Application of Multistage Life Prediction Methods to Fretting Fatigue Interactions

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ABSTRACT

The application field of the multistage prediction model developed at ONERA was extended to fretting-fatigue interaction. The model was used to achieve a preliminary evaluation of the reduction in fatigue life induced by fretting conditions in a case-hardening steel. Satisfactory agreement with experimental data was found without considering any effects on the propagation stage.

INTRODUCTION

A recent development in mechanical property theory is related to the development of reliable life prediction methods for complex fatigue load conditions. One of the mechanical properties hardest to define and predict is fatigue strength in metals, especially when creep and/or other stresses of mechanical or chemical nature are acting together.

This paper investigates fatigue life in presence of fretting. Fretting, which reduces fatigue life in much the same way as chemical corrosion, is characterized by small relative displacements of two surfaces pressing against each other. The underlying microstructural mechanisms of fretting and several theoretical approaches for quantitatively fitting the available experimental data are reported by Waterhouse (1981). Fretting action on fatigue life is related to various parameters, among which environmental effects and mating conditions (mainly the normal force or pressure and the frequency and amplitude of relative sliding between the surfaces) (Nishioka et al, 1968, 1969, 1972; Sander, 1987; Berthier et al, 1988).

In an experimental investigation of fatigue and fretting-fatigue of a commercial-quality case-hardening steel (Zonfrillo et al, 1988), fretting action was correlated to the normal force and the relative stiffness of the test bar and of the specially designed fretting-inducing device. A schematic drawing of the experimental apparatus is reported in Fig. 1. The investigation was limited to constant normal force conditions. Further studies are under way to investigate the influence of fretting parameters on tribologic phenomena and fretting-fatigue life (Zonfrillo et al, 1989).

MULTISTAGE FATIGUE

Even with ambient temperature fatigue, several successive stages have to be introduced to interpret the phenomena at microscopic level and the resultant fractographic characteristics. Thus, the first stage involves the growth of numerous microscopic cracks from dislocation movements caused by the load-generated shear stresses. Sliding along crystallographic planes entails crack development and the formation of surface steps which give rise to inclusions and extrusions at an atomic-to-microstructural level.

At the outset of the next stage when one of the cracks reaches critical length, the complex situation of the structural defects is considerably simplified. Material damage concentrates in this crack, which is the only one whose propagation causes fracture when the residual sections become too small to withstand the applied loads. This two-stage scheme, however, is a simplification of the fatigue fracture process: only a more detailed scheme could provide a complete agreement with experimental observations at the microstructural level.

The superposition of fretting on fatigue will mostly affect the nucleation stage. This stage is dependent on the surface state, to the extent that nucleation virtually disappears if notches large enough are made on the specimen surface. Fretting action may be viewed as a source of microscopic notches which significantly reduces the time needed for a surface crack to reach critical dimensions. The morphologic characteristics of fretting-induced surface damage are illustrated in Waterhouse (1981).

Although fretting effects on propagation cannot be completely ignored, we may assume in first approximation that they play a significant role only during nucleation. Hence, multistage prediction models will be more suitable to interpret the experimental observations.

APPLICATION OF THE PREDICTION METHOD

A modified version (Savalle et al, 1982) of the continuous damage model (Lemaitre et al, 1974) developed at Office National d'Etudes et de Recherches Aérospatiales (ONERA) explicitly allows for the termination of nucleation prior to the onset of propagation. Its aptness in separating nucleation and propagation stages has been investigated (Pratesi et al, 1988). The model has the advantage of being readily applicable to a wide range of load situations, including creep, low- and high-cycle fatigue, and their interactions. Nevertheless, few applications have been implemented to date. This is because the input parameters are derived either from the literature, where usable data are few and far between, or from specific experimentation, which involves laborsome and time-consuming procedures.

The ONERA model was used to evaluate fretting-induced modifications on fatigue life. In a preliminary assessment performed with the prospect of obtaining reliable quantitative predictions, only rough agreement was attempted between the calculated curves and the experimental points. Modeling was carried out in two consecutive steps: 1) defining the fatigue curve and 2) modifying the curve to account for fretting effects.

For nucleation and propagation stages respectively, the model is based on two damage laws (Lesne et al, 1985) as follows:

$$(1) \qquad dD_a = [f_1(\sigma_{max},\sigma_o)\ dN + f_2(\sigma)t^{\alpha}\ dt]\ f_3(D_a)$$

$$(2) \qquad dD_p = [1-(1-D_p)^{\delta+1}]^a\ \frac{\sigma_{max}-\sigma_{lp}(\sigma_o)}{\sigma_u-\sigma_{max}}\ \left[\frac{\sigma_{max}-\sigma_o}{M(\sigma_o)\cdot(1-D_p)}\right]^{\delta} dN$$

With some assumptions, they can be integrated to give the number of cycles necessary for nucleation N_a and propagation N_p

$$(3) \qquad N_a = C(v) \left[\frac{\sigma_{max} - \sigma_{lim}(\sigma_o)}{\sigma_u - \sigma_{max}} \right]^{-\beta}$$

$$(4) \qquad N_p = \frac{1}{(1-a)\cdot(1+\delta)} \; \frac{\sigma_u - \sigma_{max}}{\sigma_{max} - \sigma_{lp}(\sigma_o)} \left[\frac{\sigma_{max} - \sigma_o}{M(\sigma_o)} \right]^{-\delta}$$

where D_a and D_p = damage variables for nucleation and propagation stages, σ_{max} and σ_o = maximum and mean applied stresses, σ_{lp} = fatigue limit in propagation, σ_u = ultimate strength, v = frequency, σ_{lim} = fatigue limit, and the other coefficients are functions of material and temperature. Note that the accumulation of nucleation damage is assumed as a function of fatigue (f_1) and oxidation (f_2).

Optimization for Fatigue

To obtain good agreement between experimental points and calculated curves, selected parameters were input. These can be divided into two groups, one in which the experimental data such as tensile strength and the fatigue limit were used directly, and one in which the parameters were derived from the experimental results according to the procedure indicated by the authors of the model. As experimental data for the second group were insufficient, some of the parameters whose influence on the prediction was slight were selected from those valid for IN 100. Then, the whole set of parameters was modified in order to fit the experimental fatigue data until satisfactory agreement was reached (Fig. 2).

Effect of Fretting on the Fatigue Curve

During our tests, only one normal force value was used and all other experimental conditions were kept constant. A shift in the fatigue curve due to fretting can be observed towards the bottom lefthand side of the plot (Fig. 2). The shift can be split into a decrease of the horizontal line corresponding to the new fretting-fatigue limit, together with a less marked shift leftward. The leftward shift may be considered as a rigid translation, since the deviation from parallel is slight.

Preliminary results show that both components of the shift are affected by variations in each of the parameters defining the experimental fretting conditions. Further experiments are under way to define these relationships. General behavior agrees with the hypothesis of fretting acting in the nucleation stage, as can be verified by decomposition of the life into its nucleation and propagation components (Bathias et al, 1981): under normal conditions in fact, the fatigue limit is determined by the nucleation stage, i.e., by the loads not high enough to reach nucleation.

Interpolating Curve for Fretting Fatigue

Our first consideration in obtaining the interpolating curve for fretting-fatigue was that nucleation is the stage most affected by fretting action. Thus, the propagation part of the model was left unaltered and only the nucleation stage was modified to fit the fretting-fatigue results.

Fretting action can be viewed as the gradual production of microscopic notches growing in the course of the fatigue process. Therefore, a suitable function should be introduced in Equation (1) to account for this effect. Moreover, the oxidation law has to be modified to account for changes in surface reactivity during fretting action, at least by modifying the α exponent in law (1).

Evidently, these modifications involve numerical integrations which give different results according to the assumptions made. Since many required dependences are unknown and the experimental data for checking the speculative laws at the differential damage accumulation level are lacking, it was decided to see whether the integrated expression (3) for nucleation could still be used. To apply (3), it was necessary to represent the cumulative fretting effect by means of both a suitable decrease in the fatigue limit and the insertion of a multiplying function.

The fretting-fatigue limit depends on the fretting conditions, which means that the more fretting conditions are severe, the more the fretting-fatigue limit deviates from the fatigue limit. In this work, the experimentally derived load was used to consider the fretting-fatigue limit in (3). The multiplying function also, which accounts for the reduction in nucleation life, is related to the fretting conditions. Note that function's effect on the integral equation (3) partly corresponds to modifications in the α coefficient of law (1) (here increasing it). Since the experimental fretting conditions were kept constant during testing, the function could be reduced to a constant factor less than unity. Thus, in the simplest possible case, the multiplying function accounts mainly for the horizontal translation of the curve leftward, whereas the introduction of a different fatigue limit accounts for the downward shift.

The problem was thus reduced to verifying whether such a simplified procedure could interpret modifications as important as the experimentally derived ones. The results (Fig. 2) show that agreement is satisfactory. This agreement might also serve to reduce experimental testing by focusing on the new fretting-fatigue limit and the shift to lower cycles for a given high stress.

Further Developments

The modification described above of the integrated expression, involving the introduction of suitable functions of the fretting conditions, will be attempted as soon as enough experimental data become available. Hopefully, both the decrease of the fatigue limit and the leftward shift of the fatigue curve will lend themselves to be represented by simple analytical expressions. On the other hand, more complex load conditions may require more complex mathematical expressions implying that the differential equation must be adjusted with modifications that cannot be represented by the integrated expression, even in modified form.

Moreover, the reported application of the model should undergo further verification for complex load conditions with fatigue following fretting-fatigue and vice versa before the assumption of fretting essentially modifying the nucleation stage and the use of the integrated expression (3) can be fully validated.

CONCLUSIONS

The ONERA multistage prediction method, which considers two separate fatigue-life stages, nucleation and propagation, was applied to complex fatigue load conditions involving fretting-fatigue interaction. In the prediction, it was assumed that only nucleation was affected by fretting. Comparison with experimentally derived values showed good agreement.

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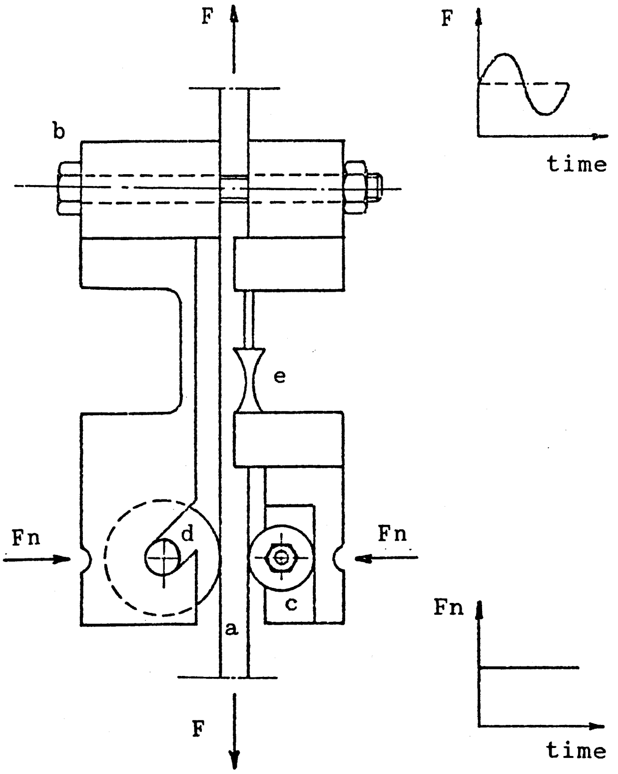

Fig. 1 - Scheme of the experimental apparatus.
a) test bar. b) clamping device. c) pin. d) rolling pad.
e) friction force gauge.

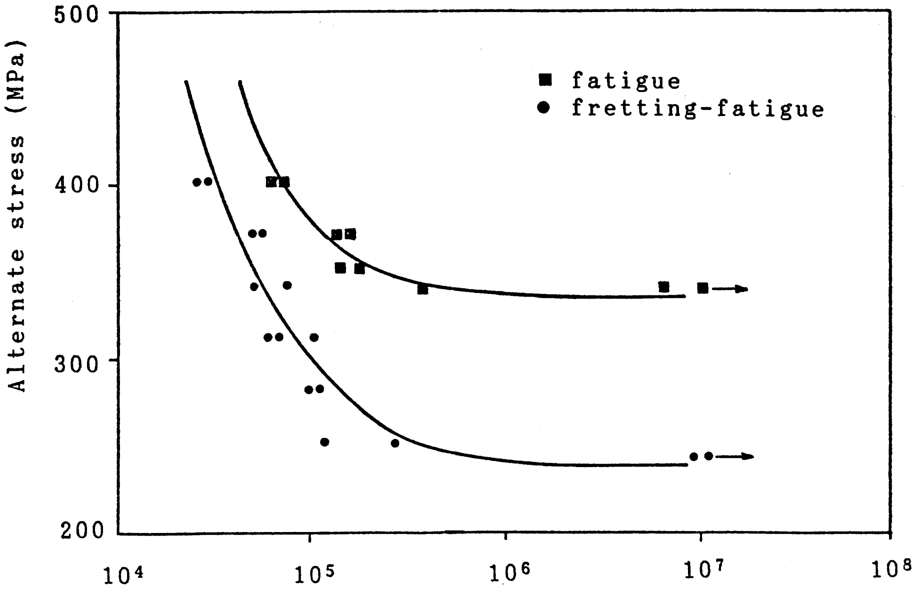

Fig. 2 - Model fitting the fatigue and fretting-fatigue data.