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A Recent Development in Creep-Fatigue Testing

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ABSTRACT

Procedures for the assessment of components subject to cyclic loading at high temperatures require material property input data that characterize the creep-fatigue deformation response and resistance to cracking. For many years, there was no testing standard or code of practice to ensure that such information was generated in a uniform way. This was mainly because the creep-fatigue test data requirements for organizations in various industrial sectors appeared to be so different that the need for standardization was questioned. In the mid-2000s, it was recognized that even though it would make no sense to be prescriptive about such details as cycle shape, there were many aspects of creep-fatigue testing for which guidance would be beneficial to ensure acceptable uniformity in deformation and endurance data generation. In response to this realization, the state of the art relating to creep-fatigue interaction was extensively reviewed by an international group of specialists, and the generated knowledge base was used to underpin a new ASTM testing standard, ASTM E2714-09. The gathered knowledge is reviewed. There is a requirement for all ASTM standards to include a precision and bias statement, and an international interlaboratory creep-fatigue test comparison activity was facilitated to form the basis of this section of ASTM E2714-09. An integral part of the guidance given in the new standard is the recommendation for post-test metallurgical inspection and the way in which this information can be used to give added value to creep-fatigue crack initiation endurance results. The evidence gathered from this study is also examined.

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Keywords

creep-fatigue testing, P91 steel, interlaboratory study, post-test inspection

Introduction

Creep-fatigue crack formation and development can lead to the failure of high-temperature components in a variety of engineering applications, most notably in the power generation, petrochemical, automotive, and aerospace industries. Mechanical assessment to prevent the risk of such failures relies on material property parameters determined using published laboratory testing procedures (see, e.g., Refs 1–14). However, until recently, there was no standard procedure to specifically cover the determination of creep-fatigue deformation and damage properties. The thermo-mechanical service duty histories experienced by critical high-temperature components operating in various industrial sectors were so diverse that for many years it was judged that no single standard could satisfy the requirements of all end-users. It was then realized that although there were details that could only be application dependent, there were many aspects of creep-fatigue testing for which guidance would be beneficial to ensure acceptable uniformity in deformation and endurance data generation. For example, in such a standard concerned with the response of plain and notched specimens, although it would not be practical to be prescriptive about an appropriate notch geometry to be representative of a range of applications, general guidance on notched specimen creep-fatigue testing could be appropriate. This paper reviews the background to the development and effectiveness verification of the new ASTM standard procedure for creep-fatigue testing, ASTM E2714-09 [15].

The extent of creep-fatigue interaction experienced by a material depends on the applied strain range, operating temperature, duration and type of hold period (the amount of time and the position in the loading cycle during which the stress or strain is held constant), and frequency of loading (strain rate) [16]. **Figure 1** shows schematic examples of different types of creep-fatigue damage mechanisms that can be encountered in engineering materials at elevated temperatures. In the absence of a significant hold time (or at relatively high strain rates), creep-fatigue crack initiation and growth can be dominated by fatigue even at temperatures high in the creep regime for the material [**Fig. 1(a)**]. With increasing hold time (or decreasing strain rates) and decreasing strain amplitude at high temperatures, creep damage becomes increasingly influential to the limit beyond which creep-fatigue crack development becomes fully dominated by creep [**Fig. 1(b)**]. At intermediate hold times and strain amplitudes, fatigue cracking interacts with creep damage, consequentially or simultaneously, resulting in accelerated crack growth [see **Figs. 1(c)** and **1(d)**, respectively] with the extent of any interaction increasing with decreasing creep ductility [16,17].

In light of this complex interdependence of a material's creep-fatigue response and the test variables, a number of laboratory tests need to be conducted to systematically characterize the influence of each of these parameters. Thus, laboratory creep-fatigue tests are typically performed to intentionally induce varying degrees of interaction between creep and fatigue deformation/damage for the material of

FIG. 1 A schematic representation of creep-fatigue damage mechanisms in polycrystalline materials: (a) fatigue dominated; (b) creep dominated; (c) creep-fatigue interaction (due to consequential creep damage accumulation); and (d) creep-fatigue interaction (due to simultaneous creep damage accumulation) [16].

interest. Creep-fatigue tests, usually involving a simplified cycle shape representative of the service transients experienced by the target component, are particularly informative in the provision of data to indicate the concurrent influences of cyclic (or creep) loading on creep (or cyclic) deformation or damage [14]. While creep-fatigue data have been generated by individual laboratories for many years [18–20], there was no testing standard or formal code of practice to ensure that such information was generated in a uniform and reliable way until the mid-2000s.

A generic flow diagram is shown in **Fig. 2** to represent the concept of a number of published [21–24] and in-house procedures adopted to assess the integrity of “defect-free” components subject to creep-fatigue loading [14]. Other approaches are possible [25–27] but not so widely adopted. As a first step, the stress/strain state at critical locations of the target component is established to then enable determination of the fatigue (D_F) and creep (D_C) damage fractions with reference to the material’s endurance property data. Whereas, in principle, testing procedures for the determination of pure fatigue and pure creep data already exist [1–13], the results of creep-fatigue tests are required in order to determine the effects of creep deformation on cyclic plasticity, and vice versa [14]. Finally, with reference to **Fig. 2**, D_F and D_C fractions are compared with the crack initiation locus in a creep-fatigue damage summation diagram, and the risk of cracking is evaluated [28]. Typically, creep-fatigue damage summation diagrams are constructed with reference to the results of creep-fatigue tests [20].

The development of ASTM E2714-09 first involved a review of relevant testing standards and practices adopted worldwide [29].

FIG. 2

A generic representation of the integrity assessment procedure for “defect-free” components under creep-fatigue loading conditions [21–24].

Background to New Testing Standard

Prior to the preparation of a first draft of the proposed new standard for creep-fatigue testing, a questionnaire was circulated to high-temperature fatigue-testing specialists in Europe, North America, and Asia to survey existing testing practices. In addition, the guidance contained in all relevant national and international testing standards relating to fatigue, creep, and stress relaxation testing was reviewed [1–13]. The review included, but was not limited to, the types of tests employed, test specimen geometries and dimensions, measurement and control of strain and temperature, testing machines, and data acquisition. Twenty-three responses were received from 10 countries following an initial circulation to 57 specialists in 13 countries. The major findings from this survey are briefly outlined below.

TYPE OF TEST

The most commonly adopted creep-fatigue waveform corresponded to a loading cycle with one or more hold times with durations typically varying between 1 min

FIG. 3 Creep-fatigue test cycle shapes.

and 24 h [e.g., **Figs. 3(c)** through **3(f)**]. The survey indicated that most specialists performed cyclic/hold creep-fatigue testing under strain control rather than load control, although the choice of test-control mode was mainly determined by the target practical application [29].

With the recent improvements in test machine technology and digital control systems, thermo-mechanical fatigue (TMF) testing was increasingly being adopted for characterizing material response to creep-fatigue loading. Procedures for TMF testing were well covered by existing standards [10,11].

TEST SPECIMEN GEOMETRY

The most widely employed test specimen geometry was the uniform parallel gauge section uniaxial test piece, without ridges for extensometer fixation, but with a variety of grip-end connections (e.g., screw threaded, button-end, or cylindrical bar grip-ends were employed). Gauge section diameters were typically in the range of 5 to 10 mm.

TESTING MACHINE

Servo-controlled testing machines involving hydraulic or electro-mechanical-based drive systems were the most commonly adopted, with the former used

comparatively more than the latter. Furthermore, the load cells in these machines were most commonly calibrated to meet the Class 1 requirements of standards such as ISO 7500-1 [30]. There was a relatively high awareness of the consequences of specimen bending due to misalignment, and most laboratories performed regular alignment checks in accordance with one of the available standard practices [31,32].

STRAIN MEASUREMENT AND CONTROL

Side-entry contact extensometers were the most widely used type of strain measurement transducer. A minimum axial extensometer requirement of Class 0.5 as in ISO 9513 [33] was recommended. Despite the reliability of such devices, it was essential to check the credibility of specimen attachment by conducting elastic modulus checks at room temperature and at the test temperature immediately prior to the start of the test.

Initially, creep-fatigue tests were performed to determine crack initiation endurance, but a knowledge of deformation response from such experiments has become of equal importance, and reliable cyclic stress-strain-time records are now a required output [14].

TEMPERATURE MEASUREMENT AND CONTROL

The most commonly adopted heating solutions were those based on resistance furnaces or induction coils, although radiant lamp furnaces and direct resistance heating were also employed in certain circumstances. Among the types of thermocouples that were either tied or spot-welded to the specimen for temperature measurement and subsequent control, Type K and Type R were reported to be the most common. The adopted tolerances during testing ranged from $\leq \pm 1^\circ\text{C}$ to $\leq \pm 10^\circ\text{C}$, with values in the range of $\leq \pm 2^\circ\text{C}$ to $\leq \pm 0.01 \cdot T$ being the most frequent (where T is the test temperature in degrees Celsius). A number of uncertainties associated with the temperature indicated on a digital display or gathered by the data acquisition system were also identified. For this reason, it was important that indicated temperature tolerances included all uncertainties [34,35]. The cyclic/hold test cycles shown in Figs. 3(c) through 3(f) are essentially cyclic stress relaxation or cyclic creep tests (depending on control mode), and it was therefore logical to adopt the same temperature tolerances defined in Refs 12 and 13 in the new standard (i.e., $\leq \pm 2^\circ\text{C}$, for indicated temperatures up to 600°C , with due consideration to all combined sources of error). Based on feedback from the survey, it was overwhelmingly clear that temperature measurement and control required particular attention in the new creep-fatigue testing standard.

TEST RESULTS

Typically test results were gathered via digital acquisition systems, with the recognition that this needed to be done efficiently to avoid the generation of unnecessarily large data files that could be difficult to interpret. Peak and user-defined key-event values of stress and strain were usually recorded for all loading cycles, but only selected hysteresis loops were permanently stored (~ 250 stress-strain data coordinates per loop) (e.g., based on a linear or logarithmic sampling strategy). Data

acquisition during selected hold periods also required careful management, in particular for long hold times, and a target of ~ 250 balanced stress-strain-time coordinates per hold time was regarded as reasonable.

Almost the most important outcome from a creep-fatigue test is the crack initiation endurance, and in order for this quantity to have practical significance, the crack initiation criterion needs to be specifically defined. Although many organizations adopt a 2 % load drop criterion, because of its coincidence with the formation of 0.5- to 1.0-mm-deep cracks in an ~ 8 -mm-diameter specimen [36], the survey in fact revealed that a range of criteria were adopted, varying between 2 % and 25 % reductions in steady-state maximum stress.

During the course of the knowledge review, it became clear that the scope of the new creep-fatigue testing procedure should not simply provide specific guidance for the determination of standard material property data but should also provide more generic guidance for a wide range of standard and benchmark creep-fatigue testing practices.

Creep-Fatigue Test Interlaboratory Study

In accordance with ASTM rules, the development of a definitive statement on precision and bias was necessary in order for the provisional standard [15] to become permanent [37]. For this purpose, *precision* is defined as the closeness of agreement between independent test results obtained under stipulated conditions, and *bias* is the difference between the expectation of the test results and an accepted reference value. Precision and bias statements were based on the results of an interlaboratory study (ILS) involving the systematic evaluation of intra- and interlaboratory variability while following the guidelines prescribed by the new standard.

Previously, fatigue-based ILSs had been mainly conducted for tests involving pure low cycle fatigue (LCF) loading conditions [38–41]. In only one case had a thorough post-test microscopic characterization of the surface cracks been performed [41], with this evaluation involving a 2 % load drop crack initiation criterion. Although results for a creep-fatigue-based (with hold time) ILS existed for a temperature of 550°C [42], that study involved very limited global participation, and hence a new ILS was initiated to rigorously determine precision and bias statements for ASTM E2714-09 [15].

TEST MATERIAL

The ILS activity proposed to underpin ASTM E2714-09 included consideration of a heat of P91 steel, with the details summarized in Table 1 [43,44]. P91 was adopted primarily because of the high interest in the steel on the part of the organizations who had volunteered to participate in the ILS.

TABLE 1

Details of chemical composition and quality heat treatment of used heat of steel P91.

C, %	Si, %	Mn, %	P, %	S, %	Ni, %	Cr, %	Mo, %	As, %	V, %	Nb, %	Al, %	Cu, %	N, %	Sb/Sn, %	Fe, %
0.11	0.31	0.45	0.011	0.009	0.19	8.22	0.94	0.005	0.21	0.07	0.006	0.16	0.039	0.001	Balance

Normalized: 1 h 1040°C to 1060°C, air cooled; tempered: 2 h 760°C to 780°C, air cooled

FIG. 4

Interlaboratory comparison pilot test results showing the influence of hold time on the creep-fatigue crack initiation endurance of P91 steel at 625°C (# reference is ILS participant number; data points for 1 % $\Delta\epsilon$ have been offset for clarity).

TEST CONDITIONS

Interlaboratory comparison activities are mainly dependent on voluntary contributions, and the P91 creep-fatigue test ILS activity was no exception. Testing conditions were therefore a compromise between the provision of circumstances leading to the generation of both creep and fatigue damage and the most efficient use of limited available resources. The main interlaboratory comparison was therefore preceded by a small pilot study to identify the most practical test conditions to be adopted. The results of the pilot study are summarized in **Fig. 4**. The strain-controlled test cycle shape adopted for the pilot and main studies was the waveform shown in **Fig. 3(c)**, with a strain rate of 0.025 %/s during the transient ramps. A 2 % load drop criterion was adopted to indicate crack initiation.

Maximum application temperatures for P91 steel are typically in the range of 580°C to 600°C, but a test temperature of 625°C was proposed to improve the likelihood of creep damage generation in creep-fatigue tests with relatively short hold times without excessive thermal enhancement influencing the mechanism. The influence of hold times of between 10 and 60 min, for strain ranges ($\Delta\epsilon$) of 1.0 % and 1.5 %, was then investigated to determine their effect on crack initiation endurance (**Fig. 4**). On the basis of the post-test inspection results from these tests it was concluded that cyclic/hold tests with a 30-min hold time at 625°C would be necessary to ensure generation of creep and fatigue damage. Such tests formed an integral part of the adopted test matrix shown in **Table 2**. The test matrix also included shorter hold-time tests to provide a link with other available data [45].

In the main study (**Table 2**), the ILS participants had the flexibility of choosing their preferred testing hardware and other in-house practices while following the prescribed guidelines recommended in the new creep-fatigue standard [15]. Additional details are given in Refs 43 and 44.

TABLE 2

Test matrix adopted for the ASTM E2714-09 interlaboratory study [43,44].

Participants	P91 Crack Formation					
	Strain Amplitude					
	$\pm 0.25\%$	$\pm 0.5\%$	$\pm 0.75\%$	$\pm 0.5\%/10\text{-min hold}$	$\pm 0.75\%/10\text{-min hold}$	$\pm 0.5\%/30\text{-min hold}$
Idaho National Lab: L. Carroll	2	2		2		
EMPA Switzerland: S. R. Holdsworth				4		4
Tech U. Darmstadt: A. Scholz	2	2	2			
CRIEPI, Japan: Y. Takahashi		2	2	2	2	2
GE, Schenectady: D. Knorr		2	2		2	
NASA, Glenn: B. Lerch			2	2	2	
ANSTO Australia: W. Payton	2			2	2	
Georgia Tech: R. Neu	2	2		2	2	
NRC, Canada: J. Tsang			2		2	2
University of Arkansas: A. Saxena	Conduct creep deformation and rupture testing and metallography/microscopic characterization of tested specimens					
EDF Energy: M. Spindler	2	2	2	2		
Poli di Milano: S. Beretta, M. Filippini					2	2
BiSS, India: R. Sunder		2		2		4

INTERLABORATORY STUDY OBSERVATIONS

Mechanical Response

The creep-fatigue test interlaboratory comparison involved the scope of testing shown in **Table 2**. Each of the strain-controlled cyclic/hold creep-fatigue tests, irrespective of hold time, exhibited three phases of stress response (**Fig. 5**). In the first phase, peak stresses decreased significantly, generally acknowledged to be associated with dynamic recovery in the form of subgrain formation and/or growth [36]. In the second phase, peak stresses decreased in magnitude at a lower (steady) rate before a small number of surface microcracks developed to become macrocracks.

FIG. 5

Typical plot of maximum stress as a function of cycles for tests conducted on P91 steel at 625°C with no hold (dashed line) and with a 10-min hold (solid line).

FIG. 6

Overall results of P91 interlaboratory study at 625°C showing the influence of hold time on creep-fatigue crack initiation endurance (data points at 1% and 1.5% $\Delta\epsilon$ have been offset for clarity).

The apparent increase in the rate of softening indicated by the tensile peak stress in the third phase is in fact a consequence of compliance change due to the development of macrocracking. A comparison of these characteristics is shown in **Fig. 5** for P91 in tests without and with a 10-min hold time at peak strain in tension [i.e., **Fig. 3(c)**], with softening occurring at a faster rate in the hold time test, consistent with the observations of others [46].

All the ILS creep-fatigue crack initiation endurance results are contained in **Fig. 6**. Predictably, crack initiation endurance increased with decreasing strain range. Increasing hold time was, on average, responsible for reducing crack initiation endurance, with the effect becoming more notable with reducing strain range. Unlike the results of the pilot study (**Fig. 4**), the evidence from the main study, involving multiple intra- and interlaboratory tests (**Fig. 6**), indicated that there was

FIG. 7

Intra- and interlaboratory variation in zero hold time creep-fatigue test crack initiation endurance for P91 steel at 625°C (# reference is ILS participant number; CI is confidence interval).

FIG. 8

Intra- and interlaboratory variation in 10-min hold time creep-fatigue test crack initiation endurance for P91 steel at 625°C (# reference is ILS participant number; CI is confidence interval).

not a significant influence of hold times of up to 30 min on the crack initiation endurance of P91 at the highest strain range of 1.5 % at 625°C.

Crack Initiation Endurance

The creep-fatigue crack initiation endurance results for the tests with zero hold time, 10-min hold time, and 30-min hold time at peak strain in tension are shown in **Figs. 7, 8, and 9**, respectively. These figures also contain mean and 95 % confidence interval (CI) data lines (assuming the endurance data coordinates to be normally distributed). The variability factors (integer value ratios of maximum to minimum creep-fatigue crack initiation endurance from the 95 % CI representations) are in the range of 2 to 3 for the zero hold time data, ~3 for the 10-min hold time data, and ~5 for the 30-min hold time data.

FIG. 9

Intra- and interlaboratory variation in 30-min hold time creep-fatigue test crack initiation endurance for P91 steel at 625°C (# reference is ILS participant number; CI is confidence interval).

FIG. 10 Features associated with premature crack initiation endurance during ILS creep-fatigue testing of P91 steel at 625°C.

Post-test Inspection

According to guidelines given in the new standard [15], post-test inspection comprises visual and optical examination of tested specimens to characterize their external and microstructural appearances [43,44]. Whereas specimens subjected to zero-hold-time testing exhibited multiple transgranular crack initiations and insignificant evidence of dimensional instability, visual observations indicated that with increasing hold time, there was a tendency toward increased gauge section barreling (ranging from 3 % to 20 % with increasing hold time), in particular for those tests involving heating by induction or radiation. Dimensional instability of this type was typically the result of local plastic ratcheting associated with the high axial temperature gradients that can be experienced with such heating forms without careful thermal control [47]. In principle, the temperature gradient tolerances in ASTM E2714-09 had been specified with this prior experience in mind. The ILS experience seemed to suggest that the guidance in the new standard was not strong enough. There was evidence to indicate that smaller gauge section specimens were not so prone to this form of instability during creep-fatigue testing [44].

The adoption of too high ramp rates between the hold times of creep-fatigue tests can lead to extensometer leg slippage. One way to avoid loss of strain control due to this occurrence is to place the extensometer legs on deposits of ceramic [Fig. 10(a)]. However, if not applied with care, such deposits can lead to premature crack initiation. An integral part of ASTM E2714-09 is the recommendation to check for specimen misalignment prior to the start of a creep-fatigue test campaign [31,32]. There was post-test inspection evidence to indicate the consequences of not following such guidance [Figs. 10(b) and 10(c)].

As a generality, optical metallographic examination of the tested specimens revealed crack development in specimens subjected to zero hold time or 10-min hold time cycles at 625°C to be predominantly transgranular. Specimens subjected

FIG. 11 The appearance of crack development in P91 specimens subjected to 30-min hold time cycles at 625°C (1 % strain range), in ILS creep-fatigue tests, with heating by (a) resistance furnace and (b) induction (for which $N_{2\%}$ was not reached for example shown).

to 30-min hold time cycles provided more evidence of creep damage influencing the development of fatigue cracking (Fig. 11) [43,44].

ASTM E2714-09 permits heating by resistance furnace and induction coil. Although resistance furnaces provide the preferred solution for isothermal testing, the use of induction heating is equally acceptable with careful control of temperature along the specimen gauge length. It is not recommended to use single-bead thermocouples attached adjacent to the external surface of the specimen for this heating method, because they invariably indicate a higher temperature than the specimen at the axis of the coil. Alternatively, individually spot-welded thermocouple wires to the specimen, or ribbon-type thermocouples, are recommended in these circumstances [11]. The consequences of not being aware of this situation are illustrated by the post-test metallography conducted on two specimens subjected to 30-min hold time cycles, one heated by resistance furnace and the other heated by induction (Fig. 11).

The evidence shown in Fig. 11 is from two 30-min hold time creep-fatigue tests (1 % $\Delta\epsilon$), one heated by resistance furnace and the other by induction. The $N_{2\%}$ crack initiation endurance of the former was 400 cycles, whereas that in the latter was >1039 cycles. Significantly, the incidence of creep damage and oxidation was less evident in the induction-heated specimen, implying a lower specimen metal temperature than that of the resistance-furnace-heated specimen.

BASIS FOR PRECISION AND BIAS STATEMENTS

In order to formulate the precision and bias statements needed for the new creep-fatigue testing standard [15], statistical analyses of the ILS results were performed in accordance with the guidance given in Ref 37 (Table 3 and Figs. 7 to 9). These provided a measure of the intra- and interlaboratory variability (or repeatability and reproducibility, respectively) revealed by the interlaboratory comparison conducted in accordance with the test procedure prescribed in ASTM E2714-09.

TABLE 3

Statistical analysis of the reported endurance results for developing precision and bias statements of ASTM E2714-09 (quantities defined in Ref 37).

Strain Range, %	Hold Time, min	Average N_2 %, cycles	Repeatability Standard Deviation S_r	Reproducibility Standard Deviation S_R	Repeatability Limit r	Reproducibility Limit R
0.5	0	3957.5	488.9	1902.8	1368.9	5328.0
1.0	0	869.8	105.8	207.0	296.3	579.5
1.5	0	491.5	82.3	84.0	230.5	235.3
1.0	10	740.8	143.7	266.3	402.3	745.8
1.5	10	456.7	47.1	102.9	132.0	288.2
1.0	30	696.3	163.8	247.3	458.5	692.4

The repeatability (r) and reproducibility (R) limits, determined according to Ref 37, are listed in **Table 3**. Formally, a repeatability limit means that two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the r value for that material, r being the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment in the same laboratory. In contrast, a reproducibility limit means two test results shall be judged not equivalent if they differ by more than the R value for that material, R being the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories. Quantities for r and R normally have a 95 % probability of being correct [37], although the precision statistics observed in this ILS should not be treated as exact mathematical quantities that are applicable to all circumstances and uses. The repeatability and reproducibility limits are therefore only general guides and the associated probability of 95 % only a rough indicator of what can be expected.

Discussion

GENERAL

Following identification of the need for a creep-fatigue crack initiation testing standard in the mid-2000 s, the state of the art was reviewed and the knowledge gained used to form the basis of a new ASTM standard, ultimately issued in 2009 [15]. ASTM E2714-09 represented a significant development for those with an interest in acquiring creep-fatigue data in accordance with a peer-reviewed standard procedure. For the first issue of ASTM E2714-09 [15], there was no basis for the necessary precision and bias statement required by ASTM, and an interlaboratory comparison (ILS) was organized for this purpose. Consideration of the information gathered to underpin the content of the new testing standard, and the ILS, has formed the main part of this paper.

SCATTER IN CREEP-FATIGUE CRACK INITIATION ENDURANCE

There have been a number of previous high-temperature LCF ILS activities for various materials [38–41], and so it is possible to compare the repeatability and reproducibility characteristics with those of the interlaboratory comparison considered here. For cyclic softening steels, high-temperature LCF crack initiation endurance

repeatability is typically around 2 to 3, with the value for some nickel-based alloys being higher [39]. Reproducibility appears to be less dependent on material and tends to be typically 1.5 to 3 times the value for repeatability [39]. The zero hold time (LCF) results from the P91 ILS are consistent with this prior experience, when clear outliers are not considered (e.g., those due to nonstandard practices of the type shown in Fig. 10). There is no basis for comparison of the hold time crack initiation endurance. Nevertheless, it seems that for the 10-min hold time tests, repeatability and reproducibility levels are consistent with those for the zero hold time (LCF) tests, perhaps unsurprisingly, as damage formation in both is fatigue dominated. In a more limited interlaboratory comparison, the results of the creep-fatigue test ILS indicated that repeatability and reproducibility limits for the cyclic/hold tests with 30-min hold times were also, respectively, ~ 2 to ~ 3 for the P91 steel at 625°C (~ 5 in terms of the ASTM E691-09 95 % CI variability factor).

TESTING PRACTICES

Perhaps the most important observation to emerge from the results of the ILS is that the new standard, while representing a significant step forward, is still not strong enough to prevent users from adopting practices that can be responsible for unacceptable uncertainties. For example, the bending apparent in the specimens in Figs. 10(b) and 10(c) could have been avoided if the alignment had been checked prior to the start of the test campaign. Similarly, excessively long creep-fatigue crack initiation endurance in tests involving induction heating (e.g., Fig. 11) could have been avoided if single-bead thermocouples had not been used to control temperature within the induced magnetic field.

When implemented with care, induction heating can be just as reliable and effective as resistance furnace heating, at least while developing crack sizes are a small proportion of the specimen gauge section. There is a high risk of low specimen temperatures when single-bead thermocouples are fixed adjacent to the external surface for temperature control. In these circumstances, it is likely that crack initiation endurance associated with induction heating can be longer, simply because the actual specimen temperature is lower than indicated. For induction heating systems, the careful application of individual thermocouple wire spot welding or the use of ribbon-type thermocouples is recommended.

OTHER CONSIDERATIONS

As a consequence of the review of testing and data utilization organizations, the original version of the draft standard included guidelines for the generation and assessment of creep-fatigue deformation data and short creep-fatigue crack growth data. Although ultimately these guideline were not included in ASTM E2714-09, it is strongly recommended that in the future such guidance be included in a revision of this ASTM standard or form the basis of a new standard. As can be seen from Fig. 2, knowledge of the cyclic deformation response (as well as crack initiation endurance) is essential for the effective creep-fatigue lifetime assessment of high-temperature components [14], in particular for evaluations involving nonlinear finite element analyses.

The consideration of short creep-fatigue crack development can also be an important part of high-temperature component assessment [24] (e.g., crack growth

within a cyclic plastic zone generated by differential thermal strain transients). The relevance of this to creep-fatigue testing generally conducted using uniaxial parallel gauge section specimens is that short creep-fatigue crack growth tests are also typically conducted with the same type of test-piece geometry (albeit with a short crack starter notch in the middle of the gauge length) [48]. It therefore seemed logical to include procedures for this type of test within the same creep-fatigue testing standard. This continues to be a goal for the future.

Concluding Remarks

The background knowledge gathered to underpin a new creep-fatigue testing standard has been reviewed. A requirement of modern international testing standards is a precision and bias statement, and the results of a creep-fatigue test ILS of P91 steel at 625°C conducted to form the basis of this in ASTM E2714-09 are also described.

In addition to cyclic/hold creep-fatigue tests, zero hold time (LCF) tests were performed as part of the ILS, and it was therefore possible to compare repeatability and reproducibility levels from this evaluation of P91 steel with the results of LCF interlaboratory comparisons for other materials. The repeatability and reproducibility levels determined in the P91 ILS were of the order of 2 to 3, in line with the values previously obtained for other cyclic softening steels. The repeatability and reproducibility levels for 10-min and 30-min hold time tests of P91 steel at 625°C are similar to those for the zero hold time (LCF) tests. On the basis of a larger population ILS, the reproducibility level for 30-min hold time tests is likely to have been larger.

Evidence from the ILS indicated that there was some guidance in the new standard that could be further strengthened to minimize uncertainties associated with the outcome of tests conducted in accordance with the new procedure.

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