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Classification of metallic alloys for fatigue damage accumulation: A conservative model under strain control for 304 stainless steels

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ABSTRACT

Fully reversed uniaxial tests performed under total strain and stress control on 304 stainless steels specimens show that, under strain control the fatigue damage for High–Low (H–L) cycling is more significant than that using Miner's rule, but under stress control opposite results are obtained. This has been attributed to opposite effects of pre-hardening under strain and stress control. Classical non linear damage accumulation models are not able to take into account this difference in sequence effect. Smith–Watson–Topper (SWT) and Fatemi–Socie (FS) criterion combined to linear damage accumulation can take into account this difference in sequence effect through the presence of maximum stress. However these models require an elastic–plastic constitutive law which is difficult to propose due to the presence of high cycle secondary hardening observed on 304 stainless steel. A conservative model for damage accumulation under variable amplitude strain control loading is thus proposed, which does not require a constitutive law. Linear damage accumulation is used, while sequence effect is taken into account using the elastic–plastic memory effect through cyclic strain–stress curves (CSSC) with pre-hardening. This modeling classifies metallic alloys in two groups for damage accumulation, with a stable (independent to pre-hardening) CSSC as for aluminum alloys and with an unstable (dependent to pre-hardening) one as for austenitic stainless steels. For the former case the modeling is identical to Miner's rule. The modeling is approved based on a large number of tests on 304 stainless steel and is compared with SWT and FS models. In presence of mean stress the modeling permits in a qualitative way to explain the fact that tensile mean stresses in constant amplitude strain control tests are more detrimental than for constant amplitude stress control tests. Moreover it is shown that the SWT model is not always able to predict accurately the fatigue life in presence of a mean stress. Finally, it is concluded that for a 304 stainless steel, in order to take into account the mean stress in fatigue life, the mean stress effect has to be decomposed into two parts: maximum and "intrinsic" mean stress effects.

1. Introduction

The most frequently used methodology for fatigue damage accumulation under variable amplitude loading in industry employs Miner's rule after using a counting method such as rainflow counting. Miner's rule is the linear accumulation of damages of subcycles, where the damage is defined as the cycle ratio (usage factor) under strain or stress control. The shortcoming of Miner's rule is that it cannot take into account the sequence effect [1–3], which occurs for ASSs. However Miner's rule is preferred to non linear damage accumulation rules because of its robustness and ease of use as concluded in the review paper [4].

Sequence effects on two step tests have been reported in literature through different definitions:

(a) A test under a Low amplitude cycle followed by a High amplitude cycle (L–H) is less damaging than that under a High amplitude cycle followed by a Low amplitude cycle (H–L).
(b) For an H–L cycling, the damage computed using Miner's rule appears to be smaller than that obtained in tests.

Abbreviations: ASS, austenitic stainless steel; CSSC, cyclic strain stress curve; CPH, cyclic pre-hardening; MPH, monotonic pre-hardening; HCF, high cycle fatigue; UT, University of Toledo; CEA, Commissariat à l'Energie Atomique; H–L, High–Low; POL, periodic overloading.

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Many phenomenological rules for fatigue damage accumulation accounting for sequence effects have been proposed to obtain more accurate results than with Miner's rule. These rules are divided into five groups in [4]. Most referenced in the literature are: (a) non linear damage curves with load dependent damage, with a first proposal in [1], where the two stage linearization approach is a particular important case separating crack nucleation and crack propagation [5], and (b) continuum damage mechanics [6] where damage is defined as the change of tensile load carrying capacity using the effective stress concept.

The aim of these models is to obtain more damage with an H–L cycling than would be obtained using Miner's rule and L–H loading. This aim has been achieved in previous damage rules in both strain control and stress control. However, recent data on 304 stainless steels [7,8] show that opposite results are obtained under stress control, i.e. H–L loading is less damaging than Miner's rule and L–H loading. These results invalidate therefore [9], the use of previous models for crack nucleation in HCF as will be detailed later.

In this paper, the difference between strain and stress control is related to the memory effect in the elastic–plastic behavior. One idea which will be developed in this paper is that, alloys have to be classified in two groups for damage accumulation in crack nucleation analysis. For the first group, CSSC is stable, as for aluminum alloys [7], or for mild ferritic steel [10,11]. For these alloys, there is no sequence effect related to memory effect in behavior. The Miner's rule is therefore valid, and no opposite result is generated between stress and strain control for sequence effects. The second group concerns alloys with no stable CSSC as ASSs [7,8,10,11]. For these alloys, there is a sequence effect due to the memory effect in the elastic–plastic behavior which generates a difference in sequence effect under stress and strain control.

Most of the results presented in this paper concern two grades of ASS material provided by EDF (formerly known as Electricity of France) to different laboratories. These are grades 304-CLI and 304-THYS. The second grade has a smaller grain size and a higher endurance limit than the first one [7,8,11], and presents a higher secondary hardening in the high cycle regime (Fig. 1a). In Fig. 1a 304-CLI grade does not present any high cycle secondary hardening although on other tests in [7] the high cycle secondary hardening is observed for this grade.

After clarifying some definitions in Section 2, sequence effect in damage accumulation will be analyzed in Section 3. In Section 4 the non-capability of classical non linear damage accumulation models to reproduce opposite sequence effects under strain and stress control in HCF is discussed. In Section 5 opposite sequence effect under stress and under strain control is related to opposite effect of pre-hardening in these cases. This difference is then explained by a modeling. In Sections 6 and 7 predictions of fatigue lives obtained respectively by Miner's rule, SWT and FS models are compared with experimental data on both grades of 304 stainless steels. In Section 8 a conservative model for damage accumulation under strain control for ASSs is proposed and validated with many data on two grades of 304 stainless steel. In this paper the emphasis is on strain control due to the fact that sequence effect is detrimental under strain control while it is not the case under stress control. Moreover high cycle thermal fatigue may be considered as a strain controlled loading [12]. Finally in Section 9 the effects of mean stress under strain and stress control are compared and discussed with an application of SWT model.

2. Fatigue curves and crack nucleation definition

This paper proposes a modeling for prediction of crack nucleation, while comparison between modeling and experimental data in this paper and in the literature is carried out with fatigue data. The validation of crack nucleation prediction through fatigue data has a clear meaning if the part of propagation can be neglected in a fatigue curve. Negligibility of propagation compared to nucleation is considered in [13] as the definition of HCF which is adapted here. For a polycrystalline alloy a representative elementary volume in continuum mechanics has a size about 3 grain sizes [13], so the presence of a crack of a smaller size is not supposed to modify macroscopic strain and stress fields. This is reported for fatigue tests on 304-THYS in [8]. This makes for a valid crack nucleation analysis under macroscopic strain and stress field in the presence of such a crack. The aim of this section is to show that for the number of cycles to fatigue about or more than 10^5 concerned by this paper, fatigue curves may be used for crack nucleation analysis.

For an AISI 304L stainless steel under a fully reversed tension/compression loading, it is shown [14] that for a fatigue life not significantly less than 10^5 cycles and greater than 10^5 cycles, 95% of fatigue life is consumed to produce a crack of 100 microns. Note that a grain size for a 304 stainless steel is about 50–100 microns [11]. This would mean that for a fatigue live of 10^5 cycles or more crack length is less than 3 grain size and so fatigue curves may be used for nucleation analysis.

Under a fully reversed tension compression test, a 10^5 fatigue life in terms of strain amplitude loading corresponds to amplitudes smaller than 0.3% [7,8,15,16]. That is why the amplitudes of the loadings considered in this paper for tests on 304 steels are equal or less than 0.3%. Fig. 1b and c shows fatigue lives for both grades of ASS 304-CLI and 304-THYS, respectively. It may be noted on these figures that all run up tests present high cycle secondary hardening for a fatigue life not significantly less than 10^5 cycles and greater than 10^5 cycles. Moreover there is an important dispersion which justifies in part the proposition of a conservative modeling in Section 8.

3. Sequence effect in damage accumulation rules

In a two-step test (but also for any case of variable amplitude loading), it may be supposed that the sequence effect comes from two different origins:

(a) Memory effect on cyclic elastic–plastic (or visco-plastic) behavior due to maximum loading (monotonic effect) or maximum hardening (cyclic effect),
(b) Damage when it is significant enough to be able to create a sequence effect.

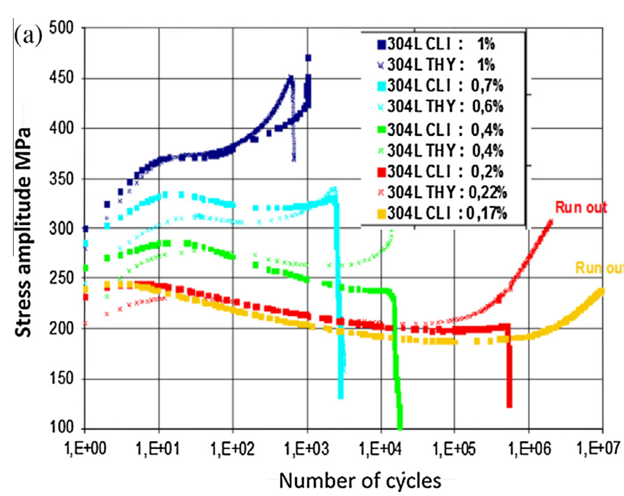

Fig. 1a. Fully reversed strain controlled tests, detection of high cycle secondary hardening for 304-THYS grade.