Materials for Low Emission Power Plants
US-UK: Advanced Materials – ODS Alloys

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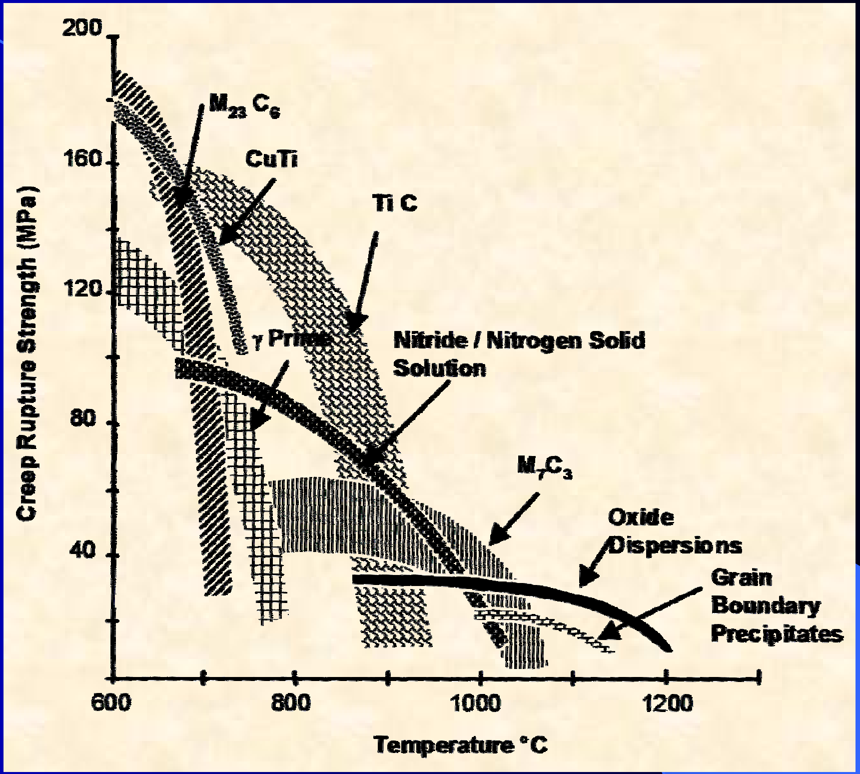
Why ODS-Alloys?

- Viable alternatives to Ni-base superalloys for engine hot section components
- Superior environmental durability than currently-used metallic materials
- Excellent oxidation, sulphidation resistance over an extended temperature range
- Thermodynamically stable phases in matrix for prolonged creep life
- Focus: ODS-Fe_3Al and ODS-FeCrAl



Unresolved Issues

- Microstructure modification for improved matching of the intrinsic material *vs.* the expected '*in-service*' design creep stress anisotropies
- Devising and validating microstructure preserving joining methodologies

US-UK Activities: Phase 1, Task 8: ODS Alloys

Unresolved Issues: our principal focus

Non Fusion Joining – of ODS alloy components

- *US – concentrating on joining tubes, rods (MA956)*
- *UK – concentrating on joining sheet (PM2000)*

Grain Fibering/Flow Forming for Hoop Creep

- *US – Cross Rolling, Flow Forming (MA956, Fe_3Al)*
- *UK- Torsion Forming, Grain Twist (PM2000)*

MA956 – supplied by US vendor: Special Metals Corp
PM2000 – supplied b EU vendor: Plansee, Austria

Sample Non-Fusion Joints in MA956

Inertia Weld (UCSD)

Magnetic Pulse (UCSD)

Flash Upset (EWI)

Inertia welding deemed the most robust industrial technique available for further exploration and HTHE construction. Process may also be applicable to USC program where joining of candidate Ni-base IN740 and IN617, H230 is an issue.

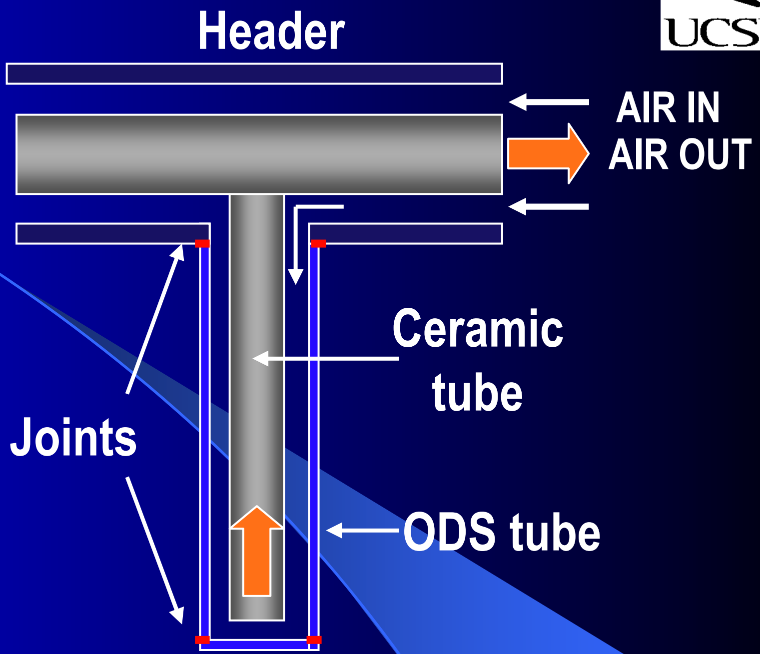
Non-Fusion Joining Efforts

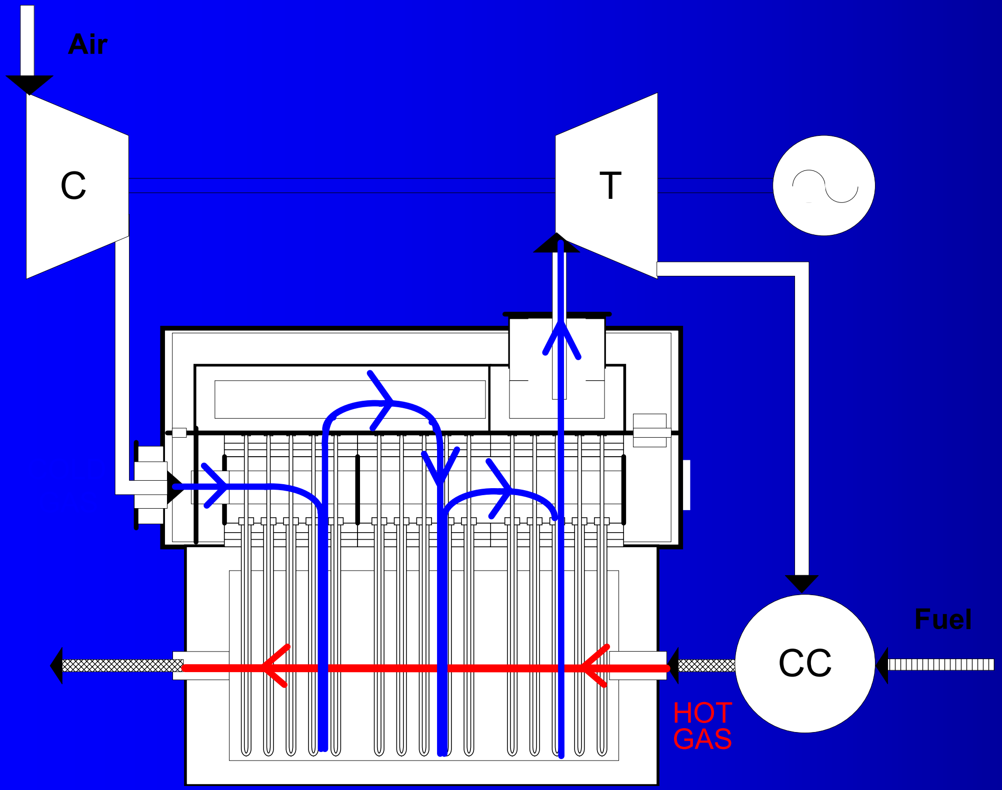
Bayonet Tube Design:

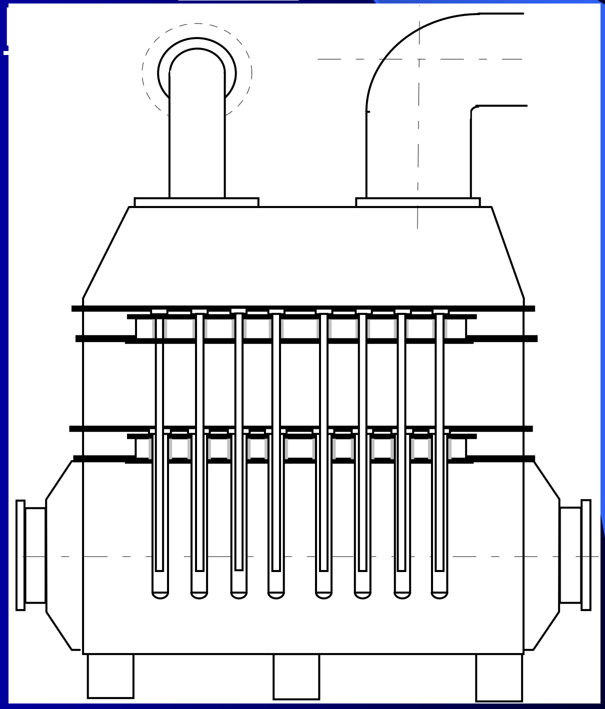
Source: UK Cost 522 Program

HTHE Prototype, Pressurized

Max 40 tubes, 2”OD, 40” long







Evaluation of Inertia Welding Variables

No.	Inertia WK^2	Weld RPM	Energy Ft.lbs	Force lbs	Weld Upset
1	111.5	1500	42700	50K	0.153”
2	71.5	3000	110000	50K	0.498”
3	146.5	1000	25000	100K	0.125”
4	146.5	1500	56000	100K	0.360”
5	146.5	1700	72000	150K	0.490”
6	71.5	3000	110000	100K	0.662”

Energy (Ft.lbs) = Flywheel Inertial (Wk^2) x $(RPM)^2/5873$

Wk^2 Depends on Mass & Diameter of headstock & flywheel assembly

Inertia Welding Variables:

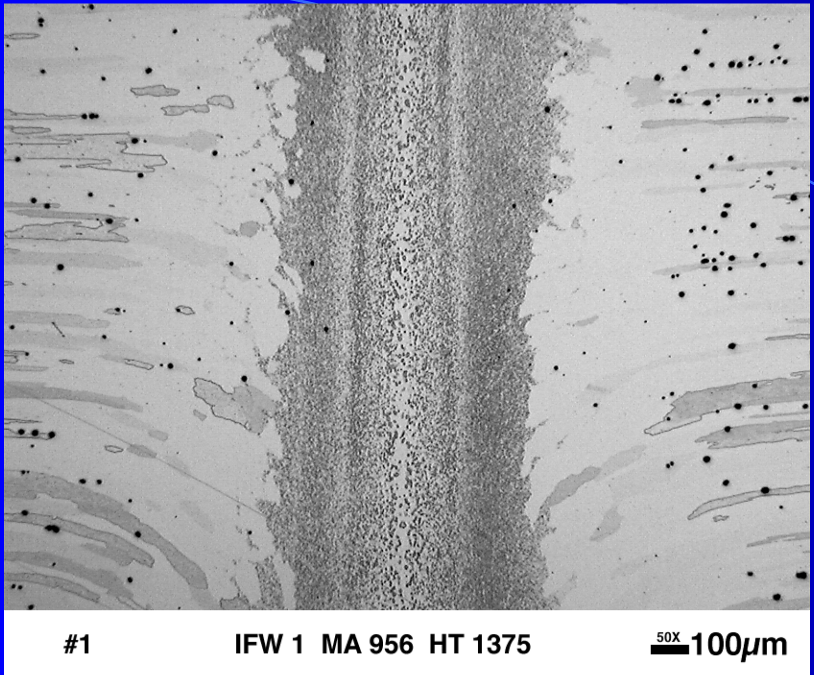
Flywheel Mass: 71.5 – 146.5

Weld Speed: 1000 – 3000

Weld Force: 50,000 – 150,000

Weld Upset: 0.125” – 0.490”

NO



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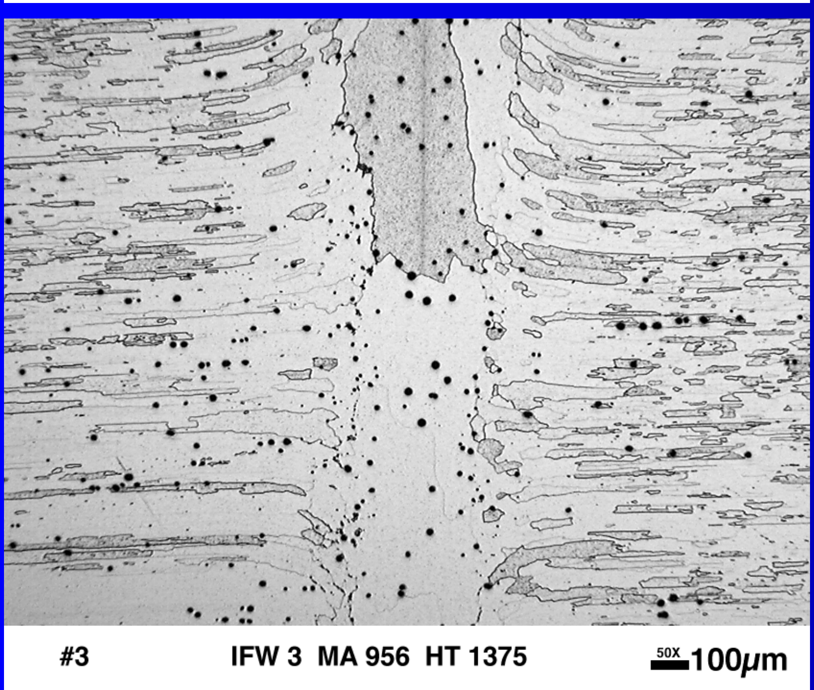
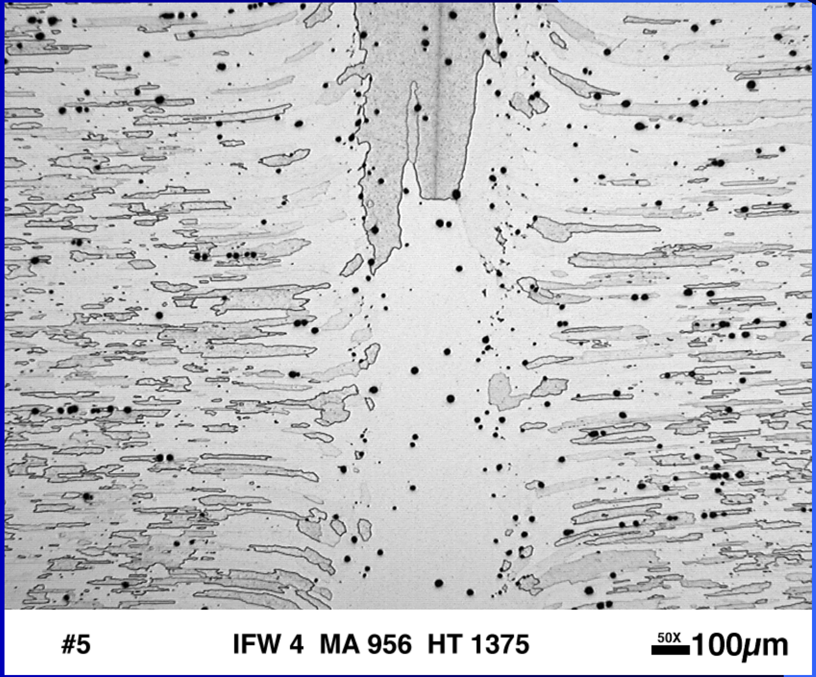


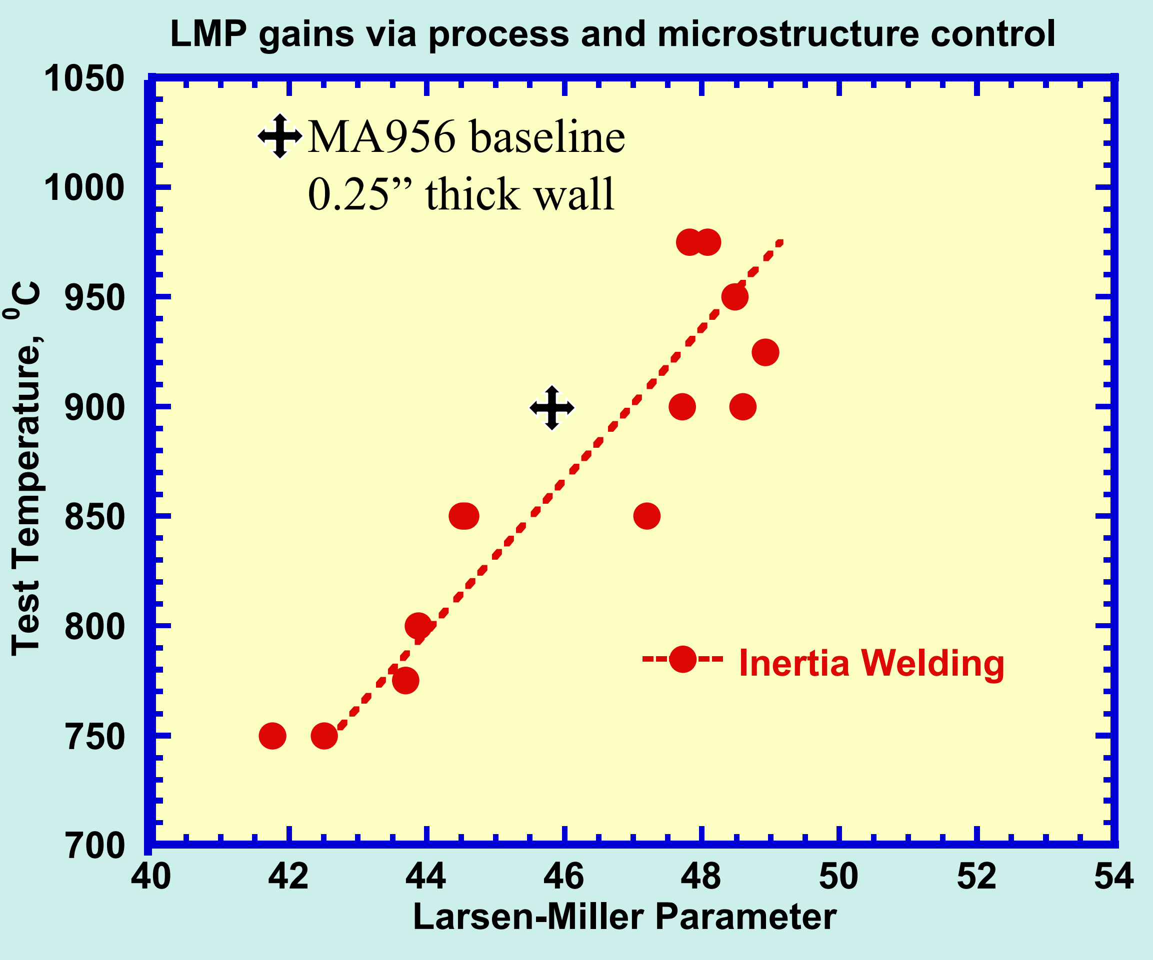


OK

Status: Inertia Welded Joint Performance

	MA956 Joint Processing and HT	Temp °C	Stress, Ksi	Life, Hrs	LMP	Strain, rate/day
1	MA956, As-received, 1375°C,1hr, Air	900	2		46.09	
2	Flash Upset, HT:1375°C, 12hr, Air	850	2	144	44.80	6.0e-4
3	Inertia Weld, HT 1375°C, 12hr, Air	850	2	2196	47.20	1.0e-4
4	Inertia Weld, HT 1375°C, 12hr, Air	900	2	390	47.71	2.0e-4
5	Inertia Weld, HT 1375°C, 12hr, Air	950	2	102.6	48.47	4.0e-4
6	Inertia Weld, HT 1375°C, 12hr, Air	975	2	19	47.81	9.0e-4
7	Inertia Weld, HT 1375°C, 12hr, Air	975	2	25	48.08	4.6e-4
8	Inertia Weld, HT 1375°C, 12hr, Air	925	2	478	48.92	2.4e-4
9	Inertia Weld, HT 1375°C, 12hr, Air	900	2	1021	48.59	1.4e-4

Status: Inertia Welded Joint Performance

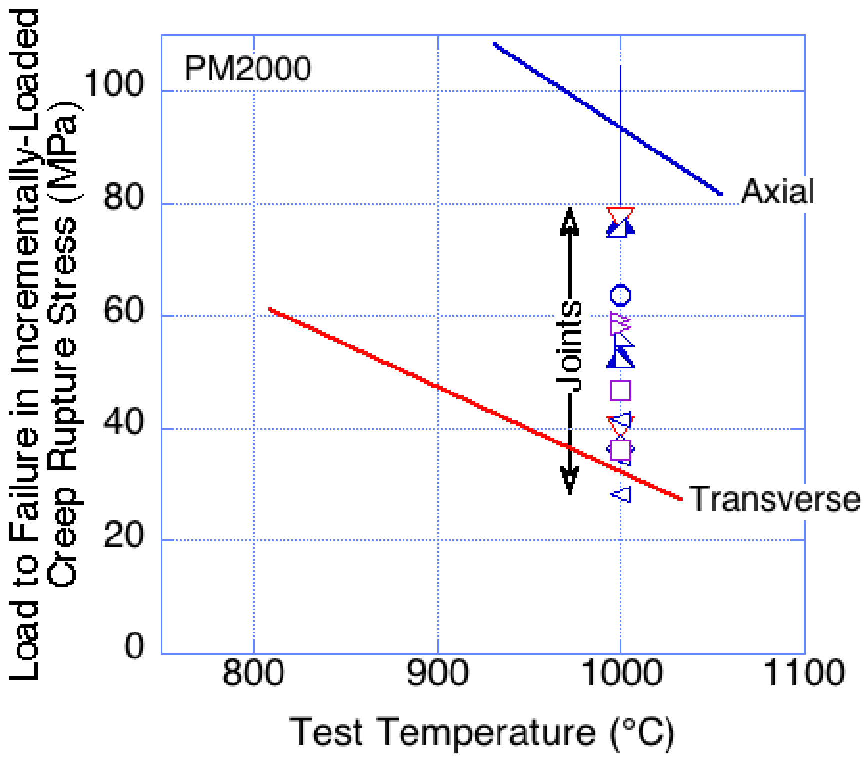


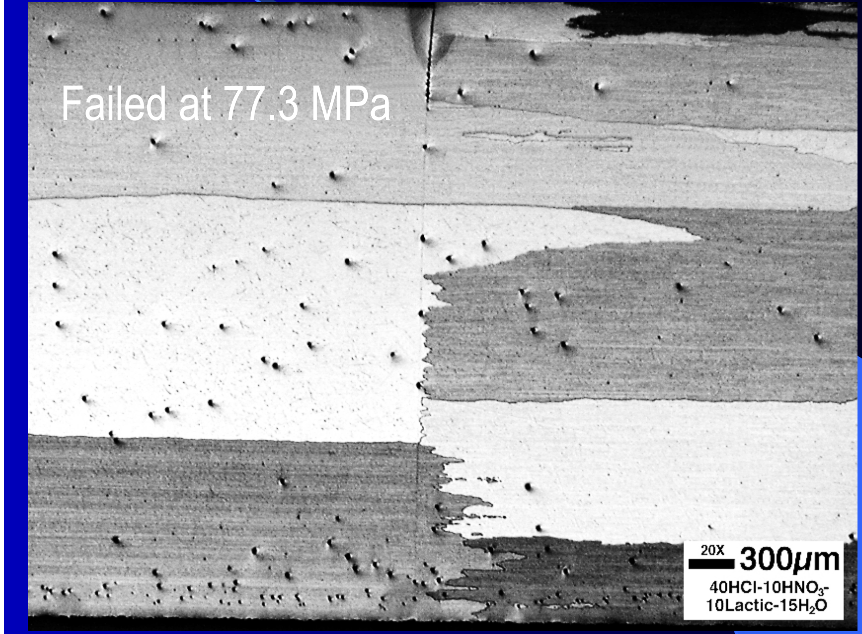
Commercial uses of Inertia Welding

Process used both for ambient and high temperature applications.

Joining for *creep environments* is aggressively pushing the window to higher temperatures.

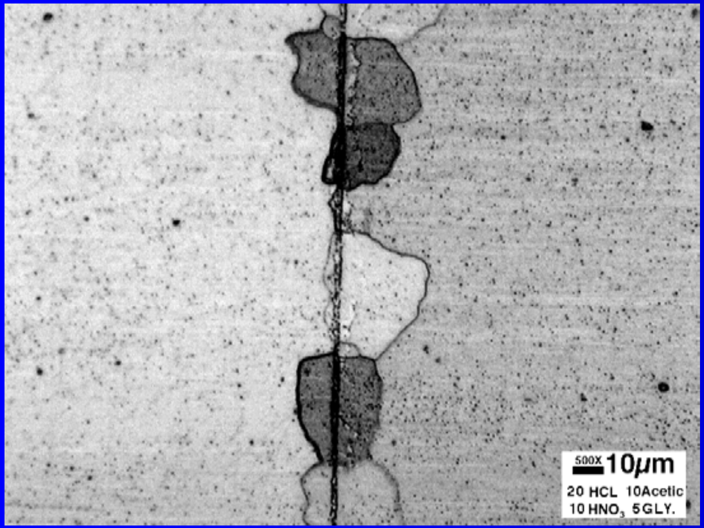
Pulsed plasma-assisted diffusion bonding (MER Corp.) gives excellent results




Failed at 77.3 MPa

- Miniature specimens/butt joints
- Joint strength highly-dependent in microstructure
- Best: >81% of load to fail monolithic

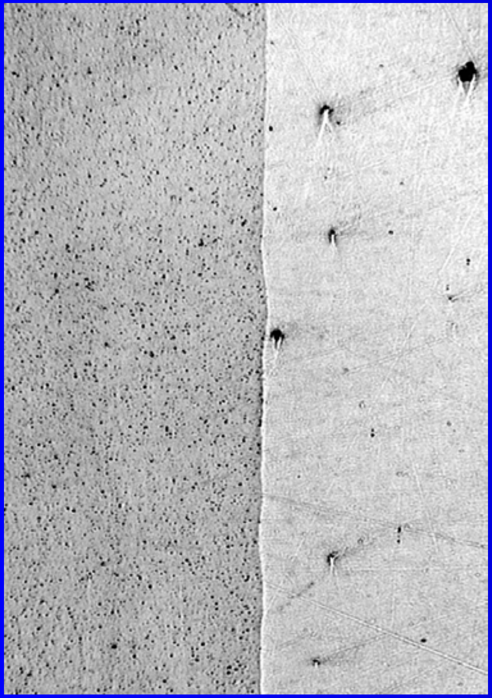
TLP bonding: limitations for ODS alloys



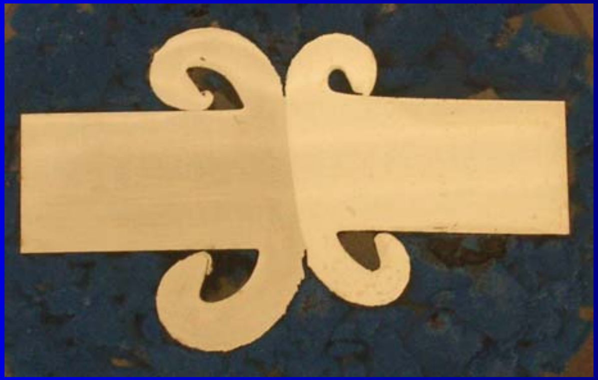
- Joining involved butt joints in 15-19 mm diam. recrystallized and unrecrystallized PM2000 rods
- All TLP processing variations used resulted in an inability to drive secondary recrystallization
- Attempt so far to introduce post-joining cold work were unsuccessful
  - grit-blasting?
- Modified TLP processing at UNDEERC reportedly produced acceptable joints in (recrystallized) MA956 tubes

Dissimilar Materials Joining
IN601-MA956, IN617-MA956, H230-MA956

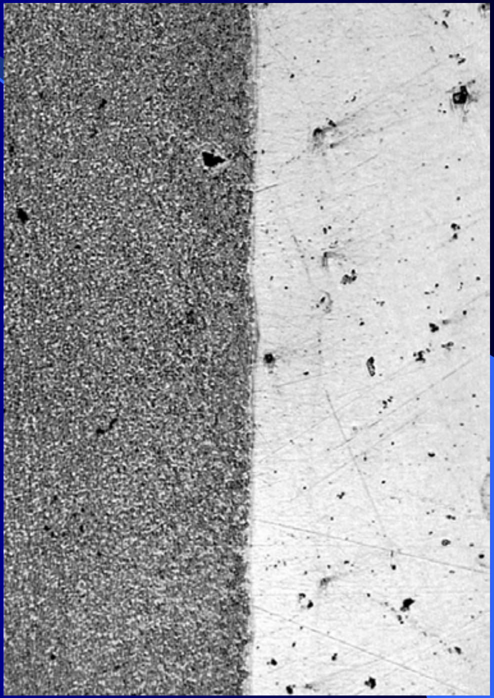
as-polished view



MA956 IN601



Etched view



Robust IN601-MA956 welds are produced with minimal process changes. Cross-section shows a smooth interface with asymmetric material flow across the interface.

Joining effort: Lessons Learned

1. Five Non-Fusion Joining Techniques evaluated:
   Inertia Welding,
   Pulsed Plasma Assisted Diffusion Joining,
   Transient Liquid Phase (TLP) Joining
   Magnetic Pulse Welding
   Flash Butt Welding

2. Inertia Welding – readily available industrial technique, produces robust joints with acceptable high temperature creep performance. Technique well situated for Phase II prototype HTHE construction

3. Plasma Assisted Diffusion produced joints with performance 75% of the base material in incremental load tests

4. TLP – failure to propagate recrystallization limits application scope

5. Magnetic Pulse joining successful in providing hermetical seals and Joints. Technique applicable only to thin sections. Limited Scope

6. Flash Butt – Could be reliable for complex non-symmetric welds. Some melting observed. Strength less than corresponding Inertia Joints.

Microstructure Modification: Grain Growth and Fibering

Objective: to improve the limited hoop creep performance of ODS-Alloys

1: Torsion Forming

Ian Wright, Oak Ridge National Laboratory, TN
Gordon Tatlock, Andy Jones, Univ. of Liverpool, UK

2: Flow Forming & Drawing

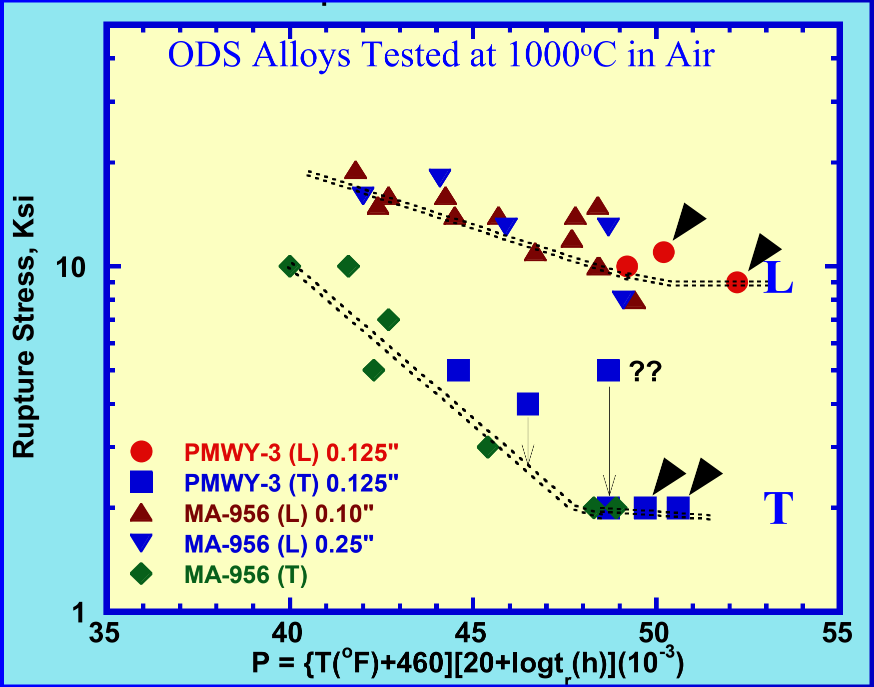
Bimal Kad, University of California-San Diego, CA
Brian Baker, Gaylord Smith, Special Metals Corp. WV

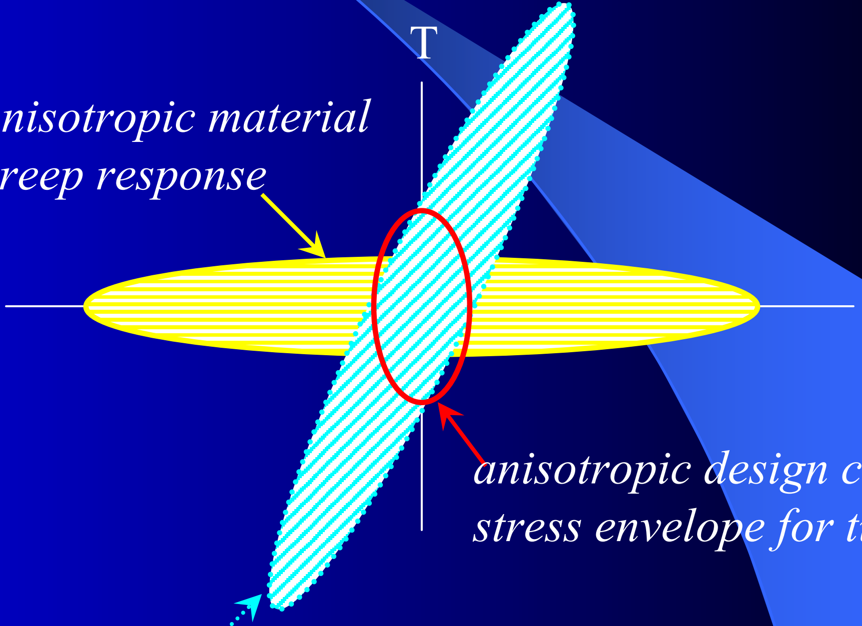
3: Cross-Roll Forming

Bimal Kad, University of California-San Diego, CA

Motivation for Grain Fibering in ODS Alloy Tubes

To optimally align the intrinsic material creep anisotropy with the expected in-service anisotropic design stress envelope.



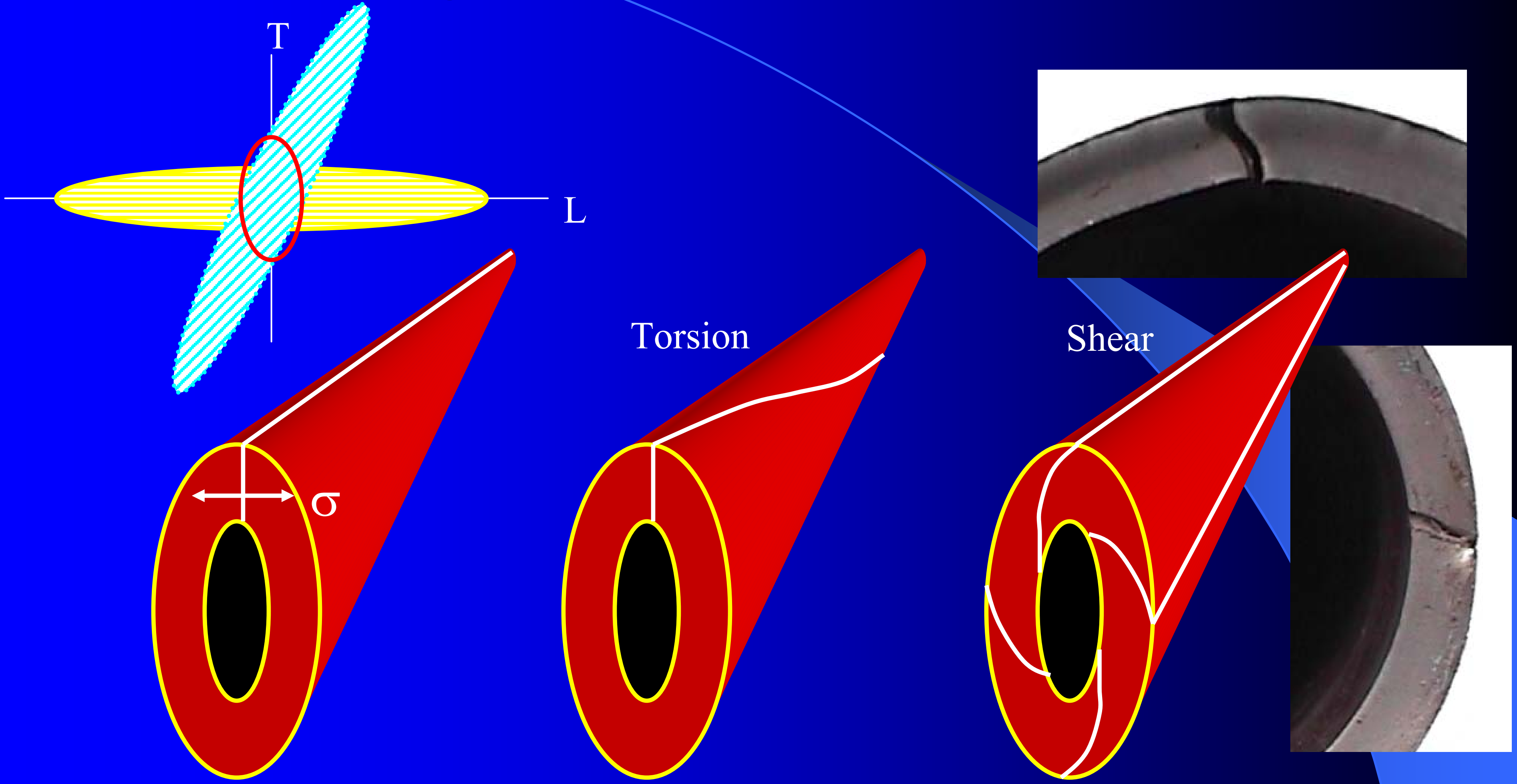


anisotropic material creep response

anisotropic design creep stress envelope for tubes

desired grain realignment for optimal creep response

Grain realignment in the hoop direction



As processed grain
boundaries normal
to hoop loading axis

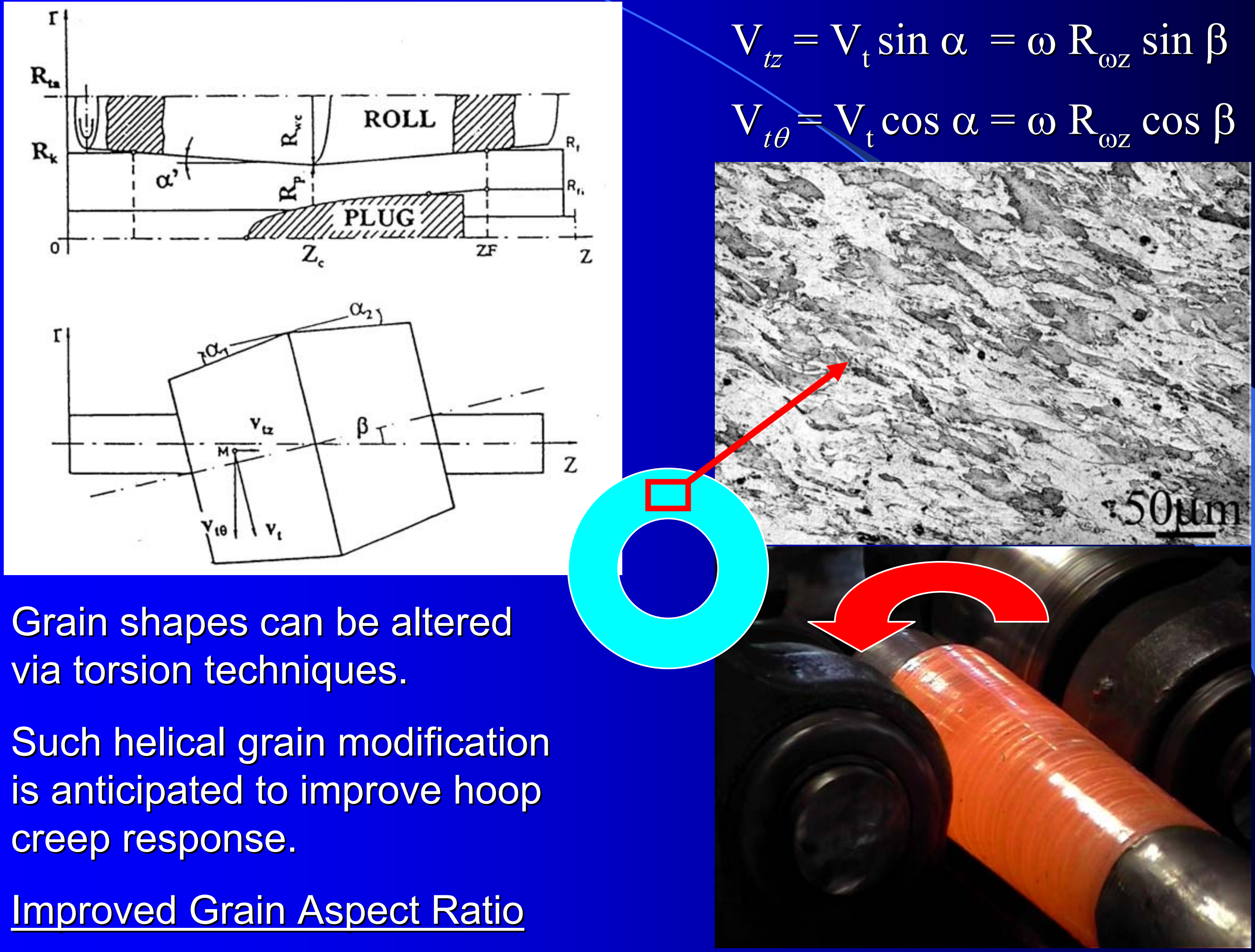
Grain realignment
along length of tube

Grain realignment
along radius of tube

Helical rolling techniques

$$V_{tz} = V_t \sin\alpha = \omega R_{\omega z} \sin\beta$$

$$V_{t\theta} = V_t \cos\alpha = \omega R_{\omega z} \cos\beta$$

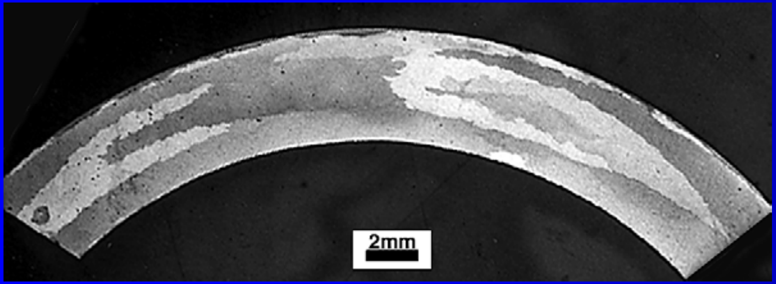


Grain shapes can be altered via torsion techniques.

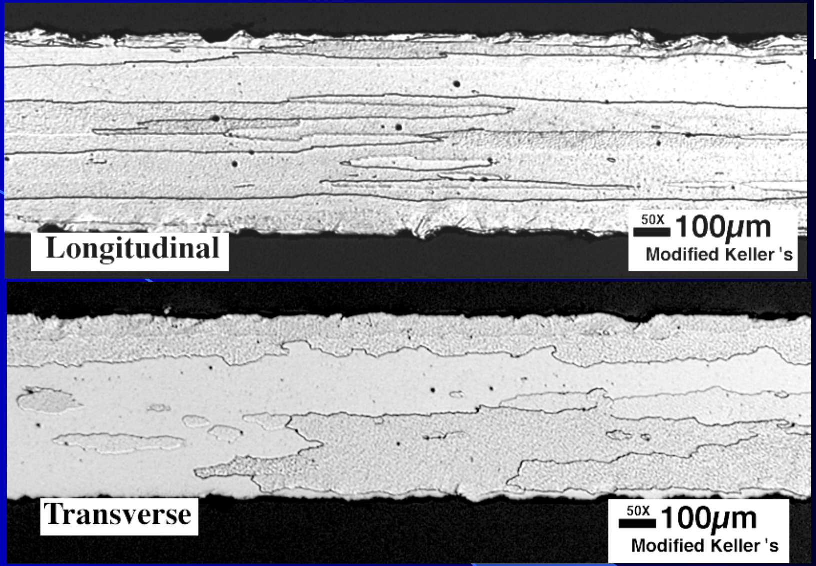
Such helical grain modification is anticipated to improve hoop creep response.

<u>Improved Grain Aspect Ratio</u>

Coarse Grain structure achieved via Flow Forming



ODM-751,Onion-skin grain structure



MA956, flow formed grain structure

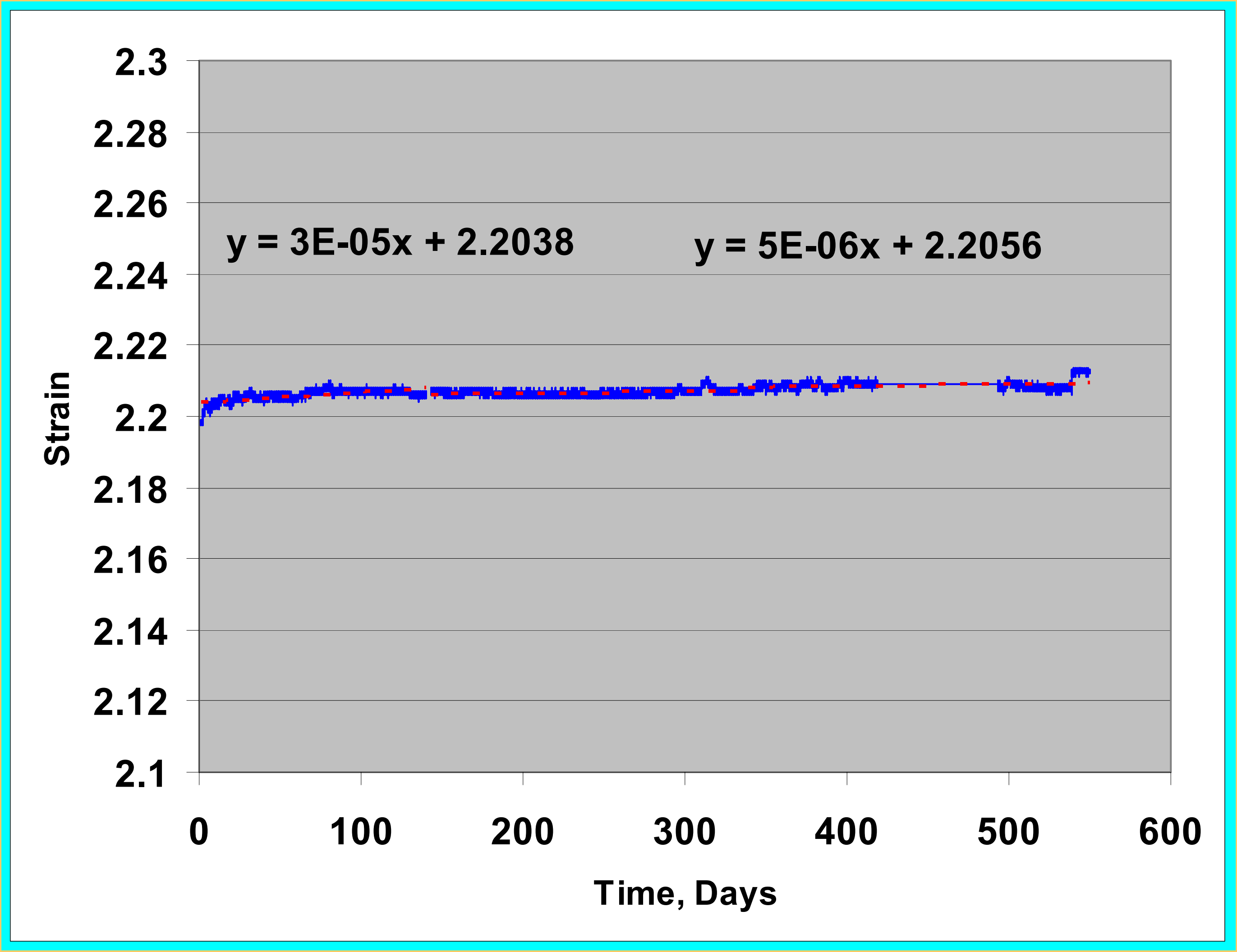
In ODS MA956, coarse, secondary recrystallized, grain structure was only possible after extreme cold-working via flow forming.

Flow forming does NOT produce any fibering.

Only contribution is Cold Working

MA956, starting tube 0.25" thick wall. ***flow formed*** tube 0.03-0.04"

Flow Formed ODS MA956 Hoop



Test @1000°C, 2Ksi, in Air, Life = 2yrs

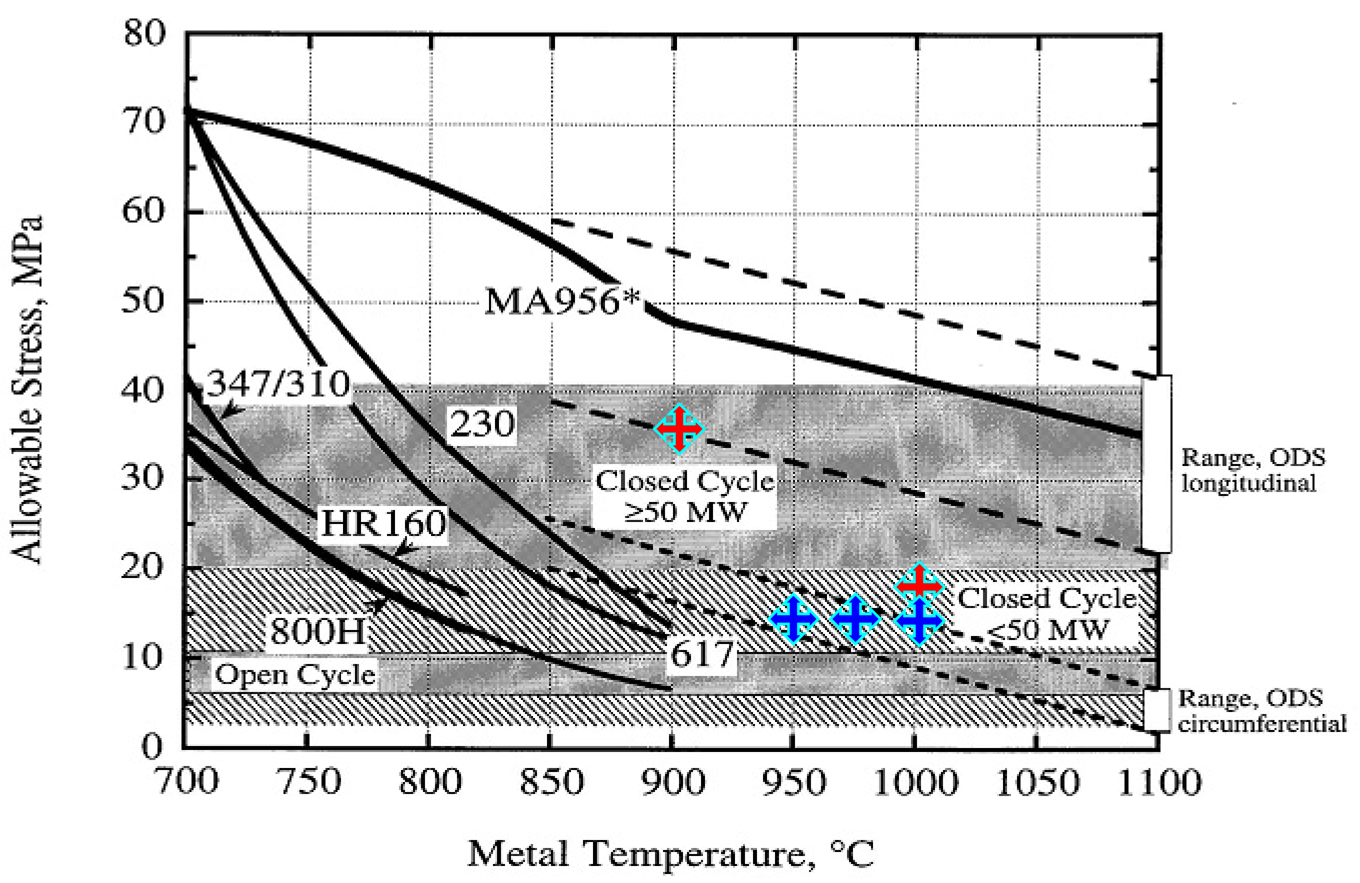
Hoop Creep: Processed MA956 Tubes

Test	MA956 Alloy Treatment & HT	Temp	Stress	Life, hrs	LM Para	rate/day
1	MA956 Tube As-Is,HT:1375°C-1hr,Air	900°C	2Ksi		46.09	$2.00e^{-2}$
2	MA956 Tube As-Is,HT:1375°C-1hr,Air	900°C	1Ksi		48.81	$2.00e^{-5}$
3	CR-20%@900C,HT: 1375°C-1hr,Air	900°C	2Ksi		48.87	$9.00e^{-5}$
4	CR-20%@900C,HT: 1375°C-1hr,Air	900°C	2Ksi		48.24	$6.00e^{-4}$
5	CR-20%@900C,HT: 1375°C-1hr,Air	900°C	2Ksi		48.89	$1.00e^{-4}$
6	CR@900C, β=8°, HT:1375°C-1hr,Air	900°C	2Ksi		46.89	$5.70e^{-3}$
7	FlowForm@RT,HT:1375°C-1hr,Air2	1000°C	2Ksi	452	51.93	$7.00e^{-4}$
8	FlowForm@RT,HT:1375°C-1hr,Air2	950°C	2Ksi	7329	52.55	$2.00e^{-5}$
9	FlowForm@RT,HT:1375°C-1hr,Air2	975°C	2Ksi	20922*	54.65	$5.00e^{-6}$
10	FlowForm@RT,HT:1375°C-1hr,Air2	1000°C	2Ksi	16757	55.52	$7.00e^{-6}$

* Data Collection continuing on Test 9.

Application Range for ODS Alloys

Objective: to improve the limited hoop creep performance of ODS-Alloys

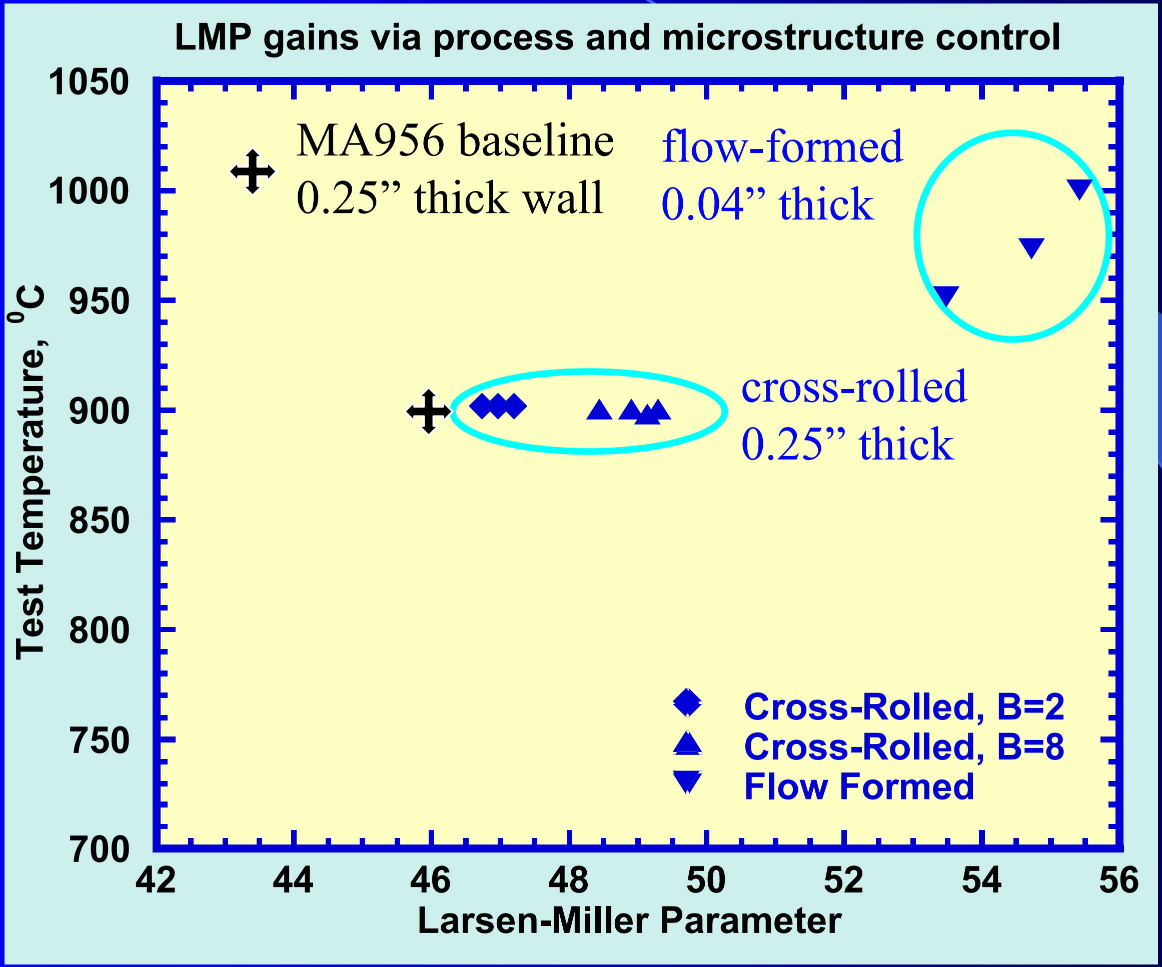


- ✚ Current hoop creep metrics for ODS-Fe_3Al tubes
- ✣ Current hoop creep metrics for *flow formed* MA956 tubes

Benefit derived from Flow Forming?

No grain fibering?
lots of cold work! Inhomogenous!

Status: Hoop Creep & Joint Performance



Lessons Learned – rolling & flow forming

1. Both hot rotary rolling and ambient temperature flow forming improved the hoop creep strength.

2. Hot rotary rolling, produced grain fibering, but a small recrystallized grain size.

3. Ambient temperature flow forming produced little grain fibering – but extremely coarse grain structure that provides large jump in hoop creep strength.

4. Cold working, or low working temperature, essential to creating coarse secondary recrystallized grain structure

5. Attempt ambient temperature rotary rolling at next iteration