ON THE INTERACTION OF HARDENING AND FATIGUE DAMAGE IN THE 316 STAINLESS STEEL

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ABSTRACT

Several steels and particularly the 316 stainless steel exhibit a very complex behaviour under cyclic loading. When structure calculations are needed, such a complex behaviour has to be modelized, as accurately as possible, by means of some macroscopic constitutive equations, taking into account monotonic and cyclic plasticity, viscoplasticity (or creep), cyclic hardening, aging, damage, damage softening, etc . . This paper deals with the tools and the modelizations which can be developed in order to include some coupled effects such as the strain hardening and the fatigue damage processes.

The damage internal variable, used as a measure of the deterioration processes, is introduced through macroscopic and continuum mechanics considerations, and previously developed damage equations are recalled. Results of an experimental study made at room temperature on the 316L stainless steel shows large increases in stress controlled fatigue life induced by monotonic prestrains. This influence of initial hardening effect is taken into account in the fatigue damage equation by introducing a new internal variable which keeps memory of the largest plastic strain range. The damage equation and the proposals to account for pre-hardening effect are validated by comparison with the damage evolution, measured in the stress controlled fatigue tests (with or without prestrain) through the effective stress concept.

KEYWORDS : Fatigue, hardening, interaction, damage, constitutive equations, stainless steel.

INTRODUCTION

Life prediction in structures undergoing cyclic loadings generally includes two main steps : – crack initiation prediction from some calculated stabilized stress-strain behaviour, –crack propagation analysis by the Fracture Mechanics concepts. With the objective to improve the first step, several works were developed during the past ten years, around the idea of a continuous damage modelling, following the concepts initially introduced by Kachanov (1958) and Rabotnov (1969) for the creep case. This mechanistic approach (Krempl, 1977 ; Lemaitre, 1979 ; Chaboche, 1979a) of the progressive material strength deterioration, focuses not only on the instant of the macroscopic crack initiation, which represents the last phase, but also on a macroscopic description of the successive processes giving rise to this initiation.

The damage concepts and damage constitutive equations have been developed in order to take into account some non linear cumulative effects, or sequence effects (Gatts, 1961 ; Bui-Quoc and others, 1971 ; Chaboche, 1974), introducing a stress (or strain) dependency of the damage evolution curves as a function of the life ratio (Marco, Starkey, 1954 ; Bui-Quoc, 1978). In several experimental studies of the cumulative damage (Erickson, Work, 1961 ; Blatherwick, Viste, 1967) possibility of some "negative damage" has been shown, which is in opposition to the normal concepts of damage and particularly to their introduction from the general framework of thermodynamics with internal variables : in such a case the second principle could be violated (Chaboche, 1977 ; Lemaitre, 1978). Then, the simple stress dependency mentioned above has to be improved by some interaction damage rules (O'Neill, 1970 ; Matolcsy, 1972 ; Bui-Quoc, 1978), where the damage evolution curve at the second stress level is modified by application of a first stress level. At the present time the interaction theories do not use the concepts of internal variables, which limit their applicability to particular loadings.

The purpose of this paper is to show how these "negative damage" effects can be modelized by the introduction of a new internal variable in the damage evolution equations, leading to a more general applicability than the usual interaction rules. The theory is supported by results of an experimental study on the tension-compression behaviour of the 316L stainless steel at room temperature, showing a particularly pronounced beneficial influence of the hardening on the fatigue life.

INTERNAL STATE VARIABLES AND CONTINUOUS DAMAGE MECHANICS

Macroscopic Crack Initiation and Continuous Damage

Before any damage theory, it is necessary to precise what we mean by the ultimate state of the damage processes : under the present development of Continuous Damage Mechanics, this final state corresponds generally to the macroscopic crack initiation, that is the presence of a material discontinuity, sufficiently large as regards the microscopic heterogeneities (grains, subgrains ...) : in such a case, the main macroscopic crack is assumed to be developed through several grains, in order to show a sufficient macroscopic homogeneity, in size, geometry and direction, leading to a possible treatment through the Fracture Mechanics concepts (Chaboche, 1979a).

The damage variable is introduced within the framework of Continuum Thermodynamics, through homogeneization concepts (Duvaut, 1976) and, incorporates in only one modelization different physical processes, depending on temperature, loading conditions and time from begining of test. Until now this damage variable describes together nucleation of submicroscopic cracks, microcrack initiation and microcrack propagation processes.

Damage Definition by the Effective Stress Concept

Damage measurement constitutes a difficult problem, with many controversial points depending on the chosen definition of damage. In the case of a material volume element several methods has been used :

— measures of defects on a microscale (density, area . . .) which are not directly usable for a mechanical analysis, but lead to some physical modelizations (Wilson, 1976 ; Levaillant, Rezgui, Pineau, 1979),

— measures by the variation of physical quantities, in a macroscopic sense, such as density (Jonas, Baudelet, 1977), or resistivity (Cailletaud, Policella, Baudin, 1980), which need the use of some model in order to attain mechanical characteristics,

— measures by the remaining life as used in creep by Woodford (1973), or in fatigue by Kommers (1945), Marco and Starkey (1954),

— measures by the reduction in fatigue limits (Gatts, 1961 ; Bui-Quoc and others, 1971), which need many tests to define the damage evolution curves,

— measures by the strain behaviour, which is now retained because on its easier applicability in each test (independently of the others) : this can be obtained in terms of elastic strain (Lemaitre, Dufailly, 1977), plastic strain range (Chaboche, 1974) or stress range (Plumtree, Lemaitre, 1978).

The theory is supported by the physical idea that crack initiation is preceeded by a progressive internal deterioration of the material, which induces a loss of strength in term of strain as well as in term of remaining life. Kachanov firstly proposed to relate these two aspects through a macroscopic damage variable, introduced with the effective stress concept. The phenomenological idea of a damage parameter D taking into account, on a macroscopic scale the microscopic deteriorations (voids, decohesions, microcracks, ...), is generally accepted (Krempl, 1977) with the following limiting values : $D = 0$ for the initially unstressed material, $D = D_c$ at failure, that is at the macroscopic crack initiation time (in several works the critical value D_c is taken as 1). The effective stress concept is used to describe the effect of damage on the strain behaviour : a damaged volume of material under the applied stress σ shows the same strain response than the undamaged one submitted to the effective stress :

$$\tilde{\sigma} = \sigma / 1-D \tag{1}$$

Under this definition D represents a loss of effective area taking into account decohesions and local stress concentrations through homogeneization concepts (Duvaut, 1976).

Equation (1) corresponds to the initial theory of Kachanov. Actually the microscopic damage process can give little loss of effective area before crack initiation, especially under fatigue loading : this give rise to very small value of the D parameter until a large fraction of life is consumed, which induces highly non linear damage evolution curves. However it must be underlined that small values of D can lead to large reductions in life : under the present approach the damage is no more proportional to N/N_F.

Application of this effective stress concept to fatigue damage measurements on 316L stainless steel gives additional informations concerning the form of damage equations (see § Fatigue Damage Evolution).

Such a concept can be generalized to any loading conditions, by introducing damage tensors on the basis of the measured strain behaviour of a damaged material as compared to the case of the undamaged material (Murakami, Ohno, 1978 ; Cordebois, Sidoroff, 1979 ; Chaboche, 1979b).

Fatigue Damage Equation

Let us begin by an important remark : these equations have to be developed under a differential form : an expression of D as a function of time for example constitutes only a response of the material to a particular forcing parameter (Ostergren, Krempl, 1979). All equations using the consumed potential as a damage parameter are so eliminated.

Second general remark : if non linear cumulative effects are needed these equations must have unseparable variables in terms of damage and the chosen forcing parameter (Krempl, 1977 ; Chaboche, 1974). In other words, the damage response functions have to be different under different loading conditions (Marco, Starkey, 1954 ; Bui-Quoc, 1978).

Three types of damage evolutions can be looked at : —as a function of stress in the static plactic failure (or in fatigue), — as a function of time for the creep processes (or for corrosion or irradiation processes), as a function of cycles for the fatigue processes. Each of them has to be identified by some specific tests, independently of the others, leading to the determination of the corresponding differential damage equations. Here we limit us to the fatigue process, through a description made in term of cycles : in its one dimensional form this equation writes :

$$dD = f(\varphi, \alpha, D, \ldots) dN \tag{2}$$

φ represents the chosen forcing variables : stress or strain or plastic strain, and α corresponds to the hardening internal variables.

The static damage, growing as a function of stress (or strain), is presently neglected : in fact, its influence can be introduced directly in the fatigue damage equation (2) through some specific choice of the function f (see section : Prediction of Fatigue Life with and without Prestrain). As mentioned above this function shows unseparability in φ and D, in order to describe non linear cumulative effects. In practice φ represents particular values of the forcing variables as defined on each cycle (maximum value, mean value ....).

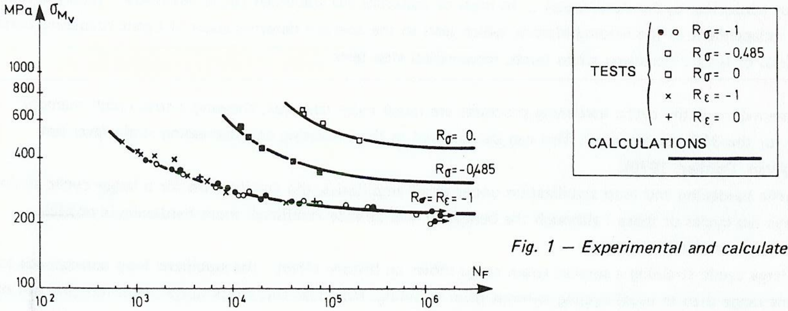

Fig. 1 — Experimental and calculated Wöhler's plot.

BENEFICIAL EFFECTS OF THE INITIAL HARDENING ON THE FATIGUE LIFE OF 316 L

Reversed Fatigue Tests with and without Prestrain

The fatigue behaviour of 316L stainless steel at room temperature has been experimentally studied in ONERA and in ENSET by various kind of tension-compression tests. The two experimental devices use cylindrical specimens with longitudinal extensometry, but two kinds of junction zones and extensometry attachments were used : toroidal junctions with large radius associated to a displacement transducer mounted on the gripping system with a plastic useful length determination (Chaboche, Policella, 1977 ; Chaboche, Policella, Kaczmarek, 1978) and a very short junction between cylindrical part and especially designed collars used as targets for an optical extensometer (Raine, 1980). Cracks initiate generally in the cylindrical part for the two technologies and stress, strain and number of cycles to failure are in a fairly good agreement as shown in figure 1 and 2 ($R_\sigma = -1.$). Correct agreement was also observed with results of other laboratories (Lieurade, 1978 ; Taupin, 1978 ; Pineau, Petrequin, 1978). More details on the experimental results were published previously (Chaboche, Kaczmarek, Raine, 1980).

The main observation for the reversed periodic loadings is the approximate equivalence between strain control and stress control in the Wöhler diagram (fig. 1), as well as for the plastic strain range diagram (fig. 2) and the dissipated energy (fig. 3), obtained from the stabilized cycle and the relation proposed by Halford (1966) :

(3) $$\Delta W = \frac{1-n'}{1+n'}\,\Delta\sigma\,\Delta\varepsilon_p$$

where the cyclic exponent n' was determined as n' = 0.25.

A number of cyclic tests under reversed stress control was made at ENSET after prestrains of 1 to 50% (apparent strain ε_a). Figure 4 indicates the large increase in life induced by this prehardening processes for the same levels of alternating stress ; applied values were corrected in order to take into account the section decrease :

(4) $$\sigma_v = \frac{F}{S_o}(1+\varepsilon_a) = \frac{F\,L}{S_o\,L_o} \qquad \varepsilon_v = \mathrm{Log}(1+\varepsilon_a) = \mathrm{Log}\,L/L_o$$

This life increase is accompanied by a large plastic strain range decrease for the stabilized conditions (fig. 5) but the correlation in the Manson-Coffin diagram (fig. 2) is very poor : for the same observed life the measured plastic strain range is lower as the one observed without prestrain, and an asymptotic effect appears for the largest lives. Correlation by energy criterium seems only a little better.

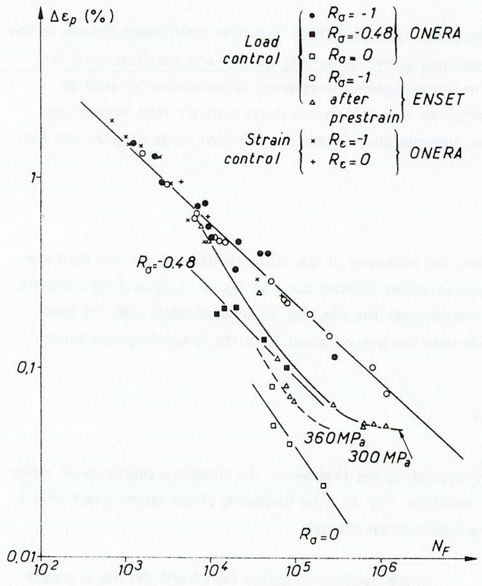

Fig. 2 — Manson Coffin curves.

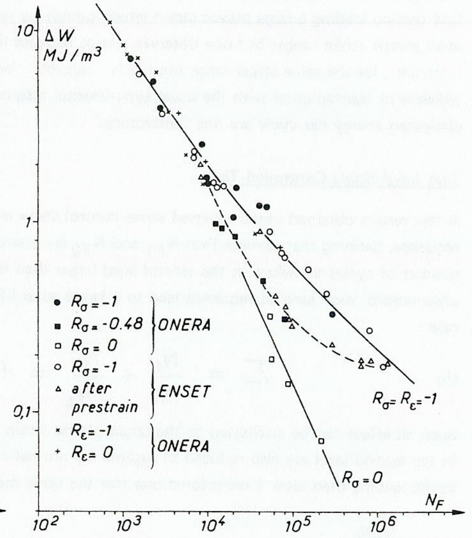

Fig. 3 — Dissipated energy versus number of cycles to failure.

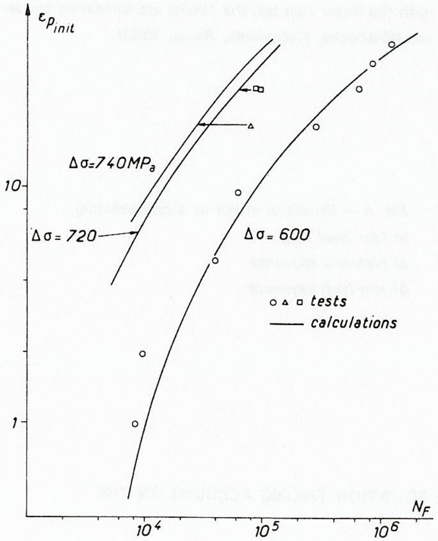

Fig. 4 — Beneficial effect of a prehardening on the number of cycles to failure (one level tests).

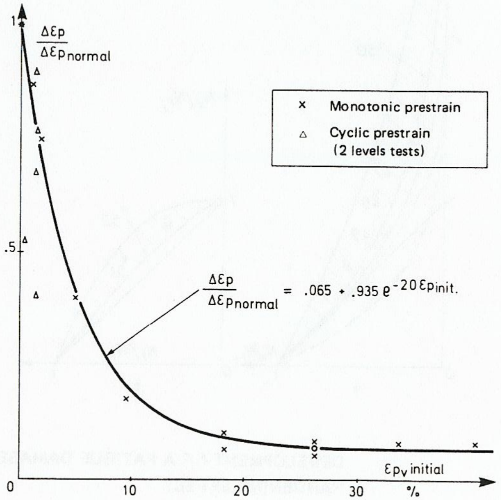

Fig. 5 — Influence of a prehardening on the plastic strain range.

Stress Control with Positive Mean Stress

This second kind of testing gives another way to observe the initial hardening effect : positive mean stress induces in the first tension loading a large plastic strain which cannot be reversed. Some ratchetting appears and stabilizes with very small plastic strain ranges but one observes a large increase in life as regards the common observations on most of materials : for the same stress range the life is sensibly larger for a positive mean stress than for zero mean stress, which is in contradiction with the usual experimental results. Interpretation in the plastic strain range diagram and the dissipated energy per cycle are not satisfactory.

Two Level Stress Controlled Tests

A few results obtained under reversed stress control show also the influence of the initial hardening : for the high-low sequence, defining the nominal lives N_{F1} and N_{F2} by a stress criterion (Wöhler curve of figure 1), several tests show a number of cycles to failure at the second level larger than the nominal one (fig. 6a). In contradiction with the usual observations, such kind of sequence lead to a larger total life than the one obtained from the linear Palgreem-Miner rule :

$$\Sigma = \frac{N_1}{N_{F_1}} + \frac{N_2}{N_{F_2}} = 1 \tag{5}$$

Such an effect can be attributed to the larger plastic strain induced by the first level ; the stabilized plastic strain range in the second level are also reduced as regards the normal conditions (fig. 5) : the hardening effect seems larger after a cyclic loading than after a monotonic one (for the same maximum strain ranges).

In the opposite sequence (low-high) the life is greater than predicted from the linear rule, which is much more usual (fig. 6b). Using criteria based on plastic strain range or dissipated energy lead to a better correlation with the linear rule but the results are somewhat scattered (Chaboche, Kaczmarek, Raine, 1980).

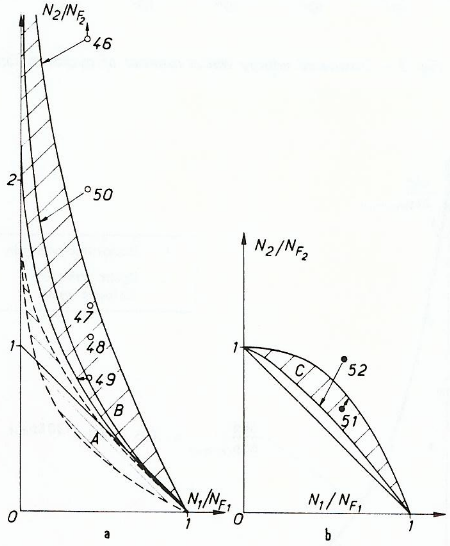

Fig. 6 — Beneficial effect of a prehardening in two level tests :
a) high-low sequence
b) low-high sequence.

DEVELOPMENT OF A FATIGUE DAMAGE EQUATION TAKING ACCOUNT ON THE HARDENING EFFECT

A New Internal Variable Keeping Memory of Hardening

At room temperature, when viscoplastic effects can be neglected, the stress-strain behaviour of a tension-compression cyclically loaded specimen indicates several complex phenomena, such as Bauschinger effects, anisotropic hardening, cyclic softening or hardening. cyclic statilization ... In most of materials the stabilized cyclic stress-strain response can be considered as independent of the loading history, which lead to the possible determination of cyclic hardening curves from different kinds of tests : increasing strain levels, incremental step tests ...

However, for some materials the cyclic hardening processes are much more complex, showing a strain path memory effect, especially for the 316 stainless steel. This can be observed in the increasing and decreasing strain level test (Chaboche, Dang-Van, Cordier, 1979).

– After cyclic hardening and loop stabilization under small amplitudes, the stabilization for a larger cyclic strain range needs always ten cycles or more : although the behaviour was already stabilized, more hardening is possible because on the increase in the strain range.

– After a large cyclic straining a smaller strain range shows an history effect : the stabilized loop corresponds to a much higher stress range than in usual cycling without prior straining. Moreover this stress range seems independent of the mean strain as long as the strain path is contained in the prior largest one.

Several other tests, such as the incremental step tests (Lieurade, 1978) indicate that the hardening effect essentially depends on the largest plastic strain range. In order to allow the description of cyclic behaviour, including this plastic strain path history effect, introduction of a new internal state variable in the plastic flow constitutive equations has been proposed recently (Chaboche, Dang-Van, Cordier, 1979). A generay way to define this variable q under complex three-dimensional loading was proposed ; addition to the classical isotropic and kinematic variables (Marquis, 1978) lead to a fairly well modelization of a large number of cyclic tests on 316L.

In the particular case of tension-compression loading this new internal variable q corresponds to the maximum plastic strain range applied to the specimen in its past history (this memory is non evanescent).

Prediction of Fatigue Life with and without Prestrain

Since the manifestations of the initial hardening effect on cyclic stress-strain behaviour and on the fatigue life seem similar, a natural way to introduce memory of hardening in the fatigue damage equation, is to use the new internal variable q just mentioned above. The equation (2) writes now :

$$dD = f(\sigma_M, \bar{\sigma}, q, D)\, dN \tag{6}$$

where the maximum stress σ_M and the mean stress $\bar{\sigma}$ in one cycle represent the forcing parameters (the choice of σ instead of ε is justified by the large range of studied lives : 500 to 10^6 cycles).

In the case of 316L steel a correct correlation is obtained by using a fatigue damage equation developed previously (Chaboche, 1974), which gave good results for cumulative damage in many materials at room or high temperature. Without the hardening effect it writes :

$$dD = \left[1 - (1-D)^{\beta+1}\right]^{\alpha(\sigma_M, \bar{\sigma})} \left[\frac{\sigma_M - \bar{\sigma}}{M(\bar{\sigma})(1-D)}\right]^{\beta} dN \tag{7}$$

where the damage D varies between 0 for undamaged conditions and 1 for the macroscopic crack initiation (complete fracture in the considered cases). In a test under periodic stress loading the number of cycles to failure N_F comes by integration :

$$N_F = \frac{1}{(\beta+1)\left[1-\alpha(\sigma_M, \bar{\sigma})\right]} \left[\frac{\sigma_M - \bar{\sigma}}{M(\bar{\sigma})}\right]^{-\beta} \tag{8}$$

Several material were correctly modelized by the following choices (Lemaitre, Chaboche, 1978) :

(9)

$$\alpha(\sigma_M, \bar{\sigma}) = 1 - a \left\langle \frac{\sigma_M - \sigma_\ell(\bar{\sigma})}{\sigma_u - \sigma_M} \right\rangle$$

$$\sigma_\ell(\bar{\sigma}) = \bar{\sigma} + \sigma_\ell (1 - b\bar{\sigma}/\sigma_u)$$

$$M(\bar{\sigma}) = M_o (1 - b\bar{\sigma}/\sigma_u)$$

where σ_ℓ play the role of a fatigue limit (N_F is infinite if $\sigma_M \leqslant \sigma_\ell(\bar{\sigma})$ (*)), and σ_u corresponds to the ultimate tensile strength.

The new hardening variable is supposed to act on the coefficients σ_u, σ_ℓ, M_o (many results demonstrate the increase of fatigue limit by prior hardening and the ultimate strength is clearly affected by cyclic straining). The relations (9) are replaced by :

(10)

$$\alpha(\sigma_M, \bar{\sigma}, q) = 1 - a \left\langle \frac{\sigma_M - \sigma_\ell(\bar{\sigma}, q)}{\sigma_u(q) - \sigma_M} \right\rangle$$

$$\sigma_\ell(\bar{\sigma}, q) = \bar{\sigma} + \sigma_{\ell_c}(1 + k_1 Z(q))(1 - b\bar{\sigma}/\sigma_{u_o})$$

$$\sigma_u(q) = \sigma_{u_o}(1 + k_2 Z(q))$$

$$M(q) = M_o(1 + k_3 Z(q))$$

where Z(q) is a power function of the maximum plastic strain range. In the present case a good correlation was obtained with $Z(q) = \sqrt{q}$ and the following values for the coefficients :

$\sigma_{\ell_c} = 222$ MPa $\sigma_{u_o} = 580$ MPa $M_o = 1650$ MPa
$\beta = 5$ $a = 0{,}9$ $b = 0{,}25$
$k_1 = 0{,}4$ $k_2 = 2{,}2$ $k_3 = 1{,}6$

The coefficient a does not influence the fatigue lives (it is multiplied by $M_o^{-\beta}$) but was determined from measures of damage evolution during some fatigue tests (see Chapter Fatigue Damage Evolution).

The predictions of number of cycles to failure for all testing conditions are made by using measured values of the maximum plastic strain range. Under reversed cycling (stress or strain) this corresponds to the first plastic strain range, which is approximated by : $q = \Delta\varepsilon_{P_1} = (\sigma_M / 813)^{5.5}$. Under non alternating conditions one use the maximum plastic strain at half life : $q = (\sigma_M / 978)^{3.8}$ for $R_\sigma = R_\varepsilon = 0$, $q = (\sigma_M / 832)^{3.8}$ for $R_\sigma = -0.425$. For tests after prestrain, q corresponds to the maximum plastic strain. All quantities are exprimed by taking account on geometric effects through relations (4).

Figures 1 and 4 show the very good modelizations of the Wöhler curves, including non zero mean stresses and of the influence of prestrain on the fatigue life.

Prediction of two level stress controlled tests was made by integrating fatigue damage equation (7) in two steps. For the

high-low sequence ($\sigma_{M_1} > \sigma_{M_2}$, $\bar{\sigma}_1 = \bar{\sigma}_2 = 0.$) one obtain :

(11)
$$\frac{N_2}{N_{F_2}} = \frac{1-\alpha_2}{1-\alpha_{2,1}} \left(\frac{M_{2,1}}{M_2}\right)^{\beta} \left[1 - \left(\frac{N_1}{N_{F_1}}\right)^{\frac{1-\alpha_{2,1}}{1-\alpha_1}}\right]$$

where $\alpha_1 = \alpha(\sigma_{M_1}, q_1)$; $\alpha_2 = \alpha(\sigma_{M_2}, q_2)$; $M_{2,1}$ and $\alpha_{2,1}$ are the values at second level taking into account the hardening effect induced by larger plastic strains during first level : $M_{2,1} = M(q_1)$; $\alpha_{2,1} = \alpha(\sigma_{M_2}, q_1)$. In such a case the interaction effect of the different levels appears clearly : figure 7 indicates schematically how the damage evolution curve at the second level is modified by the first level. For the low-high sequence no hardening is memorized ($q_2 > q_1$) and the usual prediction (Chaboche, 1974) follows from $M_{2,1} = M_2$ and $\alpha_{2,1} = \alpha_2$.

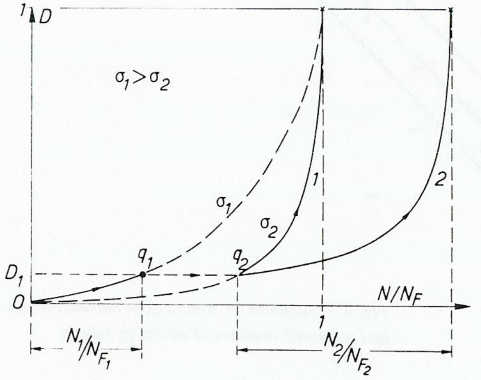

Fig. 7 – Schematic evolution of damage in the two level fatigue test :

(1) stress dependent evolution, without interaction ($q_1 = q_2$)

(2) evolution with interaction ($q_1 \neq q_2$).

Two predictions were made for the high-low sequence : –interaction is based on the measured maximum plastic strain range in first level : $q = (\sigma_M / 813)^{5.5}$;
– interaction takes into account the more pronounced hardening effect in such kind of test, evident from the larger decrease of stabilized plastic strain range (at second level) under the cyclic prestraining, as regards the monotonic prestrains (fig. 5). First kind of predictions agrees only qualitatively, showing possibility of lives larger than the nominal one (fig. 6) ; under the second procedure, agreement is quantitatively better. For low-high sequences the normal non linear cumulation rule gives a correct approximation.

All the predictions are summarized on figure 8 and compared with the measured numbers of cycles to fracture. Except for a few tests, predictions and tests are in accordance within factors less than 2.5. Correlation of a large number of tests of various kinds, accounting for the hardening effect, is possible. The quality of correlation is underlined by comparison to the factors larger than 10 or 20 when using plastic strain range or energy criteria (figures 2 and 3).

Fatigue Damage Evolution

The effective stress concept leads to the possibility of some damage quantification during the stress controlled fatigue tests by comparing the measured plastic strain in each cycle to its stabilized value (damage is supposed to be small at the stabilized cycle if this state arises for a small life ratio, as in the present case). This procedure has been detailed previously (Chaboche, 1974 ; Lemaitre, Chaboche, 1978), especially for the room temperature fatigue of 316L (Chaboche, Kaczmarek, Raine, 1980).

Typical results are indicated figure 9 for reversed stress cycling, showing the stress dependency as in many other materials. The same kind of dependency appears from measurements made during testing after prestrains (fig. 10) : the more the prestrain the more non linear damage evolution.

(*) The notation $\langle\ \rangle$ is defined by : $\langle u \rangle = \begin{cases} u \text{ if } u > 0, \\ 0 \text{ if } u \leqslant 0 \end{cases}$

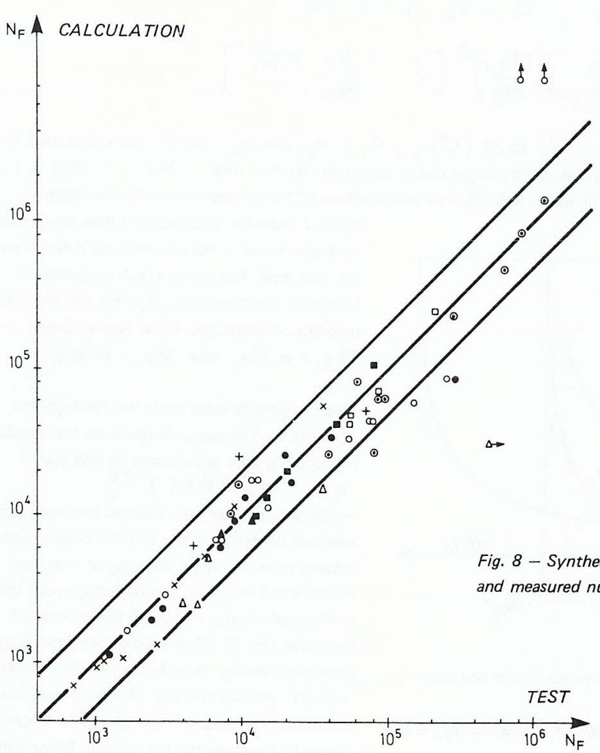

Fig. 8 – Synthesis of comparisons between predicted and measured numbers of cycles to failure.

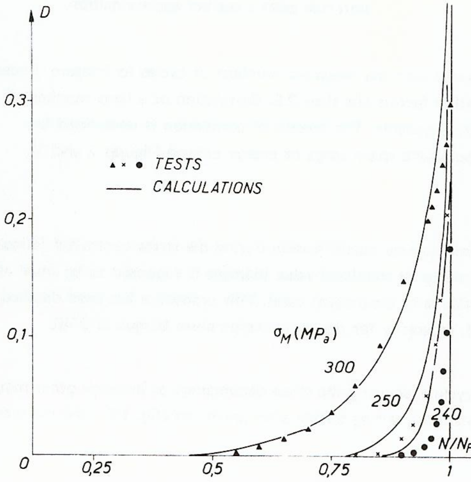

Fig. 9 – Evolution of fatigue damage in tests (without prehardening).

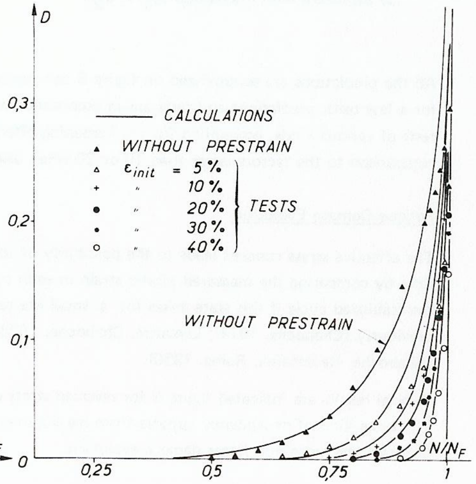

Fig. 10 – Evolution of fatigue damage in tests after prehardening (σ_M = 300 MPa).

The fatigue damage equation (7) studied above can be validated from these damage measurements : integration between 0 and D for fixed stress conditions leads to :

(12) $$D = 1 - \left[1 - \left(\frac{N}{N_F}\right)^{\frac{1}{1-\alpha}}\right]^{\frac{1}{\beta+1}}$$

The coefficient a = 0.9 in the function α(10) is determined from the normal test under ± 300 MPa. Equations (10) and (12) permits to calculate damage evolutions under any conditions : the predicted curves of figures 9 and 10 show a fairly well correlation with the measures, which justify the choice of function α , of its dependency in the prestrain q and verify the values of the whole set of coefficients. The form of fatigue damage equation is also indirectly supported by this comparison, which demonstrates the coherence between the various concepts used in this study of the interaction of hardening and damage processes.

CONCLUSION

The room temperature cyclic behaviour of 316 stainless steel results from interaction of complex hardening and damaging processes. The present study shows that :

– the influence of damage initiation and growth on the cyclic behaviour, measurable in the last part of tension-compression tests can be modelized through the effective stress concept,

– the beneficial influence of prestraining upon the fatigue damage and the fatigue life can be taken into account by introducing in the fatigue damage equation a new internal variable, keeping memory of the maximum plastic strain range.

The proposed differential fatigue damage equation was validated from a large number of tension-compression results, including zero or non-zero mean stress loadings, stress controlled tests after prestrain, two level tests. The formulation gives good predictions for the numbers of cycles to fracture as well as for the damage evolution curves : the influence of stress level and the influence of prestrain value are correctly described.

Several extensions or modifications could be studied for this macroscopic approach of damage and hardening processes :

– application of the proposed formulation with hardening and damage coupling could describe complex sequence effects with a "negative damage", as observed in some materials (Erickson, Work, 1961 ; Blatherwick, Viste, 1967),

– description of multiaxial loadings is possible by generalization of the effective stress concept, including damage anisotropy effects (Murakami, Ohno, 1978 ; Corolebois, Sidoroff, 1979 ; Chaboche, 1979b),

– the high temperature creep-fatigue interaction processes could be analyzed by similar approaches (Plumtree, Lemaitre, 1978 ; Ostergren, Krempl, 1979 ; Lemaitre, Chaboche, 1978) taking into account the possible influence of hardening in order to modelize some beneficial effects (Chaboche, 1978),

– an analoguous formulation of damage equation by means of strain variable instead of the stress variables is possible, giving rise to a direct simplified description of strain controlled cyclic tests (Plumtree, Lemaitre, 1978 ; Lemaitre, 1979),

– separation of the micro-initiation and micro-propagation processes through the introduction of two damage variables and modified damage equations could increase the possibilities, especially when different damage processes interact (such as creep and fatigue), and contribute to a better understanding between the Metallurgist and Mechanicists points of view.

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