THERMAL MECHANICAL, LOW CYCLE FATIGUE OF 25 CD4 STEEL

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This study was undertaken to develop an understanding of the fatigue resistance of 25 CD4 steel under conditions of combined thermal and mechanical strain cycling in air. Comparative evolutions were made with existing thermal mechanical fatigue data on Cr-Mo steel and with results of a comprehensive, companion study of the fatigue behaviour of this same steel under isothermal conditions. Thermal mechanical fatigue behaviour was investigated for constant amplitude, fully reversed, strain cycling of uniaxially loaded specimens at two ranges of temperature a) 100 to 300° C b) 100 to 500° C and strain in phase with maximum temperature.

INTRODUCTION

Mechanical equipment and structural components are often subjected to cyclic straining while operating at elevated temperature and thermal fatigue is a recognized failure mode as for structures such as gas turbine components with combined temperature and strain cycling. The only results in phase thermal mechanical cycling were those reported by some authors (1,2,3,4) .
In some examples the temperature may be constant, while, in other cases, the cyclic straining may be accompanied by thermal cycling. The problem becomes for more complex when the relationship between temperatures and strain must the taken into account. This paper described the results of a study where the low cycle fatigue behaviour of 25 CD4 steel was investigated for conditions of combined thermal and mechanical strain cycling. Experiments were limited to the extreme condition of in phase cycling and a model based on a relationship between thermal fatigue strength and low cycle fatigue strength is proposed and discussed.

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EXPERIMENTAL PROCEDURE

The thermal mechanical fatigue experiments are conducted using a servocontrolled electrohydraulic machine. The axial mechanical strain and temperature were controlled to follow one of the both basic constant amplitude waveforms shown in Fig. 1 : ε_{max} is in phase with T_{max}. The control program wavefrom was provided by a function generator. Heating rate was constant and determined by the thermal response of the specimens and the heating equipment with the length of the thermal cycle maintained at about 2½ min (T_{max} = 300° C, T_{min} = 100° C) or 5 mn (T_{max} = 500° C, T_{min} = 300° C). The total strain amplitude $\Delta\varepsilon_t$ varies from 0,1 % to 1,2 %.

The chemical composition of the sheet is shown in table I.

Element	C	S	P	Si	Mn	Ni	Cr	Mo	V
Weight %	0,26	0,009	0,012	0,325	0,635	0,56	1,08	0,980	0,3

Table I

Experimental conditions in isothermal low cylce fatigue are as follows ;
- strain rate 3,2 $10^{-3} s^{-1}$
- testing temperature 100° C - 300° C - 500° C

RESULTS : Isothermal low cyle fatigue

Experimental relations between the total strain rage $\Delta\varepsilon_t/2$ and the number of cycles to failure N_R is shown in table II :

$\Delta\varepsilon_t/2$	0,3 %	0,5 %	0,7 %	1 %	1,2 %
500° C	3 300	1 116	-	330	-
300° C	-	2 485	1 120	673	500
100° C	-	3 735	1 550	705	508

Table II

The total strain amplitude can be separated into its elastic and plastic components. In low cycle fatigue testing, the plastic component of the strain amplitude is characterized by the fatigue ductility properties and the elastic component by the fatigue strength properties of the material according to MANSON COFFIN BASQUIN equations :

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma'_f}{E} \cdot (2\,N_R)^b \qquad (1)$$

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f \cdot (2N_R)^c \qquad (2)$$

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_p}{2} + \frac{\Delta\varepsilon_e}{2} \qquad (3)$$

with b = fatigue strength exponent
c = fatigue ductility exponent

The different parameters of these equations are shown in table III

T° C	σ'_f/E (%)	b	ε'_f (%)	c
100	0,451	- 0,0737	52,396	- 0,648
300	0,459	- 0,0758	50,363	- 0,659
500	0,367	- 0,0849	43,797	- 0,698

Table III

Thermal mechanical, low cycle fatigue

Typical hysteresis loop generated in type 25 CD4 stainless steel in shown in Fig. 2 Results of all experiments are summarized in table IV.

	N_R (cycles)	
$\frac{\Delta\varepsilon_t}{2}$ (%)	ΔT : 100 à 500° C	ΔT : 300 à 500° C
1,21	183	230
1,01	210	397
0,7	583	1 185
0,505	2 690	-
0,5	3 000	-
0,1	430	615
0,014	2 500	936

Table III

DISCUSSION

According to JASKE (2) plastic strain in thermochanical fatigue $\Delta\varepsilon_{ptm}$ is defined by the relation

$$\Delta\varepsilon_{ptm} = \Delta\varepsilon_t - \left(\frac{\sigma}{E}\right)T_{max} - \left(\frac{\sigma}{E}\right)T_{min} \qquad (4)$$

TAIRA /4/ has suggested the use of the concept of an equivalent temperature for correlating thermal fatigue behaviour with isothermal behaviour. This concept states that, regarding thermal fatigue cycling between two temperatures, the same fatigue life will be developed by isothermal cycling at the equivalent temperature.

As for thermal fatigue of 0.16 percent carbon steel it was shown that the equivalent temperature was defined as follows

$$T_e \simeq \frac{T_{max} + T_{min}}{2} \quad \text{for } T_{max} < 400° \text{ C} \qquad (5)$$

$$T_e \simeq T_{max} \quad \text{for } T_{max} > 500° \text{ C} \qquad (6)$$

The experimental results are shown in Table V and they are compared with the life prediction given by TAIRA'S concept.

ΔT = (300° C) - 500° C			T_e = 400°C
$\frac{\Delta\varepsilon_t}{2}$ %	$\frac{\Delta\varepsilon_{ptm}}{2}$	N_R cycles	N_R cycles
1,2	0,979	183	322
1	0,857	210	392
0,7	0,498	583	873
0,505	0,304	2 690	1800
0,5	0,293	3 000	1910
0,1	0,263	430	2230
0,014	0,204	2 500	3240

ΔT = 100 - 500° C			Te= 300°C
$\frac{\Delta\varepsilon_t}{2}$ %	$\frac{\Delta\varepsilon_{ptm}}{2}$ %	N_R cycles	N_R cycles
1,2	0,974	230	398
1	0,783	397	555
0,7	0,511	1 185	1060
0,1	0,312	615	2240
0,014	0,237	936	3400

Table V

DEGALLAIX / 5 / et al fit the damage with the following expression where A1, B1, A2, B2 are material constants and Q is an apparent activation energy. The values obtained from a computer code are for our material

$$\frac{1}{N_R} = A_1\ (\Delta\varepsilon_p)^{B_1} \exp\left(-\frac{Q}{RT}\right) + A_2\ (\Delta\varepsilon_p)^{B_2} \qquad (7)$$

A1 = 70 550 10^{-5}
B1 = 1,334
A2 = 224 10^{-5}
B2 = 1,543
R = 2 10^{-3} Kcal/mole.K
Q = 8,891 Kcal/mole K

From eq. (7) it is clear that in an isothermal fatigue tests and during each half cycle, plastic strain $\delta\varepsilon_p$ changes from the value 0 to $\Delta\varepsilon_p$ and damage $\delta\varphi$ from 0 to $\Delta\varphi$ as :

$$\delta\varphi = \frac{A_1}{2}\,\delta\varepsilon_p^{\,b_1} \exp\left(-\frac{Q}{Rt}\right) + \frac{A_2}{2}\,\delta\varepsilon_p^{\,b_2} \qquad (8)$$

Although eq. (8) describes originally isothermal damage, it is assumed that this equation is applicable to thermal fatigue in which the variation of T has to be considered. Then the increment of damage $d(\delta\varphi)$, connected with the increments of plastic strain $d(\delta\varepsilon p)$ and of temperature dT, is given, differentiating eq.(8) by :

$$d(\delta\varphi) = \left[\frac{A_1 B_1}{2}\,\delta\varepsilon_p^{\,B_1-1} \exp\left(-\frac{Q}{RT}\right) + \frac{A_2 B_2}{2}\,\delta\varepsilon_p^{\,B_2-1}\right] d(\delta\varepsilon_p)$$
$$+\left[\frac{A_1}{2}\,\delta\varepsilon_p^{\,B_1}\,\frac{Q}{RT^2} \exp\left(-\frac{Q}{RT}\right)\right] dT \qquad (9)$$

With numerical values εp and T taken on the stabilized hysteresis loop, the integration of eq. (9) allows the damage evaluation during the heating ($T_1 \to T_2$) and cooling ($T_2 \to T_1$) paths.

Then the thermal fatigue damage per cycle, i.e :

$$\Delta\Phi_{[T_1 \rightleftarrows T_2]} = \Delta\Phi_{[T_1 \to T_2]} + \Delta\Phi_{[T_2 \to T_1]} \qquad (10)$$

gives an estimation of the fatigue life . By using eq(7), parameters $\Delta\varepsilon$ p and T of equivalent isothermal tess can be determined.

Making up evolution of $\frac{\Delta\varepsilon_p}{2}$ as a function of temperature results are shown in table VI.

ΔT : 300° C-500° C		DEGALLAIX	ΔT : 100° C-500° C		DEGALLAIX
$\frac{\Delta\varepsilon_t}{2}$ %	N_R (cycles)	N_R (cycles)	$\frac{\Delta\varepsilon_t}{2}$ %	N_R (cycles)	N_R (cycles)
1,21	183	332	1,21	230	395
1	210	439	1	397	547
0,7	583	904	0,7	1 185	1 040
0,505	2 690	1 900	0,1	615	2 490
0,5	3 000	1 980	0,014	936	3 910
0,1	430	2 740			
0,014	2 500	4 320			

Table VI

The fatigue life values obtained from experiments were much lower than life predicted from isothermal fatigue data. Results of the thermal mechanical fatigue experiments are compared with the isothermal fatigue data in terms of $\Delta\varepsilon t$ in fig. 3.

Based on $\Delta\varepsilon_t/2$ (also true for $\Delta\varepsilon_p/2$/2) the thermal mechanical results fell below the isothermal results. In thermal mechanical fatigue it is necessary to take into account the evolution of thermal strain. So the mechanical strain $\Delta\varepsilon_m$ can be written by the equations

$$\Delta\varepsilon_m = \Delta\varepsilon_t - \Delta\varepsilon_{th} \text{ for } \Delta\varepsilon_t > \Delta\varepsilon_{th} \quad (11)$$

or

$$\Delta_m = \Delta\varepsilon_t + \Delta\varepsilon_{th} \text{ for } \Delta\varepsilon_t < \Delta\varepsilon_{th} \quad (12)$$

where $\Delta\varepsilon_{th}$ represents thermal strain between T_{max} and T_{min}.

Table VII gives the values of $\Delta\varepsilon_m/2$ for different experiments.

	$\frac{\Delta\varepsilon_t}{2}$ (%)	ΔT(° C)	$\frac{\Delta\varepsilon_m}{2}$ (%)	N_R cycles
$\Delta\varepsilon_t > \Delta\varepsilon_{th}$ + 0,2 %	1,21	300-500	0,936	183
	1,21	100-500	0,814	230
	1	300-500	0,731	210
	1	100-500	0,614	397
$\Delta\varepsilon_m = \Delta\varepsilon_t - \Delta\varepsilon_{th}$	0,7	300-500	0,426	583
	0,7	100-500	0,312	1 185
	0,505	300-100	0,226	2 690
	0,5	300-500	0,221	3 000
$\Delta\varepsilon_t < \Delta\varepsilon_{th}$ - 0,2 %	0,1	100-500	0,496	615
$\Delta\varepsilon_m = \Delta\varepsilon_t \Delta\varepsilon_{th}$	0,014	100-500	0,406	936
	0,1	300-500	0,379	430
	0,014	300-500	0,293	2 500

$\frac{\Delta\varepsilon_{th}}{2}$ = 0,396 % (100-500° C)

$\frac{\Delta\varepsilon_{th}}{2}$ = 0,279 % (300-500° C)

Table VII

Life as a function of mechanical strain in thermal fatigue $\Delta\varepsilon_m$, plastic strain in isothermal fatigue is shown in Fig. 4
The relation between mechanical strain and life is given by the equation

$$\frac{\Delta\varepsilon_m}{2} = 12{,}16\, N_R^{-0{,}505} \qquad (13)$$

We can see in fig.5 that straight line breaks through the plastic strain lines in isothermal fatigue for three points A,B,C corresponding with the thermal strain amplitude between 20°C and the considered temperature as it is seen in Table VIII.

T(°C)	Point position	value of $\Delta\varepsilon/2$ (%)	$\frac{\Delta\varepsilon_{th}}{2}$ 20-T°C
100	A	0,07	0,06
300	B	0,12	0,19
500	C	0,43	0,40

Table VIII

So we can write that thermal mechanical fatigue experiments with mechanical strain, $\Delta\varepsilon_m$, are equivalent to isothermal fatigue experiments with plastic strain, $\Delta\varepsilon_p$.
For each temperature in isothermal fatigue, the number of cycles to failure, N_R, can be expressed as

$$N_R = \left(\frac{\Delta\varepsilon_p}{2\,\varepsilon'_{fT}}\right)^{1/C_T} = g\left(\frac{\Delta\varepsilon_m}{2}\right)^s \qquad (14)$$

Where C_T and C_{fT} are the coefficients of the MANSON COFFIN law at the considered temperature, T, in isothermal experiments, g and s are material constants no functions of temperature. Mechanical strain can be written $\Delta\varepsilon_m = \alpha\,(T_1 + 20°\ C)$ but neglecting thermal strain between 0 and 20° C we obtain $\Delta\varepsilon_m = \alpha\,T_i$ so equation 14 can be written :

$$g\left(\frac{\alpha T_i}{2}\right)^s = \left(\frac{\alpha T_i}{2\varepsilon'_{fT}}\right)^{1/C_T} \qquad (15)$$

and $$N_R = g\left(\frac{\Delta\varepsilon_m}{2}\right)^s \qquad (16)$$

Material constants g and s, are determined from the MANSON COFFIN coefficients in isothermal experiments, which give an estimation of the thermomechanical fatigue life using equation.16.

For the 25 CD4, the value of constants g and s in equation (16) are obtained from the test results as follows:

$$g = 11{,}68\ 10^{-3}$$

$$s = -\ 2{,}022$$

Also shown in Fig. 6 calculated fatigue lifes using isothermal fatigue curves are compared with experimental thermal-mechanical fatigue life.
On the basis of $\frac{\Delta\varepsilon_m}{2}$ versus N_R, the thermal-mechanical fatigue life is well correlated with the isothermal fatigue life.

CONCLUSION

Many criteria for thermal fatigue failure have been proposed but almost all of them seem to be little authorized. Both of the combined effects of temperature and strain as well as the wide variations of test methods make it difficult to find a general rule.

The experimental results in thermal-mechanical fatigue were compared with the predicted life of the material obtained from the low cycle fatigue data at constant temperatures. The results obtained are summarized as follows :

The relationship between the mechanical strain range $\Delta\varepsilon_m$ and the number of cycles to failure N_R under fixed Tmax and Tmin can be described by $\Delta\varepsilon_m = 12{,}16 N_R^{-0{,}505}$

A model based on a relationship between thermal fatigue and low cycle fatigue strength is proposed. According to the relation

$$g\left(\frac{\alpha T}{2}\right)^{s} = \left(\frac{\alpha T}{2\varepsilon' f_T}\right)^{1/C_T} = N_R$$

we observe good agreement between experimental results and those predicted by the proposed model.

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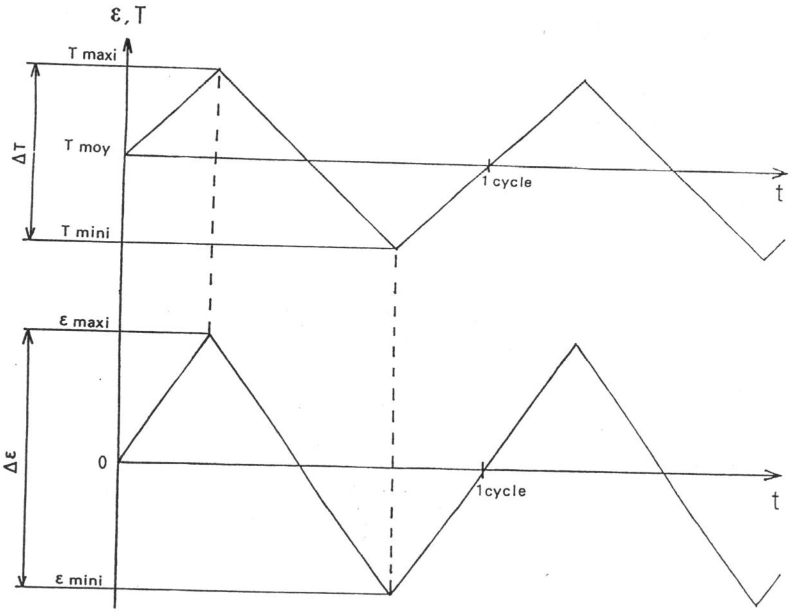

Figure 1 : Illustration of control waveforms

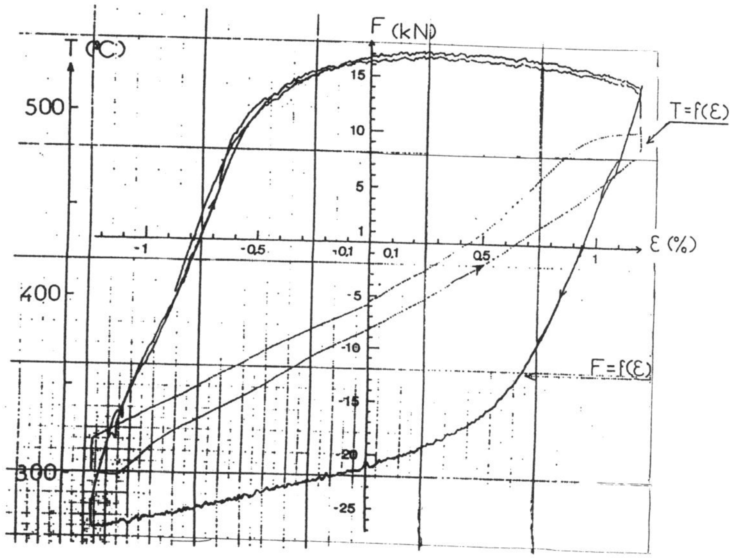

Figure 2 : Stress-strain hysteresis loop for 300 to 500° C cycle with ε_{max} at Tmax

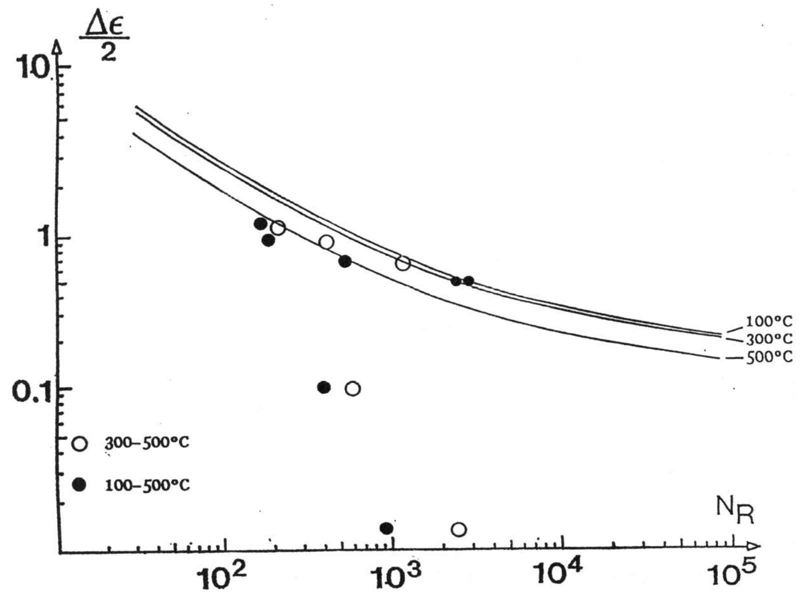

Figure 3 : Isothermal and thermal cycle fatigue tests on 25CD4 steel

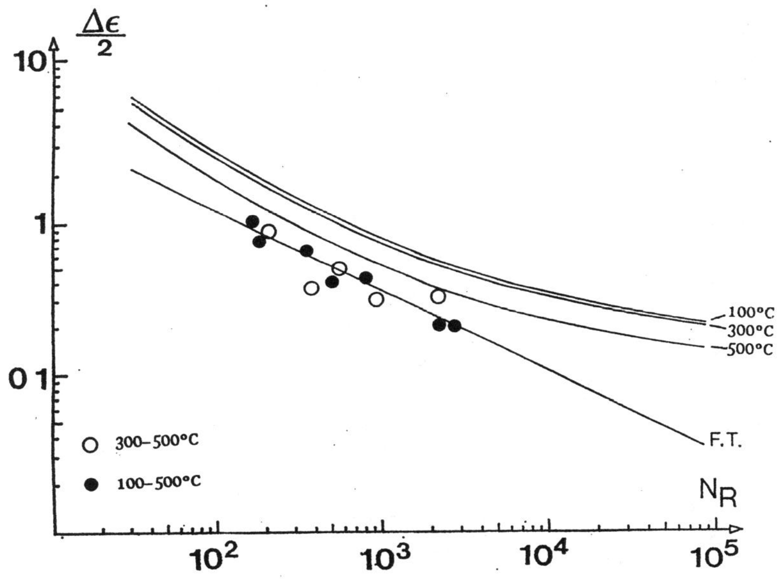

Figure 4 : Comparison of mechanical strain in thermal fatigue with total strain in low cycle fatigue

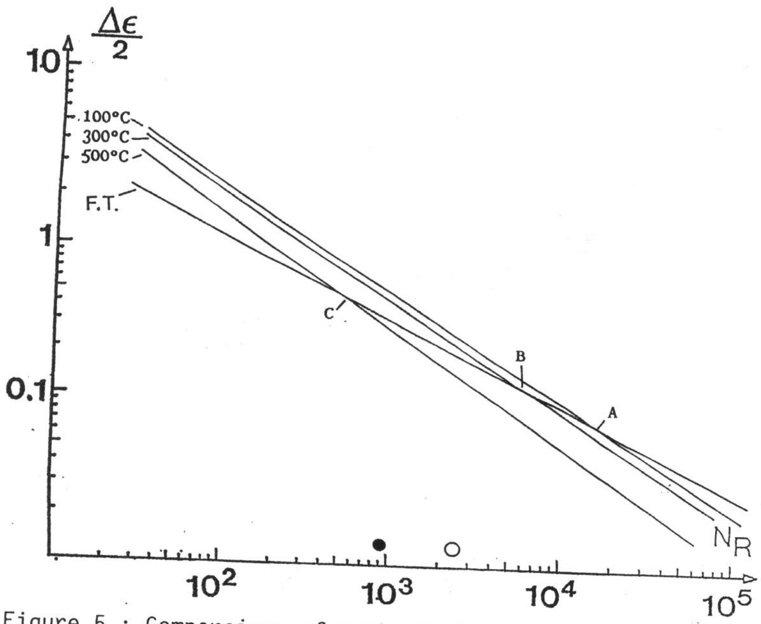

Figure 5 : Comparison of mechanical strain in thermal-fatigue with plastic strain in low cycle fatigue

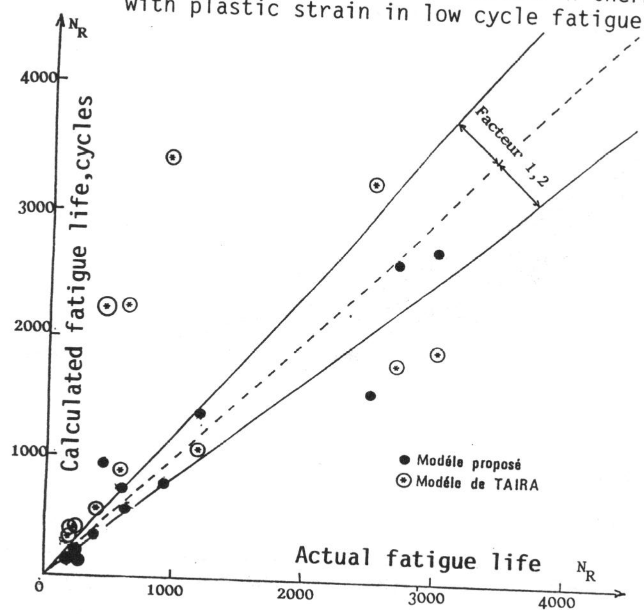

Figure 6 : Comparison of actual thermal-mechanical fatigue life with cyclic life calculated from isothermal fatigue curves