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Solid State Joining of Creep Enhanced Ferritic Steels

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Department of Energy – Office of Fossil Energy
National Energy Technology Laboratory
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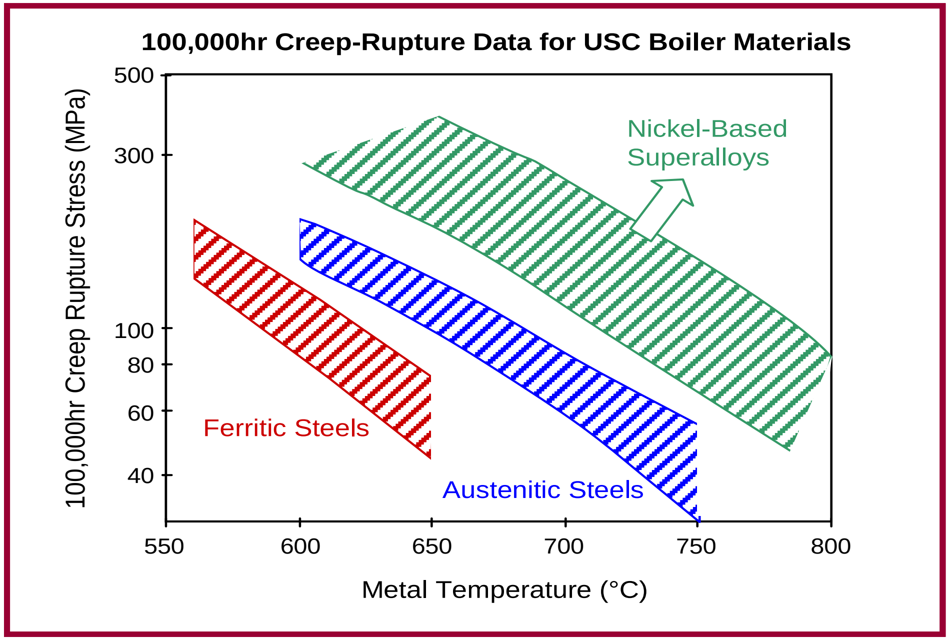
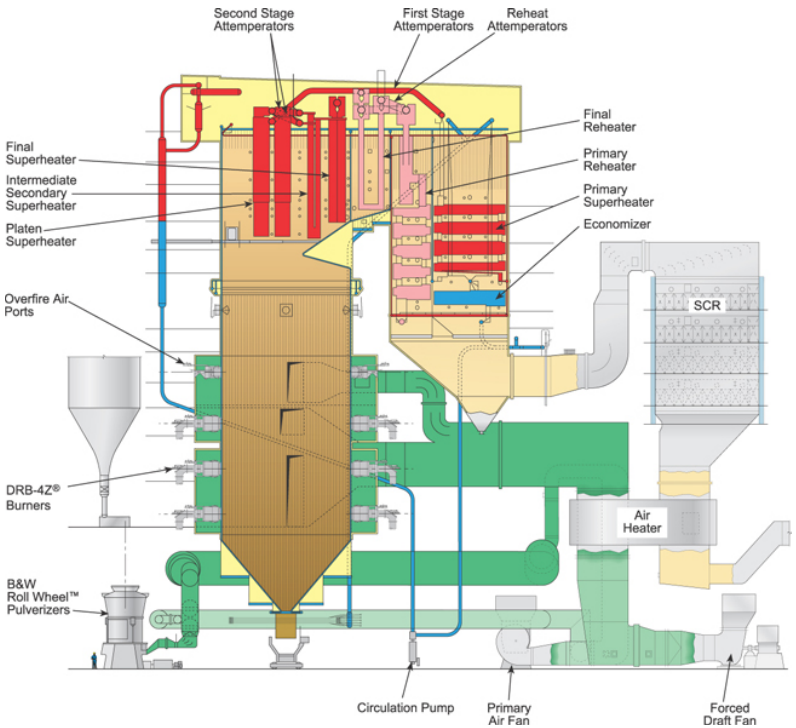
Motivation





- Creep Strength Enhanced Ferritic Alloys
  - Low-cost, workhorse alloy 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 leads to earlier than expected creep failure in the HAZ of weldments- “Type IV like” Creep failure.

Performance issues with welded CSEF steels

Problem leads to difficulty in predicting service life

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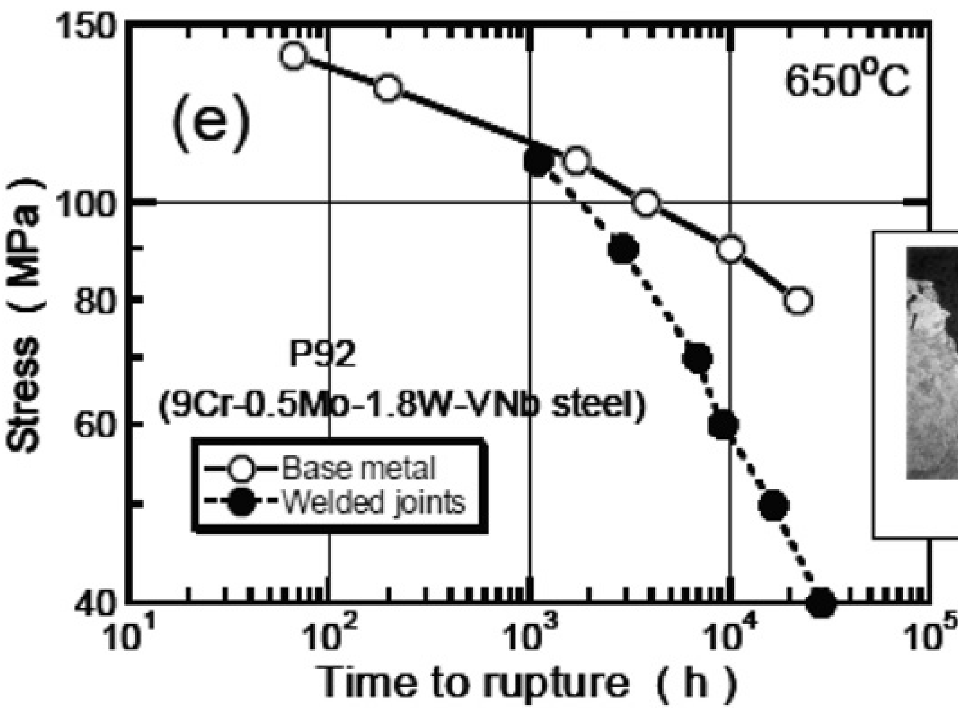
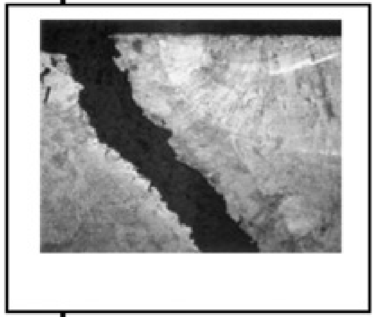
- WSRF can be as low as 0.50 at long creep times.
- This leads to greater allowances in pipe and tube wall thicknesses (higher material cost and heat transfer inefficiency) and/or reductions in operating temperature and/or pressure, that also leads to a reduction in plant efficiency.

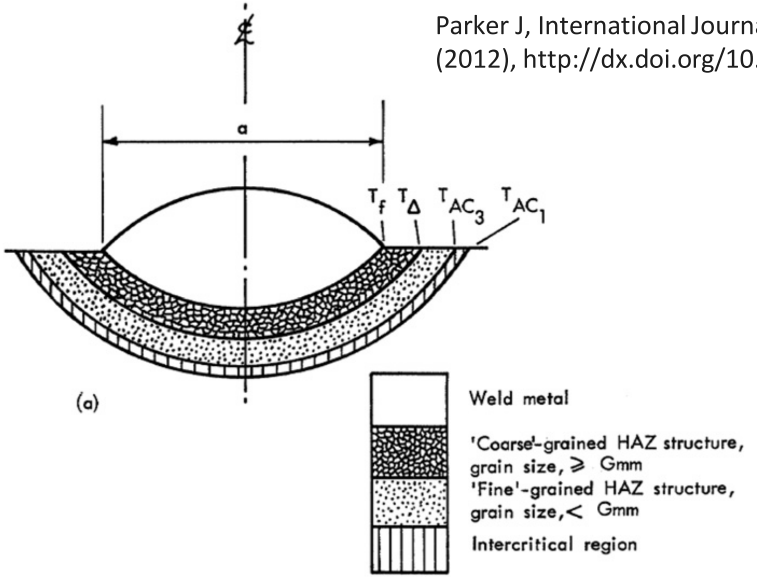




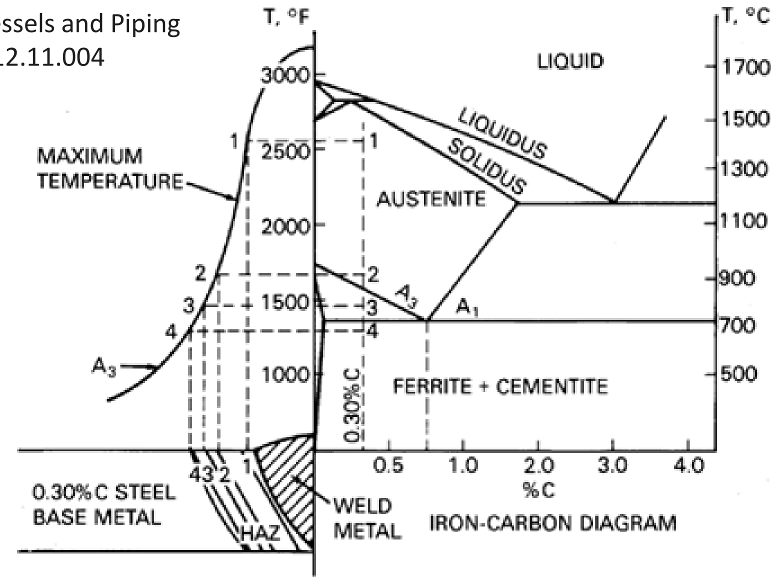
- Creep “softness” occurs in the fine grained heat affected zone

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

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
- ICHAZ: Niether the $M_{23}C_6$ nor the MX are dissolved. During the heat cycle they coarsen, which reduces the amount of fine carbides in the intergranular areas. This leads to softening.
- In addition, in the ICHAZ an incomplete transformation to austenite takes place – on cooling any austenite that formed goes to untempered martinsite in a matrix of original (and now over aged) tempered martinsite (ferrite). This can create strain concentrations under stress and can initialize locallized creep cavitation.

Motivation

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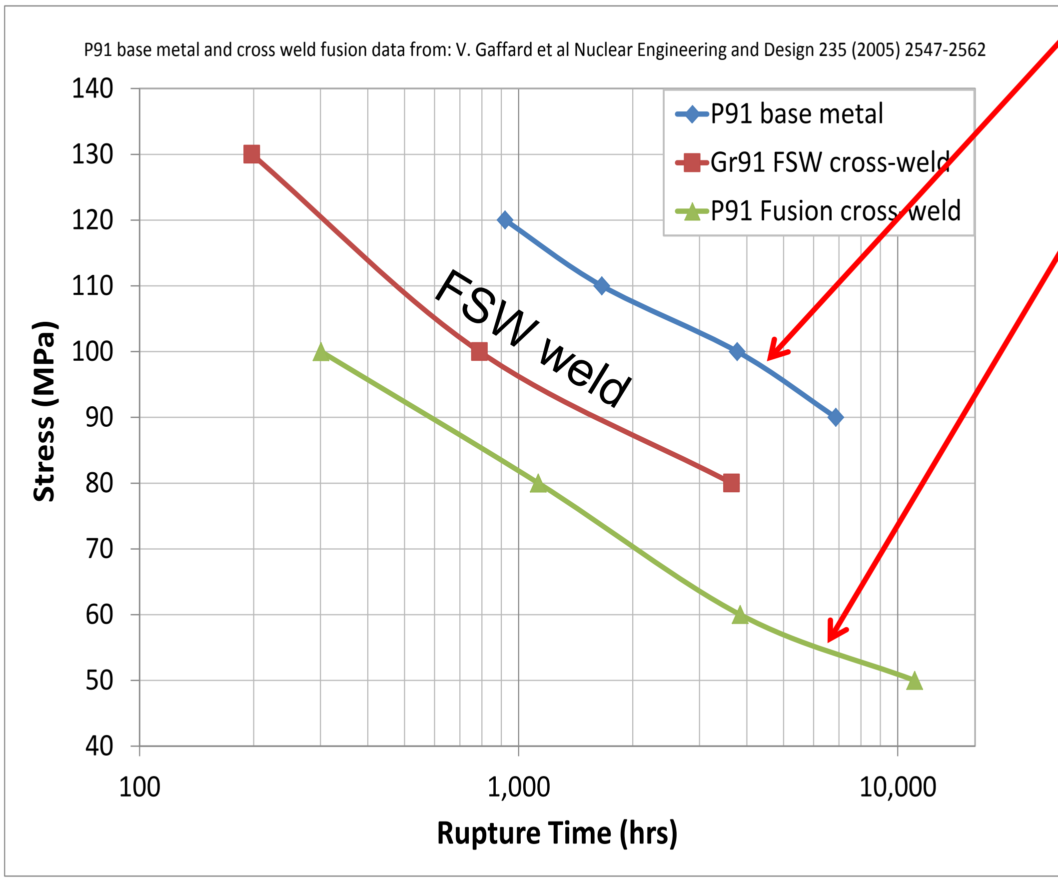
Can a new welding process create a microstructure that will show a reduced long term microstructure degradation compared to conventional fusion weldments?

- Solid state welding techniques, like Friction Stir Welding, may be able to introduced a significantly lower energy input to the weld.
  - Potentially creating weldment peak temperatures only just above Ac3, between Ac1 and Ac3, or in some cases below Ac1.
  - Low temps make small PAG and short times in the intercritical temperature ranges
- Will low temp and control of temp allow a "tunable" carbide precipitation sequence?
- FSW produces new microstructures, both in the nugget and in the strained part of the HAZ, does this promote fine MX or prevent carbide coarsening or the development of new phases (Laves etc) over time?

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

Motivation - Creep Results From Previous FE Funded Efforts at PNNL

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)**

Project Objective

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Objectives:

- Develop a FSW weld process that produces defect free FSW welds that pass ASME Sec. IX for overmatched condition in cross weld tension tests.
- Develop this weld process for Gr91, P92, and a boron/nitrogen (Co, Ta) enriched 9Cr ferritic steel (CPJ-7).
- Test these weldments in cross weld tensional creep and develop the relationship between weld process parameters and creep performance
- Publish new WSRF for FSW welds in the as-welded and in the PWHT condition.

Approach:

- Execute a detailed experimental weld process development and creep testing plan to study the effect of FSW parameters and PWHT on creep performance.

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What is Friction Stir Joining ?

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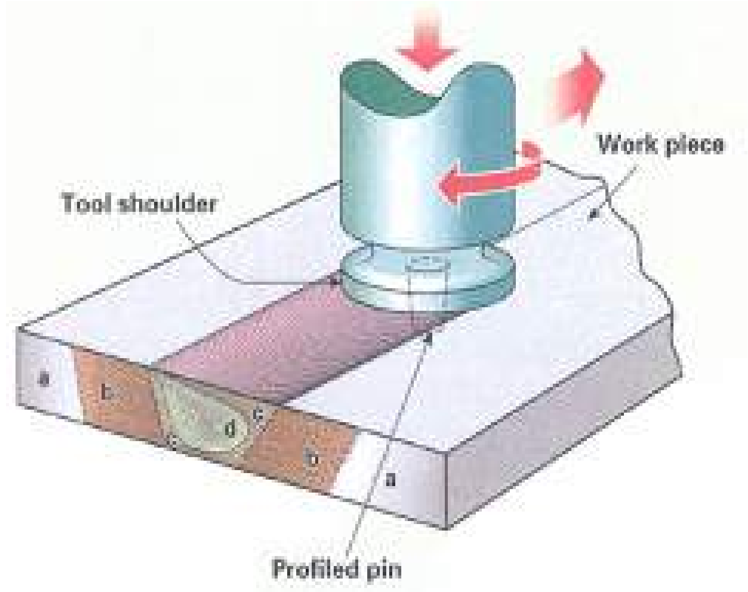
Solid-state joining processes (no material melting)

- 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)



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

Tools for Steels

Can FSW be applied to Fossil Energy Applications

- Can it weld the alloys?
- Can it weld the thicknesses?
- Can it weld the geometries?
- Is it cost competitive with fusion welding?
- Are there Codes and Standards?
- Are the properties acceptable?

Steel Friction Stir Welding – State of the Art

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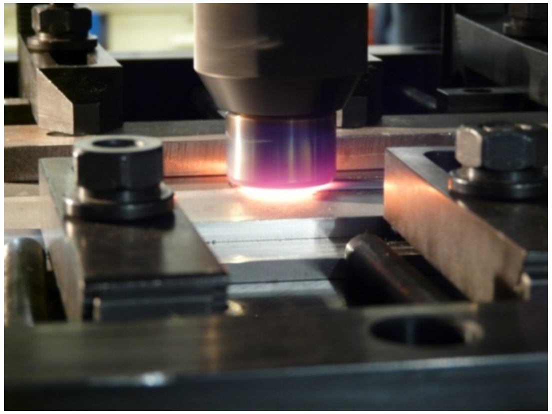
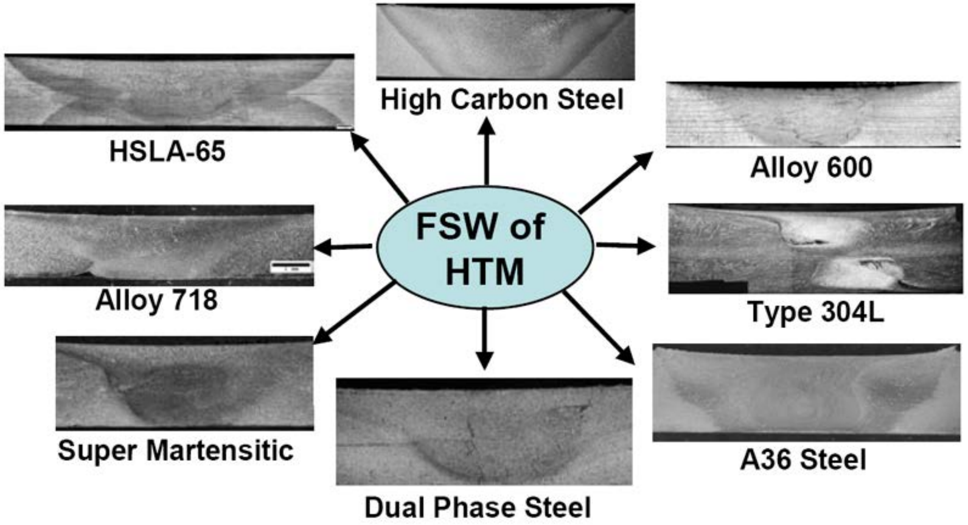
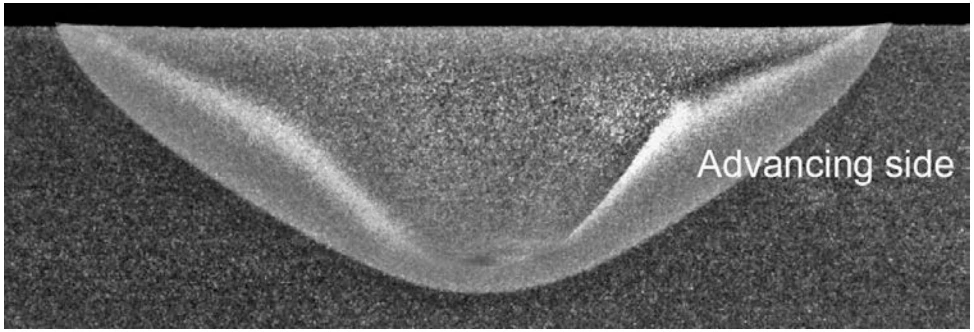
- Can it weld the alloys? Yes





- 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?

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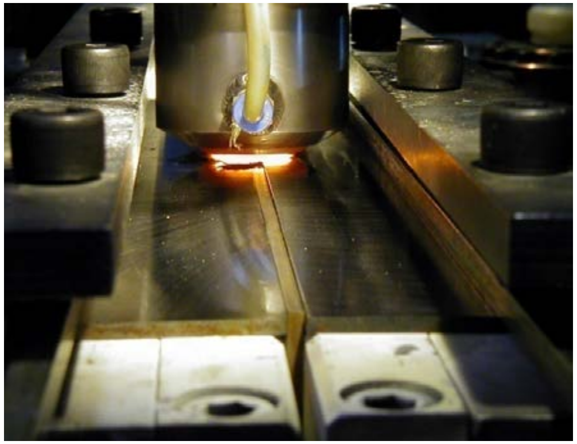
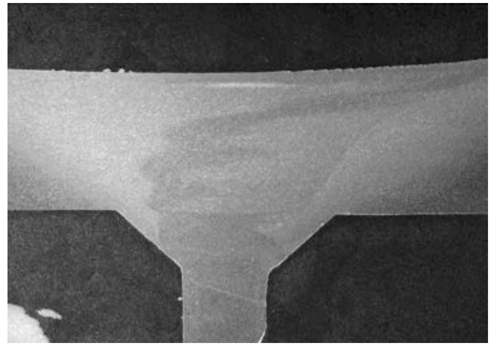
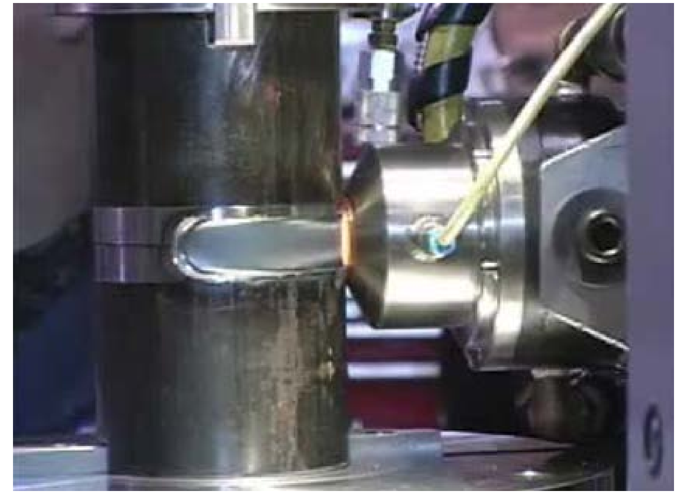
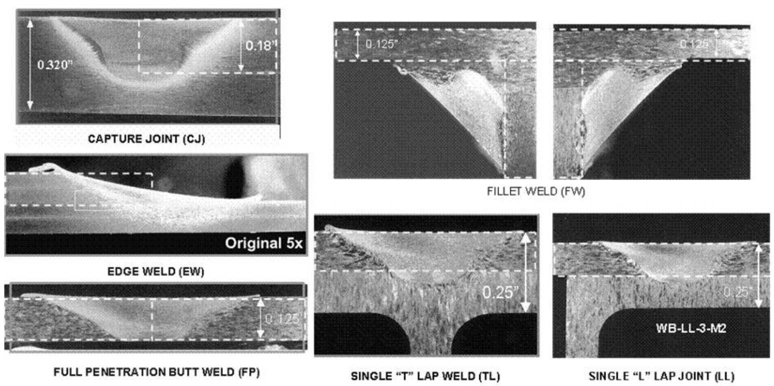


Megastir, Inc.



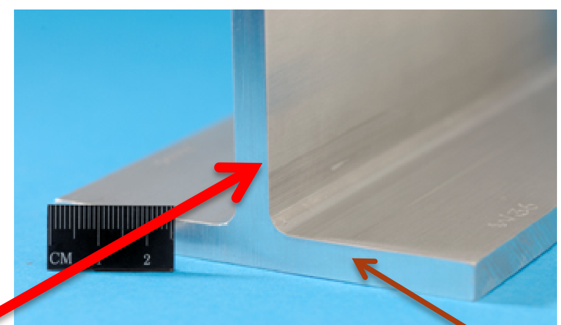


Circumferential butt weld on pipe and tube

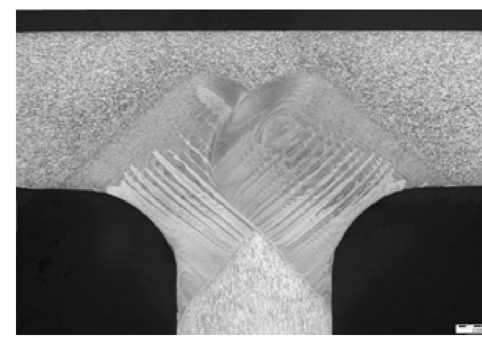


Arbegast 2004

Butt, Lap, Fillet and T Joints



a)



b)

TWI Technology Centre

Membrane wall application?

Imagine this was a tube

Is it cost competitive with Fusion Welding?

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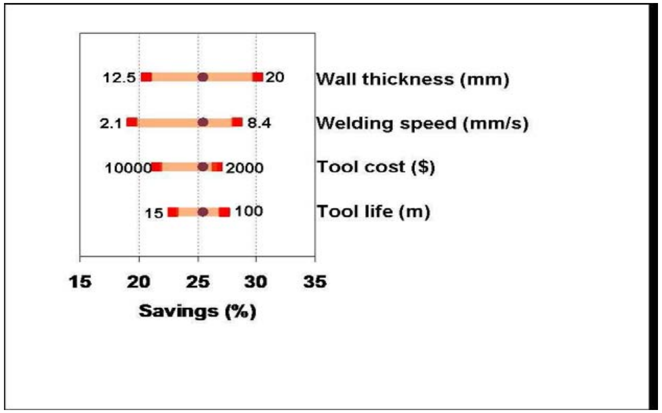
Cost Advantages

- 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 there Codes and Standards?

- 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
  - SAE D17.1(aluminum)
  - NASA (aluminum)
- Code Cases
  - 2 approved ASME Code cases running in Section IX
- WPS PQR Environments
  - Qualification for Specific Applications or internal standards (Coiled tubing)
  - Other countries (Sweden and Norway) have down selected FSW as the method to produce closure welds on their long term spent fuel storage systems (2” thick single pass welds in copper) – Government Regulatory approval of process

Are the properties acceptable?

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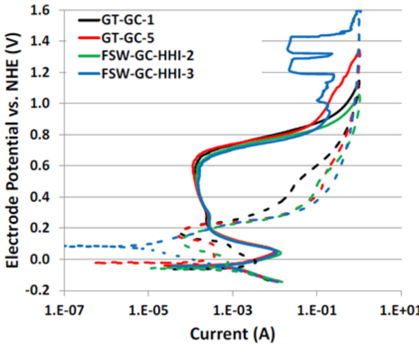
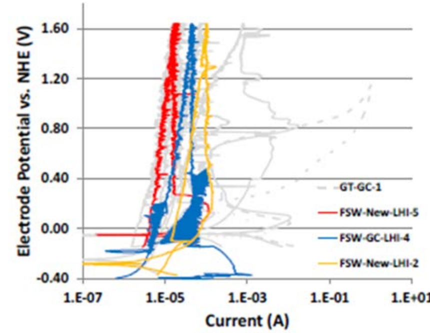
Property Advantages

- 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)

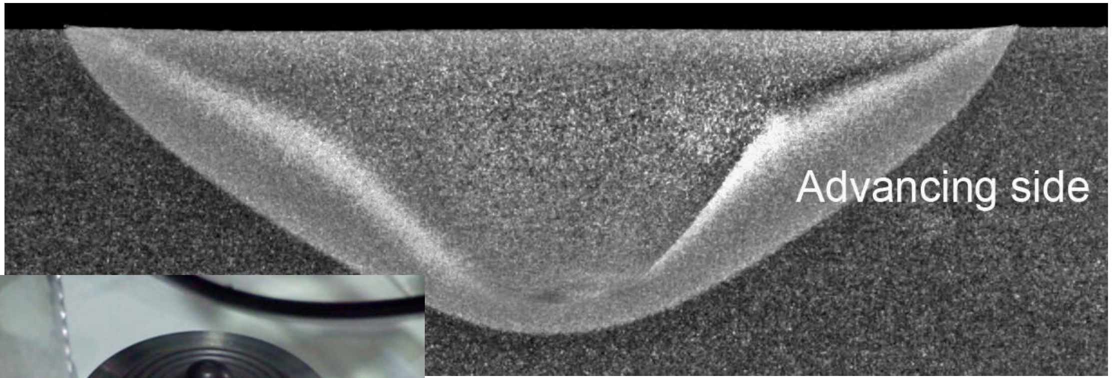
Weld Process	Dome Height (mm)	Concavity (Z/X ≤ 0.2)	Convexity (Z/X ≤ 0.1)	Mismatch (Y/X ≤ 0.1)	Undercut (Angle ≥ 90˚)
Single Spot	11.7 ± 0.3	0.22 – 0.23	/	/	/
Twin Spot (across weld)	15.1 ± 0.4	/	/	0 – 0.21	116 - 180
Twin Spot (along weld)	14.3 ± 1.0	0.19 – 0.36	/	0.12 – 0.25	51 - 180
Laser-Plasma	11.9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

Flat plate FS welds in HSLA65 plate, stay flat !

Water wall distortion control in modular fabrication

Current Program (Gr91,P92, CPJ-7)
ASTM 387 Gr91 Class2 FSW Welds

- 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
  - 2-6 IPM, <100-400 RPM
  - Tool Temperatures 715-1000C
- Analysis
  - Creep
  - Hardness
  - Microscopy

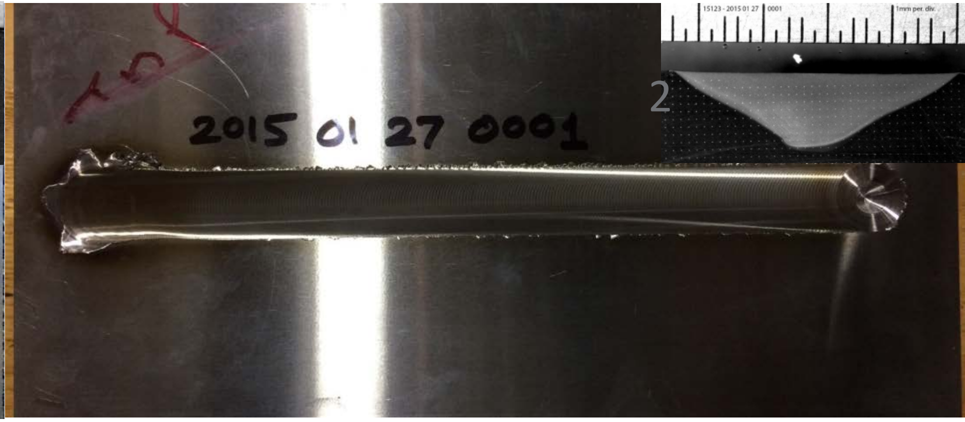


FSW welds in Gr91

- Defect free welds made at a variety of conditions and weld temperatures
- In addition to fixed parameter welds, we also do constant temperature welds under closed loop temperature control.

4IPM/100RPM/715C

4IPM/100RPM/800C



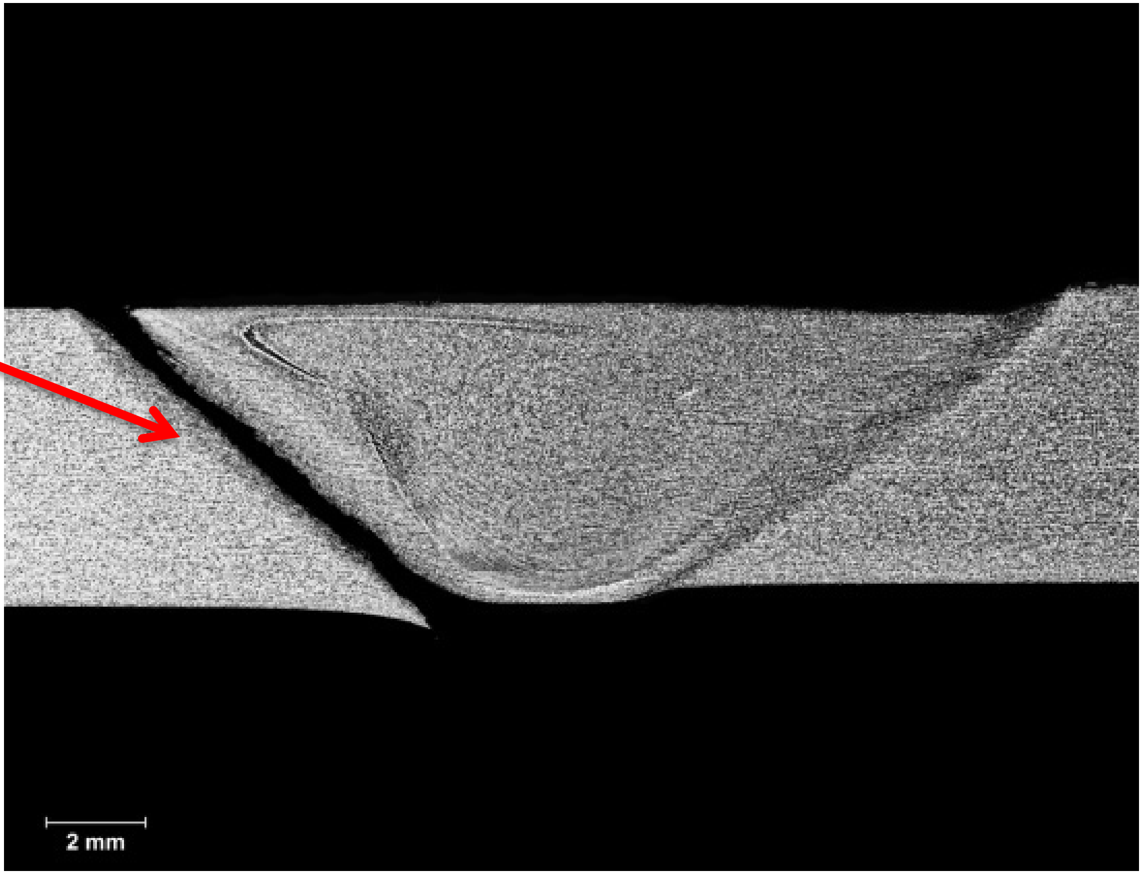
2IPM/100RPM/865C

6IPM/400RPM/950C

Creep Rupture Testing

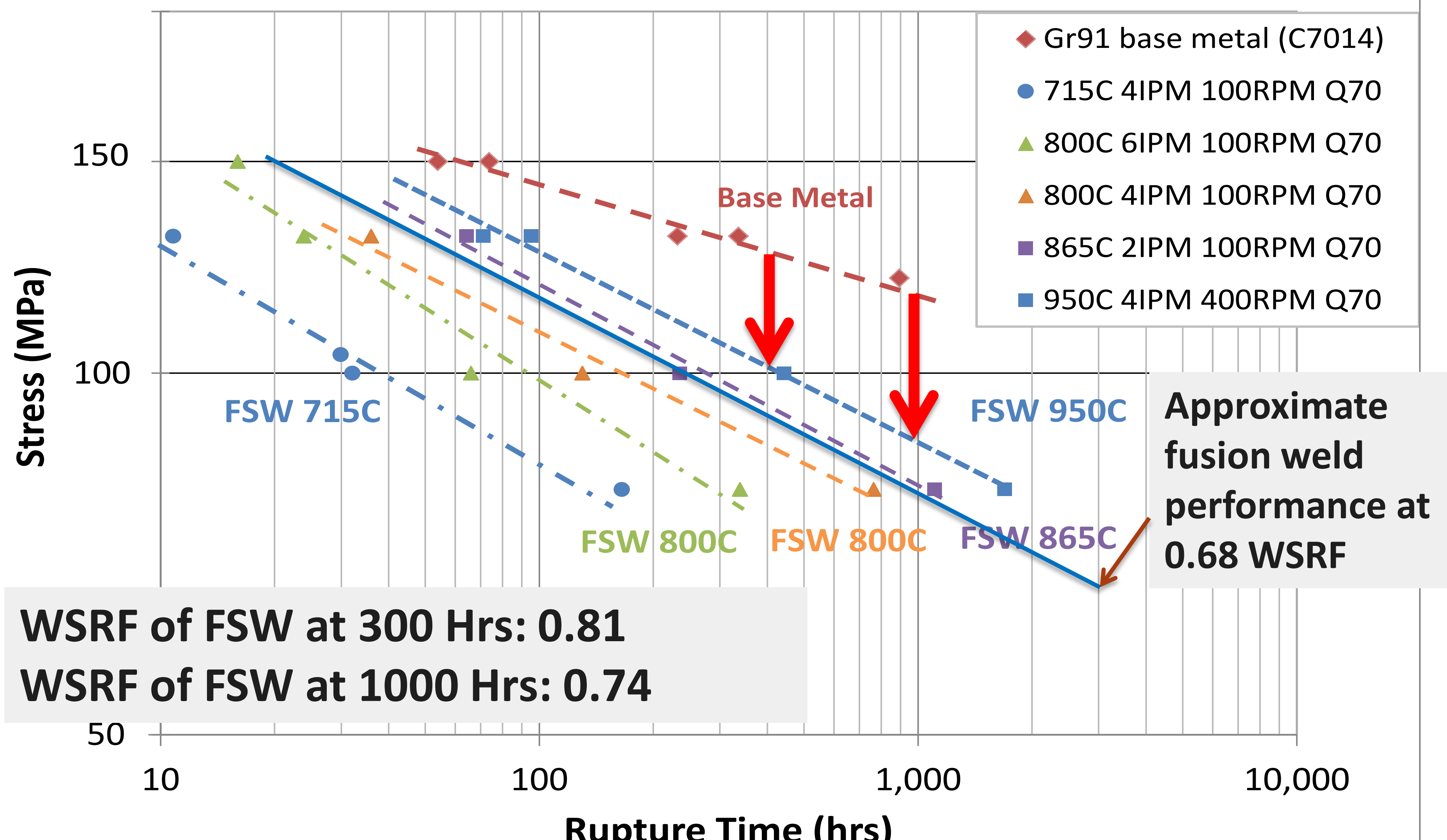
- Testing is conducted on constant load creep frames at 625 C
- Each weld condition is tested at 80, 100, 130 Mpa, which leads to creep failure generally below 2000 hrs.
- Limited testing above 2000 hrs in the current round of testing (Next steps)

FSW shows creep failure in the FGHAZ similar to a fusion weld



625°C Transverse Creep at different weld temperatures - WSRFs

FSW welds made at 950C showed better creep performance than literature values for fusion welds



Previous data showed flattening slope to 4000 hrs for FSW (FSW weld not PWHT)

Post Weld Heat Treat effects on Gr91 FSW welds -760°C/2hrs

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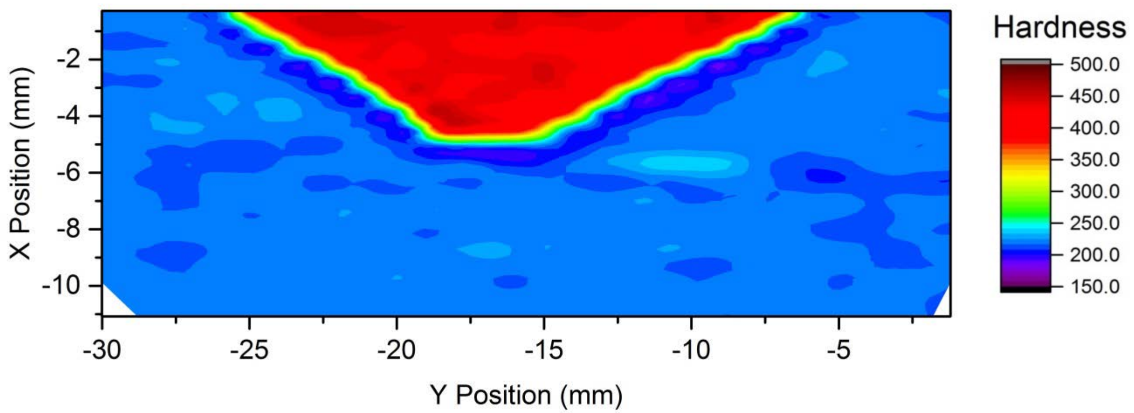
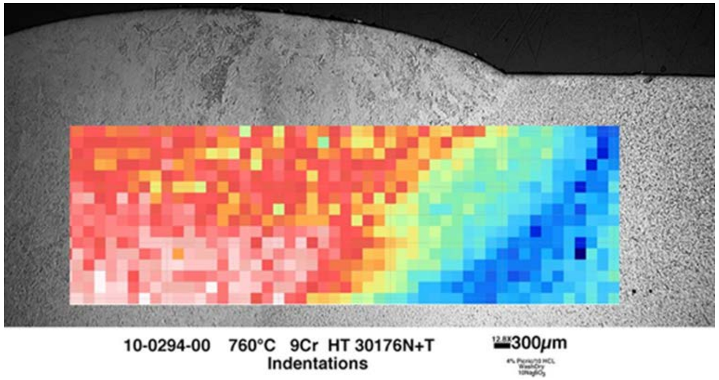
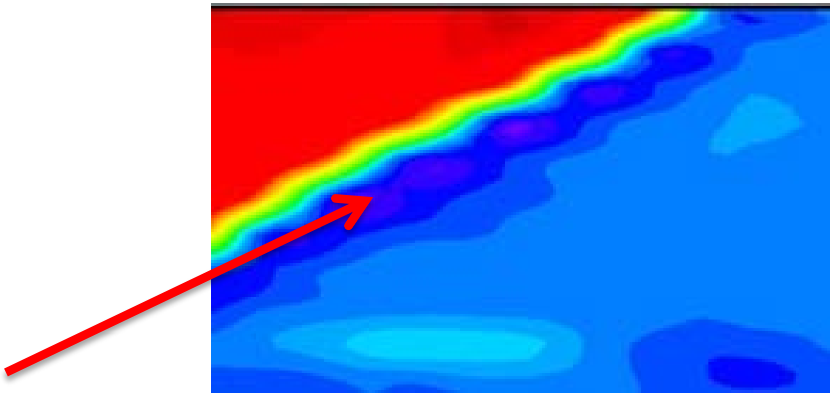
- Testing the PWHT response of the Gr91 FSW welds is in progress
- Primary function is to decrease nugget hardness (increase toughness) without making creep performance worse (coarsen the carbides)

The martensitic structure left behind after FSW is similar to fusion welding

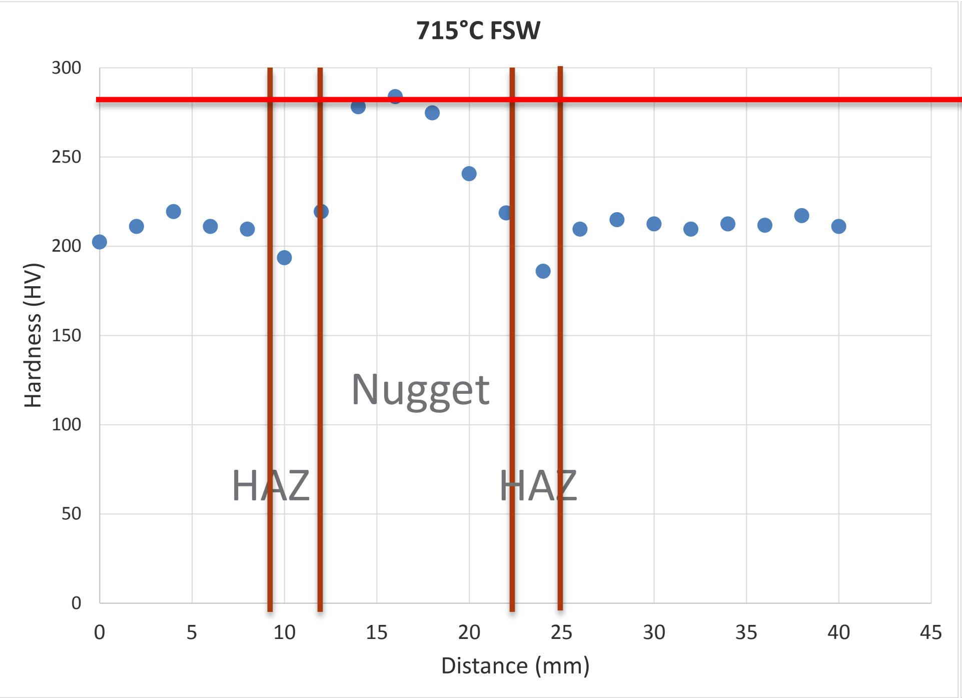


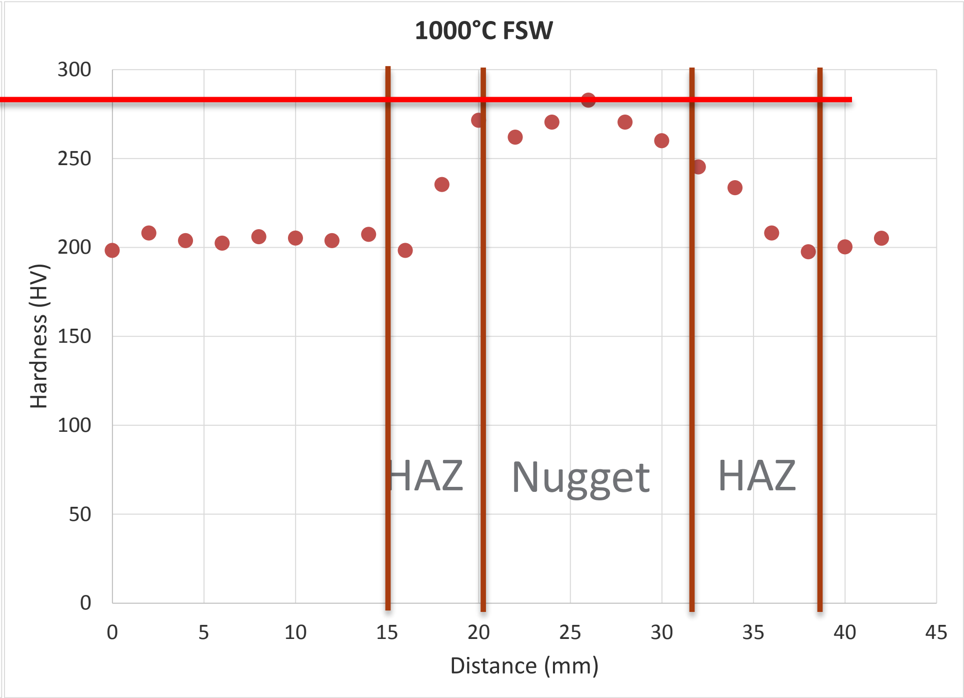


- FSW also shows a low hardness zone at the edge of the HAZ, not necessarily coincident with the creep failure



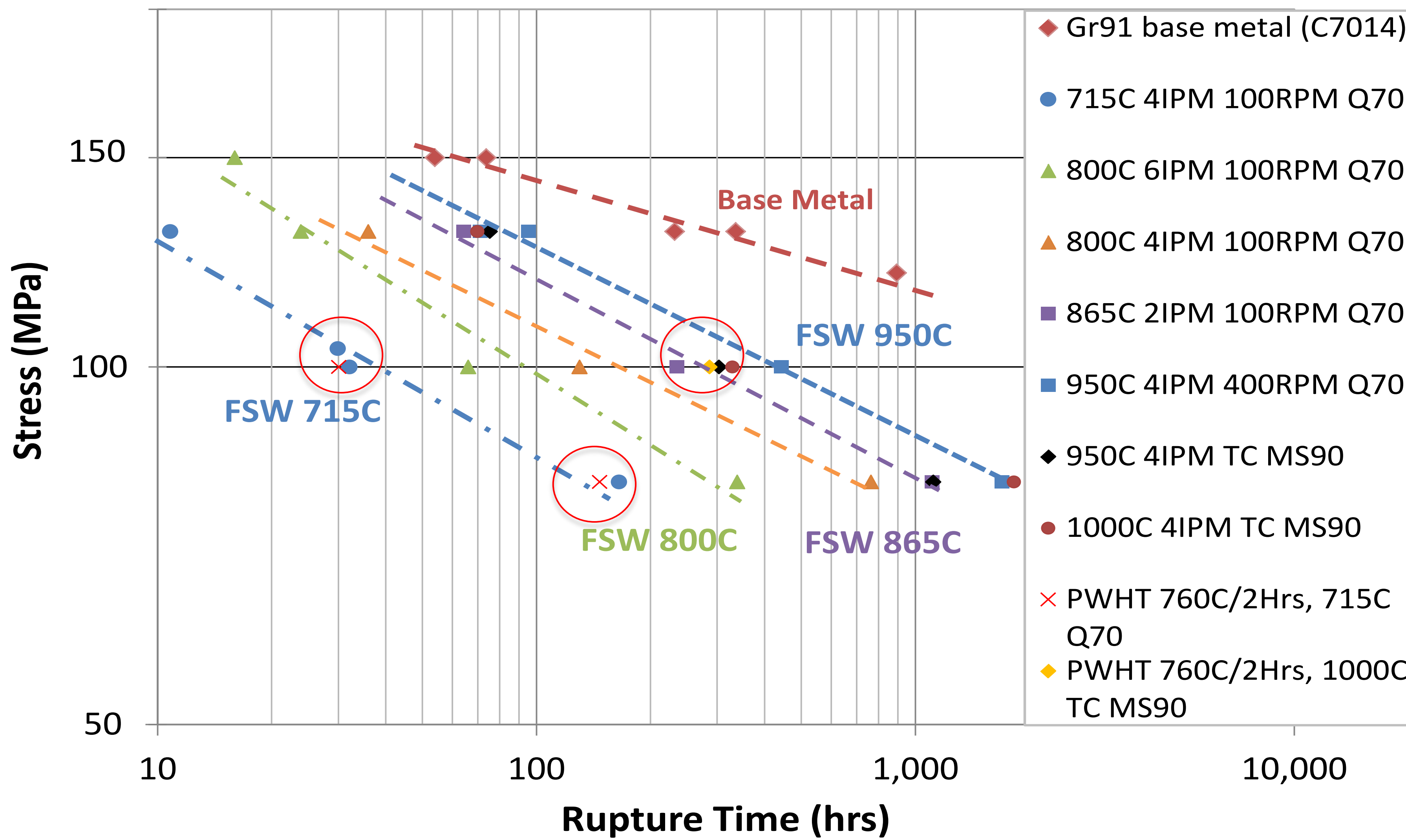
Hardness after PWHT





- PWHT at 760°C/2hrs of FSW Gr91 reduces nugget hardness from 400-500HV to <300HV

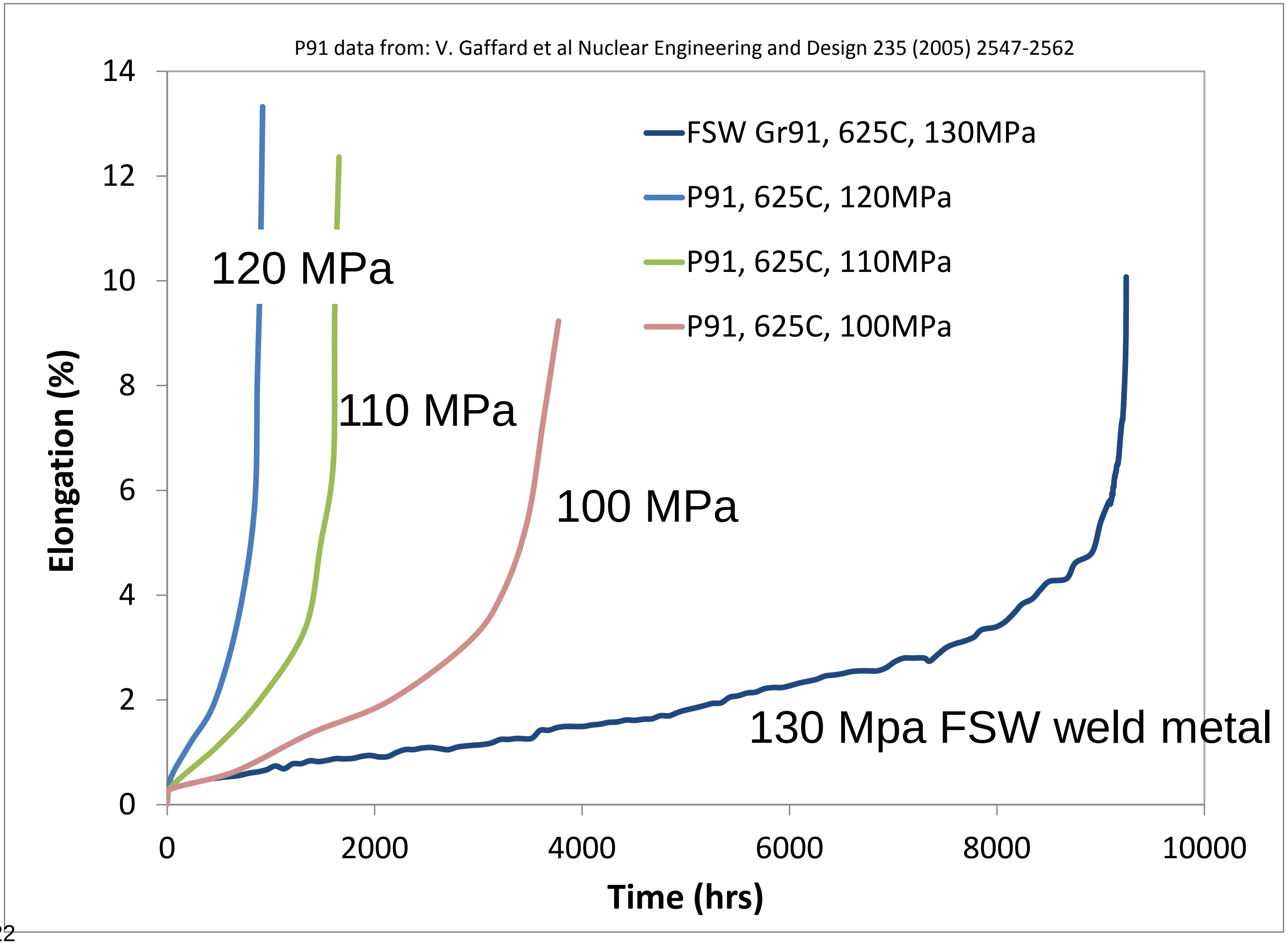
625°C Transverse Creep - PWHT 760°C/2hrs



- Ongoing tests of PWHT welds suggest little if no effect on creep life.

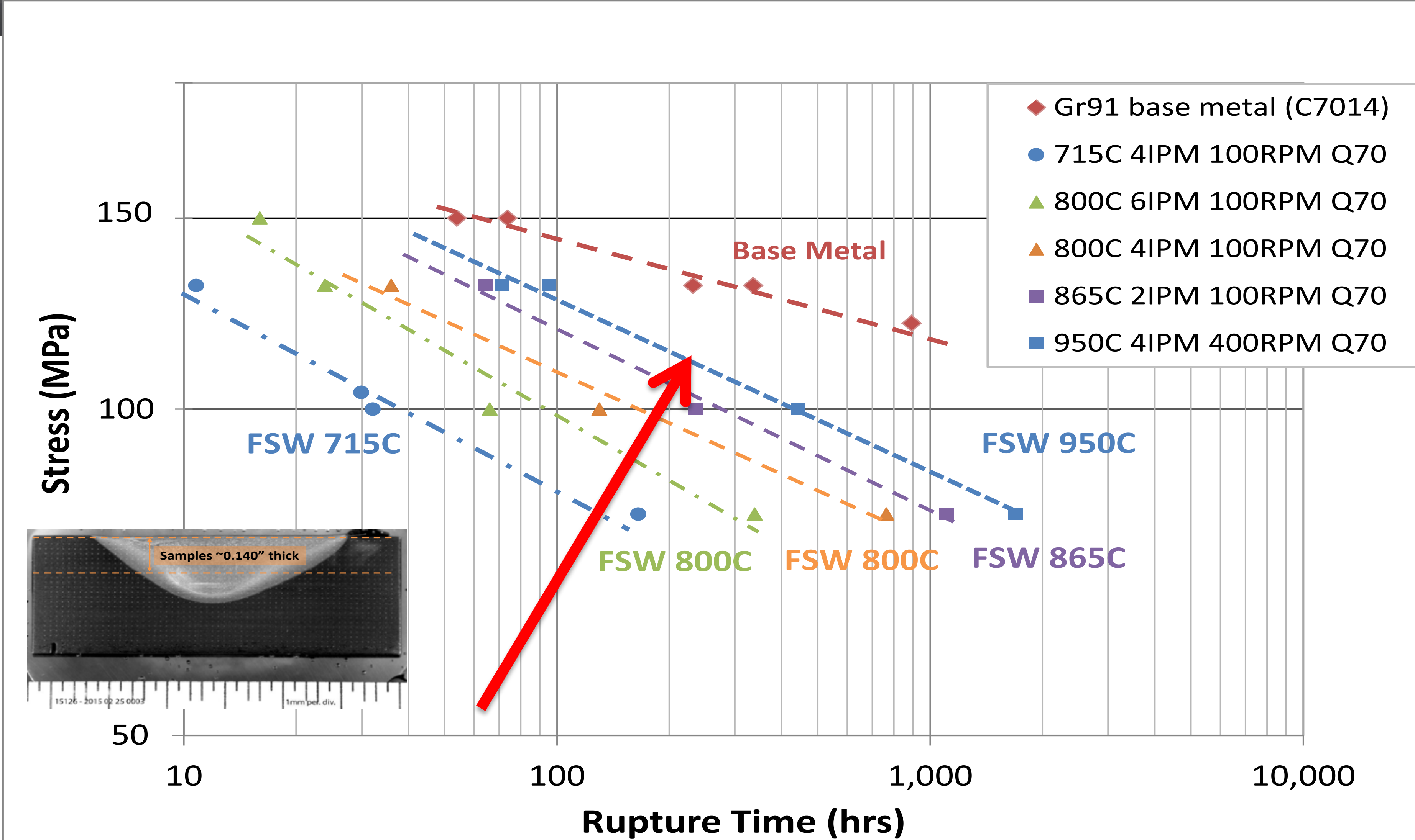
Creep results Gr91 FSW Weld Metal only (just nugget material with no PWHT)

- FSW all weld specimen ruptured after 9,247hrs at 625ºC/130MPa
  - Minimum strain rate: 1.3E-9/sec, All FSW weld material at 625ºC/130MPa is similar to T91 tested at 600ºC and 105MPa (S. Spigarelli, Mat. Sci. Tech. v.15 p1433-1440 1999)
- Second longitudinal all weld FSW ruptured after 3464hrs at 625ºC/175MPa



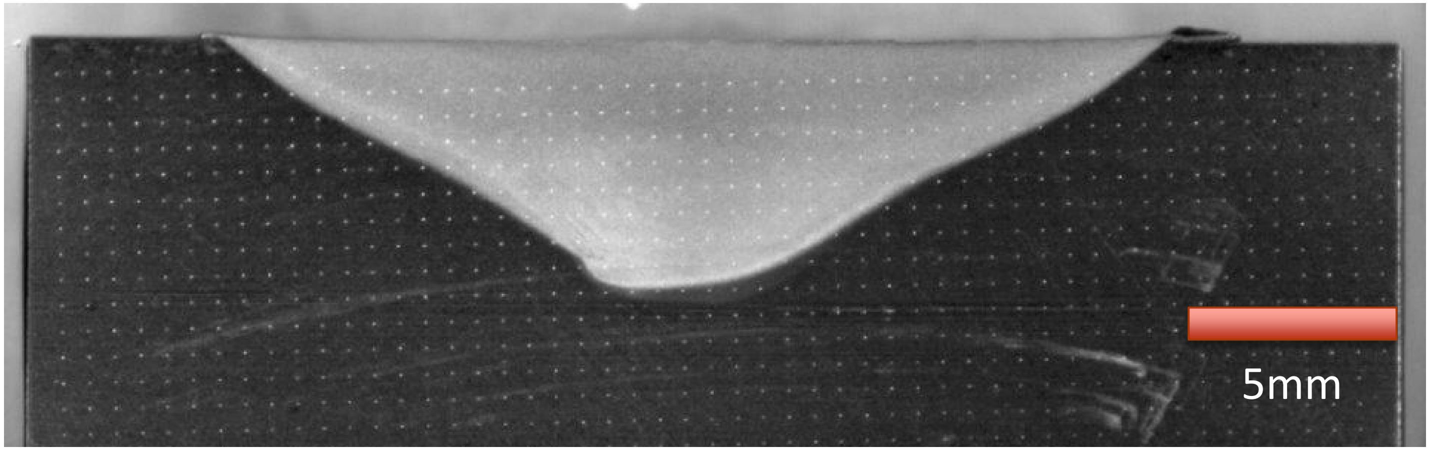
- FSW nuggets have better creep performance than base metal
- Why?
- Weld metal is ultra fine grained and devoid of M23C6 after welding
- MX network develops during creep test?
- Repeat these tests on PWHT sample
- Fine grained may have good implication for performance in creep fatigue

625°C Transverse Creep at different weld process temperatures

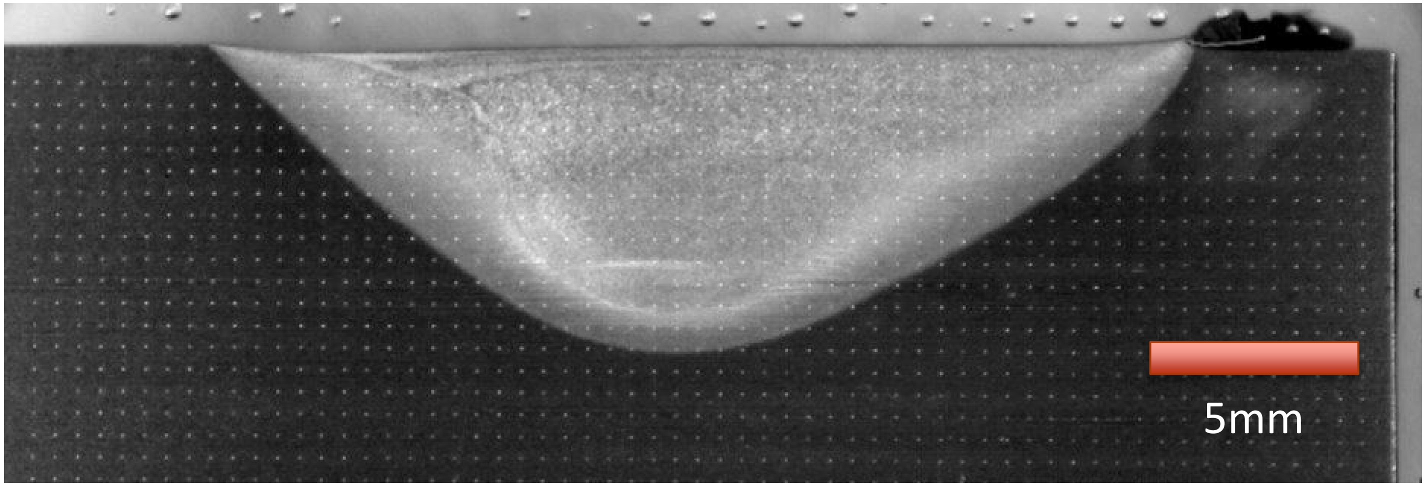


Increasing Weld Process Temperature leads to increasing creep performance

Why does a cold weld perform worse than a hot weld? What are the differences?



Cold Weld
WSRF 0.61



Hotter Weld
WSRF 0.81

- Much wider and diffuse FGHAZ in the hotter weld
- Lower temp weld shows sharp boundary between FGHAZ and base metal

What drives differences in creep in these alloys

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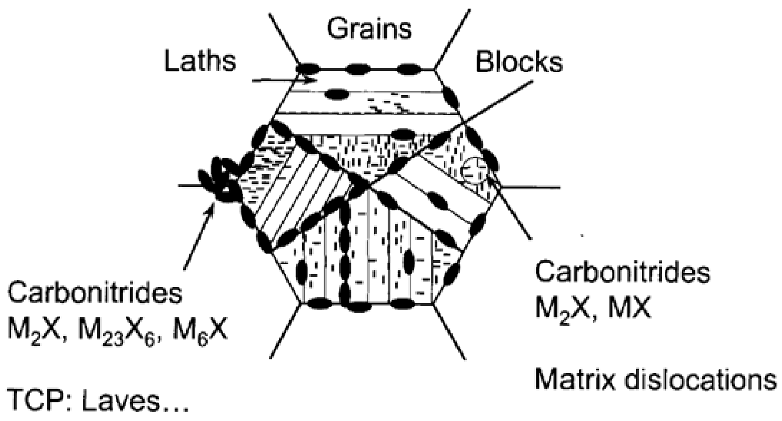
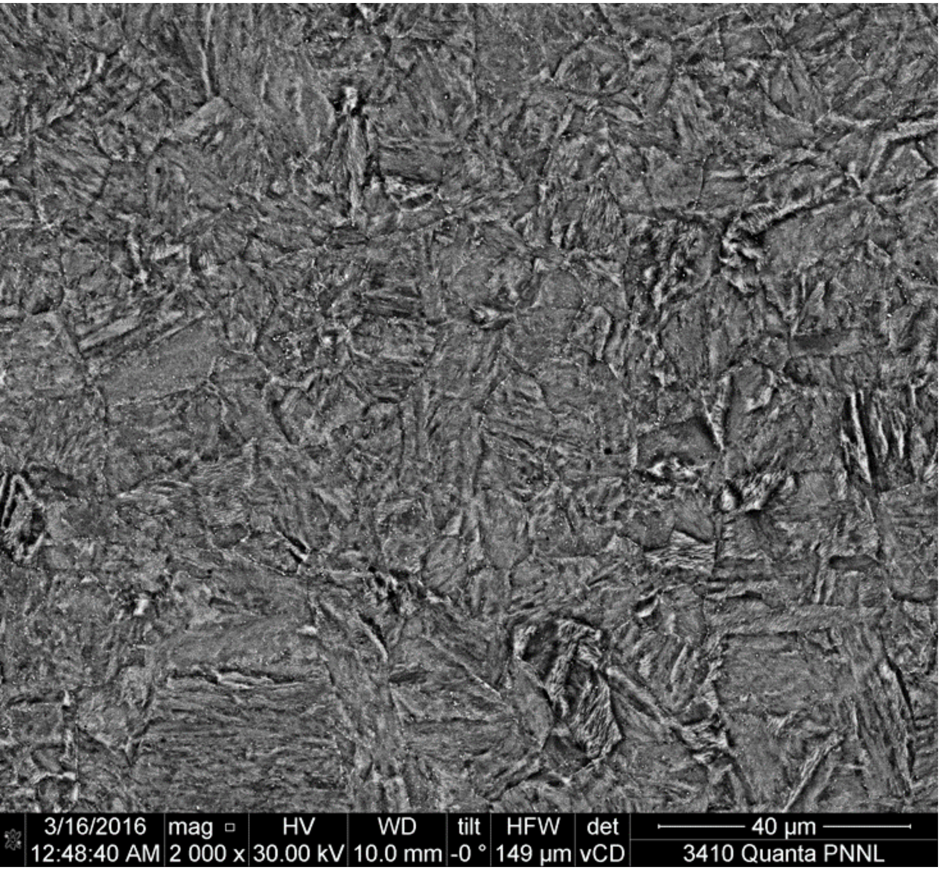
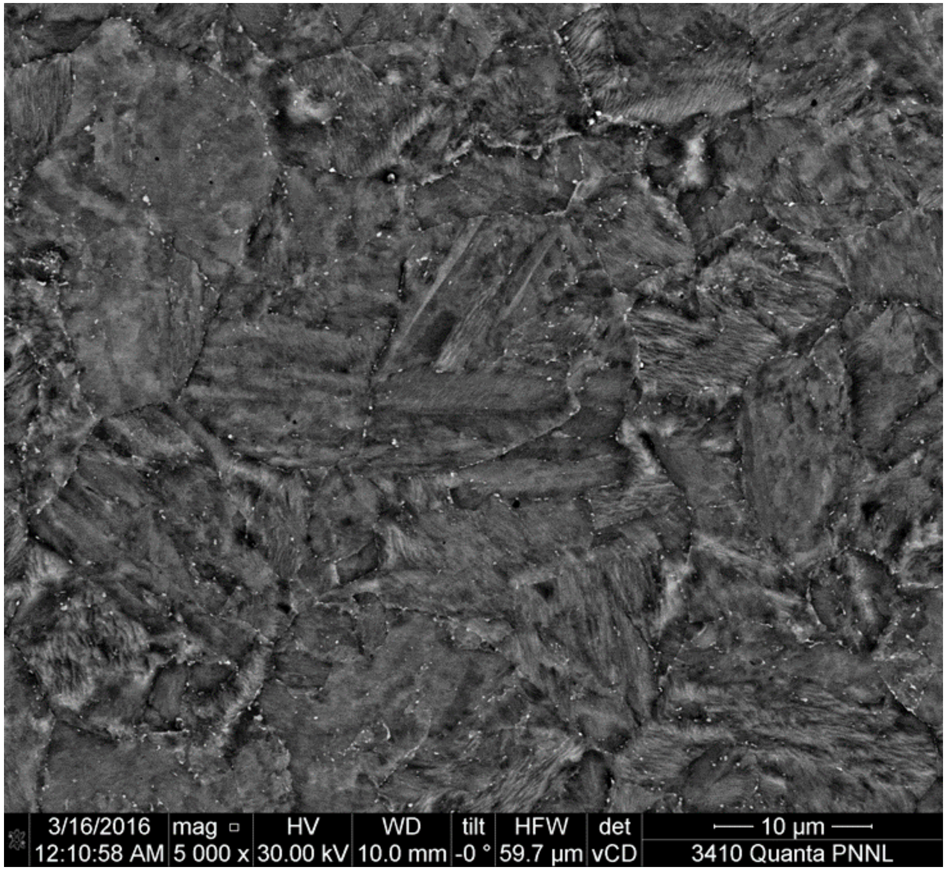
- Fine carbides and carbonitirdes $M_{23}C_6$ and MX precipitates play a critical role in creep strength.
- Where these precipitates are located and their size are key parameters.
- It is hypothesized that a well distributed network of preferably intergranular (or on martensitic lath boundaries) MX precipitates forms the ideal microstructure.
- Coarse $M_{23}C_6$ on prior austenite grain boundaries without significant fine MX is perhaps the worst.



Schematic representation of non-uniform precipitation states in tempered martensitic 9-12%Cr steels (Gocmen et al., 1998)

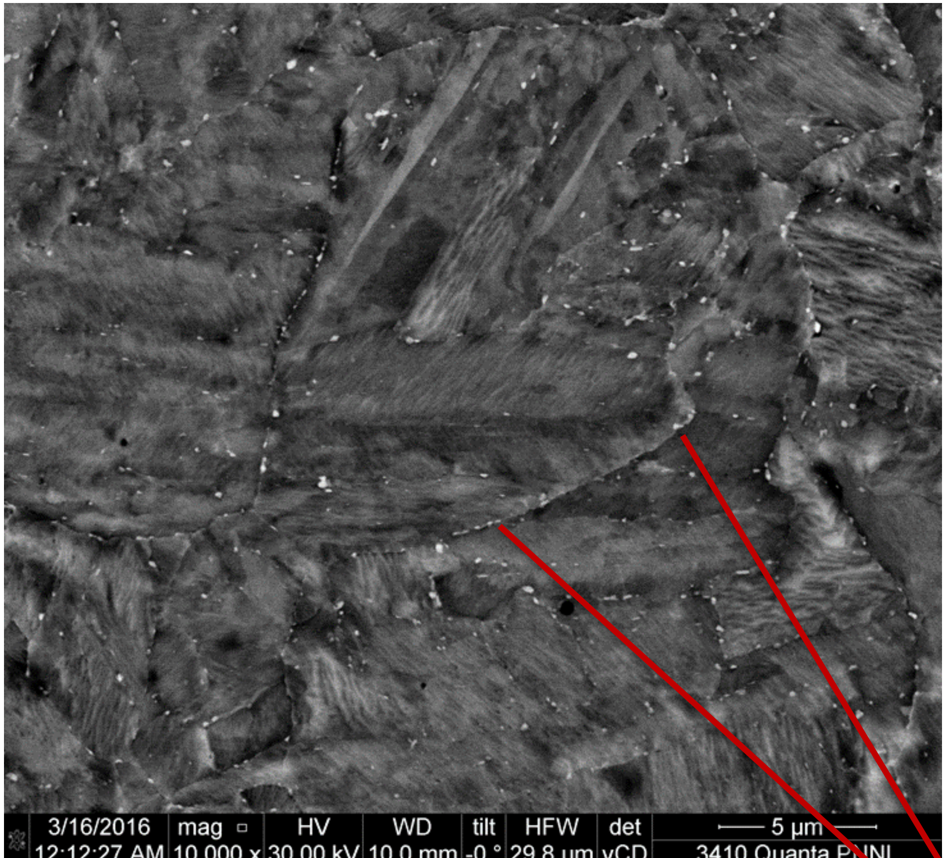
P91 base metal

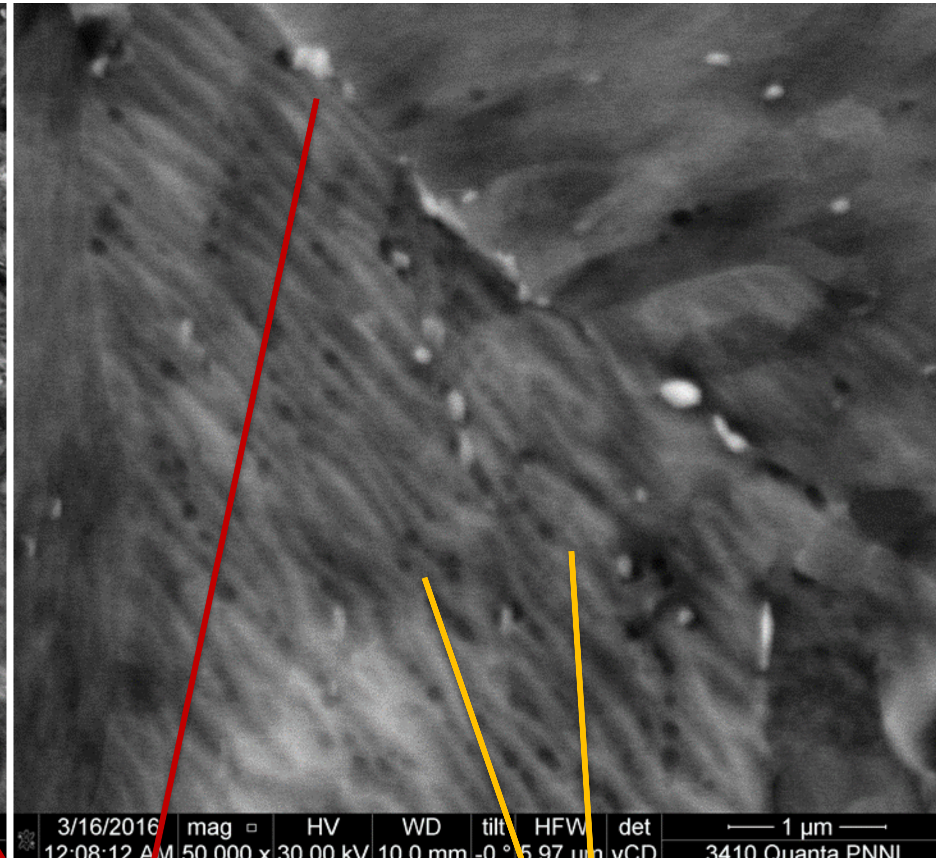




- Microstructure is tempered martensite.
- SEM reveals prior austenitic grain boundaries decorated with white contrast precipitates $M_{23}C_6$ precipitates

Gr91 Base Metal
High resolution SEM imaging

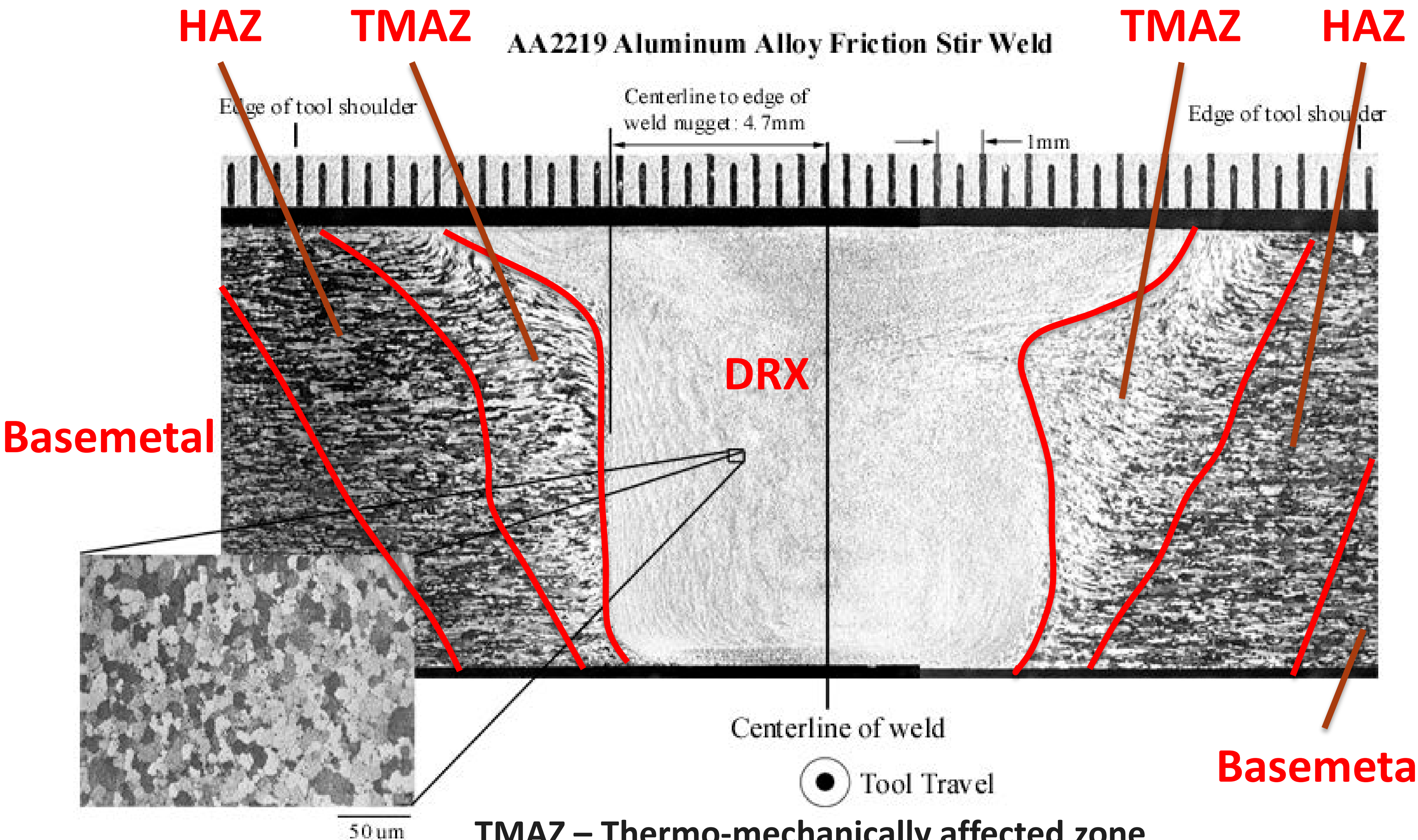




Precipitates at PAG ~up to 100nm+

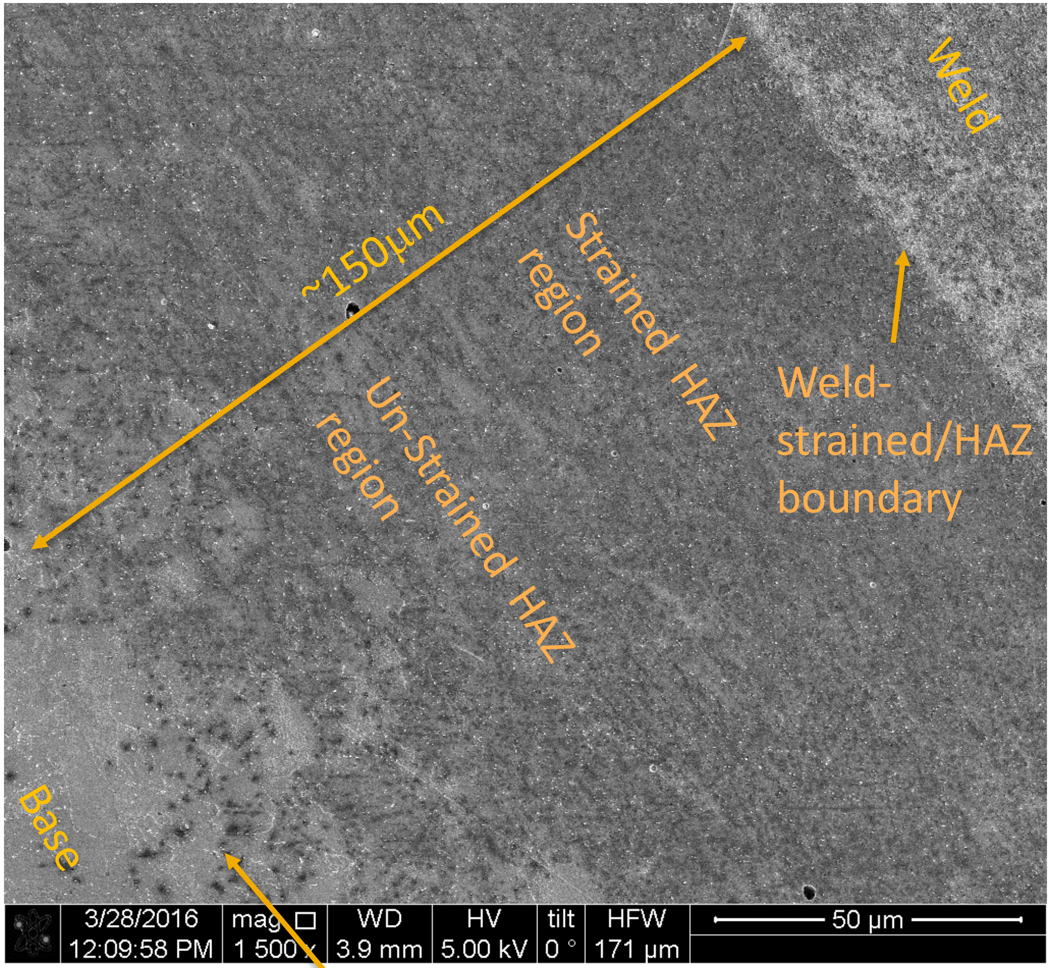
Small dark contrast Precipitates at martensite lath boundaries <100nm size

Typical regions of a Friction Stir Weld
-The TMAZ is unique to FSW



TMAZ – Thermo-mechanically affected zone

Cold Friction Stir Weld
This weld had WSRF of 0.61



base metal-HAZ (ICHAZ) region boundary

- Sharp boundary between the DRX and transformed “nugget” and the FGHAZ region.
- Very narrow “strained” HAZ
- About 150 micron region seen immediately adjacent to the nugget boundary where microstructure is a very fine grained transformation product.

Cold Friction Stir Weld
This weld had WSRF of 0.61

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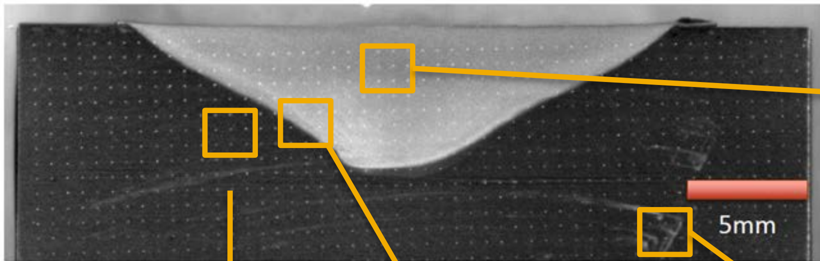
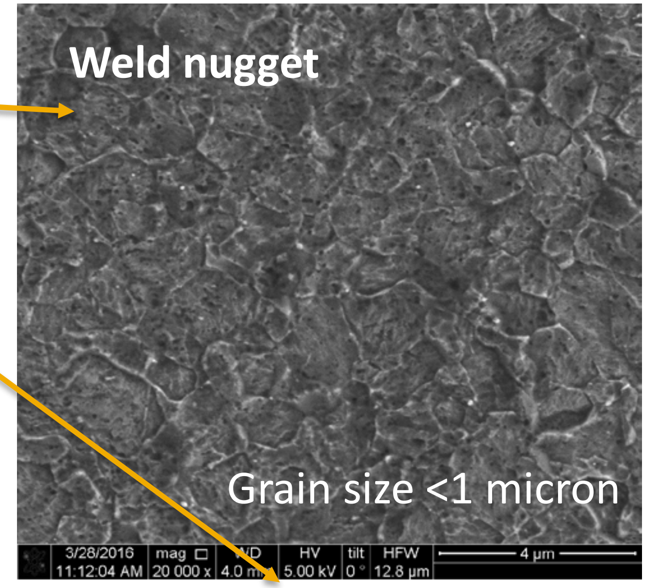
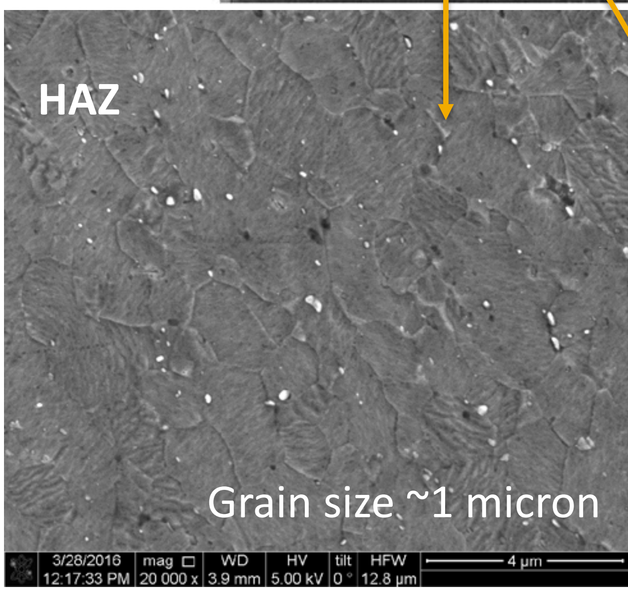
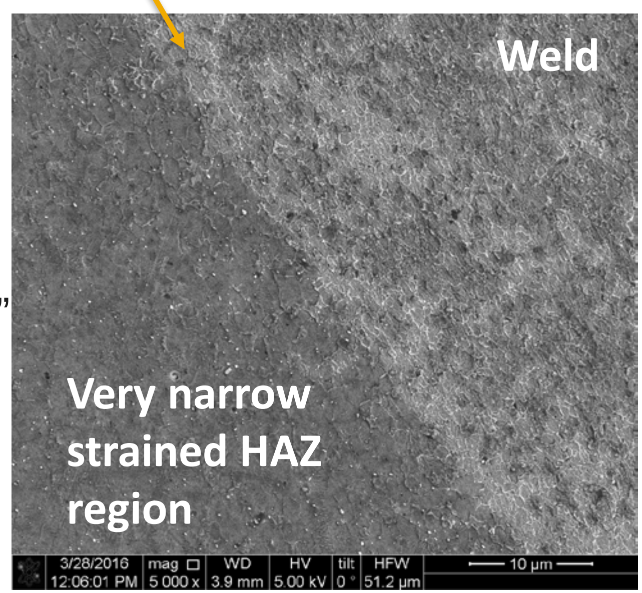
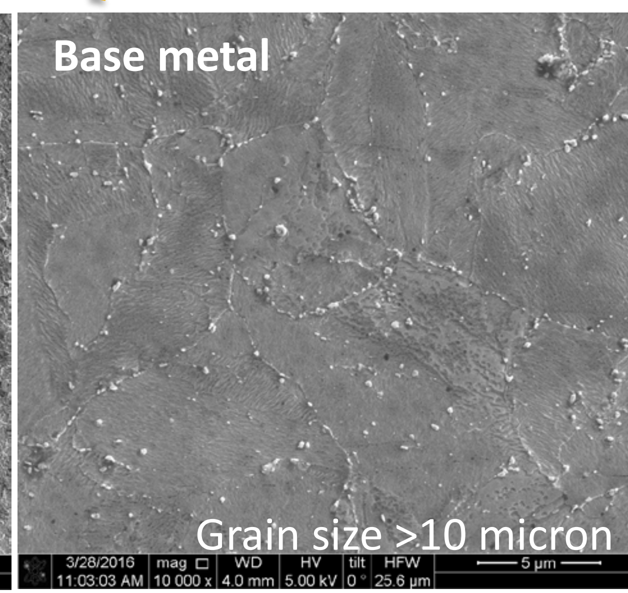




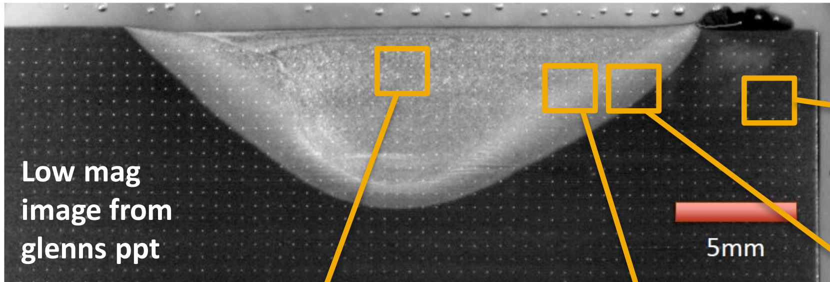


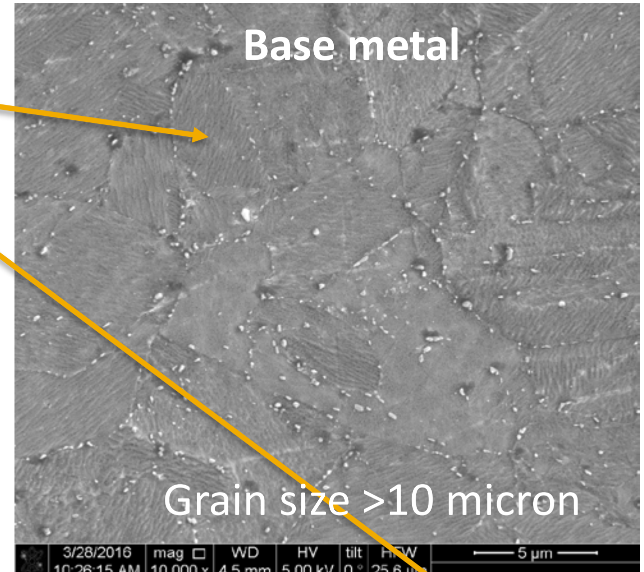




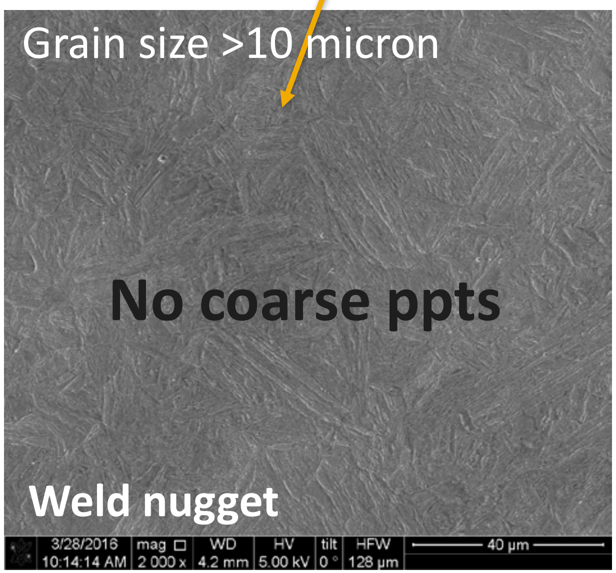
- No coarse ppts in the “nugget” or the very narrow strained HAZ
- Minor ppts in the areas of the HAZ near the base metal (unstrained?)

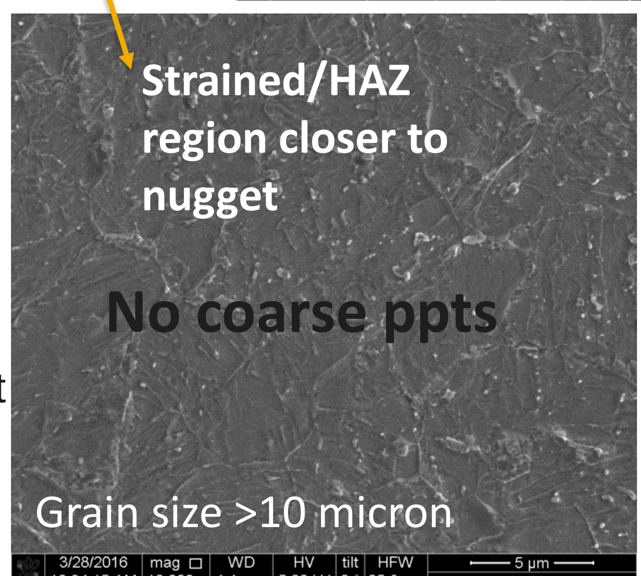
Detailed images of 1000C weld

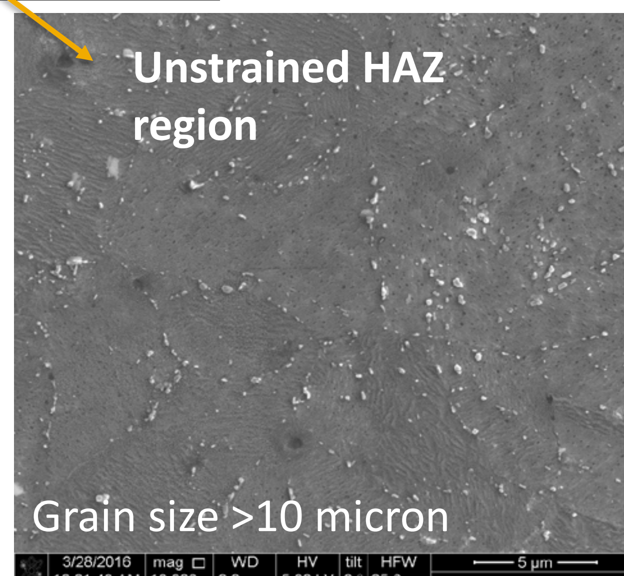




- Wide HAZ
- No sharp boundary between the weld zones

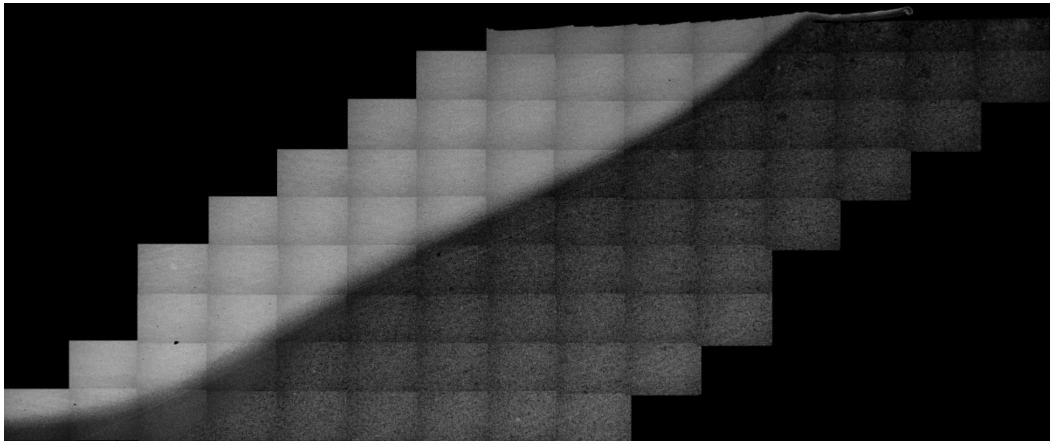






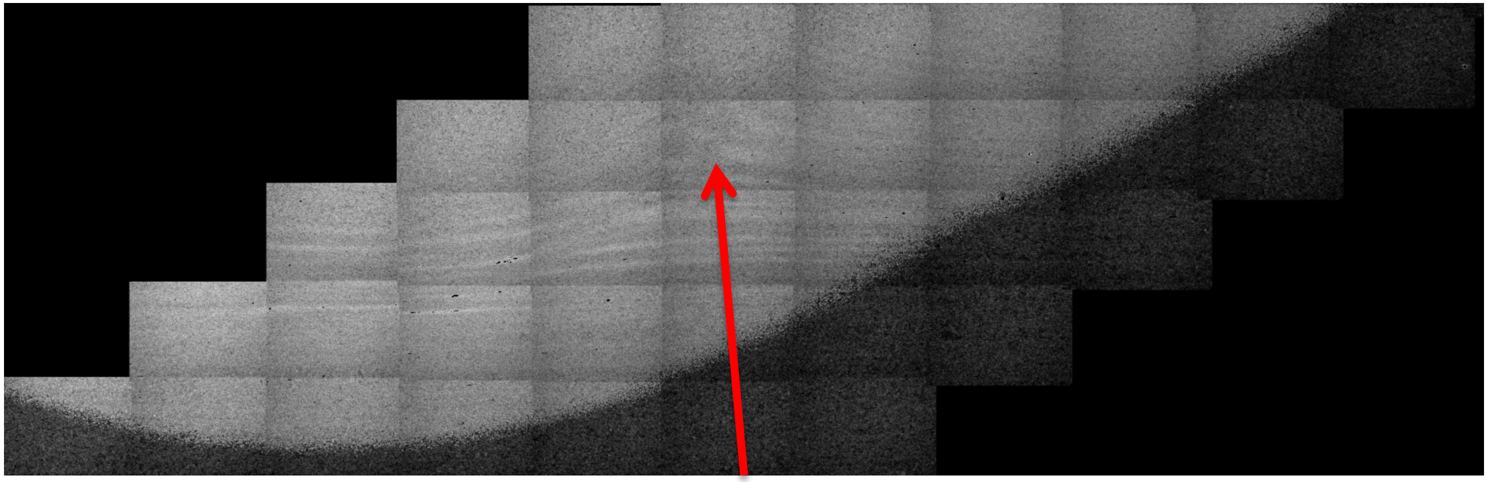
- No coarse ppts in the strained HAZ near the nugget
- Gradually more coarse precipitates as you move into the unstrained(?) HAZ

What makes these two welds different? Temp. at the time of FSW straining and width of TMAZ



Cold Weld
WSRF 0.61

- FGHAZ is narrow and does not extend far from nugget (DRX zone). Strained area is narrow, most of the weld margin is ICHAZ



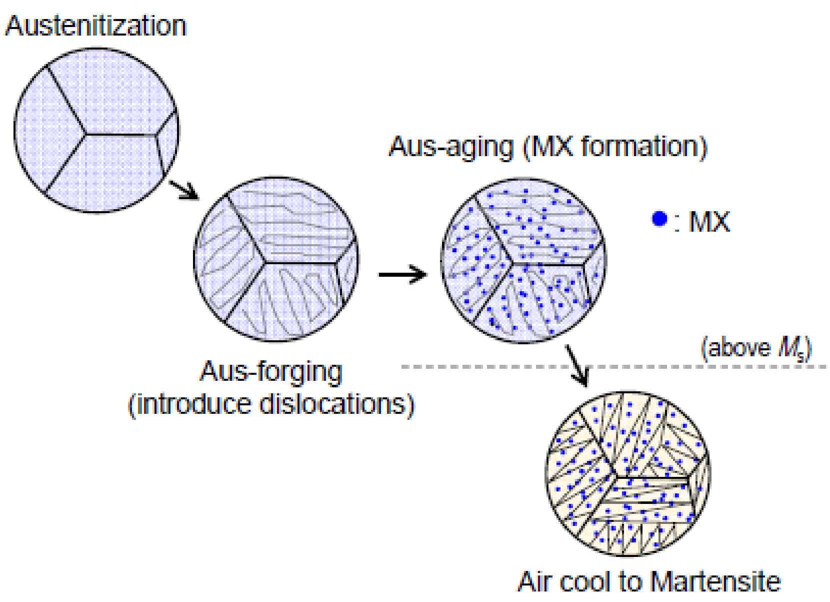
Hotter Weld
WSRF 0.81

- FGHAZ fully extends into a wide strained area (seen as convoluted bands from original plate rolled structure). This strain is introduced during the time the region is above AC3.

Why is FSW better?

- Ausforming? – strain induced dislocations from FSW in the austenite phase field may help to retain or create a dispersed MX distribution on dislocations upon cooling
- The hot welds, which performed better, had wide FGHAZs that underwent straining above AC3. The cold welds had transformed regions that barely extended past the DRX (nugget) zone and had only narrow areas of material that was strained above AC3.

Yukinori Yamamoto, et al., 2014



- A effort is underway using TEM and APT to see carbide and carbonitride distribution between these two welds and the relationship between carbide distribution, creep performance, and the effects of FSW strained microstructure on MX distribution.

Next Steps: P92 FSW welding

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- Not able to find vendor for A1017 Grade 92 plates
- Purchased ~1000lbs of NPS8” x XS x ~24ft of ASTM/ASME A/SA335 P92 pipe (JFE Steel Corporation)
- Pipe split (water jet) and flattened (750TON press break) at BBC Steel, Canby OR
  - 36 plates – 6” x 8” x 0.5”
  - 63 plates – 10” x 8” x 0.5”
- Heat treated at Pacific Metallurgical Inc. Kent, WA
  - Sandblasted to clean surface of paint etc.
  - Normalized: 1050°C, 20min. vacuum
    - Nitrogen gas quench >5C/min. (10+C/min. to below 93C)
  - Temper: 760C, 60min. Vacuum
    - Nitrogen gas quench >5C/min. (10+C/min. to below 93C)
- Plates machined flat at PNNL

Examples of some of P92 welds made

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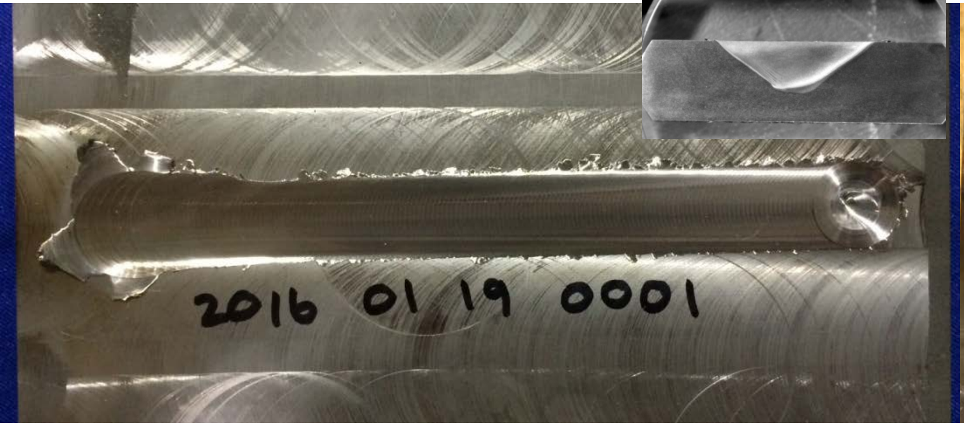
- Welds made at a variety of conditions and temperatures w/ Q70 tool
- Looking at defects, microstructures, hardness, creep

4IPM/100RPM/715C



4IPM/100RPM/800C

4IPM/TC/900C

4IPM/400RPM/960C

Next Steps - FSW Trials on other CSEF steels

- After P92 will look at CPJ-7 fabricated at NETL Albany, OR
- Interesting aspect of FSW:
  - elements added to steel do not have to also satisfy fusion weldability concerns. High Carbon and Boron present no problems to solid state welds.
  - New chemistries may be considered because of FSW.
- Fatigue and creep fatigue testing of FSW Gr 91 and 92
- Prototype weld for P91 pipe

Conclusions

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- CSEF steels are Friction Stir weldable
- Creep performance is very good, both of the weld metal and in cross weld tension – current results indicate that tool temperatures greater than 865C are beneficial and can reach WSRF of 0.81
- It is possible that WSRF can be raised by more than 10% from fusion welded equivalents and it is possible that FSW may allow for a reduced requirement for PWHT
- **FSW allows for enough knobs to be turned in the process to customized heat input.**
- **It may be possible to follow a path through thermo-mechanical space that will leave the weld region and especially 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