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FY16 Progress Report on Test Results In Support Of Integrated EPP and SMT Design Methods Development

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August 8, 2016

OAK RIDGE NATIONAL LABORATORY
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Materials Science and Technology Division

FY16 PROGRESS REPORT ON TEST RESULTS IN SUPPORT OF INTEGRATED EPP AND SMT DESIGN METHODS DEVELOPMENT

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ASME	American Society of Mechanical Engineers
CC	Code Case
CF	Creep-Fatigue
DOE	Department of Energy
EPP	Elastic-Perfectly Plastic
ORNL	Oak Ridge National Laboratory
SMT	Simplified Model Test

ACKNOWLEDGMENTS

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We would also like to acknowledge Richard Wright for supplying the Alloy 617 materials to support the testing task of this work.

ABSTRACT

The proposed integrated Elastic Perfectly-Plastic (EPP) and Simplified Model Test (SMT) methodology consists of incorporating an SMT data-based approach for creep-fatigue damage evaluation into the EPP methodology to avoid using the creep-fatigue interaction diagram (the D diagram) and to minimize over-conservatism while properly accounting for localized defects and stress risers. To support the implementation of the proposed code rules and to verify their applicability, a series of thermomechanical tests have been initiated. This report presents the recent test results for Type 2 SMT specimens on Alloy 617, Pressurization SMT on Alloy 617, Type 1 SMT on Gr. 91, and two-bar thermal ratcheting test results on Alloy 617 with a new thermal loading profile.

INTRODUCTION

The goal of the proposed EPP-SMT approach is to incorporate an SMT data based approach for creep-fatigue damage evaluation into the EPP methodology to avoid the use of the D diagram and to minimize over-conservatism while properly accounting for localized defects and stress risers. To support the development of the proposed code rules and to verify their applicability, a series of thermomechanical tests have been initiated. One test concept, the Simplified Model Test (SMT), takes into account the stress and strain redistribution in real structures by including representative follow-up characteristics in the test specimen. The second test concept is the two-bar thermal ratcheting tests with cyclic loading at high temperatures using specimens representing key features of potential component designs. A third test concept combines the effect of the SMT cyclic loading and sustained primary stress levels due to pressure in a pressurized cylinder. This report presents the recent test results for SMT specimens on Alloy 617 and Gr. 91, two-bar thermal ratcheting test results on Alloy 617, and pressurized and cyclic loaded tubular Alloy 617 specimens.

1. BACKGROUND

There are two approaches of interest to the proposed integrated evaluation of cyclic service life that have received attention over the last several years. One of these approaches is identified as the Elastic-Perfectly Plastic (EPP) methodology and the other is identified as the Simplified Model Test (SMT) methodology. The EPP cyclic service methodology greatly simplifies the design evaluation procedure by eliminating the need for stress classification that is the basis of the current rules. However, the EPP methodology for evaluation of creep-fatigue damage still requires the separate evaluation of creep damage and fatigue damage by placing a limit on the allowable combined damage, the "D" diagram based on the calculated individual damages.

The goal of the EPP-SMT approach is to incorporate an SMT data based approach for creep-fatigue (CF) damage evaluation into the EPP methodology to avoid the use of the D diagram and to minimize over-conservatism while properly accounting for localized defects and stress risers. Fig. 1 is a flow chart that identifies key issues, assumptions and the proposed path to resolution and verification of the EPP-SMT approach. EPP based design methods have already been qualified for ASME Sec. III Div. 5 applications via approved two code cases: strain limit code case (EPP strain limit CC) and EPP creep-fatigue code case (EPP C-F CC). The major elements in this flow chart include: three key assumptions that have been made to move forward; the near term test and evaluation actions required to validate these assumptions; and the long term test and analytical development required depending upon the outcome of the near term validation efforts. Fig. 1 is an update of the original flow chart from the initial plan (Sham, et. al., 2016) and it shows the impact of recent test results from pressurization SMT.

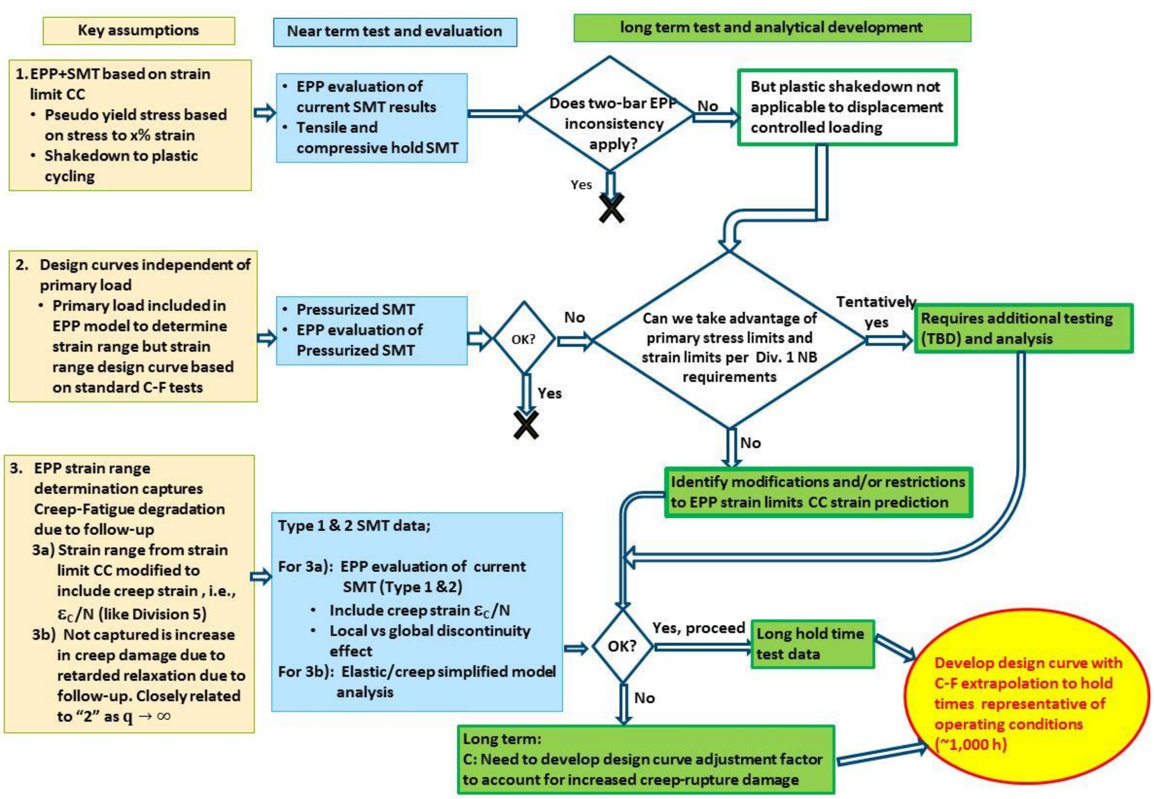


Fig. 1. Progress in the development of the EPP-SMT approach.

Shown under the category of “Near term test and evaluation” for assumption 1, is a comparison of tension hold data with data from tests with alternating tension and compression hold times. The reason for this is twofold. First, it would be desirable to base the validation on the more conservative data. However, perhaps the more important reason is to minimize the barreling effect that clouds the interpretation of the tension-hold only test data.

Pressurized SMT capsule tests are being used to assess the second assumption that the stress level associated with primary loading will be small compared with the secondary and peak stress levels and shouldn’t have a significant effect on the total life. In addition to the pressurized SMT data, the modified two bar test shown in Fig. 2, Long Term Tests, will provide valuable data for verification of the effects of superimposed primary loading. The advantage of this two bar modified configuration is that all the relevant test parameters can be measured directly. If it turns out that the effect of primary loading is significant, then the proposed solution, as shown under the long term test and analytic development column, is to develop mean stress type design curves analogous to the mean stress correction curves for the fatigue evaluation of some materials below the creep regime.

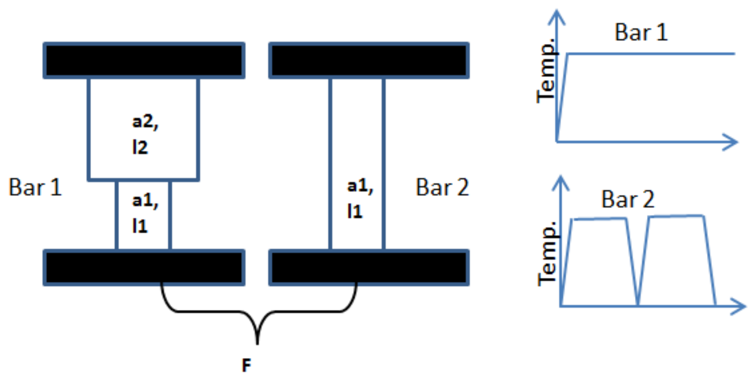


Fig. 2. Modified two-bar test (a_i, l_i refer to cross-sectional area and length of the i-th bar).

The third assumption, that the EPP strain range determination captures the creep-fatigue degradation due to follow-up effects**,** will be evaluated using results from both the Type 1 and 2 SMT test specimens to determine if adjustment factors will be required for the SMT based design curves

Longer term tests are required to develop the SMT design curves and to support the development of adjustment factors to account for such effects as sustained primary loading and retardation of stress relaxation due to follow-up, if needed.

2. EXPERIMETNAL DETAILS

2.1 MATERIALS AND SPECIMENS

Although the initial priority for the SMT approach is to generate data to support validation of the EPP Code Case for evaluation of creep-fatigue damage, the broader goal of the SMT approach is to develop a methodology for evaluation of creep fatigue damage which is simpler to implement than the current complex rules and applicable to the full temperature range from ambient conditions to the very high temperature creep regime of 900°C to 950°C. Also, guidance has been received from ASME Code committees that the proposed EPP methodology for evaluation of creep-fatigue damage should be extended to the other Subsection HBB materials to the extent feasible. Thus, the scope of testing has been expanded to include Gr.91 in this reporting period.

SMT tests on Gr. 91 were initiated using a historical ORNL plate with heat number 30176, manufactured by Carpenter Technology Corporation in the early 1980s. ORNL technical report, ORNL-6303, has documented the chemical compositions of this plate which are also listed in Table 1 below. It is noted that the silicon content is 0.11%, lower than the ASME specification of 0.2-0.5%. This plate was characterized for its mechanical properties and the data were used as reference data for Gr. 91 development program.

Table 1. Chemical compositions of Gr. 91 plate with heat number 30176 (weight %)

C	**P**	***Si****	**Ni**	**Mn**	**N**	**Ti**	**Sn**	**V**	**Fe**	**As**
0.081	0.010	*0.11*	0.09	0.37	0.055	0.004	<0.001	0.209	balance	0.001
Zr	**S**	**Cr**	**Co**	**Mo**	**Al**	**W**	**Cu**	**Nb**	**B**	
<0.001	0.003	8.61	0.010	0.89	0.007	<0.01	0.04	0.072	**<0.09**	

*Note: heat 30176 is low in Si content.

A picture of the Gr. 91 plate with heat number 30176 is shown in Fig.3. This plate was hot forged and hot rolled. The thickness of the plate is nominal 1 in. A section with a total length of 61in and plate width of 25in was cut off from this plate as the supply material for specimen machining. This section of plate material was normalized at 1050 ^{o}C for one hour and then tempered at 760 ^{o}C for 2 hours followed by air cooling. The heat treatment was performed by Bodycote Thermal Processing, Inc. at Morristown, TN. The microstructure of the plate was characterized using back scatter electron microscopy (Fig. 4) and it is shown to have typical tempered martensitic features with no untempered martensite. Additional hardness test results show an average Vickers value of 227 kg/mm^2, which is within the range of 195-265Hv specified in ASTM A-213. The microstructure analysis and hardness test results confirm that the heat treatment was done correctly.

Fig. 3. Gr.91 plate with heat number 30176.

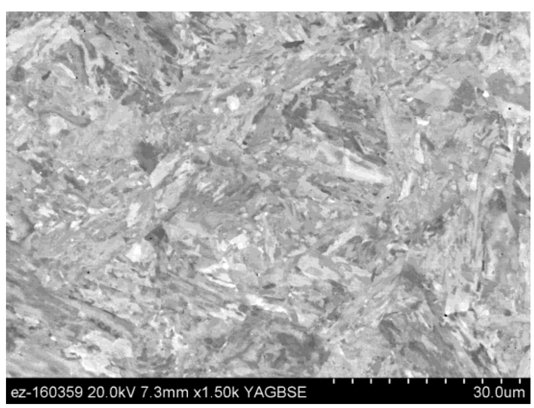


Fig. 4. Back-scatter image of the Gr. 91 plate (heat 30176) after heat treatment.

2.2 SMT TEST FOR ALLOY 617 AND GR. 91

Type 1 SMT geometry specimens were machined out of the Gr. 91 plate with heat number 30176. The Type 1 specimen geometry shown in Fig. 5 is the same as what was previously used for SS304H and SS316H in this testing program as reported in ORNL/TM-2016/76.

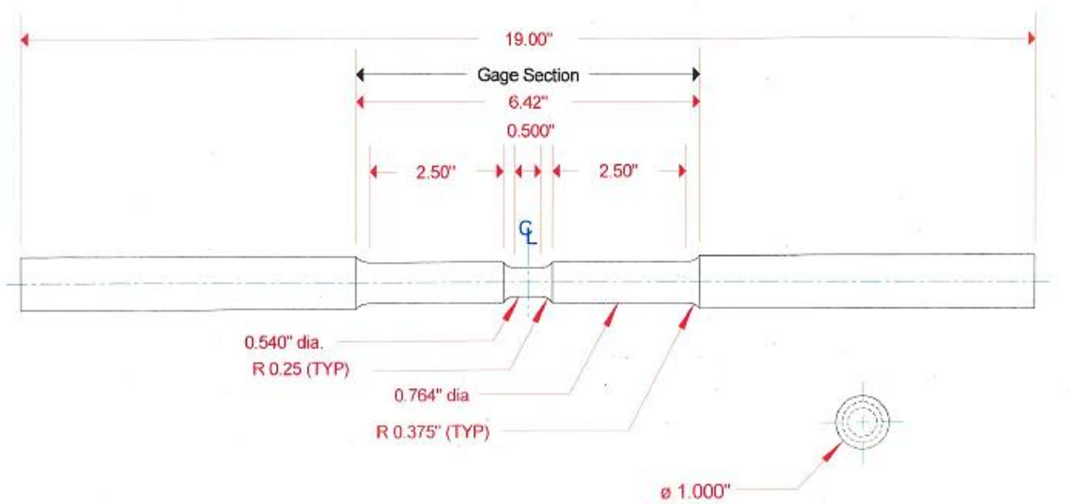


Fig. 5. Type 1 SMT solid bar specimen geometry for Gr. 91. Units are in inches.

New Type 2 SMT and SMT pressurization tests were performed for Alloy 617 using the plate material with heat number 314626. The specimen geometries are the same as what was used previously and presented again below in Fig.6 and Fig. 7. The SMT pressurization specimen for Alloy 617 is made of three sections, i.e., a center section with two extension tabs welded together.

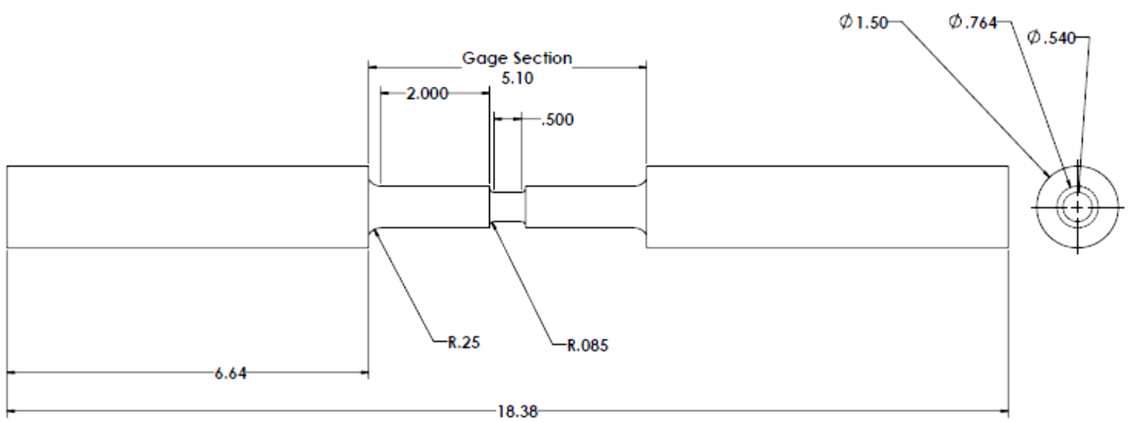
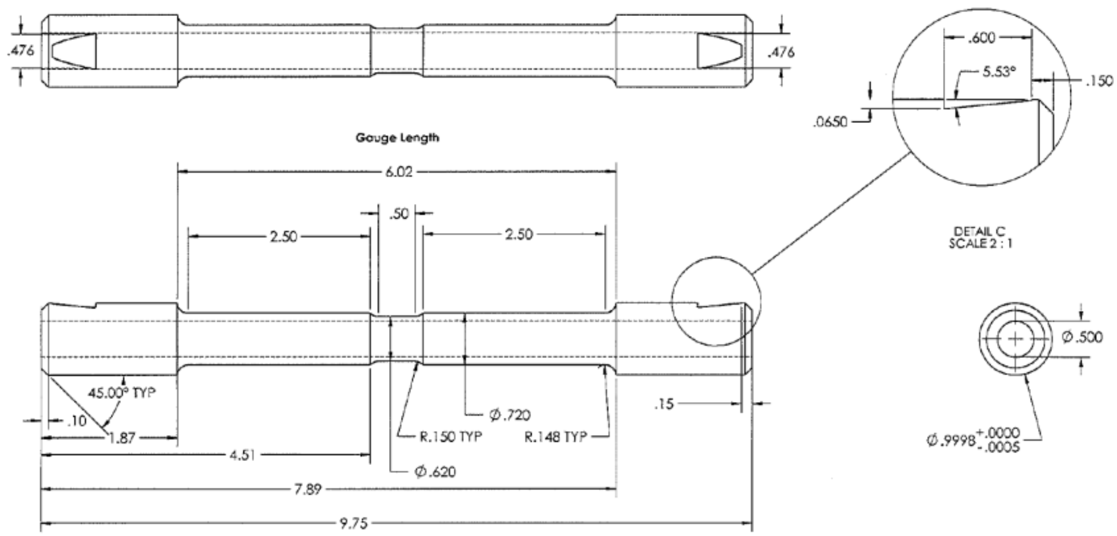
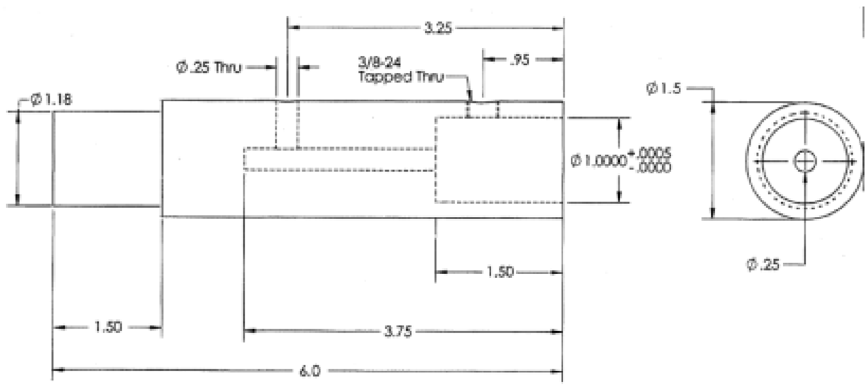


Fig. 6. Type 2 SMT geometry for Alloy 617. Units are in inches.



(a) Center section of the tubular SMT pressruziation specimen

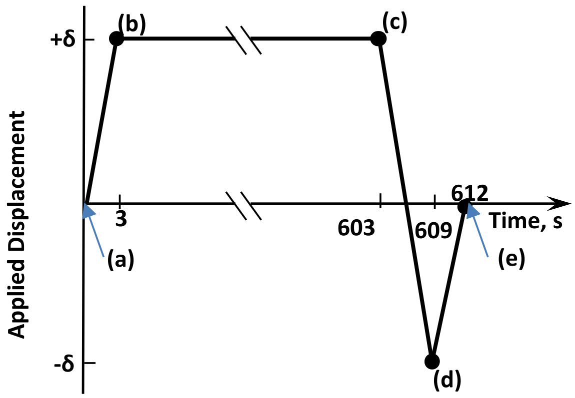


(b) Tab extension for both ends of the tubular SMT pressurzation specimen

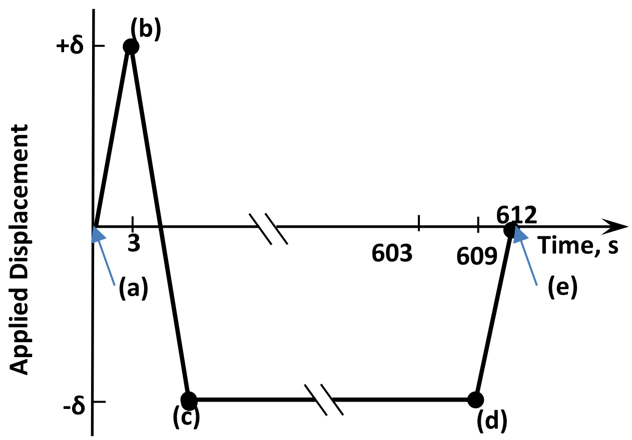
Fig. 7. SMT pressurization specimen (a) with adaptor (b) for Alloy 617. Units are in inches.

In order to achieve the designed elastic follow ups for each specimen geometry, the end-displacement amplitude was applied to a controlled gage length section which consists of a thicker and longer driver section, a 0.5 in long necked test section and the transition regions from the driver to the necked test section. The controlled gage length is 5 in. for the Type 1 SMT and the pressurization SMT tests, and 2.9 in. for Type 2 SMT. An extensometer with gage length of 0.4 in. was placed to the necked test section to measure the average axial strains during SMT testing. The measured axial strains were used to generate the hysteresis loops along with the applied stresses.

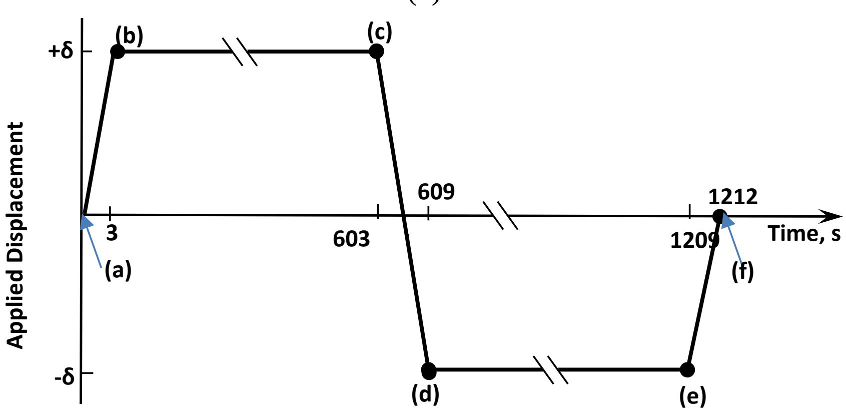
There are three types of end-displacement profile used for the SMT testing, and they are fully reversed loading with peak tension hold, peak compression hold or combined peak tension and peak compression hold (schematically shown in Fig. 8). The loading was automated through a LabVIEW program. The purpose of SMT testing with these different loading profiles was to evaluate the material behavior under SMT testing condition and to identify the most damaging deformation mode. The tension-hold or compression-hold test had a hold time of 600 s with a 612 s per cycle. The combined compression-tension hold had a hold time of 600 s on the tension peak and a 600 s hold on the compression peak with a total of 1212 s per cycle.



(a)



(b)



(c)

Fig. 8. Applied end-displacement profile for one cycle of creep-fatigue testing with tension hold (a), compression hold (b) and combined tensile-compression hold (c).

2.3 TWO-BAR THERMAL RATCHETING TEST ON ALLOY 617

Two-thermal ratcheting tests were performed on Alloy 617 using a new temperature profile to establish a baseline for the future modified two-bar thermal ratcheting test proposed under the longer term plan in Fig.1 to establish a design curve that is independent of primary load. This new temperature profile kept one bar at constant temperature of 950°C but allow the second bar to be thermally cycled. Two temperature ranges were used with one between 650 °C and 950°C for Bar 1 and the other between 800 °C and 950°C for Bar 1. The temperature profile is schematically shown in Fig. 9 and the thermal loading parameters for Bar 1 are listed in Table 2.

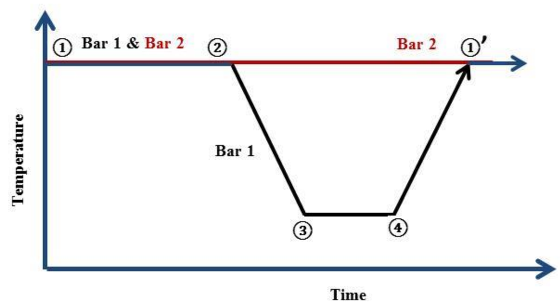


Fig. 9. Two-bar thermal ratcheting test temperature profile.

Table 2. Thermal profile for Bar 2

Cycled temperature range, °C	Temperature ①, ②	Temperature ③, ④	Time ① s	Time ② s	Time ③ s	Time ④ s	Time ①' s
650-950	950	650	t_o	t_o+3600	t_o+4200	t_o+4800	t_o+5400
800-950	950	800	t_o	t_o+3600	t_o+3900	t_o+4200	t_o+4500

The test instrumentation and the test specimen geometry were the same as what were used previously. The heating source was a three-zone temperature controlled system with igniter heating elemets and resistance heating coils that are capable of providing faster heating and cooling rates such as $30^{o}\mathrm{C/min}$. The temperature difference within the gage length of the specimen was less than 1% of the target temperature. The total length of the specimen was 7 in with gage section 0.75 in. and diameter of 0.25 in. A drawing of the specimen geometry is shown in Fig. 10.

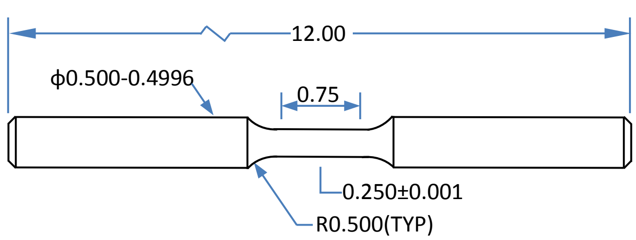


Fig. 10. Specimen geometry of Alloy 617 used in two-bar thermal ratcheting experiments. Units are in inches.

3. RESULTS AND DISCUSSIONS

3.1 SMT TEST RESULTS

3.1.1 Type 2 SMT on Alloy 617

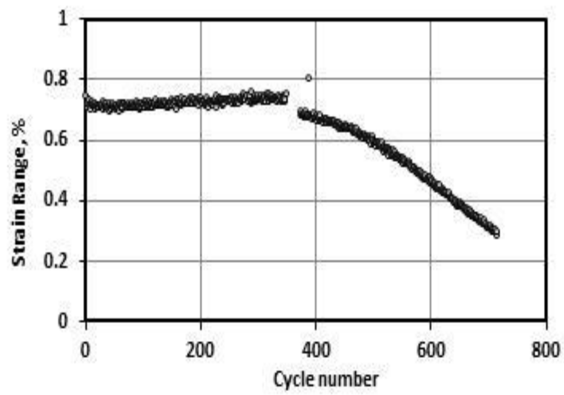
The broader goal of the SMT approach is to develop a methodology for evaluation of creep fatigue damage which is simpler to implement than the current complex rules. To support the development of the new design methodology, additional Type 2 SMT tests were performed on Alloy 617. Test #35 was performed with combined tension and compression hold and #36 was compression hold, both with the same elastically calculated strain range of 0.3% at the necked test section. The results are summarized in Table 3 along with the previous Type 2 SMT test results on Alloy 617 for comparison purpose.

Table 3. SMT creep-fatigue for Type 2 Alloy 617.

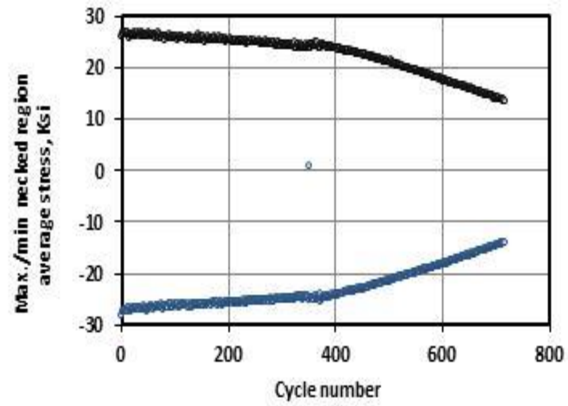
Test No.	Specimen ID	Amplitude, δ value, mil,	Elastic calculated strain range inside gage	Hold time, s	Initial strain range	Test temperature ^{o}C	Life time, hr	Cycles to failure	Applied displacement profile
#4	R6C2	2.75	0.296%	600	0.66	950	63	370	Tension hold
#5	R6C3	2.75	0.296%	600	0.62	950	60	350	Tension hold
#8	R7C2	1.8	0.194%	600	0.31	950	160	940	Tension hold
#9	R7C1	1.8	0.194%	600	0.32	950	162	950	Tension hold
#35	R15C1	2.8	0.3%	600	0.7%	950	134.7	400	Combined tension and compression hold
#36	R16C2	2.8	0.3%	600	0.6%	950	170	1000	Compression hold

Shown in Fig. 11 and Fig. 12 are plots of the measured strain range and maximum (tension) and minimum (compressive) stress as a function of cycle number, representative hysteresis loops, stress history, ratcheting strain and picture of the failed specimen test #35 and #36. The SMT #35 failed at about 400 cycles or 134.7 hr, more than twice of the life time of those tested with tension hold only. The average strain measured at the necked test section was found to be ratcheting to the compression direction. The specimen failed at the transition radius without noticeable barreling. Test #36 had SMT creep-fatigue life of 1000cycles or 170 hr. The specimen failed at the center of the necked test section with significant amount of necking. This observation is consistent with the effect of large amount of tensile ratcheting for this test #36.

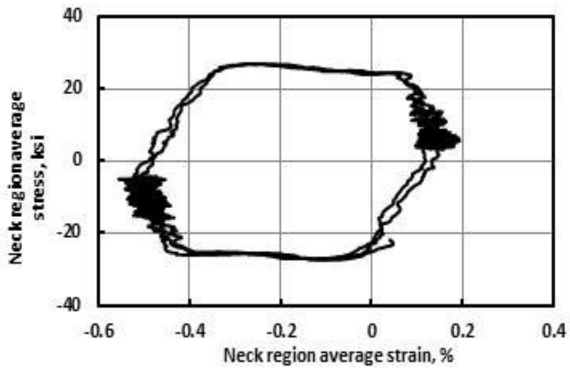
Comparing these two tests with previous tension-hold only tests #4 and #5 listed in Table 3, both compression hold only test and the combined tension-compression hold tests showed much longer life time. This set of test data indicate that the tension-hold only SMT testing for Alloy 617 is more damaging at elastically calculated strain range of 0.3%. This is consistent with what was reported for Type 1 SMT in Wang, et. al. (2016).



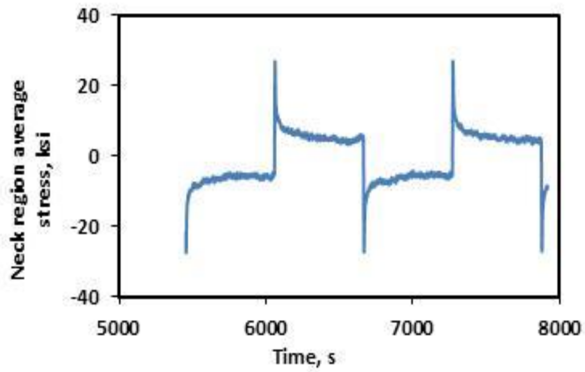
(a) Strain range



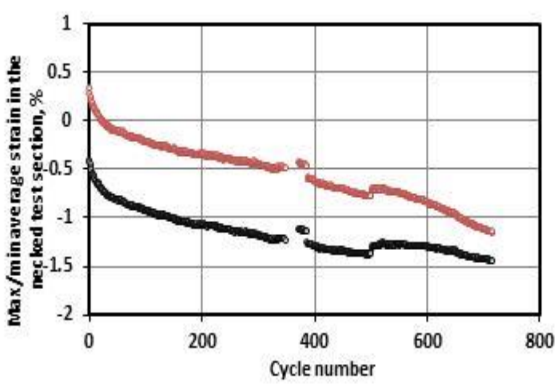
(b) Max/Min stresses



(c) Hysteresis Loop



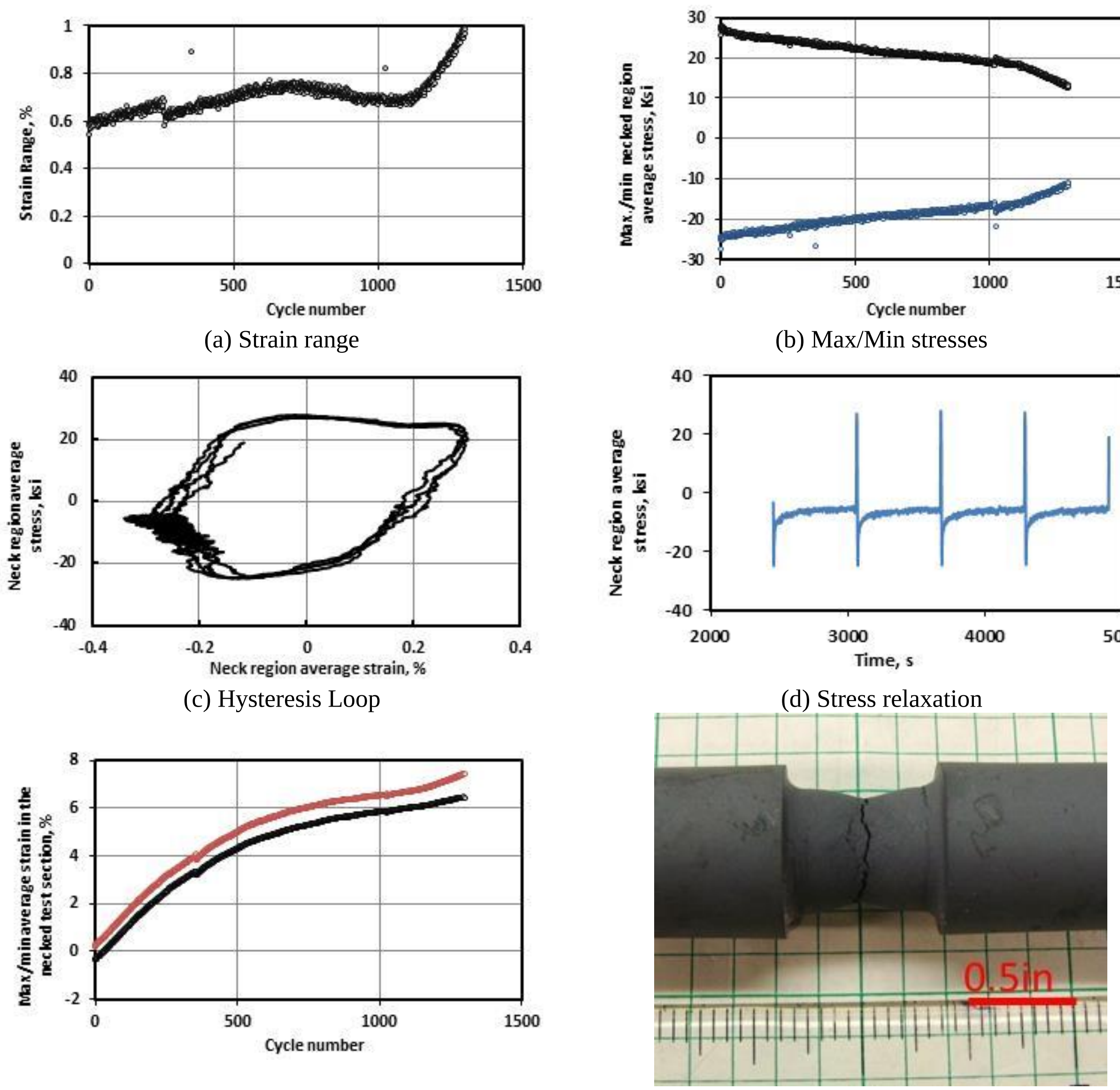
(d) Stress relaxation



(e) Ratcheting strain

(f) Failed specimen

Fig. 11. Test results for test #35.



(a) Strain range (b) Max/Min stresses

(c) Hysteresis Loop (d) Stress relaxation

(e) Ratcheting strain (f) Failed specimen

Fig. 12. Test results for test #36.

3.1.2 SMT Pressurization Testing on Alloy 617

SMT pressurization tests are being used to assess that the effects of stress levels associated with primary bending will be small when compared to the secondary and peak levels. Previous two pressurization tests on Alloy 617 at nominal internal pressure of 200psi and 2psi showed no significant impact on the SMT creep-fatigue life or the measured mechanical responses. In this reporting period, additional pressurization tests were performed on Alloy 617 at higher internal pressures and also with different types of loading profiles. The results are summarized in Table 4 along with the previous two test results for comparison. INC617-P04 was tested at internal pressure of 500psi and showed life time of 200 cycles or 34 hr. Both INC617-P03 and INC617-P06 were at the same nominal internal pressure of 750psi. Specimen INC617-P06 failed after ~140 cycles or 23.8 hr, similar to what was shown with specimen INC617-P03. The SMT creep-fatigue life at higher internal pressure was found to be shorter than those tested at 200psi and 2psi, indicating the impact of large primary load. The high pressure of 750psi has decreased the creep-fatigue life time by more than 30% when tested under tension hold.

Tests on INC617-P05 and INC617-P07 were with combined tension and compression hold and with nominal pressure of 2psi and 750psi, respectively. Although the initial strain ranges measured were larger than tension hold-only tests, the SMT creep-fatigue life was found to be larger than tension hold-only test condition for both pressure levels. The high pressure of 750psi has decreased the creep-fatigue life time by 43% compared to that with negligible internal pressure of 2psi.

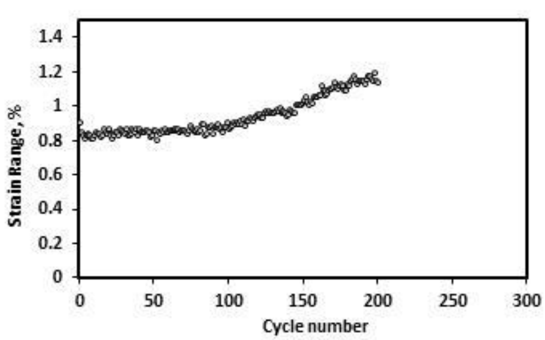
Table 4. Tubular SMT pressurization for Alloy 617 with elastic calculated strain range of 0.3%

Specimen ID	Amplitude, δ value	loading condition	Hold time	Initial strain range	Test temperature °C	Internal pressure	Life time, hr	Cycles to failure
INC617-P01	4.5 mil	Tension hold	600s	0.8%	950	2 psi	37.4	220
INC617-P02	4.5mil	Tension hold	600s	0.8%	959	200 psi	37.4	220
INC617-P04	4.5mil	Tension hold	600s	0.8%	957	500 psi	34	200
INC617-P03	4.5mil	Tension hold	600s	0.75%	958	750 psi	25.5	150
INC617-P06	4.5mil	Tension hold	600s	0.8%	950	750 psi	23.8	140
INC617-P05	4.5mil	Combined tension and compression	600s	1%	955	2psi	107.7	320
INC617-P07	4.5mil	Combined tension and compression	600s	1.05%	950	750psi	60.6	180

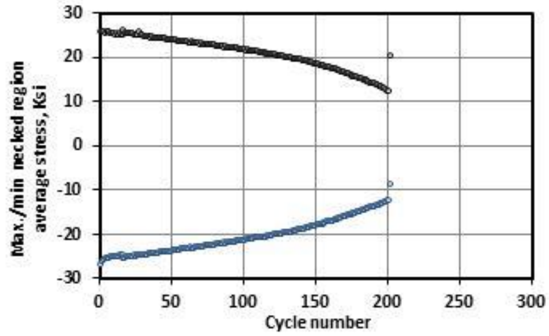
Plots of the measured strain range and maximum (tension) and minimum (compressive) stress as a function of cycle number, representative hysteresis loops, stress history, ratcheting strain and failed specimen for the these pressurization SMT tests on Alloy 617 are presented in Fig.13 to Fig. 17.

All the pressurization SMT tests with tension hold-only showed ratcheting to the compressive direction except for Inc617-P03 although the ratcheting rate was different with different levels of internal pressure. There is an indication that increasing internal pressure decreases the ratcheting rate. The ratcheting strain measured for Inc617-P03 was not consistent with Inc617-P06 although both were tested under the same conditions. It might be due to the highly localized deformation when the internal pressure is high and the localized deformation was not reflected correctly by the strain measurements. The internal pressure also increases the elastic follow up factor slightly for the pressure range tested.

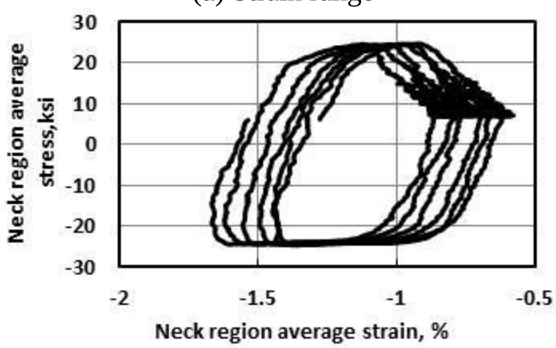
In addition, all the specimens tested with tension hold-only loading profile showed significant amount of barreling at the necked test section. The failure locations have changed from center of necked section when tested at 500psi and lower internal pressures to the transition radius for tests at 750psi. For Inc617-P03 and Inc617-P06, the maximum outer diameter at the center of the necked test section showed 30% increase when compared to the original specimen geometry. The changes in dimensions for all the failed specimens are summarized in Table 5. When the internal pressure was lower, the maximum outer diameter of the barreled region was smaller and the thinning of the wall thickness was less after testing.



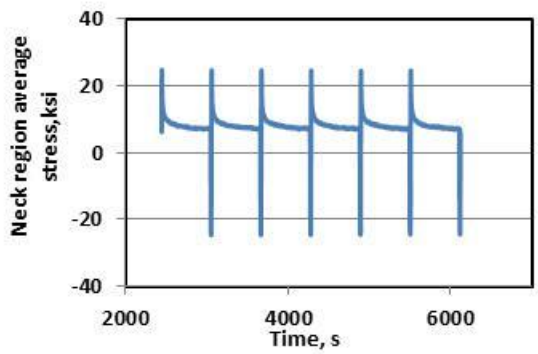
(a) Strain range



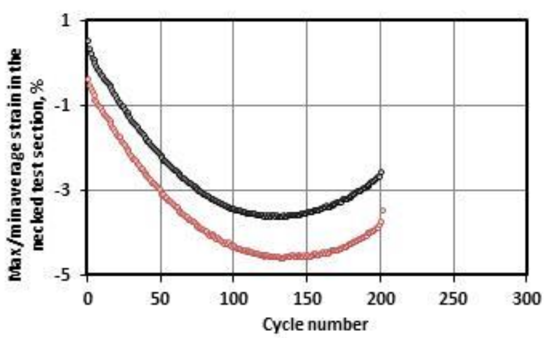
(b) Max/Min stresses



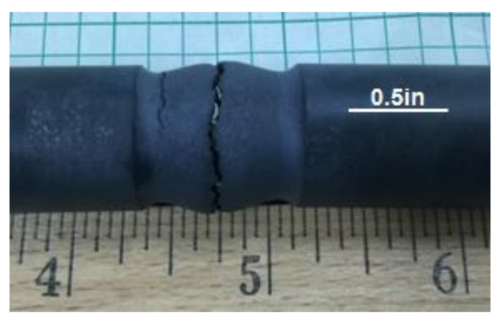
(c) Hysteresis Loop



(d) Stress relaxation

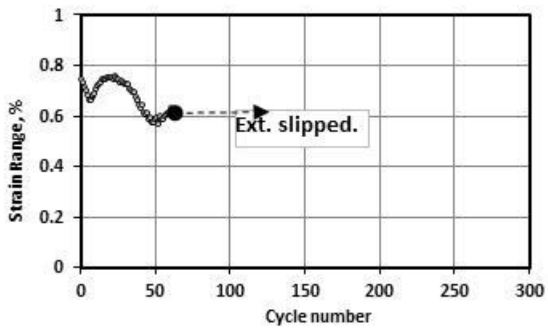


(e) Ratcheting strain

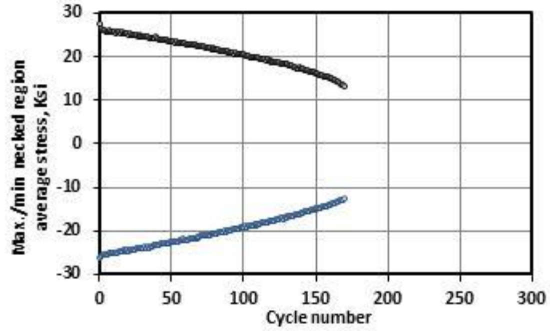


(f) Failed specimen

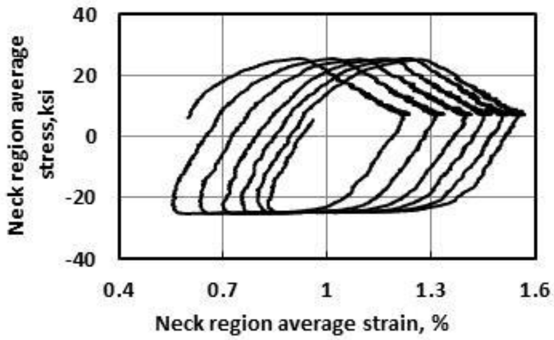
Fig. 13. Test results for test Inc617-P04.



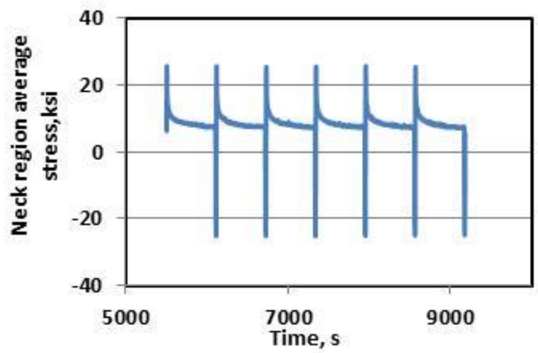
(a) Strain range



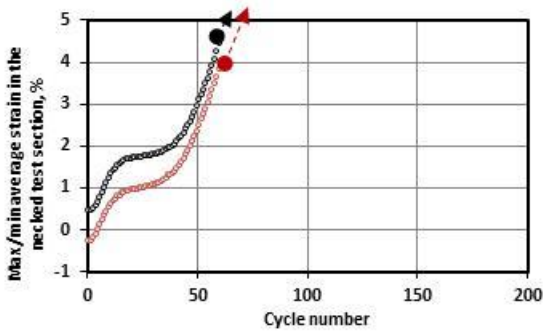
(b) Max/Min stresses



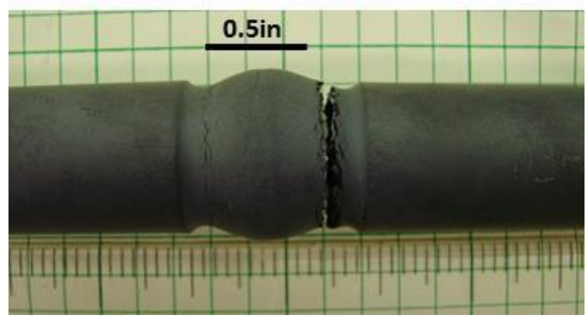
(c) Hysteresis Loop



(d) Stress relaxation

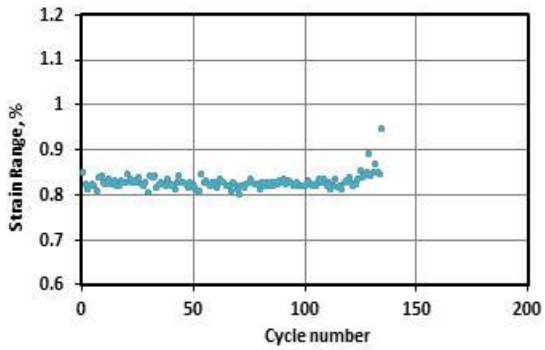


(e) Ratcheting strain

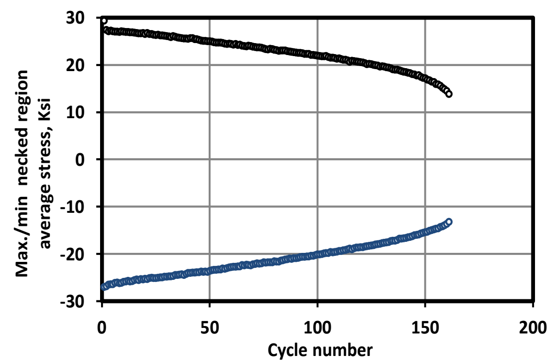


(f) Failed specimen

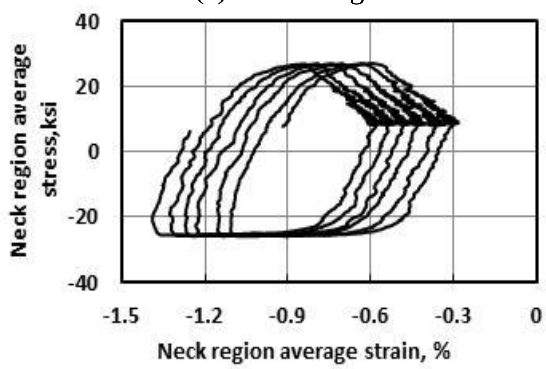
Fig. 14. Test results for test Inc617-P03.



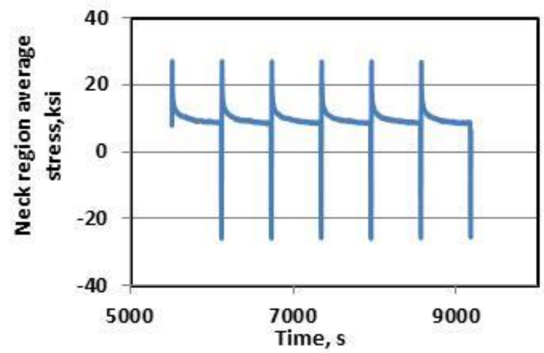
(a) Strain range



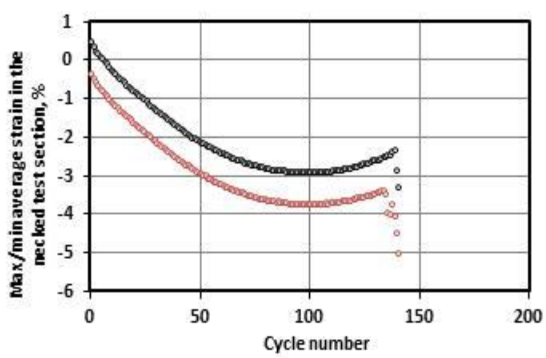
(b) Max/Min stresses



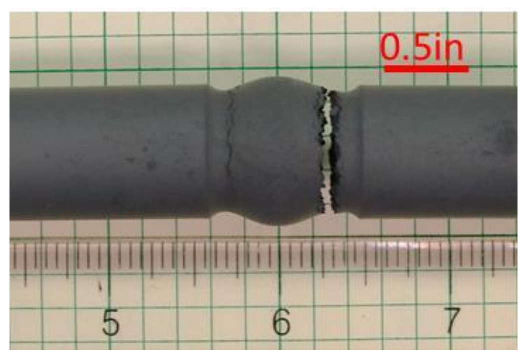
(c) Hysteresis Loop



(d) Stress relaxation



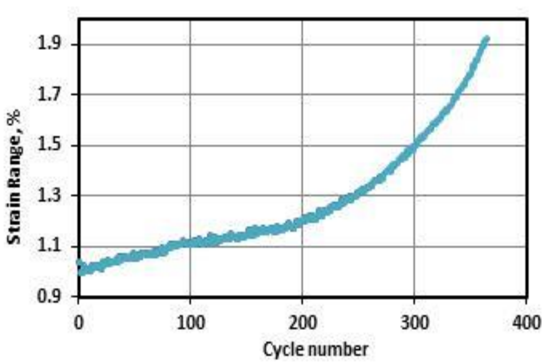
(e) ratcheting strain



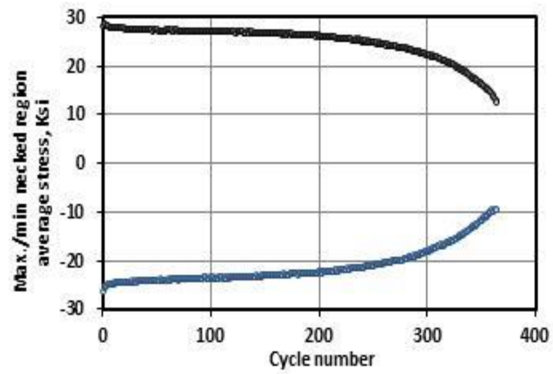
(f) failed specimen

Fig. 15. Test results for test Inc617-P06.

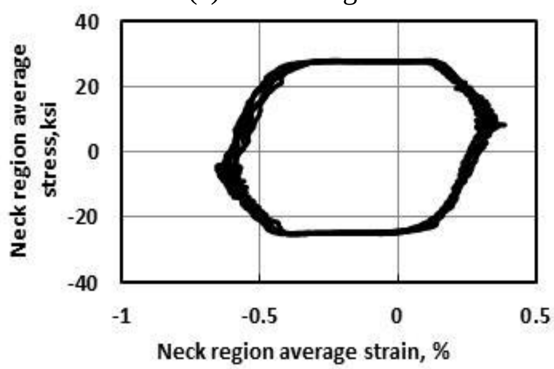
Based on past experience evaluating solid bar SMT specimens, combined tension and compression hold loading profile tends to minimize the barreling in the necked test section. Thus, Inc617-P05 and Inc617-P07 were tested with combined tension and compression hold loading condition, at internal pressure of 2psi and 750 psi, respectively. Both tests showed ratcheting toward the tensile direction. Inc617-P05 showed much smaller barreling than what was seen for that tested with tension hold only. However, the combined tensions and compression loading did not decrease the barreling of Inc617-P07 with internal pressure of 750psi. In fact, the maximum outer diameter measured at the center of the specimen Inc617-P07 showed 53% increase when compared to the original specimen geometry.



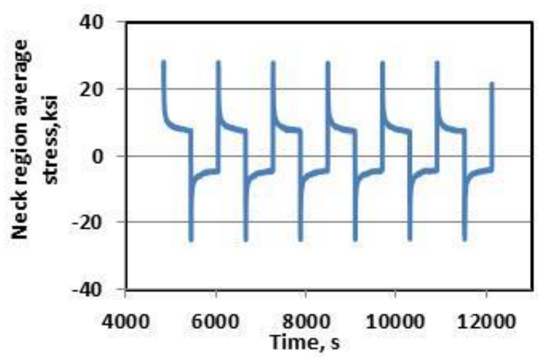
(a) Strain range



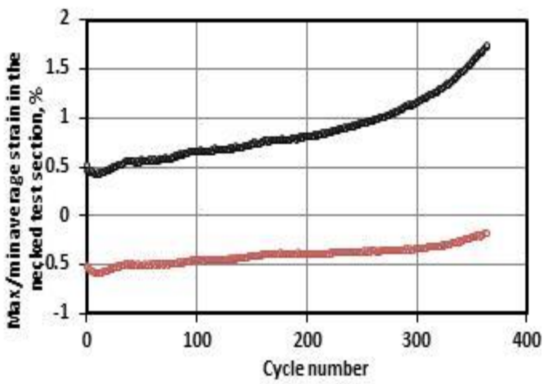
(b) Max/Min stresses



(c) Hysteresis Loop



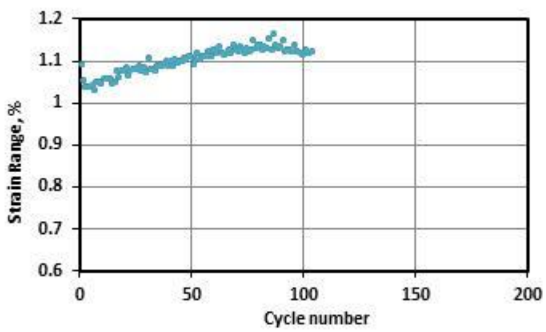
(d) Stress relaxation



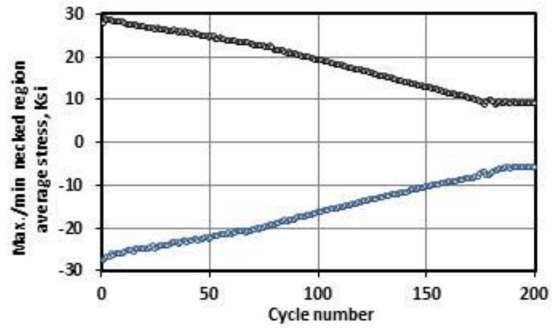
(e) ratcheting strain

(f) failed specimen

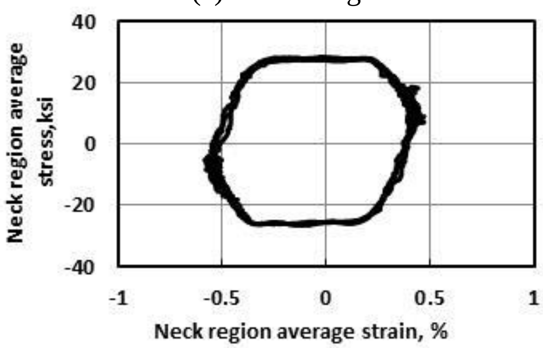
Fig. 16. Test results for test Inc617-P05.



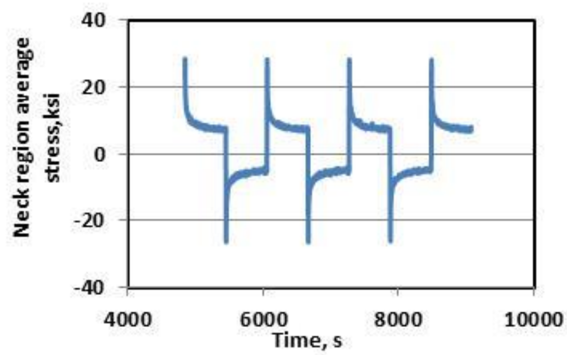
(a) Strain range



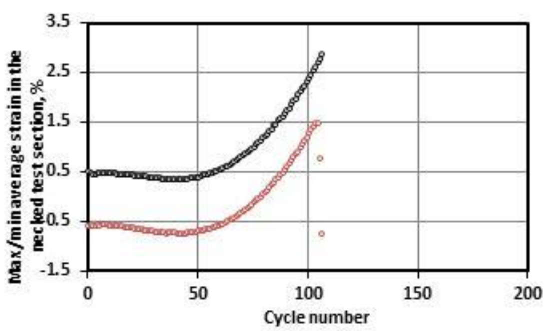
(b) Max/Min stresses



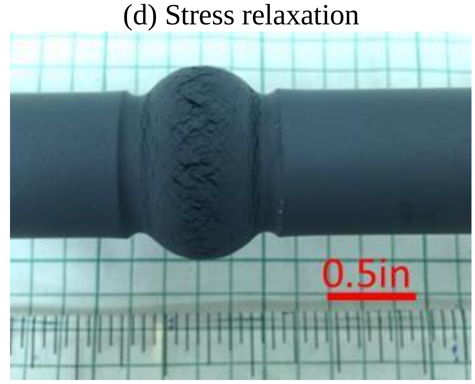
(c) Hysteresis Loop



(d) Stress relaxation



(e) ratcheting strain



(f) failed specimen

Fig. 17. Test results for test Inc617-P07.

Table 5. Comparison of the pressurization SMT on Alloy 617

Specimen ID	Internal pressure	Original ID/)D	Original wall thickness	Max OD after testing	Wall thickness at failure location	Failure location	Q factor
INC617-P01	2 psi	0.5in/0.62in	60mil	~0.68in	~68mil	Center	~3.8
INC617-P02	200 psi	0.5in/0.62in	60mil	~0.72in	~62mil	Center	~3.8
INC617-P04	500 psi	0.5in/0.62in	60mil	~0.75in	~54mil	Center	~4.0
INC617-P03	750 psi	0.5in/0.62in	60mil	~0.81in	~41mil	Transition radius	~4.1
INC617-P06	750 psi	0.5in/0.62in	60mil	~0.80in	~42mil	Transition radius	~4.1
INC617-P05	2psi	0.5in/0.62in	60mil	~0.64in	59 to 62mil	Center	---
INC617-P07	750 psi	0.5in/0.62in	60mil	~0.95in	43 to 34mil	All over	--

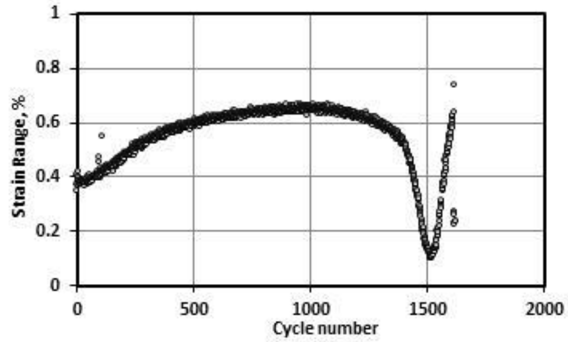
3.1.3 Type 1 SMT Testing on Gr.91

Three SMT tests were performed at 650°C for Type 1 Gr.91 solid bar specimens to evaluate the effect of different loading profile on the SMT creep-fatigue life. The basic test parameters are summarized in the Table 6; Shown below in Fig. 18 though Fig. 20 are plots of the measured strain range and maximum (tension) and minimum (compressive) stress as a function of cycle number, representative hysteresis loops and stress history for the above tabulated test conditions. All three tests had the same elastically calculated strain range of 0.3% at the necked test section.

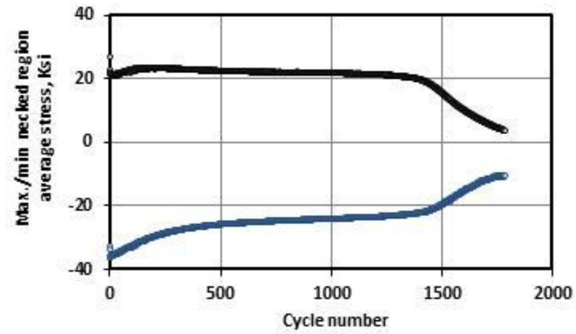
Table 6. SMT creep-fatigue for Gr.91 (heat 30176)

Test No.	Specimen ID	Amplitude, δ value, mil	Elastic calculated strain range inside gage	Hold time, s	Loading profile	Initial strain range	Test temperature °C	Life time, hr	Cycles to failure
#28	GrM1	4.5	0.296%	600	Fig. 8a	0.37%	650	238	1400
#29	GrM2	4.5	0.296%	600	Fig. 8b	0.33%	650	187	1100
#30	GrM3	4.5	0.296%	600	Fig. 8c	0.46%	650	408	1200

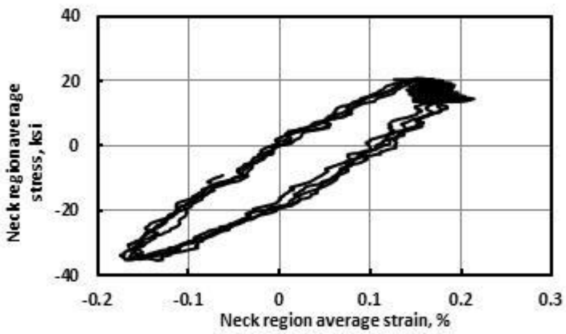
Specimen GrM1 was tested with tension only hold and the specimen failed at approximately 1400 cycles or 238 hr. The specimen slightly barreled and failed at the transition radius region. The ratcheting direction of the measured strain changed from compressive ratcheting to tensile ratcheting after about 500 cycles. The measured strain range at the necked test section started with 0.37% and increased to 0.65% after 1000 cycles. The abnormal decrease in the strain range after 1400 cycles is likely due to the highly localized deformation around the failure location and that was not being reflected by the measurement extensometer.



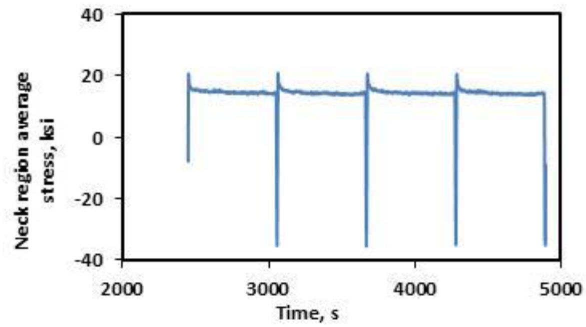
(a) Strain range



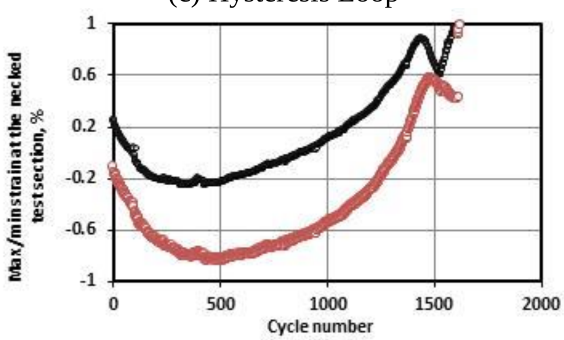
(b) Max/Min stresses



(c) Hysteresis Loop



(d) Stress relaxation

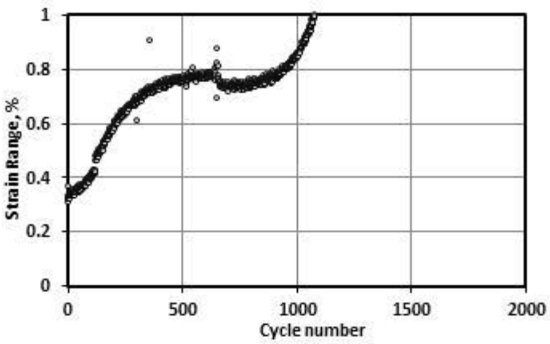


(e) ratcheting strain

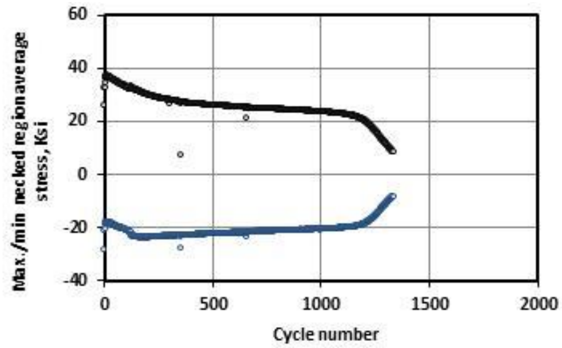
(f) failed specimen

Fig. 18. Test results for test GrM1.

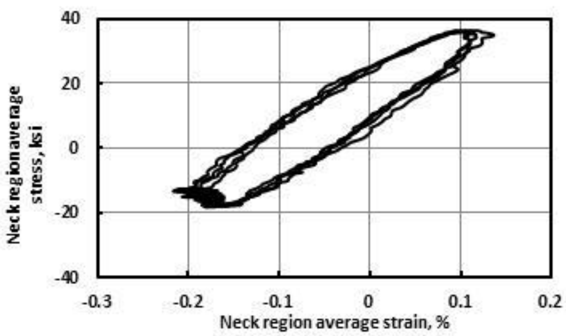
Specimen GrM2 was tested with compressive hold and it failed at approximately 1100 cycles, which is about 300 cycles less than GRM1 which was tested with tensile hold at the same elastically calculated strain range. The measured strains continued ratcheting to the tensile direction, consistent with the observation that the specimen failed at the center of the necked section with significant amount of local necking. The measured strain range at the necked test section started with 0.33% and increased to 0.8% after 1000 cycles.



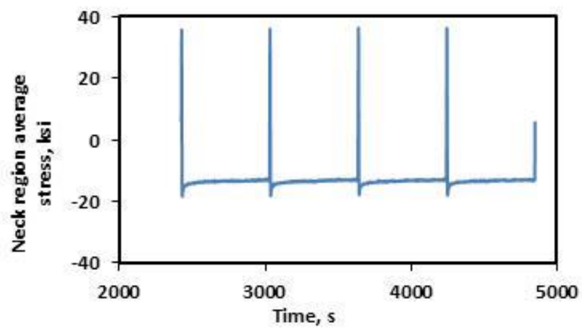
(a) Strain range



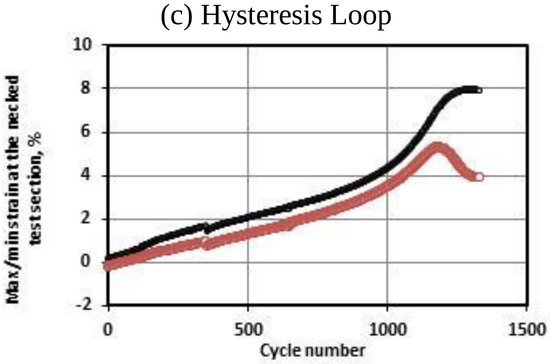
(b) Max/Min stresses



(c) Hysteresis Loop



(d) Stress relaxation



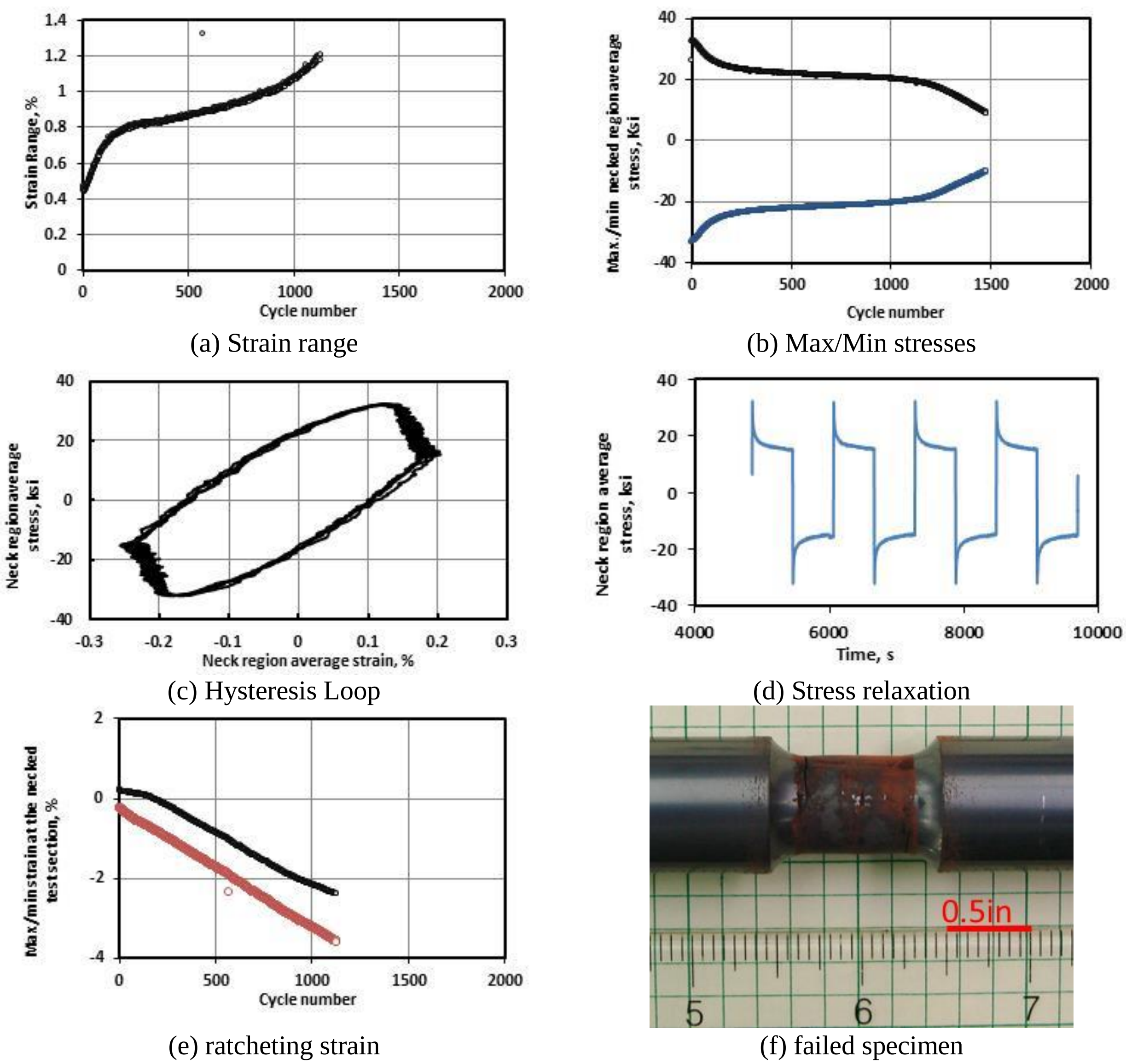
(e) ratcheting strain

(f) failed specimen

Fig. 19. Test results for test GrM2.

The third Type 1 Gr. 91 specimen was tested with combined tension hold and compression hold, and it failed at about 1200 cycles or 408 hr. The average strain measured at the necked test section was found to be ratcheting to the compressive direction for this test condition. The measured initial strain range at the necked test section was 0.46% and was the largest among these three tests. The strain ranged increase to about 1.1% after 1000 cycles. Minimum barreling at the necked test section was observed.

The results indicate SMT creep-fatigue tests with compressive hold are more damaging to Gr. 91, consistent with what was reported in literature for this steel. In addition, all three specimens showed obvious signs of oxidation, especially at the highly stressed necked test section.



(a) Strain range (b) Max/Min stresses

(c) Hysteresis Loop (d) Stress relaxation

(e) ratcheting strain (f) failed specimen

Fig. 20. Test results for test GrM3.

3.2 TWO-BAR THERMAL RACHETING TEST RESULTS ON ALLOY 617

In this reporting period, two-bar thermal ratcheting tests were performed on Alloy 617 to assess the material response to cyclic thermal loading under a new two-bar testing thermal loading profile shown in Fig. 9, where Bar 2 was kept at 950 ^{o}C constant temperature but Bar was cycled between 650 ^{o}C and 950^{o}C or 800 ^{o}C and 950^{o}C. The purpose of this test is to establish baseline reference test data for future modified two-bar SMT proposed in Fig. 2 to support the development of the integrated EPP-SMT design methodology.

Consistent with the preceding work by Wang et al. (2013, 2014, 2015, 2016), the ratcheting strain is defined as the difference in the mechanical strain at a time point in a cycle and that at the same time point in the reference cycle. The mechanical strain is the sum of the elastic strain and inelastic strain, and it can be extracted from the test data by subtracting the thermal expansion from the total strain. When the same reference point in the thermal cycle is selected, the amount of ratcheting strain calculated based on the total strain is the same as that calculated based on mechanical strain. The first cycle for each testing was ignored in the ratcheting strain extrapolations and cycle number 2 was used as a reference cycle. The ratcheting behavior was steady and the ratcheting rate was near constant from the reference cycle forward. The ratcheting strains were calculated from the maximum total strains of each cycle, and they were approximately the same values when calculated based on the minimum strains. The test parameters and the test results are summarized in Table 7. Results from shorter test periods were extrapolated to obtain the ratcheting strain at 200 hr to provide information to our parallel theoretical studies on EPP strain limits and the data are plotted in Fig. 21. It is shown that the ratcheting strains were within ±1% strain limits for a slightly wider range of the combined total load when Bar 2 was thermally cycled at temperature range of 650 to 950^{o}C than at 800 to 950^{o}C.

Table 7. Summary of the two-bar thermal ratcheting experiments on Alloy 617 for baseline reference evaluation of two-bar SMT

Test No.	*T26-1*	*T26-2*	*T26-3*	*T26-4*	*T26-6*	*T26-8*	*T26-9*	*T26-10*
Actual total load, lbs	58.8 ±12.1	256.4 ±14.0	307.2 ±14.4	150.8 ±5.6	45.0 ±19.3	195.0 ±11.6	148.6 ±8.2	241 ±8.5
Applied mean stress, MPa	4.16 ±0.8	18.1 ±1.0	21.7 ±1.0	10.7 ±0.4	3.2 ±1.4	20.8 ±0.8	10.5 ±0.6	17.0 ±0.6
Temperature range, ^{o}C	650-950	650-950	650-950	650-950	800-950	800-950	800-950	800-950
Total No. of cycles tested	35	35	34	17	54	37	42	56
Min. total strain of the reference cycle, %	-0.63	-1.44	-1.24	-0.86	-0.29	-0.24	0.43	0.40
Ratcheting rate (per cycle), %	-0.025	0.004	*0.012*	-0.003	-0.013	0.019	-0.0008	0.0054
Initial stress on Bar 1, MPa	-1.9	-4.5	-0.7	-7.5	4.6	12.5	0	1.1
Initial stress on Bar 2, MPa	6.3	22.3	21.9	18.1	-1.7	9.3	9.4	15.2
Initial residual total strain, %	0	-0.91	-0.7	-0.28	~0	~0	0.71	0.67
Extrapolated ratcheting strain in 200hr, %	**-3.3**	**0.55**	**1.65**	**-0.39**	**-2.04**	**3.0**	**-0.13**	**0.86**

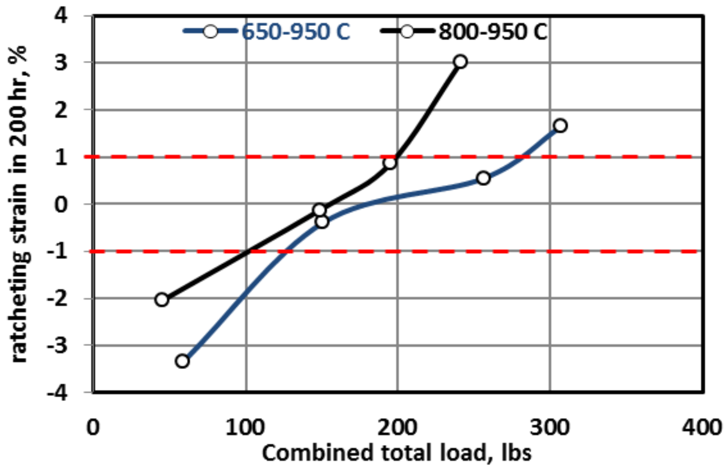


Fig. 21. Comparison of the 200 hr ratcheting strain.

SUMMARY

The concept of Elastic-Perfectly Plastic (EPP) combined integrated creep-fatigue damage evaluation approach is presented. The goal of the proposed approach is to combine the advantage of the EPP strain limit methodology that avoids stress classification with the advantage of the Simplified Model Test (SMT) method for evaluating creep-fatigue damage without deconstructing the cyclic history into separate fatigue and creep damage evaluations. The EPP methodology for strain is based on the use of a pseudo yield stress that limits creep and plastic strain accumulation and intrinsically reflects the stress and strain redistribution currently based on the use of stress classification procedures. The resulting strain ranges are then assessed for combined creep and fatigue damage using the SMT approach. In this approach, the enhanced damage resulting from strain redistribution and slowed stress relaxation due to follow up effects is accommodated in the design of the test specimen, sized to bound redistribution effects in typical components. A path forward to merge these methodologies was identified along with the anticipated problems, facilitating assumptions, and required steps and test data needed to verify their applicability. In this report, additional test results of Type 2 SMT and pressurization SMT on Alloy 617, Type 1 SMT on Gr.91 and modified two-bar thermal ratcheting test on Alloy 617 are summarized. These key featured testing results are critical for the verification of EPP code cases and also for the development of the proposed integrated EPP-SMT design methodology.

REFERENCES

1. DisStefano, J. R., SiKKa, V.K., Blass, J.J., et. al., (1986), "Summary of Modified 9Cr-1Mo Steel Development Program: 1975-1985", ORNL-6303, Oak Ridge National Laboratory, Oak Ridge, TN.

2. Sham, T.-L., Jetter, R. I., and Wang, Y., (2016), "Elevated Temperature Cyclic Service Evaluation Based on Elastic-Perfect Plastic Analysis and Integrated Creep-Fatigue Damage", Proceedings of the ASME 2016 Pressure Vessels and Piping Division Conference, Vancouver, Canada, July 2016, PVP2016-63730, American Society of Mechanical Engineers, New York, NY.

3. Wang, Y., Sham, T.-L, and Jetter, R. I., (2013), "Progress report on the development of test procedure for the two-bar thermal ratcheting experiment for Alloy 617", ORNL/TM-2013/318, Oak Ridge National Laboratory, Oak Ridge, TN.

4. Wang, Y., Jetter, R. I. and Sham, T.-L, (2014), "Application of Combined Sustained and Cyclic Loading Test Results to Alloy 617 Elevated Temperature Design Criteria", ORNL/TM-2014/294, Oak Ridge National Laboratory, Oak Ridge, TN.

5. Wang, Y., Jetter, R. I., Baird, S. T., Pu, C. and Sham, T.-L., (2015), "Report on FY15 Two-Bar Thermal Ratcheting Test Results", ORNL/TM-2015/284, Oak Ridge National Laboratory, Oak Ridge, TN.

6. Wang, Y., Jetter, R. I., and Sham, T.-L., (2016), "Preliminary Test Results In Support Of Integrated EPP and SMT Design Methods Development", ORNL/TM-2016/76, Oak Ridge National Laboratory, Oak Ridge, TN.

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