



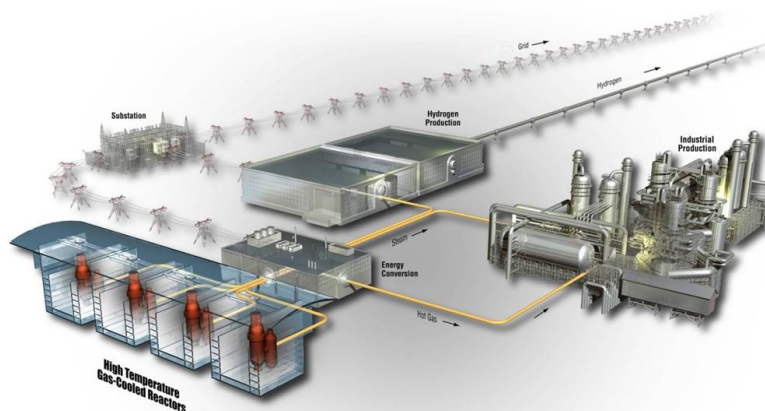
Effects of Notches on the Intermediate Creep-Rupture Life of Alloy 617 Weldment

September 2020

Changing the World's Energy Future

Michael D. McMurtrey

Ryann E. Rupp



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Michael D. McMurtrey

Ryann E. Rupp

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**Idaho National Laboratory
Advanced Reactor Technologies
Idaho Falls, Idaho 83415**

<http://www.ART.INL.gov>

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Richard Wright

Richard Wright
Emeritus Laboratory Fellow

09/16/2020

Date

Approved by:

Gerhard Strydom

Gerhard Strydom
INL ART GCR National Technical Director

09/16/2020

Date

HELEN GUYMON (Affiliate)

Digitally signed by HELEN GUYMON
(Affiliate)
Date: 2020.09.16 12:49:12 -06'00'

Helen Guymon
INL ART Project Manager

Date

Michelle Sharp

Michelle T. Sharp
INL Quality Assurance

9/16/2020

Date

ABSTRACT

A Code Case has recently been completed that adds Alloy 617 to Section III, Division 5 of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, which covers high temperature nuclear components. However, additional information is needed to address concerns raised by the Nuclear Regulatory Commission that are not covered by the Code Case. The effects of notches (geometric discontinuities) and multiaxial stress on the expected creep life of a component are among these concerns. This report covers state of the testing of Alloy 617 notched specimens at Idaho National Laboratory, with a particular focus on intermediate length (8,000–20,000 hours) creep tests of Alloy 617 weld metal. While most of this testing is ongoing, the current state of the tests indicates that the multiaxial stress state imposed by the notch geometry does not negatively impact the creep-rupture life of the Alloy 617 weld metal. While the weld metal is notch strengthening in short-term (1,000–2,000 hours) testing, it is not clear if this characteristic will continue to hold for intermediate and long-term testing. Ongoing tests will provide additional information to address this concern of a crossover from notch strengthening to notch weakening for intermediate and long-term creep lives.

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ACRONYMS

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
CT	computed tomography
GTAW	gas tungsten arc welding
INL	Idaho National Laboratory
NRC	Nuclear Regulatory Commission
RD	rolling direction

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Effects of Notches on the Intermediate Creep-Rupture Resistance of Alloy 617 Weldment

1. Introduction

A Code Case was recently accepted to include Alloy 617 in the American Society of Mechanical Engineer's (ASME) Boiler and Pressure Vessel Code (BPVC), Section III Division 5 for use in constructing high temperature nuclear components, allowing the alloy to be used at temperatures up to 950°C and a design life of up to 100,000 hours [1]. Alloy 617 is of interest for use in constructing intermediate heat exchangers for the very-high-temperature reactor concepts [2,3]. The Code Case covers the high temperature design methodology for construction as well as welding processes and inspection requirements.

Section III, Division 5 of the ASME BPVC for elevated-temperature nuclear reactors is currently under review by the Nuclear Regulatory Commission (NRC) for potential endorsement. The NRC sponsored an assessment on the application of a previous version of these rules for elevated-temperature nuclear reactor designs, including the Clinch River Breeder Reactor. This assessment found, among other things, that the impact of notches, multiaxial stress states, and structural discontinuities on the service life of components at elevated temperatures have not been adequately addressed by the BPVC [4].

The allowable stress limits set forth in the Alloy 617 Code Case are based on uniaxial-creep data [5]. Loading in real components, however, is complex, resulting in multiaxial stress states, which may affect the component life. In addition to the multiaxial stress, real components are not smooth, uniform bars like those tested in typical laboratory creep measurements used to generate data for Code Cases. Geometric discontinuities can potentially negatively impact creep life via a mechanism referred to as "notch weakening." The opposite (a longer than expected life around a notch or discontinuity) is referred to as "notch strengthening." As these (multiaxial stress, notch weakening behaviors) can affect a component life in a way that could lead to premature and unexpected failure, there is a need to better understand these issues in the elevated-temperature materials allowed in BPVC Section III Division 5. Alloy 617 has been selected for an in-depth study as a prototypical material that may be used to investigate these concerns. There is a large amount of data generated from the recent Code Case and material available for additional studies.

The impact of a geometric discontinuity on creep behavior is not an innate property of the material, but instead is dependent upon a number of factors, including alloy, heat treatment, temperature, stress, specimen size, and discontinuity geometry [6–11]. Notch behavior has been associated with the redistribution of stress, lateral flow constraints, and the multiaxial stress state associated with a notch [6,7,11,12]. As notch-rupture behavior can vary with changes in temperature and stress, despite all other factors remaining constant, it is important to study conditions related to operations. Prior work has examined short-term (1,000–4,000 hours) creep tests and found Alloy 617 to be notch strengthening, with no detrimental effects of multiaxial stress on the creep life. [13] Work has also been performed to characterize the damage and deformation mechanisms of these short-term tests. [14] This report covers work performed to examine the effects of multiaxial stress and notch strengthening behavior for intermediate creep-rupture life tests (expected life of approximately 8,000–20,000 hours).

2. Experimental Procedure

2.1 Materials

A nominally 37 mm thick, solution-annealed Alloy 617 plate from ThyssenKrupp Vereinigte Deutsche Metallwerke, heat number 314626, was used in this investigation. This is the same Alloy 617 plate used in the ASME BPVC Section III, Division 5 Code Case for elevated-temperature nuclear component construction [1]. The chemical composition of the plate is provided in Table 1. This table also includes the ASME-specified chemistry requirements for Alloy 617 [15]. The plate had an as-received average lineal intercept grain size of 150 μm . Carbide banding, approximately 100 to 300 μm in width, and stringers were present in the as-received microstructure parallel to the rolling direction (RD). The carbides formed on a prior finer-grain structure unrelated to the as-received microstructure. Apart from the carbide banding, a small number of titanium nitrides were present in the as-received microstructure.

An Alloy 617 welded plate with Alloy 617 filler was constructed in accordance with Idaho National Laboratory (INL) Welding Procedure Specification I5.0. [16] A double-V butt-joint weld was fabricated using an automated multiple pass gas tungsten arc welding (GTAW) process. Figure 1 shows the through-thickness profile of the weld. The base metal was the Alloy 617 plate discussed above. The ERNiCrCoMo-1 weld wire was from Oxford Alloys, heat number XX3703UK. The chemical composition of the weld wire is provided in Table 1. The weld did not require a post-weld heat treatment, and all weld characterizations were made of the as-welded condition. The weld meets the Section IX requirements of the ASME BPVC [16,17]. Tensile and bend testing were used to qualify the INL welding procedure. The results from these tests are reported in the INL Procedure Qualification Record [18]. Welds fabricated in accordance with this procedure passed ASME BPVC Section III, Division 5 examination criteria, including two different angles of radiographic examination. Optical images of the welded-plate microstructure are provided in Figure 2. From this figure, it is apparent that the weldment did not comprise a heat-affected zone. This was expected for a solid-solution austenitic alloy.

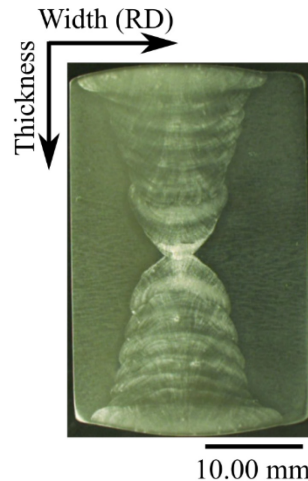


Figure 1. Optical-microcopy image of the Alloy 617 GTAW double-V butt weld profile.

Table 1. Alloy 617 chemical compositions in weight percent.

		Ni	Cr	Co	Mo	Fe	Mn	Al	C	Cu	Si	S	Ti	B
ASME	Min	44.5	20.0	10.0	8.0			0.8	0.05					
	Max	—	24.0	15.0	10.0	3.0	1.0	1.5	0.15	0.5	1.0	0.015	0.6	0.006
Plate (Heat 314626)		54.1	22.2	11.6	8.6	1.6	0.1	1.1	0.05	0.04	0.1	<0.002	0.4	<0.001
Weld wire (Heat XX3703UK)		53.91	22.41	11.49	8.98	1.37	0.11	1.10	0.089	0.04	0.04	0.001	0.34	Not reported

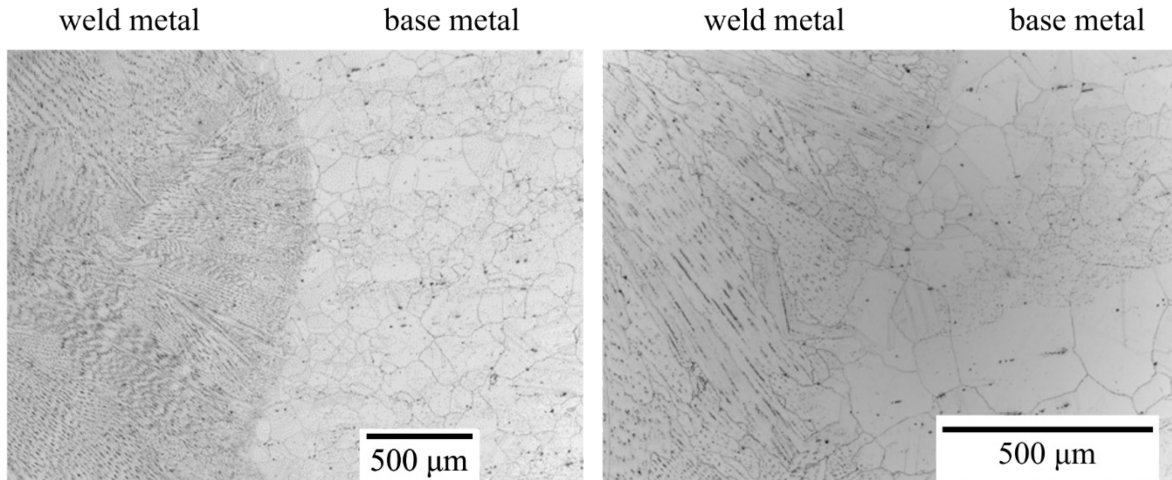


Figure 2. Optical-microscopy images of the welded-plate fusion line.

2.2 Specimen Geometry

Notched specimens were fabricated from the as-received and welded plates. In the case of welded plates, specimens were machined such that notches and locations of interest were located within the weld metal. Threaded ends and shoulders for some specimens were located outside of the weld metal. This will not affect the testing of the weld metal. Two different categories of specimens, U-notch (sometimes referred to as a Bridgman notch) and V-notch, were used in this investigation, which are described below.

U-notch specimens are used to examine the effect of multiaxial stress on creep behavior. The benefit of this geometry is that it can be used with similar style equipment as standard uniaxial-creep tests. This work investigated two different multiaxial stresses by varying the severity of the notch. The severity of the notch is quantified by the notch-acuity ratio, which is the ratio of the specimen diameter at the notch, d_{no} , to the radius of the semicircular notch, r_{no} ; see Figure 3 for a depiction of these terms. The notch-acuity ratio is dimensionless because the same unit of measurement is used for both dimensions. A notch severity of 4.83 and 1 were used in this investigation. These notches were fittingly labeled small radius for the former and large radius for the latter. A larger notch-acuity ratio results in a more severe multiaxial stress. [19] The largest notch-acuity ratio that can be achieved with a semicircular notch is 4.83.

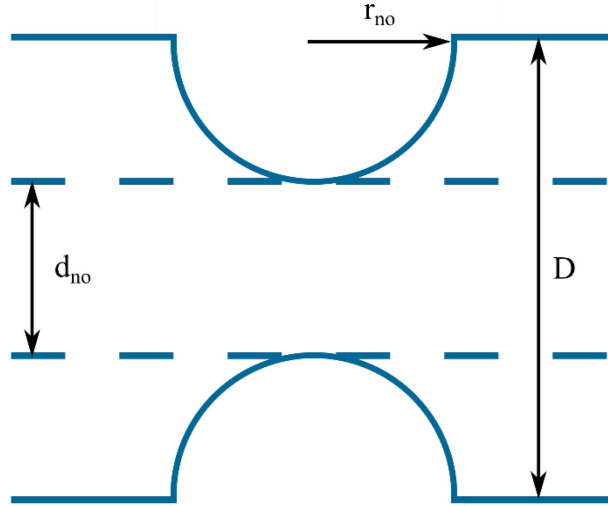


Figure 3. Important dimensions defining a U-notch or Bridgman notch.

Base-metal U-notch specimens consisted of two notches with the same notch severity. This enabled the specimen at failure and just prior to failure to be characterized by analyzing the ruptured notch and unruptured notch, respectively. Modeling by Othman and colleagues [20] calculated the rupture life of a double U-notch specimen to be within 95% of a single U-notch specimen. This difference in rupture life is inconsequential compared to the typical scatter observed in creep-rupture data [20, 21]. The distance separating the two U-notches for both notch geometries met the requirements specified in the Code of Practice [19]. As the longitudinal axis of weld-metal U-notch specimens was perpendicular to the length of the weld, and with the narrow geometry of the weld, weld-metal U-notch specimens only consisted of a single U-notch, which was located entirely within the weld metal. Schematics of both base-metal and weld-metal specimens are depicted in Figure 4.

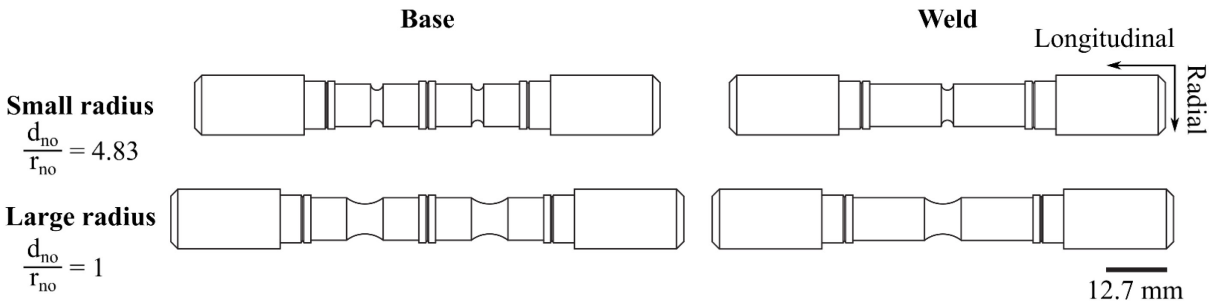


Figure 4. Schematics of small- (top) and large- (bottom) radius U-notch specimens for base (left) and weld (right) metal.

V-notch specimens are used to determine the notch strengthening or weakening behavior of Alloy 617. This was achieved with a specimen comprising of a 60° V-notch and a straight gauge, each with a 6.4 mm diameter. A schematic of the V-notch specimen is provided in Figure 5. For a given load and temperature, Alloy 617 can be classified as weakening or strengthening, depending on where rupture occurs. Rupture in the notch indicates notch weakening, while a failure in the straight gauge indicates notch strengthening. The reduced section length of the straight gauge was 25.4 mm. The geometry of the V-notch specimen was in accordance with the American Society for Testing and Materials (ASTM) Standard E292-09 [22]. The longitudinal axis of weld-metal specimens was parallel to the length of the

weld so that the entire specimen (most importantly, both the V-notch and the straight gauge portions) was comprised of weld metal.

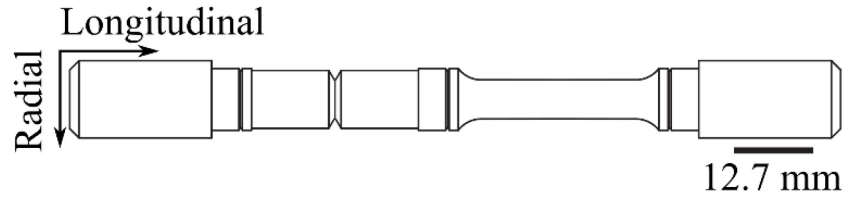


Figure 5. Schematic of the V-notch specimens.

2.3 Mechanical Testing

Elevated-temperature creep-rupture tests in air were performed with the load applied in tension, typically via a load-multiplying lever arm. The temperature and load remained constant throughout the duration of the test. V-notch and U-notch testing was performed to the requirements specified in ASTM standard E292 and the Code of Practice, respectively [19, 22].

Test temperatures ranged from 750 to 1,000°C. The applied stress was determined using the Alloy 617 Larson-Miller curve comprised of uniaxial-creep data [23]. Based on the test temperature, a stress was chosen to achieve the desired life. There were three targeted creep-rupture lives: 1) short, 2) intermediate, and 3) long. Short-term testing (1,000–2,000 hours) is an accelerated creep test (creep tests are accelerated via higher temperature and/or loads) and, in this case, was used to rapidly collect data and gain a basic understanding of the creep behavior of notched Alloy 617 specimens. Though short-term testing permits the rapid collection of data, there is a concern that the material may crossover from notch strengthening to weakening with lower temperatures and stresses (longer creep life), which better represents the conditions of actual components. Diehl and Sonsino predict a cross from strengthening to weakening with lower stress and a longer rupture life for Alloy 617 for temperatures investigated in this study. [24] Intermediate (8,000–20,000 hour creep life) and long-term creep testing (>80,000 hour creep life) aim to address this by examining the results of tests performed at lower stresses.

Waiting 100,000 hours, approximately 13 years, to resolve notch behavior was not feasible. This necessitated developing a technique to pinpoint where failure will occur prior to rupture, thus enabling notch behavior to be determined in a shorter time frame. Traditional methods for shortening creep tests by raising temperatures or increasing stresses would not achieve the needed goals, as this method would take the test outside of the area where the crossover may occur. X-ray computed tomography (CT) was used to shorten the tests by nondestructively analyzing creep damage with periodic scans throughout the creep life. This requires an understanding of the correlation between creep damage and creep life. In order to achieve this, shorter baseline V-notch creep tests, with targeted rupture lives between 1,000 and 10,000 hours, were performed. These specimens were periodically characterized with X-ray CT to determine the relationship between the creep damage and rupture location (at the notch or the straight gauge). While the main goal of this report was to cover the intermediate length weld-metal creep tests, an update will also be provided on all notch testing, including the ongoing long-term base-metal and weld-metal V-notch specimen creep tests.

3. Results and Discussion

A summary of all Alloy 617 notch testing is shown in Table 2. Tests that generated new data in this year are shown in the green rows. Nine tests are ongoing, denoted with an asterisk and a red font color of the rupture time (indicating the current time of the test, as rupture has not yet occurred). The double V (specimen 2VN-1) refers to a new geometry not discussed in this report, as there are currently no results. The goal of this specimen is to determine the degree of notch strengthening.

Table 2. Summary of all Alloy 617 notch testing at INL.

ID	Metal	Notch Type	Temp, °C	Stress, MPa	Rupture Time, hr
VN-1	Base	V	900	36	1,511
VN-3	Base	V	900	36	1,944
VN-4	Base	V	800	80	840
VN-5	Base	V	800	80	1,437
VN-6	Base	V	750	145	2,204
VN-9	Base	V	750	145	2,806
VN-11	Base	V	1000	20	1,190
VN-13	Base	V	800	35	23,500*
VN-14	Base	V	800	65.3	2,860
VN-16	Base	V	800	65.3	2,824
VN-17	Base	V	800	60	1,000*
WV-1	Weld	V	800	110	527
WV-2	Weld	V	800	35	16,300*
WV-4	Weld	V	800	100	707
UN-101	Base	small U	800	80	5,074
UN-102	Base	small U	750	145	12,463
UN-103	Base	small U	900	36	4,476
UN-105	Base	small U	800	80	4,019
UN-106	Base	small U	1000	20	2,626
UN-108	Base	small U	1000	20	3,450
UN-109	Base	small U	800	100	1,111
UN-110	Base	small U	800	100	1,107
UN-112	Base	small U	900	28	8,600*
UN-113	Base	small U	800	60	8,200*
WU-101	Weld	small U	800	110	2,662
WU-103	Weld	small U	750	225	748
WU-104	Weld	small U	900	28	8,400*
WU-105	Weld	small U	850	54	7,072
UN-201	Base	large U	800	80	1,845
UN-202	Base	large U	750	145	5,732
UN-203	Base	large U	900	36	1,831
UN-204	Base	large U	800	80	2,114
UN-205	Base	large U	1000	20	1,580
UN-206	Base	large U	900	28	7,662
UN-207	Base	large U	800	60	7,600*
WU-201	Weld	large U	800	80	786
WU-202	Weld	large U	800	110	1,181

ID	Metal	Notch Type	Temp, °C	Stress, MPa	Rupture Time, hr
WU-203	Weld	large U	850	54	5,835
WU-204	Weld	large U	750	225	342
WU-205	Weld	large U	900	28	8,400*
2VN-1	Weld	double V	800	80	1,200*
*Test is ongoing, not ruptured					
New test data from FY20					

Weld-metal creep tests tended to exhibit a longer creep life than base-metal specimens under the same conditions. A summary of all creep tests (including data used in the Alloy 617 Code Case) is shown in Figure 6. The Larson-Miller parameter is a method to combine both temperature and rupture life: a higher Larson-Miller parameter indicates higher values for either temperature or rupture life (or both). The darker colors are the weld-metal tests, which generally fall on the line or to the right, indicating similar or longer times for rupture life than expected for base metal. The notched tests, in particular, tend to fall to the right of the line for both the base metal and weld metal. A direct comparison of standard uniaxial base-metal and weld-metal creep tests with weld metal U-notch tests is shown in Table 3. While weld metal exhibits a longer life in the standard uniaxial testing, the notched specimens (particularly the small-radius U-notch), exhibit a significant increase in rupture life, suggesting that the multiaxial stress imposed by the U-notches do not result in a decrease in rupture life. The particularly long rupture life of the small-radius U-notch specimens is likely related to the notch strengthening behavior of the weld (and base) metal.

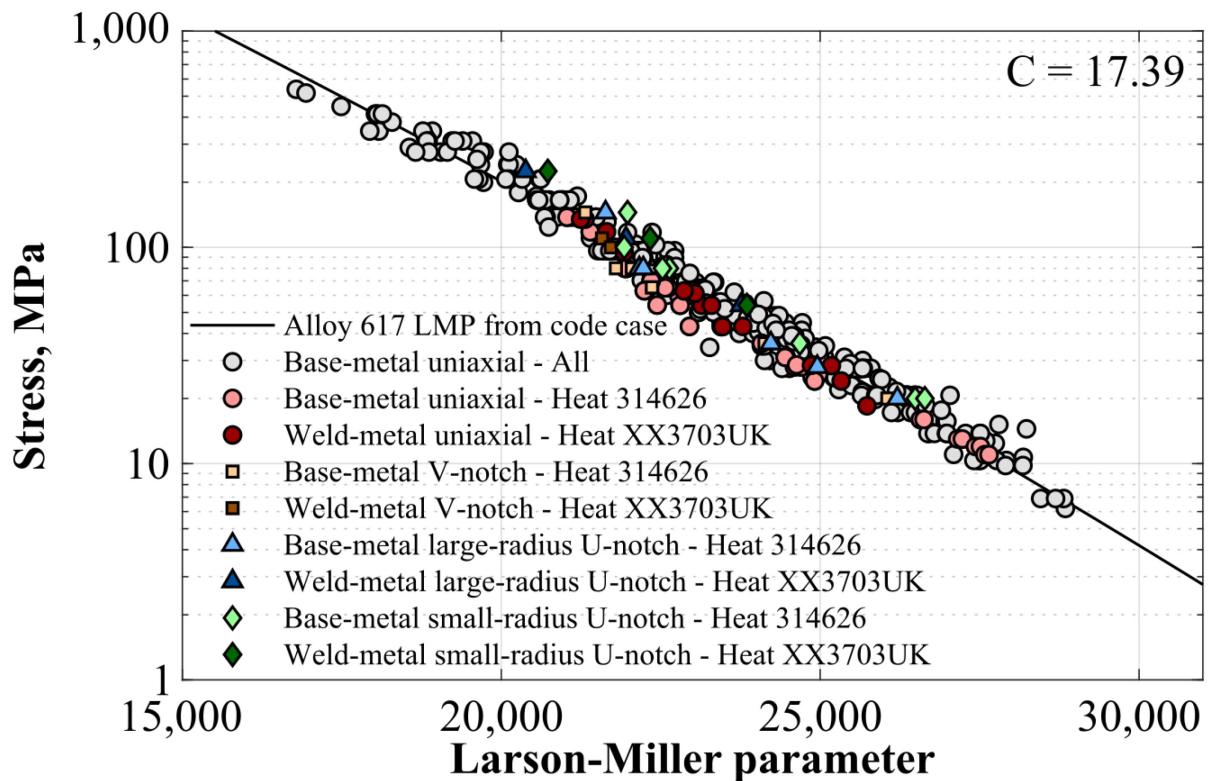


Figure 6. A Larson-Miller plot of Alloy 617 creep data, including the Code Case data from straight gauge specimens for comparison.

Table 3. Comparison of standard uniaxial test results with U-notch weld-metal results.

Specimen type	Metal	Temp, °C	Stress, MPa	Rupture Time, hr
Standard	Base	850	54	826
Standard	Base	850	54	394
Standard	Weld	850	54	1,649
Standard	Weld	850	54	2,265
Small U-notch	Weld	850	54	7,072
Large U-notch	Weld	850	54	5,835

The creep curves of the weld-metal U-notch tests are shown in Figure 7. In all cases, the small-radius U-notch exhibited a longer creep life. The smaller displacement of the small-radius U-notch is expected, due to the smaller effective gauge length. Gauge length is difficult to determine on notched specimens, as some degree of displacement occurs outside of the narrowest portion of the U-notch, and thus the total displacement is reported instead of strain. Base metal and weld metal are reported together for the 900°C, 28 MPa condition to allow for direct comparison. While only the base-metal large-radius U-notch test has finished, the general trend of the weld metal to exhibit a significantly reduced elongation during creep testing compared to the base metal is clear. Rupture life and total elongation are not tied, and, in all cases, the weld metal exhibited significantly lower elongation and, in most cases, had a longer rupture life than base metal tested at the same or similar conditions.

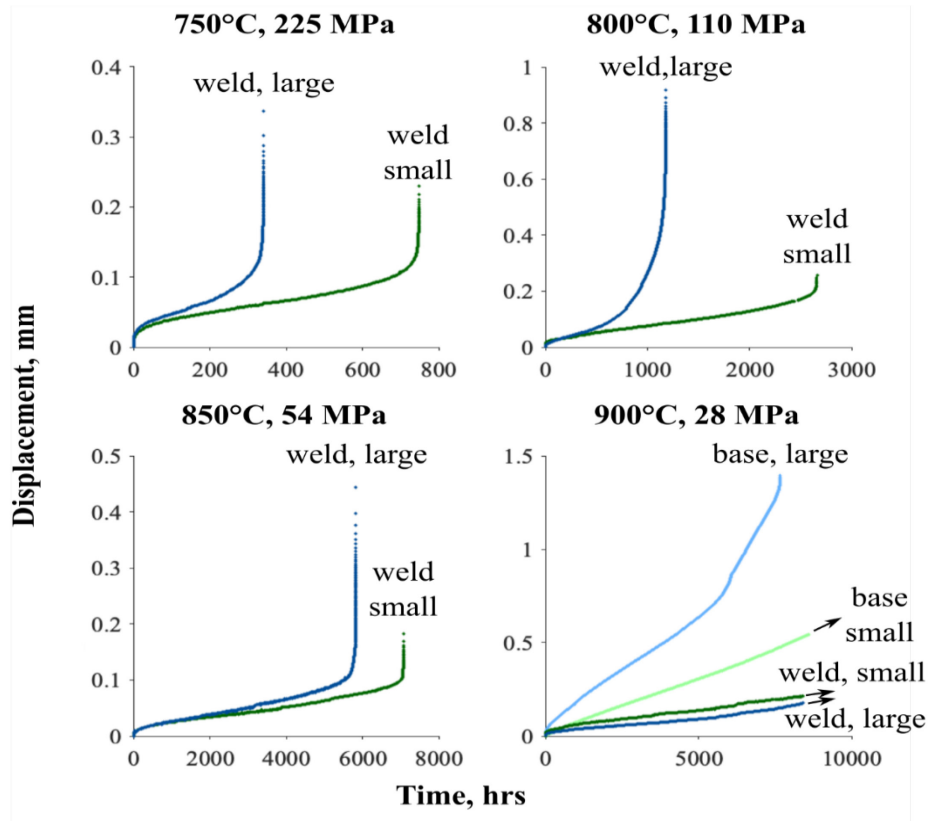


Figure 7. Creep curves (displacement *versus* time) for the Alloy 617 weld-metal U-notch tests (both large radius and small radius U-notch specimens).

Given that the V-notch weld-metal specimens must be cut entirely within the weld to ensure that the V-notch and straight gauge are both composed of weld metal, they consume a significant amount of weld material to produce, and few were made in the original machining request. Additional plate was welded last year following the same procedures, and new weld-metal V-notch specimens were machined; however, there were delays, due largely to a lack of lab access as a result of COVID-19, in starting new tests once the specimens arrived. New tests are now starting, which include a weld-metal V-notch specimen tested at 800°C and 60 MPa. The estimated creep-rupture life of this test would fall under intermediate testing. These results will be reported as the tests are completed. The long-term tests are ongoing and are currently over 23,000 and 16,000 hours for the base-metal and weld-metal tests, respectively. The current status of the creep curves is shown in Figure 8. These tests will continue to be periodically interrupted to perform X-ray CT so that the creep damage can be assessed and potential failure points determined until it is known if the specimens will fail in the straight gauge or V-notch portion of the specimen.

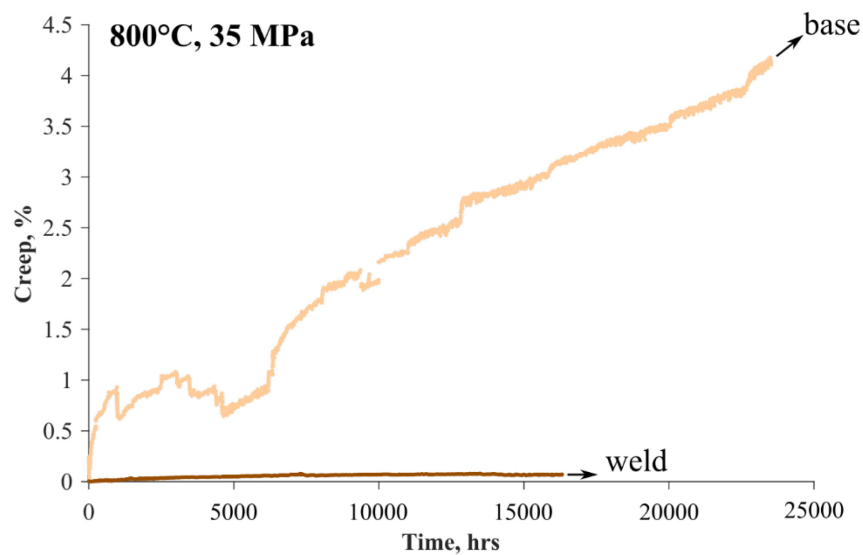


Figure 8. Current state of ongoing long-term V-notch testing.

4. Conclusions

While many of the weld-metal notched specimen intermediate creep-rupture tests are ongoing, some results are clear, based on the available data.

1. Similar to the Alloy 617 base metal, multiaxial stress, imposed by the geometry of the U-notch, does not detrimentally affect the expected creep-rupture life of the Alloy 617 weld metal, based on the uniaxial data compiled in the Larson-Miller plot.
2. For short-term testing, Alloy 617 weld metal is notch strengthening. Intermediate test results are still pending, and long-term tests are ongoing for the foreseeable future until the X-ray CT characterization indicates the location of the future rupture point.
3. Alloy 617 weld metal tends to exhibit longer creep-rupture life, though it exhibits a significantly reduced elongation during creep testing.

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