Advanced Materials (Metals) Program Summary

Michael McMurtrey

Presented at the Gas-Cooled Reactor Program Annual Review

July 16, 2020 via Videoconference from Idaho National Laboratory

ART
ADVANCED REACTOR TECHNOLOGIES

Team

- Michael McMurtrey, Ryann Rupp and Richard Wright
  - Idaho National Laboratory
- Sam Sham, Mark Messner, Xuan Zhang
  - Argonne National Laboratory
- Yanli Wang
  - Oak Ridge National Laboratory

Materials solutions - enabling design, construction, and operation of licensable Advanced Nuclear

Reduce Risk in Licensing

ASME Sec III, Div 5

- Material, design, fabrication, installation, examination, testing, overpressure protection, inspection, stamping, and certification

Regulatory Space (Materials Degradation)

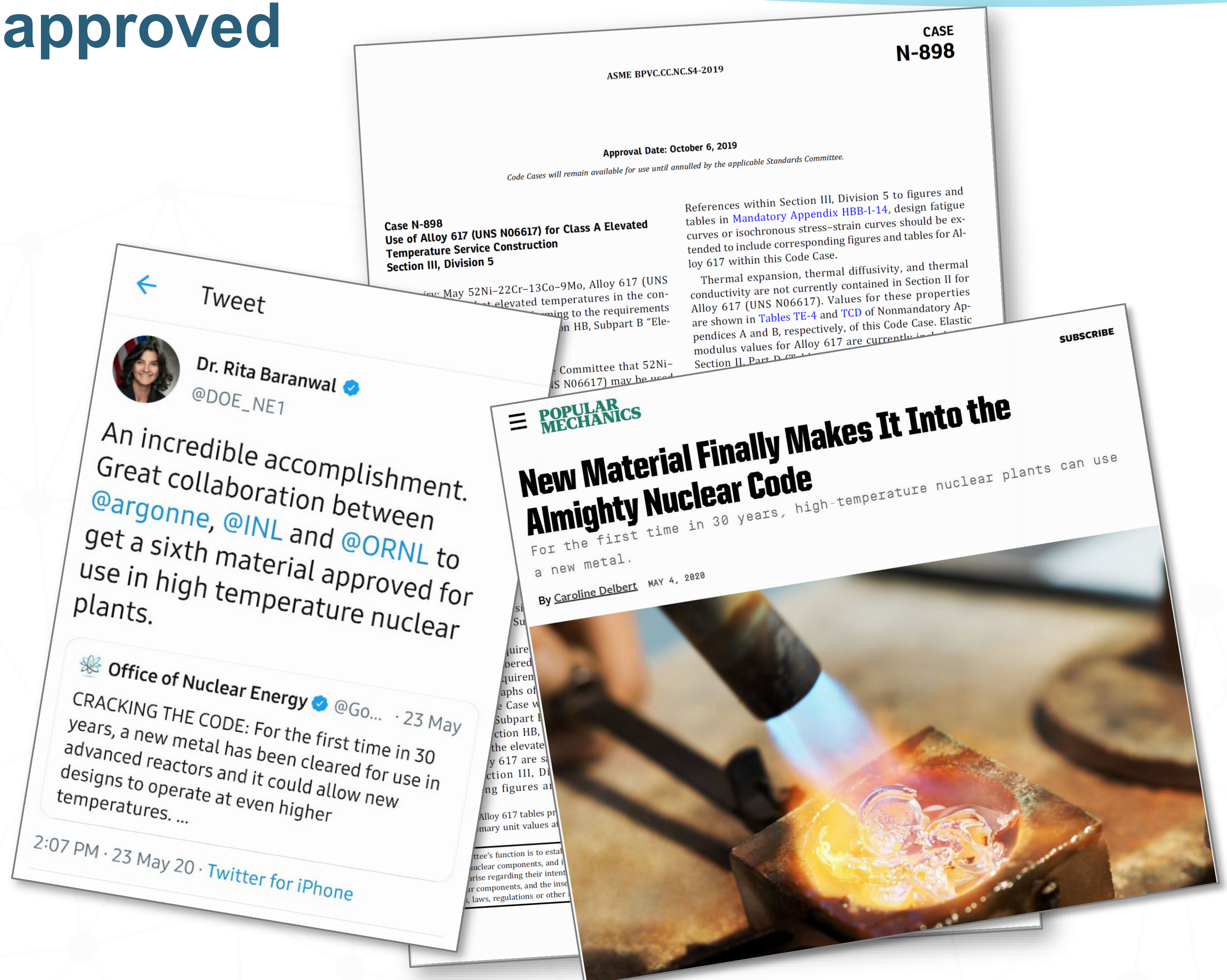
- Coolant compatibility
- Radiation
- Mass transfer
- Materials surveillance
- Etc.

ASME Sec XI, Div 2, 3

- In-service inspection
- Etc.

Alloy 617 Code Case is fully approved and published

- Richard Wright has led the Alloy 617 Program since 2008
- The publication of ASME Code N-898 in 2019 for use of Alloy 617 as a Division 5 Class A material up to 1750F for 100,000h is a great accomplishment
- In addition to the Code Case, a number of significant high temperature design methodologies were developed in support of the Code Case effort
- They can be applied to other Class A materials, benefiting other advanced reactor systems



Continued ASME Code Activities

- Support design life extension to 60 years
- A new creep-fatigue evaluation method based on EPP and SMT technology is being developed to provide a more accurate treatment of creep-fatigue damage, particularly at stress risers and geometrical or metallurgical discontinuities with multiaxial stress state
  - Issue was raised as a concern by U.S. NRC during previous review
  - Technical development will complete in FY21 and a code case will be submitted to ASME in early FY22
- Advanced manufacturing (AM) could promote the deployment of future advanced nuclear reactors by enabling complex component geometries, increasing design flexibility and thus enabling more efficient designs
  - AM could include processes such as powder bed fabrications, wire feed methods and binder-jet processes, etc.
  - To support advanced reactor deployment, reactor components fabricated by AM must be licensable by U.S. NRC

Socialize – Workshop on Section III, Division

- To introduce Division 5 to Advanced Nuclear developers and stakeholders
- To let Advanced Nuclear developers to introduce their reactor concepts and their Codes and Standards needs
- Presentations from developers (current commitment)
  - Advanced Reactor Concepts, LLC • BWX Technologies, Inc. • Flibe Energy • Framatome • GE Hitachi Nuclear Energy • Kairos Power • Moltex Energy • TerraPower • Terrestrial Energy • ThorCon • Ultra Safe Nuclear Corporation • X-Energy
- Sunday, November 8, 2020, Atlanta, GA
  - Pre-registration:

https://www.asme.org/conferences-events/events/asme-bpv-iii-division-5-workshop-high-temperature-reactors

Section III Division 5 Workshop

Sunday, November 8, 2020, Draft Agenda (Rev. 2)

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Time	Item	Presenter	Duration
8:00 AM	Welcome & Introduction	TBD	30
8:30 AM	Division 5 Overview	Sam Sham	25
8:55 AM	Division 5 Gap Analysis Reports	Bob Jetter	25
9:20 AM	Regulatory Guidance	Andrew Yeshnik (US Nuclear Regulatory Commission); Xuejun Wei (Canadian Nuclear Safety Commission)	40
10:00 AM	Break		30
10:30 AM	Design and Materials - Metallic	Mark Messner; Richard Wright	40
11:10 AM	Design and Materials - Nonmetallic	Will Windes	25
11:35 AM	ASME and Advanced Reactor Developers Interaction	Mike Cohen	25
12:00 PM	Lunch (On Your Own)		60
1:00 PM	Presentations from Advanced Reactor Developers (I) Advanced Reactor Concepts, LLC • BWX Technologies, Inc. • Flibe Energy • Framatome • GE Hitachi Nuclear Energy • Kairos Power • Moltex Energy • TerraPower • Terrestrial Energy • ThorCon • Ultra Safe Nuclear Corporation • X-Energy (List will be updated with more confirmation.)		120
3:00 PM	Break		30
3:30 PM	Presentations from Advanced Reactor Developers (II)		90
5:00 PM	ASME-Advanced Reactor Developers Discussion		30
5:30 PM	Workshop Adjourns		

Gas-cooled reactor metals activities at INL

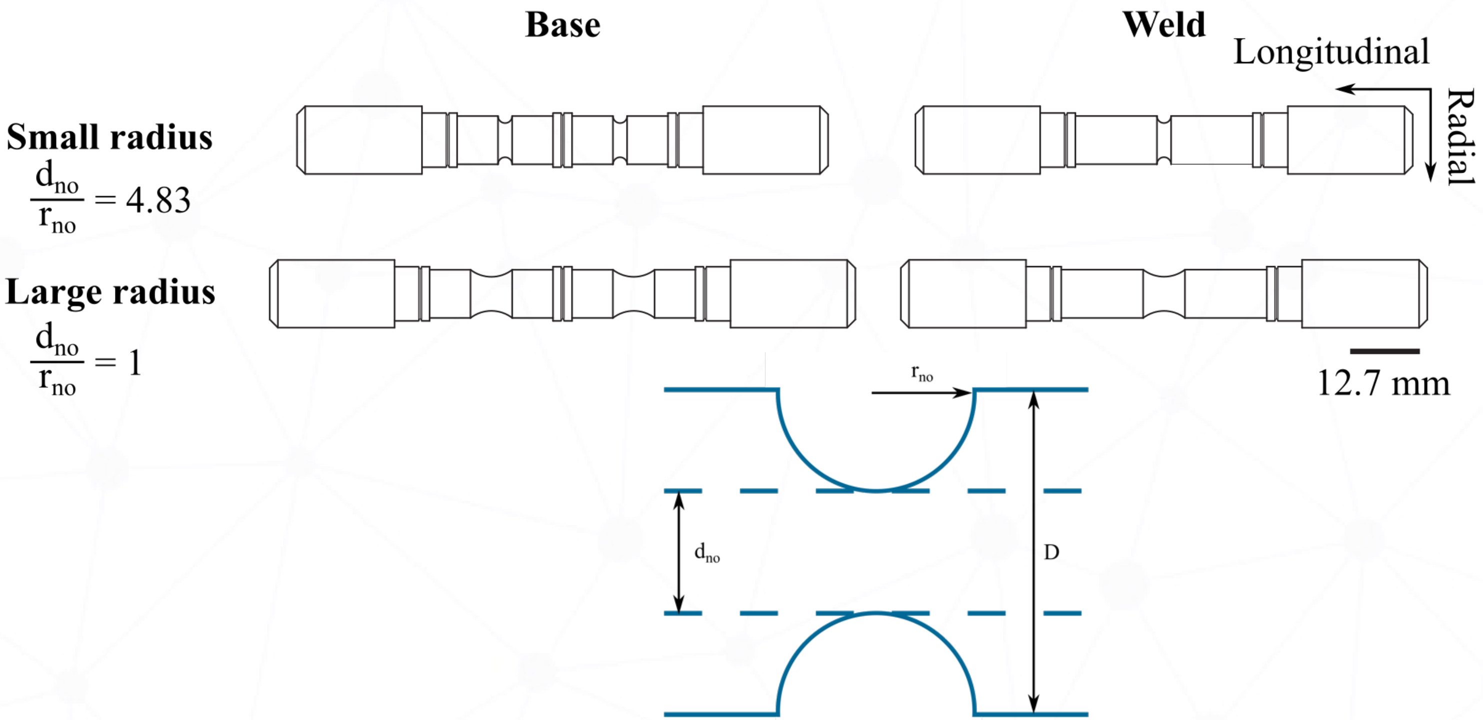
- The high-temperature materials development gas-cooled reactor work has three focus areas
  1. Addressing issues flagged by an NRC sponsored assessment of a previous version of Section III, Division 5 of the ASME Boiler and Pressure Vessel Code (BPVC)
  2. Probing the incorporation of advanced manufactured materials and components into Section III, Division 5 of the ASME BPVC
  3. Acquiring data to allow life extension for code materials
- The work corresponds to three specific research activities
  1. Alloy 617 notch specimen testing
  2. Diffusion welding of Alloy 617
  3. Testing of Alloy 800H weldments with Alloy 617 filler

Alloy 617 notch: introduction

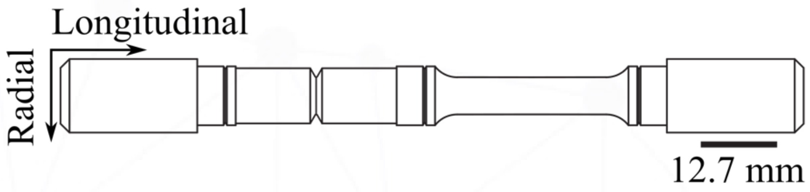
An inadequate understanding of the impact of multiaxial stress, structural discontinuities, and notch effects was identified as needing addressed by the NRC-sponsored assessment of a previous version of Section III, Division 5 of the ASME BPVC.

U-notch

(Bridgeman notch)



V-notch



Figures from: Rupp, R.E., & McMurtrey, M.D. (2020). The Impact of Geometric Discontinuities on Alloy 617 Creep-Rupture Behavior (PVP2020-21587). In *Proceedings of the ASME 2020 Pressure Vessels & Piping Conference.* The American Society of Mechanical Engineers.

Alloy 617 notch: short-term

Alloy 617, at the conditions tested, was found to be notch strengthening

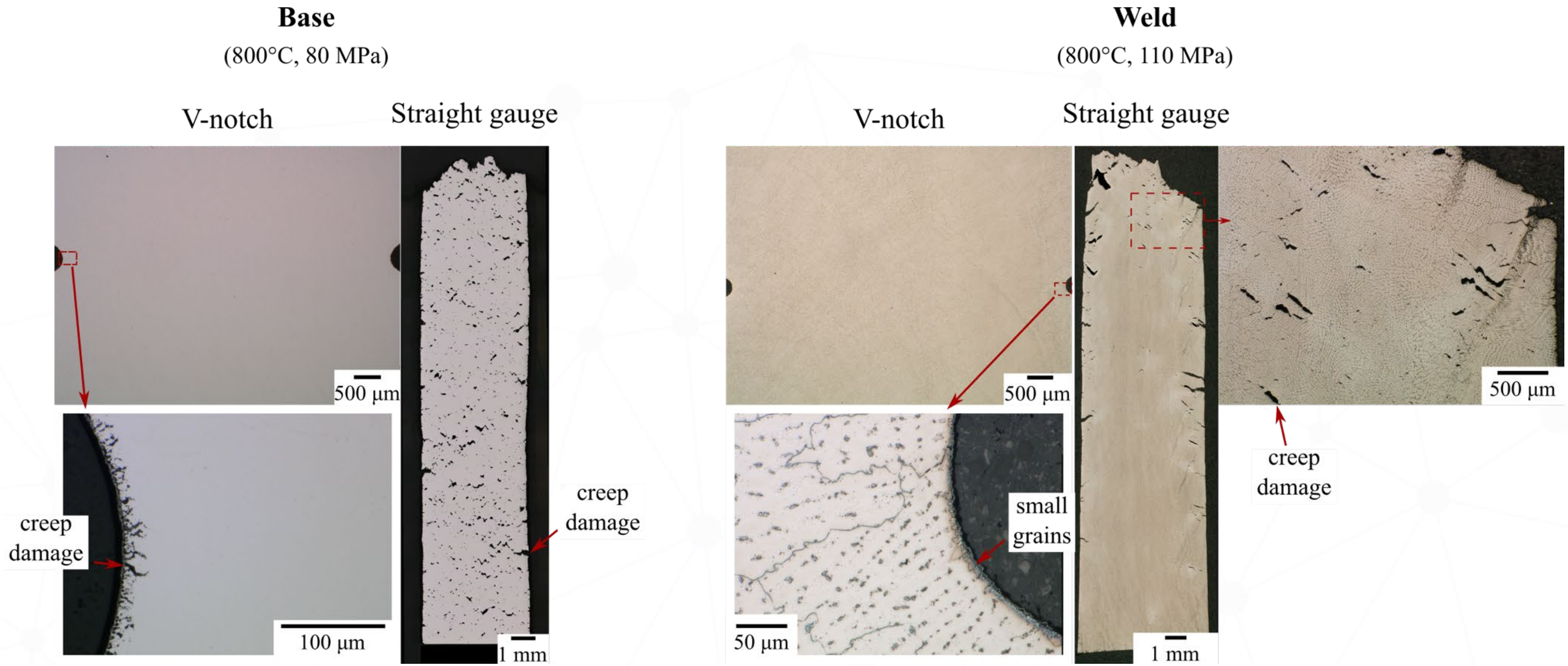


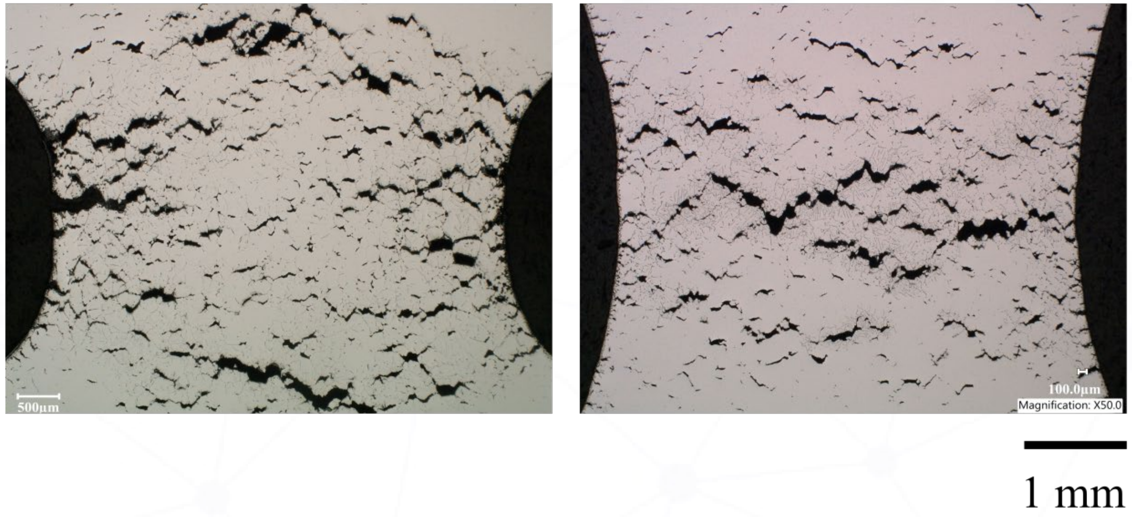
Figure modified from: Rupp, R.E., & McMurtrey, M.D. (2020). The Impact of Geometric Discontinuities on Alloy 617 Creep-Rupture Behavior (PVP2020-21587). In *Proceedings of the ASME 2020 Pressure Vessels & Piping Conference.* The American Society of Mechanical Engineers.

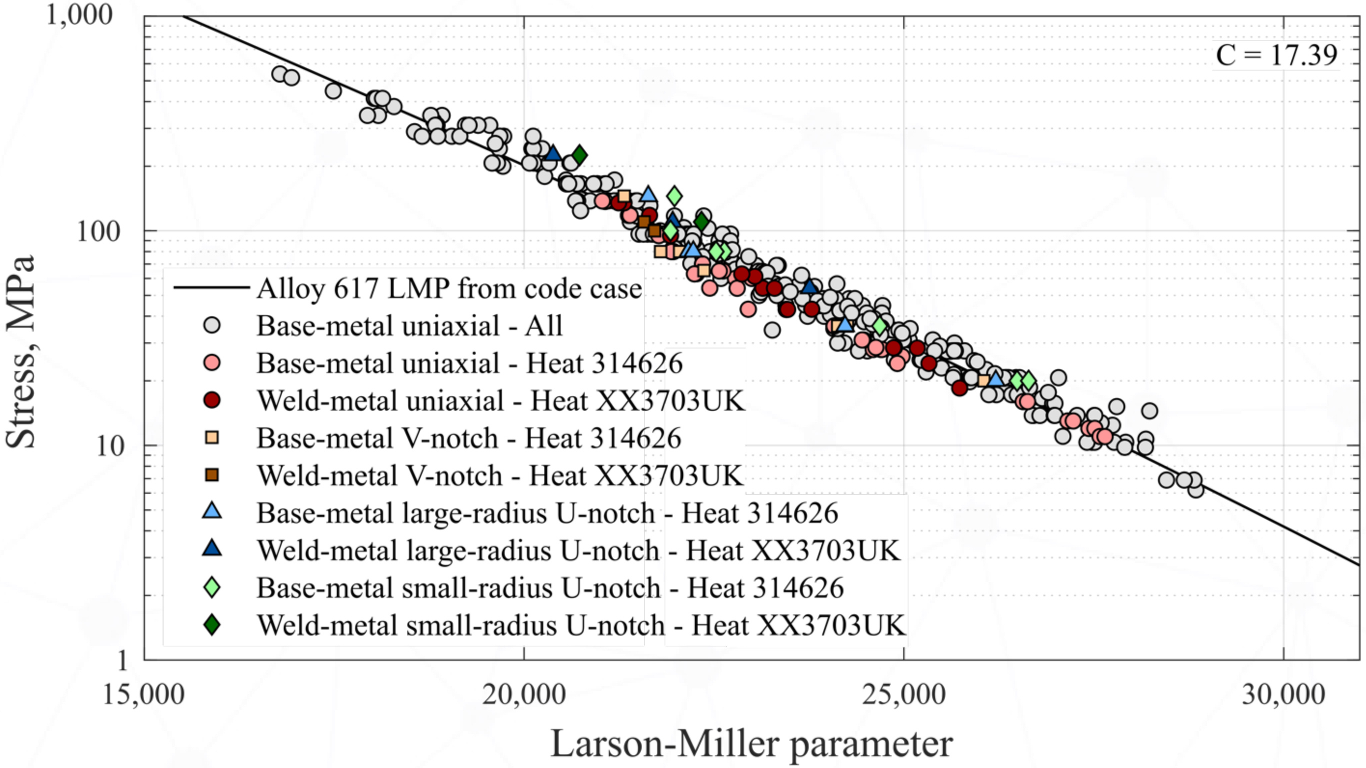
Alloy 617 notch: short-term

A stronger multiaxial stress increased the rupture life, possibly due to the notch strengthening nature of the material

1,000℃, 20 MPa

Small radius | Large radius





Right figure from: Rupp, R.E., & McMurtrey, M.D. (2020). The Impact of Geometric Discontinuities on Alloy 617 Creep-Rupture Behavior (PVP2020-21587). In *Proceedings of the ASME 2020 Pressure Vessels & Piping Conference.* The American Society of Mechanical Engineers.

Alloy 617 notch: short-term

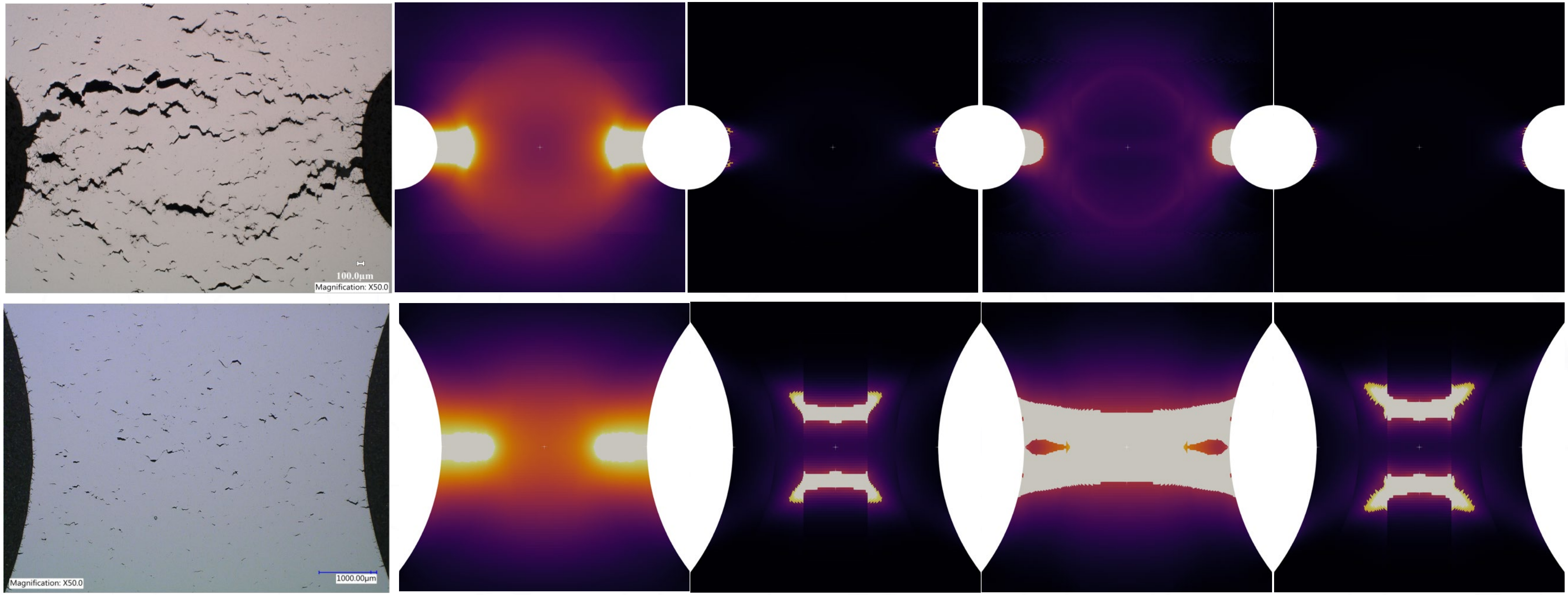
Work is in progress to evaluate a variety of damage models by comparing creep damage predicted by finite-element models with experimental observations.

900℃, 36 MPa

Experimental | Von Mises | Max principal | Huddleston | 0.37 Von Mises + 0.63 Max

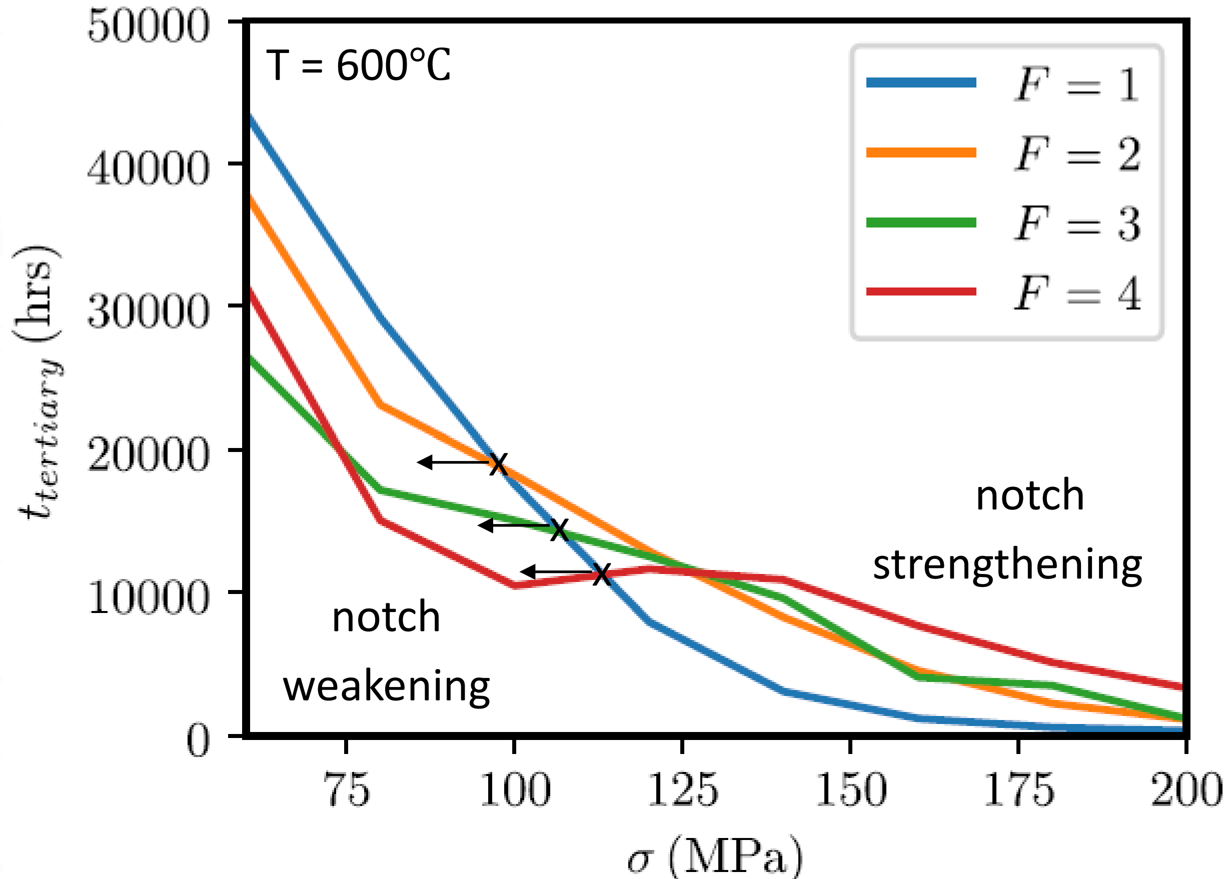
Small radius

Large radius



Alloy 617 notch: long-term and intermediate

- Notch rupture behavior is sensitive to a variety of elements including temperature and stress. Consequently, there is concern of notch weakening at temperature and stress combinations that result in a long rupture life.
- Long-term (aim 100,000 hours rupture life) and intermediate (aim 12,000 to 16,000 hours rupture life) creep-rupture testing of the base and weld-metals are in progress.



$$F = 3\frac{\sigma_m}{\sigma_e}$$

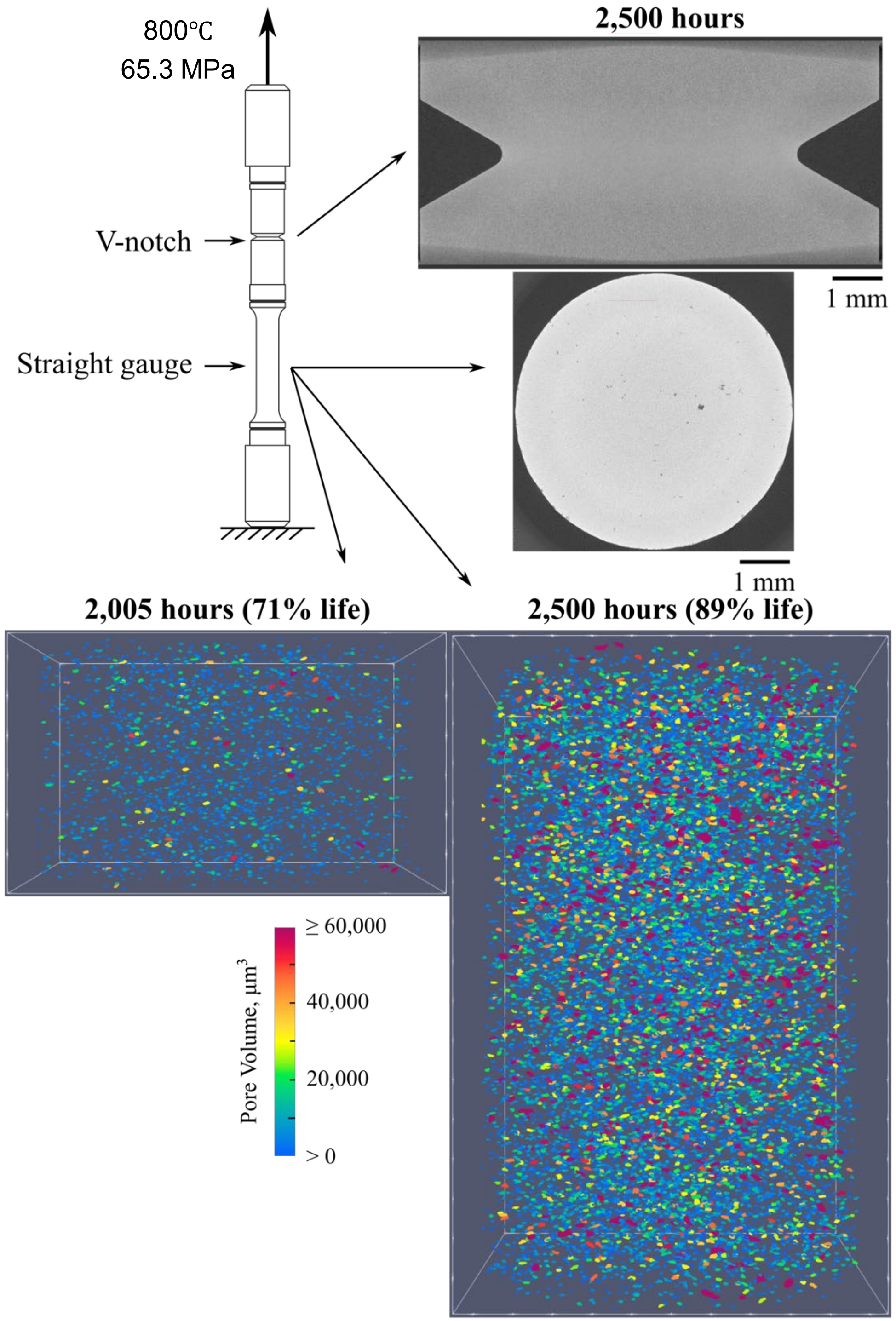
F = triaxiality ratio

σ_m = mean stress

σ_e = effective stress

Alloy 617 notch: baseline

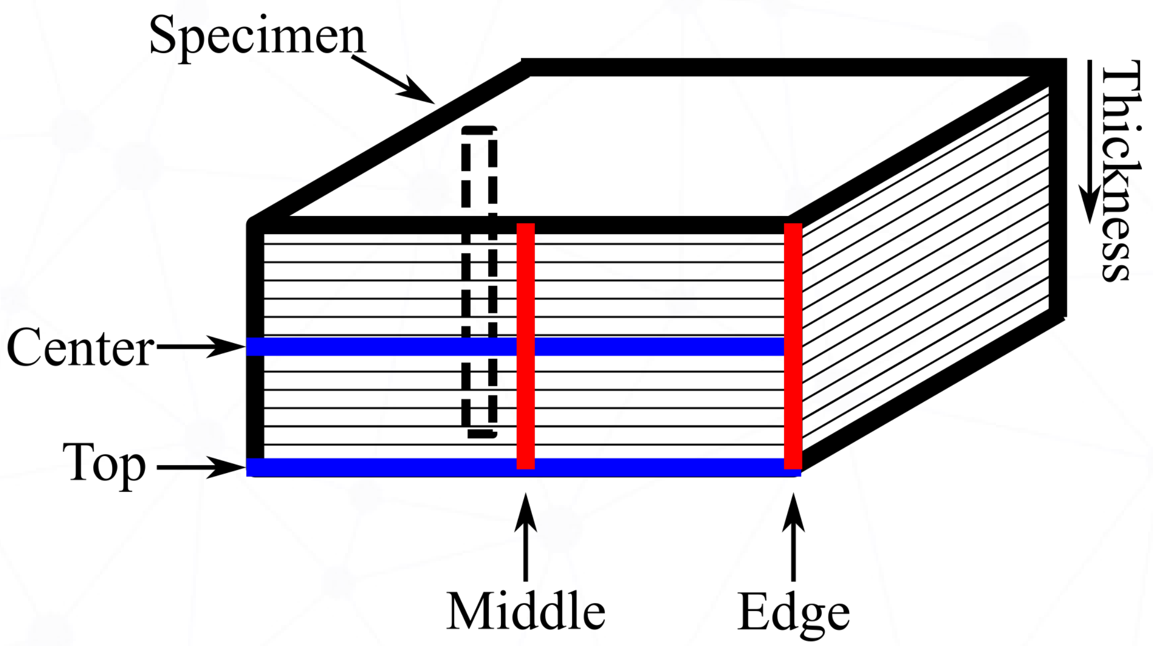
- Waiting 100,000 hours (~13 years) to learn the outcome of a test is impractical.
- A technique utilizing X-ray computed tomography (CT) to periodically, non-destructively characterize a creep-rupture specimen throughout a creep test has been developed.
- The goal is to enable identification of the failure location prior to rupture.
- This requires baseline testing in order to correlate creep damage to rupture life.
- A specimen tested at 800℃ and 65.3 MPa was characterized with X-ray CT at 2,005 and 2,500 hours. Pores greater than or equal to the resolution of the X-ray CT were not detected in the notch at either of these times. The maximum void density of the straight gauge at these two times was 0.02% and 0.1%, respectively. The specimen failed in the straight gauge at 2,824 hours.
- As the test progressed, the number and size of the cavities increased.
- Baseline testing is ongoing.



Alloy 617 diffusion welds: introduction

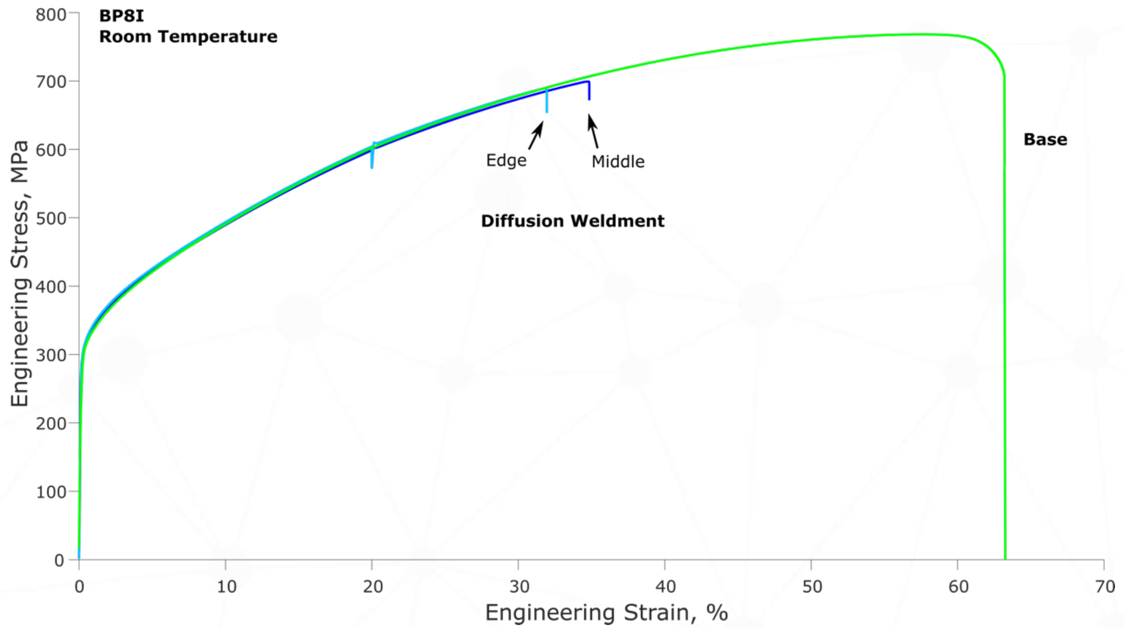
- Two diffusion welded (DW) A617 test blocks were fabricated by the Korea Atomic Research Institute (KAERI).
  - The dimensions of the test blocks meet size requirements specified in Section IX of the ASME Boiler and Pressure Vessel Code (BPVC).
    - 200 mm x 200 mm x ~90 mm
    - Comprised of 60 A617 sheets (59 DW interfaces)
- KAERI characterized BP8K.
- INL characterized BP8I.

BP8I



Alloy 617 diffusion welds: room-temperature tensile properties

- Room-temperature tensile tests met the requirements specified in QW-153 in Section IX of the Code.
- Tensile facture occurs in a brittle manner at a diffusion-weld interface.



	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
BP8K[1]	730 ± 15	318 ± 4	37.1 ± 1.4
BP8I edge	690	310	30.9
BP8I middle	700	310	33.4
Base	765	302	63.3
Sec. IX QW-185	655	-	-

Longitudinal axis is perpendicular to DW interfaces

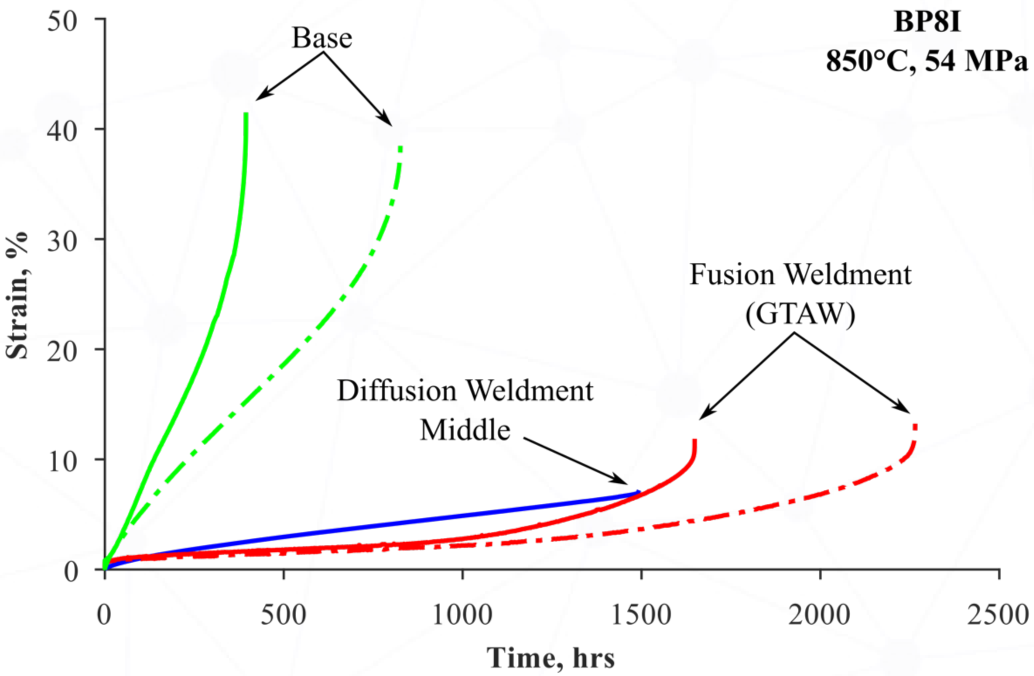
Edge

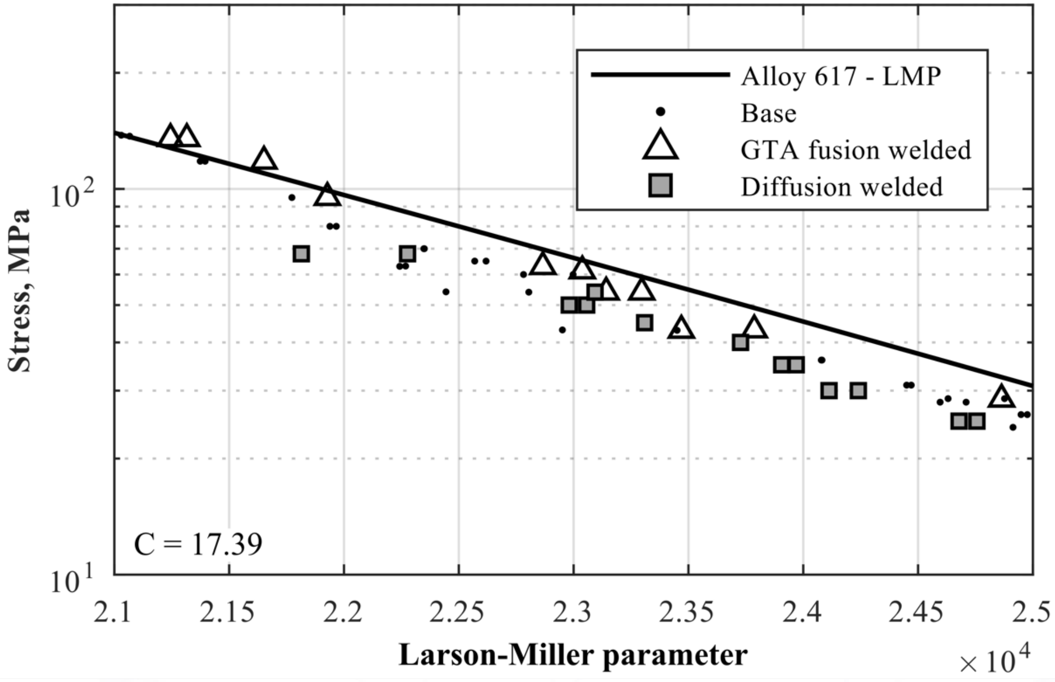
Middle

[1] Sah, I., Hwang, J. B., Kim, W. G., Kim, E. S., & Kim, M. H. (2020). High-temperature mechanical behaviors of diffusion-welded Alloy 617. *Nuclear Engineering and Design*, 364, 110617.

Alloy 617 diffusion welds: creep

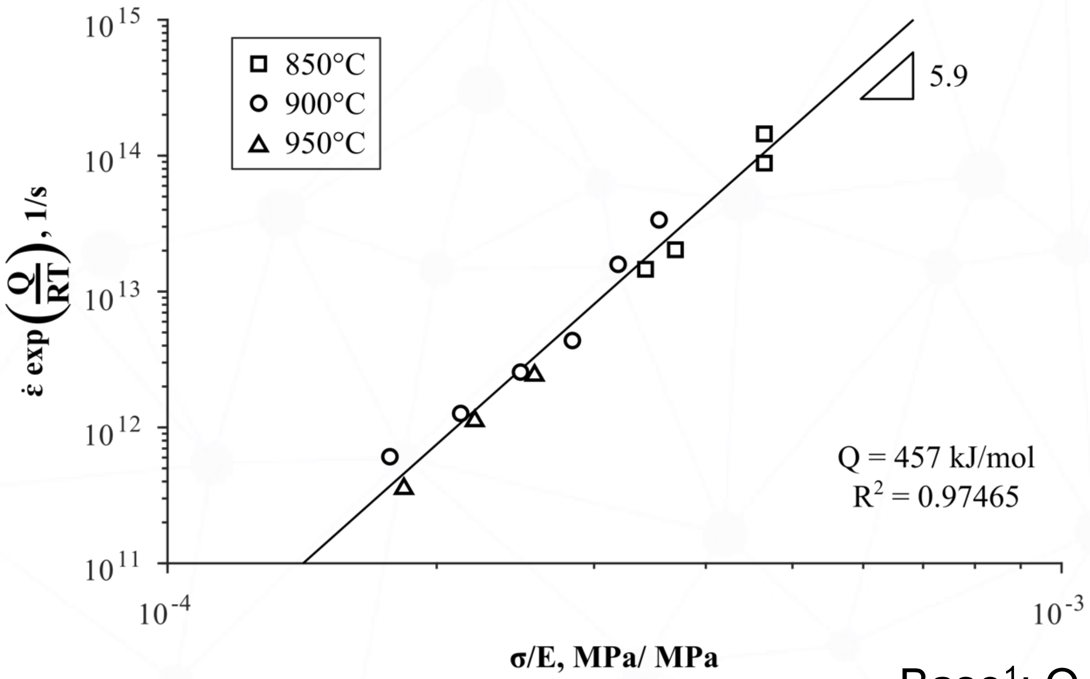
- Creep rupture occurred at a DW interface.
- The creep-rupture lives of the DW material are similar to the base material but shorter than the GTAW fusion weldment.
- DW rupture occurs at lower engineering strains than both the base metal and GTAW fusion weldment.
- Specimens from the edge of the DW plate ruptured earlier than specimens from the middle of the plate.





Alloy 617 diffusion welds: creep

- The creep mechanisms of the DW metal is the same as the base metal.
- Cavitation damage was primarily located at DW interfaces.
- Differences in creep behavior between the DW and base metal must be the result of the interface quality.



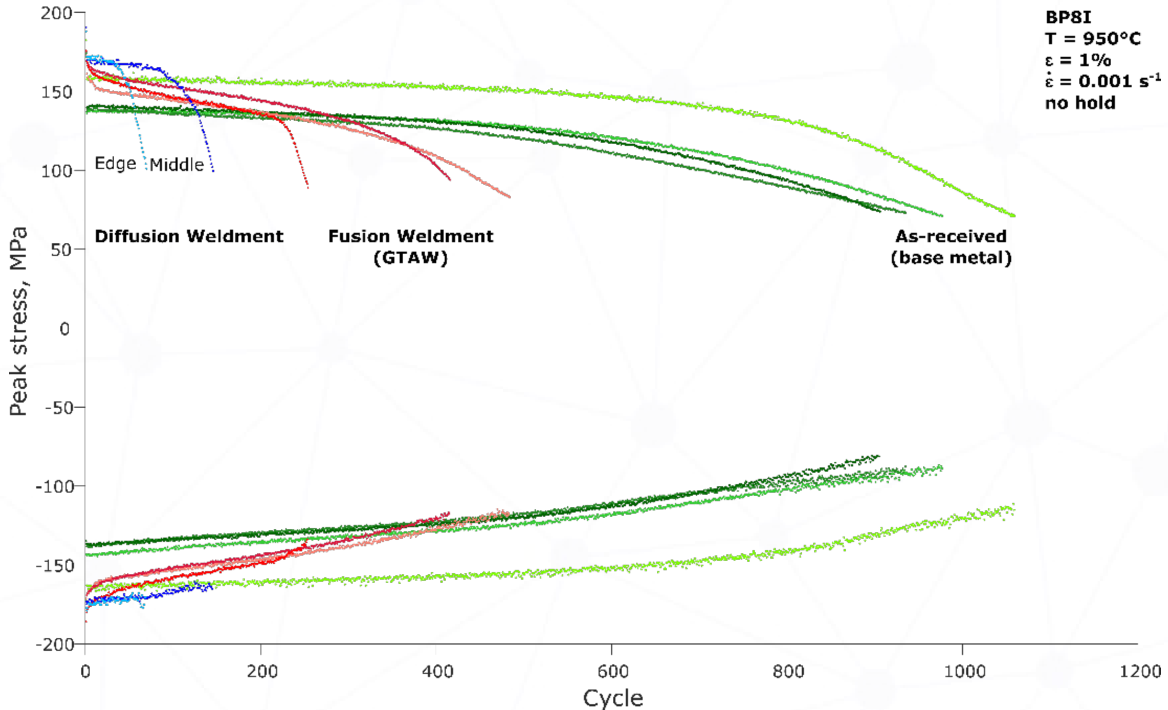
850℃, 67.9 MPa, Middle of the DW plate

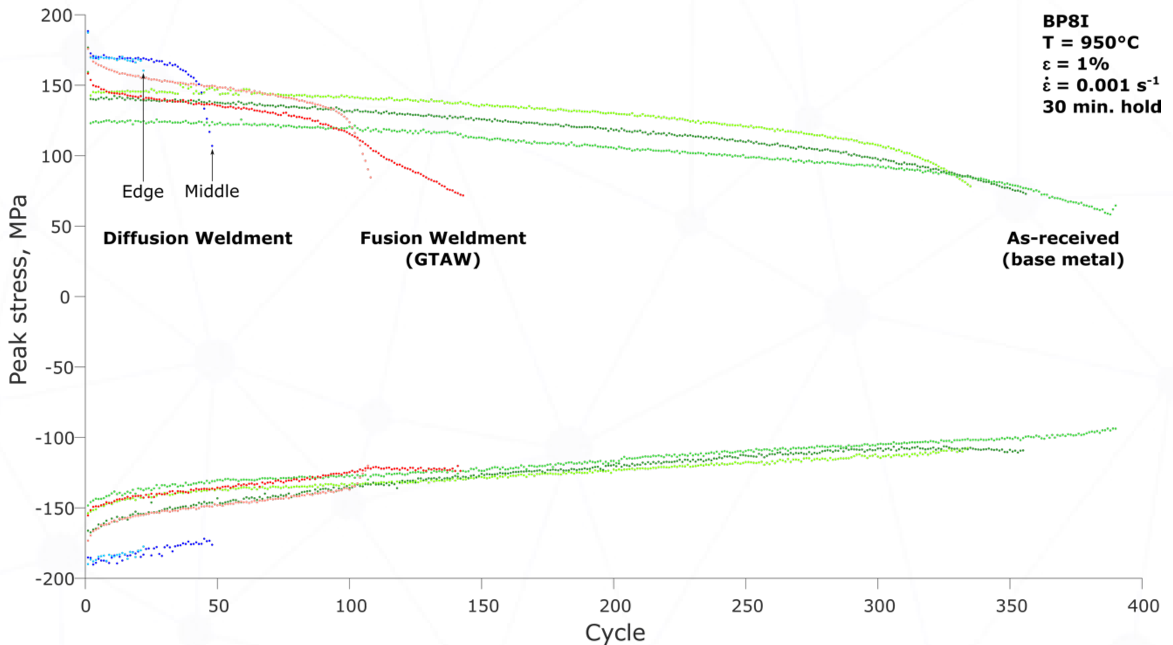
Base[1]: Q = 410 kJ/mol, n = 5.6

[1] Benz, J. K., Carroll, L. J., Wright, J. K., Wright, R. N., & Lillo, T. M. (2014). Threshold stress creep behavior of alloy 617 at intermediate temperatures. *Metallurgical and Materials Transactions A*, 45(7), 3010-3022.

Alloy 617 diffusion welds: cyclic

- The number of cycles to failure of the DW metal was lower than the base and GTAW fusion-welded metal.
- Specimens from the edge of the DW plate has a lower number of cycles to failure than specimens from the middle of the plate.



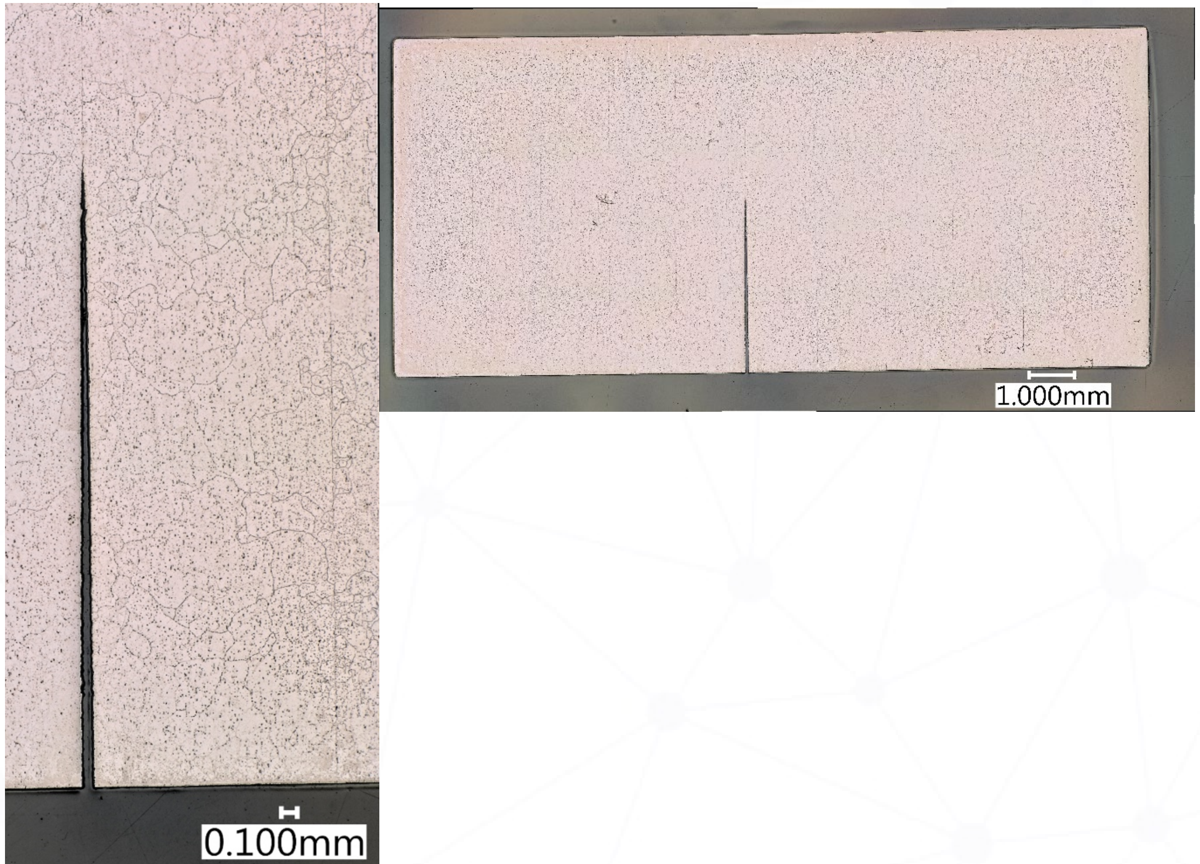


Alloy 617 diffusion welds: cyclic

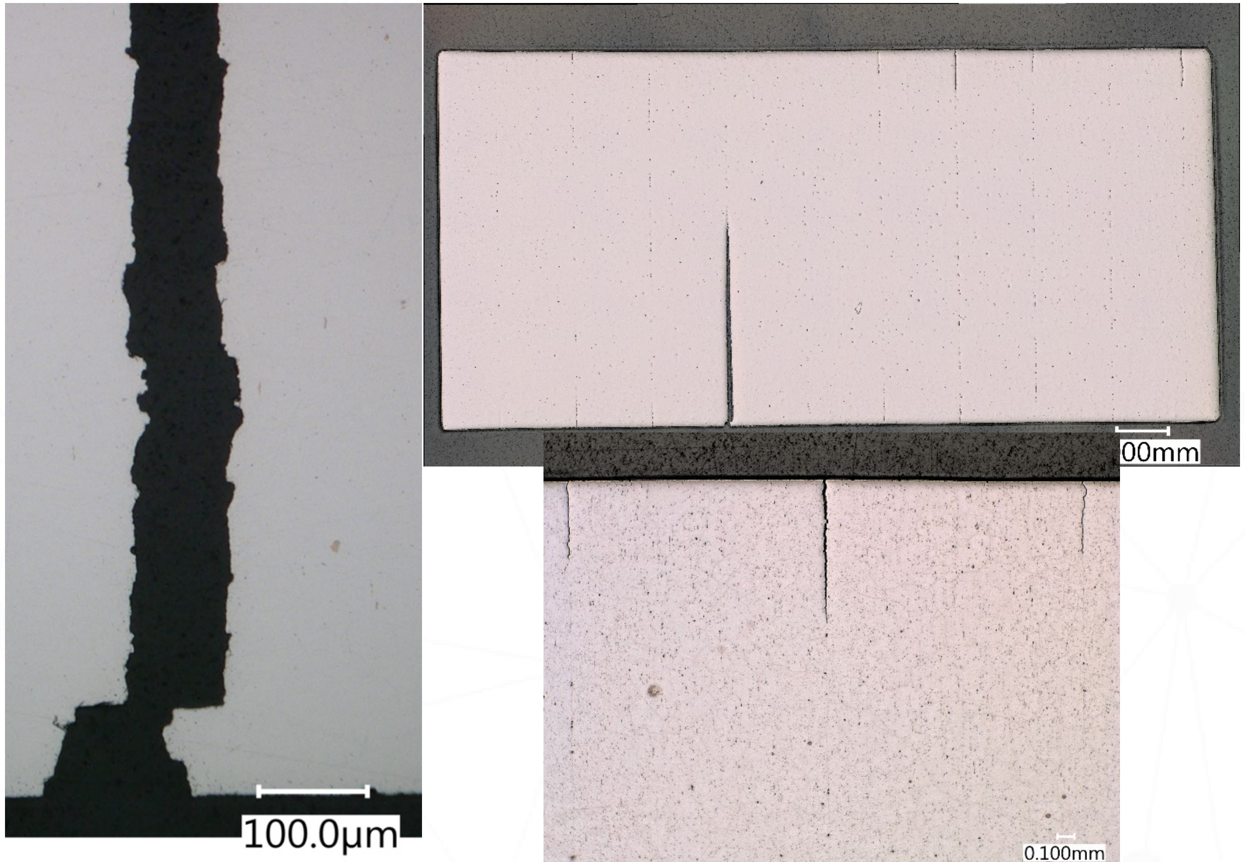
- The cyclic life is limited by the weakest interface.
- Interface quality is improved by grain growth across the interface.

950℃, ε = 1%, no hold

Edge (N_f = 61)



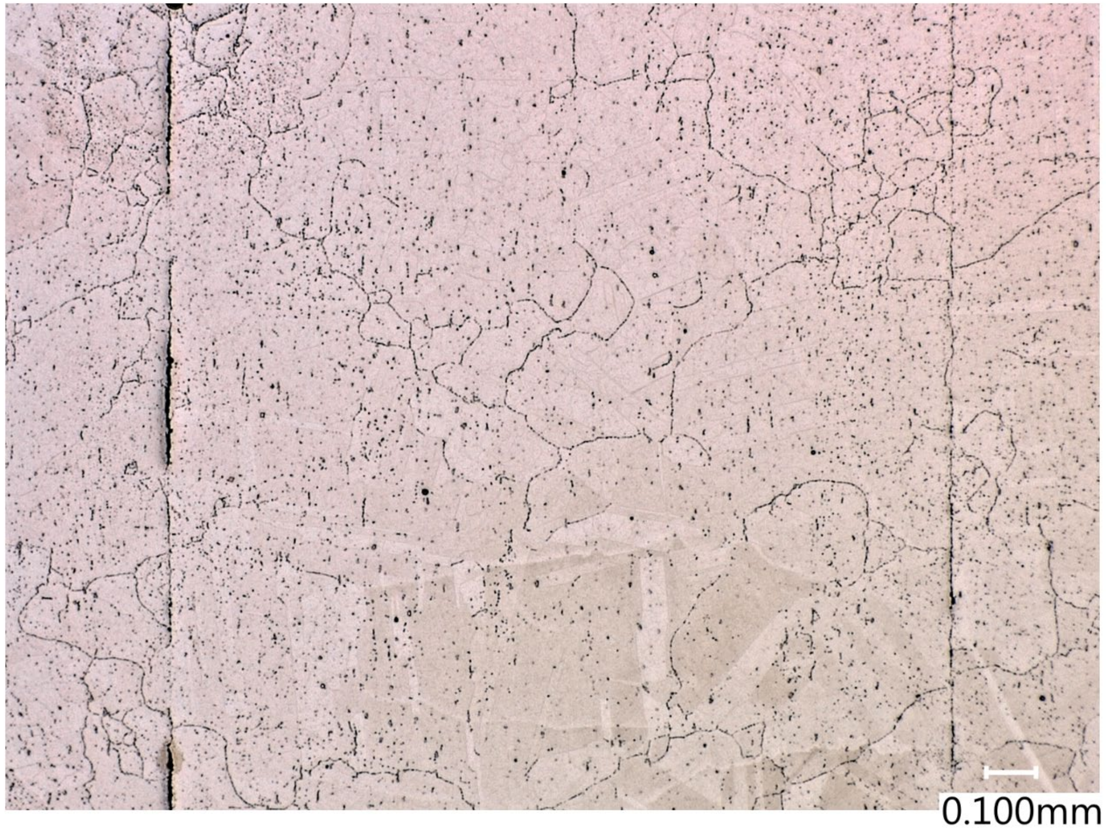
Middle (N_f = 136)



Alloy 617 diffusion welds: conclusions

1. Room-temperature tensile properties exceeded the minimum tensile strength specified by QW-153 in Section IX.
2. The creep-rupture life of DW material is similar to base material but shorter than GTAW fusion weldments. The ductility of DW material is significantly shorter than both the base material and GTAW fusion weldments.
3. The number of cycles to failure during fatigue was lower for the DW material than compared to the base material and GTAW fusion weldments.
4. The creep and cyclic properties of DW material are dependent upon the quality of the interfaces. Failure occurs at the weakest interface.
5. Grain boundary migration across the DW interface improves the interface quality.

Creep 850°C, 50 MPa



Alloy 800H weldments: introduction

- Components fabricated from Alloy 800H welds with Alloy A and Alloy 82 filler metals are permissible in Section III, Division 5 of the ASME BPVC for a maximum service life of 300,000 hours.
- There is desire to extend the design life of Alloy 800H to 500,000 hours. This requires extending the stress rupture factors for weldments.
- The stress rupture factors for Alloy 800H welds with Alloy 82 filler become small at high-temperatures, long-rupture lives. This may make the use of Alloy 800H for longer design lives impracticable.
- Alloy 800H welds with Alloy 617 filler metal are being investigated to understand the effect of an overmatched weld.

Table HBB-I-14.10C-2
Stress Rupture Factors for Alloy 800H Welded With SFA-5.14 ERNiCr-3 (INCO 82)

U.S. Customary Units

Temp., °F	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
850–900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
950	0.89	0.90	0.90	0.90	0.89	0.89	0.88	0.87	0.86	0.86
1,000	0.85	0.86	0.86	0.86	0.85	0.85	0.84	0.84	0.82	0.81
1,050	0.88	0.88	0.88	0.88	0.87	0.86	0.85	0.84	0.83	0.81
1,100	0.91	0.91	0.91	0.90	0.89	0.88	0.87	0.85	0.83	0.81
1,150	0.94	0.93	0.93	0.92	0.90	0.89	0.87	0.85	0.83	0.81
1,200	0.96	0.96	0.95	0.93	0.92	0.90	0.88	0.86	0.83	0.81
1,250	0.99	0.98	0.96	0.95	0.93	0.91	0.88	0.85	0.82	0.80
1,300	1.00	1.00	0.98	0.96	0.93	0.91	0.88	0.85	0.82	0.78
1,350	1.00	1.00	0.99	0.96	0.94	0.91	0.87	0.84	0.77	0.68
1,400	1.00	1.00	1.00	0.97	0.94	0.89	0.79	0.71	0.62	0.54

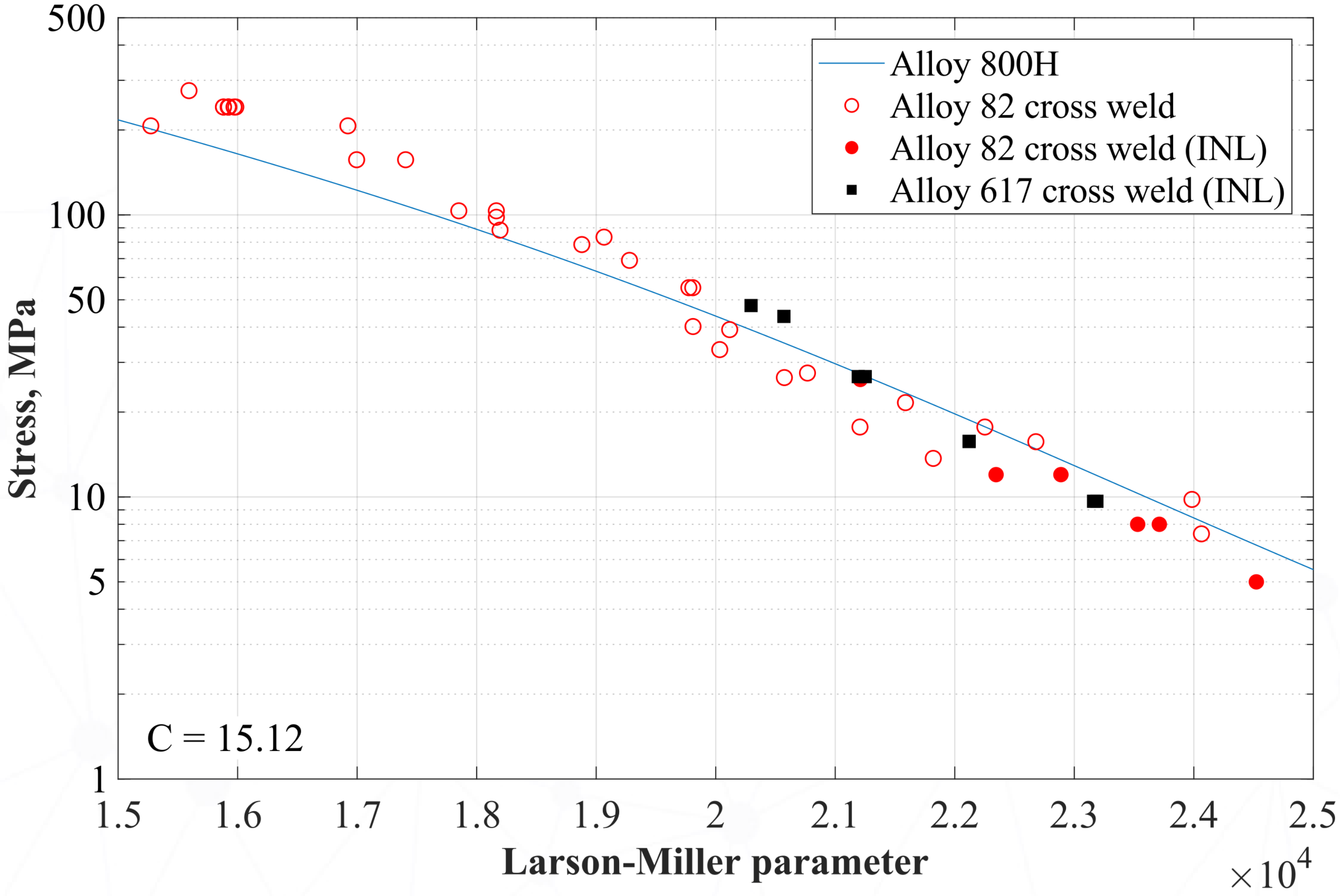
SI Units

Temp., °C	10 h	30 h	100 h	300 h	1 000 h	3 000 h	10,000 h	30 000 h	100 000 h	300 000 h
450–475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	0.93	0.94	0.94	0.94	0.93	0.93	0.92	0.92	0.91	0.91
525	0.87	0.88	0.88	0.88	0.87	0.87	0.86	0.85	0.84	0.83
550	0.86	0.87	0.87	0.87	0.86	0.85	0.84	0.84	0.82	0.81
575	0.89	0.89	0.89	0.89	0.88	0.88	0.86	0.84	0.83	0.81
600	0.92	0.92	0.92	0.91	0.89	0.88	0.87	0.85	0.83	0.81
625	0.94	0.93	0.93	0.92	0.90	0.89	0.87	0.85	0.83	0.81
650	0.96	0.96	0.95	0.93	0.92	0.90	0.88	0.86	0.83	0.81
675	0.99	0.98	0.96	0.95	0.93	0.91	0.88	0.85	0.82	0.80
700	1.00	1.00	0.98	0.96	0.93	0.91	0.88	0.85	0.82	0.78
725	1.00	1.00	0.99	0.96	0.94	0.91	0.87	0.84	0.78	0.71
750	1.00	1.00	1.00	0.97	0.94	0.90	0.82	0.76	0.67	0.59

Table from: American Society of Mechanical Engineers (ASME). (2019). *Rules for construction of nuclear facility components: high temperature reactors* (Section III, Division 5). ASME Boiler and Pressure Vessel Code: An International Code .

Alloy 800H weldments: creep-rupture life

- Cross welds with Alloy 617 filler appear to have improved creep-rupture properties compared to Alloy 800H for lower Larson-Miller parameter (LMP) values.
- Cross-welds with Alloy 617 filler crosses the Alloy 800H parametric curve between LMP values 21,000 and 22,000. Cross welds with Alloy 617 have worse creep-rupture properties compared to Alloy 800H beyond this point. Cross welds with Alloy 82 filler crosses the Alloy 800H parametric curve at a LMP of approximately 20,000.
- Short- and intermediate- length, lower-temperature creep-rupture tests of cross-welds with Alloy 617 filler are in progress.



Alloy 800H weldments: creep damage

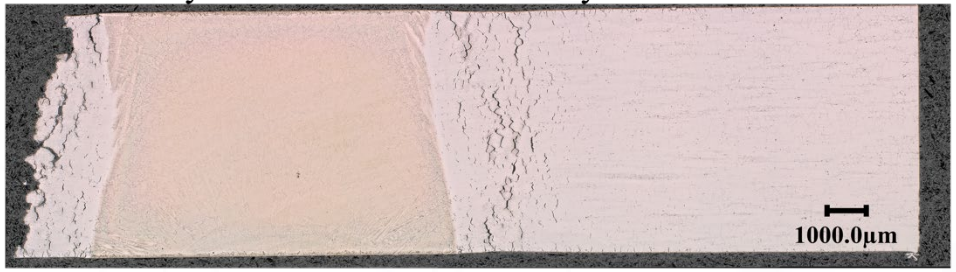
- Cross welds with Alloy 617 filler fail in the base metal. This is in stark contrast compared to cross welds with Alloy 82 filler that fail in the weld.
- The location and extent of cavitation damage varies significantly with temperature and stress.
- Work is ongoing to characterize the hardness of the weldment.

900°C, 26.7 MPa

Alloy 800H base metal Alloy 617 weld metal

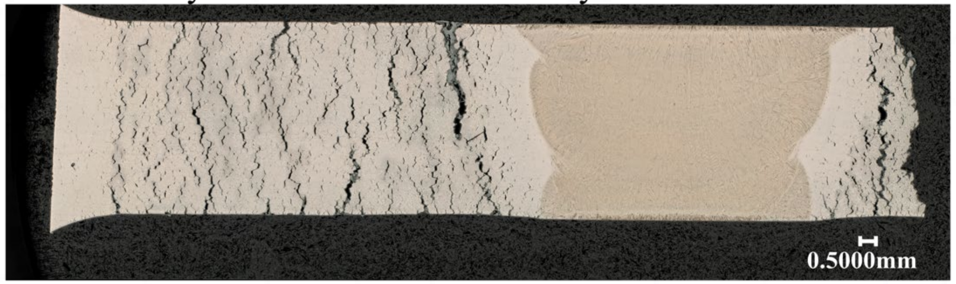
950°C, 15.7 MPa

Alloy 617 weld metal Alloy 800H base metal



1,000°C, 9.7 MPa

Alloy 800H base metal Alloy 617 weld metal



900°C, 21.6 MPa

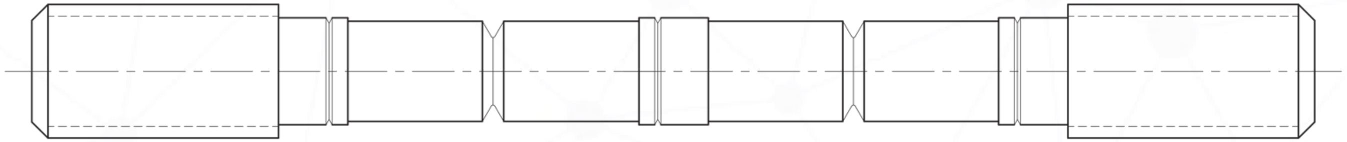
Alloy 800H base metal Alloy 82 weld metal

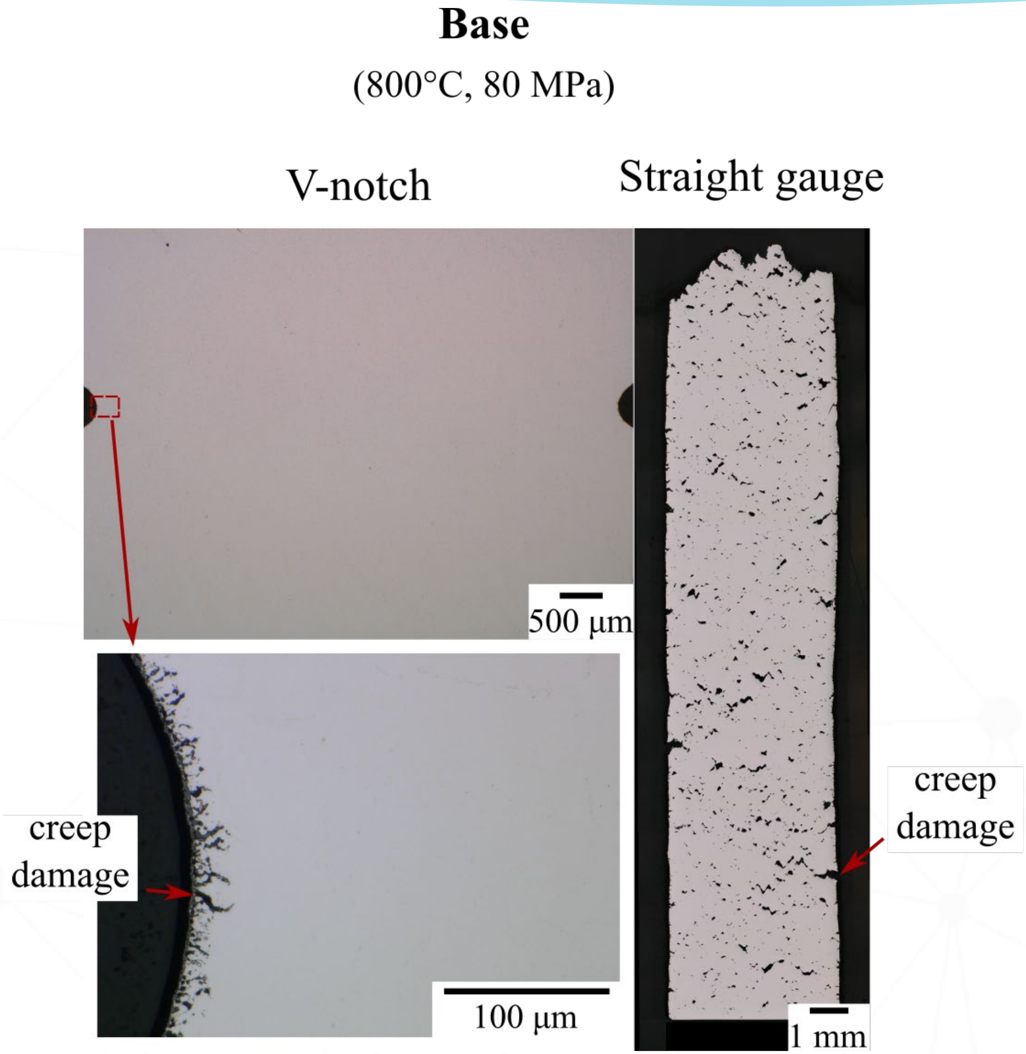
Summary

- This fiscal year, work in the gas-cooled reactor program covered a wide range of topics in order to:
  1. Address issues flagged by an NRC sponsored assessment of a previous version of Section III, Division 5 of the ASME Boiler and Pressure Vessel Code (BPVC).
  2. Probe the incorporation of advanced manufactured materials and components into Section III, Division 5 of the ASME BPVC.
  3. Acquire data for code needs.
- Work is ongoing to:
  - Alloy 617 notch effects:
    - Evaluate a variety of damage models by comparing creep damage predicted by finite-element models with experimental observations.
    - Characterize the impact of geometric discontinuities on long-term and intermediate creep-rupture properties of base and weld-metal Alloy 617.
    - Correlate creep damage to rupture life in order to facilitate identification of rupture location prior to failure.
    - Begin double V-notch creep rupture testing.
  - Alloy 800H weldments with Alloy 617 filler:
    - Understand the effect of an overmatched weld

Alloy 617 notch: new developments

- All completed V-notch creep-rupture tests to date have failed in the straight gauge with little to no creep damage observed in the V-notch.
- A double V-notch creep rupture specimen has been developed which enables the following:
    1. Identification of the distribution of the creep damage. The microstructure at failure and just prior to failure can be characterized by analyzing the ruptured and unruptured notch, respectively.
    2. Quantification of the notch strengthening effect.
    3. Correlation of creep damage to rupture life in the V-notch necessary for baseline testing.
    4. Comparison with finite element models.



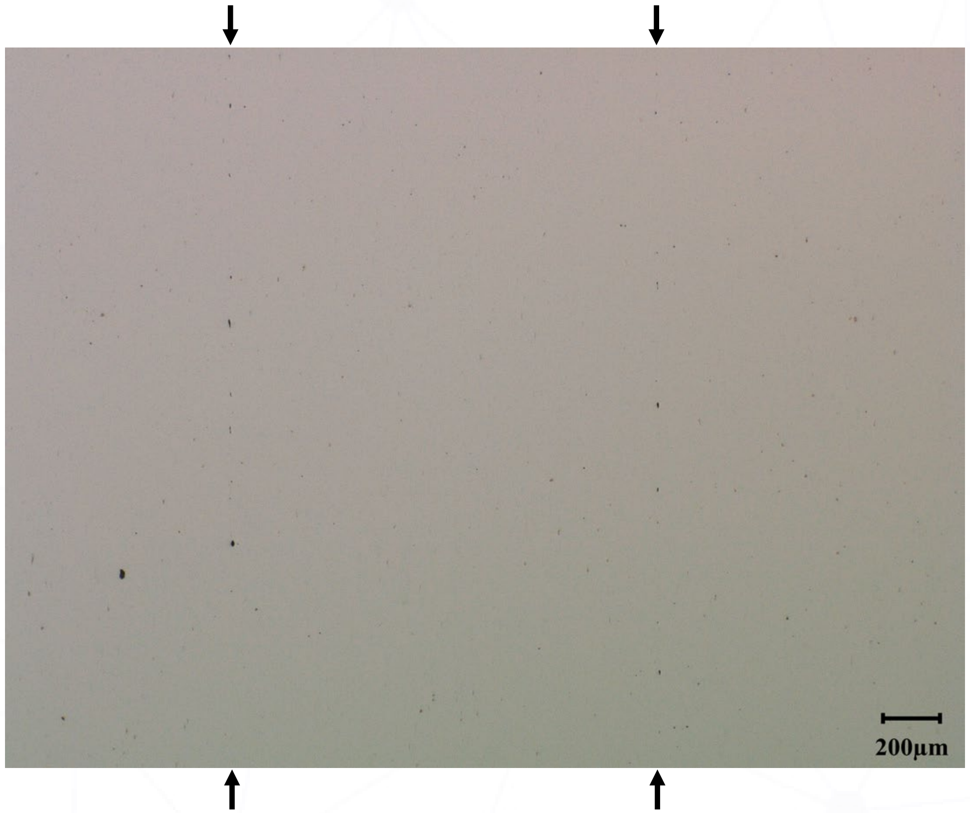


Right figure modified from: Rupp, R.E., & McMurtrey, M.D. (2020). The Impact of Geometric Discontinuities on Alloy 617 Creep-Rupture Behavior (PVP2020-21587). In *Proceedings of the ASME 2020 Pressure Vessels & Piping Conference.* The American Society of Mechanical Engineers.

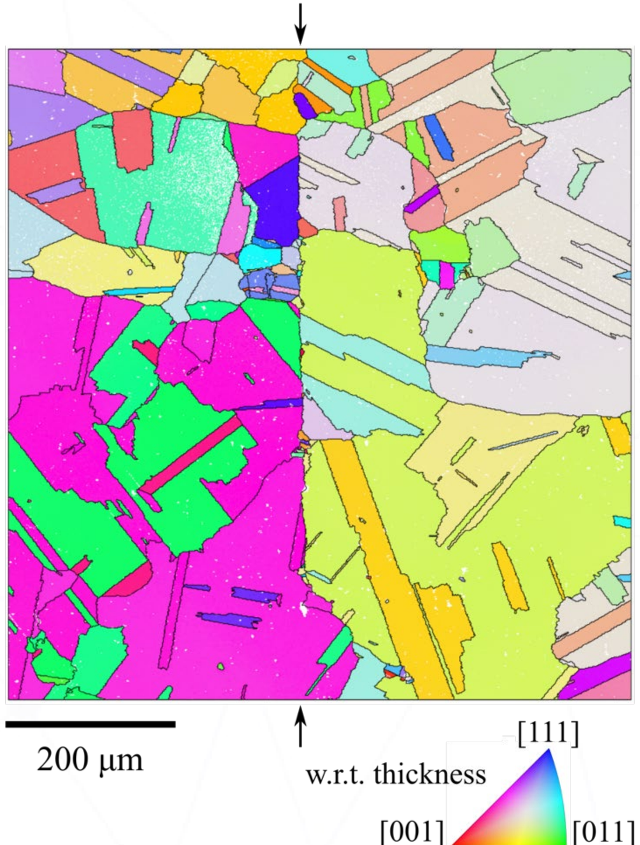
Alloy 617 diffusion welds: as-received microstructure

- Porosity is present at the DW interfaces of BP8I.
- Grain growth across the DW interface occurred in some regions.

Optical microscopy image of BP8I from the middle of the plate at 100x



IPF map from EBSD data of BP8I from the middle, center of the plate



INL

Idaho National Laboratory