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Fatigue modelling for gas nitriding

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ABSTRACT. The present study aims to develop an algorithm able to predict the fatigue lifetime of nitrided steels. Linear multi-axial fatigue criteria are used to take into account the gradients of mechanical properties provided by the nitriding process. Simulations on rotating bending fatigue specimens are made in order to test the nitrided surfaces. The fatigue model is applied to the cyclic loading of a gear from a simulation using the finite element software Ansys. Results show the positive contributions of nitriding on the fatigue strength.

KEYWORDS. Nitriding; Fatigue; Lifetime.



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INTRODUCTION

Fatigue resistance and mechanical capacity of aircraft engine components are of vital importance in aerospace industries. Thermochemical processing is exploited in order to improve superficial mechanical properties (residual stresses, hardness). Among surface treatments, the nitriding process is the most efficient despite its high cost.

This study is specifically dedicated to gas nitriding of steels which is widely used by the aerospace industry. Due to the supply of nitrogen and its co-diffusion with carbon, precipitation of nanometric alloying elements nitrides and cementite at grain boundaries occurs leading to an increase of superficial hardness and providing compressive residual stresses in the surface layers [1-4].

The present work aims of creating a model for calculating fatigue lifetime of a nitrided layer whilst taking into account of mechanical improvements generated by nitriding. Based on previous works [5], the model takes into consideration the gradient of microstructure from the diffusion of carbon and nitrogen during nitriding and calculates the resulting gradient of compressive residual stresses from the volume change accompanying the precipitation. The fatigue model is built on multiaxial criterion like Crossland [6], and the fatigue life is calculated for each mechanical loading in a nitrided layer.

The validation of the model is performed on rotating fatigue bending specimens. Indeed specimens with dedicated geometry are explored to introduce stress concentration at the material surface aiming a greater probability of rupture in the nitrated layer, and thus fatigue testing of the nitrated layer rather than the core. The work is also conducted on gears designed by Hispano-Suiza, a company of the SAFRAN Group.

MULTIAXIAL FATIGUE CRITERIA

The fatigue criteria E allow taking into account the mechanical characteristics of the nitriding layers. During this study, the choice has been made to select the linear criterion in the following form [6, 7]:

$$E = \frac{\sigma_{app}^* + \alpha P_H^*}{\beta} \quad (1)$$

The applied stress σ_{app}^* is calculated with respect to the loading the material undergoes. The residual stresses and the increased hardness induced by nitriding are taken into account in the hydrostatic pressure P_H^* and coefficient β [8, 9]. The slope α of the straight line is calculated using fatigue properties of the non-nitrated material. Hypothetically, the coefficient α does not depend on the gradient of mechanical properties provided by nitriding [5]. Two Wöhler curves with different load ratio can then be used to characterize the fatigue properties for a given failure probability. The prediction of failure follows from Eq.1. If $E < 1$, no failure will take place [10]. Otherwise, crack initiation and failure might occur. The Crossland [6] and Dang Van [11-13] criteria were used in order to predict the fatigue life of the nitride materials.

Crossland criterion

The Crossland criterion (Eq. 2) is the most used and has been studied in the case of nitrated materials (Eq. 2) [6].

$$E_c = \frac{\sqrt{J_{2a}} + \alpha_c P_{Hmax}}{\beta_c} \quad (2)$$

It uses the maximum hydrostatic pressure P_{Hmax} and the second invariant of the alternating (alternative) stress J_{2a} . Because of the relation between J_{2a} and σ_{eqVM}^{alt} (Eq. 3), the Crossland criterion is considered as a von Mises criterion.

$$\sqrt{J_{2a}} = \frac{\sigma_{eqVM}^{alt}}{\sqrt{3}} \quad (3)$$

Dang Van criterion

In case of a calculation algorithm without the determination of critical plane of the material, the second version of the Dang Van criterion is used (Eq. 4) [12, 14].

$$E_{DV} = \max_{t \in T} \left(\frac{\tau(t) + \alpha_{DV} P_H(t)}{\beta_{DV}} \right) \quad (4)$$

where t is the time of load cycle. The shear stress component $\tau(t)$ is equal to the Tresca stress. Thus, it is calculated with the eigenvalues of the stress tensor (Eq. 5).

$$\tau(t) = \frac{1}{2} \max(|\sigma_1(t) - \sigma_2(t)|, |\sigma_2(t) - \sigma_3(t)|, |\sigma_3(t) - \sigma_1(t)|) \quad (5)$$

Because the criterion of Dang Van uses Tresca, it is more restrictive than Crossland. Moreover, The Dang Van criterion takes into account the phase shift of the stress tensor components through Tresca stress by maximizing the difference of the principal stresses.

MODELLING

Calculation of the fatigue lifetime

The purpose is to determine the fatigue lifetime profile of a nitrided layer and for a given failure probability. The idea is to find the number of cycles N corresponding to $E(N) = 1$ at each depth through the nitrided layer. Despite the hydrostatic pressure and the applied stresses change along the depth, they are independent of the number of cycles N . However, the coefficients of criteria $\alpha(N)$ and $\beta(N)$ must be calculated with a new number of cycles at each iteration [5]. Some assumptions are made for the calculations of the fatigue life:

- The residual stress profiles are defined for a semi-infinite solid. The stress distribution as a function of the geometry is not taken into account.
- The loading undergone by the material comes from a finite element simulation. However, the simulations are carried out on a non-nitrided material. The alteration of mechanical properties (yield strength...) of the nitrided layers is not considered in the calculation of the loading.
- The coefficient $\alpha(N)$ does not depend on the depth of the nitrided layer. Indeed, it is calculated by means of the Wöhler curves in the non-nitrided material. The Wöhler curves were obtained from rotating bending tests ($R_\sigma = -1$) and tensile tests ($R_\sigma = 0.05$) for a given failure probability.

Simulation on simple specimens

Simulations were made on simple geometry in order to test the calculation algorithm of the fatigue lifetime. The failure must be initiated in the superficial layer in order to test the nitriding quality. To meet these objectives, the rotating bending test and specimen geometry with notches were chosen (Fig. 1) [15].

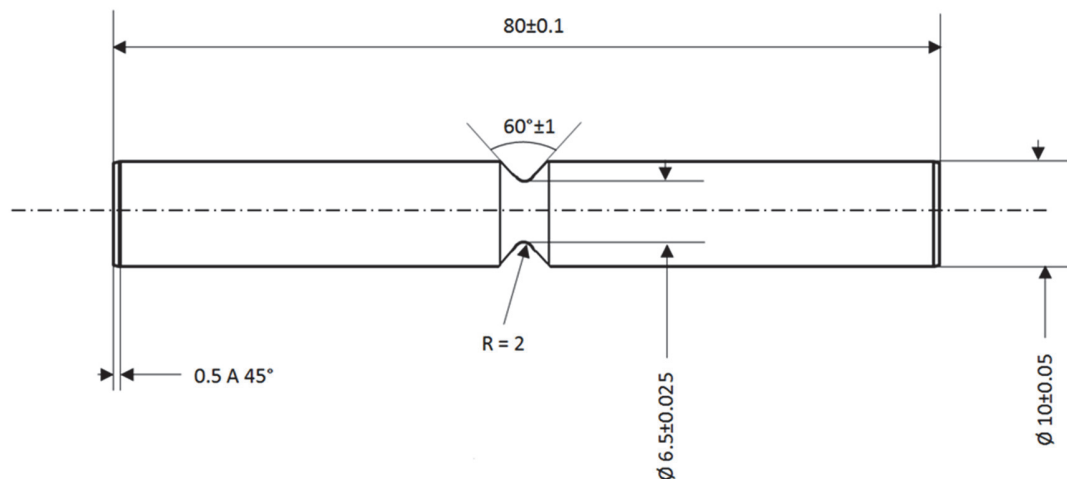


Figure 1: Geometry of notched cylindrical specimen for the rotating bending.

Simulations were performed on Ansys to justify this choice. A loading corresponding to an alternating stress of ± 900 MPa is applied. The stress tensor is calculated on the diameter of the critical section of the test specimen. The results are implemented into the fatigue algorithm in order to find the fatigue lifetime profile. Fig 2. reports the equivalent stress of von Mises and the hydrostatic pressure in the critical section. The significant effect of notch is apparent. Indeed, the stresses are very high on the edges of the specimen. However the rotating bending test generates no stresses in the center. Therefore, such a sample is suitable for testing the nitrided surfaces rather than the core.

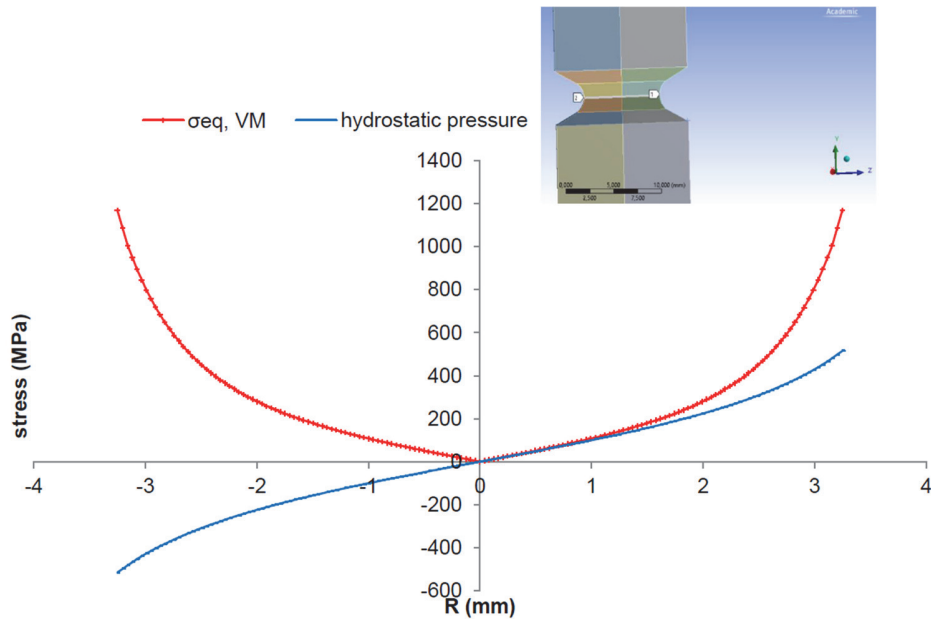


Figure 2: Hydrostatic pressure and von Mises stress profiles for rotating bending tests.

The stress profiles are implemented in the algorithm in order to obtain the fatigue lifetime. The calculations are performed in case of Crossland and Dang Van criteria according to different probabilities of failure (50 %, 10 %, 1 % and 0.1 %) [16]. The nitriding treatment applied for the bending rotative tests is performed by Aubert et Duval. The results are shown in Fig 3.

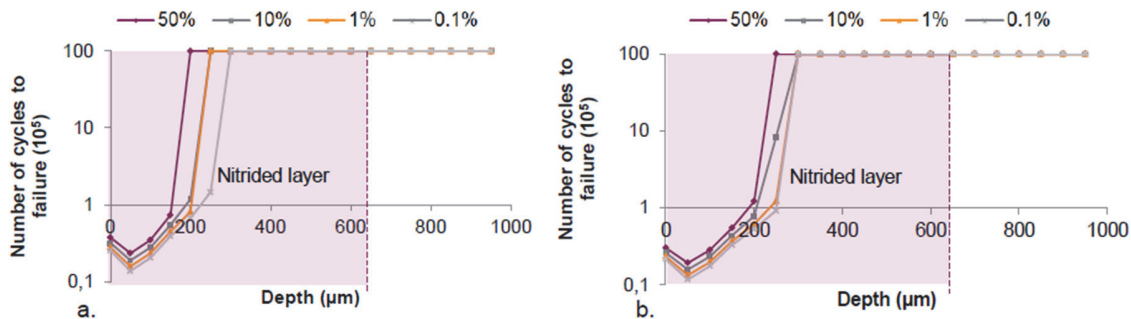


Figure 3: Fatigue lifetime profiles for nitrided layers at different failure probabilities in case of a) Crossland and b) Dang Van criteria.

The fatigue lifetime obtained with the Dang Van criterion is more restrictive than Crossland as discussed previously. There is a decrease of the lifetime close to the outer surface. This causes a high probability of failure in this area. Therefore, the results are in good agreements with the initial objective of testing the fatigue resistance of the case rather than the core. The simulations will be confronted with experimental results.

Simulation on a gear

The model was tested on a nitrided tooth of a gear designed by Hispano-Suiza. The loading is provided from simulations performed using the finite element software Ansys. The area of interest corresponds to the maximal contact pressure on the tooth flank [17]. Results are given in Fig. 4.

The implemented hardness and residual stress in-depth profiles come from a nitriding cycle developed by the Institut Jean Lamour (Nancy, France). Two modelling were carried out using the Dang Van criterion, with and without the nitriding layer for different failure probabilities (10^{-6} % and 50 %). The profiles of fatigue lifetime through the case are given in Figs. 5.a and 6.a respectively. The loading at each depth relative to the Dang Van criterion is exposed in Figs. 5.b and 6.b.

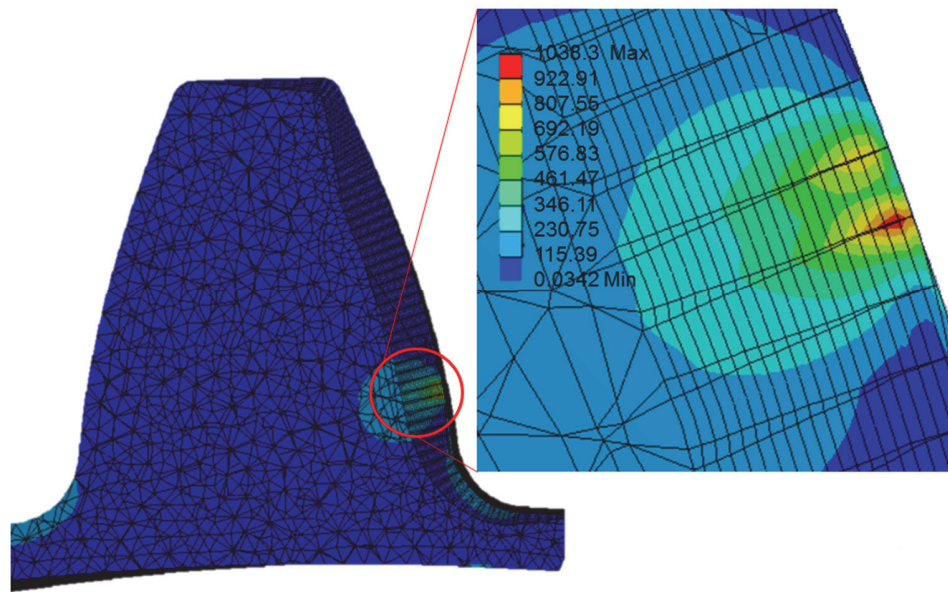


Figure 4: Mapping of von Mises stresses in a section of the critical zone on a tooth flank.

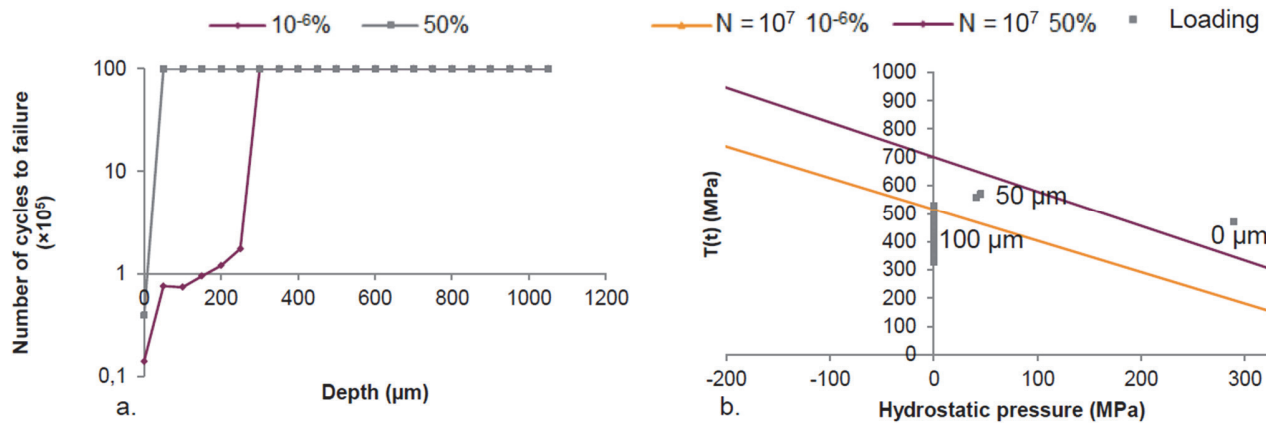


Figure 5: Case of a non-nitrided tooth. (a) fatigue lifetime profiles for two failure probabilities (b) loading according to Dang Van criterion for 10^7 cycles.

Coupled to increased hardness, the residual stresses affect the hydrostatic pressure and allow to pull away each point from the Dang Van's straight line (Figs 6.b and 6.b) [9]. The improvement of fatigue properties due to nitriding is numerically confirmed. Moreover, all Dang Van lines calculated are offset towards higher shear stress due to the influence of hardness (β coefficient) [8]. Therefore, the non-failure zone under the straight lines is widen.

Consequently, the nitrided tooth flank is not subjected to rupture. However, the fatigue lifetime for the non-nitrided tooth is lowest at the outer surface. This means that failure risks are expected in this case.

CONCLUSION

Through multi-axial fatigue criteria, a model of fatigue lifetime calculation was presented. The criteria like Dang Van and Crossland allowed to take into account the mechanical improvements provided by nitriding. The model needs some input data like the profiles of the stress tensor components, hardness, residual stresses and Wöhler curves. Fatigue tests were performed on a simple geometry to test the nitrided layers. The fatigue lifetime is calculated on nitrided

rotating bending notched samples. Simulations were performed on a gear designed by Hispano-Suiza, in order to study the effect of nitriding on the fatigue strength of a given mechanical part. It follows that the model can assist in the optimization of nitriding parameters for a given geometry. To ensure the relevance of the model, the simulations will be compared with experimental results.

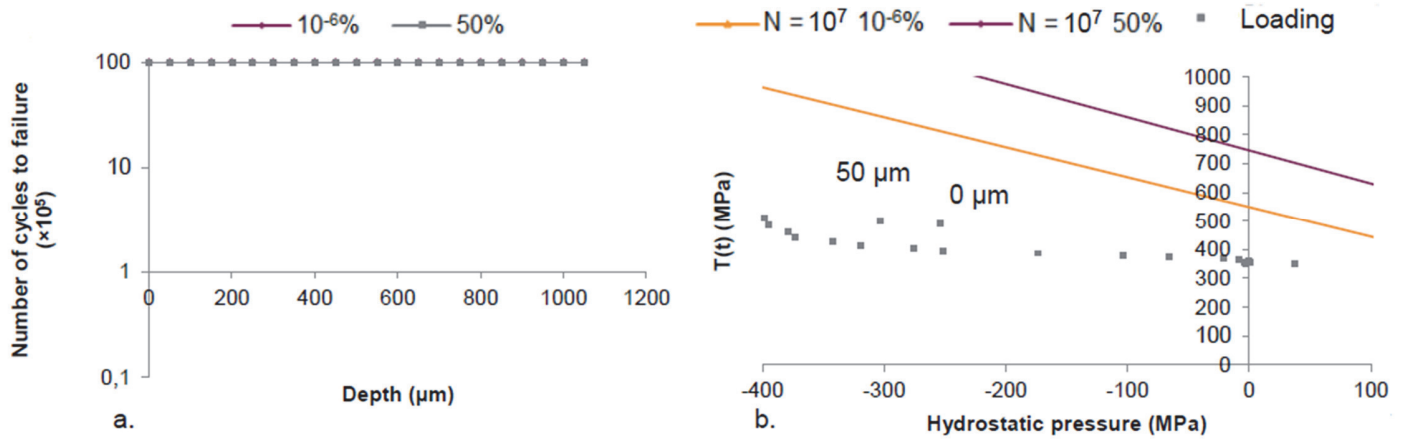


Figure 6: Case of a nitrided tooth. (a) fatigue lifetime profiles for two failure probabilities (b) loading according to Dang Van criterion for 10^7 cycles.

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