Minutes of US/UKAEA Specialists Meeting on High Cycle Fatigue Type 316
Stainless Steel Held January 10, 1980 at ORNL.

MASTER

Introduction, overview, and objectives of meeting was given by
C. R. Brinkman of ORNL. Agenda and list of those attending is shown
in Attachment I.

Carl Jaske of Battelle Columbus gave a presentation on the background,
current ASME Code position, and data needs of Type 316 SS high-cycle
fatigue. He gave a summary of his recent work including test techni-
ques and results as contained in a forthcoming report to his sponsor,
Rockwell International Corporation (~~Atomics International Division~~).

A copy of vu-graphs are shown in Attachment II.

Dave Raske of ANL gave a presentation on his test techniques and
results for the past 2 months. His test method is to use stroke
control with frequencies up to 20 Hz and adjust the stroke by
monitoring strain from an extensometer that is read periodically
when the cycling rate is slowed down to 2 Hz. If this method proves
successful, then a considerable speed-up would be realized in gener-
ating high-cycle fatigue data. A couple of scoping tests have been
conducted and the technique works well, but here is some indication
that frequency (strain rate) is an important factor. A copy of his
vu-graphs are shown in Attachment III.

Gary Korth of INEL described his test techniques and experimental
methods. His data will be generated using the same method as Carl
Jaske, namely start in strain control, cycle until stress is stabilized

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0.5 to 1.0×10^6 cycles) and then switch to load control and increase the frequency (5 - 15 Hz) and continue to failure or 10^8 cycles. First test at INEL was started incorrectly at 0.175% strain range instead of desired 0.35% and ran to $> 3.0 \times 10^5$ cycles. The strain range was then increased to 0.35% and it has currently exceeded 2×10^5 additional cycles and is still running at this writing. The incorrect low strain range hardening response was reported since it will be of value to designers performing analysis in this regime. Vu-graphs are shown in Attachment IV.

Derek Wood of UKAEA-RNL presented the UK point of view and recent results of their data. They have concluded that tests conducted with constant shoulder movement are subject to uncertainties due to the hardening characteristics of 316 SS. Therefore they have gone to a two-machine self-calibration technique wherein one machine contains a specimen with zero gage length to provide shoulder movement calibration factors for the other machine. Also they have determined that specimens should be annealed following the machining operation to eliminate any surface cold work effects. Experimental details and results are shown in his handout, Attachment V.

Len France of W-ARD described the involvement that they have in generating high-cycle fatigue of 316 SS. One air test was run with the following parameters:

593°C, Strain range=0.30%, failed after 1.1×10^7 cycles, run in strain control to 1×10^6 cycles and then switched to load control and 20 Hz to failure. A similar test in sodium at 0.28% strain range was cycled to approximately 10^6 cycles and then a machine malfunction aborted the test. No more air tests are planned as they were eliminated from their DRS. The four sodium tests still planned are shown in Attachment VI. The strain range for these tests will be selected from results as they

become available from the ANL and INEL test programs.

A table comparing the test specimens being used by all test labs was compiled and is shown in Attachment VII.

CONCLUSIONS AND MUTUAL AGREEMENTS

It was agreed that frequency effects (strain rate) and surface finish effects on high-cycle fatigue should be addressed as soon as possible especially since strain rate effects would affect the methods being used in generating base line data. The US will conduct strain rate tests and the UK will investigate surface finish effects. It was further agreed that the UK will emphasize irradiation effects and sodium effects while the US would assume a lesser role in these areas, ie. sodium effects limited to four tests identified by W-ARD (see Attachment VI) and irradiation tests planned at HEDL to be deferred to later date or perhaps eliminated.

The UK takes the stand that a firm establishment of 316 SS endurance limits is crucial to their designs and current PFR operations. D. Wood stated that an endurance limit of 0.40% strain range is equivalent to an allowable thermal striping ΔT of 63°C and an additional 5°C is gained (or lost) for every 0.10% that the endurance limit varies. Furthermore, the UK takes the position that only 1 cycle in every 100 is of sufficient amplitude to be damaging so their design limits will be based on endurance limits at 10^7 cycles. The US sees the determination of the endurance limit to be very important also since this information will be used to determine where Type 316 SS is acceptable and where Alloy 718 must be utilized. US designers desire endurance limits for Type 316 SS out to 10^8 cycles.

D. Wood read a list of concerns from the CEGB relating to high-cycle fatigue of 316 SS. Items on this list not specifically addressed elsewhere during the meeting were:

1. Random loading effects including creep-fatigue damage interaction with high-cycle fatigue.
2. Product form variability and other variables associated with fabrication (grain size, residual stress, etc.).

The meeting ended with a presentation by M. K. Booker of ORNL comparing the tensile and creep-rupture data of US and UK Type 316 stainless steels. The conclusion from this presentation was that there is no significant difference between the test data between the two countries.

OBJECTIVES AND AGENDA
U.S./UKAEA SPECIALISTS' MEETING ON
THE HIGH CYCLE FATIGUE LIFE OF TYPE 316 STAINLESS STEEL*

January 10, 1980
Oak Ridge National Laboratory
Room Z-62, Building 4500S

Objectives

1. Review recent progress in obtaining high cycle fatigue data including experimental test methods development.
2. Establish interim joint U.S./UKAEA cost effective test plans which will also maximize data output, advance the state-of-the-art in test methods and knowledge of material behavior, and minimize areas of overlap in data development.

Agenda

- I. Welcome, Introduction, Meeting Objectives, and Suggested Areas of Emphasis (U.S. point of view)
- II. High Cycle Fatigue
 - A. Experimental methods and recent results of BMI efforts (C. E. Jaske)
 - B. Experimental methods and recent results of ANL efforts (D. T. Raske)
 - C. Experimental methods and recent results of EG&G efforts (G. E. Korth)
 - D. Experimental methods, plans, point of view, and recent results of UKAEA efforts (D. S. Wood)
- III. Lunch
- IV. General Discussion
- V. Agreements and Commitments
 - A. Establish recommendations for joint cost effective programs
- VI. Comparison of U.S. vs U.K. Mechanical Properties (tensile and creep) of Multiple Heats of Type 316 Stainless Steel (M. K. Booker)

*G. E. Korth will act as secretary for this meeting.

HIGH CYCLE FATIGUE CHARACTERIZATION OF TYPE 316 STAINLESS STEEL BASE AND WELD METAL

Topic	U.S. Efforts		UKAEA Efforts	
	Planned Activity*	Laboratory Involved	Planned Activity#	Laboratory Involved
1. BASE LINE FATIGUE DATA DEVELOPMENT ¹	X	ANL, EGG ²	X	RNL ³
a. METHODS DEVELOPMENT	X	ANL	X	RNL
b. STRAIN RATE EFFECTS	X	ANL	X	RNL
c. STRAIN TO LOAD CONTROL STUDIES	x	EGG		
2. SURFACE FINISH STUDIES				
a. AIR ENVIRONMENT	X	ANL	X	RNL
b. SODIUM ENVIRONMENT			X	RNL ⁵
3. PLASTICITY AND CREEP INTERACTION STUDIES				
a. STEP STRAINRANGE	X	ANL	X	RNL
b. CREEP-FATIGUE	X			
c. LONG TERM	X			
4. IRRADIATION EFFECTS STUDIES			X	RNL-PFR
5. THERMAL AGING STUDIES	X	EGG	X	RNL
6. MEAN STRESS EFFECTS INCLUDING PRIOR CREEP	X		X	RNL
7. CRACK PROPAGATION		HEDL ⁹		
8. HEAT-TO-HEAT VARIATIONS	X	ANL, EGG	X	RNL ⁴
9. BIAXIAL ISOTHERMAL			X	Cambridge
10. COLD WORK (20%)			X	RNL
11. OFF NORMAL SODIUM CHEMISTRY				
a. CARBON			X	RNL ⁶
b. OXYGEN			X	RNL ⁶
12. THERMAL STRIPING TESTS	X	W-ARD ⁸	X	RNL-SNL ⁷

*Planned activity for U.S. efforts refers to current (1/1/80) plans for two laboratories to be completed by 4/82.

#Estimated completion of UKAEA program about 1/82.

¹Tests to be conducted at 482 and 593°C

²Includes two weld metal tests at 593°C

³Tests to be conducted at 550°C, cast 58, base and weld metal

⁴Cast 83

⁵Dynamic sodium cycle life beyond 10⁵ cycles

⁶Specimens pre-exposed to off normal sodium environments and subsequently tested in air

⁷Non-isothermal tests which also examine the influence of residual stresses

⁸Cylinder test (4" dia 3/8" wall) planned for FY 1980, 304SS, 316SS, Alloy 718, ΔT's up to 800°F

⁹Presently considering

COMPARISON BETWEEN US AND UK STRAIN CONTROLLED HIGH CYCLE

FATIGUE PROGRAMMES

Item	US Programme		UK Programme	
	Details	Completion Date	Details	Completion Date
General: Temp ($^{\circ}\text{C}$) Endurance Test method Frequency	482, 593 10 ⁸ Strain contr. then load or stroke control. 1Hz followed by 20Hz		550 5 x 10 ⁶ /10 ⁷ Strain control 1Hz, possibly 5Hz.	
1. Baseline data	1 cast	Oct '80	1 cast	June '80
2. Frequency effects	1-20Hz	Mar '81	1-5Hz	Mar '80
3. Cast to cast effects	2 casts 593 $^{\circ}\text{C}$ only	April '82	1 Type 316, 1 Type 321 cast	June '81
4. Weld metal	1 batch 593 $^{\circ}\text{C}$ only	Oct '81	1 batch	Sept '80
5. Surface finish	Coarse finish (125 μin)	June '81	Coarse finish, also polished	Jan '81
6. Prior plastic strain	593 $^{\circ}\text{C}$ only: 1000 cycles at 0.5% strain on standard and precarbured samples.	Oct '81	100 interposed cycles at 1.0% strain.	Mar '81
7. Thermal ageing	593 $^{\circ}\text{C}$ only: material aged 10,000h in sodium at 593 $^{\circ}\text{C}$.	April '82	a) Aged 20,000h at 600 $^{\circ}\text{C}$ in air. b) Aged 10,000h at 600 $^{\circ}\text{C}$ in sodium.	Oct '81 1982
8. Prior creep	Pre-creep/fatigue 1000 cycles with 0.1h hold.	(1)	Pre-creep up to 15,000h at 550 $^{\circ}\text{C}$.	Dec '81
9. Surface carburisation	Specimens with both smooth and coarse finishes.		Only smooth finished specimens.	Mar '81
10. Long term tests	Up to 2yrs with hold periods and overstrain.		-	
11. Irradiation	Includes study of welds, ageing and carburisation.		Limited programme.	Aug '81
12. Mean stress	593 $^{\circ}\text{C}$ only on annealed and carburised material.		(2)	
13. Cold work	-		20% cold worked	Nov '80
14. High purity sodium	WARD tests?		Basic tests	June '80
15. Crack propagation	Low ΔK tests		(3)	

Footnotes: (1) US work relating to items 8 onwards not committed.

(2) To be studied in temperature cycling work.

(3) To be studied in temperature cycling work; this item also included in main programme (see ND-R-107(R)).

Attendance list for US/UKAEA Specialists Meeting held January 10,
1980 at ORNL.

<u>Name</u>	<u>Company</u>
C. R. Brinkman	ORNL
J. J. Blass	ORNL
J. R. DiStefano	ORNL
L. L. France	W-ARD
E. E. Hoffman	USDOE/ORO
R. L. Huddleston	ORNL
C. E. Jaske	Battelle-Columbus
G. E. Korth	EG&G Idaho (INEL)
P. Patriarca	ORNL
D. T. Raske	ANL
R. R. Seeley	B&W
D. S. Wood	UKAEA (Risley)

BATTELLE COLUMBUS
PRESENTATION

OBJECTIVE: TO DEVELOP
HIGH-CYCLE FATIGUE DATA
FOR TYPE 316 STEEL
AT RT ~~to~~ 593 °C

BACKGROUND

- FOR MANY YEARS, ASME CODE DESIGN FATIGUE CURVES WERE LIMITED TO 10 TO 10^6 CYCLES
- DESIGN CURVES ARE NEEDED FOR $> 10^6$ CYCLES
- JASKE/O'DONNELL HAVE RECOMMENDED CURVES FOR AUSTENITIC STEELS AT 10 TO 10^8 CYCLES
- NO SUCH CURVES FOR OTHER TYPES OF STEELS
- LACK OF APPROPRIATE DATA HAS LEAD TO CONTROVERSY OVER DEFINITION OF CURVES AT $> 10^6$ CYCLES

DATA NEEDS

- LITTLE DATA WERE AVAILABLE AT $> 10^5$ CYCLES AND $\leq 427^\circ\text{C}$
- NO DATA WERE AVAILABLE AT $> 10^5$ CYCLES AND $> 427^\circ\text{C}$

SCOPE

- UNNOTCHED SPECIMENS
- UNIAXIAL LOADING
- FAILURE $\equiv$ COMPLETE FRACTURE, MAINLY
CRACK INITIATION IN SMALL SPECIMENS
AT LONG LIVES

Note: Dimensions are in mm

FIGURE 2. SPECIMEN CONFIGURATION

ACHIEVEMENT OF STRAIN CONTROL

- **USE STRAIN CONTROL THROUGHOUT TEST**
- **START IN STRAIN CONTROL, SWITCH TO LOAD CONTROL FOR REST OF TEST**
- **USE LOAD CONTROL AND MONITOR STRAIN RESPONSE TO ASSURE MINIMAL TRANSIENT EFFECTS**

Initially Elastic Stably Inelastic

875
II

Initially Inelastic

Stably Inelastic

or

Stably Elastic

Initially Inelastic

Stably Inelastic

or

Stably Elastic

Initially Inelastic

Stably Inelastic

or

Stably Elastic

Initially Inelastic

Stably Inelastic

or

Stably Elastic

DATA COMPILED WERE

E-CONTROL	224 pts.
LOAD-CONTROL	22 pts.

- 43 OF THESE WERE AT $>10^5$ cycles

E-control	24 pts
load-control	19 pts.

- 22 of 24 from BATTELLE/AI.

FIGURE 5. FATIGUE DATA FOR TYPE 316 STAINLESS STEEL AT 21 C to 650 C

FIGURE 6. FATIGUE OF TYPE 316 STAINLESS STEEL AT 20 TO 427 C

FIGURE 7. FATIGUE OF TYPE 316 STAINLESS STEEL AT 456 TO 482 C

FIGURE 9. FATIGUE OF TYPE 316 STAINLESS STEEL AT 593 TO 600 C

FIGURE 10. FATIGUE OF TYPE 316 STAINLESS STEEL AT 625 TO 650 C

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TABLE 2. SUMMARY OF FATIGUE DATA ANALYSIS
FOR TYPE 316 STAINLESS STEEL IN AIR
(STRAIN CONTROLLED AT $\geq 4 \times 10^{-3}$ SEC⁻¹)

Temperature, C	Number of Data Points	A(b)	a(b)	$\Delta\epsilon_L$ (b)
20 to 25	25(a)	1.450	0.599	0.00277
427	17(c)	1.171	0.599	0.00351
456 to 482	14	0.499	0.523	$\approx$ 0.00344(d)
538 to 566	36	0.522	0.575	0.00338
593 to 600	<u>50</u>	0.428	0.532	0.00290
625 to 650	82	0.247	0.470	$\approx$ 0.00250(e)

(a) There were also eighteen data points plotted but not included in curve fitting analysis for load controlled conditions (from Conn and Thiruvengadam).

(b) Based upon $\Delta\epsilon = A N_f^{-a} + \Delta\epsilon_L$, where $\Delta\epsilon$ = total strain range, N_f = number of cycles to failure, and A, a, and $\Delta\epsilon_L$ are constants determined by curve fitting.

(c) There were also four data points for load controlled cycling that were not used in curve fitting (from present study).

(d) Estimated by interpolation of data at other temperatures.

(e) Estimated by extrapolation of data from other temperatures.

FIGURE 11. FATIGUE CURVES FOR TYPE 316 STAINLESS STEEL

TABLE 2. SUMMARY OF FATIGUE DATA ANALYSIS
FOR TYPE 316 STAINLESS STEEL IN AIR
(STRAIN CONTROLLED AT $\geq 4 \times 10^{-3} \text{ SEC}^{-1}$)

Temperature, C	Number of Data Points	A(b)	a(b)	$\Delta\epsilon_L$ (b)
20 to 25	25(a)	1.450	0.599	0.00277
427	17(c)	1.171	0.599	0.00351
456 to 482	14	0.499	0.523	≈ 0.00344 (d)
538 to 566	36	0.522	0.575	0.00338
593 to 600	50	0.428	0.532	0.00290
625 to 650	82	0.247	0.470	≈ 0.00250 (e)

(a) There were also eighteen data points plotted but not included in curve fitting analysis for load controlled conditions (from Conn and Thiruvengadam).

(b) Based upon $\Delta\epsilon = A N_f^{-a} + \Delta\epsilon_L$, where $\Delta\epsilon$ = total strain range, N_f = number of cycles to failure, and A, a, and $\Delta\epsilon_L$ are constants determined by curve fitting.

(c) There were also four data points for load controlled cycling that were not used in curve fitting (from present study).

(d) Estimated by interpolation of data at other temperatures.

(e) Estimated by extrapolation of data from other temperatures.

TABLE 3. COMPARISON OF FATIGUE LIMIT AT $\sim 10^8$ CYCLES TO FAILURE VALUES FROM STRAIN-CONTROLLED TESTS WITH THOSE FROM LOAD-CONTROLLED TESTS^(a) OF TYPE 316 STAINLESS STEEL

Temperature C	Value of $\Delta\epsilon$ at $\sim 10^8$ Cycles		
	Jaske/O'Donnell	Present Study	Yoshida et al ^(a)
20 to 25	0.00240	0.00279	0.00242
400 to 427	0.00240	0.00353	0.00252
456 to 500	—	0.00347	0.00260
538 to 566	—	0.00339	—
593 to 600	—	0.00292	0.00249

^(a)Rotating bending fatigue tests. Strain ranges were calculated assuming completely elastic stable stress-strain response."

Taking this factor into account explains the difference between 10^8 cycles fatigue limit strain ranges of 0.24 and 0.28 percent indicated for 20 to 25 C (68 to 77 F) in Table 3. However, even when this factor is considered, the value for strain controlled conditions is about 25 percent greater than that for load-controlled conditions at 400 to 427 C (752 to 800 F). Moreover, at temperatures above 427 C (800 F), the inelastic strain range approaches zero at more than 10^6 cycles without failure, and the strain controlled limit levels also are about 25 percent greater than the load controlled ones. These differences in fatigue resistance related to test control mode are believed to be related to cyclic stress-strain response as discussed in the next section.

CYCLIC STRESS-STRAIN BEHAVIOR

The cyclic hardening (or softening) response of this alloy is illustrated in Figures 12 through 14. Except for specimen A1 (Figure 12(a)) and specimens A7 and A9 (Figure 12(b)), these results are for strain controlled tests at total strain

LOAD vs. STRAIN

- ACCOUNTING FOR INELASTIC STRAIN EXPLAINS DIFFERENCE AT $\sim$ RT
- AT $\geq 427^{\circ}\text{C}$, STRAIN GIVES $\Delta\epsilon_p \sim 25\%$ GREATER THAN DOES LOAD

(a) at 21 C

(b) at 427 C

(c) at 538 C

FIGURE 12. CYCLIC STRESS RESPONSE OF TYPE 316 STAINLESS STEEL UNDER FULLY REVERSED STRAIN CYCLING IN AIR

FIGURE 13. CYCLIC STRESS RESPONSE OF TYPE 316 STAINLESS STEEL UNDER FULLY REVERSED STRAIN CYCLING IN AIR AT 538 C

FIGURE 14. STRESS RESPONSE OF TYPE 316 STAINLESS STEEL UNDER FULLY REVERSED STRAIN CYCLING AT 593 C

STRESS AMPLITUDE VS. CYCLES
TYPE 316 STEEL AT 1100 F

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FIGURE 15. CYCLIC STRAIN RESPONSE OF TYPE 316 STAINLESS STEEL UNDER LOAD CYCLING AT ABOUT 0.5 TO 1.0 Hz AND IN AIR AT 427 C (800 F)

PRIMARY NEEDS

- REPLICATION OF EXISTING DATA
- HEAT-TO-HEAT VARIATION
- TENSILE MEAN STRESS
- PERIODIC OVERLOADS } EXPLORATORY
- EFFECT OF $\dot{\epsilon}$ (OR f) ON CYCLIC HARDENING
- SPECIMEN SURFACE FINISH
- FCP AT LOW ΔK LEVELS
- LOAD CONTROL (ϵ -MEASURED) DATA AT T 's OTHER THAN 427°C
- DEVELOPMENT OF NON-CONTACT EXTENSOMETRY

NOTES

1. DIMENSIONS AND SPECIFICATIONS
TYPICAL BOTH ENDS.
2. PROVIDE CENTERS IN ENDS
3. ALL SURFACES TO BE FREE
OFF BURRS
4. MACHINE .750 CENTER GAGE
SECTION AND 1.500 TRANSITION RADI
BY GRINDING TO $\frac{1}{16}$ FINISH. THE
FINAL .005 OF METAL TO BE REMOVED
AT A RATE OF NOT MORE THAN .002
PER PASS EXCEPT THE LAST PASS
WHICH SHALL NOT EXCEED .0005 IN.
5. DIAMETERS AT ENDS OF .750 GAGE
SECTION TO BE WITHIN .0005 OF
EACH OTHER.
6. ABRUPT CHANGES IN DIAMETER
OR UNDERCUTTING AT ENDS OF
.750 GAGE SECTION NOT ALLOWED

REPRODUCTION PRINT
NOV 20 1979

MICRO-FILMED DATE

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III

SCHEMATIC OF TEST SET-UP

III 6

AXIAL STRAIN DISTRIBUTION ON HIGH-CYCLE
FATIGUE SPECIMEN (File no. MY-B-4197)

EFFECT OF TAPER IN SECTION

STR. GAGE SECTION

$$\Delta \epsilon_{.25} \sim 0.99 \Delta \epsilon_{ext}$$

$$\Delta \epsilon_c \sim 1.01 \Delta \epsilon_{ext}$$

0.001" TAPER

$$\Delta \epsilon_{.25} \sim \Delta \epsilon_c \sim \Delta \epsilon_{ext}$$

Specimen PU-11

IIIc

TEMPERATURE PROFILE: HIGH-CYCLE FATIGUE SPECIMEN

COIL: $\frac{3}{4}$ in ID x $\frac{1}{8}$ in tubing - 5 turns top & bottom
with 1 center coil

III d.

K-E SEMI-LOGARITHMIC - 3 CYCLES X 70 DIVISIONS
REUFFEL & ESSER CO. MADE IN U.S.A.

46 5490

HIGH-CYCLE FATIGUE SPECIMEN

PU-11

EFFECT OF FREQUENCY ON
TEMPERATURE AT CENTER OF
GAGE SECTION

IIIe

PLOT USED FOR GUIDANCE FOR SELECTING STRAIN RANGE

K-E SEMI-LOGARITHMIC - 3 CYCLES X 70 DIVISIONS
KALWITZ & ESSER CO. MADE IN U.S.A.

46 5490

III f

K-E SEMI-LOGARITHMIC 7 CYCLES X 60 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 6460

IIIg

1.3.8

K-E SEMI-LOGARITHMIC 7 CYCLES X 60 DIVISIONS
KELUFFEL & ESSER CO. MADE IN U.S.A.

46 6460

MODEL

DATE

III 4

1-3-30 PU-12(263) $N_f - 787000$
 $t_f - 257h$

Fig. 2.5

EG&G IDAHO (INEL)

10 JAN 1980

TEST PROCEDURE FOR 316 SS HCF1- SPECIMEN PREPARATION

- FROM ORNL REFERENCE HEAT (HT. 8092297, 1-IN PLATE)
- LOW STRESS GRIND IN GAGE SECTION
- ANNEAL 1065°C - 0.5 HR AFTER FINAL MACHINE
- CYLINDRICAL TEST SECTION (0.25-IN DIA x 0.75-IN LG)
- SLIGHT TAPER IN GAGE SECTION (.0005 - .0010-IN)

2- SPECIMEN HEATING

- TEST TEMPERATURE - 593°C
- HEATED BY INDUCTION COIL
- MAXIMUM TEMP GRADIENT - $\pm 3^{\circ}\text{C}$
- TEMP MONITOR IN MID GAGE SECTION

3- EXTENSOMETRY

- DIRECT READING ON MIDDLE 0.50-IN OF GAGE
- GOOD CONTROL UP TO 1 Hz

4- PROCEDURE

- START TEST IN STRAIN CONTROL ($\dot{\epsilon} = 4 \times 10^{-3} \text{ s}^{-1}$)
- CONTINUE STRAIN CONTROL TO STRESS STABILIZATION
(.3 - 1.0×10^6 CYCLES)
- SWITCH TO LOAD CONTROL (MONITOR DISPLACEMENT)

HIGH CYCLE FATIGUE TEST
SPECIMENS FOR 316 SS

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LOCATION OF T/C's
DURING TEMP
CALIBRATION

SLING T/C
DETAIL

ITC

STRESS RESPONSE OF TYPE 316 STAINLESS STEEL UNDER FULLY REVERSED STRAIN CYCLING AT 593 C

FATIGUE OF TYPE 316 STAINLESS STEEL AT 593 TO 600 C

ATTACHMENT IV

USDOE/UKAEA MEETING ON HIGH CYCLE FATIGUE,
OAK RIDGE NATIONAL LABORATORY,
TENNESSEE USA, 10 JANUARY 1980

POSITION OF UKAEA-RNL STRAIN CONTROLLED HIGH
CYCLE FATIGUE TESTS ON TYPE 316 STEEL AT JANUARY 1980

BY

D S WOOD
(Risley Nuclear Laboratories)

120

Specimen Details

The specimen employed has a diameter of 0.29in. (7.39mm) and a parallel length of 0.50in. (12.7mm). It is finally fine turned to give a surface finish of better than $20\mu\text{in}$ ($0.5\mu\text{m}$). Although initial tests were performed on specimens in the as-machined condition, where possible the practice now is to solution treat for $\frac{1}{2}$ h at 1050°C after machining. See Fig 1.

Extensometry

Axial control was employed from extensometers attached to the shoulder of the specimen.

Calibration Methods

a) Single specimen calibration

The relationship between shoulder movement and gauge length strain under nominally stabilised conditions was derived by attaching a second set of extensometers to the gauge length and correlating the movement of the two sets of extensometers. Calibration previously obtained on material 58 at 625°C and a strain rate of 4%/min were utilised. Tests were subsequently performed using a constant shoulder movement.

b) Preliminary dual specimen calibration

In performing the high endurance tests it became clear that the material did not readily stabilise and that the calibrations previously employed could be in error. To check out the true strain dual machine specimen calibrations were performed at 550°C and 1Hz using a standard specimen and a dummy specimen with zero gauge length. In these tests the shoulder movement was kept constant and the true total strain was determined periodically during the test. Results obtained for nominal strains of 0.6 and 0.4% are shown in Figs 2 and 3 which indicate the true strains to be about 0.66 and 0.32% respectively.

c) Constant strain dual specimen calibration

Because of the realisation that a constant shoulder movement did not result in a constant strain range it was decided to produce calibration curves in which the shoulder movement was allowed to vary to produce a constant strain range throughout the test. Calibration curves using the two machine approach described in b) but varying the shoulder movement were obtained on material 58 at 550°C and 1Hz for total strain ranges of 0.4 and 0.37%. The calibration curves obtained are shown in Figs 4 a) and b); the curve for 0.385% strain range was obtained by interpolation. In single specimen tests subsequently performed the shoulder movement was periodically adjusted manually in accordance with the calibration curves to maintain a constant strain range throughout the test.

Results

a) Constant shoulder movement tests

The results obtained from constant shoulder movement tests are given in Table 1. Major points to note are as follows.

i) Surface cold work. The first four specimens listed in Table 1 although tested at about the same strain range gave very variable endurances. Hardness checks subsequently performed (Fig 5) show a considerable gradient from the surface inwards; the implication is that before testing a cold worked surface layer of varying degree had been introduced during machining.

ii) Endurance at $\sim 0.32\%$ strain range. Neither of the specimens failed after $\sim 10^7$ cycles. The elastically calculated strain is in excess of 0.32% , and it is therefore concluded that there is no plastic strain in the cycle, and it is likely that a much higher endurance could have been attained.

iii) Pre-aged and pre-creep specimens. The strain ranges quoted must be treated with caution since no calibrations are available for material in either of these conditions.

b) Constant gauge length movement tests

The results obtained are given in Table 2 and Fig 6; constant shoulder movement test results based on the approximate true strain are included in Fig 6. Sufficient tests have now been performed to clearly establish the behaviour of material 58 at 550°C and 1Hz from 10^5 to $\sim 5 \times 10^6$ cycles. It is clear that over this region the curve is not horizontal but has a very slight downward slope. Under the conditions examined it appears that at 10^7 cycles the strain range for failure is in the region $0.35/0.37\%$. At the longer endurances the calculated plastic strain is about 0.05% at $N_f/2$ but slightly less later in the life. Although the stress-strain loops were examined it was not possible at these high endurances to establish whether or not they had a finite width.

The variation in stress with number of cycles of the longest term test is shown in Fig 7; note that the stress range continues to increase throughout the test and at the end of the test it is more than a factor of two greater than at the beginning.

c) Higher frequency trials

In order to speed up testing some consideration has been given to increasing the cyclic frequency, and limited trials have been performed at 10Hz . Some difficulty was experienced in following the triangular waveshape at this frequency, but with a sinusoidal waveshape the machine and extensometry produced an excellent response. The influence of waveshape was checked out at 1Hz and was found to have no significant effect on the endurance (Table 2). It was found however that the stress-strain loops obtained

IVc

at 550°C and frequencies of 0.1, 1.0 and 10Hz had different shapes implying that there may be a difference in material response at these various frequencies. A temperature measuring test was subsequently performed at RT after the material had stabilised. An increase in temperature of 0, 8 and 40°C was measured at frequencies of 0.1, 1.0 and 10Hz respectively. These findings have thrown doubt on the validity of increasing the frequency as a method of speeding up testing.

TABLE 1: CONSTANT SHOULDER MOVEMENT TEST RESULTS

Material: Type 316 Steel Cast 58 Temperature 550°C, Frequency 1Hz, Triangular Waveshape

Spec No	Total Strain Range %		Plastic Strain Range at Nf/2		Stress Range N/mm ²			Cycles to Failure
	Nominal(1)	True(2)	Total-elastic(4)	Nominal(1)	1st Cycle	Nf/2	Max	
EM37(3)	0.60	0.66	0.33	0.45	318	528	535	1.3x10 ⁴
EM29(3)	0.60	0.66	0.35	0.23	339	495	-	7.5x10 ³
FC5(3)	0.57	0.63	0.21	0.13	-	659	676	6.2x10 ⁵
FC3(3)	0.57	0.63	0.24	0.13	361	620	635	3.7x10 ⁵
EM30(3)	0.50	~ 0.56	~ 0.23	0.15	433	529	531	1.9x10 ⁴
EM31(3)	0.40	~ 0.32	~ 0.00	-	-	-	523	>5.7x10 ⁶
FC2	0.57	0.63	0.32	-	290	487	495	1.4x10 ⁴
FC7	0.57	0.63	0.33	-	275	469	473	1.1x10 ⁴
FJ8	0.54	0.60	0.29	0.29	288	490	496	1.5x10 ⁴
FJ10(5)	0.60	0.66	0.35	0.39	278	478	497	1.6x10 ⁴
FC4(6)	0.40	~ 0.32	~ 0.00	-	-	-	558	>1.8x10 ⁷
FW2(7)	~ 0.45	~ 0.45	~ 0.16	0.09	385	457	466	1.5x10 ⁶
JX6(8)	~ 0.40	~ 0.40	~ 0.15	0.12	401	390	405	7.6x10 ⁴

- (1) From single specimen calibration
- (2) From preliminary dual specimen calibration (approx)
- (3) Not re-solution treated after machining
- (4) Elastic modulus used 158,340 N/mm(2); related to true total strain range
- (5) Calibration test
- (6) Specimen changed to load control at 10Hz after 4x10⁶ cycles
- (7) Specimen pre-aged 3000h at 625°C
- (8) Pre-crept 15,000h at 625°C; stress 131 N/mm²

PZ

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TABLE 2: CONSTANT GAUGE LENGTH MOVEMENT TEST RESULTS

Material: Type 316 steel, cast 58. Temperature 550°C. Frequency 1Hz, Triangular waveshape. Solution treated after machining.

Spec No	Total Strain Range %	Plastic Strain Range at Nf/2		Stress Range N/mm ²			Cycles to Failure	Test Method
		Total-elastic(3)	Nominal	1st Cycle	Nf/2	Max		
FJ5	0.4	0.09	0.13	268	493	532	$>2 \times 10^5$	Dual ca
FJ2	0.4	0.13	-	260	420	-	3×10^4	Dual ca
EM26	0.4	0.07	0.04	256	526	564	3.8×10^5	Dual ca
FC32	0.4	0.05	-	258	550	560	6.2×10^5	Manual
FX61	0.4	0.08	-	257	501	537	2.5×10^5	Manual
FX53(1)	0.4	0.06	-	258	530	564	4.9×10^5	Manual
EK13(2)	0.4	0.04	-	242	562	577	9×10^5	Dual ca
FC13	0.385	0.05	-	-	550	576	9.4×10^5	Manual
FC9	0.385	0.06	0.04	255	541	568	7.2×10^5	Manual
FC37	0.385	0.05	0.03	251	550	578	1.5×10^6	Manual
FC35	0.37	0.05	-	265	556	565	6.6×10^6	Dual ca

(1) Sinusoidal wave form

(2) Test in static sodium; specimen not heat treated after machining.

(3) Elastic modulus used 158,340 N/mm².

Technical drawing of a mechanical part, likely a shaft or coupling, showing dimensions and tolerances. The drawing includes a central section with a fillet radius of 12.5 RAD. and a diameter of 7.39 ± .01 DIA. The left end features a 31 DIA. section. The right end features a 45° - 1/2° chamfer. The overall length is 127.7. The drawing also shows a 12.67 and 12.73 dimension for the central section.

FIG. 1 DETAILS OF TEST SPECIMEN

TRUE TOTAL STRAIN RANGE %

0.9
0.8
0.7
0.6
0.5

5×10^3

10^4

1.5×10^4

CYCLE NUMBER

TYPE 316 STEEL
MATERIAL SB
TEMPERATURE 550°C
FREQUENCY 1 Hz
SPECIMEN FJ 10

FIG 2 : CONSTANT SHOULDER MOVEMENT TEST - VARIATION IN TRUE STRAIN RANGE WITH CYCLES FOR 0.60% NOMINAL STRAIN RANGE.

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FIG 3: CONSTANT SHOULDER MOVEMENT TEST: VARIATION IN TRUE STRAIN RANGE WITH CYCLES FOR 0.4% NOMINAL STRAIN RANGE

FIG 4 : TRUE STRAIN RANGE CALIBRATION CURVES (a) FOR START OF TEST

FIG 4 - TRUE STRAIN RANGE CALIBRATION CURVES (b) TOWARDS END OF TEST

PT

Fig 5: Hardness vs Distance from edge

% Total Strain Range 0.6

Nf	FC5	618000 cycles
	FC3	369300 cycles
	EM37	12700 cycles
	EM29	7530 cycles
	D7.3*	36,000 cycles

* Tested in static Na

11

Standard
C 101 001 001 001

Log 2 Cycle x 4 Cycles

FIG 6 : JANUARY 1980 : POSITION OF UKAEA-
RNL STRAIN CONTROLLED HIGH CYCLE
FATIGUE TESTS : TYPE 316 STEEL

TEMPERATURE - 550°C
FREQUENCY - 1 Hz
ENVIRONMENT - AIR (UNLESS
OTHERWISE STATED).
MATERIAL - CAST 58 (SOLUTION TREATED AFTER
MACHINING)

- CONSTANT SHOULDER MOVEMENT
- x CONSTANT GAUGE LENGTH MOVEMENT
- SPECIMEN UNFAILED
- I UNCERTAINTY BAND ON STRAIN RANGE
- 1 PREHEAT 1500h at 625°C
- 2 PREHEAT 3000h at 625°C
- 3. LOAD CONTROL AT 10Hz AFTER 4x10⁶ CYCLES
- 4 SPECIMEN TESTED IN STATIC NA (100-Hz AFTER MACHINING)

TOTAL STRAIN RANGE (%)

0.7
0.6
0.5
0.4
0.3

10⁴

10⁵

10⁶

10⁷

CYCLES TO FAILURE

11

FIG 7. VARIATION IN STRESS RANGE DURING TEST AT 0.37% STRAIN RANGE.

Document No

Im

TABLE 2

Test Plan for Fatigue Testing S.A. 316 SS Plate Material in Sodium

(a) Test Number at Indicated Test Temp., °F			(b) Sodium Exposure Time, Hours	(c) Strain Range, %	Strain Rate, Sec. ⁻¹
1100	1000	1300			
①	②		0	2	4×10^{-3}
⑨	⑩		2,000	2	4×10^{-3}
⑳	㉔		5,000	2	4×10^{-3}
35	36		10,000	2	4×10^{-3}
③	4		0	1	4×10^{-3}
⑪	13		2,000	1	4×10^{-3}
㉓	25		5,000	1	4×10^{-3}
37	39		10,000	1	4×10^{-3}
⑤	6		0	.5-.28	(d)
⑭	16		2,000	.5-.28	(d)
㉒	28		5,000	.5-.28	(d)
④①	42		10,000	.5-.28	(d)
⑦	8		0	.7	4×10^{-3}
⑰	19		2,000	.7	4×10^{-3}
29	31	㉓	5,000	.7	4×10^{-3}
43	45	46	10,000	.7	4×10^{-3}
33			5,000	1	4×10^{-4}
34			5,000	1	4×10^{-2}

HIGH
CYCLE
FATIGUE

- (a) 1. Test No. 23 to be duplicated with test in sodium for welded specimens and specimens with 0.15" and 0.1" gage diameters (9 additional samples).
2. Each Test No. represents three tests at the same conditions (triplicate tests) except 23 and 26 which include 1 specimen vacuum aged and testing in sodium.
3. For test numbers 5, 14, 26 and 40 one test each to be conducted for high cycle strain controlled fatigue to provide fatigue failure data in the range of 10^6 to 10^8 cycles. First test, Number 5, will be conducted at a strain range of .36% to failure or 10^8 cycles, whichever occurs first. For next test, Number 40, the strain range will be adjusted as necessary so as to obtain a failure data in the range of 10^7 to 10^8 cycles.

TEST SPECIMEN COMPARISONS FOR 316 SS HCF - MOST CURRENT PRACTICE

<u>TEST LAB</u>	<u>HEAT NO.</u>	<u>PRODUCT FORM</u>	<u>GAGE GEOMETRY</u>	<u>SURFACE/VOL. RATIO</u>	<u>TAPER IN GAGE</u>	<u>SURFACE FINISH, μin</u>	<u>FABRICATION SEQUENCE</u>	<u>INVESTIGATOR</u>
BCL	REF. HT. 8092297	1-in Plate	0.25-in DIA x 0.06-in Long	16.00	None	10-12	Anneal ^(a) Machine Polish	C. E. Jaske
ANL	REF. HT. 8092297	5/8-in Plate	0.20-in DIA x 0.75-in Long	20.00	1 mil	<16	Machine Anneal Polish	D. T. Raske
INEL	REF. HT. 8092297	1-in Plate	0.25-in DIA x 0.75-in Long	16.00	1 mil	8-11	Machine Polish Anneal	G. E. Korth
UKAEA	Cast 58	1 3/8-in Round Bar	0.29-in DIA x 0.50-in Long	13.79	None	<20	Machine Anneal	D. S. Wood
W-ARD	REF. HT. 8092297	1-in Plate	0.25-in DIA x .50-in Long	16.00	None	16	Machine in Mill Anneal Condition	P. N. Flagella

(a) Sequence as used in test program in Battle Columbus report for AI. Any future testing will employ the anneal as the last step.