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Effects of hold-time and neutron-irradiation on the low-cycle fatigue behaviour of type 316-CL and their consideration in a damage model

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ABSTRACT

The creep-fatigue behaviour of AISI Type 316 L(N) plate material has been investigated in the temperature range of 450°C to 750°C performing axial strain controlled test with GRIM specimens. The creep and creep-fatigue behaviour of austenitic stainless steel material is known to be prone to neutron-irradiation induced embrittlement. Therefore, the irradiation behaviour was studied by performing irradiation experiments in the High Flux Reactor (HFR) of Petten at 550°C. A newly developed damage model for time dependent damage was applied to describe the failure behaviour of AISI 316 L(N) in the cyclic tests performed.

1. INTRODUCTION

The austenitic stainless steel AISI 316 L(N), DIN designation X2 CrNiMoN 17-12-2, will be used as structural material for the EFR (European Fast Reactor). The austenitic Type 316 L(N) stainless steel is also reference steel for a future NET / ITER fusion reactor.

The operational conditions of EFR cause creep as well as fatigue damage in the structural material. To simulate these conditions, low cycle fatigue (LCF) experiments with hold-times introduced at the extreme(s) of the cycle have found extensive application. The introduction of hold-times, which corresponds to the stationary phase of the operational cycle, causes mostly a reduction in the number of cycles to failure N_f due to creep damage.

Austenitic stainless steels are known to be prone to neutron irradiation induced embrittlement at elevated temperatures [1-4]. A strong reduction in creep rupture life is observed after irradiation up to $1x10^{24}$ n/m^2 at temperatures above 450°C. The enhanced creep damage is the reason for the reduction in number of cycles to failure after introduction of hold times in the tension phase of the LCF cycle. To qualify the material for application in future fast reactors, the effect of irradiation on the creep and creep-fatigue behaviour of the material has to be quantified to be able to determine the design criteria for above core structures (ACS) [5]. This paper deals with the creep and creep-fatigue behaviour of Type 316 L(N)-SPH grade plate material.

2. EXPERIMENTAL PROCEDURES

The material used for the experiments is the AISI Type 316 L(N) plate material, designated as Type 316-CL. The chemical composition (0.025%C-0.30%Si-1.79%Mn-17.43%Cr-12.44% Ni-2.40%Mo-0.0008%S-0.021%P-0.078%N-0.024%Co-0.10%Cu-9ppmB) of this heat fulfils the RCC-MR-specification [6]. Therefore this heat can be considered as a typical 316L-SPH grade material.

The GRIM specimen fabricated for the LCF-tests has a total length of 77 mm with a slight hourglass to promote central crack initiation at the smallest diameter of 8.8 mm in the middle of the specimen. Ridges on both ends of the 21 mm gauge length allow a stable attachment of the axial extensometer system (see Fig. 1).

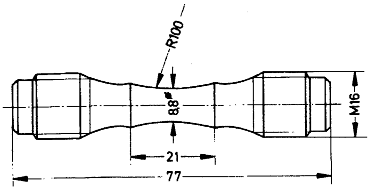

Fig. 1 GRIM LCF-specimen

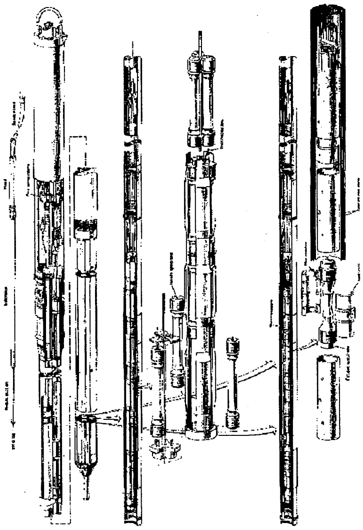

Fig. 2 SINAS-type sample holder [7]

The irradiations were carried out in the High Flux Reactor (HFR) of Petten in The Netherlands. The test specimens were irradiated in a sodium filled capsule (see Fig. 2) for one cycle (about 1 month) in an in-core position of the HFR. A fast fluence of about $7x10^{23}$ n/m^2 corresponding to about 0.1 dpa was reached within 600 hours. The accumulated amount of helium in the material during irradiation was between 1 and 5 appm, depending on the initial B-contents of the material. These conditions are representative for the above-core structures (ABS) of the EFR.

The post-irradiation experiments were carried out at a temperature of 550°C in air. A triangular waveform was employed at conventional strain rates in the range of $1x10^{-3}$ to $3x10^{-3}$ s^{-1} to determine the fatigue behaviour of the material under continuous cycling conditions. The creep-fatigue interaction is investigated either by reducing the strain rate down to as low as $5x10^{-6}$ s^{-1} or by introducing a hold time in the tension part of the cycle. More detailed information can be found in [8] and [9]. Creep properties are determined by load controlled creep rupture experiments using cylindrical specimens with a gauge length of 40 mm and a diameter of 8 mm.

The reference experiments were performed basically by FZK in Germany and the post-irradiation experiments were carried out by ECN in the Netherlands. Some reference experiments were also performed by ECN for comparison.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Continuous cycling results and effect of irradiation

The number of cycles to failure N_f of Type 316-CL plate material is plotted as function of total strain range in Figure 3 (black squares). Data of an austenitic stainless steel with German designation DIN 1.4948, which is very similar to the American structural material AISI Type 304 material, are indicated (black stars) for reason of comparison. It is obvious that for all strain ranges the 316 L(N)-material shows significantly lower N_f-values compared to the Type 304 heat. The effect of irradiation to 0.1 dpa at 550°C on the fatigue life behaviour of Type 316-CL is shown in Figure 4. The fatigue life of this material is not affected significantly by the irradiation.

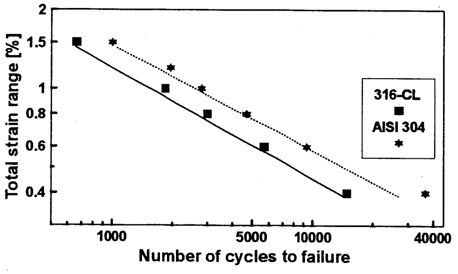

Fig. 3 Number of cycles to failure of 316-CL and Type 304 material as function of total strain range at 550°C.

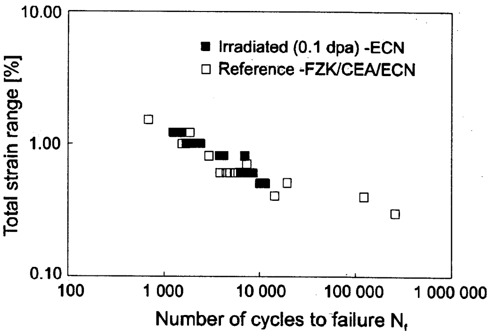

Fig. 4 The effect of 0.1 dpa irradiation on the fatigue life of Type 316-CL material at 550°C.

3.2 Creep results and effect of irradiation

The creep rupture behaviour of reference Type 316-CL material at 550°C is shown in Figure 5 as open squares. The creep results from specimens irradiated to 0.1 dpa at 550°C are shown in the same graph as filled squares, clearly indicating a considerable reduction in creep resistivity.

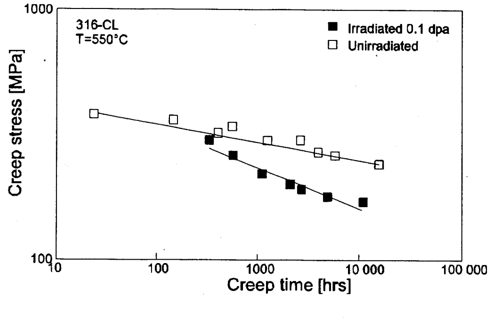

Fig. 5 Creep curves of unirradiated and 0.1 dpa irradiated Type 316-CL material at 550°C.

3.3 Creep-fatigue interaction and effect of irradiation

The fatigue life results of Type 316-CL plate material tested at 1% total strain range and 550°C is shown in Figure 6 as a function of strain rate. The two lines for unirradiated material indicate good agreement between the two laboratories. The data points of the irradiated specimens show a reduction in fatigue life at low strain rates.

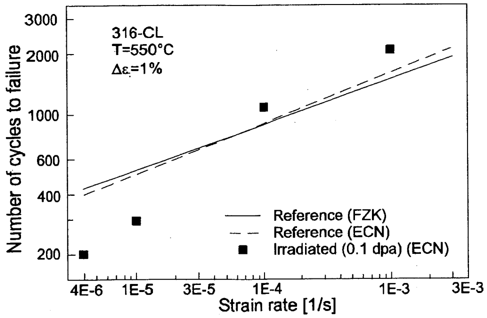

Fig. 6 Number of cycles to failure for Type316-CL material as function of strain rate and irradiation condition at 550°C

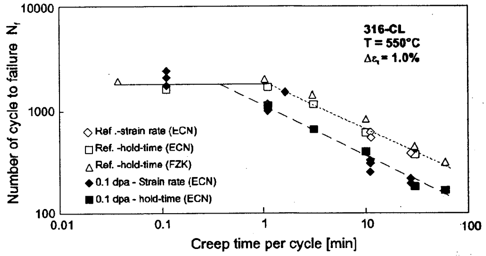

Fig. 7 Number of cycles to failure for Type 316-CL material as function of cycle-time and irradiation condition at 550°C

The fatigue life of Type 316-CL plate material at 1% total strain range and 550°C is shown in Figure 7 as a function of creep time per cycle. This graph includes results from both low strain rate experiments and experiment with hold-times in tension. As a conservative assumption, the tension part of the cycle is considered to contribute fully to the creep damage. One should keep in mind that during the cyclic part of the test the stress level changes continuously. The unirradiated material shows a reduction in fatigue life when the creep time per cycle exceeds 1 minute for one LCF cycle. This reduction increases with increasing creep time per cycle, indication creep-fatigue interaction phenomena. Irradiation to 0.1 dpa at 550°C reduces the fatigue life of the material even further. The additional reduction in fatigue life seems to start somewhat earlier and is constant over the creep time per cycle range up to 1 hour creep time per cycle and amounts a factor of about 2.

3.4 Modelling of failure behaviour

3.4.1 Model

For reliable lifetime prediction of complex loaded components a sufficiently verified rule is needed which is applicable to variable loads and at the same time takes into account the damage process correctly. At high temperatures, damage, like deformation, is affected by time-dependent mechanisms. During cyclic loading this is expressed by the frequency and hold-time dependencies of the number of cycles to failure.

In a traditional damage description, a distinction is made between time-dependent damage (creep) and time-independent damage (fatigue). Considering an interaction of these processes one tries to determine the lifetime [6]. To describe the failure behaviour of Type 316-CL material in the tests presented above, a model is used which consider damage in a unified manner, in other words without an explicit subdivision in creep and fatigue parts. The model, called ISRM-model, was developed within the framework of continuum damage mechanics on the basis of experiences known from the literature with life-time prediction rules. It is a modification of the creep damage model by Rabotnov [10] and can be applied to load cases with deformation rates higher than those under steady-state creep [11,12].

In the application presented below a slightly modified version -for simplification- of the ISRM-model was considered to calculate the lifetime:

$$\dot{D} = \langle \frac{\tilde{\sigma}}{A} \rangle^{r} \langle \frac{\dot{\varepsilon}^{in}}{\dot{\varepsilon}_{s}^{in}} \rangle^{\nu} (1-D)^{-\kappa} \qquad and \quad \tilde{\sigma} = \frac{\sigma}{1-D} \tag{1}$$

The brackets ⟨ ⟩ operate on the inbetween following the notation $\langle x \rangle = (x + |x|) / 2$. Therewith, under compression no change of damage is assumed. This assumption is based on the fact that in creep of metallic materials compression stresses are not or negligibly damaging in comparison with tensile stresses of the same order [13]. $\dot{\varepsilon}^{in}$ denotes the current inelastic strain rate, $\dot{\varepsilon}_{s}^{in}$ is the steady-state creep rate and is a function of the current stress σ, damage D and temperature T. It is set to the creep rate at the beginning of the secondary creep stage in a creep test performed under a stress and a temperature equal to the current effective stress $\tilde{\sigma}$ and the current temperature $\left(\dot{\varepsilon}_{s}^{in} = \psi_{s}(\tilde{\sigma}, T) \right)$. A, r and κ are material and temperature dependent parameters. In the case of irradiation they depend also on the irradiation doses.

The model was applied to the cyclic tests performed with Type 316-CL material in the unirradiated (reference) and irradiated state, respectively, 550°C.

3.4.2 Application

Determination of the parameters of the model

When the damage model is applied to creep tests performed at uniaxial constant stress $\dot{\varepsilon}^{in} = \dot{\varepsilon}_{s}^{in}$ over almost the whole lifetime) the following expression for the time to failure can be derived:

$$t_F = \frac{1}{1+\kappa+r} \left(\frac{\sigma}{A} \right)^{-r} \tag{2}$$

The stresses of the considered creep tests should be of the same order of the stresses, at which the damage model will be applied. Fitting this expression to the times to failure observed experimentally [14] leads to r and $A^* = A(1 + \kappa + r)^{-1/r}$. To determine the other parameters, the damage model (eq. 1) was applied to the strain controlled cyclic tests with hold time. Thereby the following simplifications were made:

- The load at the cross-section with the minimal area of the hourglass shaped specimens, where failure occurs, can be considered to be uniaxial.

- According to the strain equivalence principle [14], the evolutions of the effective stress and the inelastic strain rate during a cycle are considered to be the same for all cycles between the first saturated cycle and the cycle immediately before failure. In addition the influence of damage on the stress evolution in the cycles up to the first saturated cycle is neglected.
- The effect of change of damage on damage evolution during a single cycle may be neglected.

The number of cycles to failure N_f is then calculated using the following equation:

$$N_f = \int_0^1 \left[\int_0^{t_c} \left\langle \frac{\sigma_s(t)}{A} \right\rangle^r \left\langle \frac{\dot{\varepsilon}^{in}(t)}{\dot{\varepsilon}_s^{in}(t)} \right\rangle^\nu (1-D)^{-\kappa} dt \right]^{-1} dD \qquad (3)$$

where $\sigma_S(t)$ and $\dot{\varepsilon}^{in}$ (t) describe the stress and the inelastic strain rate evolutions, respectively, during the first saturated cycle. Due to the hourglass shape of the specimens, the strain measured by the extensometer does not correspond to the strain where failure occurs -at the middle of the specimen-. However, to obtain the effective inelastic strain rate at the failure cross-section $\dot{\varepsilon}^{in}$ the measured inelastic strain rate $< \dot{\varepsilon}^{in} >$ is multiplied with a correction factor K: $\dot{\varepsilon}^{in} = K < \dot{\varepsilon}^{in} >$. Comparing fatigue data obtained from GRIM specimens with those obtained from cylindrical specimens of Type 316-CL material at 550°C the following formula could be deduced for K:

$$K = 0.49 < \Delta\varepsilon^{in} >^{-0.155}$$

where $< \Delta\varepsilon^{in} >$ denotes the inelastic strain range measured at the GRIM specimen in the considered test. $< \dot{\varepsilon}^{in} >$ was determined by numerical differentiation. For $\dot{\varepsilon}_s^{in}(t) = \psi_s(\sigma_S(t), 550^oC)$ the Norton expression $\dot{\varepsilon}_s^{in} = B\,|\sigma_S|^n \operatorname{sgn}(\sigma_S)$ obtained from creep data was used. t_C denotes the duration of the cycle. The integrations in eq. 3 were performed numerically.

The parameters ν and κ were determined by fitting the calculated numbers of cycles to failure to the values obtained experimentally using least square methods. In Table I, the resulting parameters are listed for both the reference state and irradiated state, respectively.

Table I Parameters of the damage model determined for Type 316-CL at 550°C

Irradiation dose [dpa]	A [MPa $\cdot$ $s^{1/r}$]	r	B [$MPa^{-n} \cdot s^{-1}$]	n	κ	ν
0	1721	10.93	1.18×10^{-42}	13.57	26	0.59
0.1	6356	5.64	5×10^{-32}	9.79	26	0.57

Calculated Results

It is obvious from Fig.8 that the numbers of cycles to failure obtained in the tests with hold-times considered are reflected fairly well by the applied damage model (within a range of factor two on lifetime). In comparison to standard lifetime prediction rules like the rule of the linear accumulation of creep and fatigue damage [6] (see Fig. 9) more reliable lifetime prediction in particular for cyclic loads including hold times could be obtained.

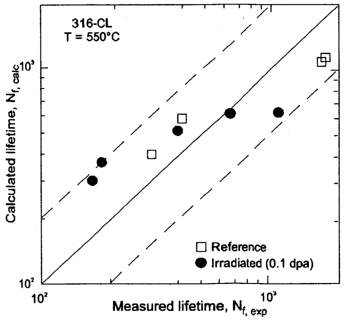

Fig. 8 Comparison of measured numbers of cycles to failure N_f and those calculated using the simplified ISRM-model.

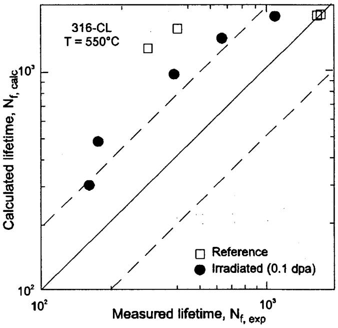

Fig. 9 Comparison of measured numbers of cycles to failure N_f and those calculated using the standard rule of the linear accumulation of creep and fatigue damage.

4. CONCLUSIONS

The following conclusions can be drawn with respect to the irradiation effects of 0.1 dpa at 550°C in Type 316-CL material:

1. there is evidence of irradiation enhanced creep damage;
2. no sign of irradiation effect on continuous LCF behaviour ot the material;
3. degradation of creep-fatigue life due to irradiation observed in LCF tests with either low strain rate or hold-times introduction in the tensile part of the cycle.

On the basis of the good results obtained with the damage model applied there is justified hope that the model can furthermore be used to describe damage under cyclic load at high temperatures in a unified manner without taking into account creep/fatigue interaction explicitly.

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