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DIFFERENT ASPECTS OF LOW-CYCLE FATIGUE

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16. Abstract

In this introduction to low-cycle fatigue, the experimental and theoretical knowledge in this field is presented. The different relations which correlate the number of cycles to rupture with strain or strain-energy are given. The application of low-cycle fatigue concepts to the crack initiation and crack propagation are briefly studied.

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DIFFERENT ASPECTS OF LOW-CYCLE FATIGUE

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ABSTRACT

In this introduction to low-cycle fatigue we present the experimental theoretical means used to study and predict fatigue leading to rupture with a small number of cycles. /3*

The different relationships between the number of cycles to rupture and deformation or the energy dissipated through deformation are briefly covered. The applications of low-cycle fatigue to crack initiation and propagation are touched upon.

Author's English Abstract

In this introduction to low-cycle fatigue, the experimental and theoretical knowledge in this field is presented. The different relations which correlate the number of cycles to rupture with strain-energy are given.

The application of low-cycle fatigue concept to the crack initiation and crack propagation are briefly studied.

1. INVESTIGATION METHOD

Low-cycle fatigue assumes several aspects the first of which is attached to the etymological meaning of the words, to the low number of cycles before rupture occurs, be it less than 50,000 cycles for Coffin (1), or less than 100,000 cycles for Cazaud (2).

Regardless of the number of cycles to which we refer, the main idea distinguishing low-cycle fatigue from fatigue is based on the deformation parameter involved in this investigation method instead of stress in

*Numbers in margin indicate pagination in original foreign text.

Woehler's method or instead of the stress intensity factor for studying cracks using Paris' relationship.

The expression "low-cycle fatigue" therefore implicitly assumes another aspect associated with the investigation method itself and means of computation used to study procedures connected with fissure initiation and generation.

Present developments in low-cycle fatigue are undoubtedly tied to the effectiveness of means of computation used, for predicting lifetimes using Morrow's method (3) as well as determining crack propagation velocities according to Tomkins (4) or evaluating the number of cycles at crack initiation from the edge of a hole (5).

The advantage of this investigation method therefore exceeds the scope of low-cycle ruptures that gave it birth but also lies in a specific concept for testing and computing damages from fatigue starting with the imposed deformation or the energy dissipated through deformation.

2. APPLICATIONS

For different reasons, low-cycle fatigue is of interest to metallurgists, mechanics and physicists specializing in solids.

From the standpoint of the evaluation of materials, we first derive a life duration characterized by a number of cycles to rupture in terms of the applied stress and of the environment, temperature in particular.

From the standpoint of the mechanical behavior of materials, the study of cyclical cold-working leads to a knowledge of cyclical mechanical properties: elastic limit, strengthening and cold-working coefficient.

From a practical standpoint, the cyclic mechanical properties make it possible to explain and to predict the behavior under fatigue, clearly revealing the influence of thermal treatments and of the microstructure in general.

Finally, from a fundamental point of view, low-cycle fatigue is approached through the application of the theory of dislocations to cyclic plastic deformations, whether the latter are generalized or, on the contrary, localized on the surface or at the leading edge of a fissure.

Low-cycle fatigue, a multi-discipline science, finds numerous applications in the nuclear industry for nuclear vessels, in the aeronautics industry for engines and landing gears, in the mechnical industry for all problems dealing with optimization of structures, when there is a concentration of stresses or strains.

It is true that there seem to be relatively few accidental ruptures of parts in use caused by low-cycle fatigue. This low number of damages is explained by the complete nature of the break, a break that takes place within the lifetime with a small amount of dispersion relative to the amount of endurance. Therefore, in this case, the probabilistic aspect has less importance than in the case of fatigue due to a large number of cycles. The deterministic aspect dominates whether we are evaluating an alloy or computing a structure. The engineer knows a priori that a part submitted to low-cycle fatigue is destined to be ruined within a more or less brief amount of time. Therefore, he will not seek to determine an endurance range as in fatigue caused by a large number of /4
cycles, but will seek a maximum lifetime as a function of stress, the state of deformation or strain and of material properties.

For that purpose, we have available theoretical and experimental means that will be explained in the following statements and that we will introduce with the help of a few examples to show the main points of this subject.

3. THE MAIN POINTS OF THEORETICAL AND EXPERIMENTAL MEANS

Within the plastic range, under cyclical stresses, metal can harden, soften or remain stable. By observing the change in the mechanical hysteresis loops, we determine a curve for cyclical metal hardening which gives the stable state of the associated stresses and deformations.

Like the steady tension curve, the cyclic curve for metal hardening is approximated by a power function of the form:

$$\sigma a = K' \frac{(\Delta \in p)}{2}^{n'}$$

where σ_a = alternate stress

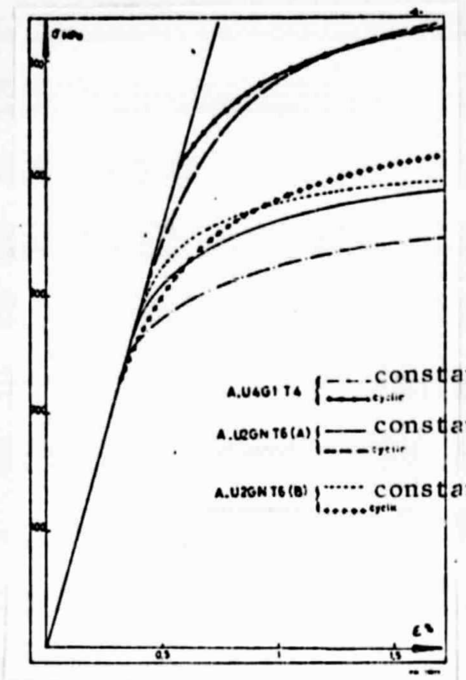
$\Delta\varepsilon p$= amplitude of plastic deformation

K' = coefficient of cyclic strengthening

n' = coefficient of cyclic metal hardening

Figure 1 gives cyclic metal hardening curves for two aluminum alloys: an A-U4G1 in the T4 state and an A-U2GN T6, heat-treated for 10 hours at 190°C and 22 Hours at 203°.

Results show that the A-U4G1 and A-U2GN alloys in the under- annealed state gain strength under cyclical plastic deformation while the A-U2GN alloy heat-treated to the maximum of its static properties has a tendency to lose strength. These considerations tend to help select materials to use, keeping in mind that, for a given elasticity limit, the more an alloy increases in strength under cyclic stresses, the more it is likely to remain in place under large deformations.



-- heat-treated at 190°C for 10 hours

-- heat-treated at 203°C for 22 hours

Figure 1. Cyclic Metal-Hardening Curves

Lifetime expressed in the number of cycles before rupture is given respectively by Manson-Coffin's relationship if we only consider the applied plastic deformation, or by Morrow's relationship if we consider total deformation.

$$\frac{\Delta \epsilon p}{2} = \epsilon'_f (2 N f)^{-c}$$

$$\frac{\Delta \epsilon}{2} = \epsilon'_f (2 N f)^{-c} + \frac{\sigma' f}{E} (2 N f)^{b}$$

where E = Young's modulus

Nf' = Number of alternations before rupture

$\Delta \epsilon p$ = Amplitude of plastic deformation

$\Delta \epsilon$ = Amplitude of total deformation

$\varepsilon'f$ = coefficient of ductility under fatigue
$\sigma'f'$ = coefficient of resistance to fatigue.

The two above relations obtained experimentally show that ductile metals with large $\varepsilon'f$ values generally show good resistance to applied deformations. These same materials will not have as good a resistance to applied stresses.

Results obtained for the two light alloys previously mentioned are recorded in Figure 2. Although the elasticity limit for the A-U2GN alloy is greater than that for A-U4G1, we find that their behavior is similar under low-cycle fatigue. Let us note that for lifetimes of very short duration not exceeding ten cycles, the under-tempered A-U2GN alloy is the best.

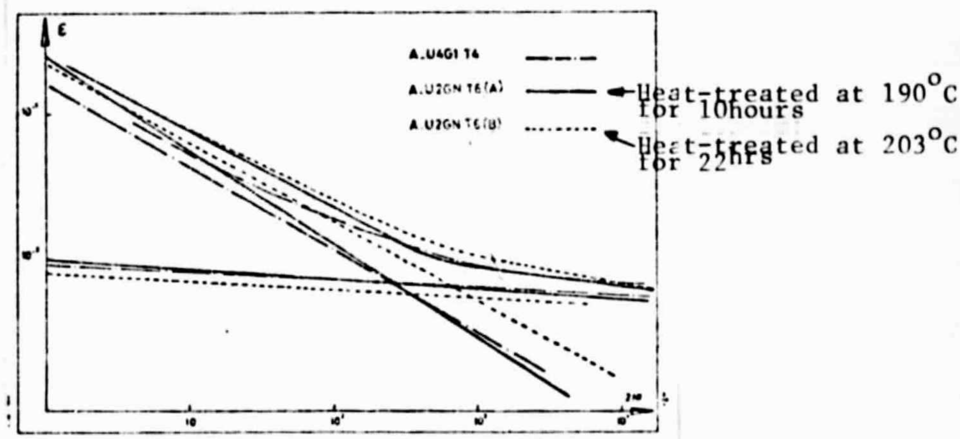


Figure 2. Lifetime as a function of the applied deformation

Another approach to low-cycle fatigue proposed by Halford and Morrow consists of determining lifetime as a function of the energy dissipated through plastic deformation:

$$Wf = Nf\,\Delta W$$

The energy of plastic deformation per cycle ΔW is computed starting with the area of the hysteresis loop, or for a sinusoidal cycle:

$$\Delta W = 2\,\sigma a \,\Delta \epsilon p \left(\frac{1 - n'}{1 + n'}\right)$$

using the same notations as before.

Figure 3 gives results for the two light alloys studied. In both cases, the energy of plastic deformation before rupture increases with the number of cycles before rupture in accordance with the exponential law:

$$Wf = c(2Nf)^a$$

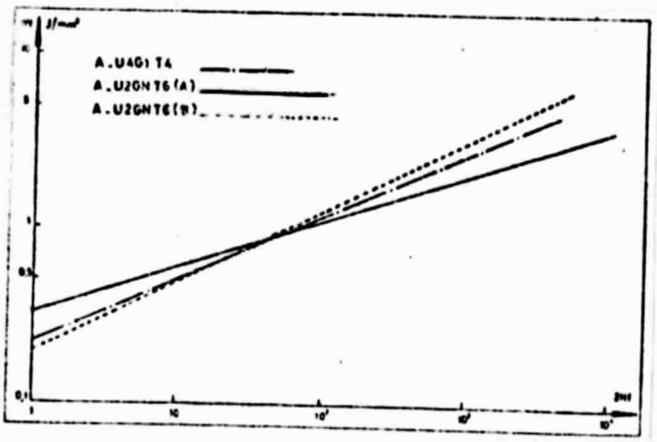


Figure 3. Lifetime as a function of the energy dissipated through plastic deformation

The three approaches that we have just described, starting with cyclic metal-hardening, deformation and dissipated energy, represent the key means used in studying low-cycle fatigue. They are covered in detail by Pineau, Lemaitre and Lieurade.

Low-cycle fatigue lifetime under the effect of variable amplitude stresses is difficult to determine. Miner's law based on the linear accumulation of the damage does not give complete satisfaction. Landgraf has recently proposed a relationship, similar to Miller's, introducing damage per alternation (6), or:

$$di = \frac{1}{2\,Nf} = \frac{1}{2\,Nt}\left(\frac{\Delta\epsilon p}{\Delta\epsilon c}\right)^{1/b-c}$$

where Nt = lifetime at the elastic / plastic transition.

There is a rupture when $\sum d\ i = 1$.

To take into account the non-linear cumulation of damages, Chaboche proposes a differential law (7) more elaborate than Landgraf's to express basic damage.

Another attempt has been made by Thang Bui Quoc (8), an attempt according to which damage would be tied to the energy of plastic deformation accumulated at each cycle. Rupture would occur when:

$$Wf = \Sigma i\ ni\ \Delta Wi$$

Let us finally note, as recalled above, that crack initiation and propagation due to fatigue can be treated by considering that in both cases, the processes result from localized low-cycle fatigue. Smith (9) has thus shown that the number of cycles at initiation confirmsthe following relationship:

$$\text{Log } Ni = A + B \text{ Log } (E\ \sigma\max\ \epsilon a)^{1/2}$$

Using a similar approach, Tomkins shows that the fissuration velocity associated with plastic deformation at the bottom of the crack is expressed by the following relationship:

$$\frac{dl}{dN} = \frac{n^2}{8}\left(\frac{K}{2T}\right)^2 \left(\Delta\epsilon p\right)^{2\beta+1\ell}$$

in which ℓ is the length of the crack, T is the rupture stress, K is the strengthening coefficient and β is the coefficient of cyclic metal hardening.

These two relationships were recently verified with steels (10, 11).

These marginal aspects of low-cycle fatigue will not be covered here but it is good to mention them to properly show that the field of fatigue is not only relegated to a technological question but that it constitutes, by itself, a multi-discipline means of investigation.

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