Isothermal and Thermal Mechanical Low Cycle Fatigue of 316 L Steel

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ABSTRACT

Isothermal and thermomechanical low cycle fatigue tests were conducted on 316 L steel to determine the behaviour of this material under strain cycling including dwell times in a total strain range of 1 % and in a temperature range of 150° C to 500° C. Some models of life prediction were used and discussed on the results of the different kind of tests.

KEYWORDS

316 L steel, Isothermal test, Thermomechanical test, modelisation of life time.

Introduction :

Isothermal and thermomechanical low cycle fatigue tests are performed to study the behaviour of materials used in mechanical equipment and structural components which are submitted to cyclic straining at elevated temperatures.

This paper describes the results of a study on a 316 L steel used in nuclear plant, submitted to complex strain and temperature cycling and discusses on the results of predicted life time from different models of life time prediction.

Experimental procedure :

All the tests were performed on a servocontrolled electrohydraulic machine drived by computer. The strain was measured and controlled by using an uniaxial high temperature extensometer with return sticks, and the temperature was obtained with an infra-red heating chamber connected to the computer. The thermal and mechanical cycles are described Figure 1. The total strain range is about : $\Delta\varepsilon_t$ = 1 % and the two extreme temperatures of the thermal cycle are : T_{min} = 150° and T_{max} = 500° C. The duration of one cycle is about 4 minutes, including dwell times of 10 and 30 seconds.

The chemical composition of the material is described table 1.

Element	C	Ni	Cr	Mo	Mn	Si	Cu	Co	S	P	To	N	B
%	.012	12	17	2.5	1.8	≤.5	≤.2	≤.25	<.01	≤.035	<.15	.06	<15ppm

Table 1 : Chemical composition of the 316 L steel.

Experimental results :

Three kinds of tests on 316 L steel were performed : One isothermal fatigue test at 150° C, one at 500°, with the mechanical cycle shown Figure 1, and one thermomechanical test with the thermal and mechanical cycles shown Figure 1. The results of life time N_r of these tests are summarized in table 2.

Test	N_r cycles
Isothermal 150° C	2515
Isothermal 500° C	971
Thermomechanical	792

Table 2 : Number of cycles to failure for the different tests.

Stabilized hysteresis loops for each test are shown Figure 2. Figure 3 describes the evolution of the maximal and minimal loads obtained on different points of the mechanical cycle : at the start and the end of each dwell time, for each kind of test. The evolution of the plastic strain $\Delta\varepsilon_p$ versus the number of cycles is shown Figure 4.

Discussion :

The evolution of the maximal and minimal loads is quite the same during each test. Figure 3 shows three different stages : hardening of the material, stabilisation in load and crack growth before rupture. The duration of each stage is shown table 3.

Test	Duration of hardening	Duration of stabilisation	Duration of crack growth
Isothermal 150° C	7 % of Nr	73 % of Nr	20 % of Nr
Isothermal 500° C	7 % of Nr	87 % of Nr	6 % of Nr
Thermomechanical	8 % of Nr	67 % of Nr	25 % of Nr

Table 3 : Duration of the three stages.

At 500° C the hardening of 316 L steel is more important than at 150° C. In the two cases, the load relaxation is greater in compression than in traction. In the three tests, the duration of hardening (in % of number of cycles to failure) is quite the same. The great

difference is on the duration of crack growth : at 500° C the duration of this stage is shorter than at 150° C or in thermomechanical fatigue test, and the number of cycles for hardening is shorter at 500° C because the speed of cells creation increases when the temperature increases. In thermomechanical fatigue test, the duration of crack growth is greater than in isothermal conditions because the maximal strain in traction is obtained at the minimal temperature and we combine the effects of temperature and mechanical cycling.
On the curves of the evolution of the plastic strain versus the number of cycles, we also see three different stages : decreasing, stabilisation and final decreasing before rupture ; the plastic strain range is greater at 150° C than at 500° C due to the fact that the influence of temperature is greater in this last case. In thermomechanical fatigue test, the plastic strain range is greater than at 500° C but lower than at 150° C.

MODELISATION OF LIFE TIME :

- According to TAIRA /1/, plastic strain in thermomechanical fatigue, $\Delta\varepsilon_{ptm}$ is defined by the relation :

$$\Delta\varepsilon_{ptm} = \Delta\varepsilon_t - (\sigma/E)_{T2} - (\sigma/E)_{T1} \qquad (1)$$

with T_1 the minimal temperature and T_2 the maximal one.

The autor has also suggested the use of the concept of an equivalent temperature for correlating thermal fatigue behaviour with isothermal one. This concept states that, regarding thermal fatigue cycling between two temperatures, the same fatigue life will be developped by isothermal cycling at the equivalent temperature defined as follows :

$Te = (T_{max} + T_{min})/2$ if the difference between T_{max} and T_{min} is small (2)

$Te = T_{max}$ if this difference is great (3)

- COFFIN /2/ proposed a concept which takes account of the frequency of cycling in traction :

$$\Delta\varepsilon_p = C_1 \; [N_r \; (\nu_t/2)^{k-1}]^{-\beta} \qquad (4)$$

which C_1, k, β constants, ν_t the frequency in traction and $\Delta\varepsilon_p$ the plastic strain.

- DEGALLAIX /3/ considers that the life time N_r is a function of plastic strain :

$$1/N_r = A_1 \; (\Delta\varepsilon_p)^{B_1} \, . \, e^{-Q/RT} + A_2 \; (\Delta\varepsilon_p)^{B_2} \qquad (5)$$

where A_1, B_1, A_2, B_2, are material constants and Q is an apparent activation energy, T the temperature. (Q = - 4,795 Kcal/mol/K for 316 L steel).

- TAIRA /4/ also introduced the concept of "Spanning Factor" which permits the calculation of the number of cycles to failure N_r in thermomechanical fatigue with results obtained under isothermal conditions at the two temperatures of the thermal cycles (T_1 and T_2).

$$N_r = \{2 [N_r (T_1)/N_r (T_2)]^{1-\delta}\} / \{1 + [N_r (T_1)/N_r (T_2)] \times N_r (T_2) \qquad (6)$$

with $\delta = 2/3\ \beta (T_2)$.

$\beta (T_2)$ is the absolute value of the slope of the plastic curve of Manson at the temperature T_2 ; $N_r (T_2)$ is the life time of the material, for a same total strain, in isothermal cycling at the temperature T_2 and $N_r (T_1)$ at the temperature T_1.

Table 4 summarizes the different values of the coefficients for modelisation, and table 5 the calculated life time obtained with the different models compared to the experimental ones.

Test	$\Delta\varepsilon_{ptm}$	C_1	k	β	A_1	B_1	A_2	B_2	R Kcal/mol/K	$\Delta\varepsilon_p$
Isothermal 150°C	.69 %	.155	.7	.35	64450×10^{-5}	1.624	69.049×10^{-5}	1.792	2×10^{-3}	.69%
Isothermal 500°C	.60 %	1.51	.94	.861	"	"	"	"	"	.6 %
Thermomechanical	.673%	.354	.84	.576	"	"	"	"	"	.66%

Table 4 : Values for modelisation.

Model	Isothermal 150°C			Isothermal 500°C			Thermomechanical		
	N_r calc.	N_r exp.	Error	N_r calc.	N_r exp.	E	N_r calc.	N_r exp.	E
TAIRA	3134	2515	25%	1501	961	56%	1544	792	95%
Frequency separation	1403	2515	44%	443	961	54%	419	792	89%
DEGALLAIX	2786	2515	11%	1183	961	23%	288	792	54%
Spanning factor	-	-	-	-	-	-	924	792	17%

Table 5 : Life time predictions obtained in calculation with the different models.

The fatigue life values obtained from experiments are lower than the ones predicted from the models of Taira and Degallaix. The frequency separation concept gives, in each case, fatigue life values greater than the experimental ones. The best results are obtained with Degallaix's model under isothermal conditions, and with the concept of spanning factor in thermomechanical fatigue test ; the other models seem not to be accurate for predicting life time in such kind of tests.

METALLOGRAPHY :

Figure 5 shows the main crack of a sample tested at 150° C. In each test the crack direction is perpendicular to the tensile direction and the cracks propagate mainly between the grains ; crack initiation occurs on the surface of the sample. At 500° C there is more oxydation than at 150° C and under thermomechanical conditions.

CONCLUSIONS :

In thermomechanical fatigue test, the life time of 316 L steel is lower than in isothermal conditions for the highest temperature of the thermal cycle. Many criteria had been used for predicting the number of cycles to failure for isothermal fatigue tests as well as for thermomechanical fatigue tests. One of the models gives good results in the first case (Degallaix) and another one, based on isothermal test, for thermomechanical conditions (Spanning Factor).
Most criteria give poor life predictions, unless they need a lot of experiments for the determination of their parameters.

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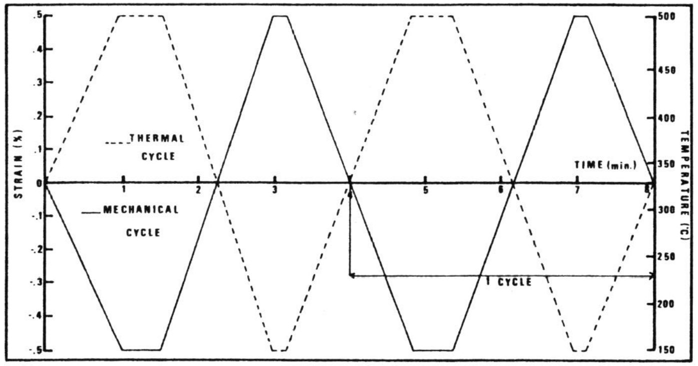


Figure 1: Thermal and Mechanical cycles

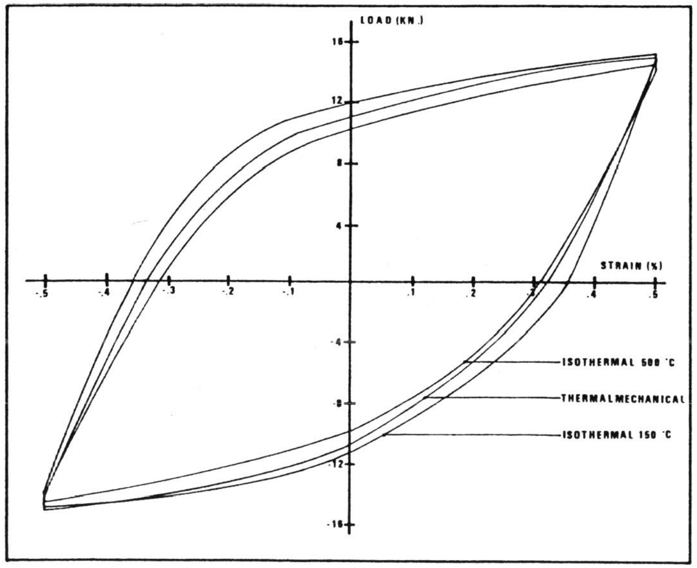


Figure 2: Stabilized hysteresis loops obtained in each test

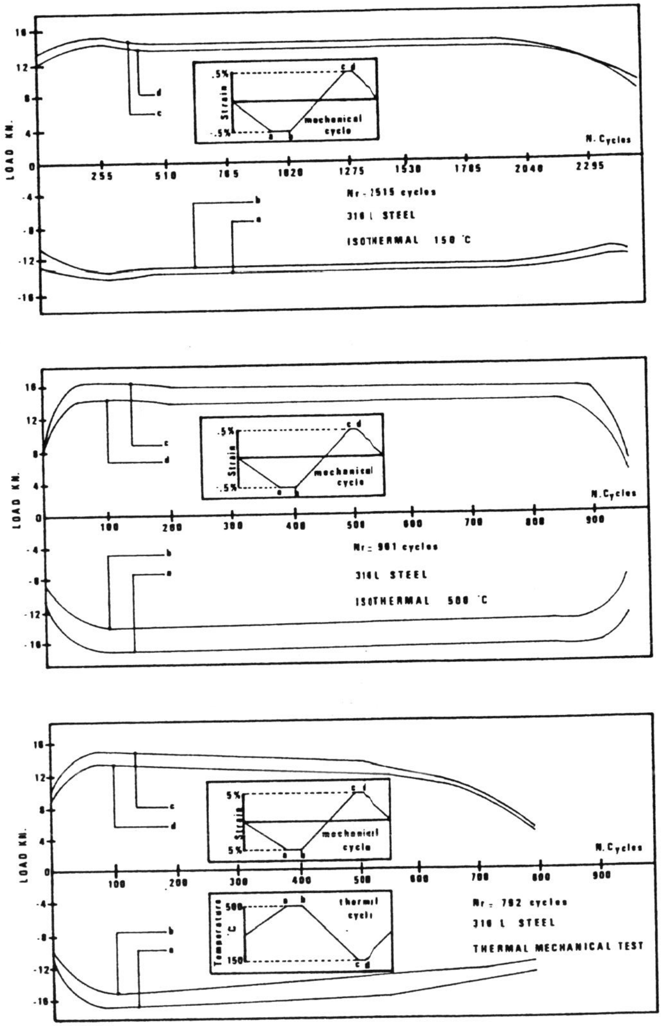


Figure 3: Evolution of the loads versus the number of cycles in each test

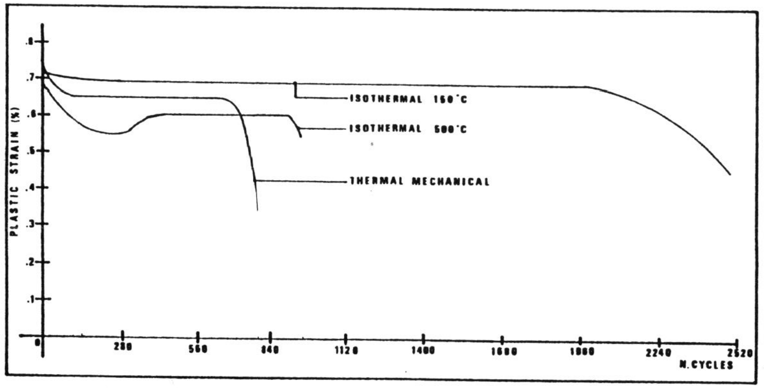
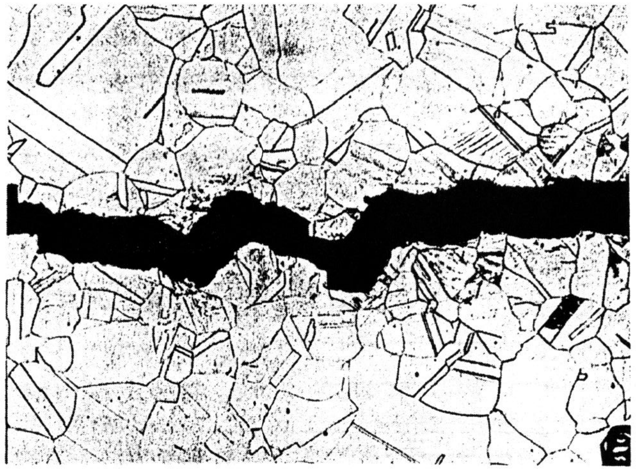


Figure 4: Evolution of the plastic strain versus the number of cycles



X 160

Figure 5: Main crack on 316L steel at 150°C