AFRL-RX-WP-TP-2011-4231

CREEP AND FATIGUE INTERACTION IN THE PWA 1484 SINGLE CRYSTAL NICKEL-BASE ALLOY (Preprint)

Christian J. Pierce and Andrew H. Rosenberger

Metals Branch
Metals, Ceramics & NDE Division

Anthony N. Palazotto

Air Force Institute of Technology
Department of Aeronautics and Astronautics

JULY 2011

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
July 2011	Journal Article Preprint	01 July 2011 – 01 July 2011

4. TITLE AND SUBTITLE
CREEP AND FATIGUE INTERACTION IN THE PWA 1484 SINGLE CRYSTAL NICKEL-BASE ALLOY (Preprint)

5a. CONTRACT NUMBER
IN-HOUSE

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
Christian J. Pierce and Andrew H. Rosenberger (Metals, Ceramics & NDE Division, Metals Branch (AFRL/RXLM))
Anthony N. Palazotto (Air Force Institute of Technology, Department of Aeronautics and Astronautics)

5d. PROJECT NUMBER
4347

5e. TASK NUMBER
20

5f. WORK UNIT NUMBER
LM106500

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Metals, Ceramics & NDE Division, Metals Branch (AFRL/RXLM)
Materials and Manufacturing Directorate, Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

Air Force Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RX-WP-TP-2011-4231

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXLM

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TP-2011-4231

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PAO case number 88ABW-2010-0984 cleared 04 March 2010. This is a work of the U.S. Government and is not subject to copyright protection in the United States. Submitted to Materials Science & Engineering A. Document contains color.

14. ABSTRACT
While methods for modeling creep behavior of single crystal turbine airfoils are generally well developed, constant load creep does not fully represent the loading conditions present in a jet engine due to cyclic loading caused by the mission profile and throttle movements. As the aerospace industry seeks to become more accurate in physics-based modeling of materials that are used in turbine blades, creep-fatigue interaction must be incorporated into characterization of turbine blade materials. PWA1484, a second generation single crystal nickel based superalloy that is used for turbine blades in many of today's high performance jet engines was tested in a creep-fatigue environment that is meant to simulate some conditions of the service environment of a jet engine. This research explores the behavior and microstructural evolution of samples of PWA1484 tested in a creep-fatigue environment at 871 °C in air. It was found that specimens subjected to prior fatigue loading exhibit a smaller region of primary creep that is proportional to the number of prior fatigue cycles, and an accelerated transition to a tertiary creep regime.

15. SUBJECT TERMS
single crystal, nickel based superalloys, creep, fatigue, high temperature, PWA1484;

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Andrew Rosenberger
Unclassified	Unclassified	Unclassified	SAR	28	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Creep and Fatigue Interaction in the PWA 1484 Single Crystal Nickel-base Alloy

Christian J. Pierce[1,3], Anthony N. Palazotto[2], and Andrew H. Rosenberger[1]

[1]Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/RXLM Wright Patterson AFB, OH 45433, USA

[2]Air Force Institute of Technology, Department of Aeronautics and Astronautics, Wright Patterson AFB, OH 45433, USA

[3]Former Graduate Student, Air Force Institute of Technology, Department of Engineering Physics , Wright Patterson AFB, OH 45433, USA

Abstract

While methods for modeling creep behavior of single crystal turbine airfoils are generally well developed, constant load creep does not fully represent the loading conditions present in a jet engine due to cyclic loading caused by the mission profile and throttle movements. As the aerospace industry seeks to become more accurate in physics-based modeling of materials that are used in turbine blades, creep-fatigue interaction must be incorporated into characterization of turbine blade materials. PWA1484, a second generation single crystal nickel based superalloy that is used for turbine blades in many of today's high performance jet engines was tested in a creep-fatigue environment that is meant to simulate some conditions of the service environment of a jet engine. This research explores the behavior and microstructural evolution of samples of PWA1484 tested in a creep-fatigue environment at 871°C in air. It was found that specimens subjected to prior fatigue loading exhibit a smaller region of primary creep that is proportional to the number of prior fatigue cycles, and an accelerated transition to a tertiary creep regime. However, specimens that are subject to a static load and allowed to creep to 2.5% creep strain exhibited an un-affected fatigue behavior. Post test microstructural analysis revealed a

coarsening of the gamma prime (γ') precipitates that was dependent on loading condition and time spent at elevated temperature.

Keywords:

Single crystal; nickel based superalloys; creep; fatigue; high temperature; PWA1484;

Introduction:

PWA1484 is a second generation, nickel based superalloy that is widely used in many jet engines as a HPT blade for both military and commercial applications. All of these applications subject the blades to various cyclic and dwell loading that depend on the throttle movement and mission profile. The main goal in the development of this alloy, developed in the mid 1980's, was an improvement in creep resistance, though creep, fatigue, and oxidation behavior of PWA1484 has been a subject of research since its inception [1-3]. The effect of prior creep on fatigue behavior (and vice versa) was not part of its development and little published work exists on the interaction of these two loading conditions. It is known that creep and fatigue behavior of single crystal nickel base superalloys is influenced by the morphology of the γ' precipitates that are present in their structure [4-6]. These precipitates have been found to coarsen or raft differently when placed under tension or compression, and are also influenced by high temperature aging [7,8]. Dislocation motion in the γ' precipitates and the gamma (γ) matrix also plays a role in the structural performance of PWA1484 in creep and fatigue. During creep that is above certain minimum thresholds of stress and temperature, dislocations are able to pass through γ' precipitates and gain access to a longer path of dislocation motion that is free of other dislocations that would hinder their movement. This phenomenon is thought to be the cause of primary creep behavior in single crystal superalloys [9,10]. A transition of PWA1484 from primary to secondary creep occurs when the gamma/gamma prime (γ/γ') interfaces become populated with dislocations and it becomes more difficult for dislocations to enter the γ' precipitates [8]. Dislocation formation also plays a role during fatigue loading of single crystal superalloys, and work by Zhang et al. has shown that during the early part of fatigue cycling dislocations are formed primarily in the γ matrix with the number of dislocations increasing with the number of applied cycles [11]. Ott and Mughrabi showed that during fatigue of single crystal nickel base superalloys cracks prefer to grow through the γ matrix and around the γ' precipitates [5]. An in depth study of fatigue in PWA1484 was conducted by Wright et al. and their research determined that the fatigue behavior of PWA1484 could be well represented by a Walker type fatigue model that also included rupture damage that occurs during the tensile portion of fatigue cycling [3]. This research also found that higher mean stresses during fatigue resulted in a failure process that is dominated by rupture processes, and low mean stresses resulted in failure dominated by fatigue processes. Based on multi-part creep and fatigue tests, it appeared that an interaction of creep and fatigue damage was occurring even under pure fatigue conditions [3]. While creep and fatigue behavior of PWA1484 have been studied as separate phenomena, little research has been undertaken to determine the effect that these two loading conditions have on one another. The ability to quantitatively describe creep and fatigue interaction in single crystal turbine blade materials will be increasingly important as the aerospace industry seeks to perform computational modeling of materials as a step in behavior/life prediction and the materials design process. This paper seeks to conduct baseline mechanical property measurements and microstructural observations regarding the effect that pre-existing creep strain will have on fatigue performance and conversely, the effect pre-existing fatigue cycling will have on creep life of PWA1484 at elevated temperatures. To reach the next step in developing a model that is capable of accounting for the interaction of fatigue and creep, more experimental data that includes combinations of creep and fatigue loading is needed. In this research, creep and fatigue in PWA1484 are studied to gain a better understanding of how the interaction of these two loading conditions will affect the performance of PWA1484 at elevated temperatures.

Experimental Details:

The material used for this testing is Pratt Whitney Alloy 1484 (PWA1484). This material is a second generation, single crystal, nickel based superalloy having the composition, Ni-5Cr-10Co-2Mo-6W-5.6Al-9Ta-3Re-0.1, by weight. Material for testing was acquired from plates of PWA1484 that remained from the study of Wright, et al. [3]. Cylindrical test specimens having a common geometry for both creep and fatigue tests were machined from the plates of PWA1484 within ±2° of the <001> direction having the dimensions shown in Figure 1.

{INSERT Figure 1 HERE}

In order to collect data on the creep and fatigue interaction behavior of PWA1484, 5 testing conditions were used. All five conditions were tested on the same computer-controlled servo-hydraulic test machine in order to avoid any variance due to equipment. All testing was performed at 871°C, using a two zone resistance furnace and controlled using thermocouples welded to the shoulders of the specimens. The same load of 517 MPa was used for creep testing and as the stress amplitude for fatigue testing. All fatigue testing was conducted in load control at a frequency of 0.5Hz with fully reversed loading, $R = \sigma_{min}/\sigma_{max} = -1$. The strain was measured during the creep and fatigue tests using a high temperature, alumina rod extensometer having a gage length of 12 mm. For a more comprehensive description of the experimental setup and test equipment see reference [12].

A series of tests was conducted that varied the relative levels of creep and fatigue loading as detailed in Table 1. As a baseline, tests #1(F) and #2(C) were pure fatigue and creep tests that were terminated in specimen failure, #1(F), and at 5 % accumulated creep strain, #2(C). The limit of 5% creep strain, i.e., the strain accumulation after the initial elastic loading, was chosen as a termination point for the creep tests for two reasons; 1) the allowable strain accumulation in turbine blades is limited to approximately 5%, and 2) so that microstructural observations could be made before large amounts of rupture damage from tertiary creep occurred in the material. Test #3(2.5C+F) was a combined constant creep test followed by fatigue. The specimen was placed under a constant load and held until 2.5% creep strain was attained. The constant load was then removed and fatigue loading was applied, the cycling continued until failure. Test conditions #4(1/4N_f+C) and #5(1/2N_f+C) were two part tests that included fatigue loading to a predetermined number of cycles followed by creep loading. The specimen was first placed under fatigue loading and cycled until approximately a quarter, #4(1/4N_f+C), or half, #5(1/2N_f+C), of the fatigue life. The fatigue life, N_f, was determined from the pure fatigue condition #1(F). After fatigue loading, the test transitioned to a constant load and specimens were allowed to creep to 5% creep strain. The fully reversed fatigue loading did not result in any appreciable strain ratcheting so that the 5% creep strain represented the total inelastic strain accumulation. The test condition descriptions in Table 1 will be used for specimen identification, meaning that a specimen that was tested in creep only will be identified as specimen #2(C).

Table 1, Test conditions used to explore creep-fatigue load interaction

Test Condition # (Code)	**Initial Loading**	**Test End State**
#1(F)	Fatigue	Fatigue Failure
#2(C)	Creep	5% Creep Strain

#3(2.5C+F)	2.5% Creep (1.2 hrs)	Fatigue Failure
#4(1/4N_f+C)	Fatigue to N_f/4 (44,206 cyc)	5% Creep Strain
#5(1/2N_f+C)	Fatigue to N_f/2 (88,412 cyc)	5% Creep Strain

The initial microstructure and its change as a result of the loading conditions was assessed using a scanning electron microscope (SEM) on electropolished specimens extracted from the gage length of the test specimens.

Results and Discussion

The results will be presented in terms of the baseline behavior, the influence of creep and fatigue interaction on the mechanical behavior of the material, and in terms of the microstructural changes in the material as a function of the different loading conditions.

Baseline Behavior

Two plates of PWA 1484 were used in this study having heat codes A2LPT and Z175T (For simplicity these will be called the "A" and "Z" plates). Though the orientation of the samples with respect the [001] growth direction was well controlled, an examination of the microstructure of the two plates found that average γ' size in plate A was 0.418 μm but 0.319 μm in plate Z as measured in the <001> orientation. This difference in precipitate size was thought to be large enough to affect the baseline properties, so baseline tests were completed for both plates and the results are shown in Table 2.

Table 2, Baseline Pure Creep and Pure Fatigue Test Results

Specimen ID/Test Condition #	Results	Plate	Average γ' size (μm)
#1(F)	Fatigue Failure at 90,075 Cycles	Z175T	0.319
#1B(F)	Fatigue Failure at 176,824 Cycles	A2LPT	0.418

#2(C)	5% Creep Strain in 38.2 hrs	Z175T	0.319
#2B(C)	5% Creep Strain in 139.5 hrs	A2LPT	0.418

When subjected to pure creep or fatigue the performance of specimens from plate A was superior to specimens from plate Z. Fatigue test #1B(F) lasted almost twice the number of cycles as test #1(F) and the time to 5% creep strain was nearly four times longer for sample #2B(C) as compared to sample #2(C). The difference in fatigue life is not terribly surprising as most materials have fatigue life scatter of 2 or greater [3]. The difference in creep life is somewhat surprising and the level of primary creep is substantially different as shown in figure 2.

{INSERT Figure 2 HERE}

Specimen #2B(C) had approximately 0.25% primary creep strain and a minimum strain rate of 0.025%/hr compared to 3.25% primary creep and a minimum creep rate of 0.045%/hr in specimen #2(C). This creep trend, lower creep rate and primary creep with an increase in the size of the strengthening phase size represents a similar trend as the work of Nathal who found that creep performance of a single crystal superalloy will increase as the γ' precipitate size increases until an optimum precipitate size is reached, after which the creep performance begins to decrease [13].

Because of the clear differences in the creep behavior and the possible difference in fatigue behavior, the remainder of the testing was conducted on specimens from plate Z since more specimens remained from that plate. However the longer fatigue life from specimen #1B(F) (from plate A) was used as the baseline fatigue life for tests #4(1/4N_f+C) and #5(1/2N_f+C) since this would result in specimens that had exhausted ¼ to ½ of their fatigue life or ½ to all of their fatigue life, respectively. It was thought that higher levels of fatigue damage would have more of an influence on subsequent creep behavior for this initial examination of creep/fatigue interaction.

The Interaction of Creep and Fatigue

Table 3 gives the results for all of the test conditions. It can be seen that 2.5% prior creep in the #3(2.5C+F) condition did not decrease the fatigue life beyond the usual scatter in fatigue life. (In fact, it's life greater than the pure fatigue sample #2(F).) However, specimens subject to fatigue cycling before creep, #4(1/4Nf+C) and #5(1/2Nf+C), had a greater time to 5% creep strain than specimens that saw no prior fatigue (when comparing specimens from the same plate of material).

Table 3, Baseline and Creep+Fatigue Test Results

Specimen ID/Test Condition #	Results	Plate
#1(F)	Fatigue Failure at 90,075 Cycles	Z175T
#1B(F)	Fatigue Failure at 176,824 Cycles	A2LPT
#2(C)	5% Creep Strain in 38.2 hrs	Z175T
#2B(C)	5% Creep Strain in 139.5 hrs	A2LPT
#3(2.5C+F)	Fatigue failure at 115,251 Cycles	Z175T
#4(1/4N_f+C)	5% Creep Strain in 69.7 hrs	Z175T
#5(1/2N_f+C)	5% Creep Strain in 72.5 hrs	Z175T

The tensile modulus of elasticity was tracked during the fatigue portion of the tests to assess any cyclic damage. A drop in modulus typically indicates crack initiation and growth.

The normalized modulus (= actual modulus / initial modulus) versus fatigue cycles, shown in figure 3, indicates that the modulus is generally stable until about 20,000 cycles. After about 40,000 cycles there is a consistent decline in the modulus until specimen failure – indicating the accumulation of damage, e.g. cracking. All of the specimens exhibit a similar trend except for sample #3(2.5C+F) that saw 2.5% creep strain prior to fatigue loading. The cause of the steep drop in modulus apparent at 500 cycles for this specimen was not determined, but it may be a result of a loss of the hardening that occurred during creep. Initial microstructure appears to have only a small impact on the softening behavior of the material. However, the specimen from plate A, #1B(F), demonstrates a slower modulus loss compared to the specimens from plate Z. This may indicate that the coarser γ' results in a slower crack growth rate compared to the finer γ' material.

{INSERT Figure 3 HERE}

The creep behavior of specimens was clearly affected by the prior fatigue loading. Figure 4 shows the creep strain as a function of time for all of the specimens that were crept to 5.0% strain. The clear influence of microstructure is apparent in comparing specimen #2(C) with #2B(C). The larger γ' precipitates in plate A substantially reduces both the primary creep strain and the minimum strain rate. Specimens with prior fatigue loading to ¼ and ½ Nf had a significant reduction in primary creep strain, as indicated in figure 5, that decreases with an increase in the number of prior fatigue cycles.

{INSERT Figure 4 HERE}

{INSERT Figure 5 HERE}

During creep only loading, the material displays a significant amount of primary creep of 3.5% followed by a region of secondary creep that continues to 5% creep strain when the test was completed. Fully reversed fatigue cycling of PWA1484 resulted in a reduction in the amount of primary creep observed during subsequent creep testing. The specimen subject to ¼ Nf, #4(1/4N_f+C), had approximately 2% primary creep strain while the specimen subject to ½ Nf, #5(1/2N_f+C), had only about 1.3% primary creep. A careful examination of figure 4 shows that the transition from secondary to tertiary creep occurs at approximately 3.5% creep strain for the specimen subject to ½ Nf, #5(1/2N_f+C). The shift to tertiary creep is also apparent in figure 5 showing the slight uptick in strain rate for this specimen. This indicates that prior fatigue cycling while reducing the primary creep has also introduced some microstructural damage. This is supported by figure 3 which tracks the modulus of the specimens during fatigue testing, and shows a steep decline in the modulus after 40K cycles for specimen #5(1/2N_f+C).

It is also of note that each specimen from plate Z had the same secondary strain rate regardless of the amount of primary creep or fatigue pre-cycling. This indicates that this secondary strain rate in PWA1484 is indifferent to prior fatigue at these test conditions. The minimum strain rate for the creep specimen from the A plate is less than that of the Z plate and the amount of primary creep strain is less than 0.1%. Previous research by Rae et al., and Wilson and Fuchs has determined that a major factor in primary creep is dislocations cutting the γ' precipitates resulting in longer unimpeded paths for the dislocation motion [8,9]. The larger γ' precipitates in the plate A material would make it more difficult for dislocations to cut them. Also, fatigue cycling has been shown to have the initial effect of populating the γ matrix channels in a single crystal superalloy with dislocations that become more numerous and tangled as the number of cycles increases [11]. It is likely that these dislocations form a barrier that does not allow dislocations to easily penetrate the γ' precipitates even at temperatures and stresses that would normally result in a large percentage of primary creep strain in PWA 1484. This phenomena is one reason that would account for the reduction in primary creep that occurs after initial fatigue cycling.

Microstructural Changes

As mentioned in an earlier section, the γ' size distribution was characterized using a scanning electron microscope on the un-tested plates and in the gage sections of the specimens that were subject to the various creep and fatigue loading conditions. The size distributions of the γ' precipitates were produced by measuring 200 γ' precipitates from representative SEM images using ImageJ analysis software. Regardless of the loading conditions, all the specimens displayed measurable coarsening of the γ' precipitates at the conclusion of the test. Figure 6 shows the initial distribution of γ' size for plates Z and A and the γ' distribution after pure fatigue testing for specimens extracted from each plate, #1(F) and #1B(F), respectively. It appears that the coarsening increases with an increase in the number of cycles as specimen #1B(F) coarsened (on average) by ~0.08 μm (176,824 cycles) and specimen #1(F) coarsened by only ~0.05 μm (90,075 cycles). This coarsening seemed to increase as a function of time at temperature and the type of testing that a specimen underwent, with any testing that included creep producing a greater percentage increase in the mean size of the γ' precipitates, Figure 7. The average γ' size even increased by ~ 0.07 μm in specimen #2(C) that crept to 5% strain in just 38.2 hours. A definite shift in the mean size of the γ' precipitates can be seen that generally scales with the creep time and/or number of fatigue cycles. Another reason for the reduction in creep strain seen in the mechanical behavior of the specimens is heat treatment affects during fatigue cycling. This phenomenon was documented by Wilson and Fuchs who found that PWA1484 exposed to a heat treatment of 871°C for 32 hours had a lower percentage of primary creep than PWA1484 that was heat treated at lower temperatures (704°C) [8]. The SEM images of the post test microstructure taken after each of the test conditions in this research also show some loss of coherency in the γ' precipitates with octodendrite structures present in the microstructure as illustrated in figure 8[14]. These physical changes in the γ' morphology are consistent with the findings of Wilson and Fuchs [8]. The morphological changes observed in the microstructure of the present study could, therefore, be a result of deformation or time at temperature. Likely a combination of the two is affecting the microstructure.

{INSERT Figure 6 HERE}

{INSERT Figure 7 HERE}

{INSERT Figure 8 HERE}

Conclusions:

Specimens of PWA1484 were subject to various creep and fatigue loading scenarios at 871°C to explore the interaction of the two damage modes. This initial study found that the γ' morphology has a greater impact on pure creep behavior than on fully reversed fatigue life. That is, the primary creep deformation is decreased with an increase in γ' size. Primary creep is also decreased by prior fatigue cycling. A reduction in primary creep was found to be dependent on the number of prior fatigue cycles - the greater the number of fatigue cycles the greater the reduction in primary creep strain. However, the onset of tertiary creep occurs earlier in specimens that were subject to considerable prior fatigue cycling. The fatigue life of PWA1484, however, was not affected by prior creep. This is consistent with fatigue life being less dependent on details of the microstructure (γ' size). Both creep and fatigue loading tend to cause coarsening of the γ' precipitates with creep generally having a greater effect. There were also indications of a partial loss of coherency of the γ/γ' interface that clearly could affect future mechanical behavior.

Acknowledgements: This work was performed at the Air Force Research Laboratory, AFRL/RXLMN, Materials and Manufacturing Directorate, Wright–Patterson Air Force Base. C.J. Pierce was partially supported by Dr. Tommy George of AFRL/RXTS, Turbine Engine Fatigue Facility, Wright–Patterson Air Force Base, Ohio.

References

[1] A.D. **Cetel, D.N. Duhl,** The Metal. Soc. Superalloys 1988(1988) pp.235-244.

[2] **Air Force Research Laboratory.** *Advanced High Cycle Fatigue Life Assurance Methodologies.* Wright Patterson Air Force Base : Materials and Manufacturing Directorate: Air Force Research Laboratory, 2004.

[3] P.K. **Wright, M. Jain, D. Cameron,** The Metal. Soc. Superalloys 2004 (2004)pp. 657-666.

[4] H. **Mughrabi,**The Johannes Weertman Symposium, (1996)pp. 267-278.

[5] M. **Ott,H. Mughrabi,** Mater. Sci. Eng. A 272 (1999), pp. 24-30.

[6] M. **Ott,H. Mughrabi,**Elsevier Appl. Sci. Fatigue '96 (1996). pp. 789-794.

[7] R.A. **MacKay, L.J. Ebert,** Metal. Trans. A 16A (1985), pp. 1969-1982.

[8]B.C. **Wilson, G.E. Fuchs,** The Metal. Soc. Superalloys 2008 (2008). pp. 149-158.

[9] C.M.F. **Rae, R.C. Reed,** Acta Mater 55.(2007), pp. 1067-1081.

[10] R.C. **Reed,** *The Superalloys: Fundamentals and Applications.* New York, 2006.

[11]J.H. **Zhang, et al.**, Metal. Trans. A 23A (1992), pp. 1253-1258.

[12] C. **Pierce,** *Creep and Fatigue Interaction Characteristics of PWA1484.* Wright Patterson AFB : Air Force Institute of Technology, 2009.

[13] M.V. **Nathal,** Metal. Trans. A 18A (1987), pp. 1961-1970.

[14] T. **Grosdidier,A. Hazotte,A. Simon,** Mater. Sci. Eng. A 256 (1998), pp. 183-196.

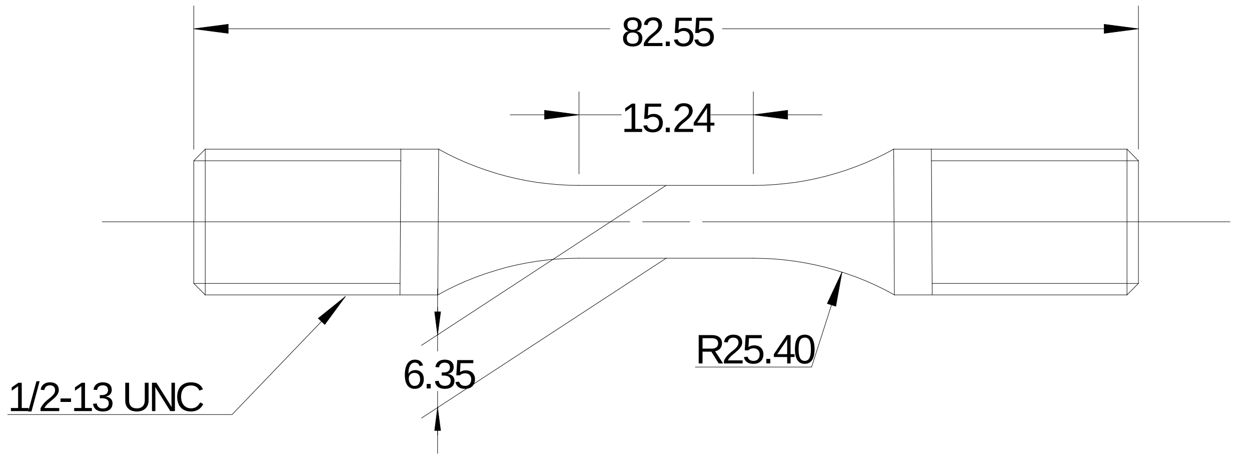

Figure 1, Specimen for creep and fatigue tests, dimensions in mm unless otherwise noted.

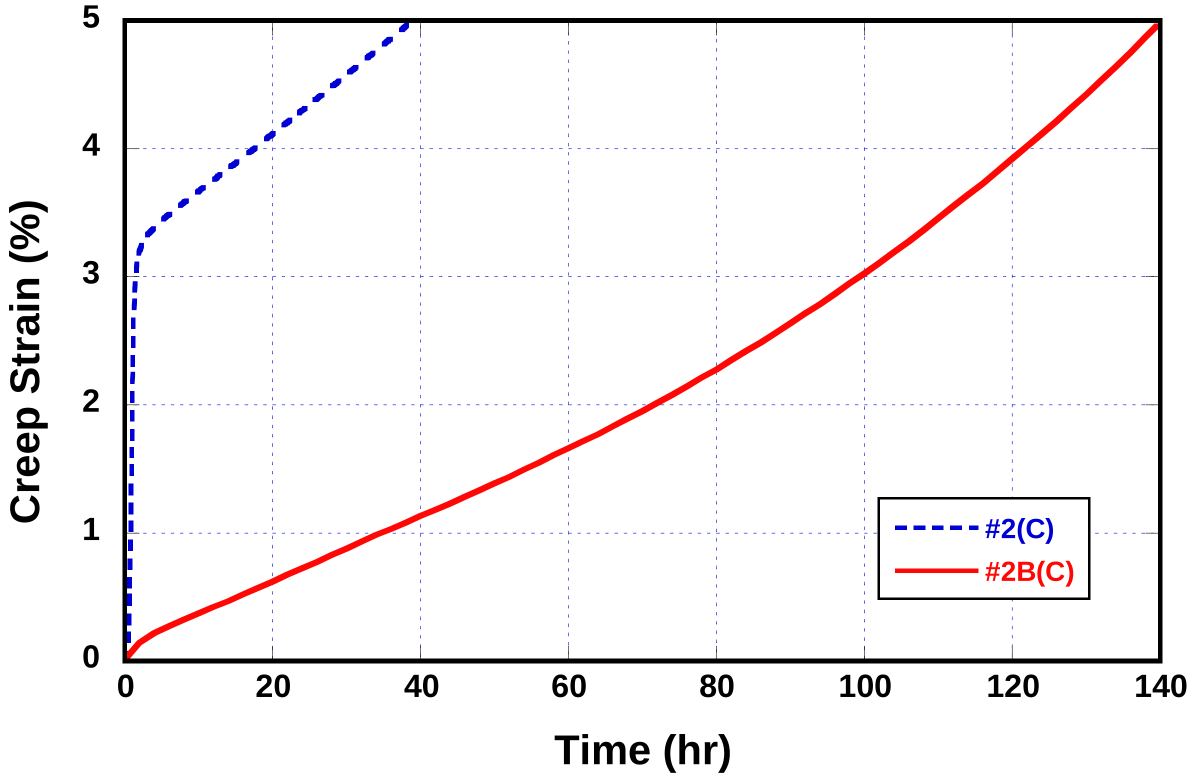

Figure 2, Baseline creep response for material from plate A and Z, 871°C, 517 MPa.

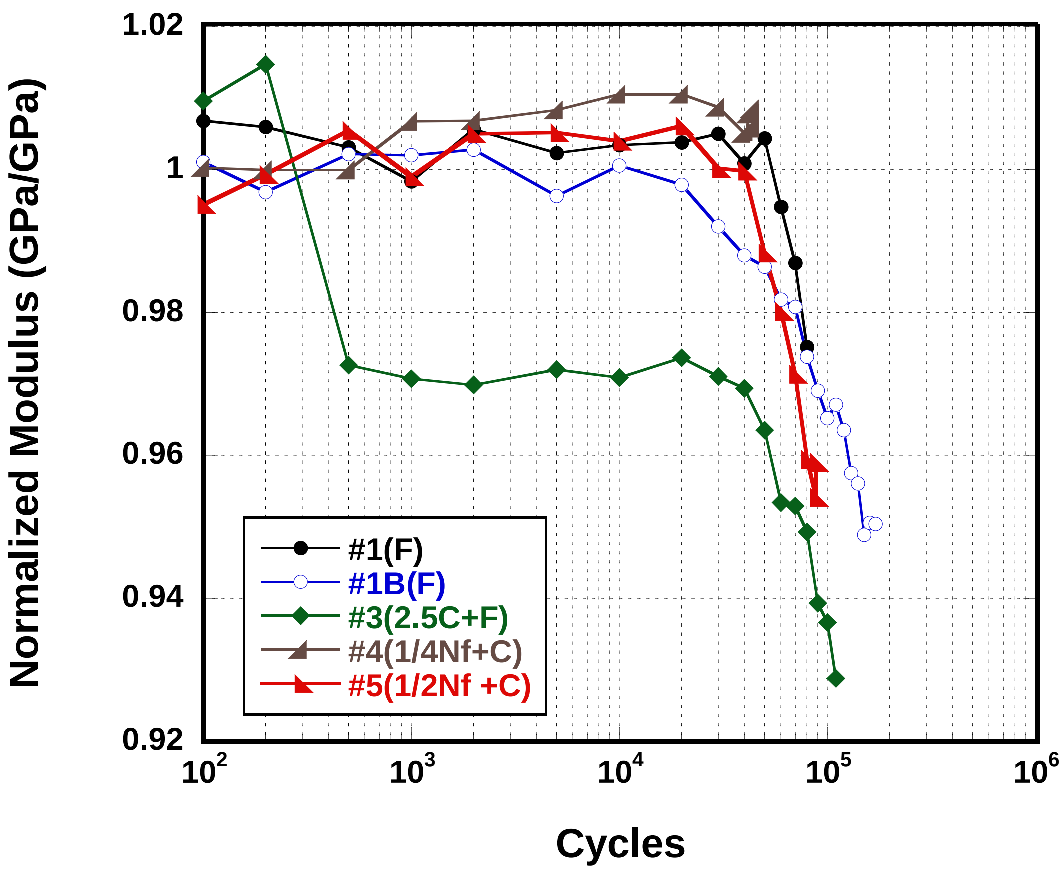

Figure 3, Normalized modulus versus cycles for specimens subject to pure fatigue and fatigue after prior creep. All testing at 871°C, R= -1, 0.5 Hz.

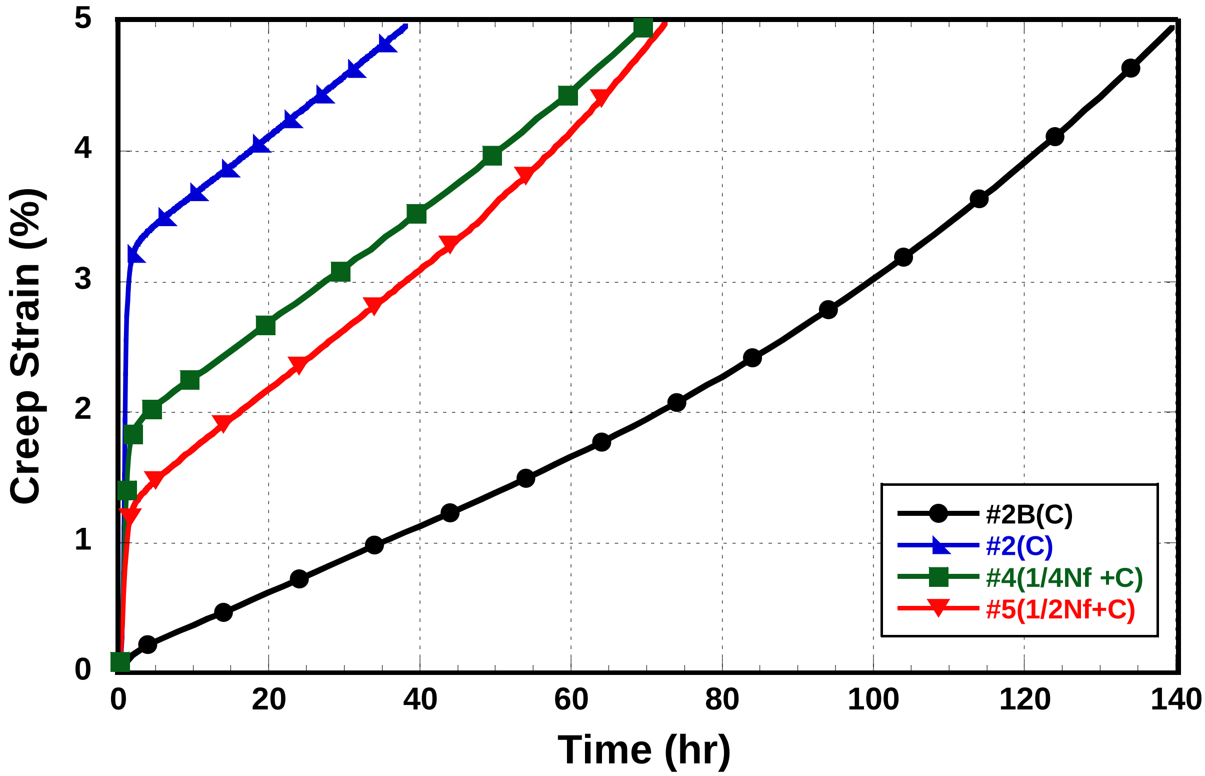

Figure 4, Creep strain as a function of time for specimens with varying numbers of initial fatigue cycles.

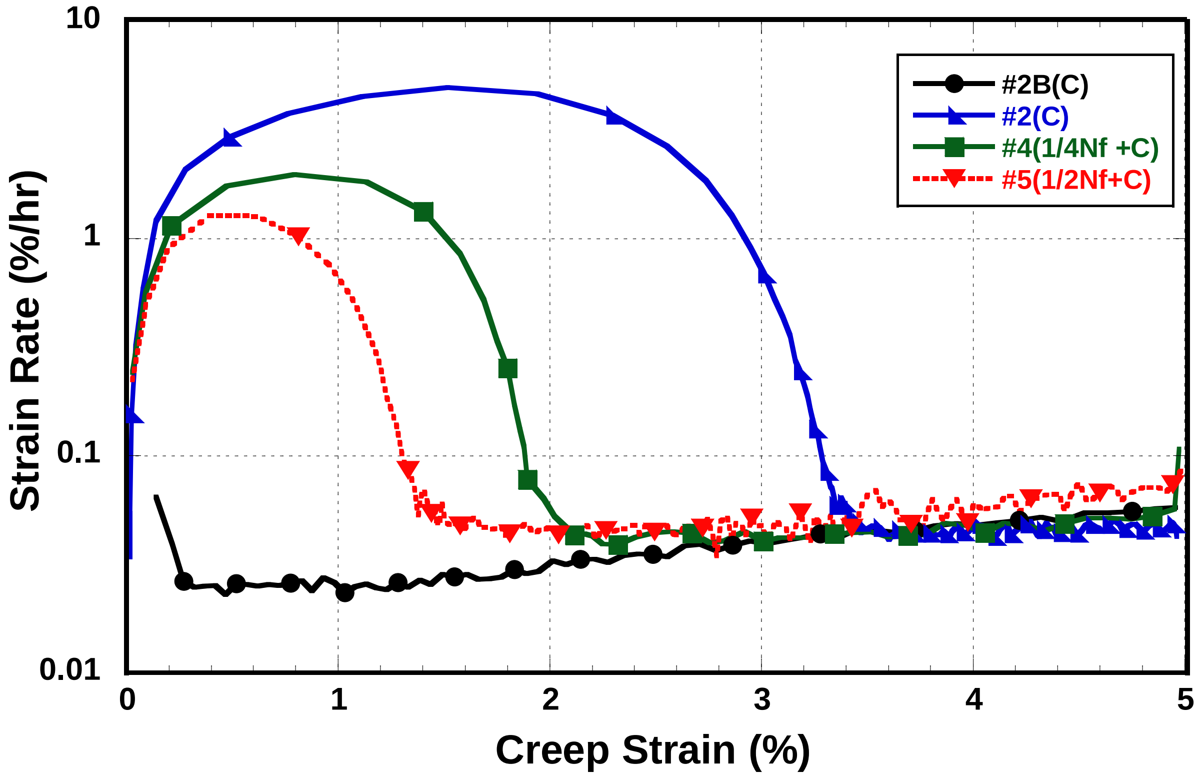

Figure 5, Primary and secondary strain rate for specimens having varying numbers of prior fatigue cycles.

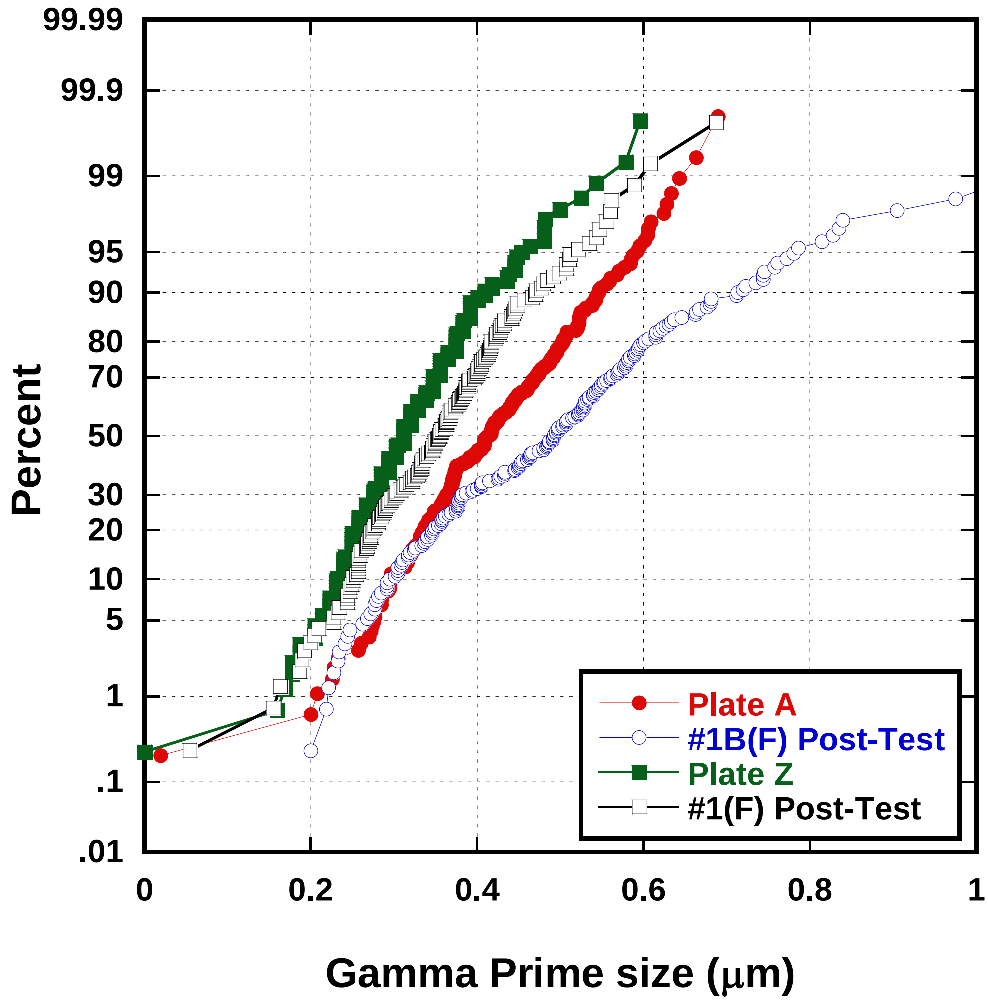

Figure 6, Cumulative distribution plot of the initial γ' size for both plates of material (filled symbols) and its evolution after pure fatigue cycling until failure (open symbols).

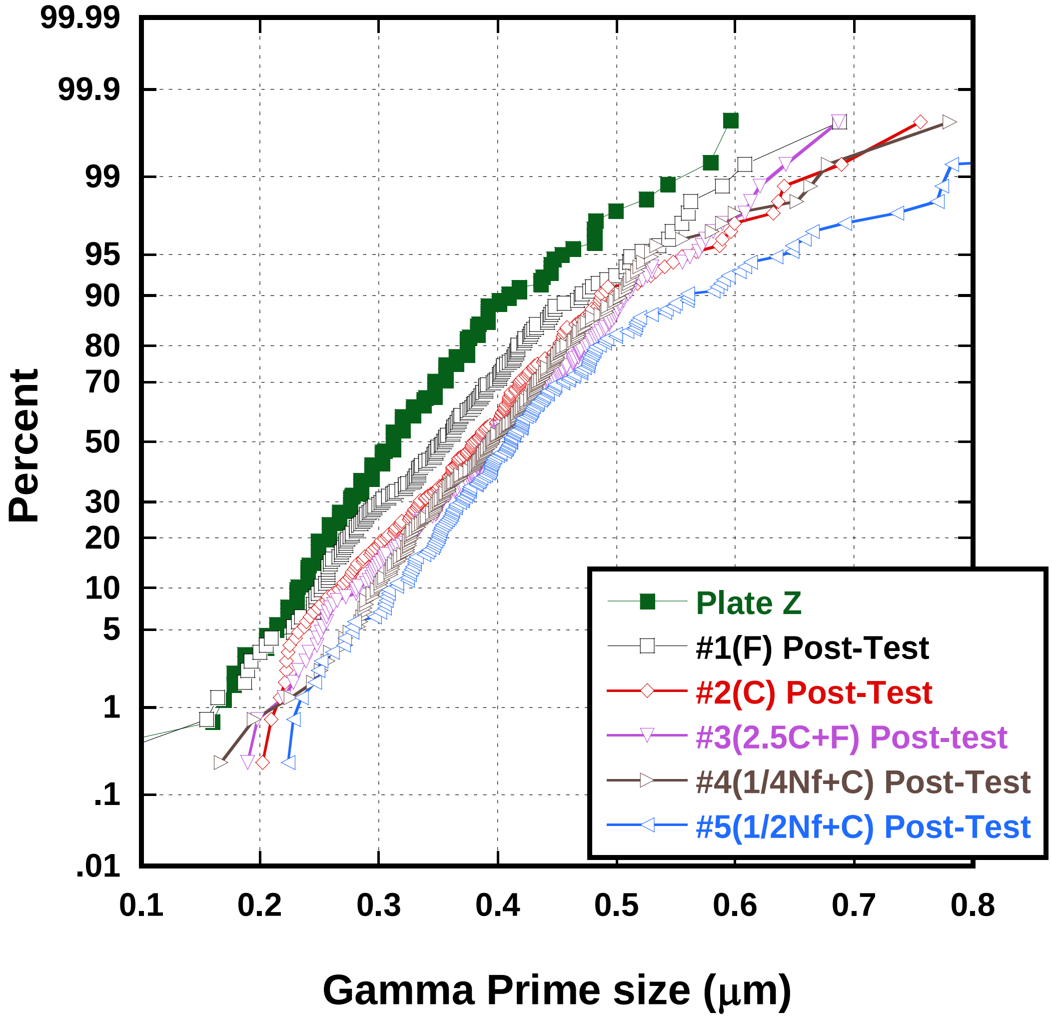

Figure 7, Cumulative distribution plot of the initial γ' size for plate Z (filled symbols) and its evolution after Creep/Fatigue testing.

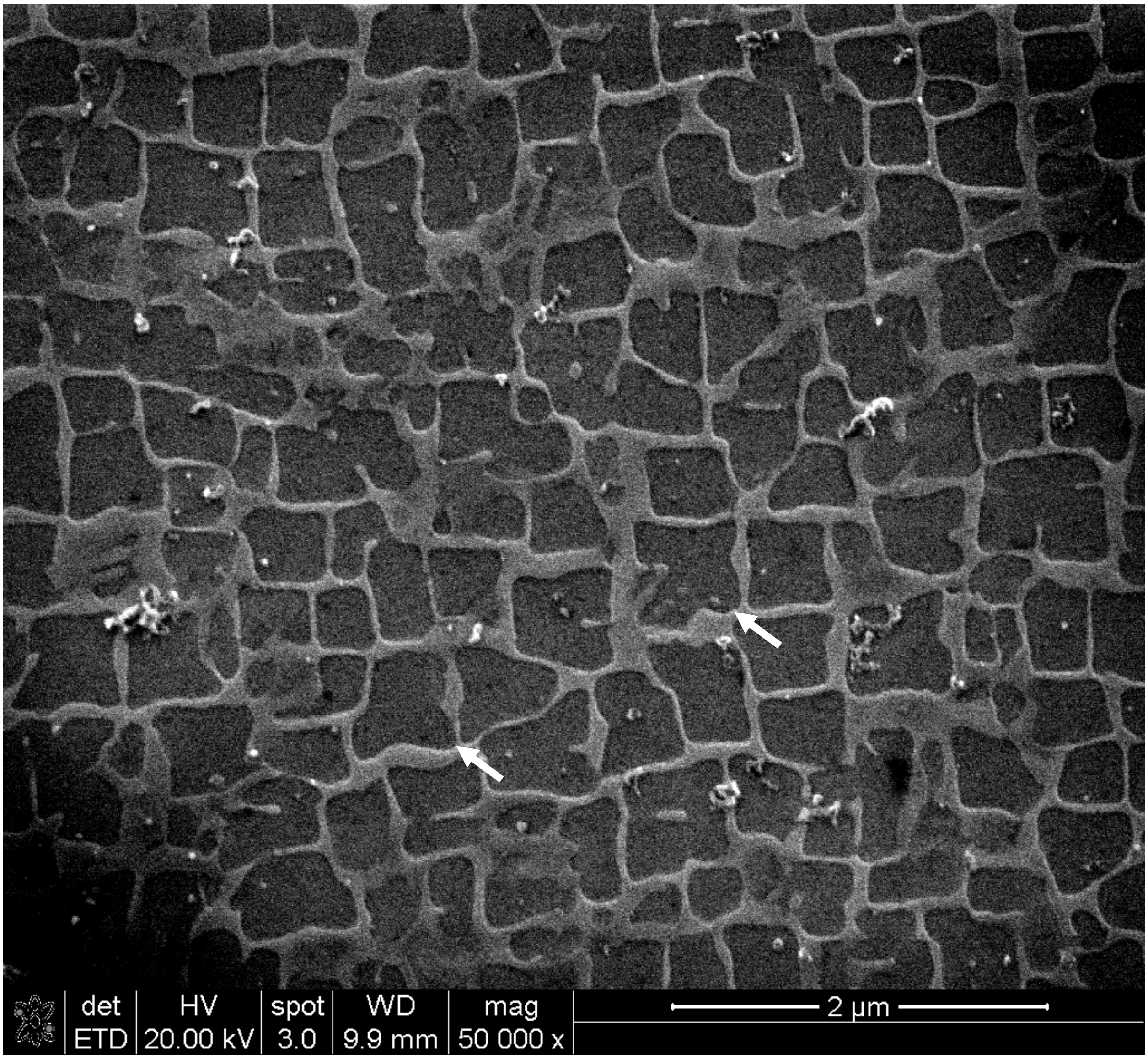

Figure 8, γ' coarsening and evolution normal to the applied stress in PWA1484 subject to test condition #3(2.5C+F), arrow showing loss of coherency and octodendrite formation.