FWP 66059

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Solid State Joining of Creep Strength Enhanced Ferritic Steels

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U.S. DEPARTMENT OF ENERGY BATTELLE

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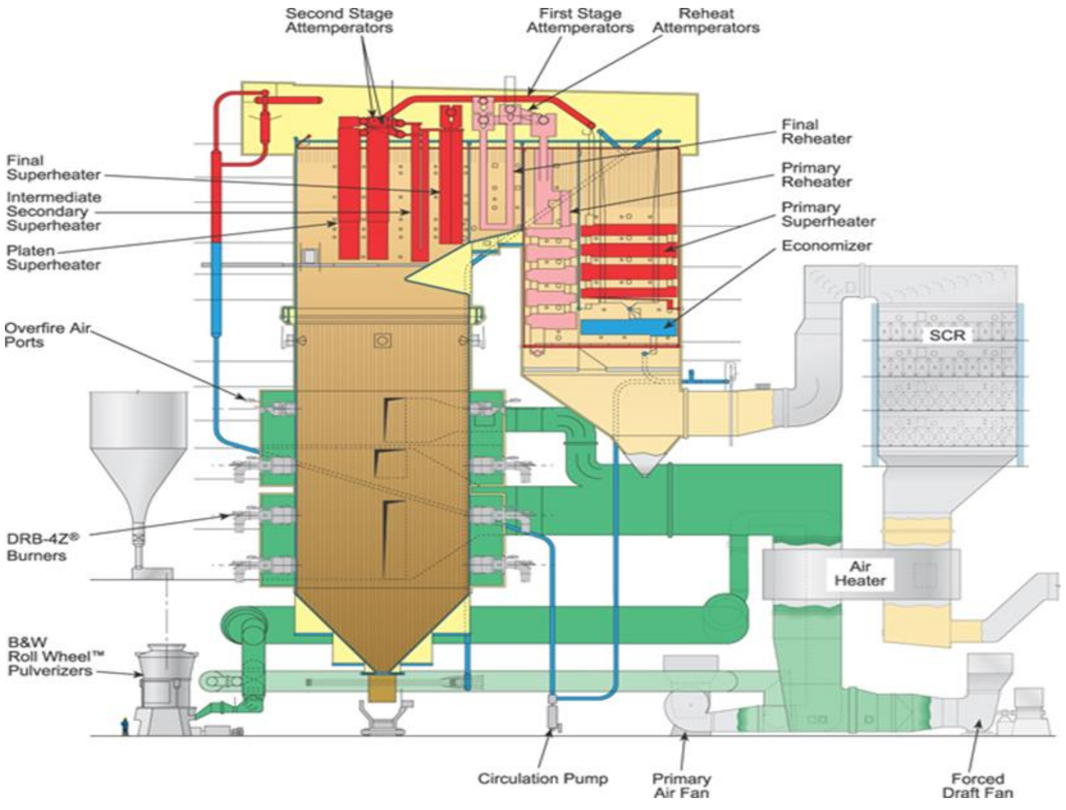
Solid Phase PROCESSING

Motivation and Project Objective

- Creep Strength Enhanced Ferritic Steels are workhorse alloys at lower end of elevated temperature applications in Thermal Power plants
  - Low-cost, low thermal expansion, high conductivity alloys for applications 570 C to 620 C (piping, waterwall / membrane wall, superheaters (SC), reheaters (SC))

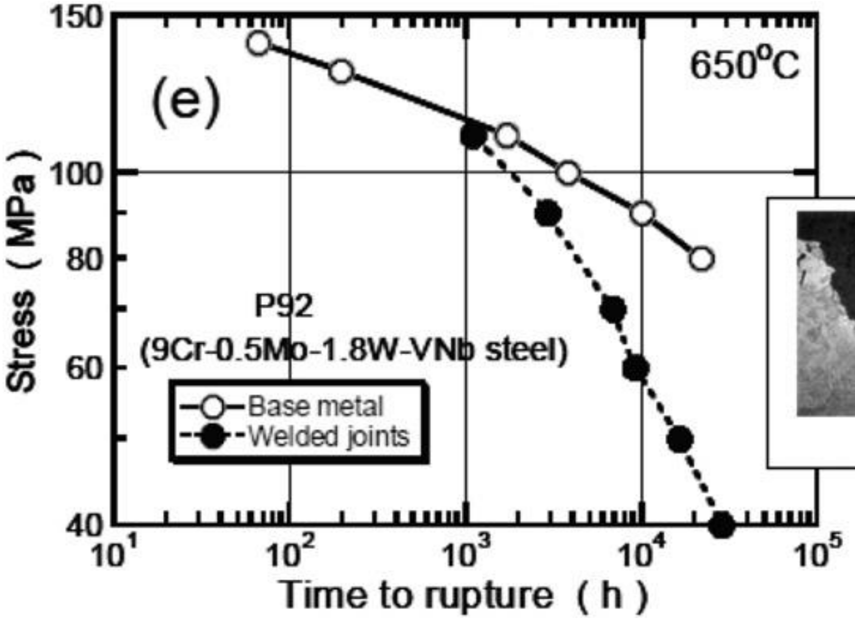
- Problem
  - Base materials have good creep performance, but they are compromised by welding
  - Microstructure instability over time leads to earlier than expected creep failure in the HAZ of weldments

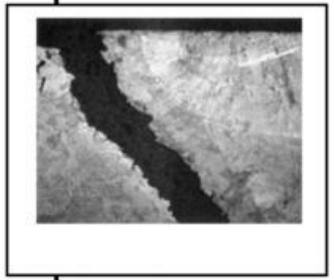


Performance issues with welded CSEF steels

Problem leads to difficulty in predicting service life

- WSRF can be as low as 0.50 at long creep times.
- This leads to greater allowances in pipe and tube wall thicknesses (higher material cost and heat transfer inefficiency)
- Forces reductions in operating temperature and/or pressure, which leads to a reduction in plant efficiency.





- Creep "softness" occurs in the fine grained heat affected zone adjacent to the weld nugget

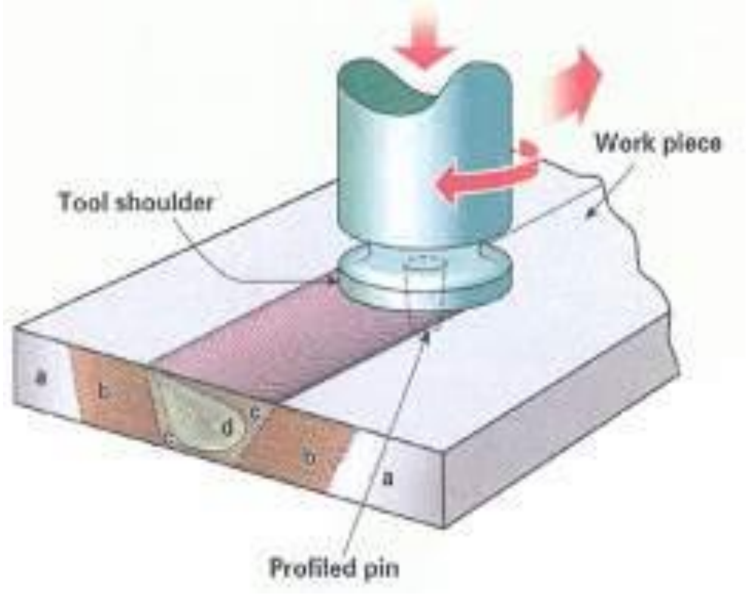
Can a new welding process create a microstructure that will show reduced long term microstructure degradation compared to conventional fusion weldments?

Parker J, International Journal of Pressure Vessels and Piping (2012), http://dx.doi.org/10.1016/j.ijpvp.2012.11.004

What is Friction Stir Welding ?

Solid-phase joining processes (no melting)

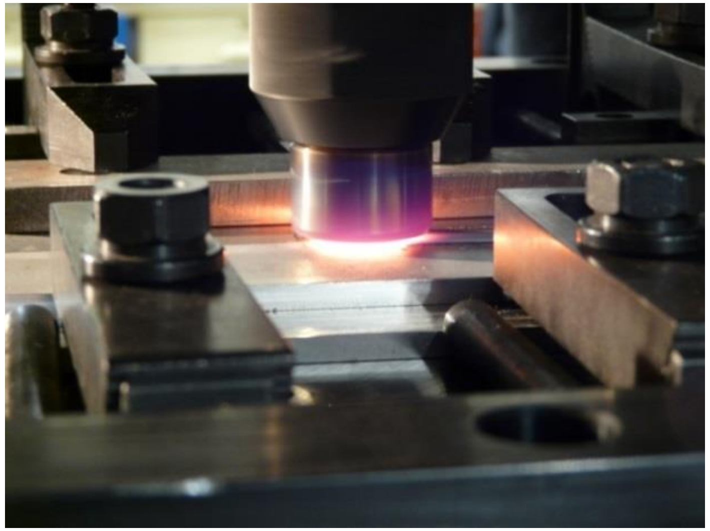
- Spinning, non-consumable tool is plunged into the surface of a material.
- Friction and plastic work energy heats the material sufficiently to lower the flow stress.
- When material softens, the tool is then translated along the joint line causing material in front of the pin to be deformed around to the back, and forged into the gap behind the traveling pin
- The resulting joint is characterized by:
  - Fine-grained “nugget” composed of recrystallized grains (d)
  - Surrounded by a mechanically deformed region (c) and a heat affected zone (b)



Tools for Steels

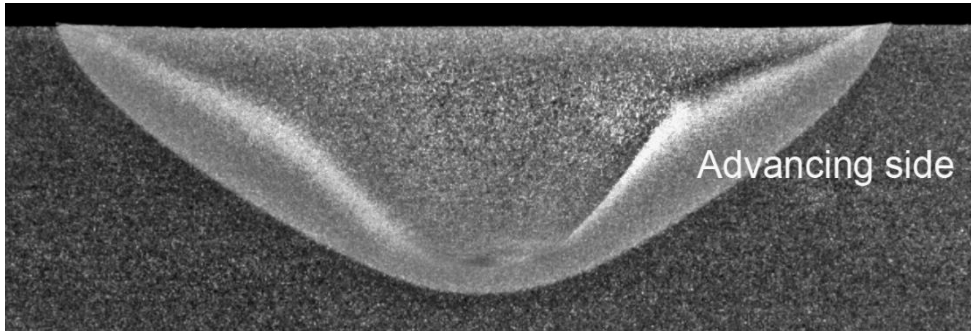
Steel Friction Stir Welding – State of the Art

- Can it weld the alloys? Yes
  - Almost all commercially relevant ferrous and nickel based alloys have had some degree of FSW welding development (High and low carbon steels, 9Cr, 12Cr, 20Cr steels, HSLA, super martensitic, DP, austenitic/ferritic stainless, Ni alloys 600, 718, 282, C22



- Can it weld the thicknesses? Some Limits, but tools are improving

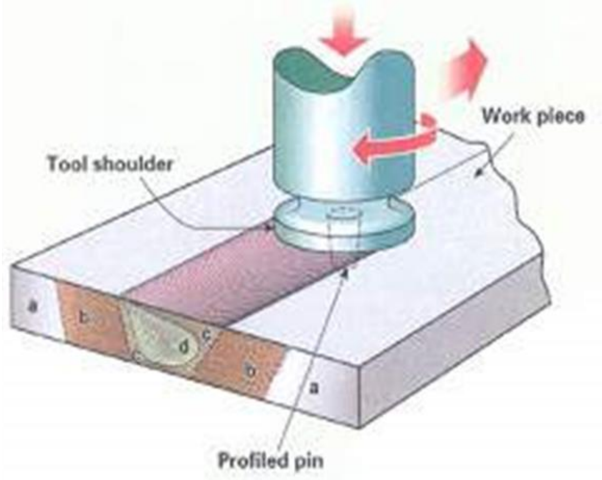
  - **We can now reach 0.375”(9.5mm) to 0.5” (13mm) with commercial tooling in most steels and Nickel alloys**
  - **Welds up to 0.67” single pass in HSLA steels have been demonstrated with PCBN/W-Re tooling**
  - **Welds up to 1.1” single pass in API 5L X70 steels have been demonstrated with W-Re tooling**



Typical macrostructure of a fully consolidated, indication-free FSW weld in Gr 91

Potential Benefits of Friction Stir Welding

- **Friction Stir Welding can introduce a significantly lower energy input to the weld than fusion welding**
  - Welds can be made at peak temperatures just above Ac3, between Ac1 and Ac3, or in some cases below Ac1 depending on process parameters
  - Lower energy results in lower peak temperature, small PAG, and smaller martensite lath width



- **FSW allows for much more control over the weld thermal cycle.**
  - Could this allow for a “tunable” carbide precipitation sequence?

- **FSW produces a unique weld microstructure where the nugget and the TMAZ has been strained above the austenite temperature.**
  - Can straining, a dislocation-rich substructure, or dynamic recrystallization promote fine MX, prevent carbide coarsening and the development of new phases over time?

Can the overall WSRF can be improved by using Friction Stir Welding?

Friction Stir Welding of Creep Strength Enhanced Ferritic Alloys

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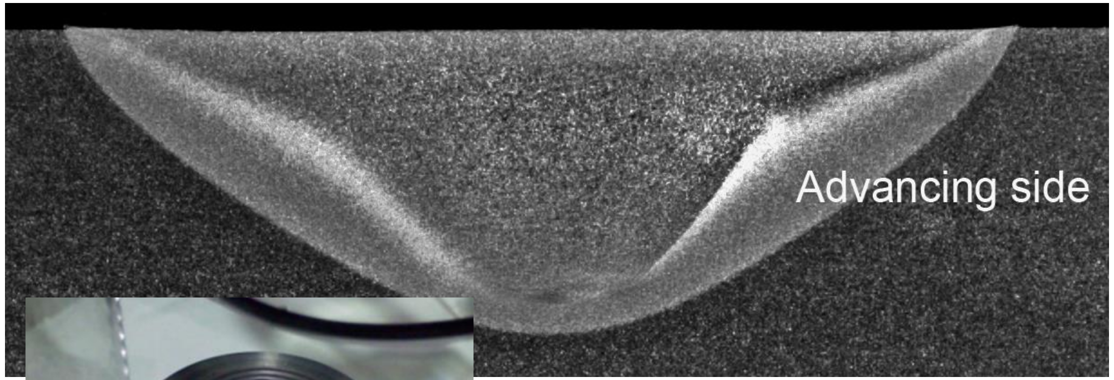
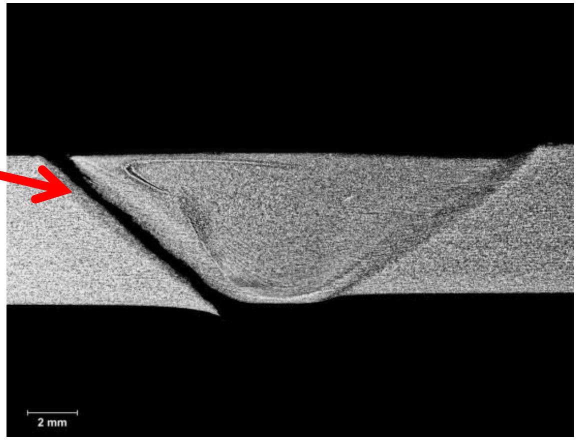
Solid Phase

- Gr91, P92, CPJ-7 have been shown to be friction stir weldable
- Defect free welds, 6mm to 10mm penetration can be made at a wide range of process parameters.
- Most welds achieved using 6-7mm Megastir Q70 or Q60 tools
- Processing Parameters
  - Welds made under temperature feedback controlled conditions at tool temperatures from 715-1000C
- Welds made in each of the alloys, and at 3 to 5 weld temperatures, depending on the alloy, were subjected to creep rupture testing

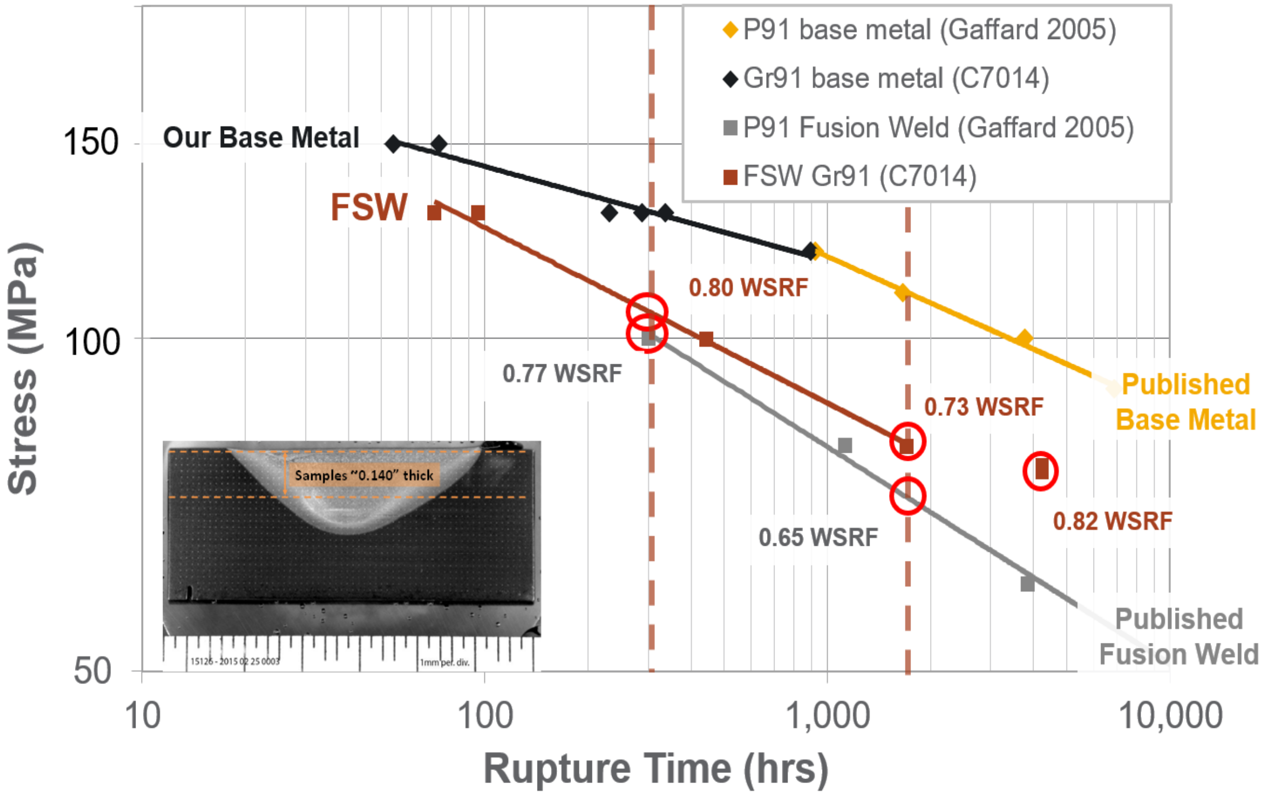


Creep Rupture Testing of Friction Stir Welds

<u>First observation</u>: Welds fail in the heat affected zone in a similar way to fusion welds with subtle differences



Gr91 Friction Stir Welds vs Fusion Welds in cross weld tensional creep at 625C

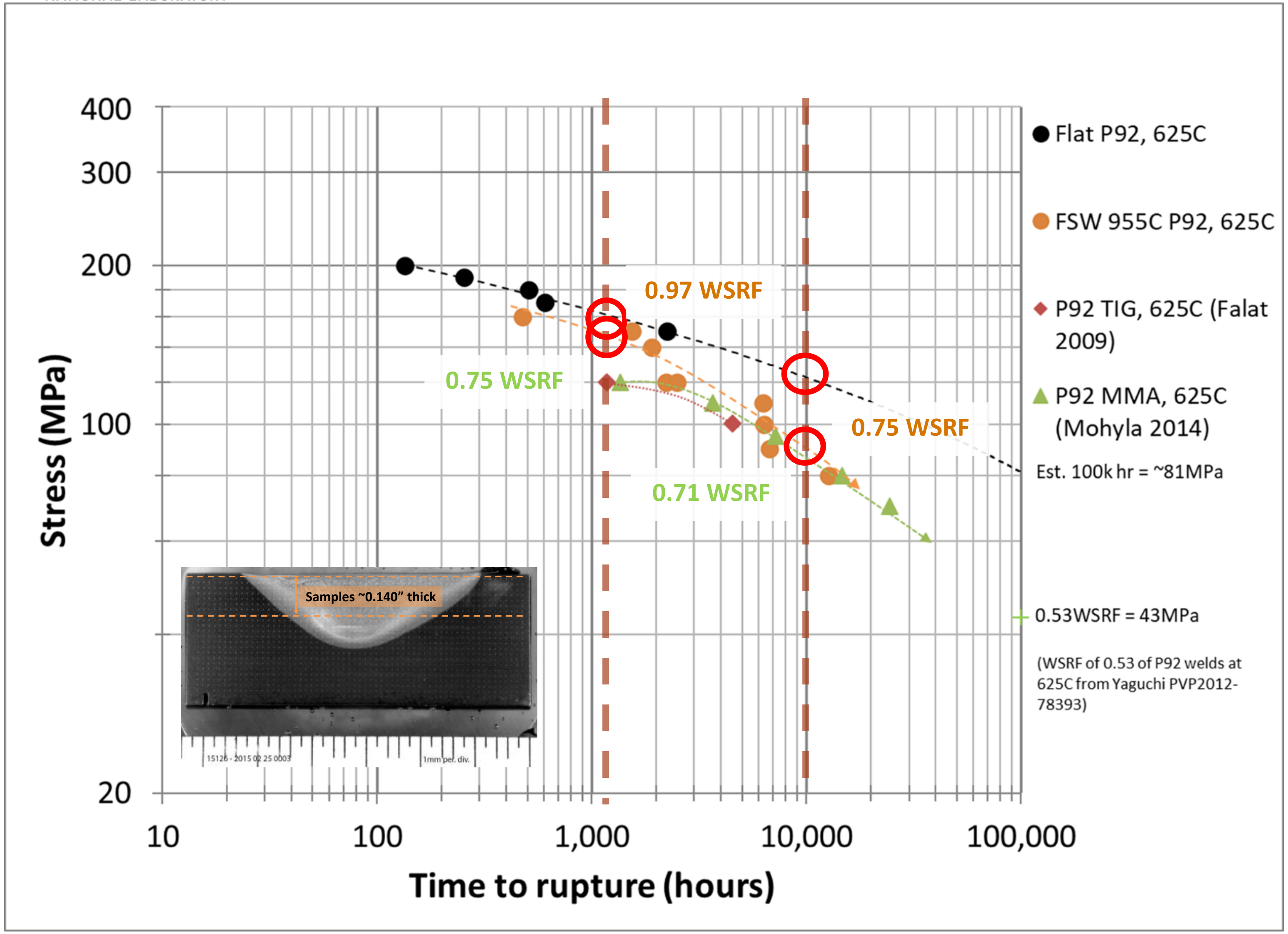


WSRF improved from 0.77 for fusion welds to 0.80 for FSW at high load, low time

At longer times (4000 hrs) FSW performance is also better at 0.68 for fusion welds and 0.82 for FSW

- **FSW weld in Gr91 shows ~2X improvement in creep life over fusion welds**

Grade 92 625°C Transverse Creep



Same is true for P92

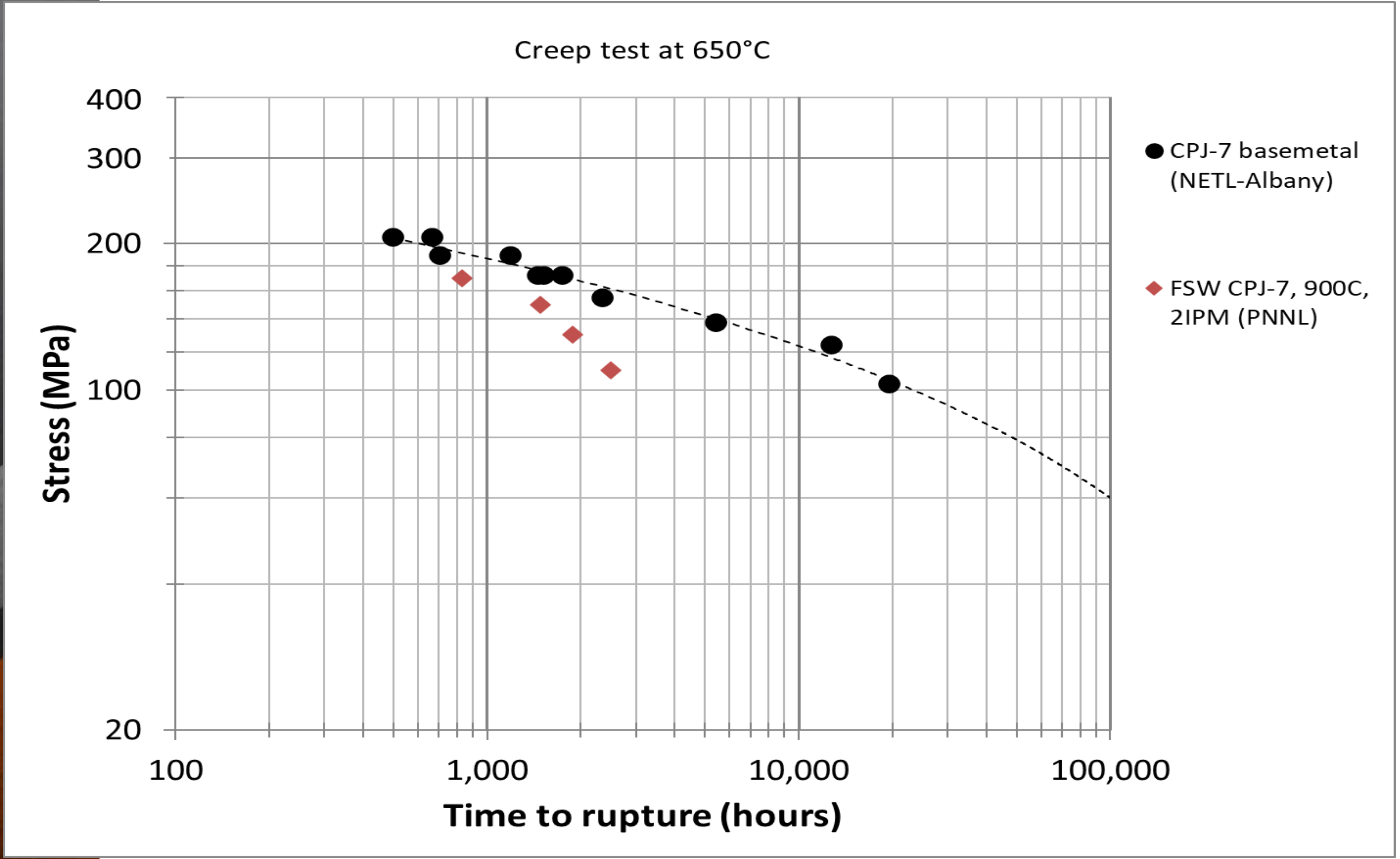
High load creep performance is very good

WSRF improved from 0.75 for fusion welds to 0.97 for FSW at high load, low time

(Base load plant might have to load cycle due to renewables!)

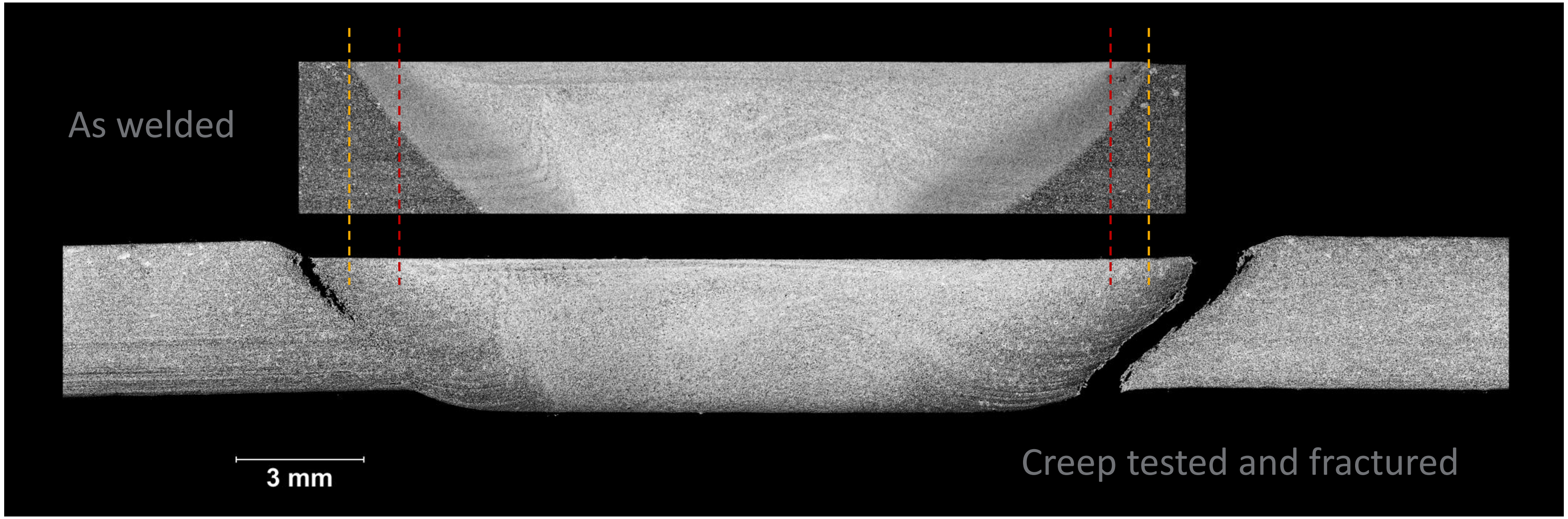
At longer times (10,000 hrs) FSW performance is closer to fusion welds

CPJ-7 625°C Transverse Creep



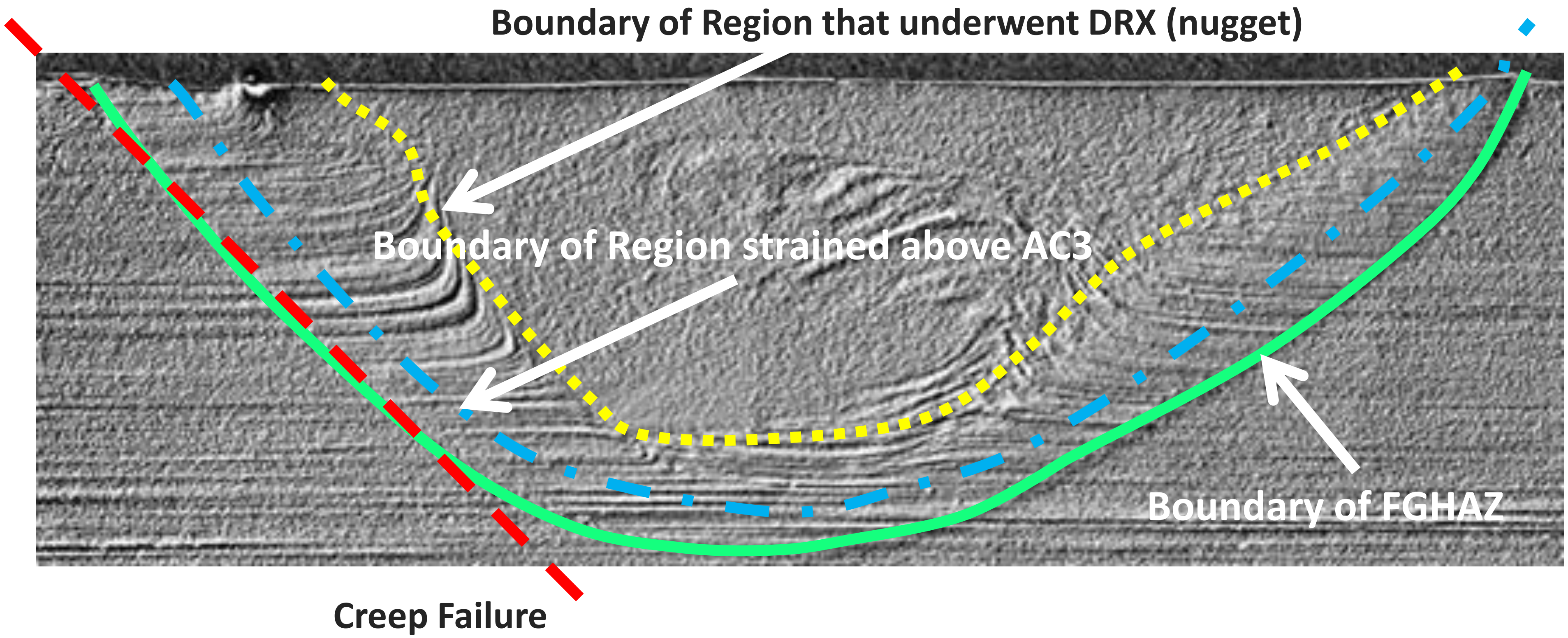
- FSWs in CPJ-7 behave similar to P-92
  - High load performance is very good compared to base metal
  - No data yet on fusion welded CPJ-7

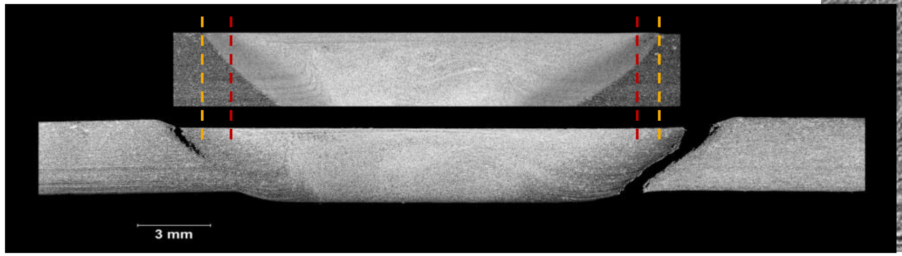
Creep cavitation begins in the FGHAZ very close to the ICHAZ, very close to the base metal HAZ interface



- Macrograph comparison of welded specimen and after creep fracture
- The creep failure appears to occur away from the nugget boundary, right on the edge of the HAZ, near the FGHAZ/ICHAZ boundary

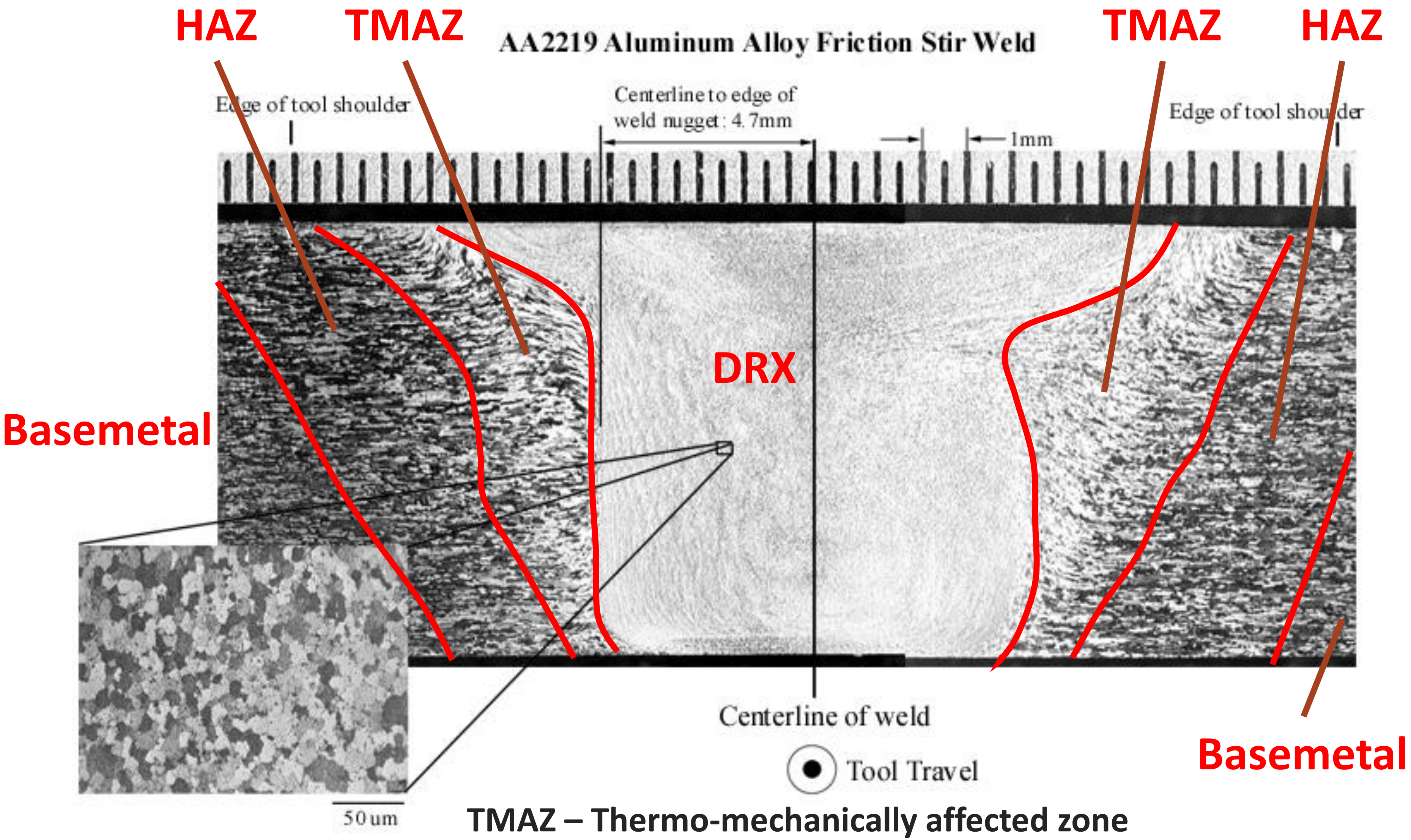
Location of failure relative to strained region as revealed by DIC*





*Differential interference contrast

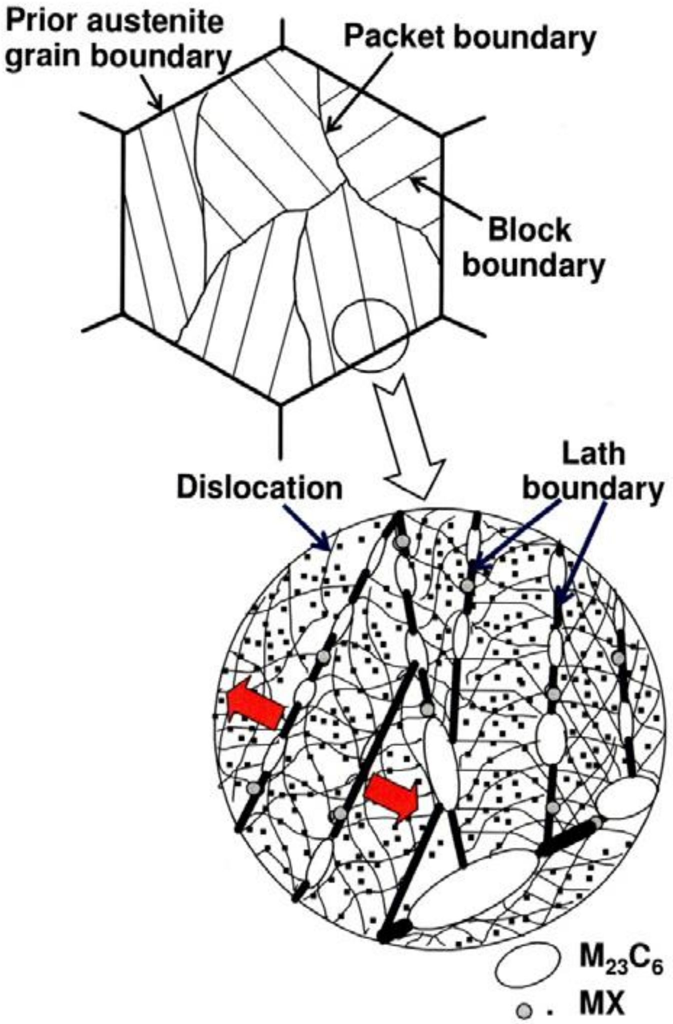
The TMAZ is unique to FSW



TMAZ – Thermo-mechanically affected zone

What drives differences in creep in these alloys ?

- Fine carbides and carbonitirdes ($M_{23}C_6$ and MX) precipitates play a critical role in creep strength.
- Where these precipitates are located and their size are key parameters.
- Is there a difference in the distribution of these important carbides between FSW and melt based welding processes?



Hawk,JA, Jablonski,PD,2018, CREEP RESISTANT 9%CR STEEL FOR BOILER AND TURBINE APPLICATIONS
Proceedings of the 2018 ASME on Elevated Temperature Applications of Materials for Fossil, Nuclear and Petrochemical Industries
ETAM2018
April 3-5, 2018, Seattle, WA, USA

FSW weld have a different carbide precipitation sequence and different amounts of carbides, esp MX

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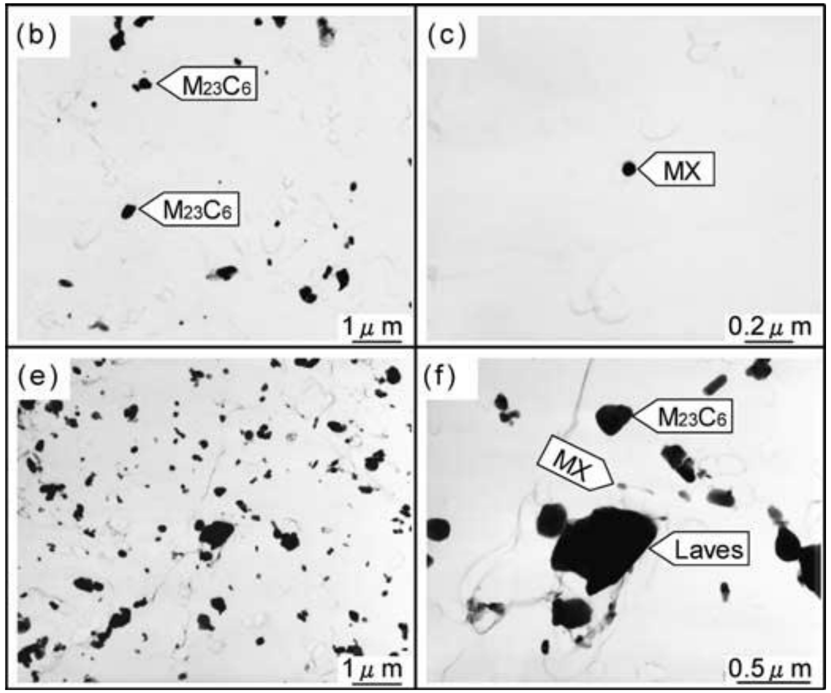
Solid Phase PROCESSING

HAZ of Fusion Welded P91



T. Watanabe et al. / International Journal of Pressure Vessels and Piping 83 (2006) 63–71

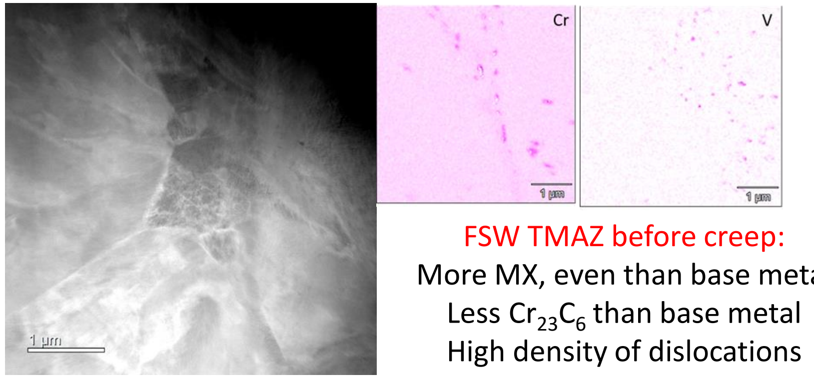
Before Creep testing

Fusion weld HAZ before creep shows very low MX

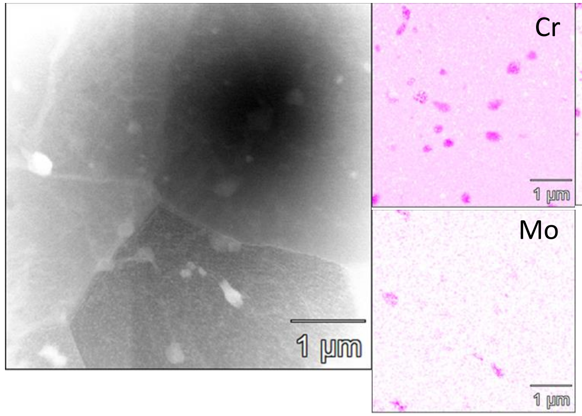
After creep testing

Fusion weld HAZ after creep shows low MX and Fast coarsening of M23C6 and Laves phase

TMAZ of Friction Stir Weld in P91



FSW TMAZ before creep:
More MX, even than base metal
Less $Cr_{23}C_6$ than base metal
High density of dislocations



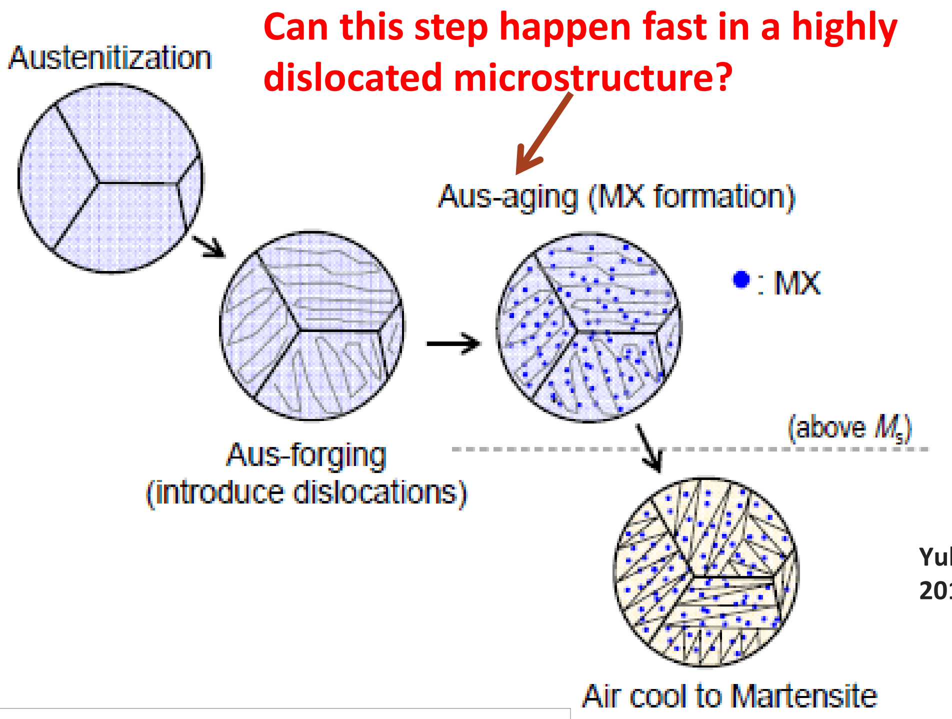
FSW TMAZ After creep: coarsening of $Cr_{23}C_6$ and Laves but more MX

The higher density of MX in FSW TMAZ prior to and after creep test could be a "good player" in making the FSW TMAZ less susceptible to Type-IV failure than that in a fusion weld

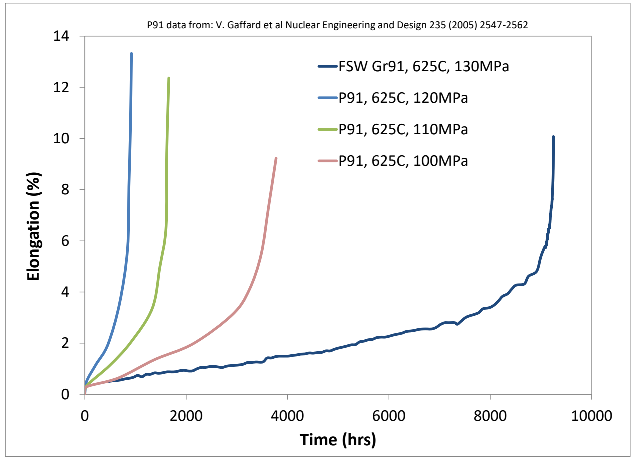
Why is there a high density of MX in the TMAZ of a FSW weld?

Is this why FSW better?

- Strain induced dislocations from FSW in the austenite phase field may be nucleation sites for MX and may help to promote a dispersed MX distribution prior to Martensite start.
- This may be the difference between a FSW and a fusion weld. There is coarsening of Cr23C6 and nucleation/coarsening of Laves phase in the HAZ, just like in a fusion weld,
    - But, the higher density of MX in FSW HAZ prior to and after creep test could be a “good player” in making the FSW HAZ less susceptible to Type-IV failure than that in a fusion weld.
- It is also possible that the highly dislocated microstructure even allows for MX nucleation in the solutionized nugget during service life (explanation of the excellent weld nugget-only tests during creep).



Yukinori Yamamoto, et al., 2014



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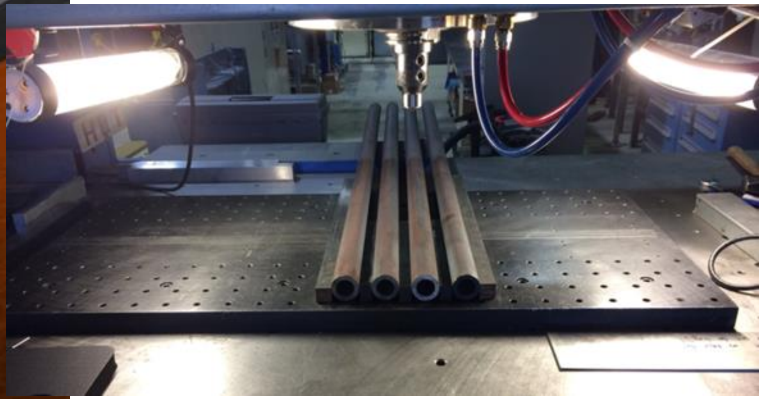
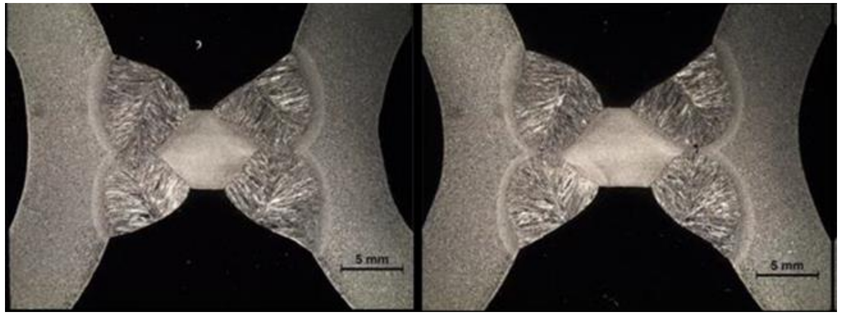
Next Steps- Putting FSW to the test

Solid Phase
PROCESSING

- Last task of the project is to show commercial potential by using FSW to fabricate a prototypic part – a P-92 membrane wall

- Possible Advantages
  - Better creep performance of weldments
  - Lower distortion of panel wall from lowered residual stresses during welding
  - Better properties in fatigue
  - Less weld penetration into tube wall and so less property depression in wall section

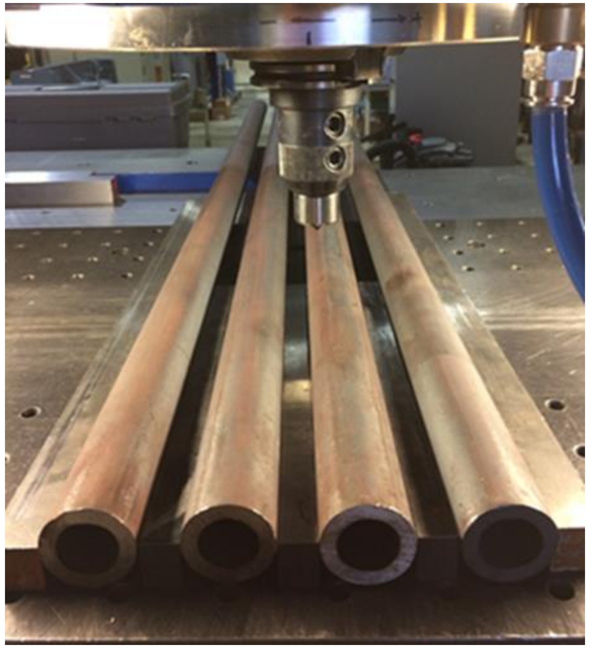




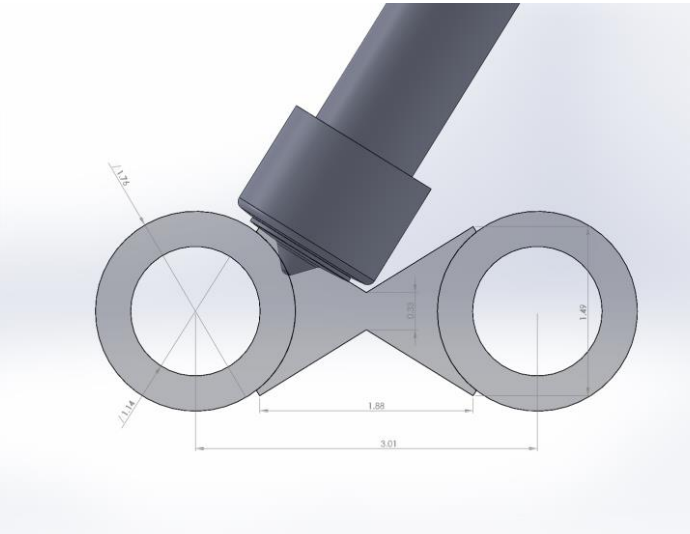
Membrane Wall Welding

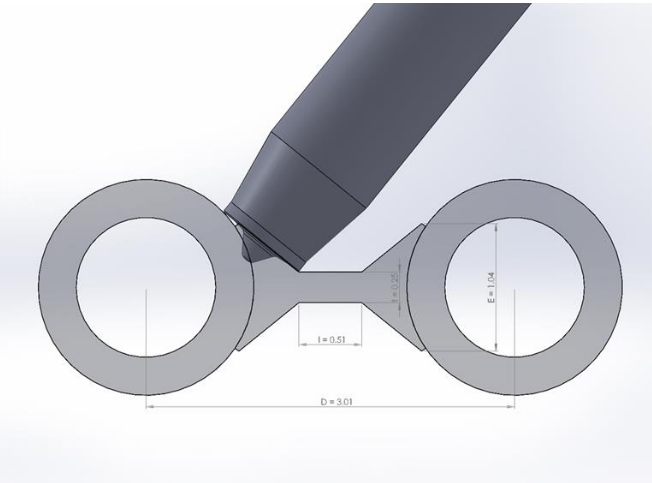
Approach

- Weld four lengths of ASTM A213-T92 tube (Vallourec, ~62" long x 1.75" OD x 0.3" wall thickness) from GE/Alstom Power Inc. to Grade 91 webbing strip
- Weld development for the Gr91 web to P-92 tube (tool design, weld process development, microstructure, hardness)
- Two FSW tool types will be utilized:
  - W-Re (W – 4HfC – 25 Re)
  - PCBN (70PCBN – 30 W-Re



- Measure distortion during fabrication





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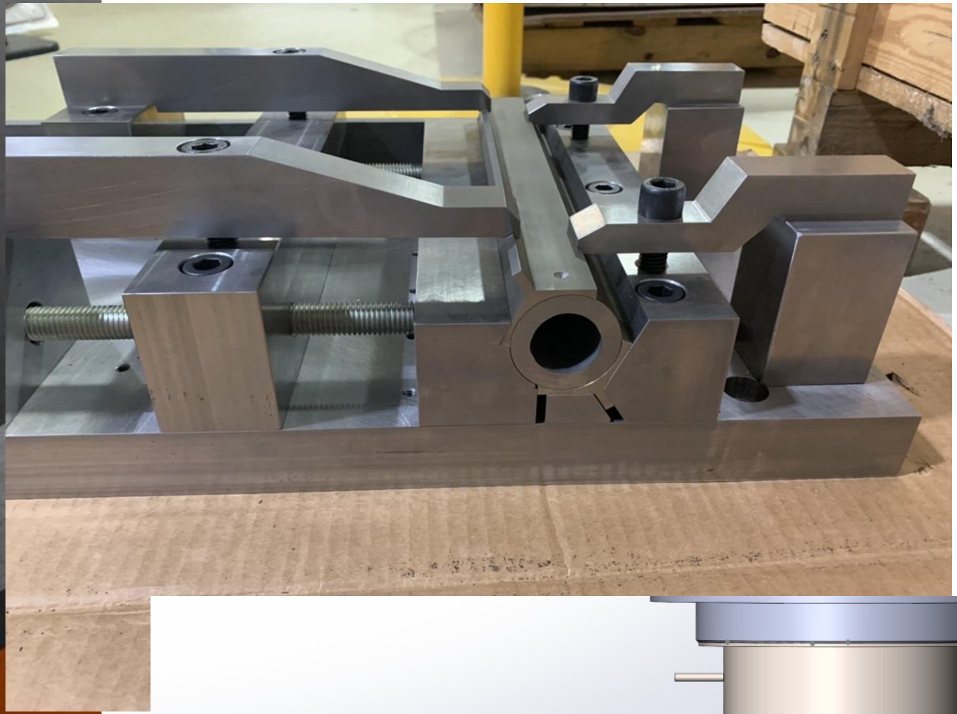
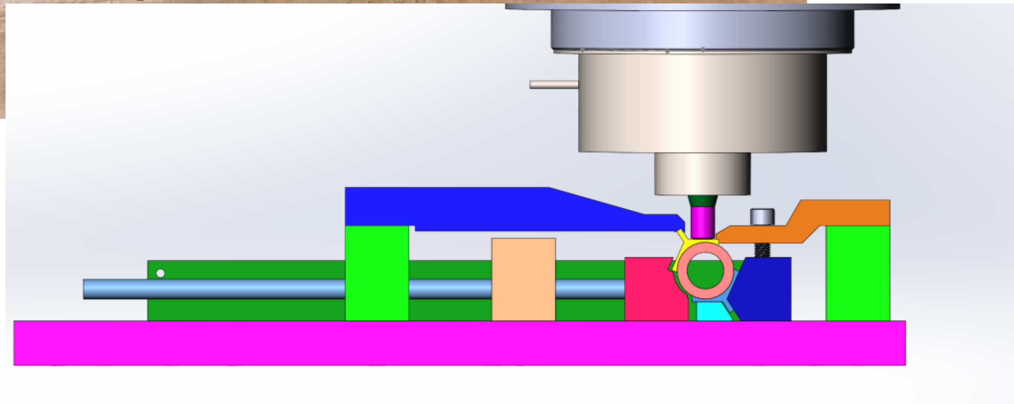
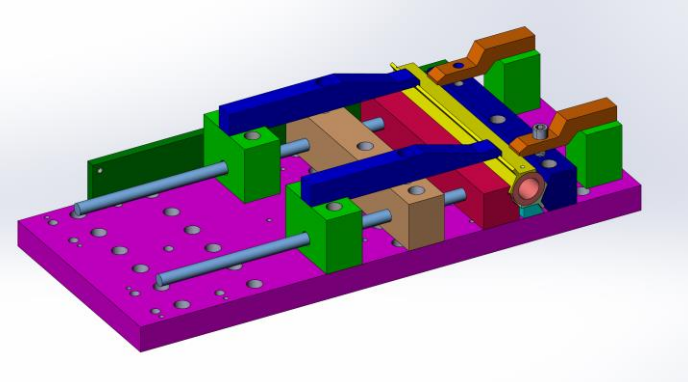
Membrane Wall Welding

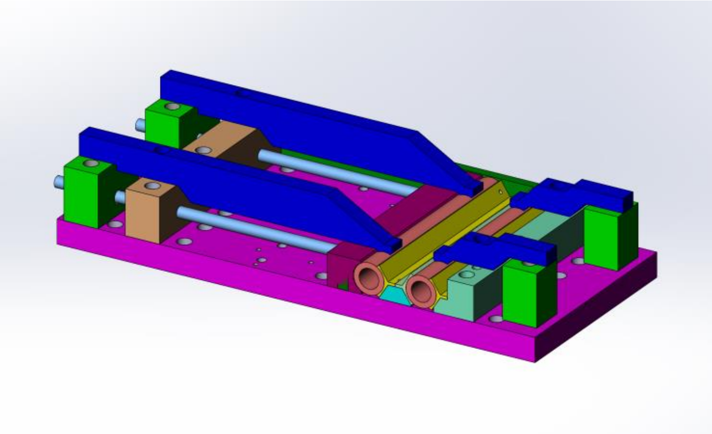
Solid Phase
PROCESSING

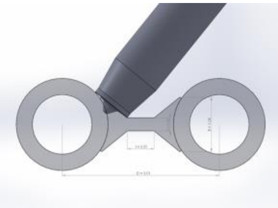
- Fixturing has recently arrived and Friction Stir welding will begin to fabricate “short section” multi-tube membrane wall prototypes

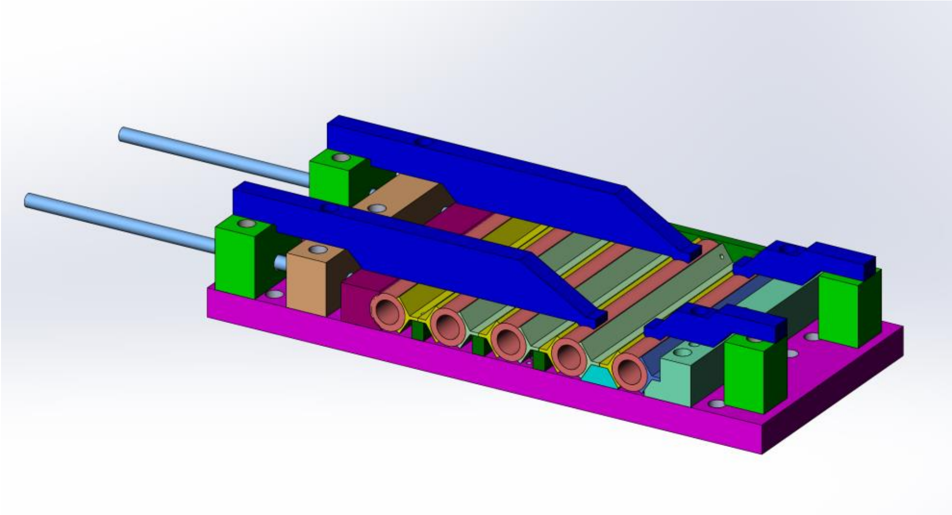






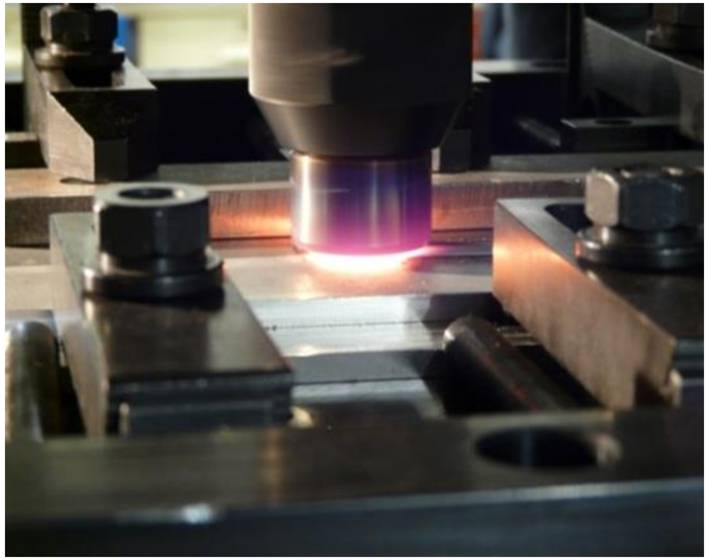


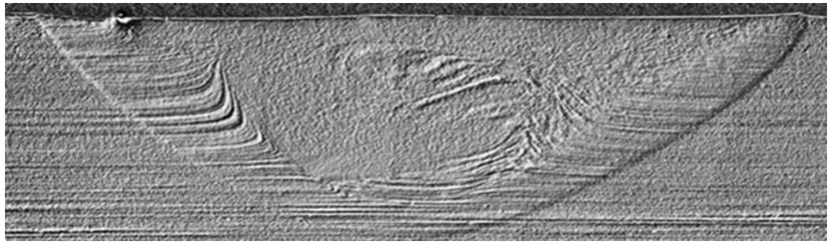




Conclusions

- CSEF steels are Friction Stir weldable
- Creep performance is very good, both of the weld metal and in cross-weld tension
  - FSW in P91 can reach a WSRF at 625C of 0.73 to 0.82 over 4000 hrs, significantly higher than fusion welds (0.65)
  - FSW in P92 and CPJ-7 show excellent WSRF at high load, but the performance trends toward fusion weld performance towards lower loads and long times 10,000 hrs
- It is possible that WSRF can be raised by more than 10% from fusion welded equivalents, esp for high load creep
- **FSW allows for enough knobs to be turned in the process to customized heat input**





It may be possible with FSW to follow a path through thermo-mechanical space that will leave the weld region, and especially the strained part of the HAZ, with a customizable carbide distribution appropriate for better creep resistance, and much closer to the parent microstructure than if it is fusion welded.

Acknowledgment

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number: FWP 66059
Office of Fossil Energy
National Energy Technology Laboratory
Vito Cedro - Technical Manager

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Gr91 FSW weld metal only (just nugget material with no PWHT) has fantastic creep performance, even compared to base metal

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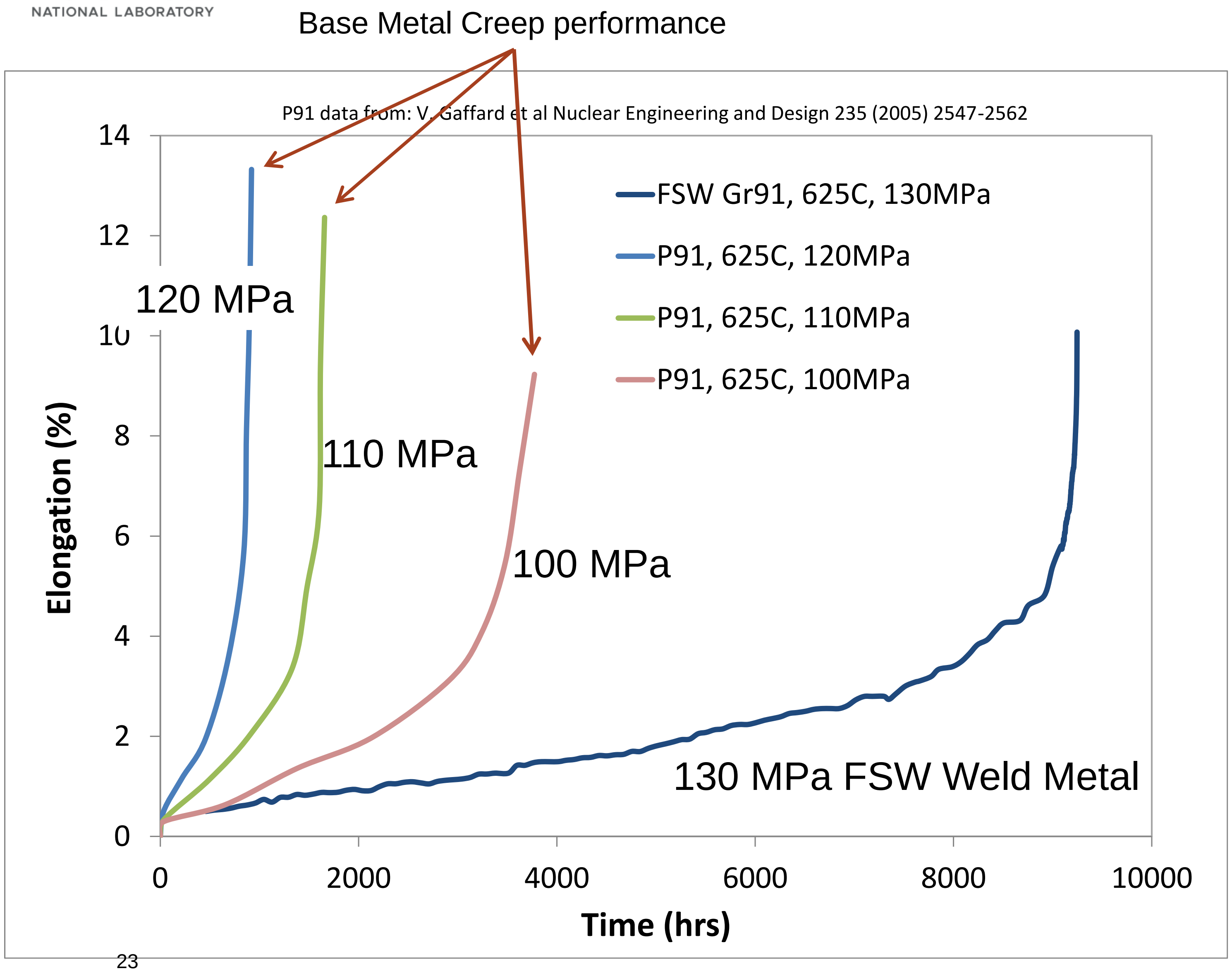
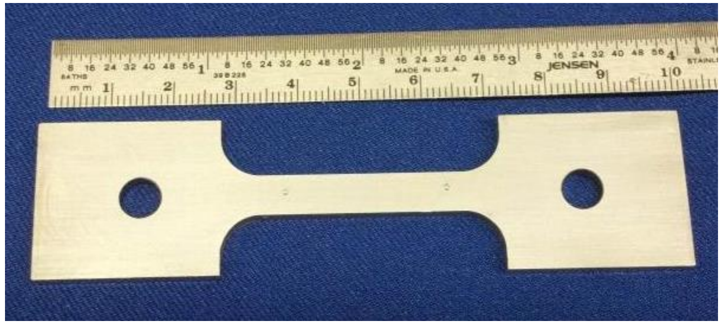
Solid Phase PROCESSING





- FSW nuggets have much better creep performance than even base metal
- Could be because weld nugget is fully solutionized. Fine MX carbides nucleate and grow during creep testing