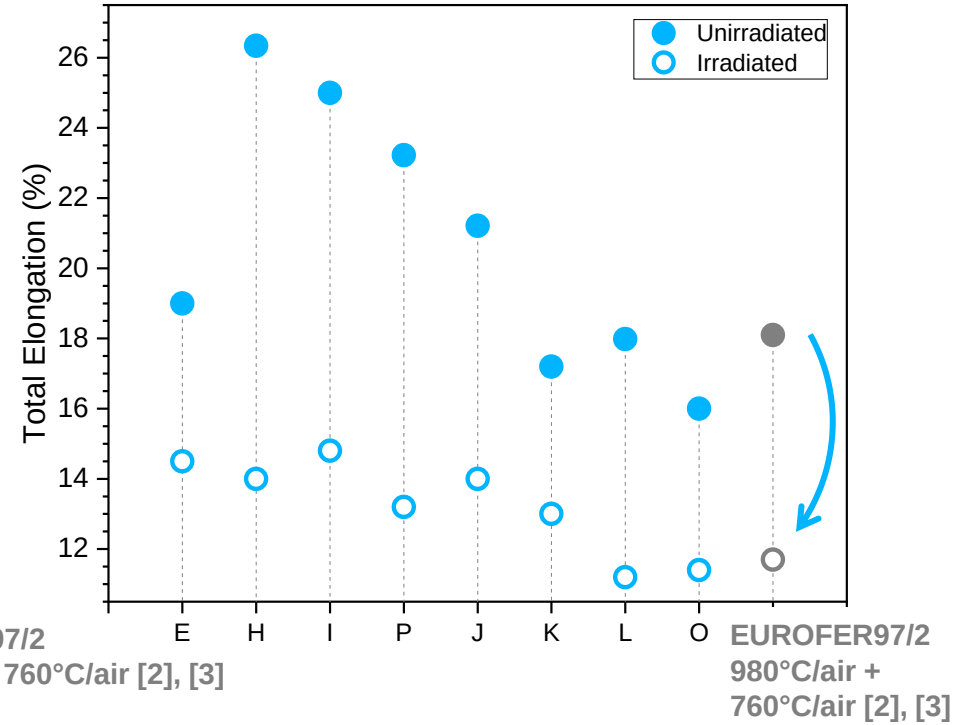
[1] M. Rieth *et al.*, "EUROFER 97 Tensile, charpy, creep and structural tests," Germany, 0947–8620, 2003.

Tensile properties

SS-J3 tensile specimens



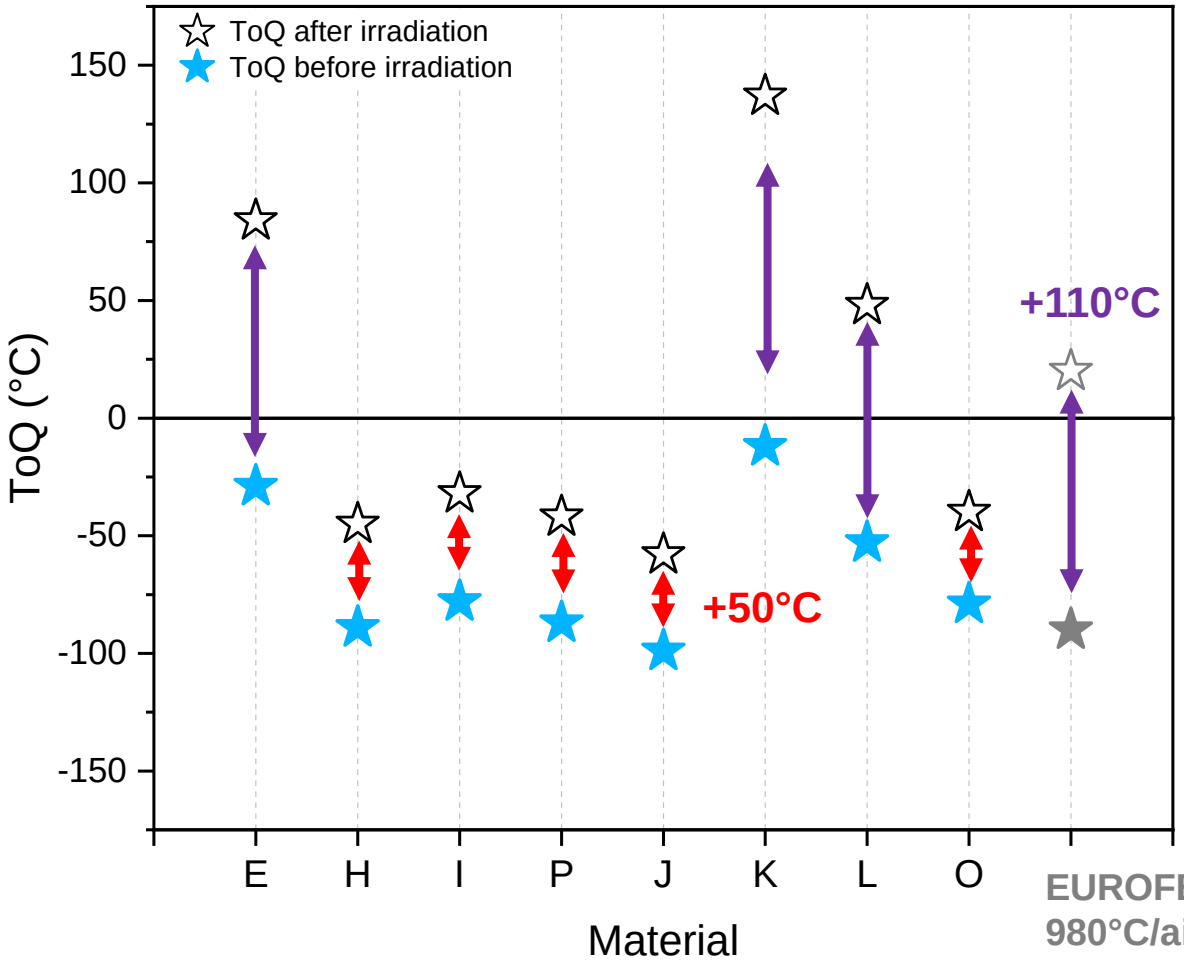




- K & L show higher strength
- Most materials prove softer than EUROFER97/2, especially after irradiation

[2] "Material Property Handbook EUROFER97 - Grant Deliverable MAT D25.15," EUROFusion, 2017.
[3] E. Gaganidze, "Assessment of Fracture Mechanical Experiments on Irradiated EUROFER97 and F82H Specimens, Final Report TW5-TTMS 001-D14, 2007.

Fracture Mechanic properties

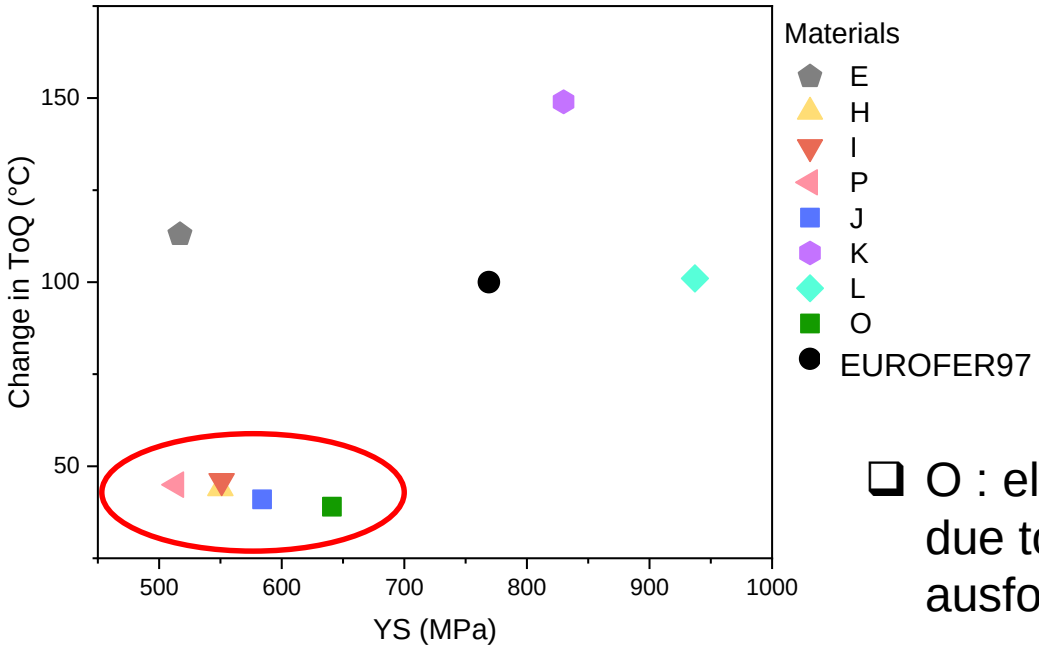


EUROFER97/2
980°C/air + 760°C/air [4]

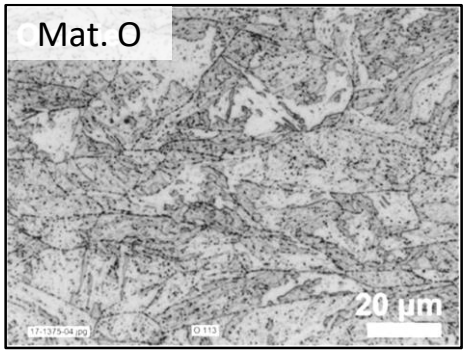
- Significantly better fracture mechanic properties for 5 alloys compared to EUROFER97/2

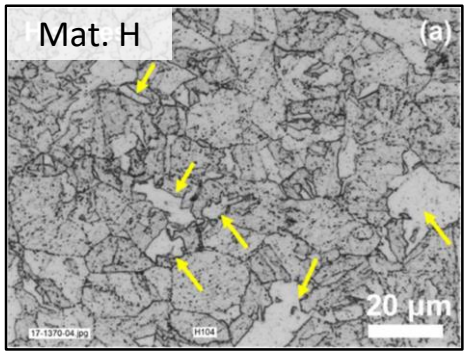
[4] E. Gaganidze and J. Aktaa, "Assessment of neutron irradiation effects on RAFM steels," *Fusion Eng. Des.*, vol. 88, no. 3, pp. 118–128, 2013

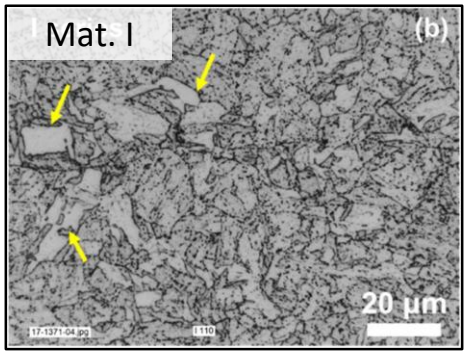
Microstructure

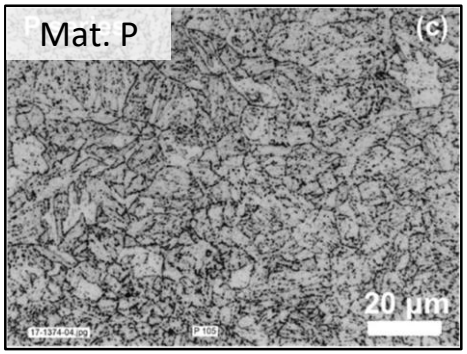


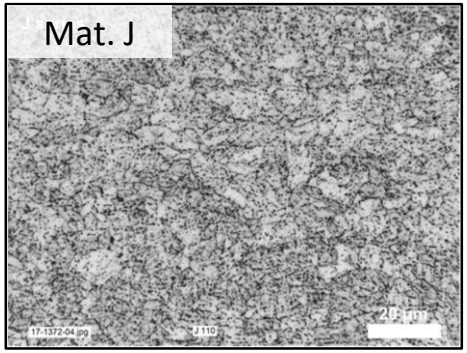
- J : optimized ausforming, low austenitization T
- H, I, P : high tempering T leading to ferrite formation
- O : elongated grains due to a specific ausforming process



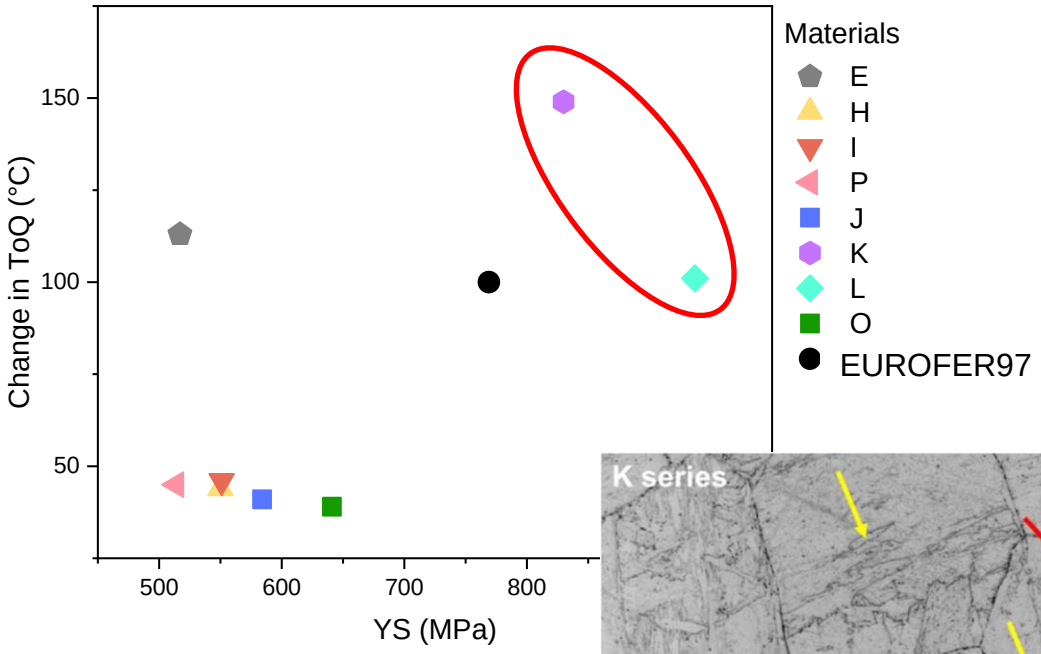


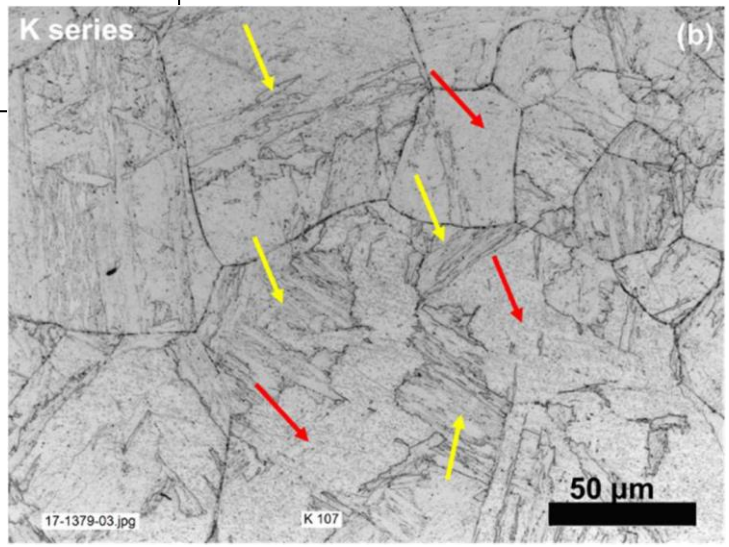


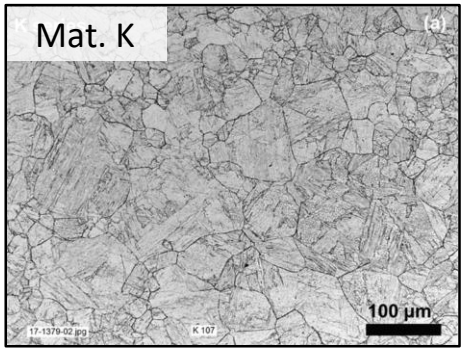


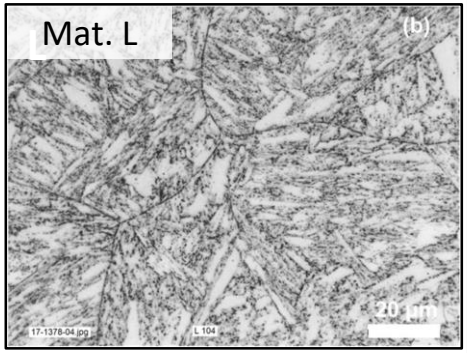


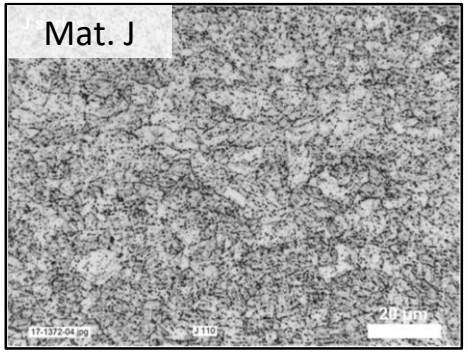
Microstructure





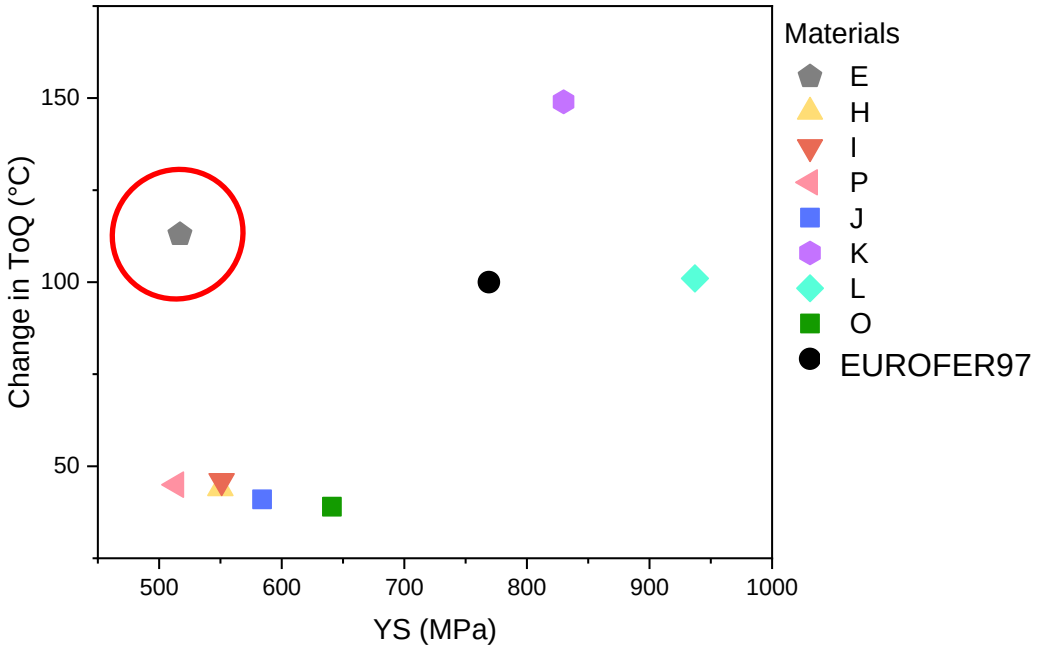


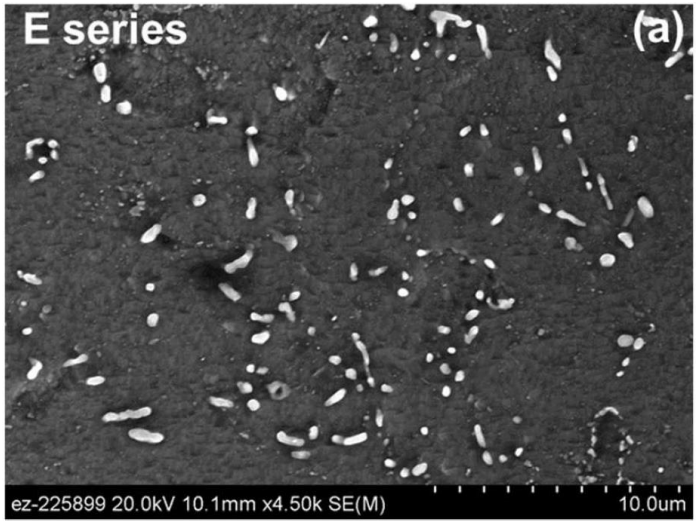


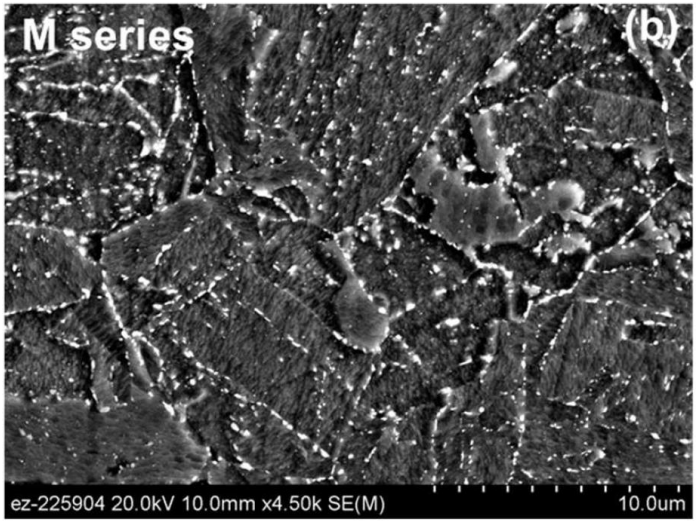


- High normalizing temperature
- Low tempering temperature
- Low C content for K

Microstructure







‘Technological Heat treatment’

Conclusion

- 8 newly developped advanced RAFM steels were irradiated at 300°C with a nominal dose of 2.5 dpa
- Better fracture toughness properties for 5 alloys
- Silght effect of micro-alloying compared to a much stronger effect of heat treatment and fabrication history.
- Technological Heat treatment leads to comparable fracture toughness behavior as EUROFER97

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.