Friction Stir Welding (FSW) of 9% Cr steel (P91)

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Microstructure and mechanical properties

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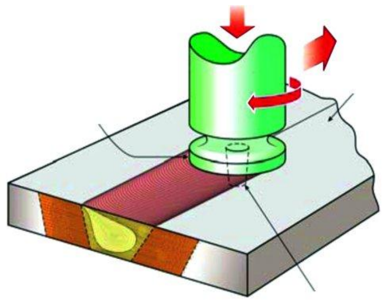
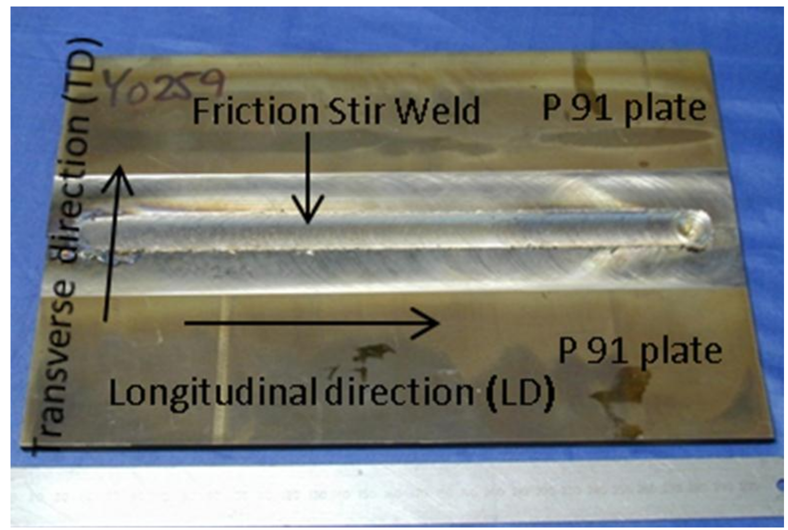




Introduction

Materials: Ferritic/martensitic (F/M) steels and ODS steels are considered as candidates for the advanced fast nuclear reactor cladding/duct materials because of their excellent radiation resistance and low swelling rate compared to austenitic stainless steels.

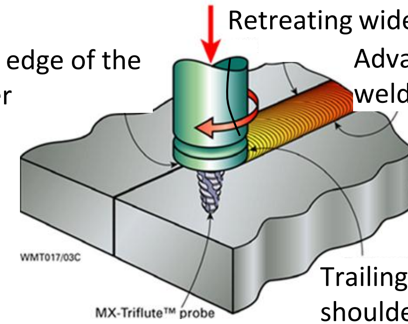
Motivation: Joining of these materials without destroying their characteristic microstructure is challenging. Consequently, suitable non-melting techniques for joining of F/M steels and ODS steels are being developed for the Generation IV nuclear reactors, e.g. *Explosion welding, brazing and Friction Stir Welding*.

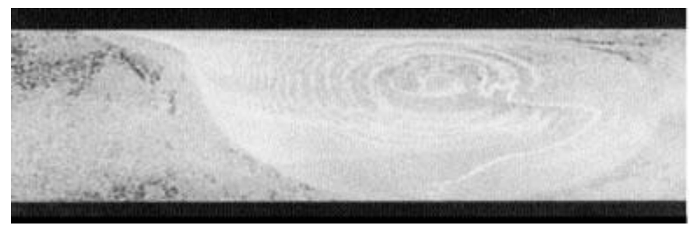
Objective: to assess its suitability of FSW for joining of the advanced steels for the Generation IV nuclear applications.

Approach: An extensive characterization of the friction stir weld produced from P91 steel was performed in comparison with its base material properties. Influence of the post weld tempering heat treatment (PWHT) on the mechanical and microscopic properties was studied.

Friction Stir Welding - Principle

- First developed for low melting metals like Aluminium at TWI
- No melting during ‘welding’.
- Metal is heating by friction and plastically deformed.
- To join parts are joint by ‘mechanical mixing’ of the materials.
- Continues development (at TWI) to other metals like steels, AISI304, AISI316, P91.
- Characterised by:
  - Low heat input, hence reduced effect on base material properties outside the ‘weld pool’.
  - No filler metals.
  - Mostly for joining of plates and simple shapes.
  - Butt welds with I-weld preparation

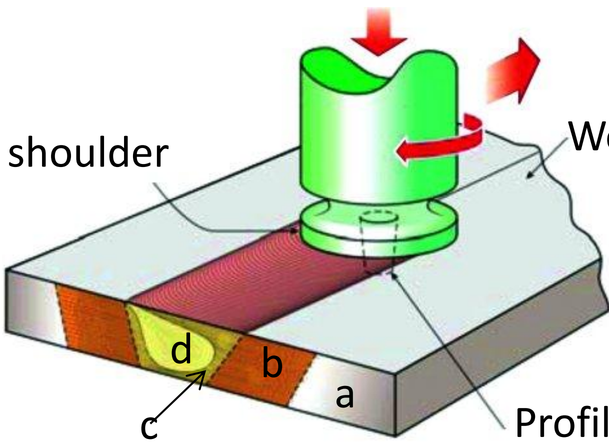


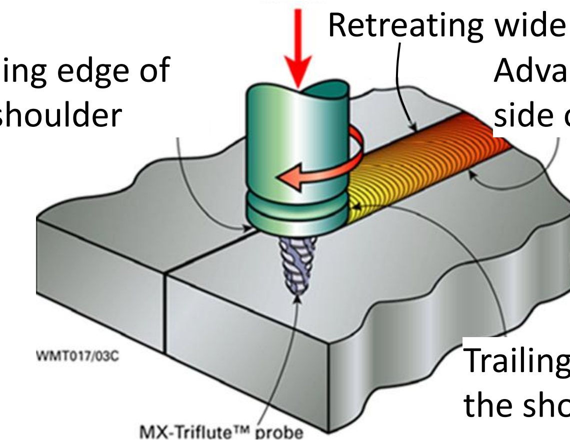


Aluminium [Alumatter.com]

9% Cr steel (P91) [ECN; NRG]

Friction Stir Welding - Principle

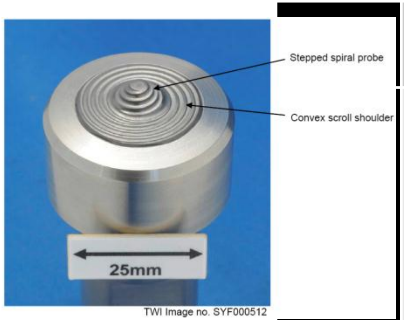


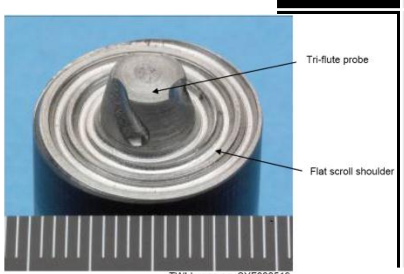


a: Unaffected material
b: HAZ (Heat Affected Zone)
c: TMAZ (Thermomechanically affected zone)
d: Weld Nugget (part of the TMAZ)

FSW – of P91 – IndicationWelding parameters

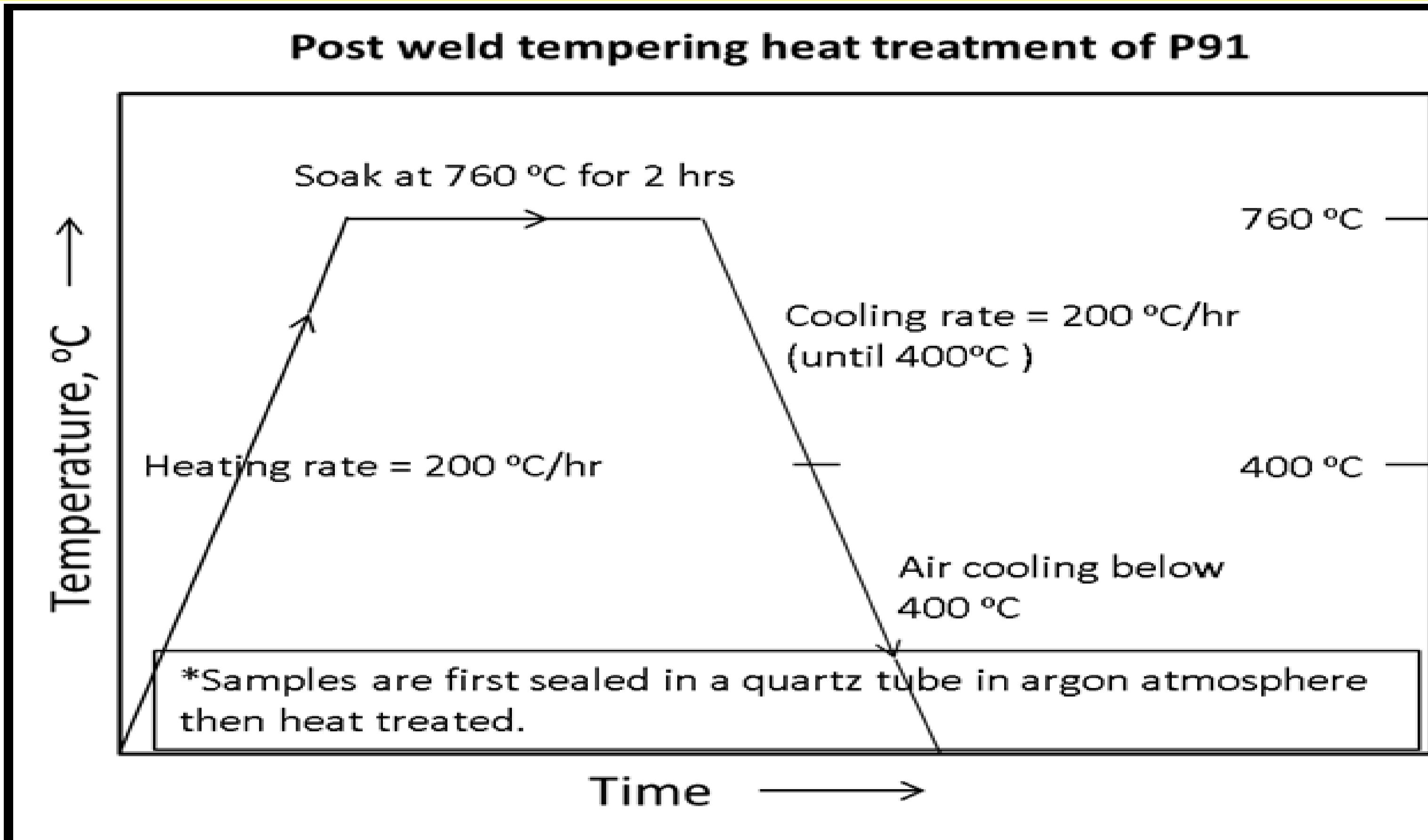
Weld No.	Tool material	Weld geometry	Pilot hole	Tilt angle	Plunge depth	Rotation speed	Traverse speed	Remarks
				[°]	[mm]	[rev/min]	[mm/min]	
	W-Re/c-BN	BW	Yes	0	4.9	200	100	
	W-Re	BW	Yes	2.5	5.2	300	150	Used in discussed welds



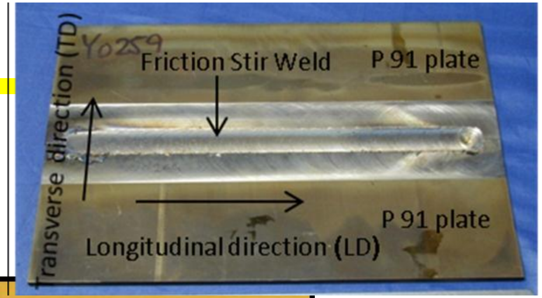


Ar-shielding gas

FSW – of P91 – Post Weld Heat Treatment



FSW – of P91 - Characterisation



Mechanical testing at RT on subsized samples:

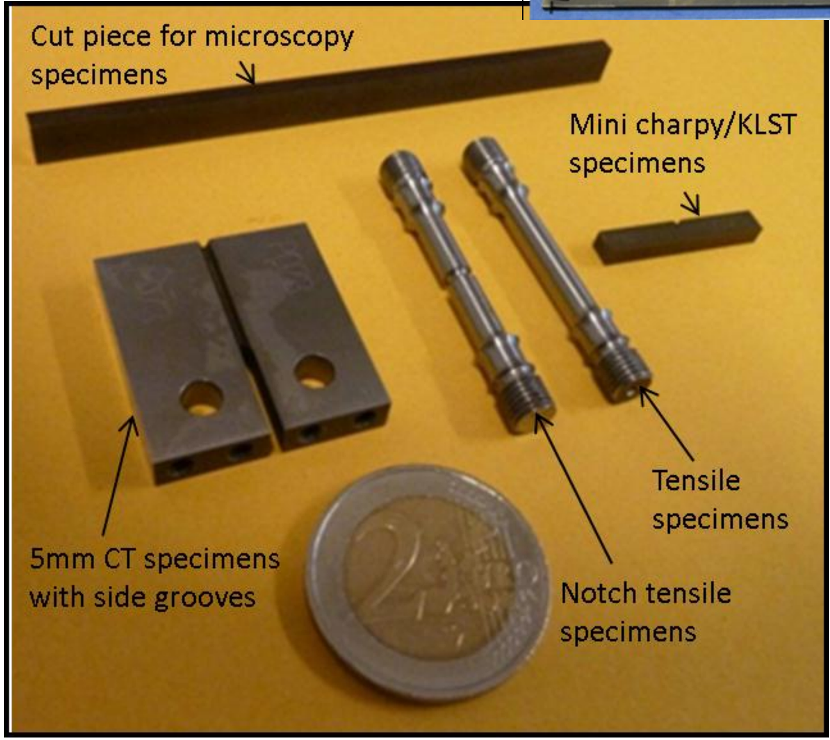
- Tensile testing (notched and unnotched)
- Charpy, mini (KLST)
- Fracture Toughness, CTS (J)
- Hardness (HV1)

Metallography:

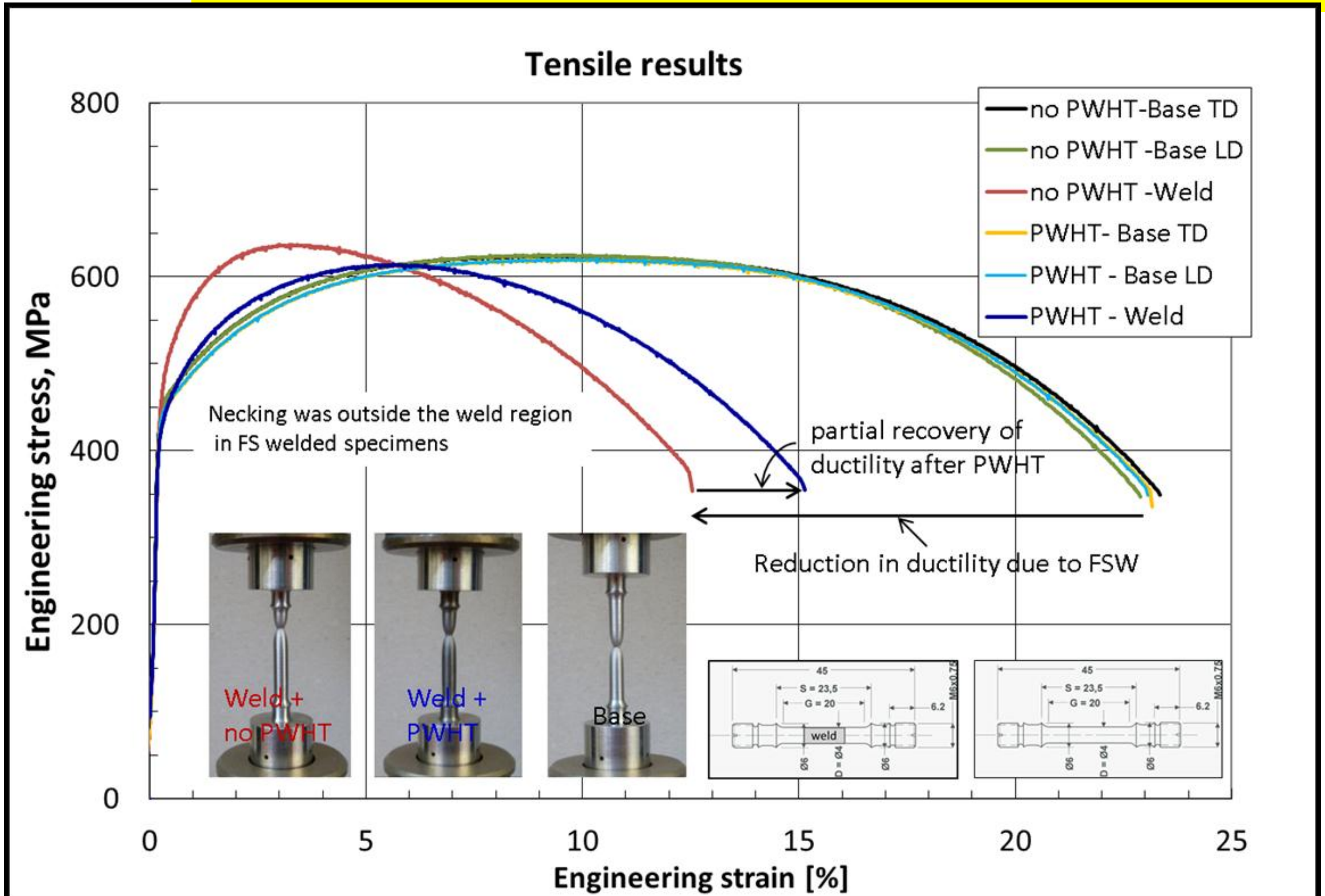
- Grain size
- Carbide precipitation
- Welding imperfections

Conditions:

- As welded
- After PWHT

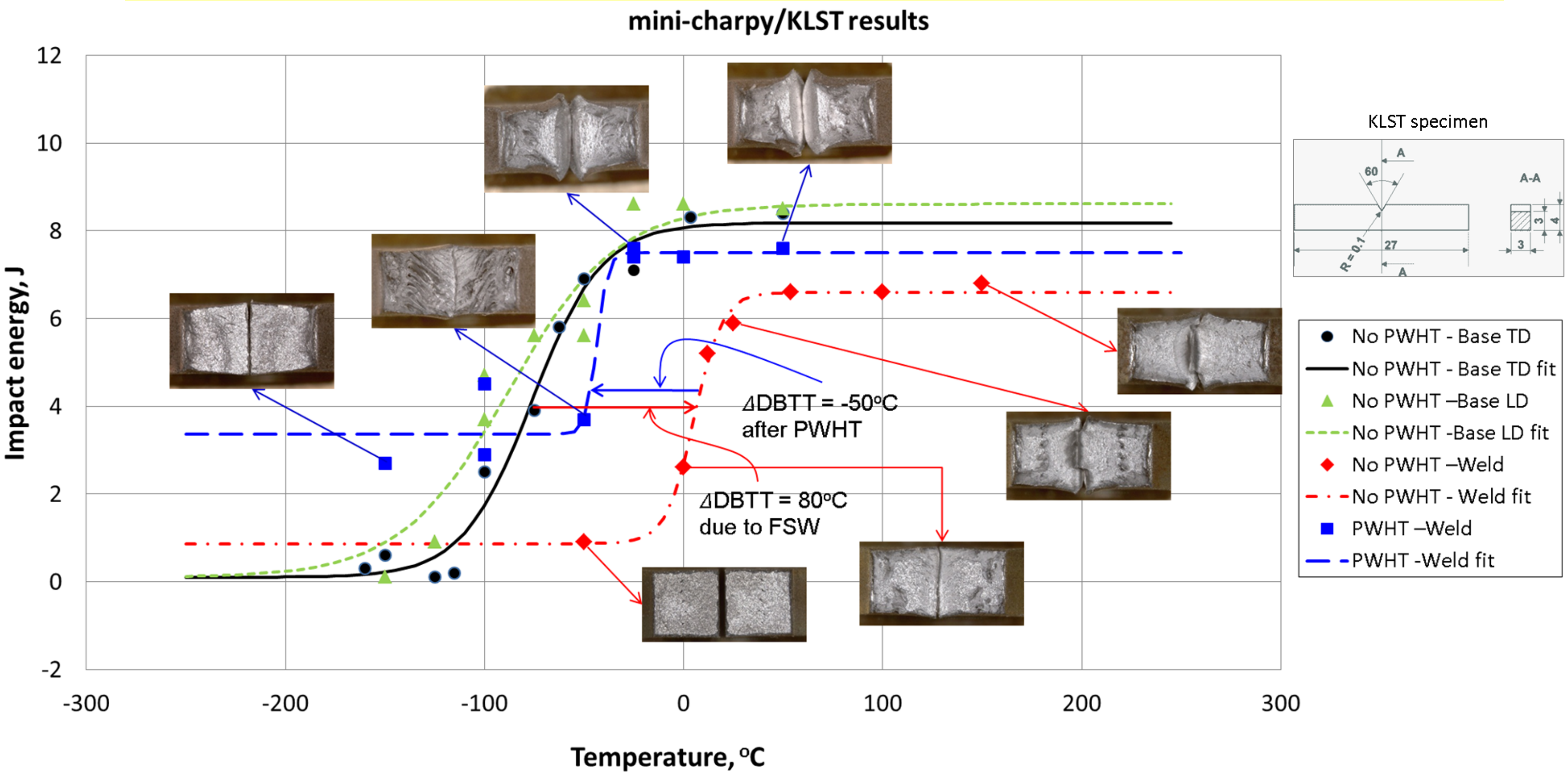


FSW – of P91 – Tensile testing (unnotched)

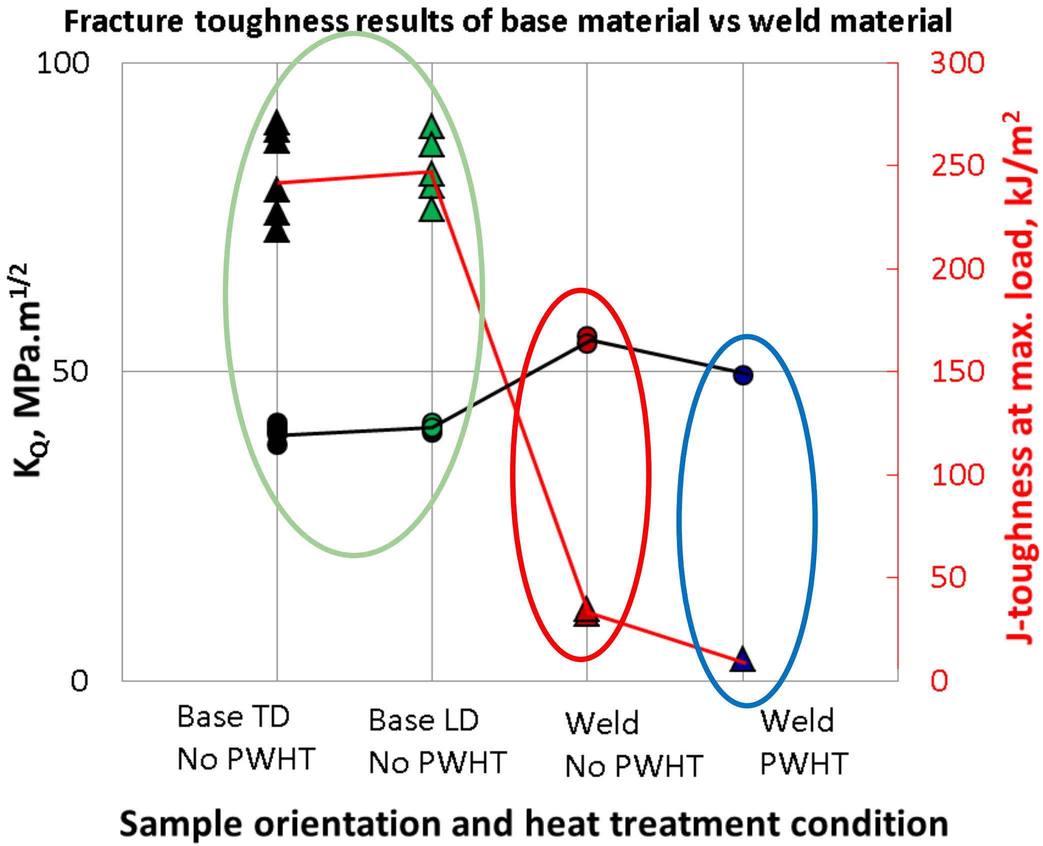


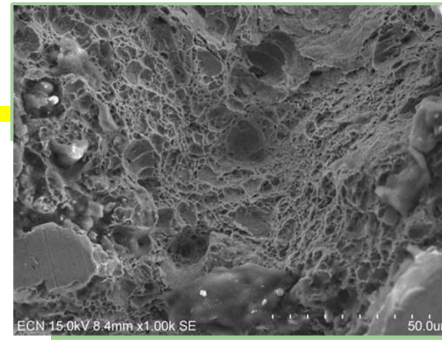
- Superior strength for as welded joint
- Reduced ductility in AW condition
- Partial recovery of the weld ductility by PWHT
- Base material unaffected by PWHT

FSW – of P91 – Mini Charpy / KLST

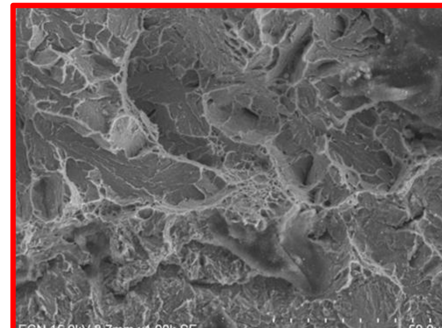


FSW – of P91 – Toughness

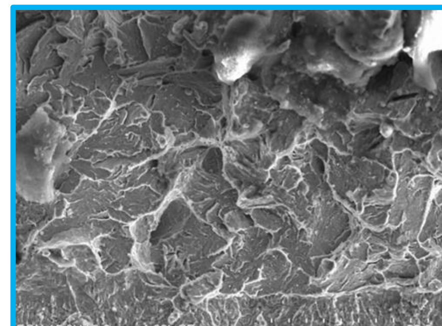




Base Material: Dimple fracture

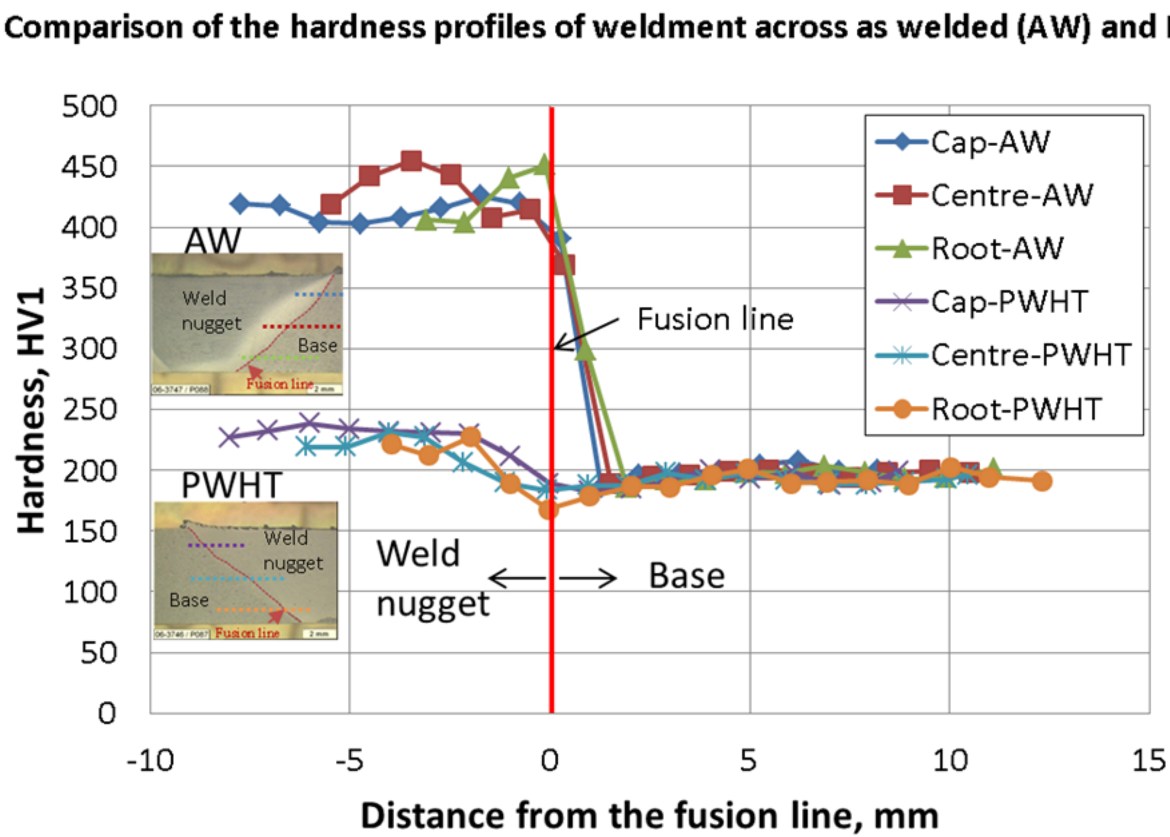


Weld AW: Dimples + quasi cleavage



Weld PWHT: Cleavage

FSW – of P91 – Hardness (HV1)



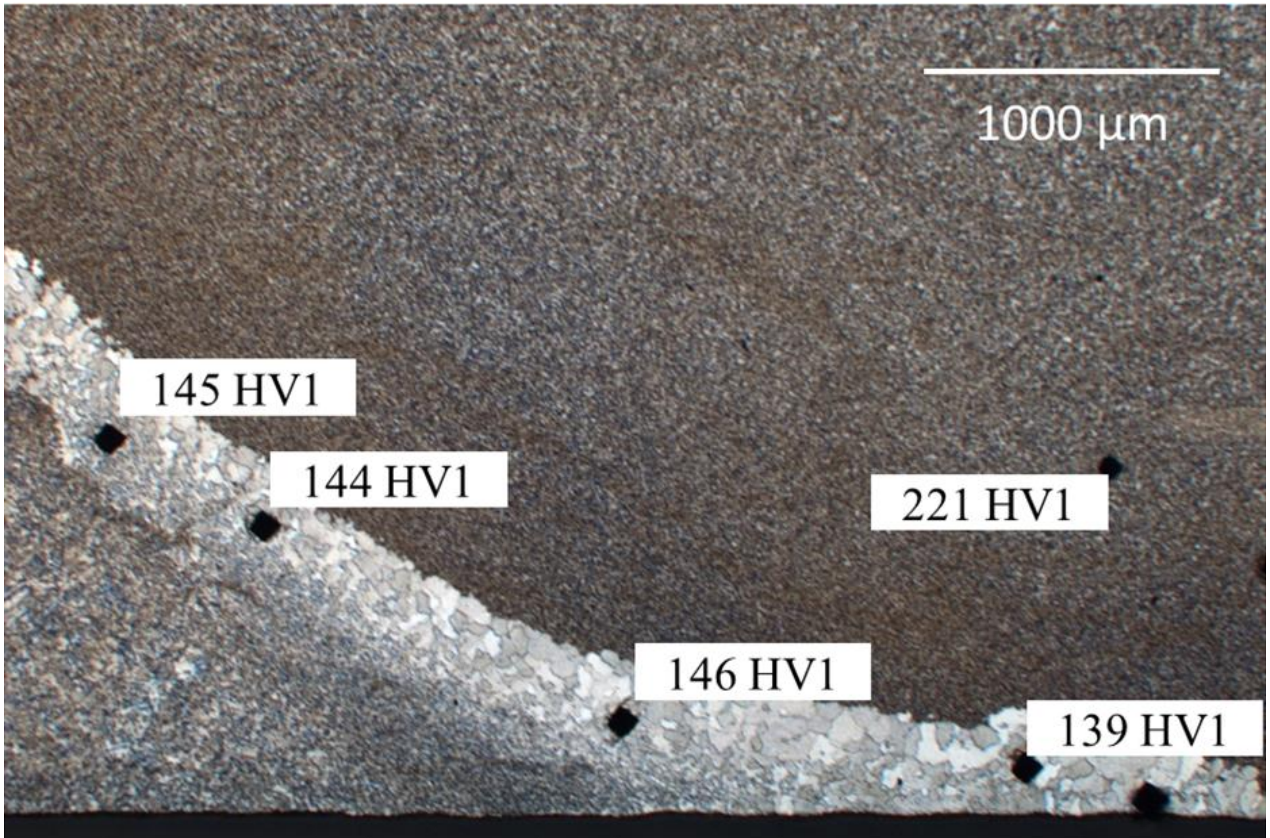
As Welded:

- Weld hardness 400-450HV1
- No hardness increase in 'HAZ'

Effect PWHT:

- Hardness BM unaffected
- Weld nugget hardness reduced to BM hardness
- Minor hardness dip at FL

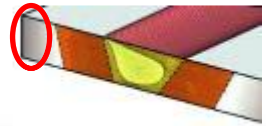
FSW – of P91 – Hardness (HV1)

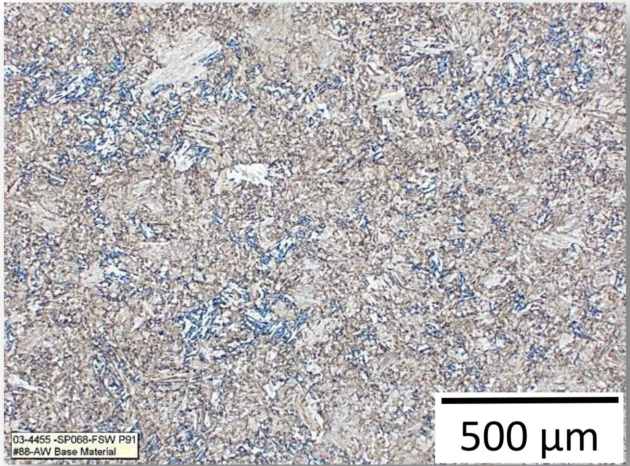


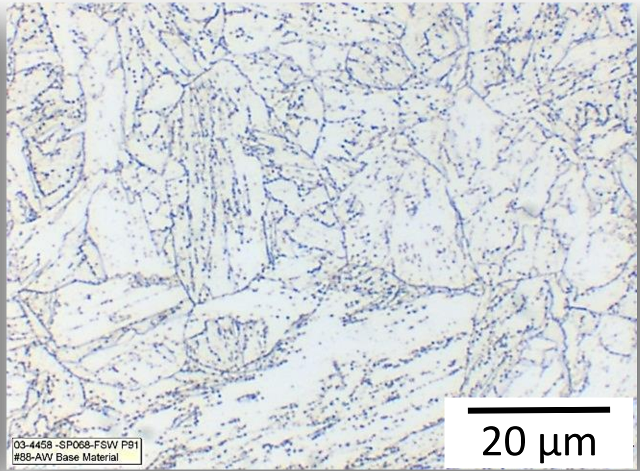
After PWHT:

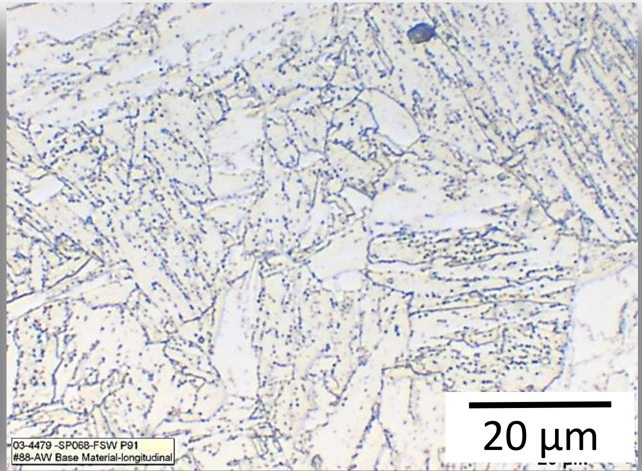
Local lower hardness due to coarse recrystallised ferritic grains
(see Metallography)

FSW – of P91 – Metallography-BM







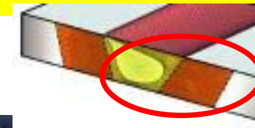


LT-ST plane

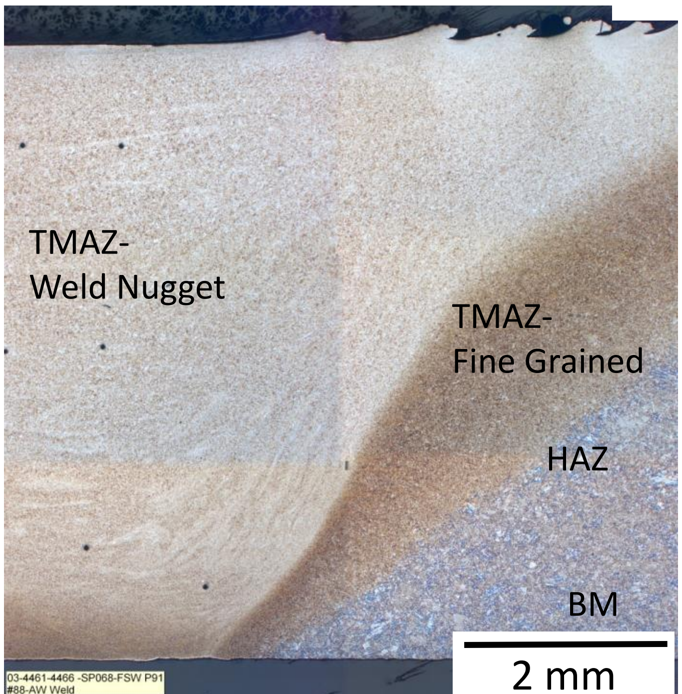
L-ST plane

Homogeneous martensitic microstructure with fine carbide precipitation and globular alumina inclusions

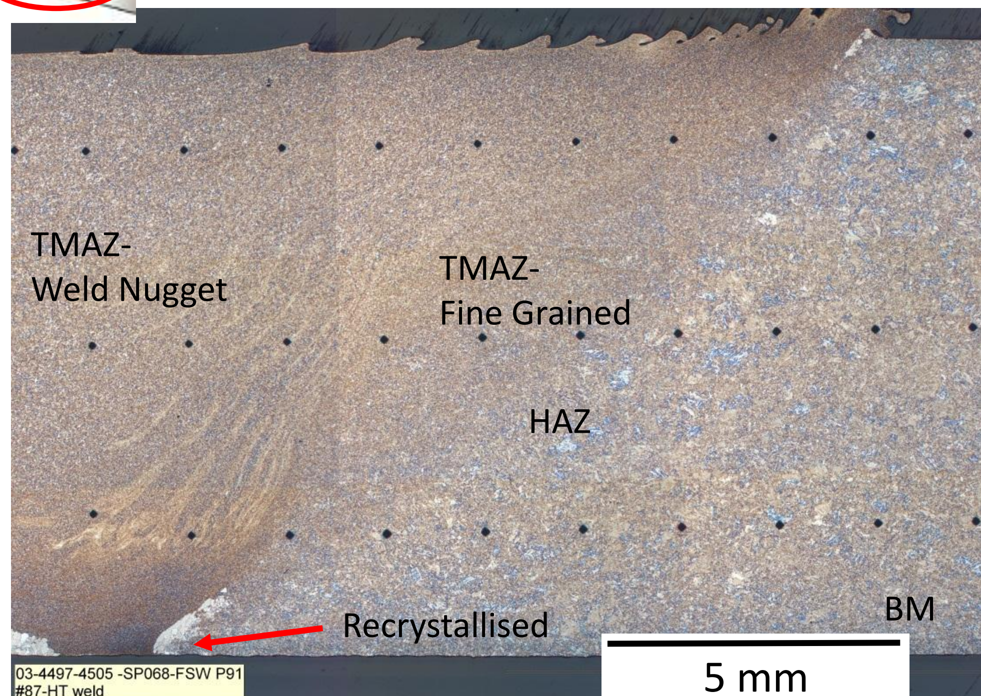
FSW – of P91 – Metallography - Weld



AW



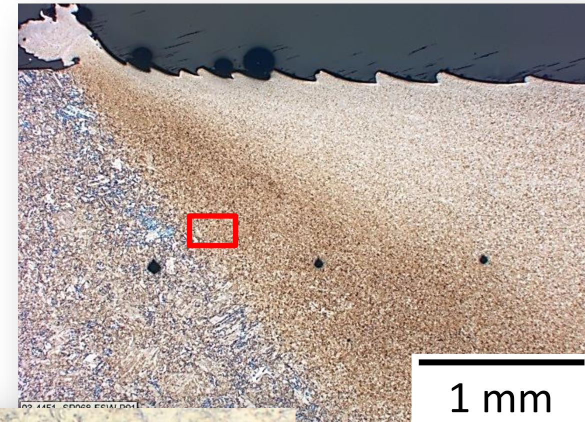
PWHT



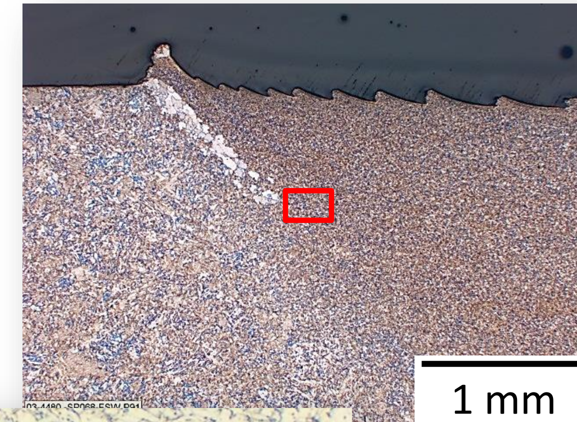
Note recrystallised areas at weld root and cap after PWHT

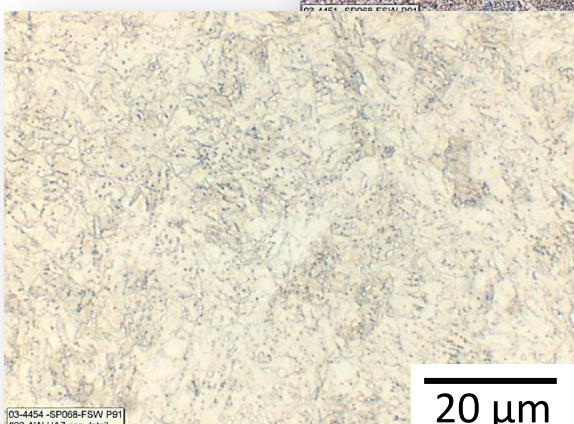
FSW – of P91 – Metallography - TMAZ

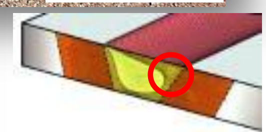
AW

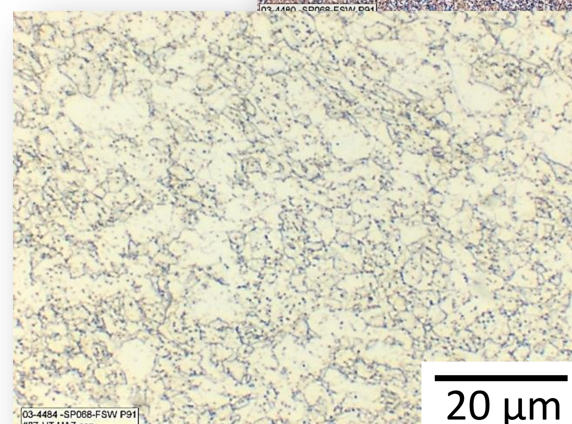


PWHT



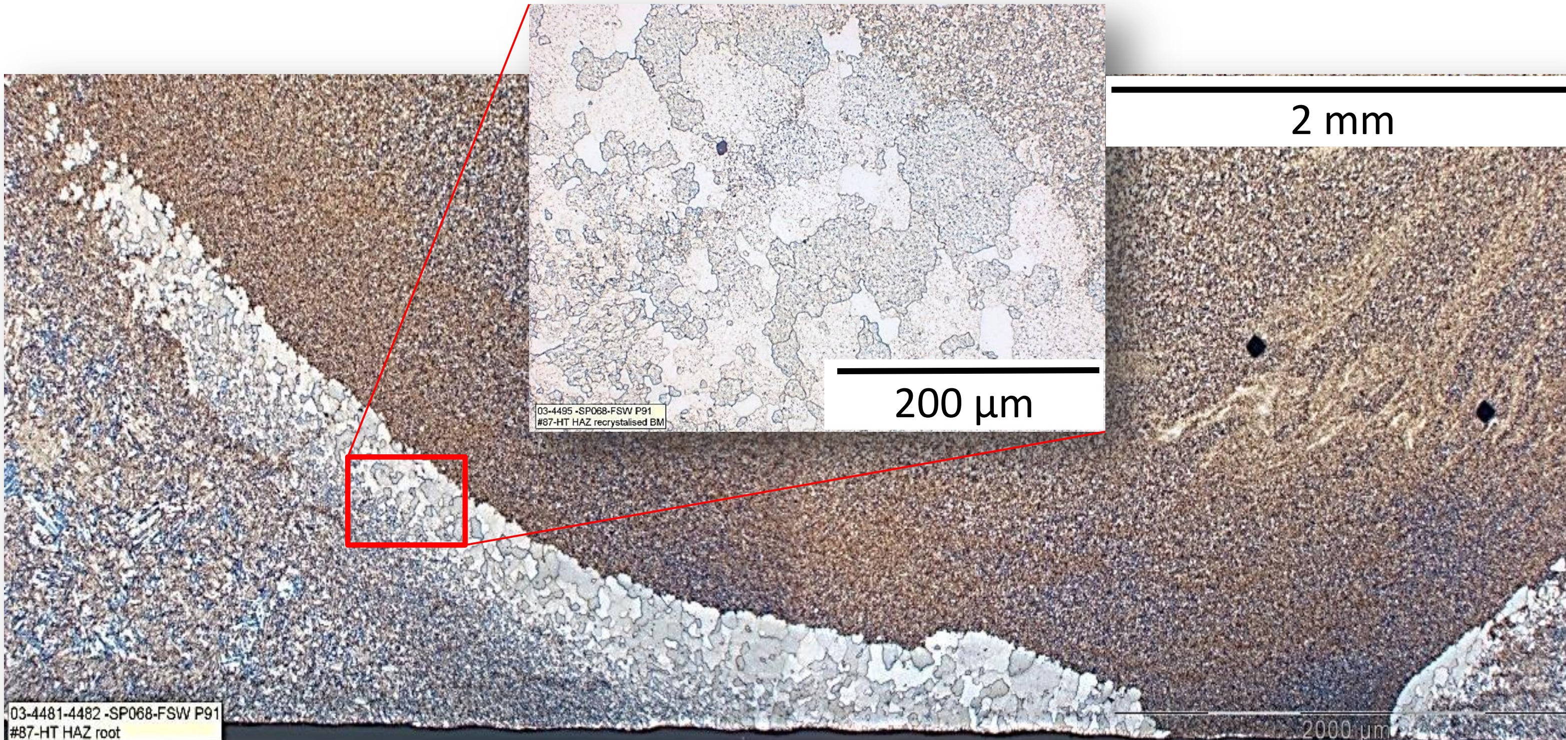






Fine recrystallised microstructure with inter- and transgranular carbides

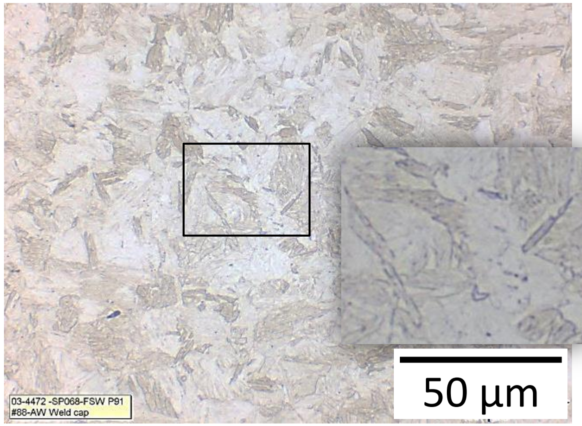
FSW – of P91 – Metallography-TMAZ/HAZ

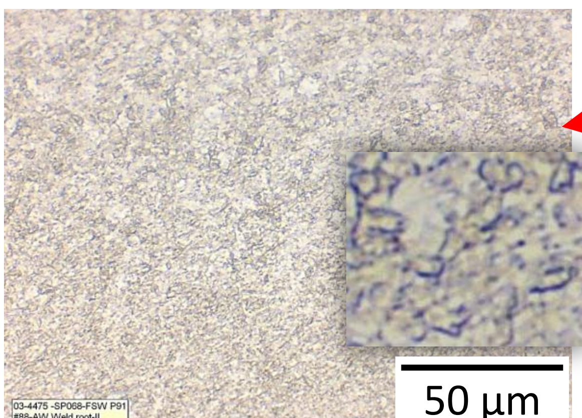


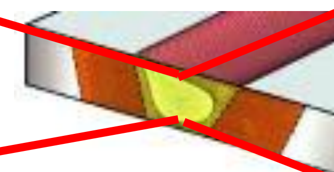
Ferritic coarse recrystallised zones at the weld cap and root after PWTH

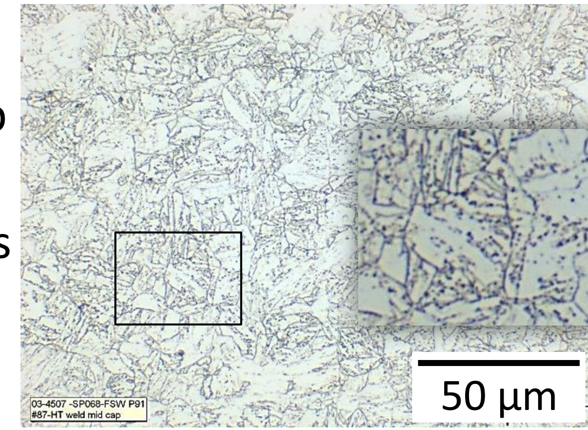
FSW – of P91 – Metallography-TMAZ-Nugget

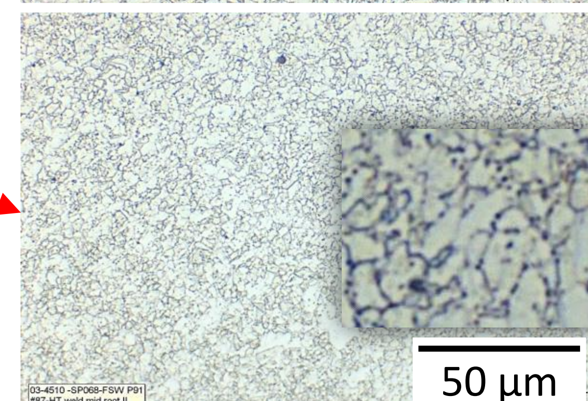
- Fine grained in the root, coarser grain towards the cap
- Fine carbide precipitation after PWHT affects Toughness







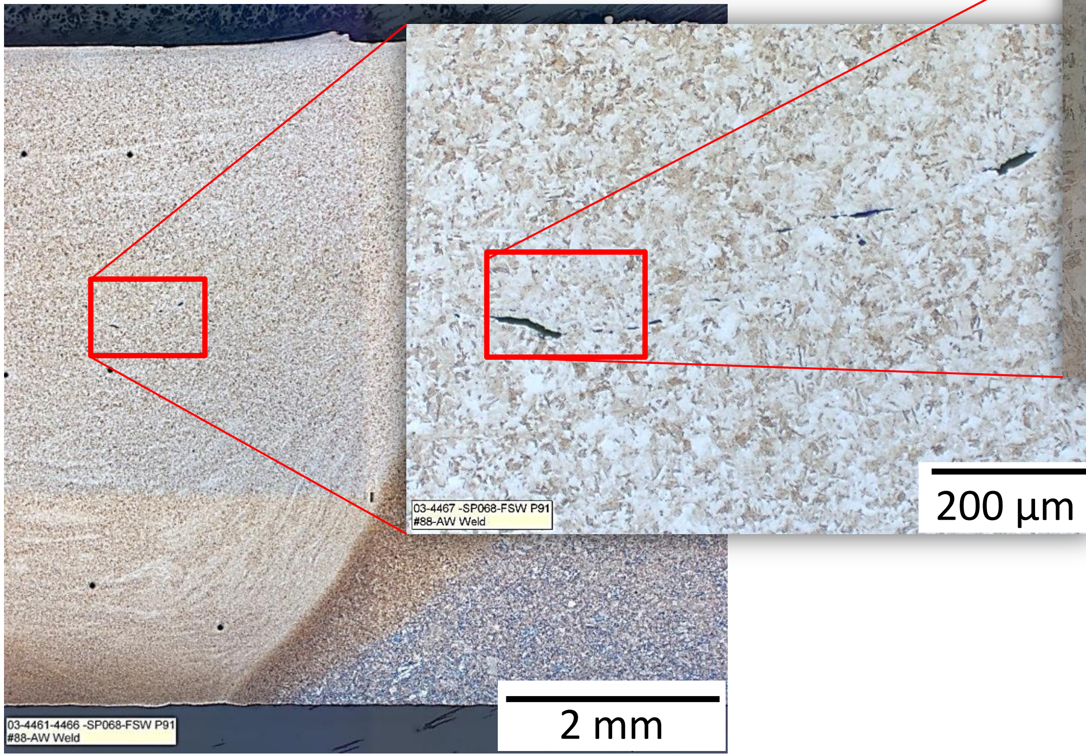


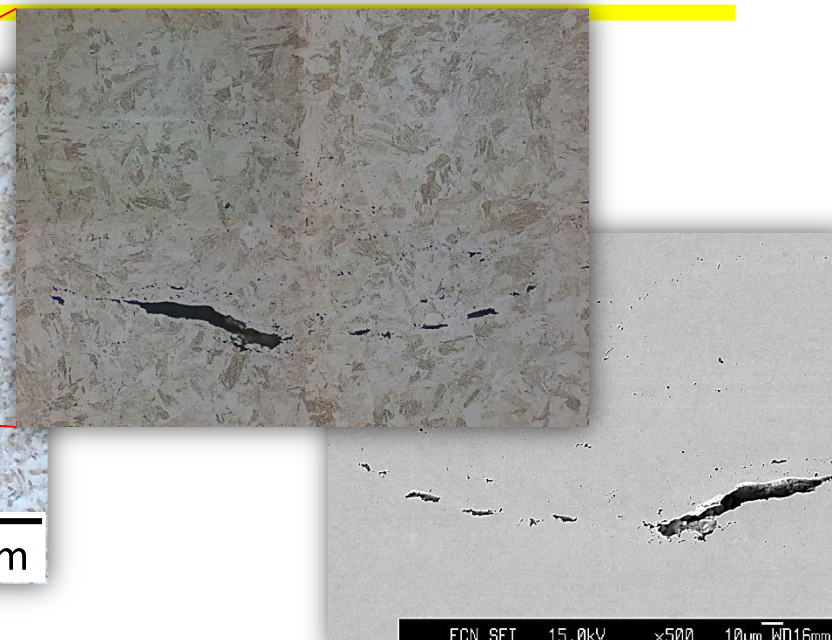


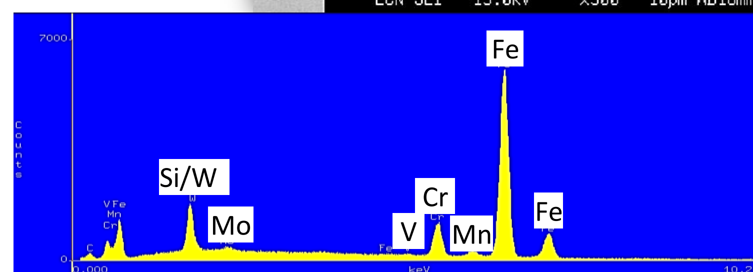
AW

PWHT

FSW – of P91 – Metallography-TMAZ-imperfections







- Possible W-debri from tool
- ‘Porosity’ due to lack of flow of material

FSW – of P91 – Conclusions (1)

Metallography:

- Hardness in the weld (TMAZ) increase to 442-412HV1, BM hardness 198HV1.
- After PWHT hardness in the TMAZ reduces by 47%, to 225HV1.
- Ferritic recrystallised zones in root and cap with hardness of 145HV1, due to overtempering of fresh formed martensite.
- Weld is almost free of imperfections.
- No effect of FSW on base material microstructure and properties in the HAZ.
- TMAZ shows a in coarsening in microstructure from root to cap
- BM carbides dissolved after FSW
- Carbide precipitation in the TMAZ after PWHT

FSW – of P91 – Conclusions (2)

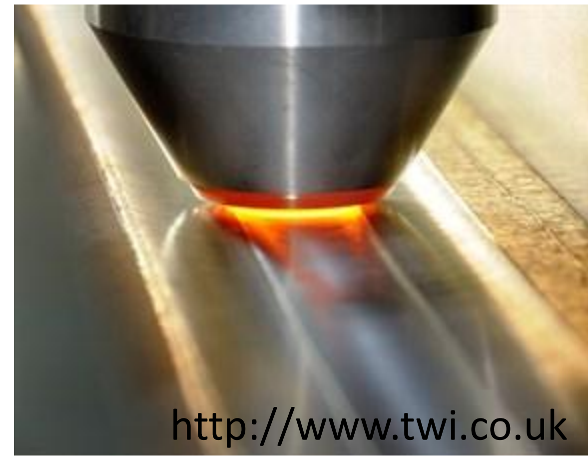
Mechanical characterisation:

- FSW AW superior tensile strenght, with considerable loss in ductility.
- PWHT partially restored weld ductility.
- Substantial DBTT increase in AW condition of 80°C.
- Almost complete recovery of DBTT after PWTH by 50°C.
- Slight increase in fracture toughness, K_Q, in AW condition. Upon PWHT lowered to BM level. Possibly related to carbide precipitiation.
- J-toughness, stable crack growth BM changed to unstable crack growth in the AW and PWHT condition. The reason(s) for lower J-toughness is not clear as yet.

Applicability:

- Improved temperature control during FSW may result in avoiding PWHT and will make FSW applicable for Nuclear applications

Thanks for your attention



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