Friction Stir Welding of ODS Steels – Steps toward a Commercial Process

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Presented at the Workshop:
Fe-Based ODS Alloys: Role and Future Applications

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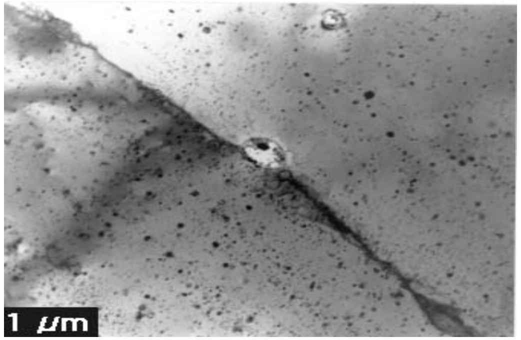
ODS Alloys: Incorporate a dispersion of nanoscale oxide particles (such as Y_2O_3) in the ferritic matrix to mitigate grain boundary movement and allow greatly improved creep and high temperature strength while maintaining good toughness



MA 956

H. K. D. H. Bhadeshia, Univ. of Cambridge website

Barriers:

- Traditionally produced by powder metallurgy methods that tend to be costly - Commercial viability requires new processing and manufacturing technology
- Unfavorable anisotropic properties can result if processed improperly for the application
- Cannot be welded by melt/solidification processes

Liquid phase methods such as brazing and fusion welding lead to regions within the joints that are devoid of the dispersoids

Alternative joining technology must be considered:

Potential methods include explosive bonding, resistance upset welding, diffusion bonding, rotary friction welding, transient liquid phase bonding, and friction stir welding (FSW)

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Approach to Producing a Commercial FSW Joining Process in ODS Alloys

- Stage 1
  - Develop a robust FSW welding process for at least ¼ inch thick ODS plate
    - Several groups worldwide looking at this, most looking at thin sheet <1/4"
  - Verify that the resulting joint will produce acceptable mechanical performance.
  - Verify the creep and creep rupture performance of welds
  - Verify the SCC and general corrosion performance at service conditions

- Stage 2 - Show that the process is deployable by:
  - Produce process/performance data for code qualification
    - Help where we can to get code cases started
    - Develop statistical confidence around essential variables (what are they and what are their ranges)
    - Develop weld quality assurance methods and statistical process control based on weld data obtained at the time of welding
  - Developing techniques to join heavier sections
  - Quantify process costs (Esp. tool durability and cost)
  - Transition joining approach to commercial-scale tube/pipe applications

Outline of Talk

- FSW Overview / Potential Process Advantages
- FSW of Kanthal APMT (as an illustration of FSW on an ODS Ferritic)
- ODS Microstructural and Mechanical Property Response to FSW
- Issues around Commercialization

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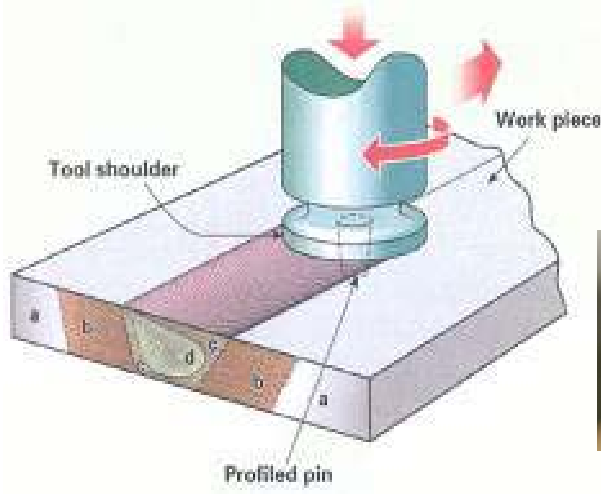
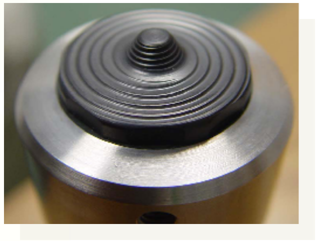
Friction Stir Joining

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 a recrystallized and transformed microstructure

Economic Advantages

- Single pass method – Faster on thick section welds
- No Consumables
- No Environmental Emission
- No “Expert” Operators
- Lower energy consumption than equivalent fusion weld

Process advantages

- Often lower peak temperature and total heat input than fusion welding, so:
  - Lower residual stress and distortion
  - Reduced HAZ
  - Less sensitization for corrosion
- Higher toughness joint, Better damage tolerance and fatigue performance
- Fine grained nugget less susceptible to hydrogen induced cracking
- Fine grain nugget is more amenable to NDE (x-ray, ultrasonics, etc.)

Friction Stir Welding of 20Cr-5Al-Y-Ti-Hf Ferritic ODS (Sandvik Kanthal APMT)

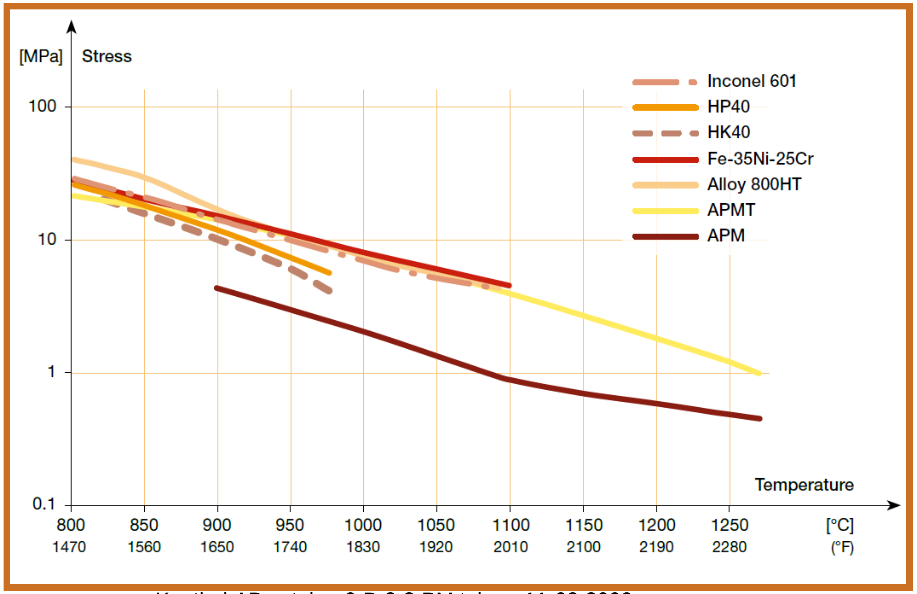
- 20Cr 5Al Ferritic steel with good high temperature creep resistance and oxidation resistance similar to some austenitic steels (contains nanophase carbides and oxides)
- Gas atomized product not an MA alloy
- Alumina former to protect against corrosion and carburization

Composition (wt%)

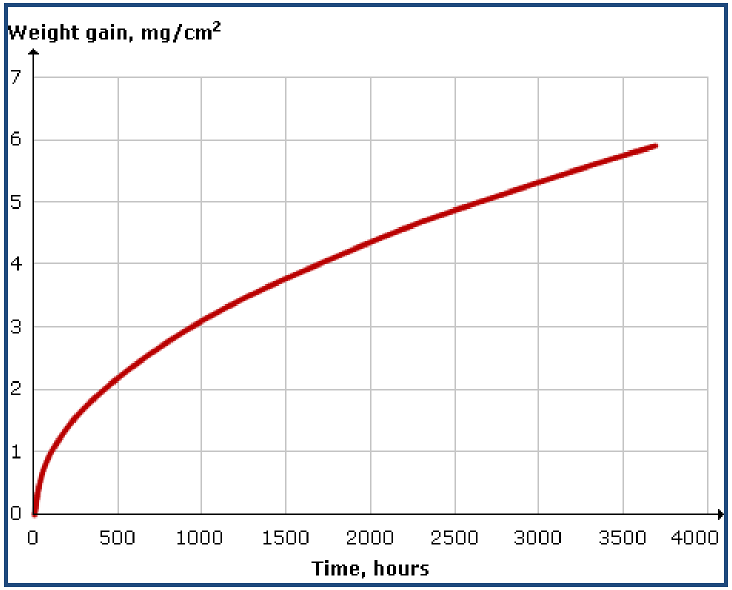
Fe	Cr	Al	Y	Zr	Hf	Ti	C	S	N
balance	20-23	5.0	0.1	0.05	0.1	0.02	0.03	0.002	0.05

G.J. Tatlock et al., Materials and Corrosion 2005, 56, No. 12

10,000 hr Creep Rupture



Kanthal AB catalog 6-B-2-3 PM tubes, 11-08 3000



Designed for very high temperature applications in ethylene production and heating elements

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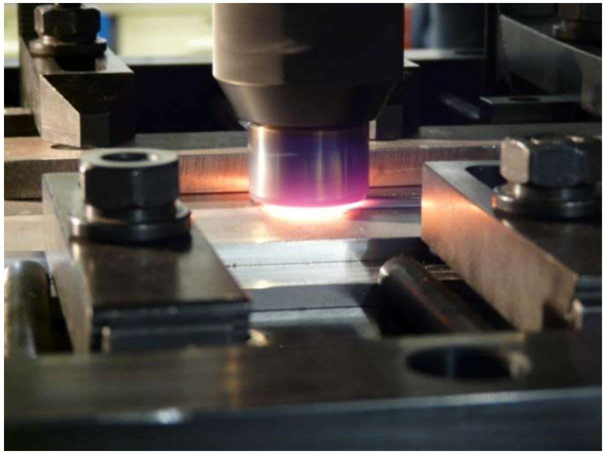
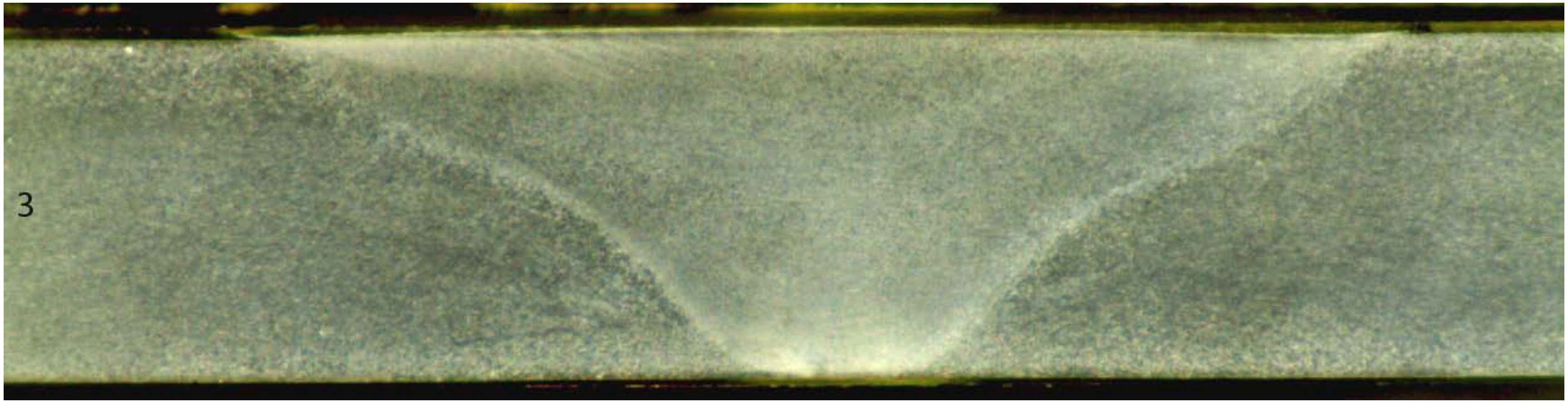
FSW Parametric Study

- **Tool: PCBN Convex scrolled shoulder stepped spiral pin tool, 0.25” pin length**
- **Process Variables:**
  - **Weld speed (4 – 8 ipm),**
  - **Spindle speed (300 – 600 rpm),**
  - **Tool load (load controlled at 3000 – 7000 lbs)**



0.25”



Fully consolidated, defect-free welds were made under a range of process parameters

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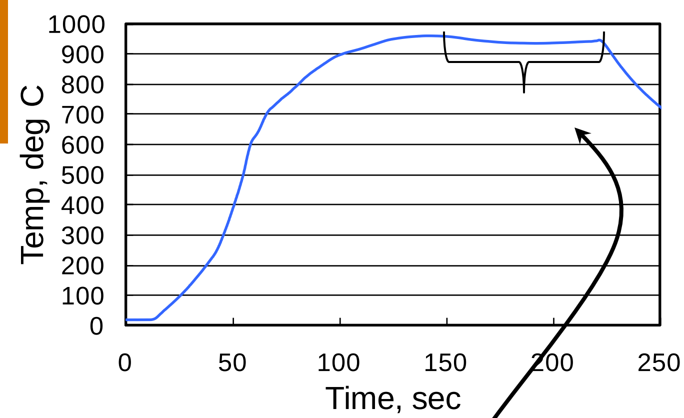
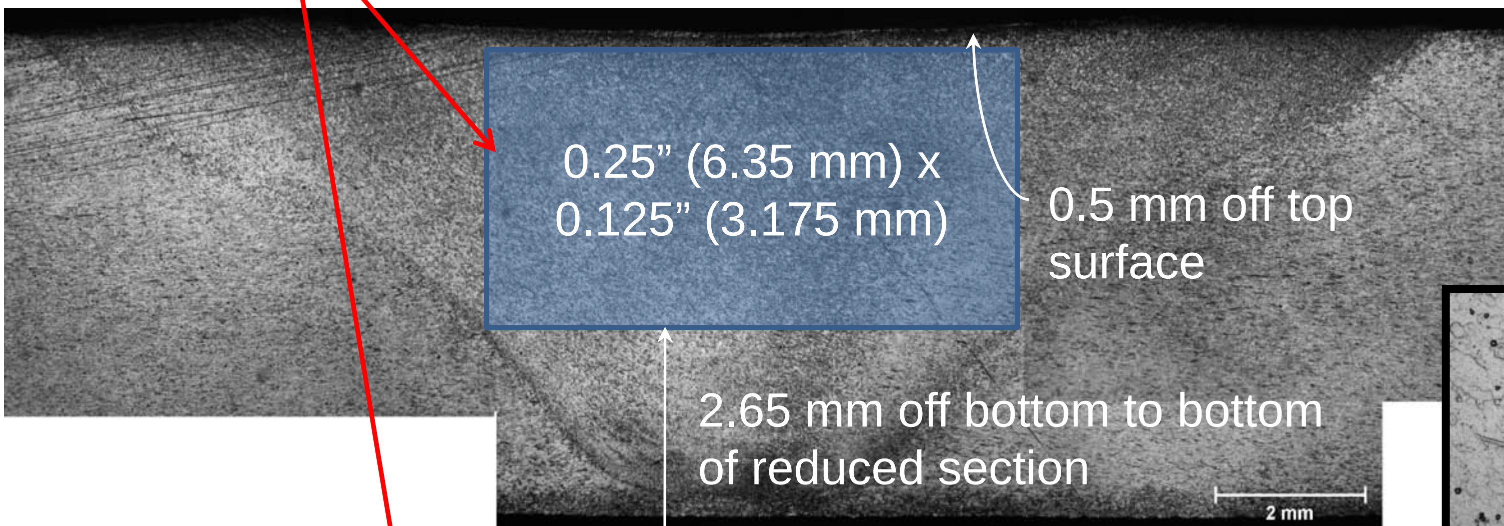
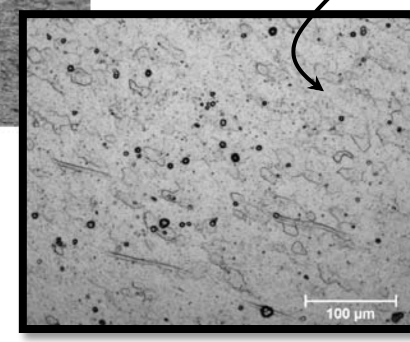
Creep Rupture Testing of Weld Metal

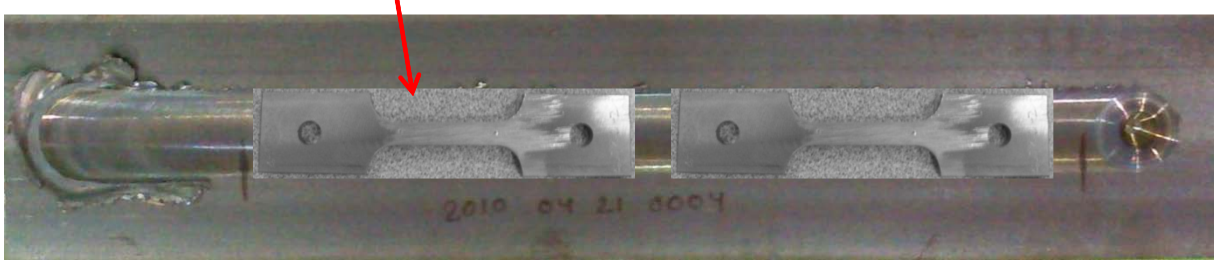
- We have not characterized the fine dispersoids in the weld vs. parent.
- Decided to go straight to creep testing as an indication of appropriate weld metal microstructure
- Creep samples cut only from weld nugget material along length of weld



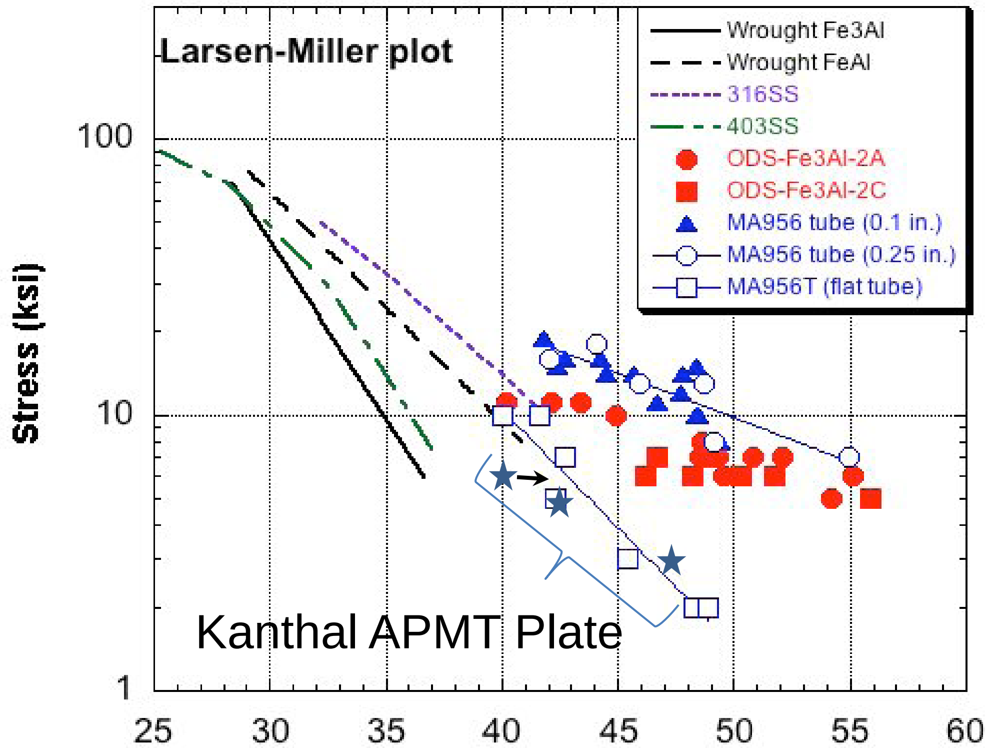
Specimens from thermally stable region With consistent grain size

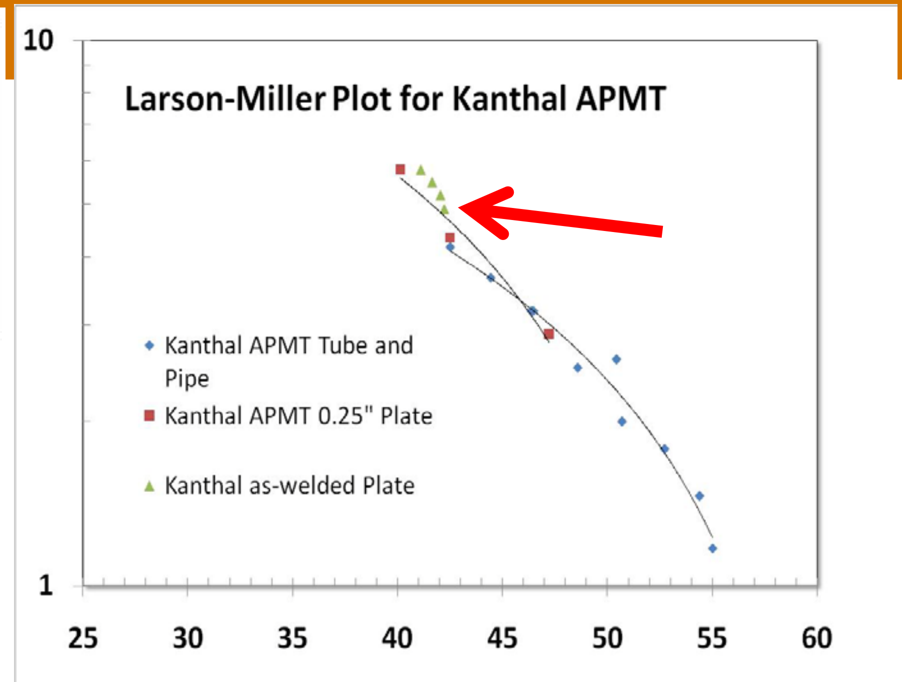






Creep Rupture data for Kanthal





$$P = [T(F)+460][20+\log t_r(h)](10^{-3})$$

- Creep Rupture Tests on Kanthal Plate Base Material
- Kanthal Weld Material tested at 750ºC
- FSW is producing weld metal with similar creep rupture properties to base material

Weld metal data is on trend, slightly higher than base metal

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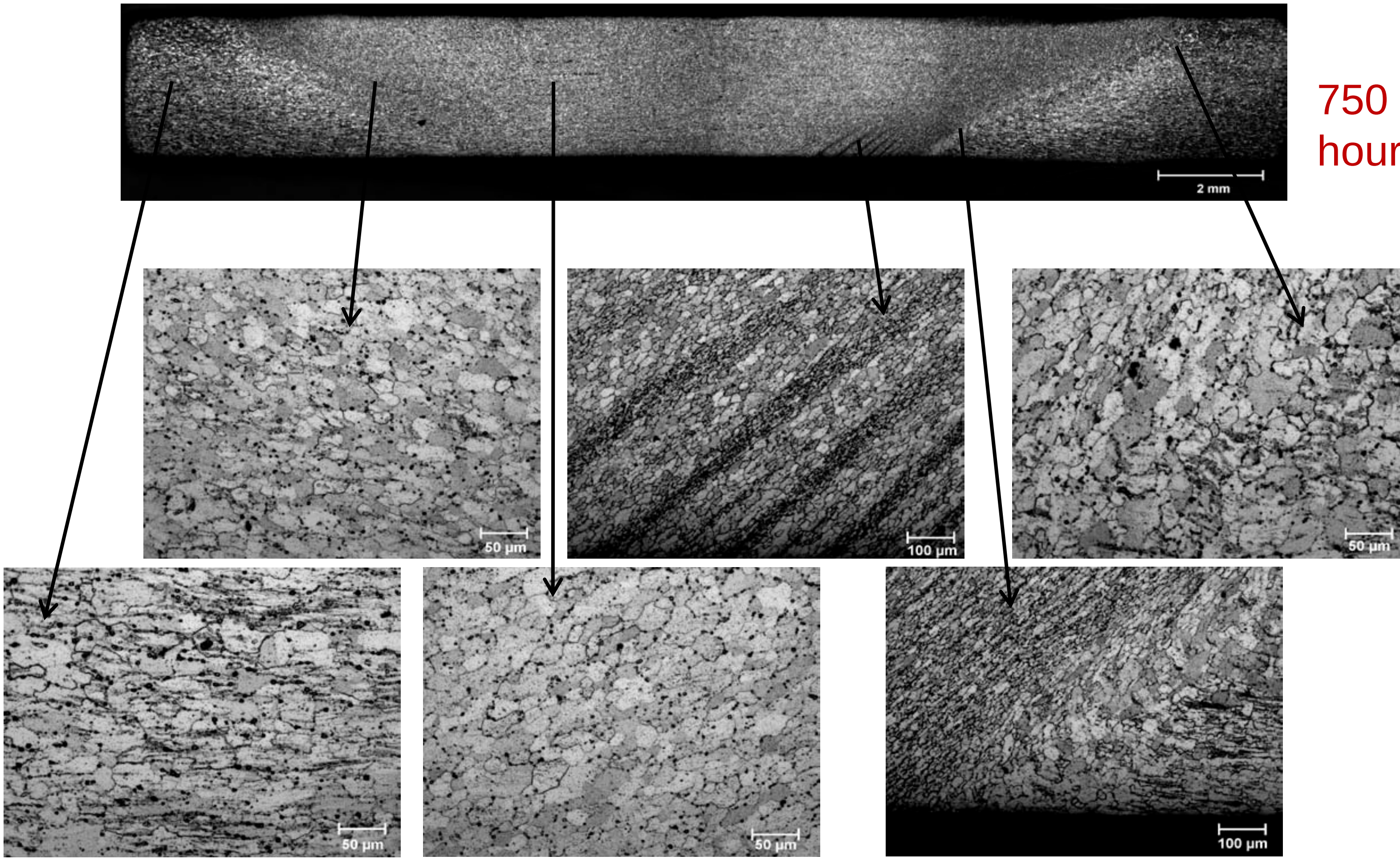
Response to high temperature of as-welded material – microstructure stability

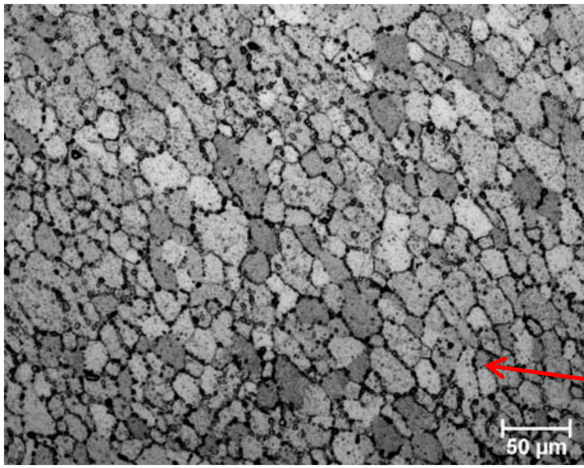
- At 670 hours nugget grain size is still same as parent plate (on ST plane). Very little grain growth observed in nugget or parent.

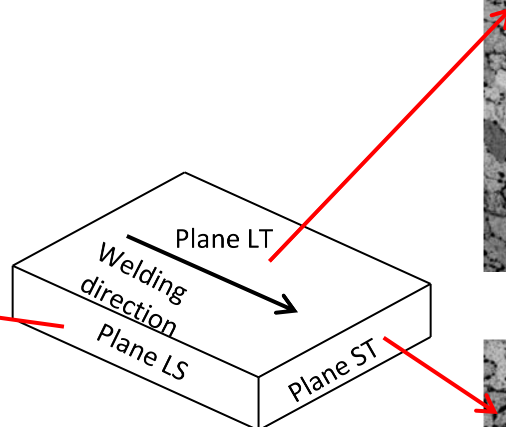


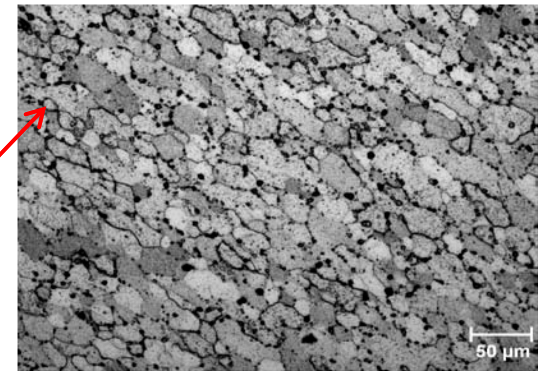
750 C for 670 hours

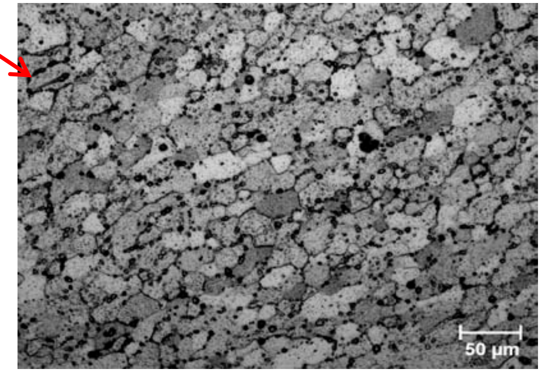
Response to high temperature of as-welded material

- Details of the weld nugget from the creep strained gage area of a creep rupture specimen tested at 750C 670 hours





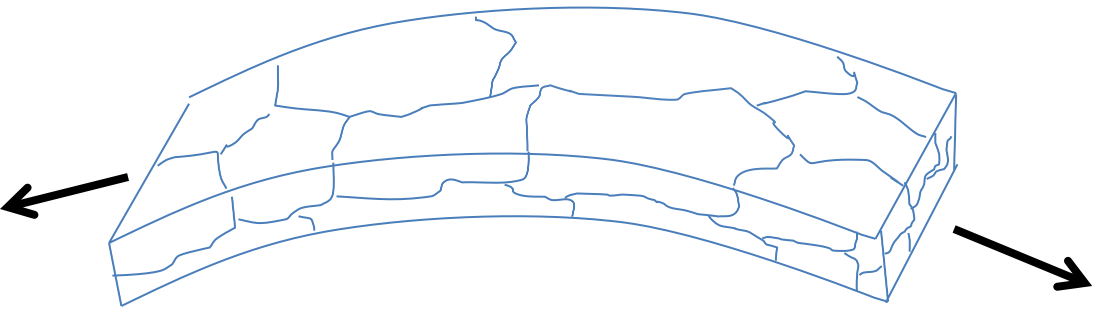


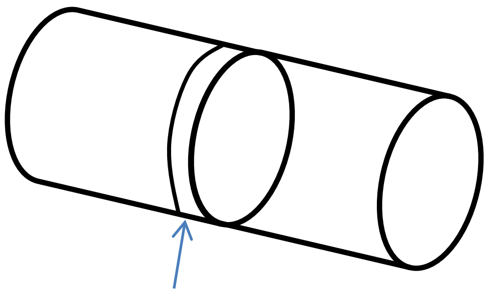


- Grain size similar to parent
- Oxide particles are no longer aligned in stringers
- Large number of particles are on grain boundaries but many intragranular as well
- Microstructures provide explanation of similar creep rupture performance between parent and weld
- What happens if we provide PWHT?

Customizing microstructure for creep

- Creep enhanced ferritic tubing materials are designed and processed to produce elongated grains in the primary direction of creep stress – the hoop direction – the “onion skin structure”





  - This structure grows during the heat treatment of highly textured, wrought precursor microstructures developed in the extrusion/forging/pilgering of the tube
  - Melt solidification joining destroys this texture
  - FSW may have a big advantage here:
    - Grain size/grain boundary energy can be adjusted by the process parameters
    - May be able to grow grains in a “good” direction

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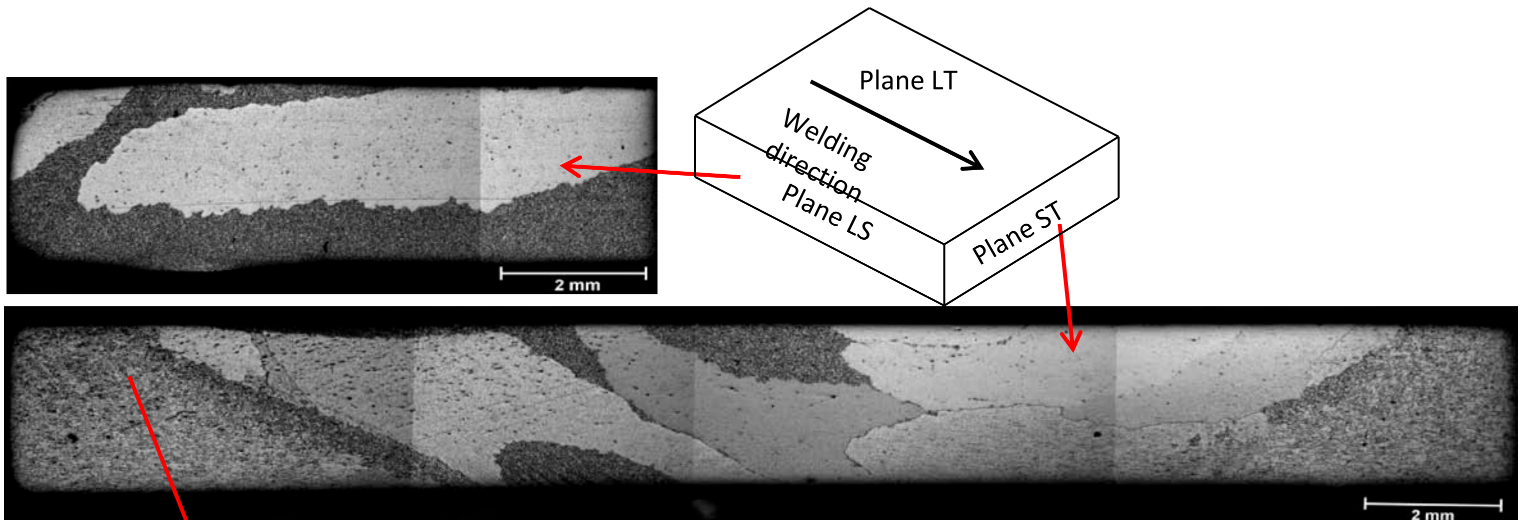
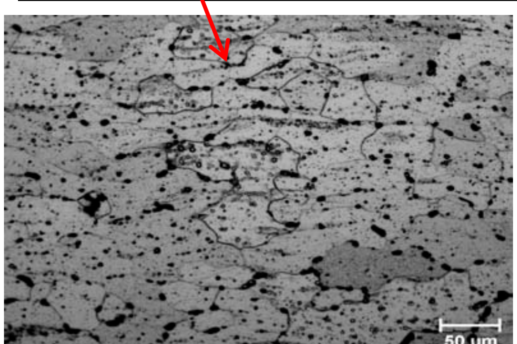
However, can get too much of a good thing

Abnormal Grain Growth in the FSW weld nugget

- If the FSW weldment is subjected to 1350 C for 1 hour, the nugget region undergoes explosive grain growth
- The grains are elongate in the weld longitudinal direction, with is the circumferential direction in a girth welded tube or pipe





- Parent metal showed slight grain growth but weld metal grew some grains over 6mm long in the LS and ST directions

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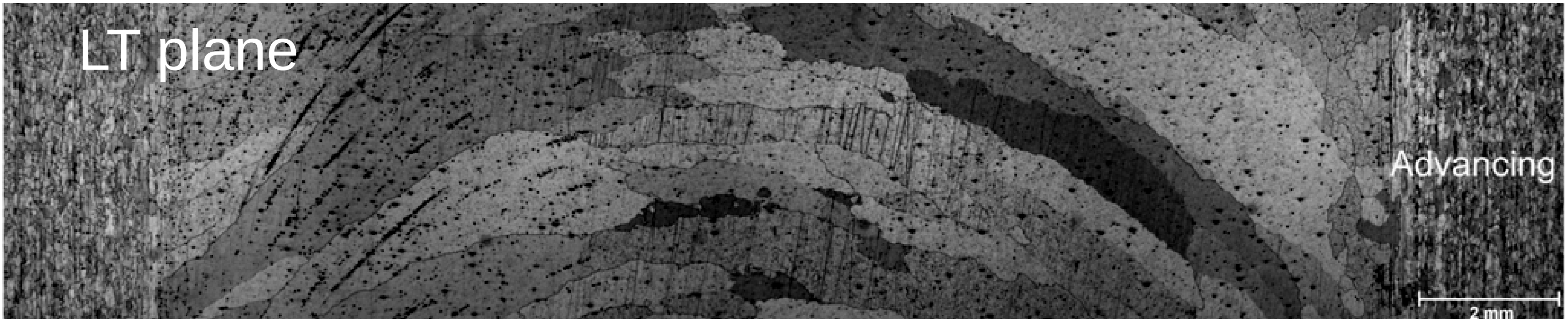
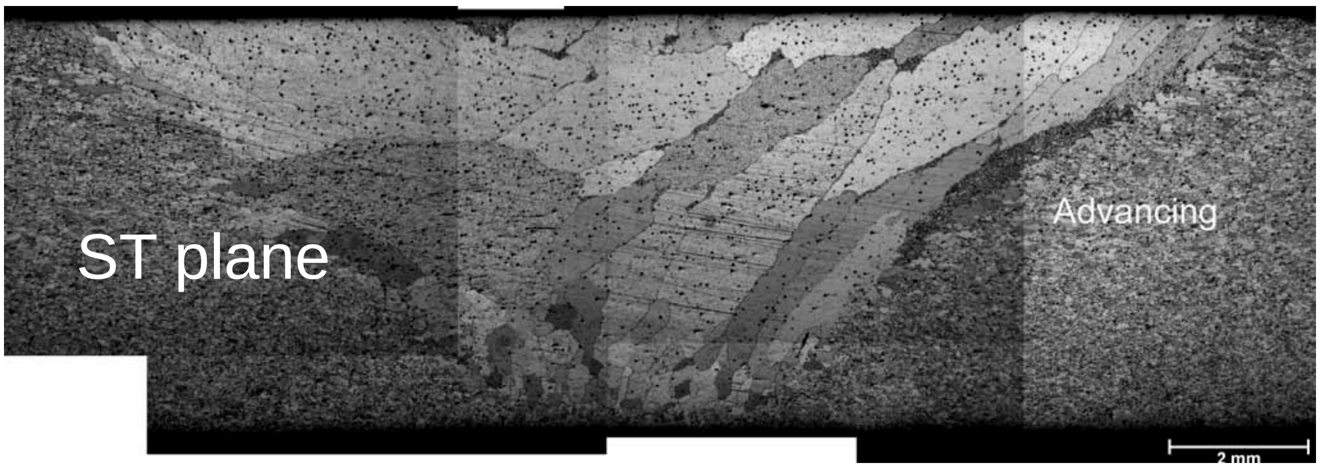
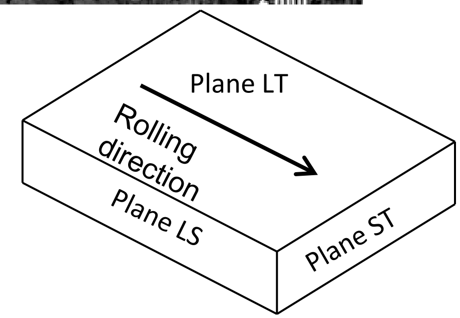
Microstructure of the welded + heat treated Kanthal plate







Heat treatment at 1350 C for 2 hrs led to generation of semi-circular shaped grains one the top surface of the weld nugget, but produced grains elongate in the weld direction just below surface.

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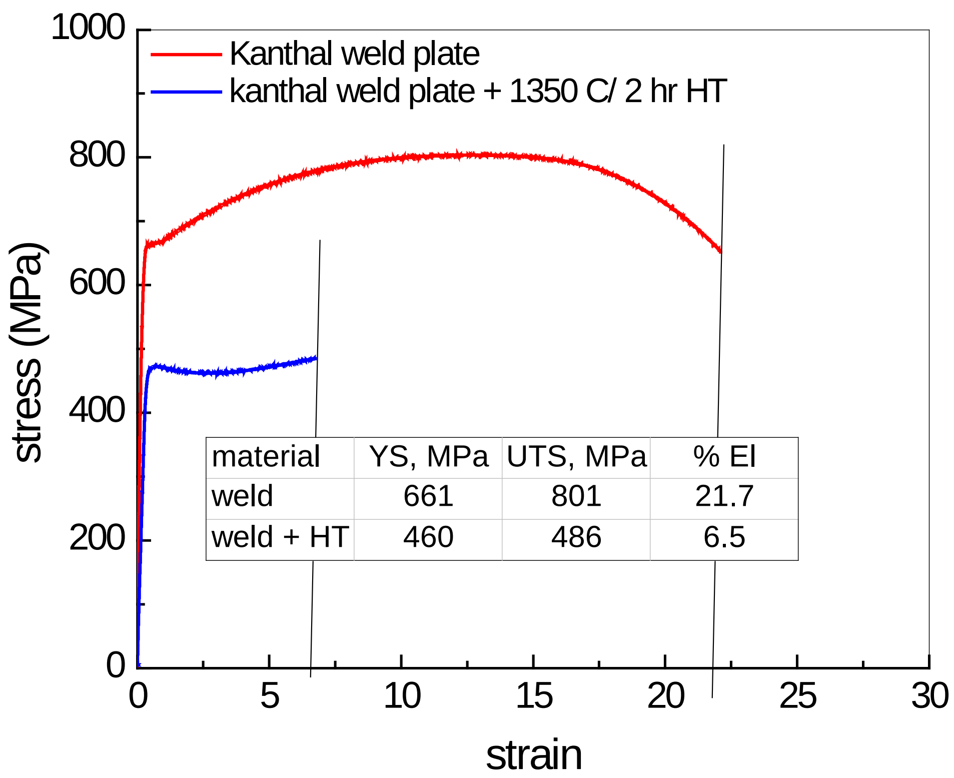
Room temperature tensile test results: as welded weld metal vs. as welded and heat treated weld metal (1350 C for 2 hr) with AGG



material	YS, MPa	UTS, MPa	% El
weld	661	801	21.7
weld + HT	460	486	6.5

As welded specimen

As welded + HT specimen

- Heat treatment (HT) led to abnormal grain growth (AGG) inside the weld nugget. Very coarse grains are clearly visible in the grip area of the heat treated tensile sample.
- AGG resulted in significant reduction on both the room temperature strength and elongation values.
- Don’t know creep performance yet
- 750 C showed no AGG, no reason to PWHT to 1350 ? If we can avoid it we should
- Other way to avoid it is with process parameters choice

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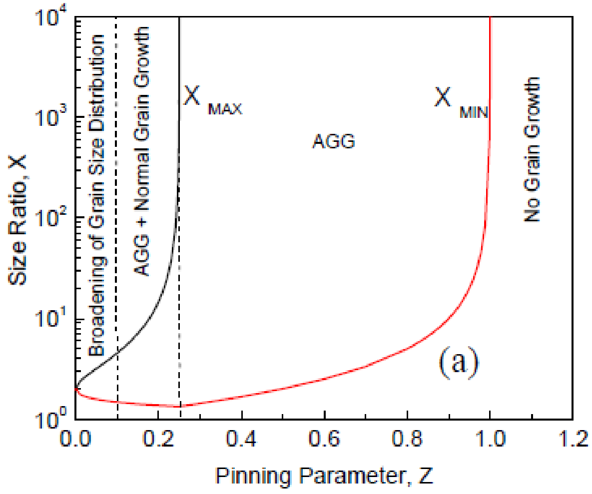
Avoiding AGG

Grain Size Ratios, Zenner Pinning parameters and 2nd Phase Homogeneity

<u>Humphries Model</u>

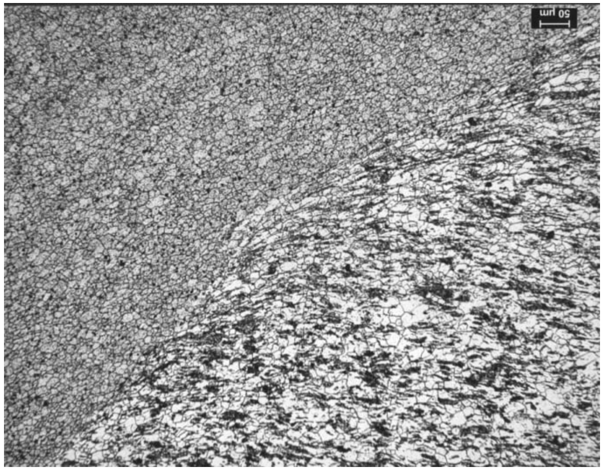
Competition between size ratio and pinning parameter (Z)

Different process parameters can produce different 2nd phase particle size (and grain size)changing both Z and X



Effect of homogeneity

- Multipass vs single pass suppresses AGG (in multipass particles are no smaller, grain size is not changed, but the particle size ratios (ratio of largest and smallest grain size to the mean grain size) throughout the nugget (especially edge to interior) are more homogeneous and AGG is suppressed



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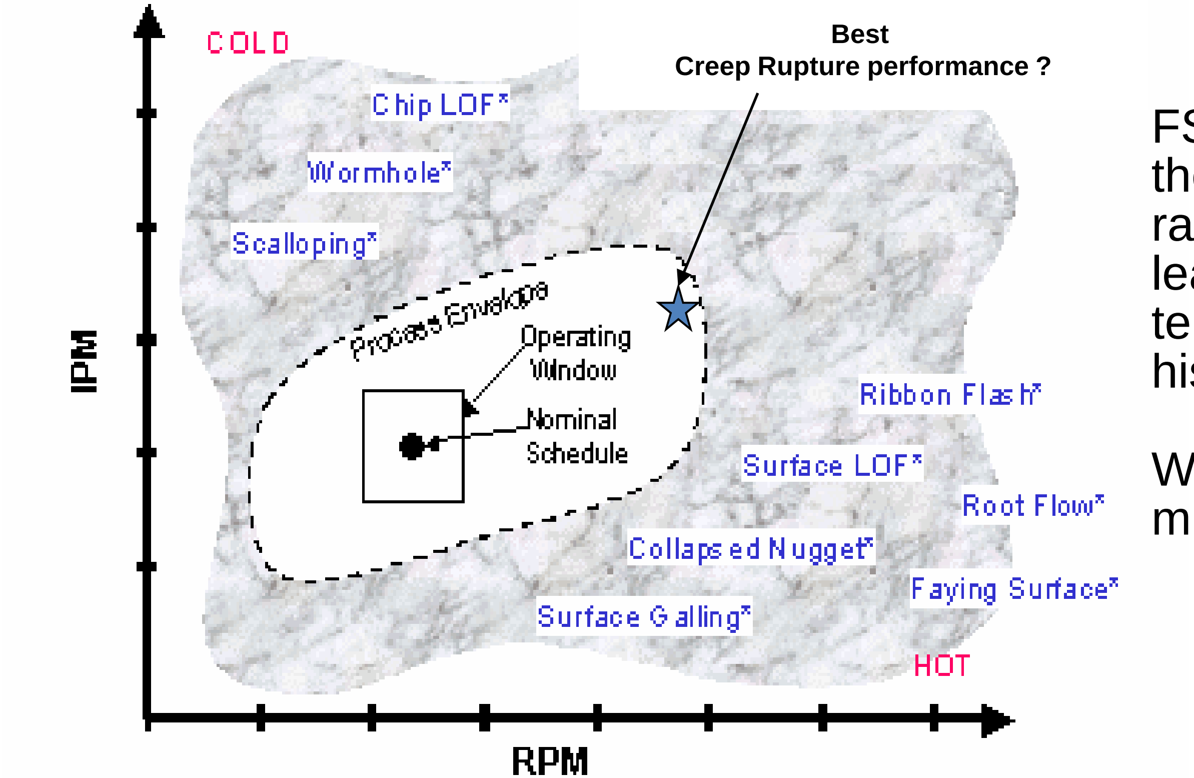
FSW is a Thermomechanical Controlled Process

- In many material systems the FSW process window is large
- A large process window means a wide range of weld specific power levels can be used and still result in a defect free weld
- We have seen many cases where the best performance in RT strength is located at a different place in the process space from say ductility or creep



FSW allows you to process the material across a wide range of specific power leading to different strains, temperatures, and thermal histories

With that you can optimized microstructures

Modified from Arbegast, 2001

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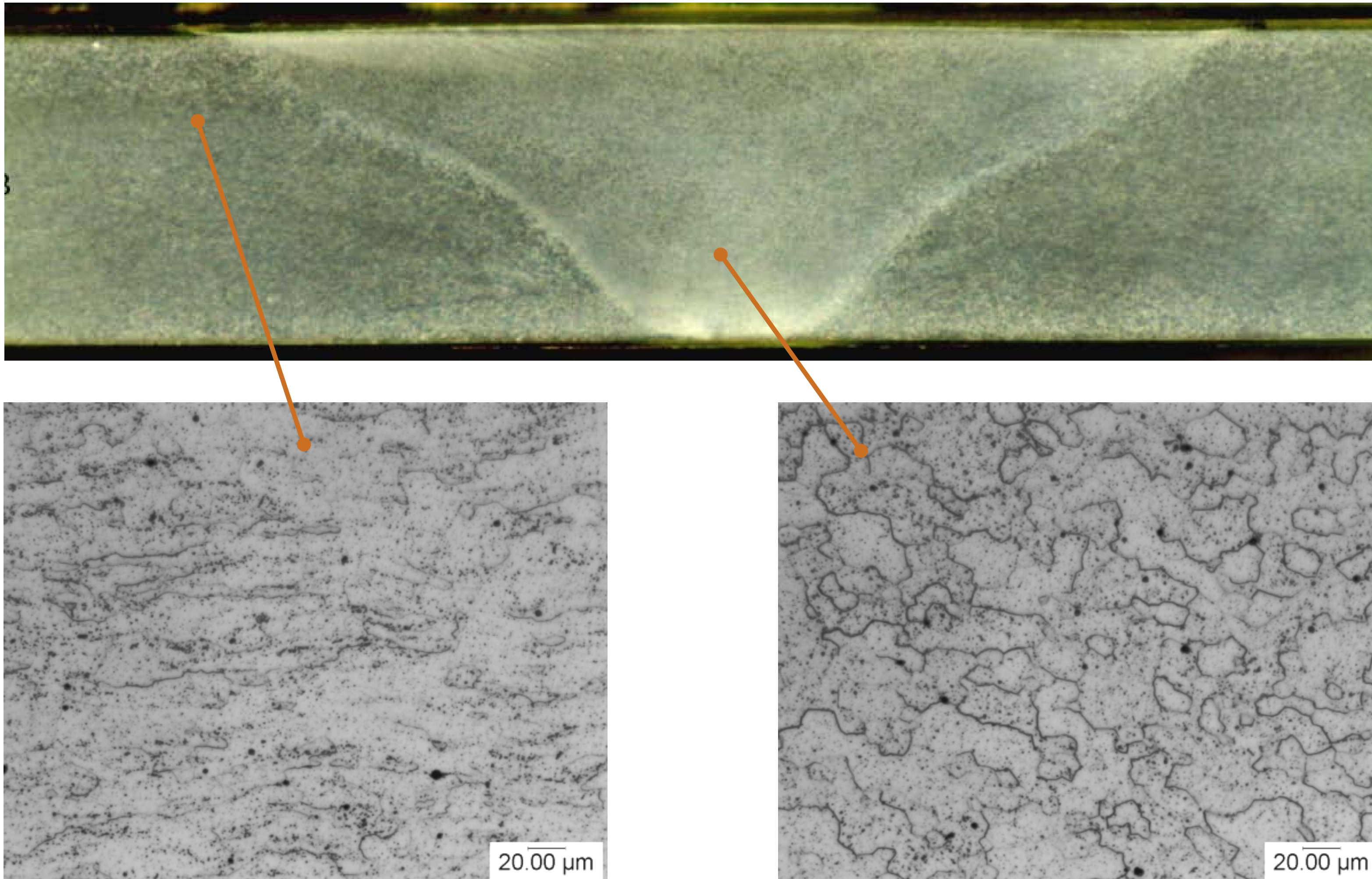
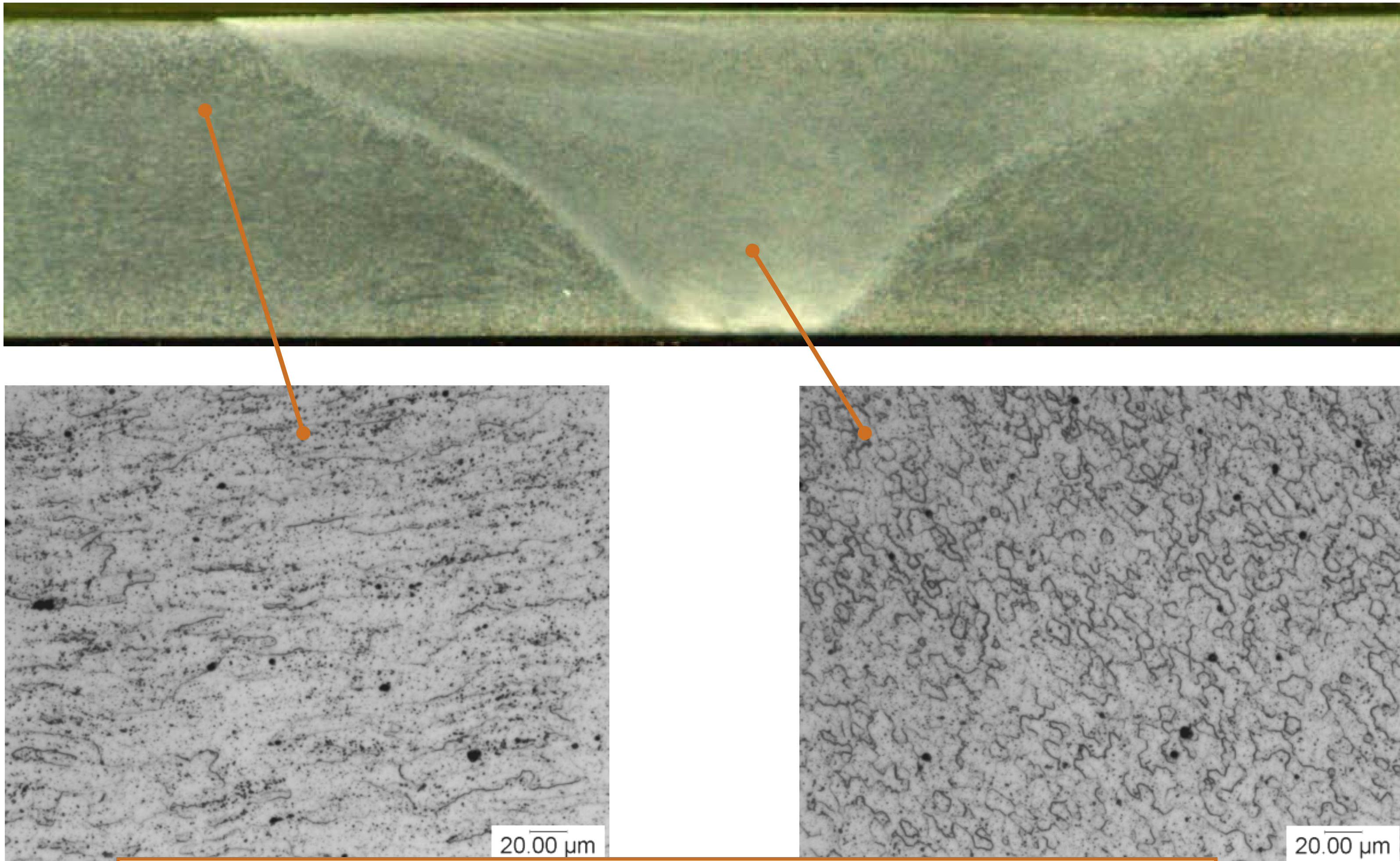
Microstructure in FSW Kanthal Weld (6 ipm)



Ferrite grain size of nugget about the same as parent sheet, but more equiaxed

Microstructure in FSW Kanthal Weld (7 ipm)

Slightly higher linear speed and x-direction load



- **Change of process conditions will change nugget microstructure- in this case, finer grain ferrite at higher travel speed**
- **Creep properties (based on grain size) can be customized to the parent sheet**

Approach to Producing a Commercial FSW Joining Process in ODS Alloys

- Stage 1
  - Develop a robust FSW welding process for at least ¼ inch thick ODS plate
    - Several groups worldwide looking at this, most looking at thin sheet <1/4”
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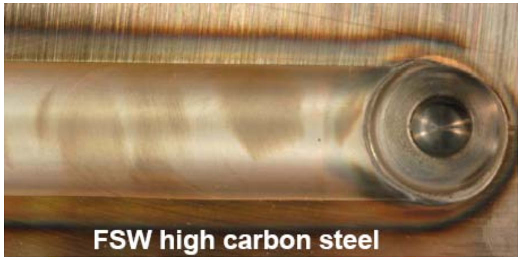
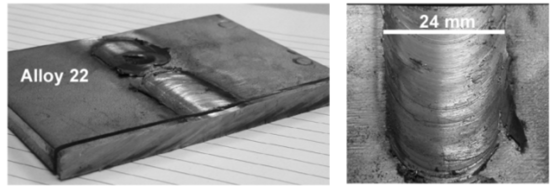
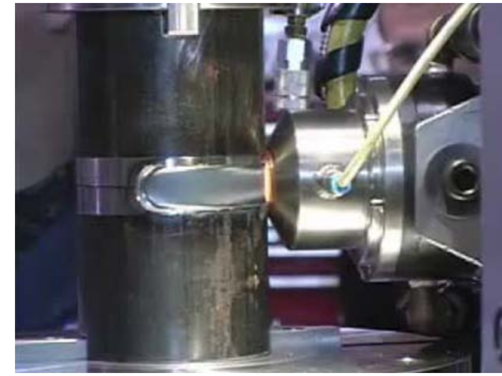
Steel FSW – Current State of the Art







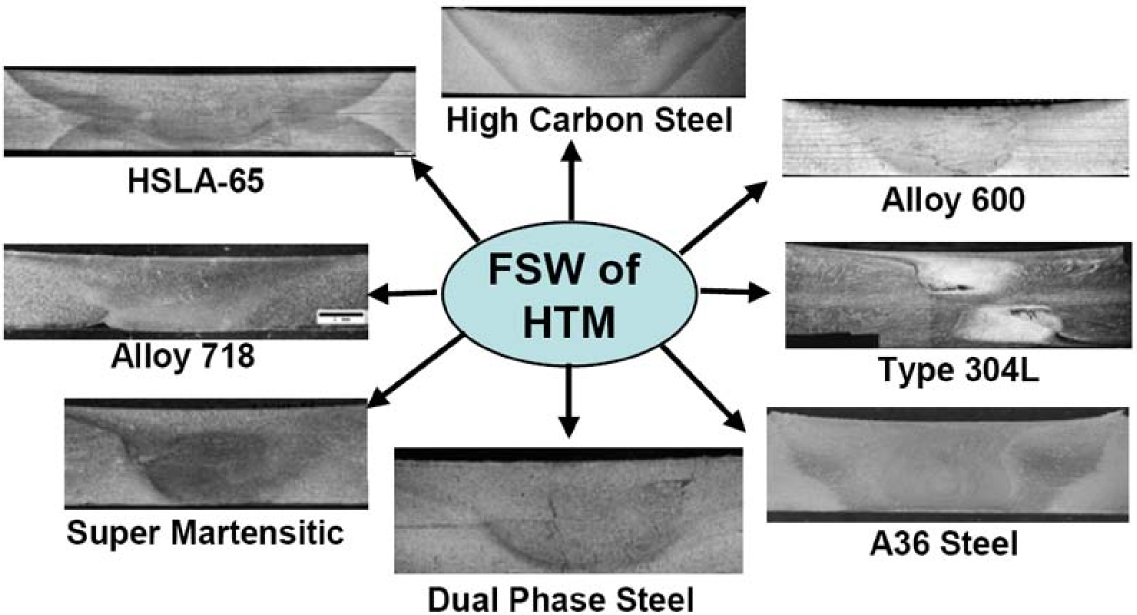


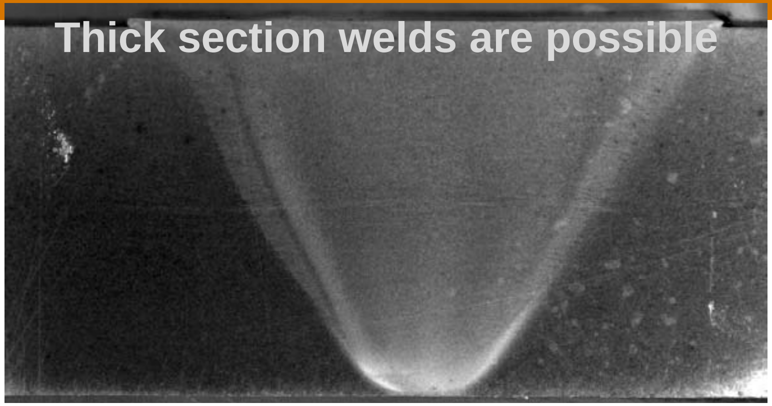
Photo courtesy Brigham Young University

Courtesy MegaStir,Inc.

For certain steels, FSW has reached a state of technology readiness where it can be considered as a viable manufacturing process. Production applications for steel FSW include pipe and tube manufacturing for the oil and gas industry (Global Tubing Inc.)

Commercial Viability

FSW equipment at Pacific Northwest National Laboratory

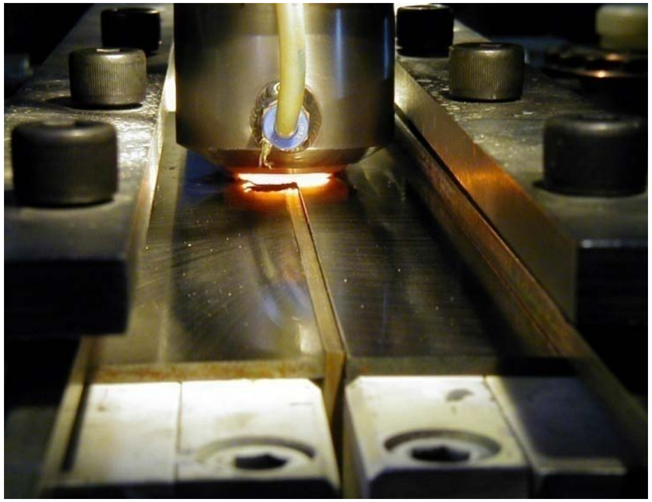


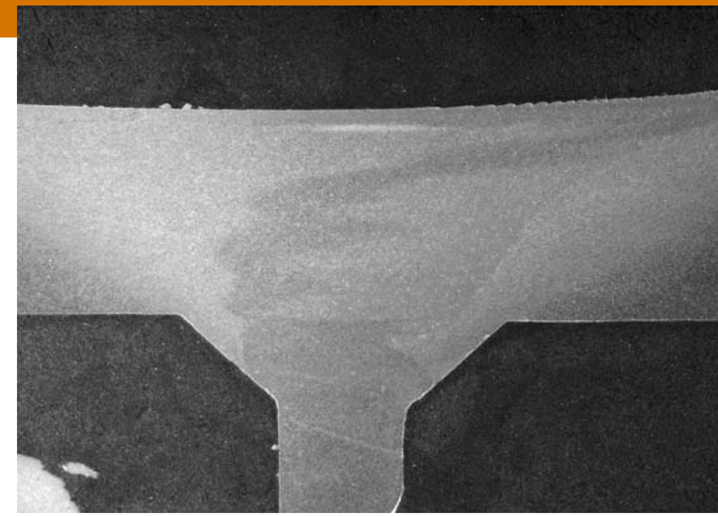
0.5” thick, single pass Friction Stir Weld in HSLA 65

Equipment does exist

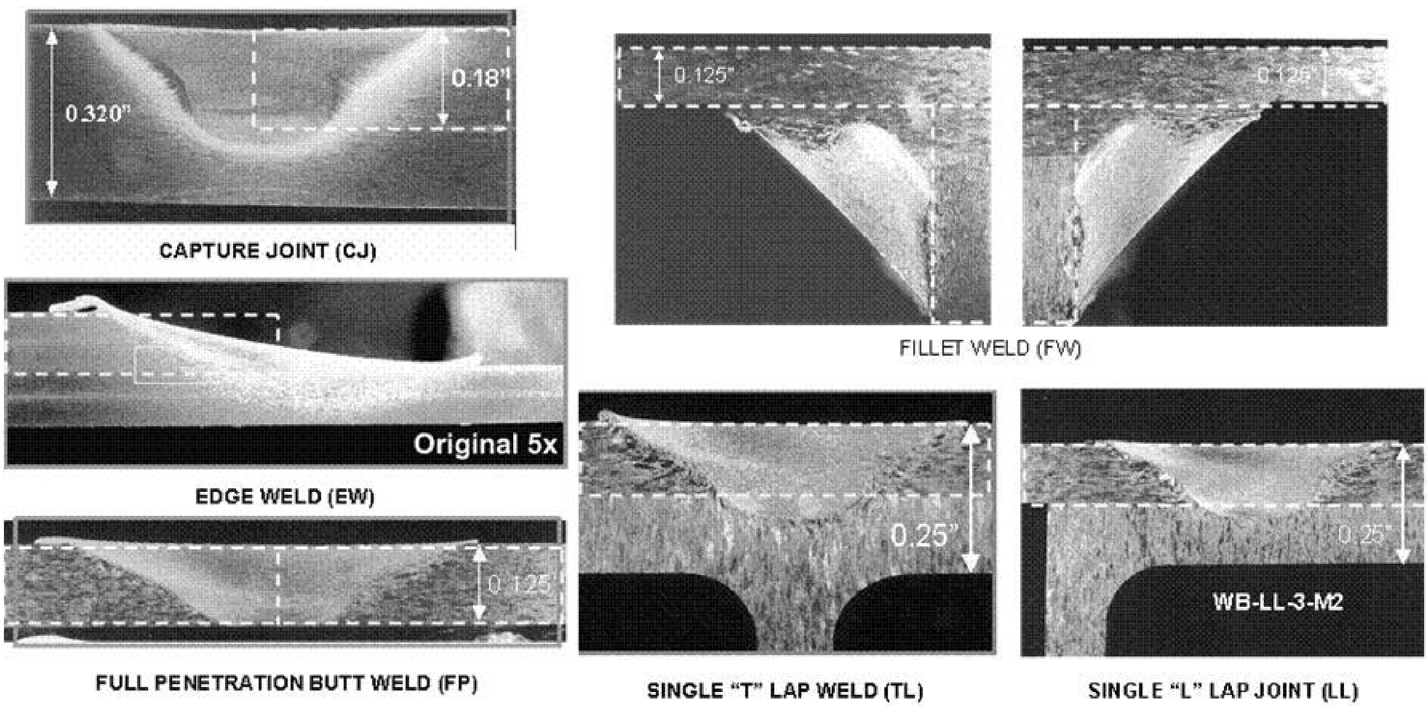
8 ft x 1 ft x 56 inch high working envelope

Joints design needs to take advantage of FSW, not just substitute FSW for fusion weld





Megastir, Inc.



Arbegast 2004

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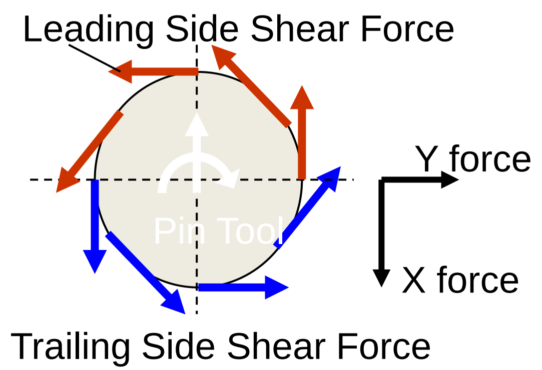
Cylindrical Vessel FSW welding

- Equipment is being developed to weld cylindrical geometry

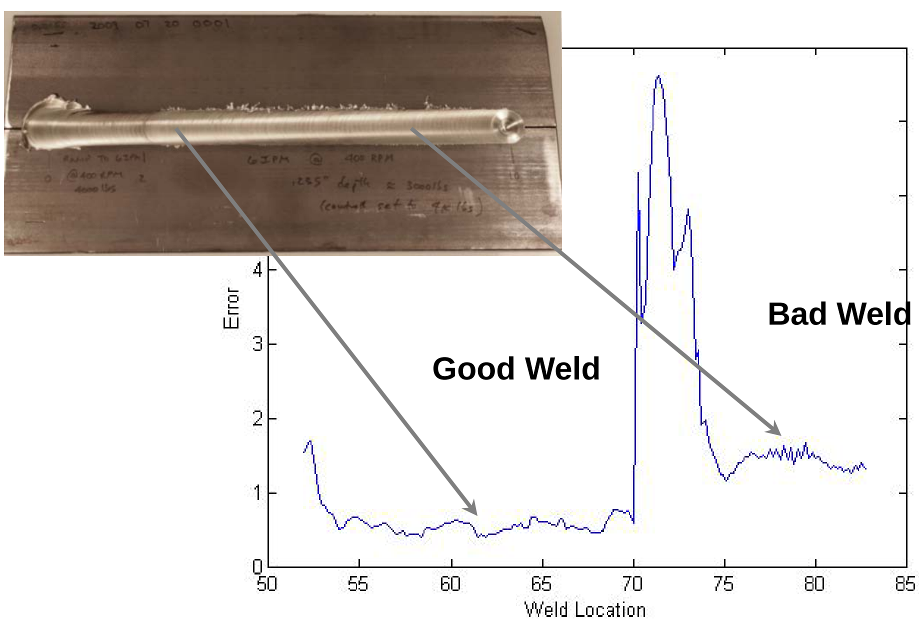
Courtesy Megastir, Inc.

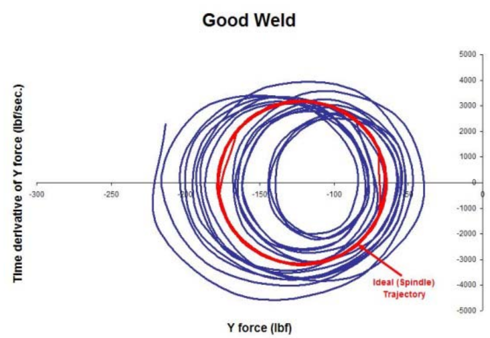
Develop weld quality assurance methods and produce process/performance data for code qualification

- **The nature of the FSW process (machine process under feedback control) means that each weld has detailed records of weld forces.**

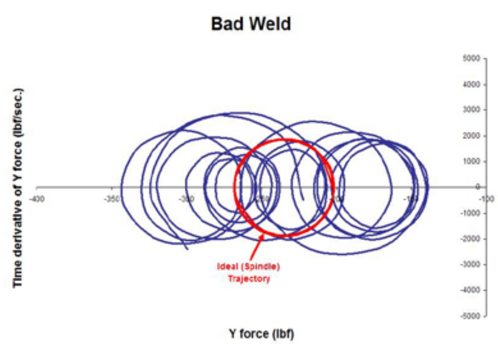


- **Y feedback force is the result of two competing shear forces – the leading side shear force and the trailing side shear force.**
- **The leading side shear force tends to decrease Y force, while the trailing side shear force tends to increase Y force**
- **These two competing shear forces define the equilibrium point of Y force**

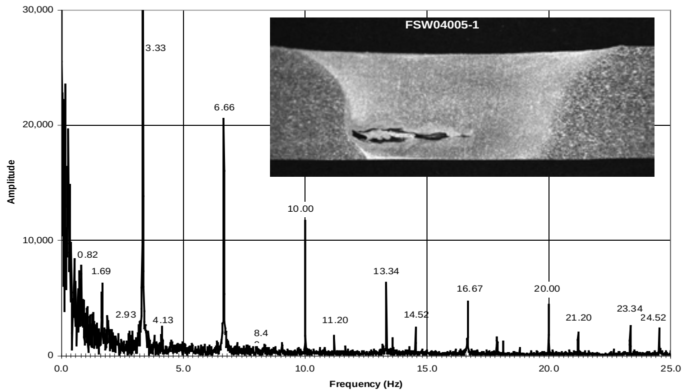


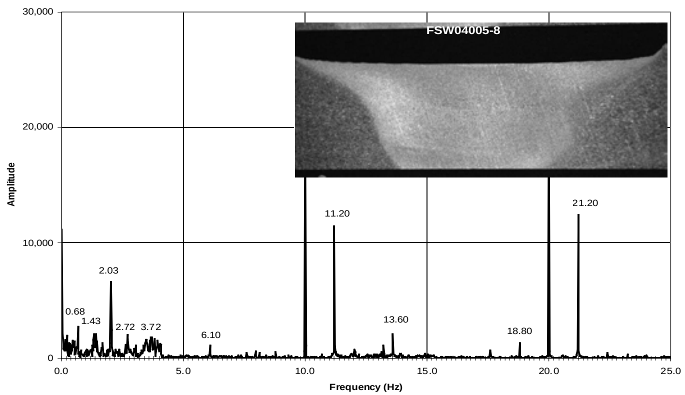


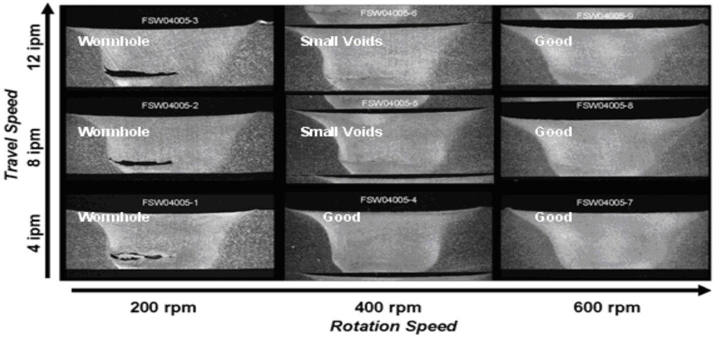
Time derivative of Y force

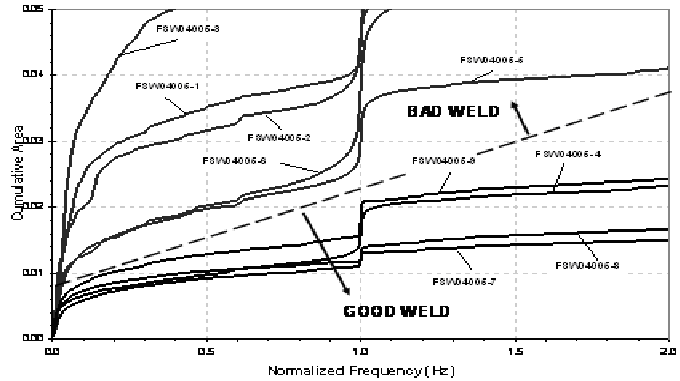


In-Situ Weld Quality Measurement/Control









(W. Arbegast, SDSMT, 2004)

- **The nature of the FSW process (machine process under feedback control) means that each weld has detailed records of weld forces.**
  - **Welds Certs and quality assurance**
  - **Can potentially replace NDE in difficult to inspect environments (inner walls or tube/tube sheet joint)**
  - **SPC real time process control**
- **Currently started a round robin series of tests with 5 universities to test weld quality algorithms and POD on different machines.**

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FSW Suppliers are slowing developing

- Most commercial suppliers of FSW welding services are focused on aerospace or marine and few have steel FSW experience
  - AJT,Inc
  - Friction Stir Link
  - HF Webster,Inc
  - Megastir
  - Remelle
- Most industrial implementers are keeping process in house
  - Boeing
  - Airbus
  - Global Tubing
  - GM, Ford, Toyota, Mazda, Honda
  - Hitachi, Mitsubishi, JFE, Sumitomo
  - Auto Tier 1 Suppliers (Tower Automotive)

Codes and Standards

- Generalized Standards Efforts
  - AWS
  - ISO
  - SAE
  - NASA
  - MNPDS Mil Spec
- Code Cases
  - ASME Section IX Code case ongoing
  - May also be pipe code case ongoing?
- WPS PQR Environments
  - FAA
  - Specific Applications / Internal Standards

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Summary of FSW work on ODS

- Creep Enhanced Ferritic ODS alloys can be successfully Friction Stir Welded
- FSW welds in 20Cr-5Al-Y-Ti-Hf Ferritic ODS Alloy (Kanthal APMT) show mechanical properties (especially creep at 750C) that are virtually identical in the weld nugget as in the parent rolled plate (in the longitudinal and rolling direction)
- FSW is able to create a fine grain structure inside the weld nugget in a Kanthal APMT plate that remains stable when tested at 750° C for over 670 hours.
- FSW may be a particularly appropriate method to joint these materials since
  - The microstructure can be “customized” to the parent through changes in weld process parameters making FSW a TMCP process (not just a joining process)
  - Texture and particle distribution in weld nuggets can lead to grain growth in a favorable direction for creep. However under some weld conditions, when PWHT to 1350C, AGG occurs, causing large grain growth that may be detrimental to strength and ductility
- Developments needed for commercial application are progressing
  - Thicker section
  - Weld data and quality measures for codes and standards
  - Installed FSW machine base and supplier base is growing

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