A New Experimental Procedure for Investigating the Effect of Long Hold Times on HTLCF Life

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Abstract

A new experimental procedure is presented for investigating the effect of long hold time on HTLCF life, consisting in repeated tensile creep loading on axisymmetric sharply notched specimens. This testing methodology seems reliable enough to get much longer rupture times than classical LCF strain controlled testing machines. The general rupture behaviour of notched specimens is analysed through experimental results showing three domains : for short hold times, rupture is fatigue-dominated; conversely for large hold times, rupture life is creep-dominated; there exists a transitional regime where creep fatigue interaction occurs corresponding to limited creep ratchetting and to confined viscoplastic cyclic strains at the notch root. Lowering nominal stress levels and temperature would allow to reach sollicitations more representative of fast breeder reactors working conditions.

1. Introduction

In the literature devoted to high temperature low cycle fatigue (HTLCF) behaviour of stainless steels components in fast breeder reactors, there is much concern about the effect of long hold times at maximum strain on the number of cycles to failure as shown by recent works of HALES |1|, WAREING |2|, WOOD WYNN et al. |3|, MOTTOT, PETREQUIN et al. |4|. LEVAILLANT, PINEAU |5|. Most of available creep fatigue data on smooth specimens deal with tests conditions corresponding to rather large plastic strain ranges ($\Delta\varepsilon p \simeq 0.5, 1\%$) and short hold times (a few hours) : longest tests durations are of about one year : This is essentially due to the lack of reliability of classical experimental procedures using servohydraulic testing machines with closed loop strain regulation. However designers need safe extrapolations for low plastic strain ranges ($\Delta\varepsilon p \simeq 0,2\%$) and long hold times ($\simeq$ 100 hours), i.e. extrapolations of more than one order of magnitude on the total time to failure. In spite of the efforts for modelling creep fatigue interaction for smooth specimens, no method is actually efficient to lead to a reliable prediction as illustrated in the recent review by CAILLETAUD, NOUAILHAS et al. |6|.

In this paper a new experimental procedure is presented which enables to perform easily long duration tests because of the simplicity of the testing device. The basic idea is to use the creep test technique consisting of loading the specimens with weights and to reduce periodically the load with a mechanical device. Creep ratchetting that occurs on plain specimens can be limited in the case of notched specimens for which cyclic accomodation is possible. This study intends to demonstrate that creep fatigue conditions can be produced in the notch vicinity even if the global loading consists of repeated creep.

2. Experimental procedure

2.1. Specimen geometry

The specimen geometry was choosen from the following considerations :

i. For notched specimens, stresses and strains can be determined only by finite elements computations; so an axisymmetric geometry is preferred because it requires only a biaxial calculation without assumption of plane stress or plane strain as in the case of notched plates;

ii. the notch must be sharp enough to concentrate the cyclic deformation at the notch vicinity for pure fatigue conditions and to prevent general yielding and ratchetting effects when short or intermediate hold times are introduced at maximum load.

A notch geometry with a 0.1 mm radius of curvature and a 2.12 mm depth was choosen (figure 1). Such a notch which leads to a stress concentration factor K_t of about 6 was prepared by electrosparkling machining using a 0.15 mm diameter copper thread, the specimen turning around its axis at 0.167 revolution per minute. Total machining requires about 4 hours. The precision on depth is of 0.1 mm all around the circonference. Metallographic observations of a longitudinal section of as machined specimens show that the notch tip is semi circular with a 0.1 mm radius and no microcracking or other alteration of the microstructure of the material was detected.

2.2. Testing apparatus

The loading system consists of a lever arm of high mechanical amplification on which a mobile weight is actuated by an endless screw coupled with a reversible electric motor (figure 2). The total displacement of the weight is determined by mechanical detectors connected with a two clocks system allowing hold times at minimum or maximum load, or immediate reversal of the weight movement. One continuous fatigue cycle is performed in about 20 seconds. Hold times up to 12 hours can be imposed with the clock system. Larger hold times requires manual operation.

The specimen is heated by a resistance furnace and an electrical potential drop technique may be used to detect specimen cracking.

2.3. Material

Tests were performed on a type 316L (AISI) austenitic stainless steel supplied by CREUSOT-LOIRE in the form of a 15 mm rolled sheet. Chemical composition of this product which was used in the experimental fast breeder reactor PHENIX is given in table I whereas conventionnal tensile properties in the annealed condition are reported in table II. Material was tested in as received annealed conditions (1100°C - water quenched). The mean grain size is about 50 μm.

The low cycle fatigue with or without hold times at maximum tensile strain and the pure creep properties at 600°C of this material are well documented through the studies by REZGUI, PETREQUIN et al. |7|, LEVAILLANT, PINEAU |8| and, more generally, results obtained during the course of a cooperative programm including Electricité de France, Commissariat à l'Energie Atomique, CREUSOT-LOIRE |9|. One relaxation fatigue test lasting more than one year |5| suggests a saturation in the detrimental effect of hold times on the number of cycles to failure (for a 24 hours hold time at $\Delta\varepsilon p = 0.88\%$ at 600°C).

2.4. Testing conditions

Tests were conducted at 600°C with a load ratio R of 0.1 if R is defined by :

$$R = P_{min}/P_{max} \tag{1}$$

P_{min} : minimum load

P_{max} : maximum load.

The loading and unloading times between P_{min} and P_{max} are of about 10 seconds.

Three maximum nominal stress levels were investigated, $\sigma_{nom\ max}$ = 227, 250, 290 MPa where :

$$\sigma_{nom\ max} = P_{max}/S_o \tag{2}$$

S_o : initial minimum section of the specimen.

Hold times over the range from 1 minute to 72 hours were applied on creep fatigue specimens.

3. Experimentals results

Experimental results including number of cycles to failure and total time to failure are reported in Table III. Maximum test duration is about 3000 hours in the investigated domain. The influence of hold times on fatigue life is clearly observed in figure 3 where the number of cycles to failure N_f is plotted against the maximum nominal stress $\sigma_{nom\ max}$ for various hold times. It is worth noting that fatigue life N_f decreases continuously for hold times longer than 6 minutes. For one hour hold the decrease is stronger at high stresses. This behaviour is less pronounced for 72 hours hold, where the reduction of life reaches a factor of about 400 as compared to continuous fatigue life. Another interesting presentation of the results is shown in figure 4 : in this bilogarithmic diagramm plotting the number of cycles to failure N_f as a function of the hold time t_h, results of continuous fatigue, creep fatigue and pure creep are presented together if the time axis is truncated to plot zero hold data. Creep data correspond to the hold time leading to rupture in one cycle. For each nominal stress level, experimental data show two asymptotic regimes (figure 4). For short hold times, $N_f \simeq N_f^{C.F.}$ (C.F: continuous fatigue); for the longest ones , the fatigue life N_f decreases when the hold time t_h increases but the total time to failure t_f seems to be roughly constant and equal to the creep time to rupture t_f^c : the second asympote then obeys the following equation :

$$t_f = N_f \times t_h = t_f^c \tag{3}$$

This equation corresponds to a line of -1 slope in the bilogarithmic diagramm. These asymptotic behaviours suggest the existence of two extreme testing domains : a domain of pure fatigue rupture (very short hold times) and a domain of pure creep rupture (large hold times) as indicated schematically in figure 5 : for intermediate hold times, there exists a transitionnal regime where the number of cycles to failure does not decrease linearly with the reciprocal of hold time. This latter regime may correspond to a true creep fatigue interaction regime.

A notch strengthening effect in pure creep loading is observed when comparing rupture times for the notched specimens of this study, with results obtained on smooth specimens |9| as indicated in figure 6. For a given failure time, notched specimens support nominal stresses about 15% higher than plain specimens.

The evolution from a fatigue dominated regime towards a creep dominated regime when hold times increase is also clearly indicated by electrical potential variations. In figure 7, normalised potential V/V_o (ratio of current potential V to initial potential V_o reached just after the first loading) is plotted as a function of life fraction, N/N_f for cyclic loading or t/t_f for creep loading : For life fractions greater than 0.5, normalised potential decreases obviously for increasing hold times : upper and lower bound of normalised potential evolution are given respectively by continuous fatigue and pure creep loading.

Fracture surfaces examinations show that cracking initiates at notch root for every testing conditions. The crack front is annular and not roughly off-centered as respect to the specimen axis. Scanning electron microscopy indicates that continuous fatigue gives a transgranular crack path with fatigue striations and that pure creep cracking is fully intergranular. Creep fatigue specimens exhibit a mixed fracture mode for the shortest hold times and a mainly intergranular fracture mode for the longest ones.

4. Discussion

The aim of the present study is to demonstrate that repeated tensile creep loading on sharply notched specimens can produce cyclic relaxation in the notch vicinity i.e. local sollicitations with limited strain ranges. The evidence of two asymptotic behaviours of experimental results, one of continuous fatigue and the other one of pure creep, leads to the conclusion that local cyclic relaxation can only be achieved for an intermediate hold times domain : this domain may be approximately located around the intersection of the asymptotic lines, for a critical hold time t_h as indicated schematically in figure 5. The new experimental procedure for investigating the effect of long hold times on HTLCF life will be efficient if loading conditions can be found for which the hold times domain giving local cyclic relaxation - or more roughly the critical hold time t_h^c - is more representative of the components working conditions than hold times investigated by the classical testing method on plain specimens.

It seems essential to describe correctly the general behaviour of notched bars under repeated tensile loading. In this paper, qualitative interpretations together with some experimental verifications are presented but quantitative analysis involving finite elements calculations conducted at ONERA and reported elsewhere by LEVAILLANT, PINEAU, CHABOCHE |10| supports these interpretations.

Depending on maximum nominal stress and hold time duration, accomodation or ratchetting strains may occur in notched specimens under repeated tensile loading. Ratchetting effects are due to general plastic or viscoplastic yielding of the specimen at every cycle. For sharp notched specimens as in the present case, cyclic accomodation occurs for continuous fatigue loading. Experimental verification of this accomodation was achieved by measuring axial elongation δ, of a 24.3 mm gauge length centered on the notched section during continuous fatigue loading. The experiments were run on a servohydraulic testing device in order to use an axial extensometer developped for HTLCF specimen |8|. Results are reported in Table IV : they indicate a very weak ratchetting strain for no hold time cycling : the first loading induces an initial elongation of about 200 µm but the variation $\Delta\delta$ of elongation during the next thousand cycles ($N/N_f \simeq 0{,}23$) is only of 5 µm. The specimen accomodates therefore the loading after only one cycle : the cyclic plastic zone is perfectly confined at the notch root.

If hold times are applied, viscoplastic strains occur as well as stress redistributions and may induce general yielding of the specimen at every cycle for sufficiently severe load and hold time conditions. This behaviour gives way to creep ratchetting strains. According to the concept of creep ductility exhaustion introduced by EDMUNDS, WHITE |11|, cumulated elongation in creep fatigue specimens would be limited to pure creep elongation at rupture. For the longest hold times and low numbers of cycles to failure conditions, it may be assumed that periodic unloadings have only minor effects on creep behaviour; creep ductility exhaustion would then account for the creep dominated regime. For intermediate hold times, viscoplastic strains would be essentially confined in the notch vicinity, giving locally cyclic relaxation loading and cumulated elongation remains largely below pure creep elongation at fracture. Then the critical hold time value t_h^c typical of the creep fatigue interaction domain may be interpreted as the hold time separating a domain where ratchetting elongation leads to creep controlled fracture by ductility exhaustion, from a domain where rupture is governed by cyclic relaxation and intergranular damage processes |8| at the notch root and not by global cumulated elongation. This assumption is well supported by ratchetting elongation measurements reported in Table IV. For a maximum nominal stress of 227 MPa, the critical hold time t_h^c is about 30 minutes. For a 10 minutes hold time test, ratchetting elongation per cycle $\Delta\delta_c$ decreases rapidly. The total creep elongation at rupture is evaluated by multiplying the lowest elongation per cycle $\Delta\delta_c$ by the remaining number of cycles before failure and adding to the cumulated measured elongation. This elongation at rupture $\Delta\delta_R$ is twice lower for the 10 minutes hold test than for the 300 minutes hold test. In the latter case, rupture will be creep dominated according to the experimental results (fig. 4). The elongation to rupture $\Delta\delta_R$ must then be close to that of pure creep loading. Measuring a twice lower elongation to rupture for 10 minutes hold test indicates that failure is not creep dominated in that case because of a more effective confinement of viscoplastic strains at the notch root. Globally there is a competition between progressive yielding of the structure and local creep and fatigue damages interaction leading to earlier crack initiation and propagation at the notch root. This latter phenomenon is evidenced by electrical potential measurements (figure 7), the shortest hold times tests showing higher potentials for a given test time.

The last point to discuss is how to reach critical hold time t_h^c values representative of working components conditions. As a matter of fact, experimental hold times t_h^c are still very short (t_h = 30 min. for $\sigma_{nom\ max}$ = 227 MPa) for tests lasting about 2500 hours. Two tests parameters may be modified for that purpose. The first one is the temperature which has a drastic influence on creep properties. Lowering the test temperature to 550°C (which is closer to the design conditions), increases the creep rupture time of plain specimens by a factor of about 22 |9|. Moreover LCF with no hold times resistance is not largely influenced by test temperature between 550 and 600°C |4| since the numbers of cycles to failure are increased only by a maximum factor of 2. Transposing these results to notched specimens, the critical hold time t_h^c for $\sigma_{nom\ max}$ = 227 MPa at 550°C, determined by the intersection of continuous fatigue and pure creep asymptotes is about 7 hours, for a total time to rupture of 53,000 hours. For higher creep resistant type 316L stainless steel such as the one used for SUPERPHENIX reactor, presenting creep rupture lifes 10 times longer than the heat of the present study and rather similar continuous cycling LCF properties |8|, critical hold time t_h^c would reach 70 hours for $\sigma_{nom\ max}$ = 227 MPa at 550°C. It becomes clear that variations of creep properties with temperature and chemical composition have drastic influence on the critical hold time t_h^c value.

Lowering the maximum nominal stress increases also the critical hold time t_h^c in the experimental domain as indicated in Figure 8. The results can be fitted as :

$$\sigma_{nom\ max} \cdot (t_h^c)^k = A \qquad (4)$$

with k = 0.149 and A = 205 (t_h^c in hours, $\sigma_{nom\ max}$ in MPa).

According to the theoretical approach by RIEDEL |12| for creep deformation at crack tips, in the case of small scale yielding the viscoplastic zone size R is given by :

$$R = B\ (\sigma_{nom} \cdot t^{1/n-1})^2 \qquad (5)$$

n is the exponent of the secondary creep rate (NORTON law);

n = 7.87 for the present material at 600°C |9|.

Comparing equation (4) (with 1/k = 6,71) and equation (5) (with n-1 = 6,87), suggests that the critical hold time t_h^c might correspond to the time needed to developp a critical value of the viscoplastic zone size R. Using empirical correlation (4) which seems to be supported by some theoretical considerations leads to a critical hold time of 50 hours for $\sigma_{nom\ max}$ = 114 MPa i.e. the yield stress of the material. These loading conditions are quite representative of working components sollicitations.

5. Conclusions

The new experimental procedure for investigating the effect of long hold times on HTLCF life presented in this paper shows the different behaviours of notched specimens submitted to repeated tensile creep loading. For an intermediate hold times domain, cyclic relaxation is produced at the notch root and creep ratchetting strains do not control life of specimens. This reliable test technology seems to be able to give designers very long HTLCF data representative of components conditions, if tests parameters (maximum stress, temperature) are correctly choosen.

Acknowledgments

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Table I - Chemical composition (weight %)

C	Cr	Ni	Mo	S	Mn	Si	S	B	Co	Cu	P
0.033	16.4	13.6	2.12	0.022	1.55	0.44	0.25	0.012	0.18	0.07	0.0022

Table II - Tensile properties at 600°C

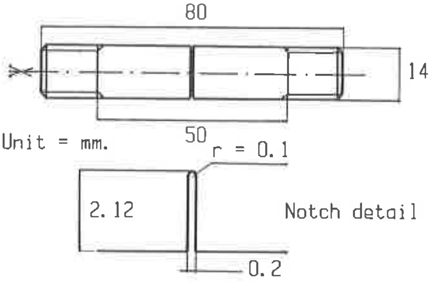
Young's Modulus E(MPa)	Yield Stress at 0,2% σ_y (MPa)	Ultimate tensile strength R_m (MPa)	Rupture elongation A (%)	Reduction of area Σ (%)
144000	116	377	49	74

Table III - Results of continuous fatigue, creep fatigue and creep tests on notched specimens.

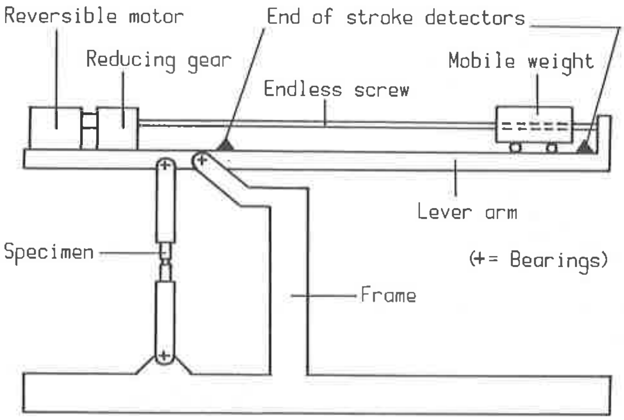
$\sigma_{nom\ max}$ (MPa)		Continuous fatigue	Creep fatigue with hold time t_h =					Creep
		t_h = 0 min.	1 min.	6 min.	1 hour	10 hours	72 hours	
290	N_f(cycles)	2384		1088	148	17	3	1
	t_f(hours)	13		109	148	170	216	106
250	N_f(cycles)	3300 3007	3918	1819	375	49	9	1
	t_f(hours)	18 17	87	182	375	490	648	249 362
227	N_f(cycles)	4719 3986		3237	1150 2151	327	21	1
	t_f(hours)	26 22		324	1150 2151	3270	1544	2345

Table IV - Ratchetting strains measurements on notched specimens. $\sigma_{nom\ max}$=227MPa, θ=600°C.

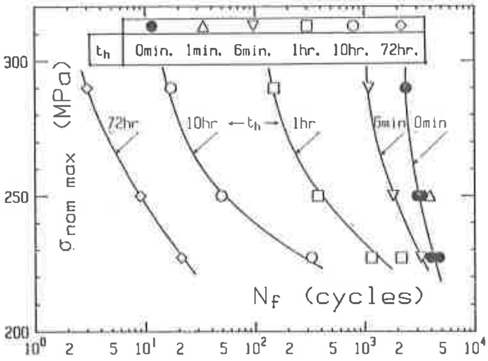
Hold time t_h (min)	Number of cycles to failure for this hold time	Cycling between cycles n°	Variation of elongation during this period $\Delta\delta$ (µm)	Variation of elongation per cycle $\Delta\delta_c$ (µm/cycle)	Extrapolated variation of elongation at rupture $\Delta\delta_R$ (µm)
0	≃ 4400	1-1000	5	0.005	22
10	≃ 3000	1- 132	30	0.227	110
		132- 270	6	0.043	
		270- 458	5	0.027	
300	≃ 480	1- 50	80	1.600	217
		50- 90	14	0.350	
		90- 238	47	0.317	



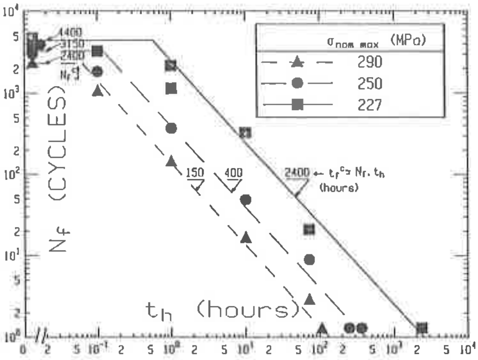
1 **FLE 0.1. Specimen geometry.**



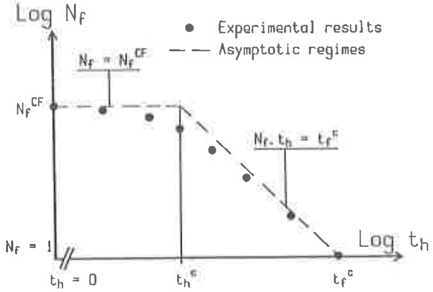
2 **Scheme of testing apparatus.**



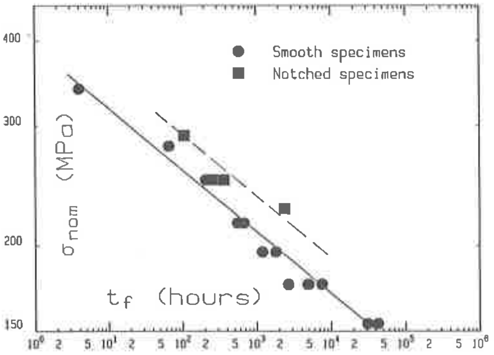
3 Influence of hold times on the number of cycles to failure at 600°C.



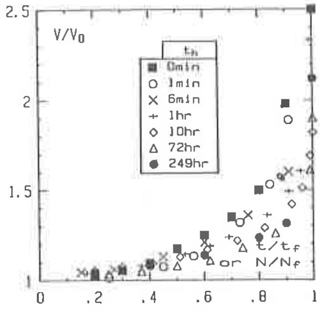
4 Variations of the number of cycles to failure with hold time duration at 600°C.



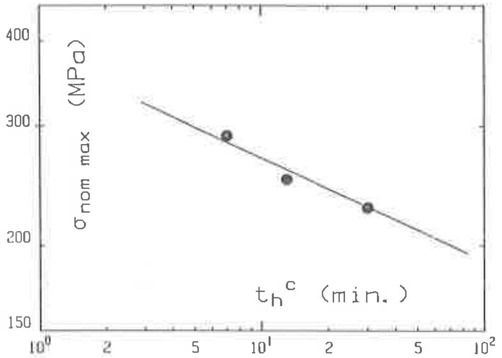
5 Schematic response of notched specimens under repeated tensile loadings.



6 Comparison of creep resistance of notched and plain specimens at 600°C.



7 Evolution of normalised potential as a function of life fraction.



8 Variation of critical hold time with maximum nominal stress.