Solid State Joining of Creep Enhanced Ferritic Steels

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Pittsburgh, PA

Improving the performance of welded Creep Strength Enhanced Ferritic Alloys

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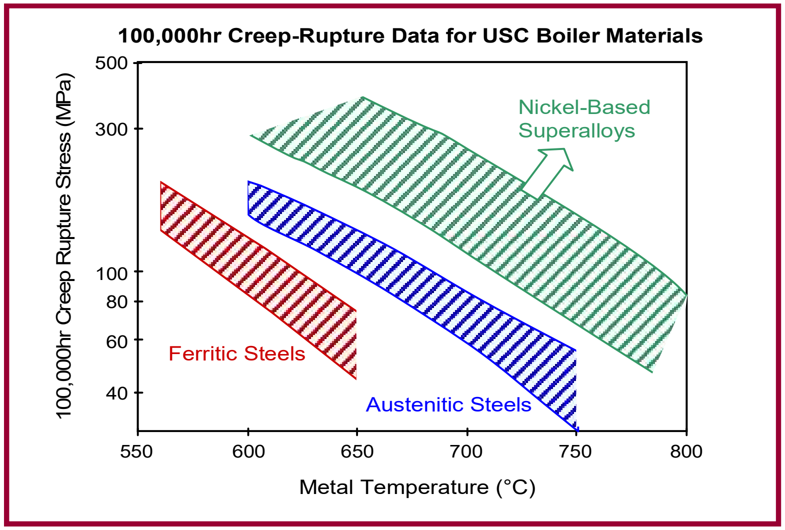
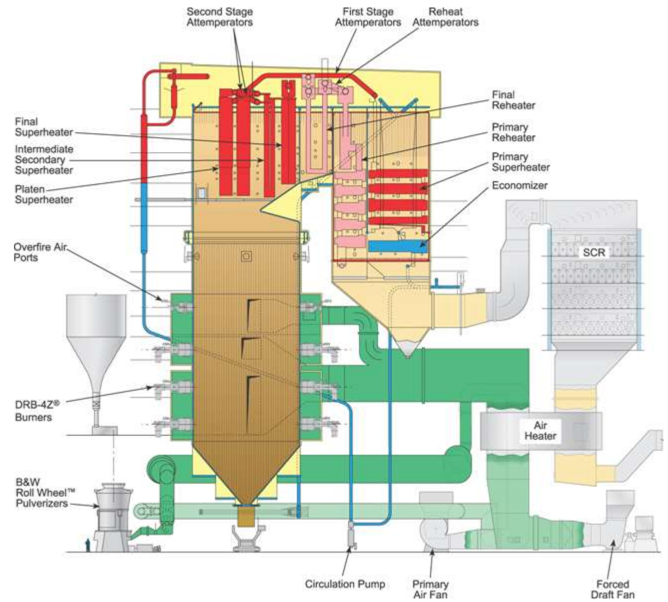


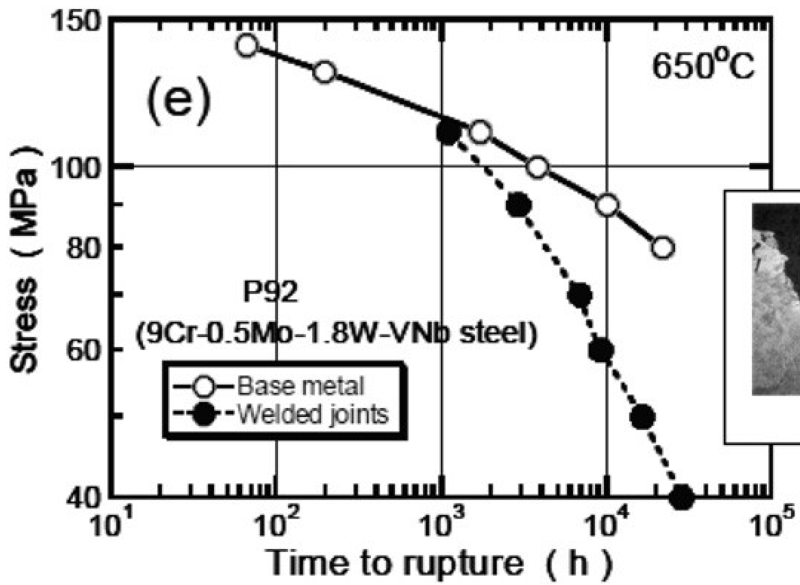


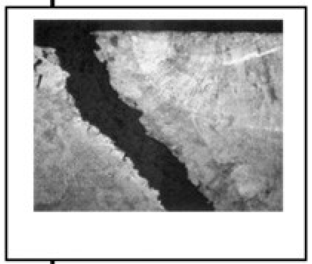
- Creep Strength Enhanced Ferritic Alloys
  - Low-cost, low thermal expansion, high conductivity workhorse alloys for applications 570 C to 620 C (piping, waterwall / membrane wall, superheaters (SC), reheaters (SC))
- Problem
  - Base materials have good creep performance, but they are compromised by 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

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

Motivation for this Project

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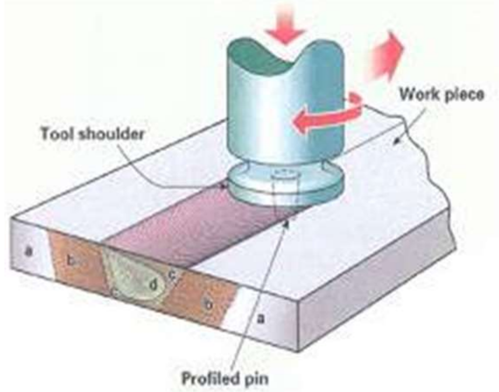
Can a new welding process create a microstructure that will show a reduced long term microstructure degradation compared to conventional fusion weldments?

- Solid state welding techniques, like Friction Stir Welding, can introduce a significantly lower energy input to the weld than fusion welding.
  - Potentially creating weldment peak temperatures only just above Ac3, between Ac1 and Ac3, or in some cases below Ac1.
  - Lower energy results in lower peak temperature and 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 or prevent carbide coarsening or the development of new phases over time?



FSJ was invented and patented by TWI, Ltd. in 1991

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

Objective

- Demonstrate that solid phase welding (ie FSW) can outperform an equivalent fusion weld in long term performance (creep, creep-fatigue)

- Demonstrate scale up of the welding process on a prototypic part of interest to the Fossil Energy community

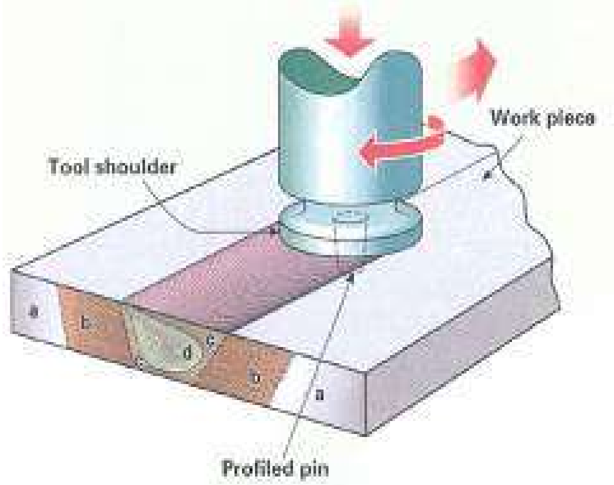
Approach

- Develop a robust welding process in three ferritic-martensitic alloys, and show creep rupture performance through testing at 625C
  - P91
  - P92
  - CPJ-7
- Fabricate a 4 foot long, three tube section of a membrane wall using FSW with P92 tubes and a Gr91 tab connector

What is Friction Stir Joining ?

Solid-phase joining processes (no material 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)



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Tools for Steels

Steel Friction Stir Welding – State of the Art

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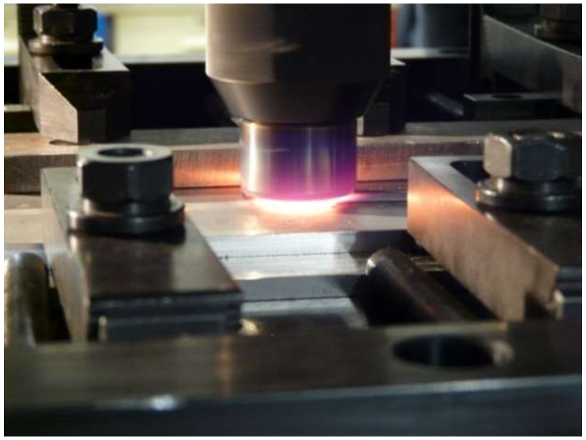
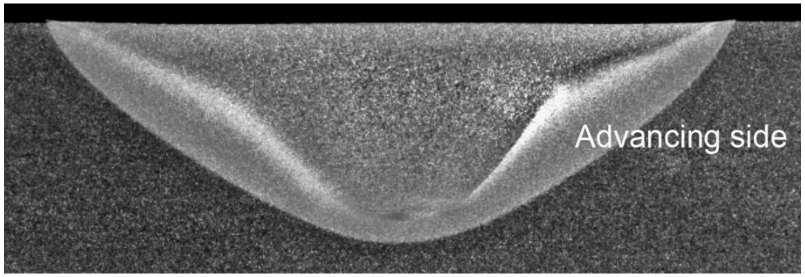
- Can it weld the alloys? Yes
  - Almost all commercially relevant ferrous and nickel based alloys have had some degree of welding trials (High and low carbon steels, HSLA, super martensitic, DP, austenitic/ferritic stainless, Ni alloys 600, 718, 282, C22

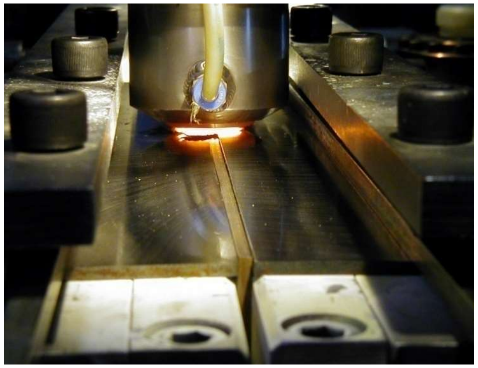


- Can it weld the thicknesses? Some Limits, but tools are improving
  - **We can now reach 0.375"(9.5mm) to 0.5" (13mm) with commercial tooling in most steels and Nickel alloys**
  - **Welds up to 0.67" single pass in HSLA steels have been demonstrated with PCBN/W-Re tooling**
  - **Welds up to 1.1" single pass in API 5L X70 steels have been demonstrated with W-Re tooling**

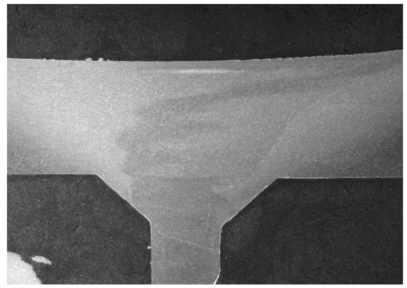


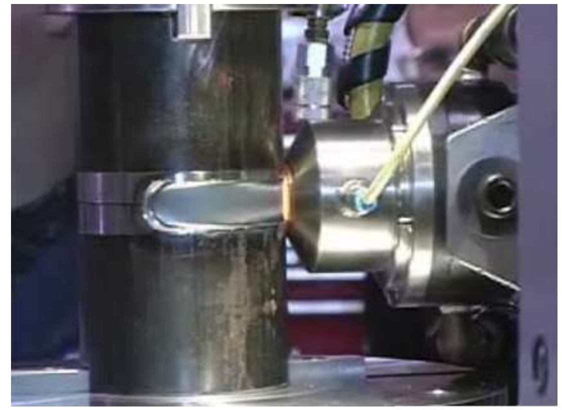
Typical macrostructure of a fully consolidated, defect-free steel FSW weld in Gr 91

Can it weld the geometries?



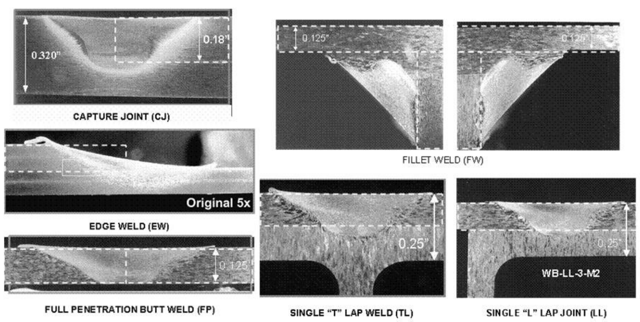
Megastir, Inc.





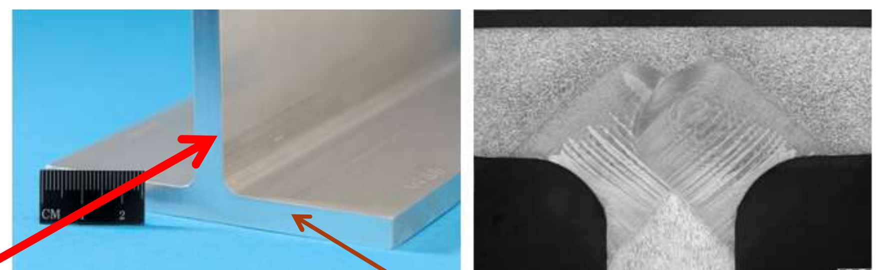
Megastir, Inc.

Circumferential butt weld on pipe and tube



Arbegast 2004

Butt, Lap, Fillet and T Joints



a) b)

TWI Technology Centre

Membrane wall application?

Imagine this was a tube

Friction Stir Welding of Gr91, P92, CPJ-7

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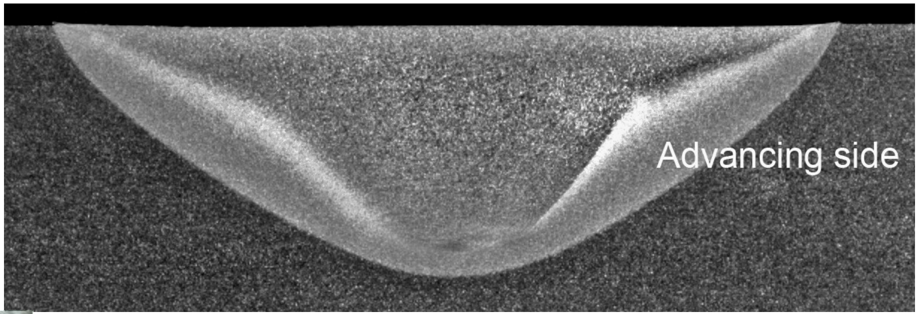
- Gr91 is easily FSW welded.
- Defect free welds, 6mm to 10mm penetration can be made at a wide range of process parameters.
- 6-7mm FSW tool "Q70" (supplier: MegaStir, Inc.)
- Processing Parameters
  - Welds made at tool temperatures from 715-1000C
- Analysis
  - Creep
  - Hardness
  - Microscopy



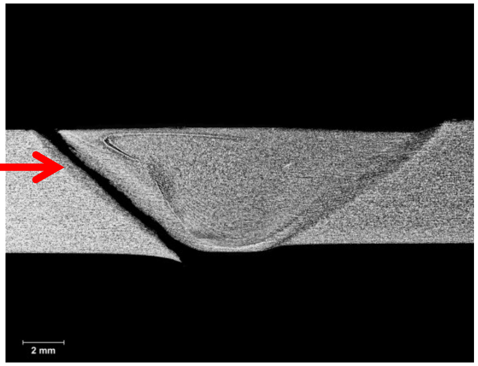
Current Project Status

FSW of P-91 and creep testing- Completed
FSW of P-92 and creep testing In progress
FSW of CPJ-7 and creep testing – In progress

Creep Rupture Testing

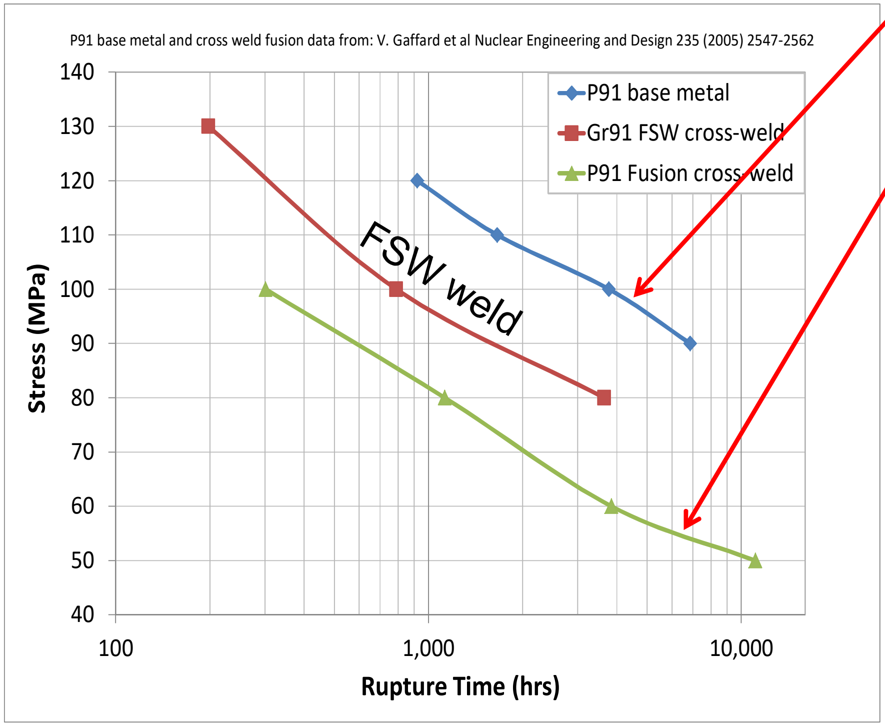
- Weld process development focuses on making temperature controlled welds at 4 or 5 different temperatures from 700C to 950C.
- Each weld condition is tested at 80, 100, 130 Mpa, which leads to creep failure generally below 2000 hrs.
- Creep Rupture Testing is conducted on constant load creep frames at 625 C
- Currently testing P92 above 2000 hrs

FSW shows creep failure that looks similar to a fusion weld



Motivation – Initial Creep Results From applying FSW to Gr91 alloys

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



P91 base metal – normalized and tempered

P91 (N&T) welded by submerged arc then PWHT 2 hr 760C

- **FSW weld in Gr91 shows ~3X improvement in creep life over PWHTed fusion weld**
- **Design knockdown in strength is 32% for SMAW with PWHT (WSRF 0.68) vs. 18% for FSW (WSRF 0.82)**

Grade 91 625°C Transverse Creep

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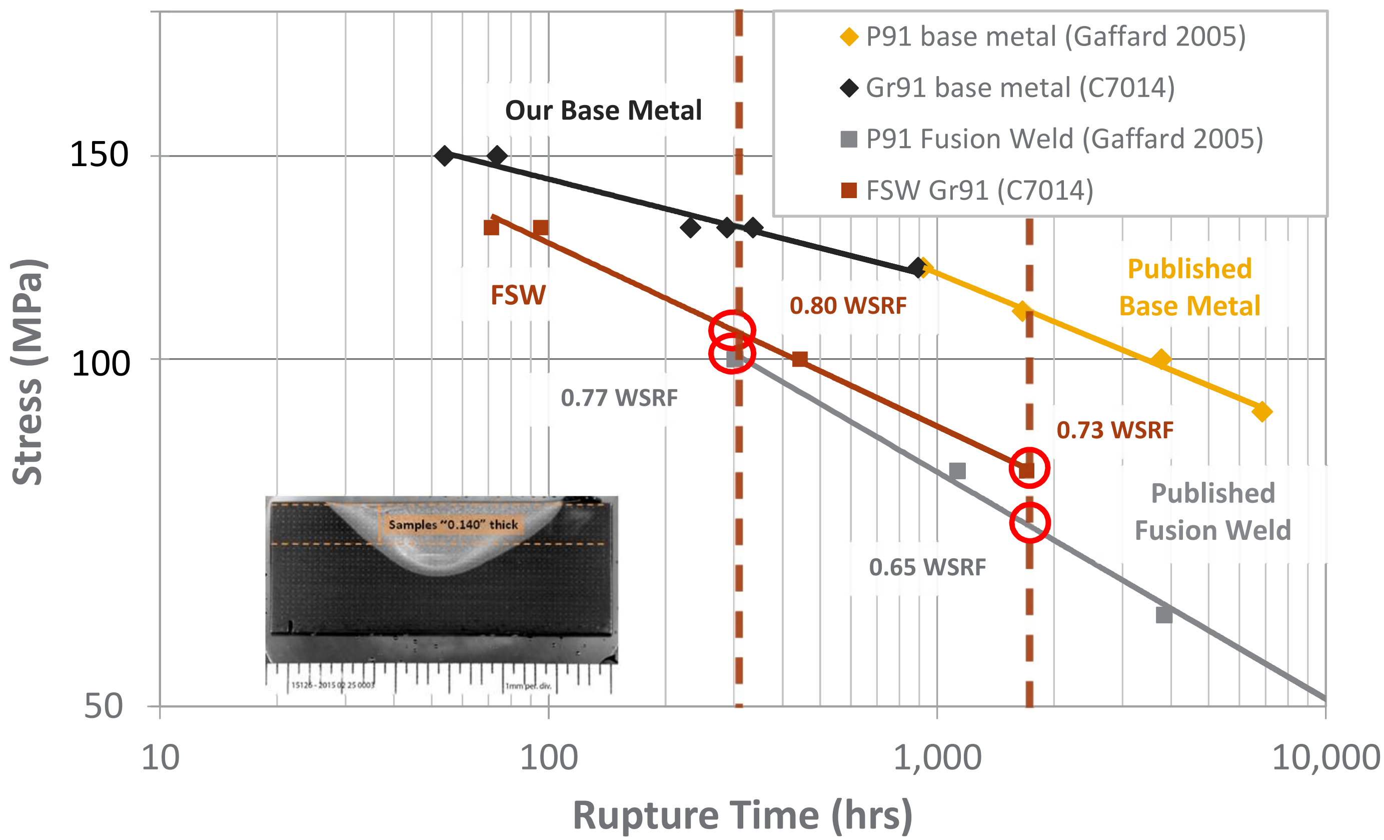
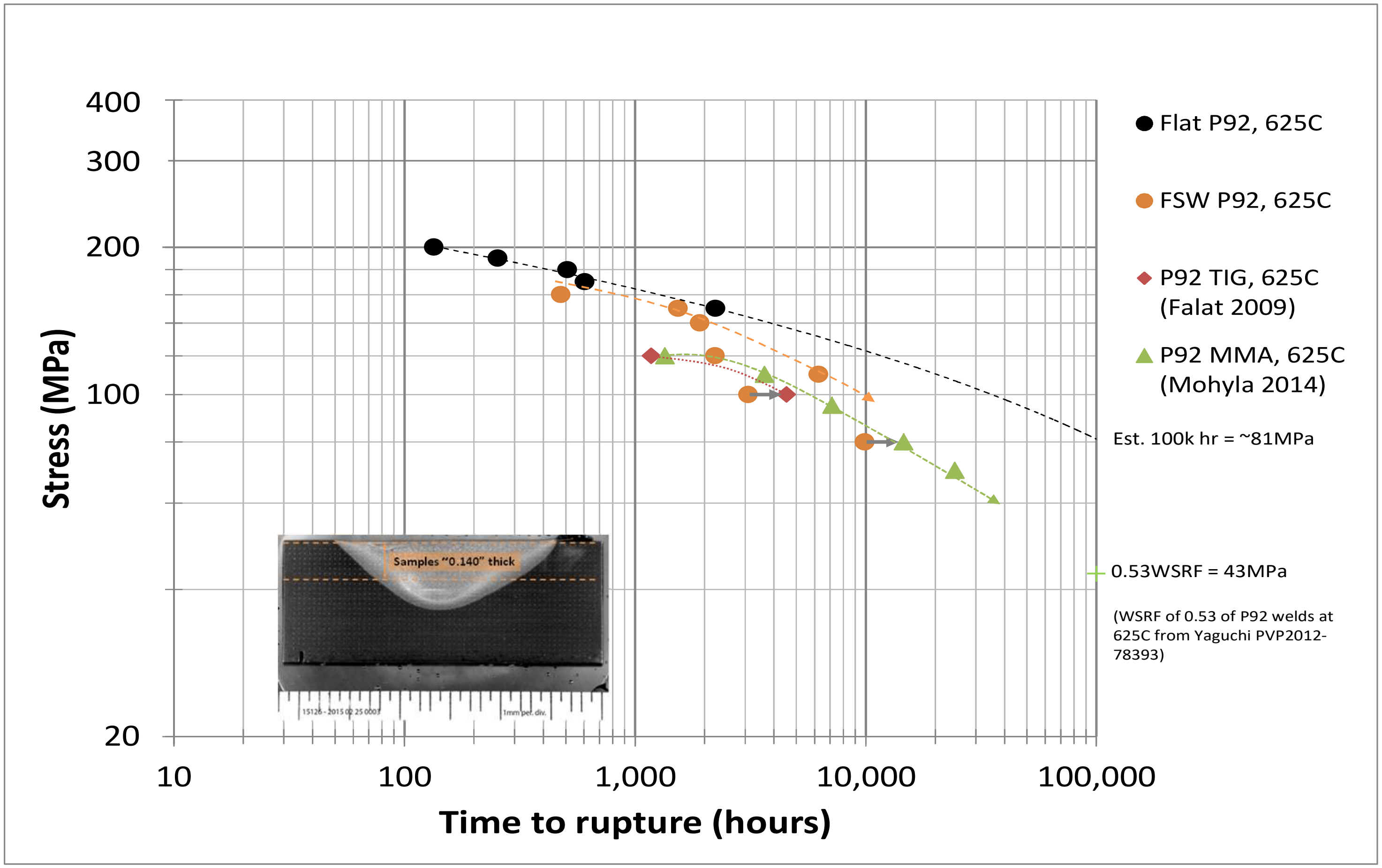


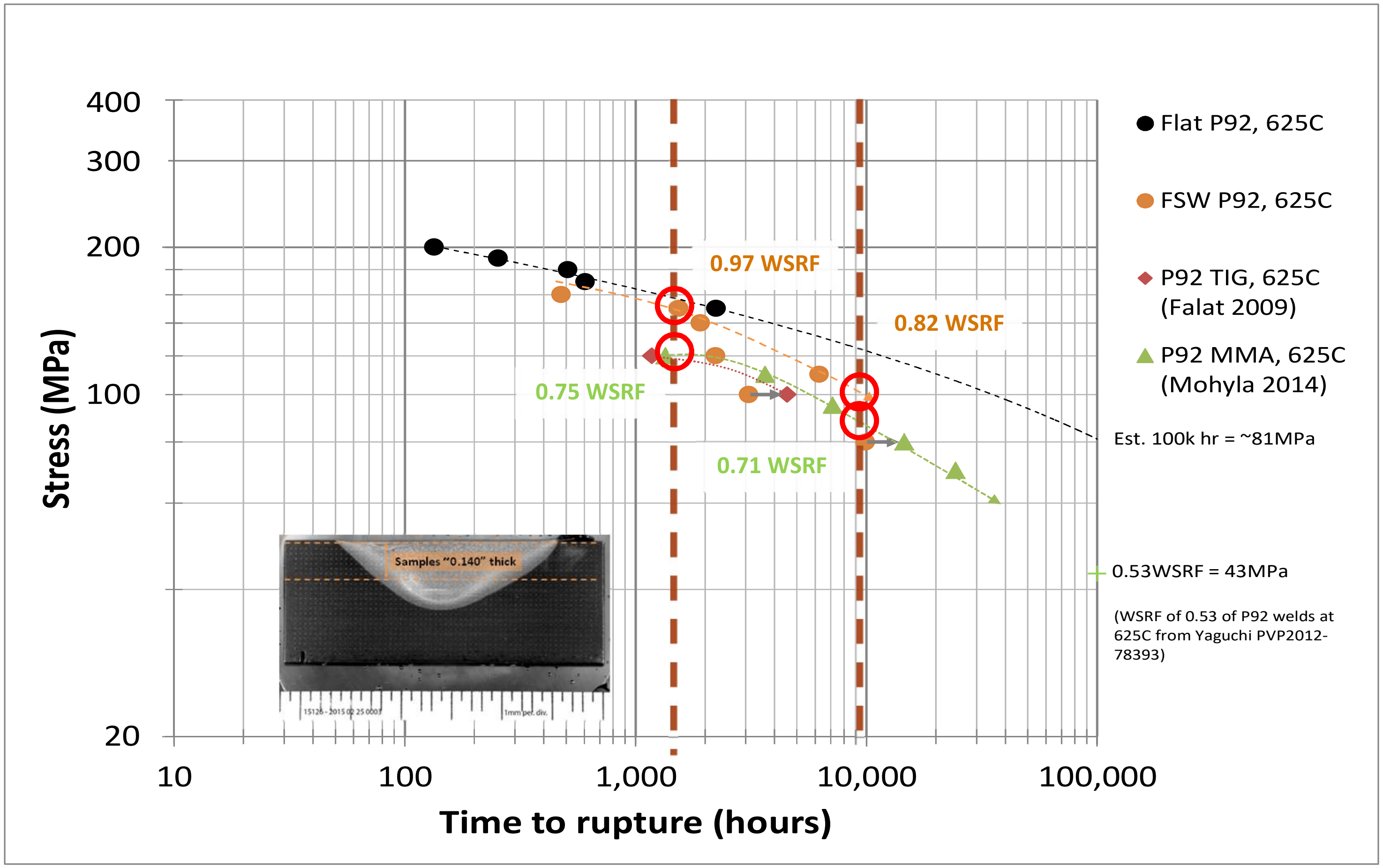
- Our results indicate increase in creep life using FSW

Grade 92 625°C Transverse Creep



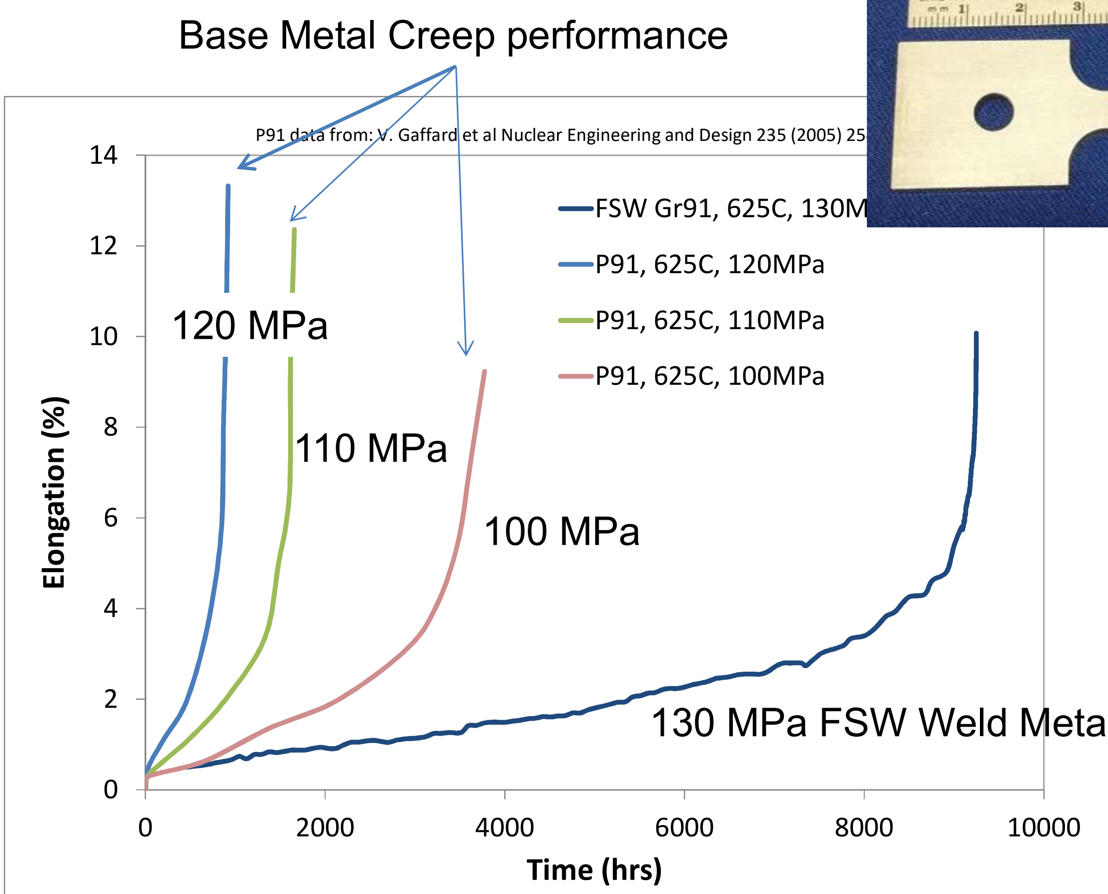
- Preliminary results indicate increase in creep life using FSW

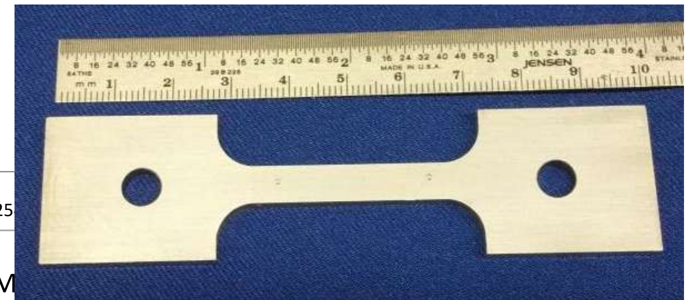
Grade 92 625°C Transverse Creep



- Preliminary results indicate increase in creep life using FSW

Gr91 FSW Weld Metal only (just nugget material with no PWHT) vs base metal





- FSW nuggets have better creep performance than base metal
- Important for creep resistance in the circumferential direction

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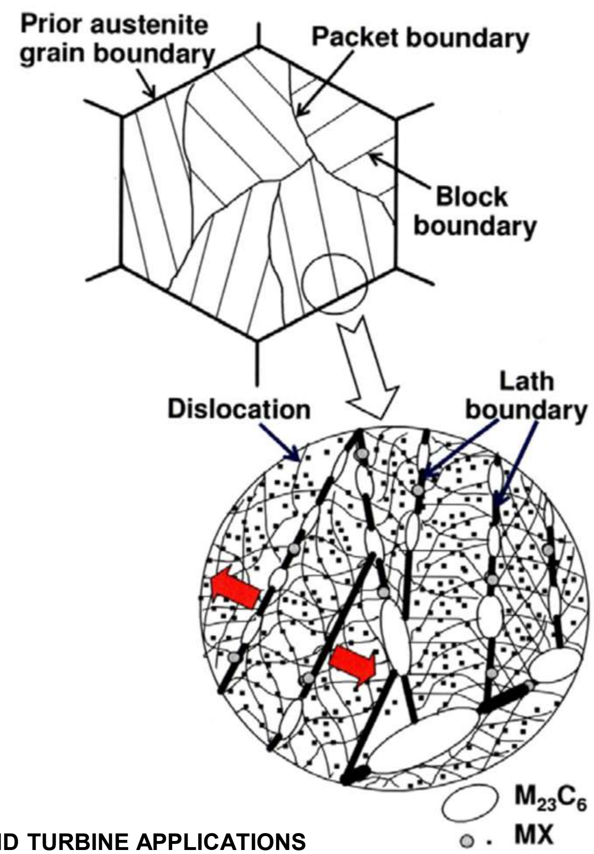
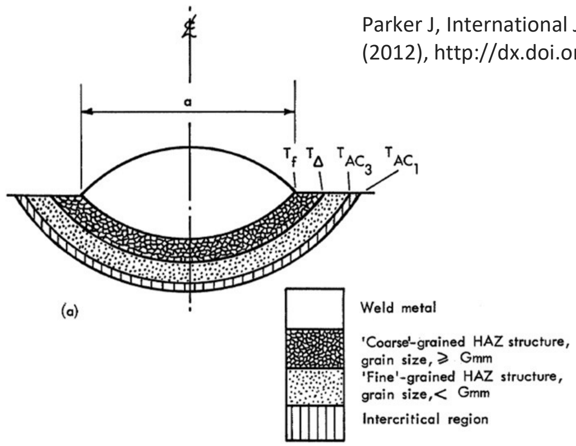
What drives differences in creep in these alloys ?

- 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.
- It is hypothesized that a well distributed network of preferably interlath (or on martensitic lath boundaries) MX precipitates forms the ideal microstructure.

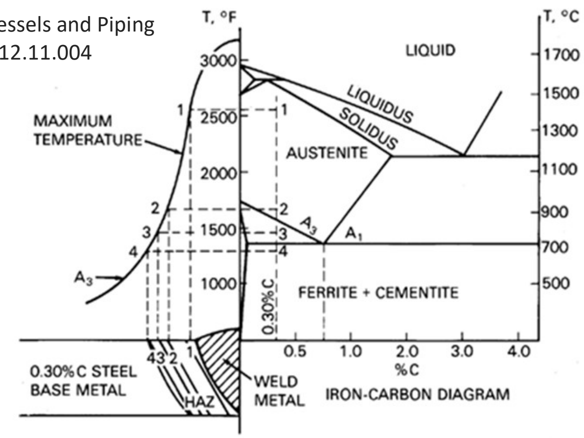


Hawk,JA, Jablonski,PD,2018, CREEP RESISTANT 9%CR STEEL FOR BOILER AND TURBINE APPLICATIONS
Proceedings of the 2018 ASME on Elevated Temperature Applications of Materials for Fossil, Nuclear and Petrochemical Industries
ETAM2018
April 3-5, 2018, Seattle, WA, USA

Microstructure changes with welding

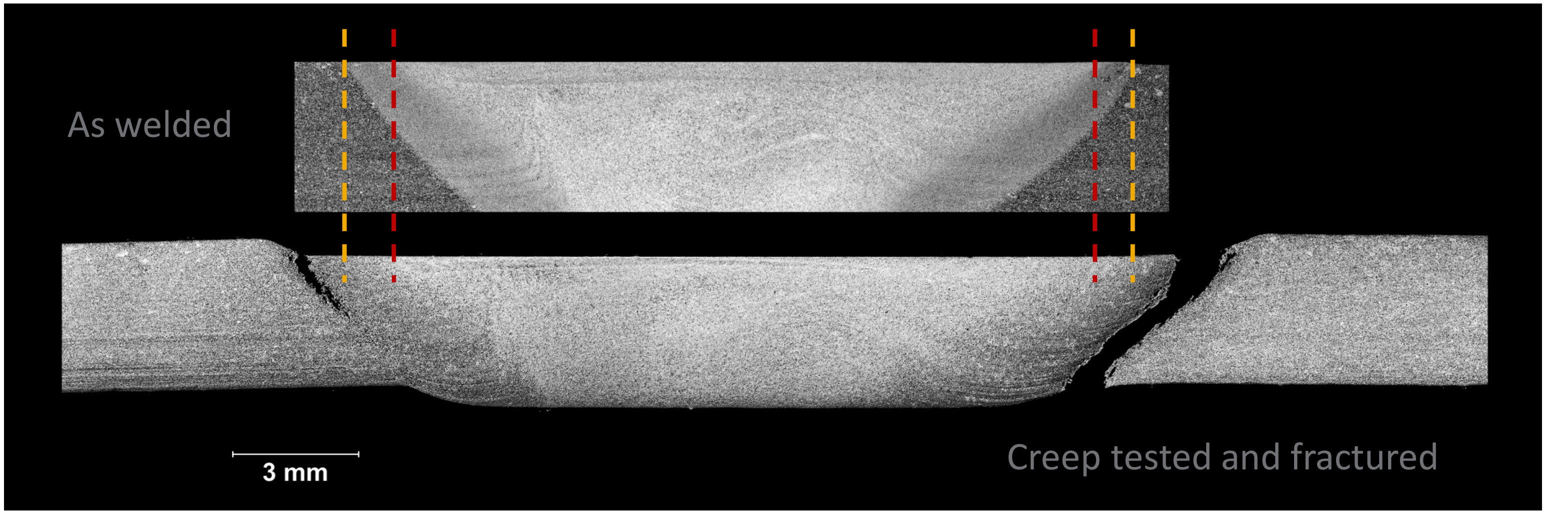


Parker J, International Journal of Pressure Vessels and Piping (2012), http://dx.doi.org/10.1016/j.ijpvp.2012.11.004



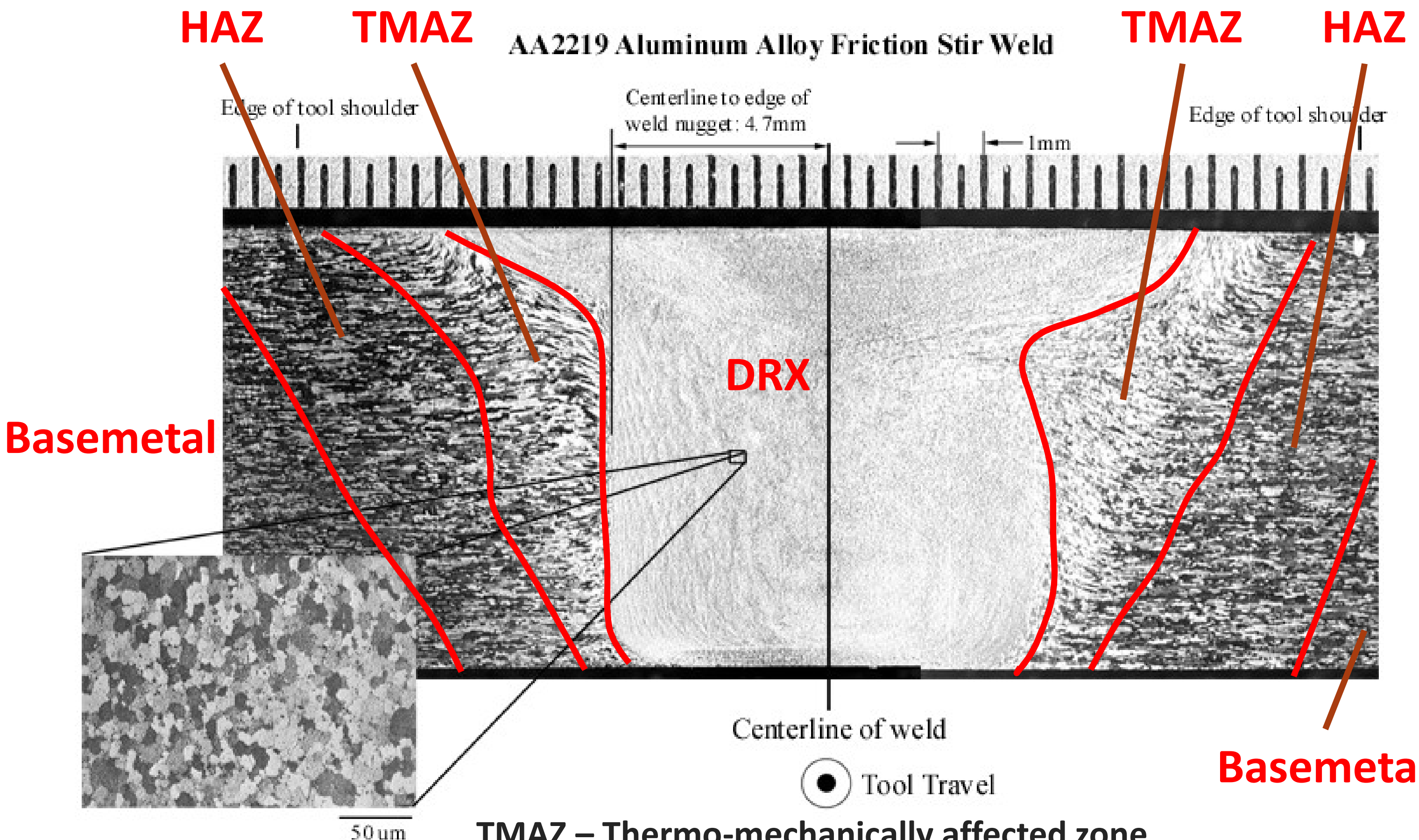
- CGHAZ: $M_{23}C_6$ dissolves, maybe some MX too – big PAG
- FGHAZ: not all precipitates dissolve – smaller PAG (This is where CSEF alloys fail in creep)
- ICHAZ: Neither the $M_{23}C_6$ nor the MX are dissolved.

But the failures are not in the FGHAZ, they are at the base metal HAZ interface



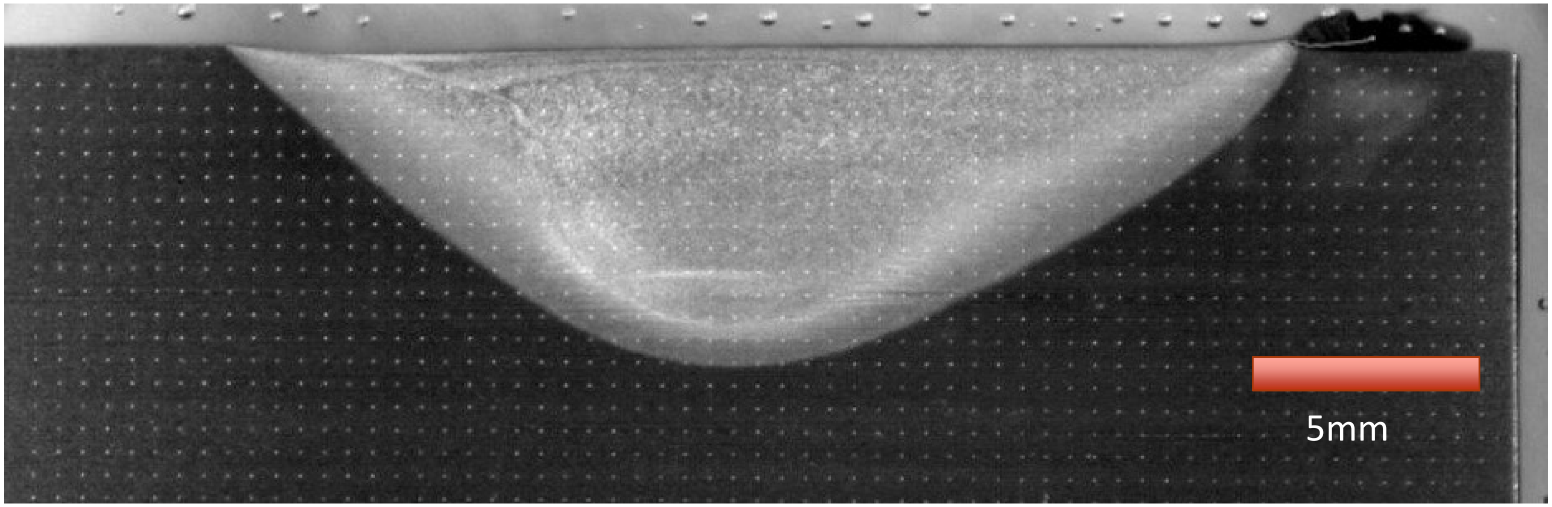
- Macrograph comparison of welded specimen and after creep fracture
- The creep failure appears to occur away from heat affected region, in the base metal, or right on the edge, and not in the FGHAZ

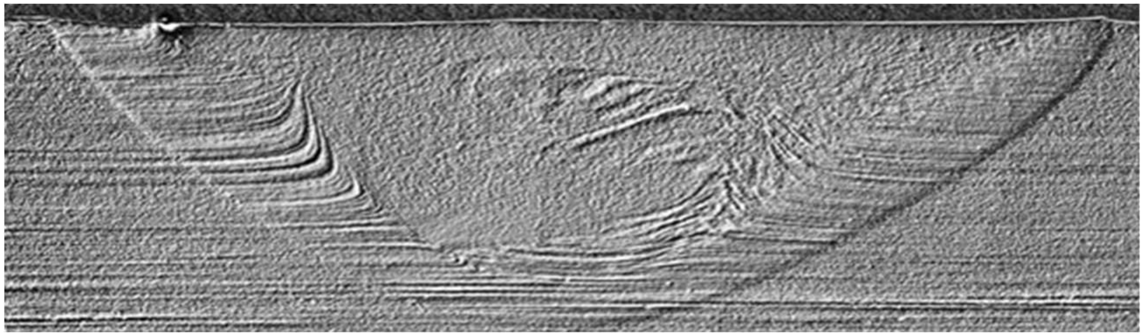
What is different between a fusion weld and a friction stir weld? -The TMAZ is unique to FSW



TMAZ – Thermo-mechanically affected zone

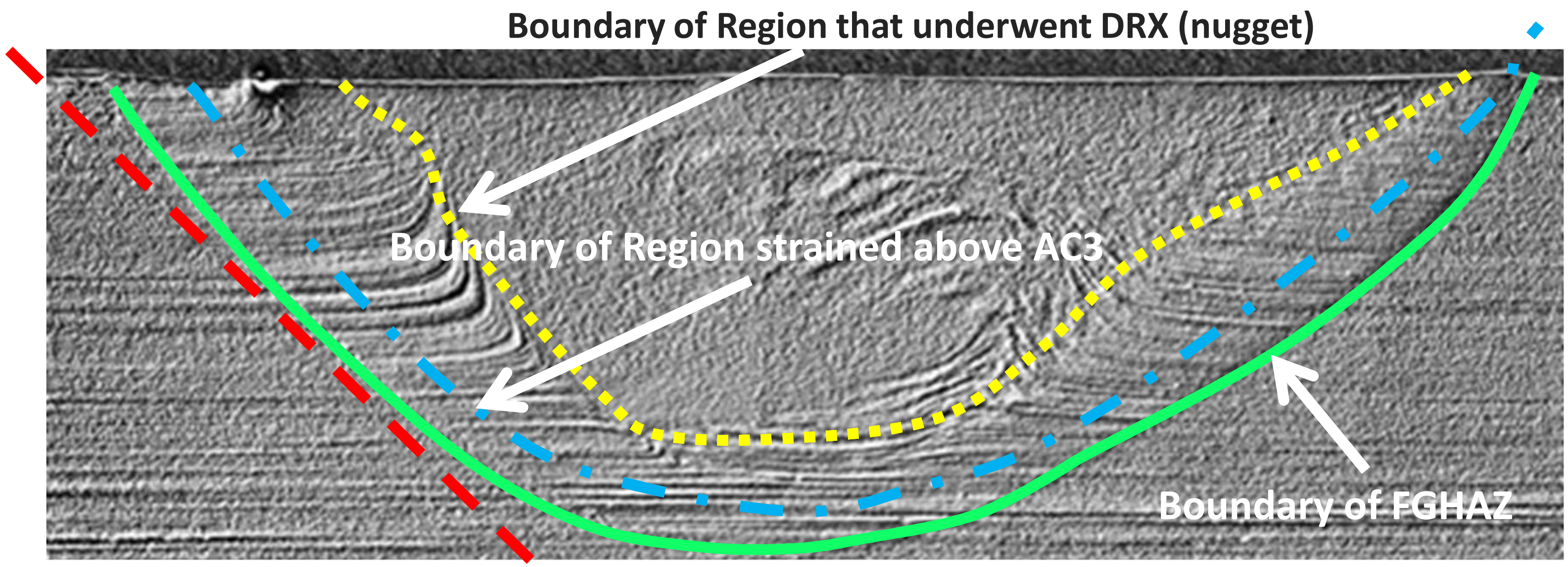
The TMAZ is hard to see after a martensitic transformation, but optical DIC can sometimes pick it out



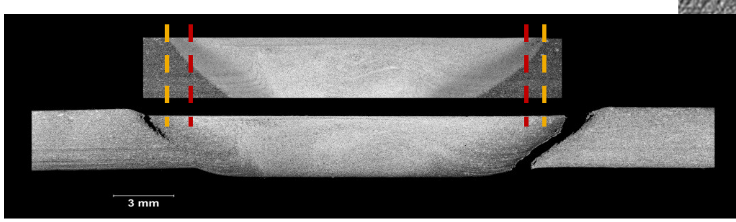


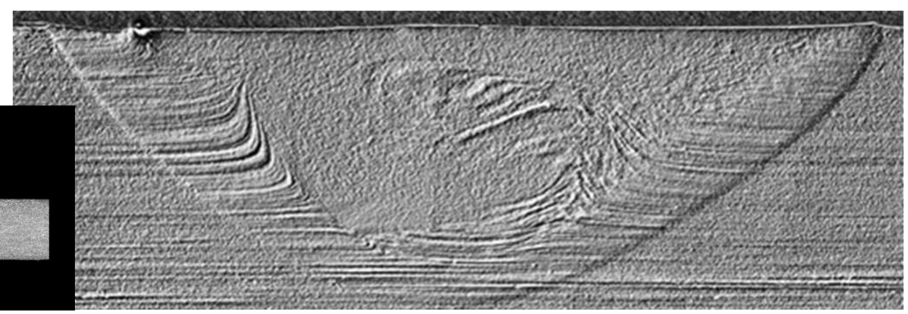
(Differential Interference Contrast, not digital image correlation)

Location of failure relative to strained region as revealed by DIC



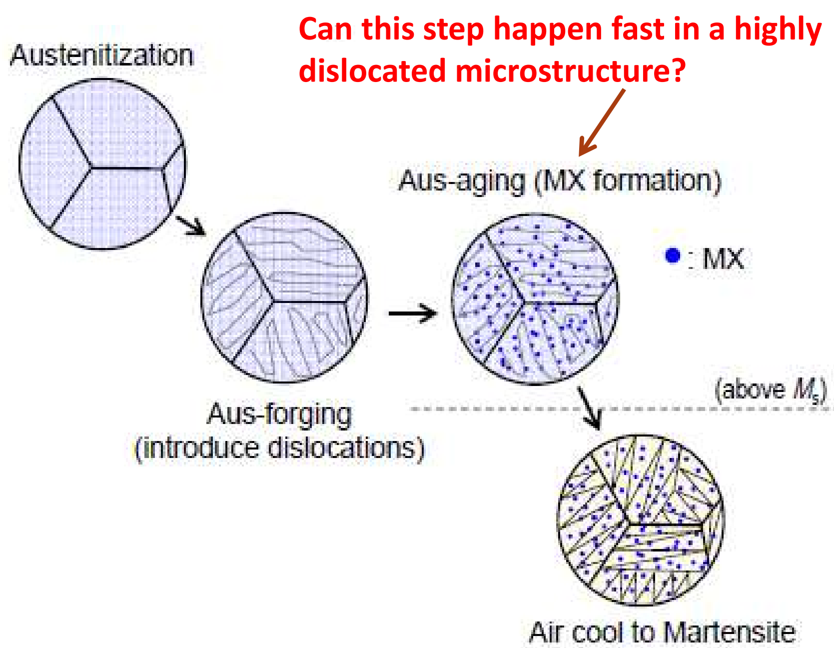
Creep Failure





Why is 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.
- Is it possible that a region near the nugget has a better distribution of fine carbide MX that helps resist creep deformation, driving the failure closer to base metal.
- It is 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.



Yukinori Yamamoto, et al., 2014

High resolution SEM imaging -base metal

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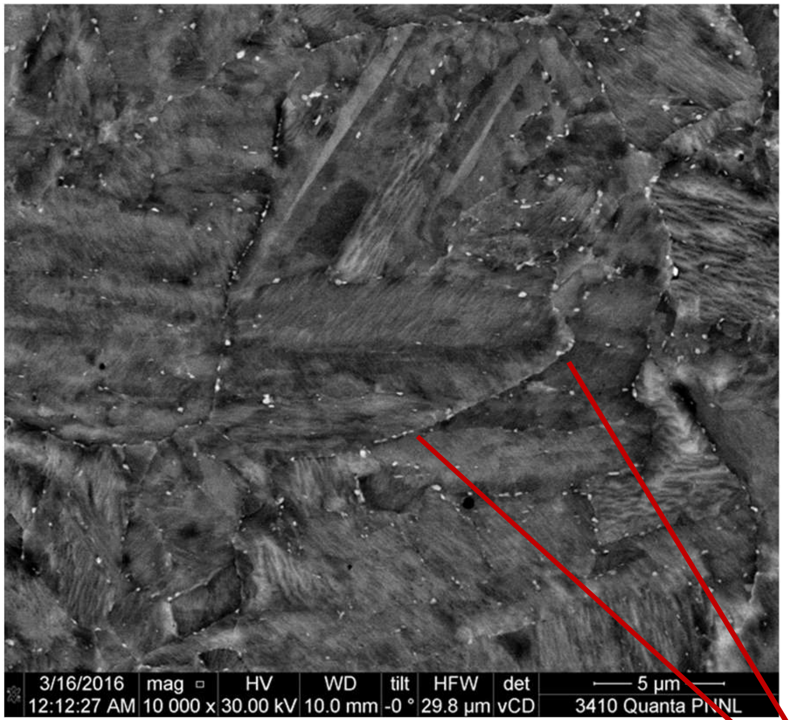
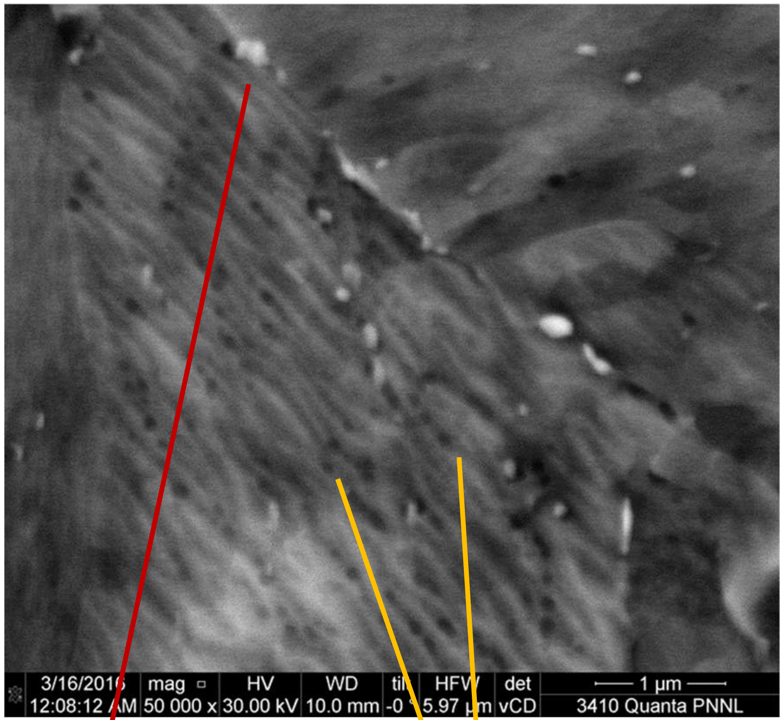


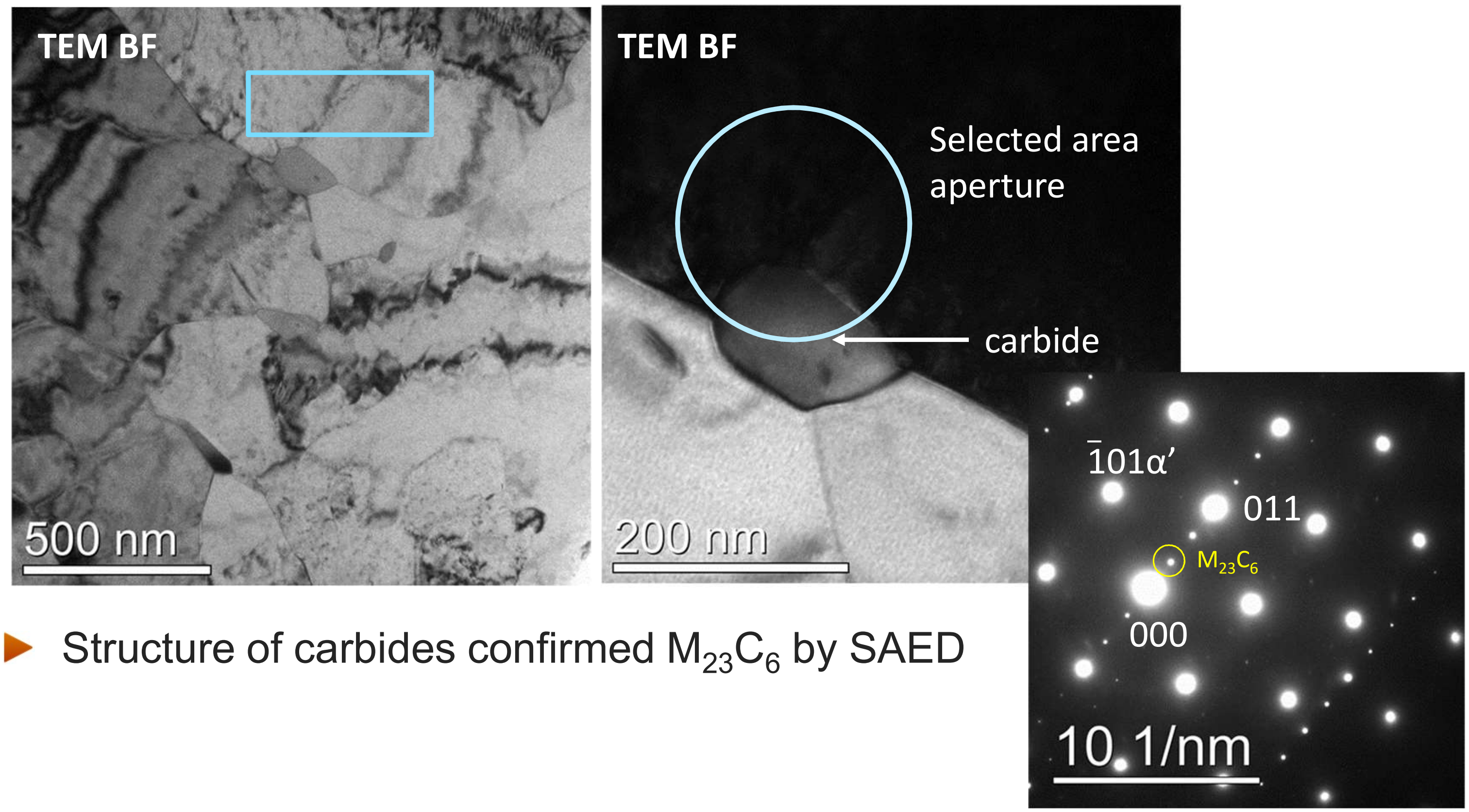


- Microstructure is tempered martensite.
- Prior austenitic grain boundaries decorated with white contrast precipitates M23C6 precipitates

Precipitates at GB ~up to 100nm+

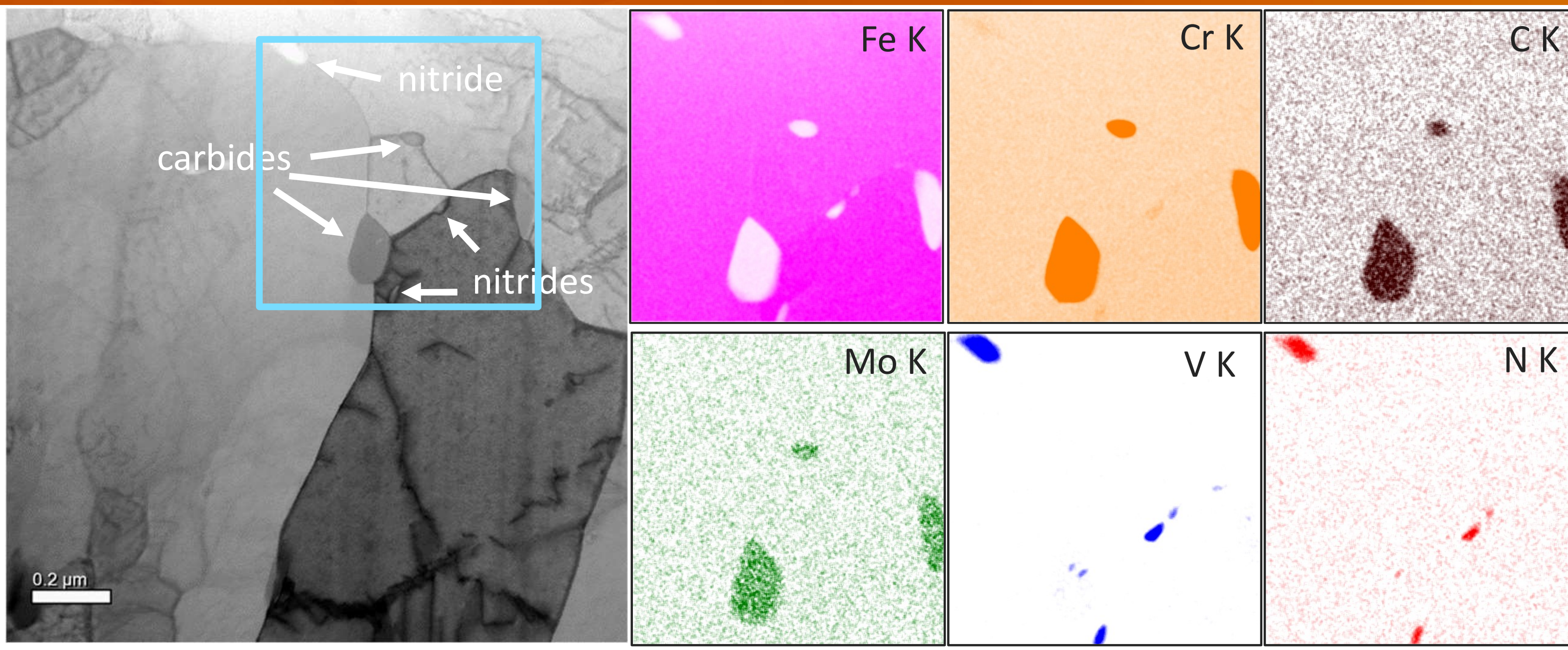
Small dark contrast Precipitates at martensite lath boundaries <100nm size

Detailed structural analysis of Carbides using diffraction



- Structure of carbides confirmed $M_{23}C_6$ by SAED

STEM-EDS analysis of M23C6 and MX precipitates.



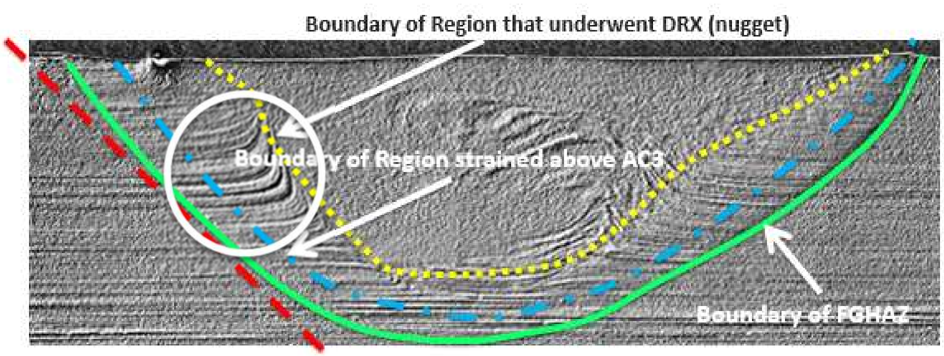
- STEM imaging and EDS analysis can identify the location of M23C6 carbides with Cr, Mo, C enrichment situated along prior austenitic grain boundaries.
- MX precipitates with VN concentration has also been identified to locate along prior austenitic grain boundaries and inside the grains.

April 18, 2018 25

Mechanism of Creep Softness

- If the FGHAZ of FSW weld is resisting creep cavitation better than a fusion weld what are the microstructural differences that lead to this?
- What is the nature of the carbides and nitrides in the HAZ of a fusion weld compared to a FSW weld? (size, location in the microstructure, number density)
- Studies of FSW weld HAZ region are in progress currently to check the variation in number density of MX precipitates to correlate it with Creep crack location.

FSW Weld



Creep Cavitation on line

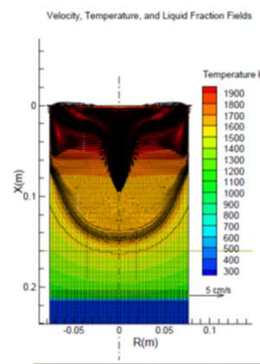
Fusion Weld

Creep Cavitation on line

White circle is area of interest for detailed TEM study

Next steps

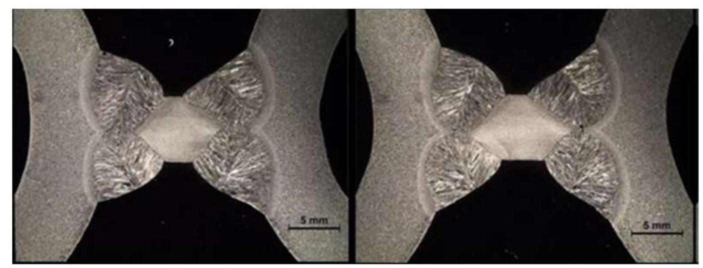
- P-92 - continue creep testing
  - All testing is now focused on >2000 hour creep rupture
- Develop the FSW process for the final alloy of the project – NETL's CPJ-7
  - NETL Albany has cast ingots of a boronated 9Cr material (CPJ-7).
    - Vacuum Induction Melting (VIM) followed by Electro Slag Remelting (ESR) has been utilized to make several 75+ kg heats.
    - Computational fluid dynamics have been utilized to help refine the process.
    - Excellent ingot quality has been achieved.
    - Four heats have been fabricated into plate
    - These have been sectioned, homogenized, and hot rolled to final dimensions.
- FY19 -Begin friction stir weld process development on CPJ-7, followed by creep testing

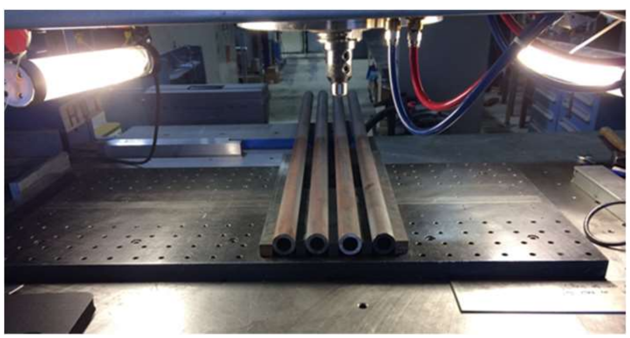


Final Task - Prototypic part demonstration

- 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

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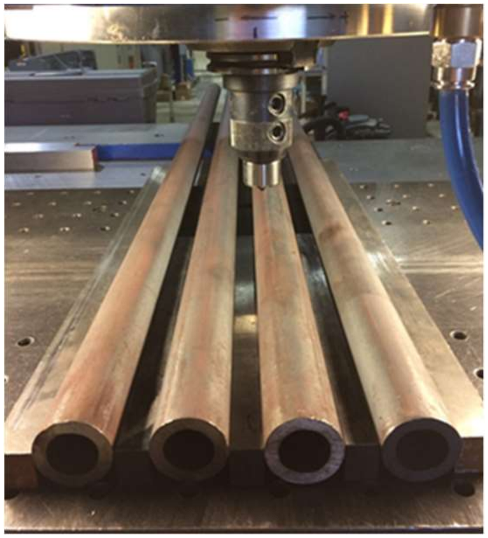
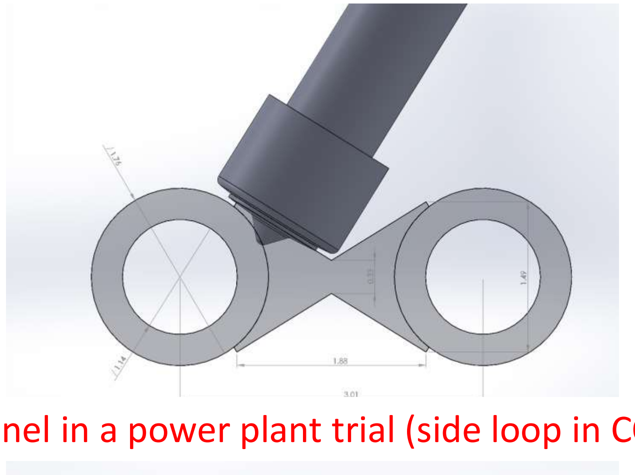
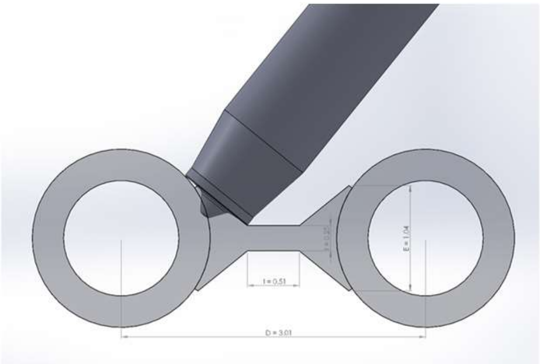
▶ Approach

- We have received four 62" lengths of ASTM A213-T92 tube (Vallourec, ~62" long x 1.75" OD x 0.3" wall thickness) from GE/Alstom Power Inc. We are in the process of procuring Grade 91 strip to use for webbing
- 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
- NDE (Xray, PT, UT?) for weld defect



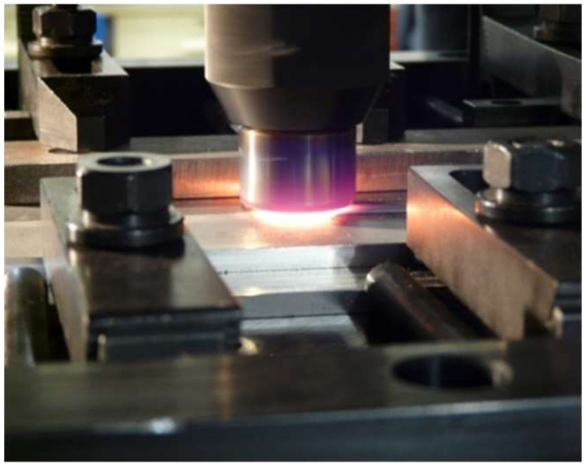


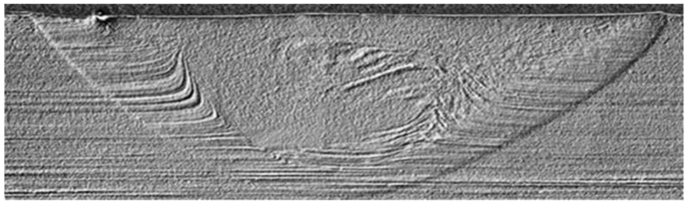


Looking for opportunity to insert panel in a power plant trial (side loop in COMTEST or other)

Conclusions

- CSEF steels are Friction Stir weldable
- Creep performance is very good, both of the weld metal and in cross weld tension
  - P91 can reach a WSRF at 625C of 0.73 over 1000 hrs
  - P92 can reach a WSRF at 625C of 0.82 at 10,000 hours (as compared to a fusion weld of 0.50 to 0.70 at 10,000)
- It is possible that WSRF can be raised by more than 10% from fusion welded equivalents
- **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.

END

Acknowledgment

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Regis Conrad DOE FE HQ
Vito Cedro NETL

Backup slides

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Is it cost competitive with Fusion Welding?

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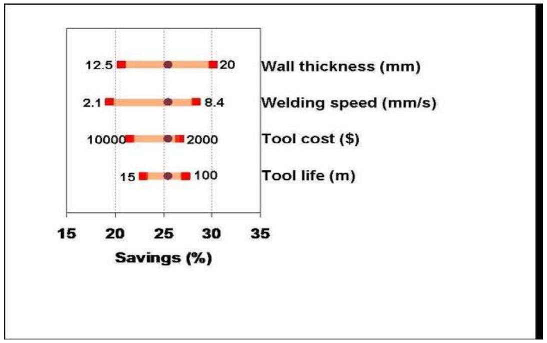
Cost Advantages

- Single pass method – Faster on thick section welds
- No Consumables
- No Environmental Emission (Mn or hexavalent Chrome)
- No "Expert" Operators
- Lower recurring costs (but higher initial capital costs than GTAW/GMAW)
- Lower energy costs
- Reduced downstream costs (from residual stress and distortion management)

Terrestrial Linepipe Cost Sensitivity

7% Cost savings



Offshore Laybarge Cost Sensitivity

25% Cost savings

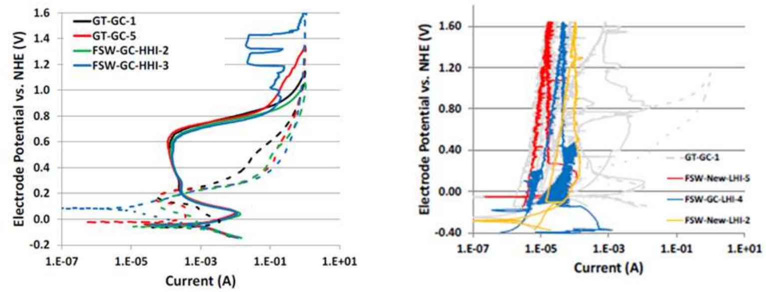
A. Kumar, D. P. Fairchild, M. L. Macia, T. D. Anderson
ExxonMobil Upstream Research Co., Houston, TX, USA
H. W. Jin, R. Ayer, N. Ma, A. Ozekcin, R. R. Mueller
ExxonMobil Research and Engineering Company, Annandale, NJ, USA:

in: Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference, Maui, Hawaii, USA, June 19-24, 2011, Copyright © 2011 by the International Society of Offshore and Polar Engineers (ISOPE), ISBN 978-1-880653-96-8 (Set); ISSN 1098-6189 (Set); www.isope.org

Are the properties acceptable?

Property Advantages

- Higher Toughness,Better Damage Tolerance
- Better Fatigue Performance
- Often Lower Total Heat Input:
  - Reduced HAZ degradation
  - Less sensitization in HAZ of Austenitic Alloys
- Lower Residual Stress and Distortion
- Fine grain nugget more amenable
  to NDE (x-ray, UT, etc.)
- Better results in Creep Rupture
- Better tolerance to gap, fit-up, and cleanliness
- High quality and repeatability (machine technology)



Cyclic Potentiodynamic Polarization (CPP) scans of GTAW welds in 304SS compared to FSW. GTAW shows potential for localized corrosion while FSW shows passivation behavior

No visible distortion in 50' of continuous welding in 4'x8' panels. (courtesy of BYU)

Flat plate FS welds in HSLA65 plate, stay flat !

Water wall distortion control in modular fabrication

Weld Process	Dome Height (mm)	Concavity (Z/X ≤ 0.2)	Convexity (Z/X ≤ 0.1)	Mismatch (Y/X ≤ 0.1)	Undercut (Angle ≥ 90˚)
Single Spot	11.7 ± 0.3	0.22 – 0.23	/	/	/
Twin Spot (across weld)	15.1 ± 0.4	/	/	0 – 0.21	116 - 180
Twin Spot (along weld)	14.3 ± 1.0	0.19 – 0.36	/	0.12 – 0.25	51 - 180
Laser-Plasma	11.9 ± 4.0	0 – 0.28	0.31 – 0.69	/	/
FSW	15.4 ± 0.5	/	/	/	/

Are there Codes and Standards?

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- Generalized Standards Efforts
  - FSW rules language has been added to the new 2013 ASME Section IX
  - AWS Subcommittee C6D – Best Practices Docs being written, training documents for weld inspectors being written
  - Efforts underway in book codes: Section 3 and 8
  - ISO, IIW
  - SAE D17.1(aluminum)
  - NASA (aluminum)
- Code Cases
  - 2 approved ASME Code cases running in Section IX Boiler/Pressure Vessel
- WPS PQR Environments
  - Manufacturer qualification for specific applications by internal standards (Coiled tubing)
  - Government Regulatory approval of process. Sweden has down selected FSW as the method to produce closure welds on their long term spent nuclear fuel storage systems (2” thick single pass welds in copper)