Analysis of Biaxial Experiments on 316 Steels at Elevated Temperature

G. Clement, C. Guionnet
C.E.A., CEN Saclay, DEMT/SMTS, F-91191 Gif-sur-Yvette Cedex, France

Abstract

A tubular test specimen made of 17-12 SPH austenitic steel was subjected to cyclic torsional stressing at 600°C by maintaining a constant axial load and applying a cyclic twisting force with a symmetric amplitude. The aim of the tests was to study the effect of hold time at cycle limits (between 10 and 10 000 seconds) on the evolution of maximum stresses and ratcheting.

Hold time was observed to significantly reduce the maximum values of the stresses encountered in the cycling and apparently more than in the uniaxial case. Increasing the hold time strongly increases ratcheting ; the results of the tests carried out are interpreted in the framework of the viscoplastic model of J.L. Chaboche : the stress/strain diagrams are represented in a realistic way although ratcheting is overestimated.

1. Introduction

The creep fatigue life prediction of materials used to construct the components of liquid-metal fast breeder reactors requires a good knowledge of the stresses and strains set up in their structures during operation, and, in particular, of the effects of thermal transients. It is therefore important to be able to judge the validity of the constitutive equations to represent stress and strain states in a real geometry.

The parameters required for these calculations are generally obtained by fitting to the results of uniaxial tests. A first test of the applicability of a model to a multidimensional structure can be made by interpreting biaxial experiments such as torsional stressing of a thin walled tube. This type of test has been widely used in the CEA in order to study ratcheting [1-5]. In these tests, stresses and strains can be determined without any ambiguity, stresses from measurements of moments and axial load and strains from the torsion angle and the elongation of the test specimen.

Comparisons between experiment and theory were performed for 17-12 SPH austenitic steel at 600°C because of the usefulness of this material in the construction of liquid metal fast breeder reactors. The experiments described here were principally designed to evaluate the effect of the time between thermal transients on the resulting stresses and ratcheting.

As a result of the importance of time, a viscoplastic model developed by J.L. Chaboche of O.N.E.R.A [6,7] was retained to interpret the results.

2. Description of tests

The apparatus used has already been described [1-5] . Figure 1 shows the tubular test specimen used and indicates its dimensions (mean radius r = 10.5 mm, thickness t = 1.30 mm, useful length L = 240 mm). The test specimen is subjected to an axial loading that remains constant with time (primary stress) onto which a cyclic torsional load with a symmetrical amplitude $2\Delta\theta$(secondary stress) is superimposed ; different constant hold times, HT, being imposed at the cycle limits. Figure 2 illustrates the loading mode applied to the test specimen. 17-12 SPH steel originating from an 1100°C annealed and water quenched sheet obtained from EDF Renardieres Research Center was used. The percentage chemical composition was : 0.03 C, 0.001 S, 0.021 P, 0.44 Si, 1.84 Mn, 12.30 Ni, 17.54 Cr, 2.47 Mo, 0.075 N and 0.175 Cu. The elastic limit at 0.2 % was Sy = 143MPa with a Young's modulus E = 138,000 MPa.

The test program is summarized in table 1 :

the axial load used throughout all the tests was 50 MPa

the half-amplitude of the rotation was ± 9.2°

the hold times for the 4 tests considered were 10, 100, 1000 and 10000 seconds respectively.

3. Analysis of experimental results

Moments are represented as reduced moments $Mr = \dfrac{M}{2\pi r^2 t \times Sy}$ equal to stresses normalized to the value of Sy. Maximum reduced moments are reported as a function of the number of the cycle involved for each of the tests (figure 3) ; these moments, that is to say normalized maximum stresses, decrease significantly when the hold time increases and notably more than in the uniaxial tests performed on the same steel at the same temperature, and, in particular, in the tests of Mottot et al [8] .

The curves giving axial elongations, that is to say the ratcheting occurring in the different tests, are reported in figure 4. Hold time effects are very significant and it should be noted that almost all of the axial elongation takes place during the torsional motion and not during the hold time. Figure 8 demonstrates this fact ; in this figure elongation is shown as a function of the angle of torsion for a hold time of 10,000 seconds. This can also be confirmed from the figures given in table 2 which translate elongation as a function of hold time for different time lapses in the tests (including hold times) ; for a duration of 690 mn the elongation therefore reached 3.38 % with a hold time of 10 seconds but only 0.81 % with a hold time of 10,000 seconds.

4. Interpretation of experimental results using a viscoplastic model

The viscoplastic model used to interpret the results was formulated by J.L. Chaboche [6,7] in a framework of general thermodynamics. This model enables the behavior of a material to be described in terms of internal variables. A hypothesis of the partition of the total deformation into an elastic part obeying Hooke's law and a plastic part ε_p is employed. The plastic part is represented by the following formulation : $\dot{p} = \sqrt{\frac{2}{3}\,\dot{\varepsilon}_p : \dot{\varepsilon}_p} = \left\langle \frac{J(\sigma - \mathcal{X}) - R - R_0}{K} \right\rangle^n$

$$\dot{\mathcal{X}} = c\, f(p) \left[\tfrac{2}{3}\, a\, d\varepsilon_p - \mathcal{X}\, dp\right] \qquad J(\sigma - \mathcal{X}) = \left[\tfrac{3}{2}(\sigma' - \mathcal{X}') : (\sigma' - \mathcal{X}')\right]^{\frac{1}{2}}$$

$$\dot{\varepsilon}_p = \frac{3}{2}\,\dot{p}\,\frac{\sigma' - \mathcal{X}'}{J(\sigma - \mathcal{X})} \qquad f(p) = \ell + (1-\ell)\,e^{-\beta p} \qquad R = R_m(1 - e^{-\gamma p})$$

the symbol <u> signifies <u> = u if u ⩾ 0 and <u> = 0 if u < 0.

The two parameters K and n determining the viscous behavior of the material were obtained from J.L. Chaboche of ONERA and result from fitting creep test results for the same material.

The other parameters were obtained from fittings with results of cyclic tensile compression tests on specimens from the same metal sheet as was used for the torsional stressing tests, the results of which have been communicated by G. Rousselier of EDF. The monotonic curve, first and sixth cycles and the stabilized cycle have been represented as best as possible. The results of the fittings are compared with experimental results (see figures 5a, 5b and 5c). The following parameters have been obtained in this way :

E = 138,000 MPa ν = 0.33   K = 110 MPa   n = 20
a = 60 MPa   C = 1500   1 = 0.38 β = 100
R_o = 5 MPa R_m = 138 MPa γ = 8.1

Calculations carried out for tests 511 (HT = 10 s) and 514 (HT = 10000 s) employed these parameters. Stress/strain diagrams determined for the first, sixth and stabilized cycles are compared with the experimental values of figures 6a, 6b, 6c and 7a, 7b and 7c respectively. Overall agreement is satisfactory. Nevertheless, the shape of the stabilized curve is only in approximate agreement as the model used only allows isotropic work hardening to be considered. Finally, the maximum stress in the HT = 10000 s calculation is overestimated.

Calculated and measured axial strains encountered in the two tests are reported in figures 7 and 8. The model considerably overestimates ratcheting, the error being less for long hold times. From a more general point of view, an examination of figures 7 and 9 relating to stress/strain loops and figures 6 and 8 relating to ratcheting shows that calculations do not take the effect of hold time into account.

5. Conclusion

Cyclic torsional stressing tests carried out on 17-12 SPH steel have shown that increasing the hold time considerably increases ratcheting and that this deformation is not in any way due to creep occurring during the hold time. Another observation is that the reduction in the maximum stress attained during cycling as a result of the hold time appears to be significantly greater than that encountered in uniaxial tests.

The viscoplastic model of J.L. Chaboche enabled the experimental stresses occurring in a biaxial structure to be explained in a reasonable way : this was done using parameters obtained in uniaxial tests. Ratcheting is, however, very much overestimated. In both cases, the effect of hold time is not reproduced by the calculation.

6. Acknowledgements

The authors wish to express their gratitude to Mr G. Rousselier and Mr J.J. Engel of the EDF Renardieres Research Center for very useful discussions. They also wish to thank Mr J.L. Chaboche of ONERA for having let them use the computer program to interpret the results of the tests performed.

References

|1| Roche, R.L., Moulin, D., Lebey, J., "Practical analysis of ratcheting", Nucl. Eng. and Design, 71, 51-66 (1982)

|2| Clément, G., Cousseran, P., Lebey, J., Moulin, D., Roche, R., Tremblais, A., "Règles de Dimensionnement des Structures mécaniques des Réacteurs - Dommage dû aux chargements variables - Déformation progressive - Analyse pratique de l'effet de Rochet" Rapport CEA R-5178 (1982)

|3| Clément, G., Lebey, J., Roche, R.L., "Design Rule for thermal ratcheting" 5th Int. Conf. Press. Vess. Tech., 251-264 (1984)

|4| Clément, G., Cousseran, P., Lebey, J., Tremblais, A., "Essais de déformation progressive de l'acier inoxydable 316L à la température de 650°C", Note CEA-N-2409 (1984)

|5| Clément, G., Lebey, J., Tremblais, A., "Essais de déformation progressive de l'acier inoxydable 17-12 - SPH", Note CEA (à paraître)

|6| Chaboche, J.L. "Description Thermodynamique et Phénoménologique de la Viscoplasticité Cyclique avec Endommagement", Thèse de Doctorat, Paris VI, 1978

|7| Chaboche J.L. et Rousselier G., "on the plastic and viscoplastic constitutive equations.." ASME Publication PVP-vol. 59 ORLANDO June 1982

|8| Mottot, M., Petrequin, P., Amzallag, C., Rabbe, P., Grattier, J. and Masson S., Behavior in Fatigue Relaxation of high creep resistant type 316 L Stainless steel, ASTM STP 770, 1983.

Table 1 - Experimental design

N° test	Primary Stress Mpa	Angle Degree	Nber Cycles	Hold Time second	Temperature
511	50	± 9.2	2542	10	600
512	50	± 9.2	690	100	600
513	50	± 9.2	1232	1000	600
514	50	± 9.2	152	9950	600

Table 2 - Cumulative elongation comparison as a function of time

N° Test									
511	time mn	34	172	345	690	1754			
HT : 10 s	ε %	1,55	2,22	2,72	3,38	4,71			
512	time mn	41	165	330	690				
HT : 100 s	ε %	0,80	1,42	1,93	2,72				
513	time mn	34	168	337	673	1683	3367	10100	33668
HT : 1000 s	ε %	0,40	0,94	1,27	1,64	2,26	3,08	5,28	9,14
514	time mn			334	668	1670	3340	10019	33398
HT : 9950 s	ε %			0,52	0,81	1,43	2,17	4,16	7,62

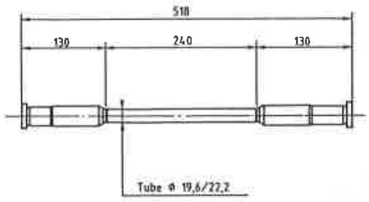

Fig. 1 Biaxial test specimen

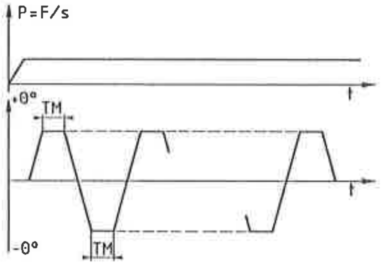

Fig. 2 Loading history

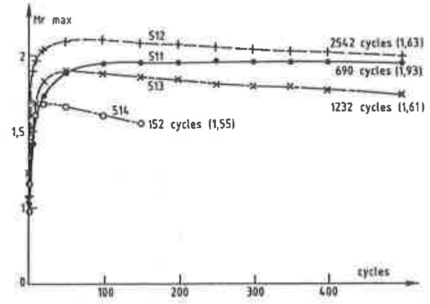

Fig. 3 Normalized Torsion Torque. Measured Torque/$2\pi.r^2.t.Sy$

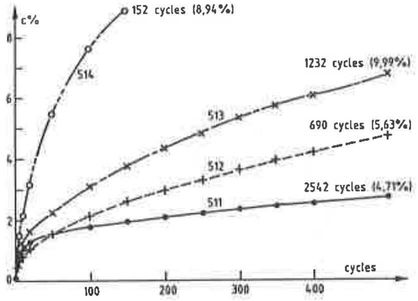

Fig. 4 Cumulative elongation

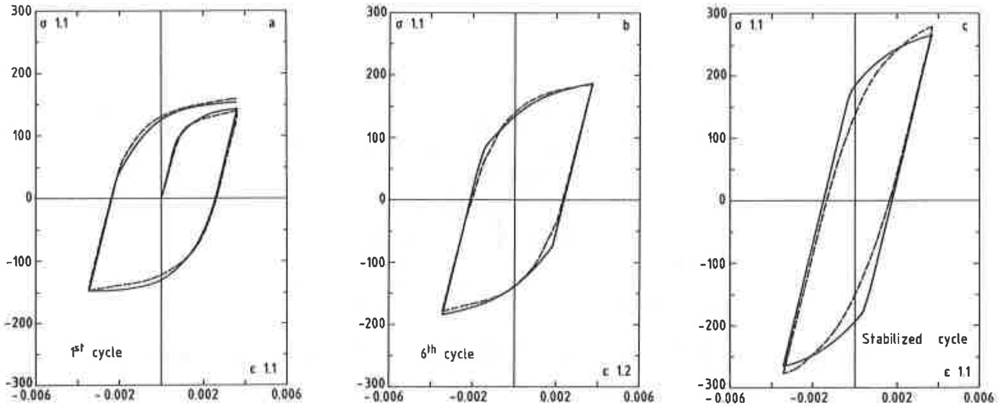

Fig. 5 Cyclic uniaxial stress-strain curves (---- experiments, —— model)

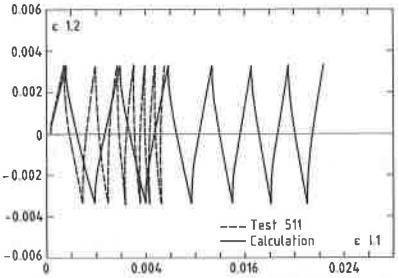

Fig. 6 Test 511 experimental and calculated progressive elongation

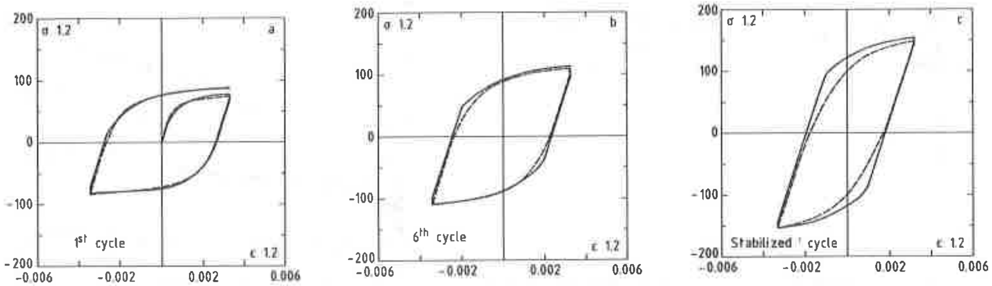

Fig. 7 Test 511 cyclic torsion stress-strain curves (----- experiments, ——— model)

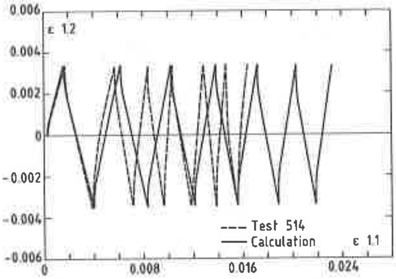

Fig. 8 Test 514 experimental and calculated progressive elongation

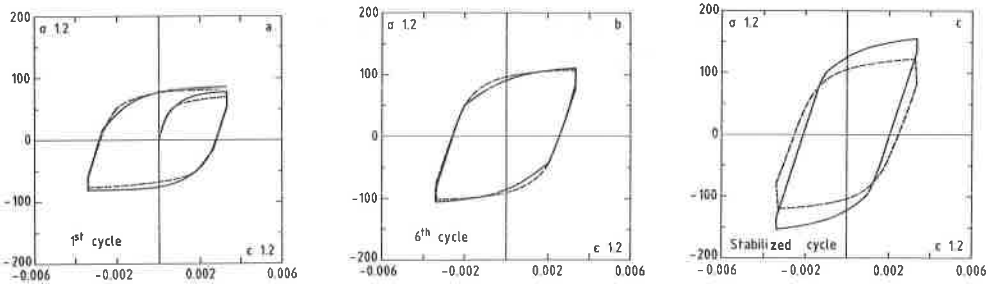

Fig. 9 Test 514 cyclic torsion stress-strain curves (----- experiments, ——— model).