# FATIGUE CRACK GROWTH BEHAVIOR OF NITRIDED AND SHOT PEENED SPECIMENS

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ABSTRACT

Due to its proved effectiveness shot peening is one of the most widely used surface treatments to alleviate fatigue, rolling contact fatigue, fretting, stress corrosion cracking mechanical components. Generally, shot peening is applied as last treatment and follows the application of some surface hardening process, most of times carburizing. Less investigated is the application of nitriding followed by shot peening. In this paper the fatigue crack growth properties of a nitrided shot-peened steel is dealt with: different peening intensities were considered and the resulting residual stresses measured by means of an X-ray diffractometer. Rotating bending fatigue tests were executed on specimens including a micro blind hole, acting as a pre-existent crack. The broken specimens were observed with a SEM to detect the crack growth initiation point. The run-out specimens were broken after the test and the presence of non-propagating cracks detected. The results allowed determining the threshold of propagation of the nitrided and of nitrided and shot peened material. It was also possible to put into relation the crack initiation point with the applied and the residual stresses.

## 1 INTRODUCTION

The need of improved performances and more rational use of materials is making more and more popular the use of surface treatments to improve the mechanical behavior of structural and machine elements [1].

Among these treatments, shot peening is one of the most widely used, due to its ability in increasing the resistance to fatigue, fretting, rolling contact fatigue, stress corrosion cracking, corrosion and fatigue and so one. The better fatigue strength due to shot penning is mainly to be related with the residual stress induced by the action of the impact of the shot flow against the metallic surface. The effectiveness of the treatment can strongly change by using different peening parameters (shot material, dimension and velocity, that is to say by using different Almen intensity values). Shot peening is generally applied as last treatment: in this way the modification of the residual stresses induced is prevented. Shot peening generally is applied after some hardening process, i.e. quenching and tempering, induction hardening, case hardening or carburizing. The effect of the application of carburizing and shot peening was very diffusely studied in the past [1, 2, 3], due to the fact that gears are one of the most important field of application of shot peening. Gears, in fact, are generally carburized to enhance their surface hardness and to improve their strength with respect of wear and rolling contact fatigue. Shot peening further improve the behavior of gears with respect of rolling contact fatigue and with respect of bending fatigue at the gear tooth root.

However, carburizing requires high process temperature (~800°C), and induce geometrical distortion, making necessary further working processes: in the light of preventing this additional step, gear manufacturers are ever more considering nitriding as a possible substitute of carburizing. In fact, nitriding requires lower temperature (~530°C) and does not deform the gear teeth.

The effective depth of the treatment is lower than the one due to carburizing, even if the surface hardness increases, and the case/core transition depth is near to the one where there is the maximum tangential stress, according to Hertz theory. These considerations prevented for a long time the application of nitriding to gears and only recently this thermo-chemical treatment is becoming more and more used in gear power transmissions. In this light the application of shot peening should be useful to improve the performances of nitrided gears both as concern rolling contact fatigue and bending fatigue at the root of the tooth. The recent interest of gear manufacturers for nitriding can partially explain also the few reference data that is possible to find. In [4] the effect of shot peening on a low-alloy steel is analysed and the synergetic effect of the very hard layer due to nitriding and of the residual stress field induced by shot peening evidenced. In [5] the effect of shot peening of contact fatigue behavior of 40Cr steel after a compound heat treatment that includes nitriding is analysed and the different failure modes under different pressure values are underlined. From ths S-N curves included in that paper it is evident that shot peening have a positive effect on the fatigue behavior of nitrided elements. Oshawa et al. [6] studied the improvement of shot peening on gas-nitrided elements. They considered both glass beads and steel shots and were able to assess that shot peening increases the rotating bending fatigue limit of about 20%. Also the influence of the peening media and parameters on surface roughness was investigated.

In [7] the fatigue strength of a shot-peened nitrided low-alloy steel is investigated and the choice of the peening parameters is optimized by means of design of experiments. In this latter paper it is underlined that shot peening is useful only in the case of notched element; in fact, if smooth ones are considered, shot peening is able to move the crack initiation point from the surface to a sub-surface inclusion with negligible improvement of the fatigue limit. As concern notched specimens the fatigue crack starts sometimes from the surface and sometimes from an internal inclusion, depending on the applied load, on the thickness of the nitrided layer and on the choice of the peening parameters.

Indeed the choice of the best treatment parameters is a complicate problem and only a quantitative and general model that considers residual stresses can orient the choice of the treatment parameters with the aim to obtain the most effective self-stress distribution in the hardened layer of material. In the case of nitrided materials the problem is even more complex due to the strong changing of the properties from the case to the core

This paper intends to be a contribution in this field of materials science. Starting from the well-known evidence that the residual stresses induced by shot peening are effective not in preventing crack initiation but in arresting its propagation, rotating bending fatigue tests were carried out on specimens including a microhole (depth equal to 0.1-0.15 mm), acting as a crack. Three series of specimens were considered: nitrided specimens, nitrided and shot peened (peening intensity 12 A), nitrided and shot-peened (peening intensity 18A). This type of tests allowed to analyze the behavior of the nitrided layer with respect of crack propagation and to assess the threshold value of $\Delta K$ of the nitrided layer and its variation with respect of the residual stress distribution. It was also possible to observe cracks starting from an internal inclusion and to relate this occurrence with the residual stress field. These latter were measured by using an X-ray diffractometer.

On the basis of the experimental results a model based on fracture mechanics is being developed, with the aim to assess the resistance of the nitrided layer to fatigue crack propagation in relation to the residual stresses induced by shot peening. The model will be based on the weight function technique and will allow considering the presence of the residual stresses in simple way. The computational time required should be short and the results will be compared with the ones obtained by a complex FE analysis.

The model will enable also the calculation of the stress intensity factor of an internal crack-like sub-surface defect (an inclusion): by comparing these results it will be possible to assess the point of crack initiation in relation to the type and the value of the applied load.

## 2 EXPERIMENTAL TESTS

Cylindrical specimens were constructed by means of 39NiCrMo3 (UTS=1053 MPa, Yield Strength=940 MPa, Elastic Modulus E=206,000 MPa, Elongation A=20%). All the specimens were gas- nitrided (temperature T=520°C, duration=50 h). Some of the specimens were then treated by peening characterized by intensity 12A and some by intensity 18A. In the central zone of all the specimens a micro-hole was realized by means of electro-erosion to introduce the presence of a like-crack defect, see Fig.1.

The specimens can be divided in the following groups:

-Nitrided, N;

-nitrided and shot peened 12A100-12A150 (peening intensity: 12A, hole depth d=100μm and 150μm);

-nitrided and shot peened 18A100-18A150 (peening intensity:18A, hole depth d=100μm and 150μm).

The residual stress values and trends, shown in Fig.2, were measured by using the X-ray diffraction technique.

Rotating bending fatigue tests were carried out and the fatigue strength values determined are reported in Table 1: the improvement induced by shot peening is evident.

By looking at the results it is interesting to note the different fatigue behavior of the different specimen groups. In the case of the N and 12A150 specimens the fatigue cracks start always from the hole and some interrupted cracks were evidenced in run-out specimens, broken after the end of the test and observed by means of a SEM. The extension and the shape of an interrupted crack found in a specimen nitrided, loaded by $\sigma_a$=360 MPa are shown in Fig. 3. The 12A100 specimens, on the contrary, broke by cracks initiating from internal inclusions and not from the holes.

The different fatigue behavior is correlated to the residual stress patterns. In fact it is possible to note from Fig.2 that at the hole bottom the corresponding compressive residual stress values in the case of N and 12A150 specimens are lower than in the case of 12A100. Moreover it is important to note that the 12A100 specimens internal inclusions, from where cracks propagate, are positioned in the tensile residual stress zone.

These different modes of failure are an index of the ability of residual stresses in preventing crack propagation in the nitrided material. Moreover, the depth at which the residual stresses change sign could be considered an index to evaluate the optimal peening parameters, by relating it with the depth and the dimension of typical inclusions of this material. A run-out specimen ($\sigma_a$=360) was broken and an arrested crack was detected.

As regards run-out 12A100 specimens, an interrupted crack, loaded by $\sigma_a$=760 MPa is shown in Fig.4.

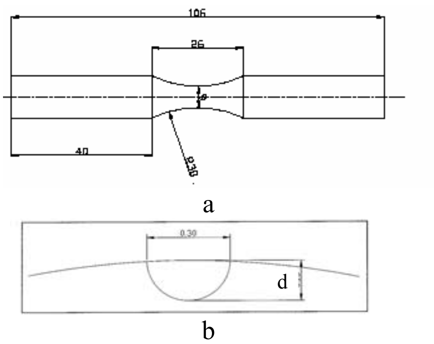


Fig.1 a) Specimen used for the rotating bending fatigue tests; b) particular of the micro-hole.

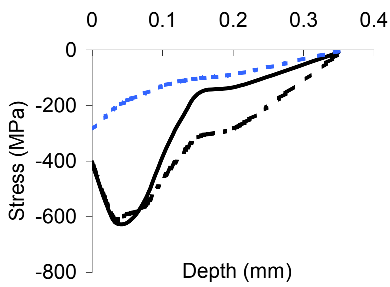


Fig.2 Residual stresses measured on:--- nitrided specimens;—12A specimens;-·-18A specimens.

Table 1- Experimental fatigue test results

| Specimen type | Bending fatigue strength [MPa] | Notes |
|---|---|---|
| Nitrided N | 379 | The fractures begin from the holes |
| Shot peened 12A150 | 674 | The fractures begin from the holes |
| Shot peened 12A100 | 748 | The fractures begin from inclusions |
| Shot peened 18A100 | 762 | The fractures begin from inclusions |
| Shot peened 18A150 | 724 | The fractures begin from inclusions |

This crack shape is different from the one of Fig.3, probably due to the different trend of residual stresses. A behavior similar to the one of 12A100 specimens was observed on the 18A ones, which present a compressive residual stress profile larger with respect of 12A samples. For these specimens the crack started from an inclusion (diameter≈20 μm) at a depth of about 0.5mm, that is in the tensile residual stress zone.

## 3. NUMERICAL ANALYSIS

In order to define an approach allowing the understanding of this phenomenon a three-dimensional finite element model was realized by following the sub-modeling approach and by including the presence of the residual stresses.

The model with the particular of the micro-hole schematized is shown in Fig.5. The contact between the crack faces is schematized too. The stress intensity factor values along the crack fronts were calculated by varying the stress applied. Their values for some particular cases are shown in Fig.6. It is interesting to note that the stress intensity factor values along the crack fronts are in good agreement with the experimental crack shape. For example the specimen shown in Fig. 3 shows a regular and uniformly propagated crack front and has a iso-K trend along the crack (Fig.6), while the specimen shown in Fig.4 has a preferential crack propagation direction. This is justified by the SIF trend along the crack which shows a larger value near the zone where the crack propagates.

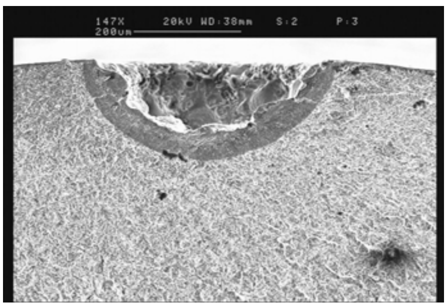

Fig.3 An arrested crack found in a nitrided run out specimen, $\sigma_a$=360 MPa.

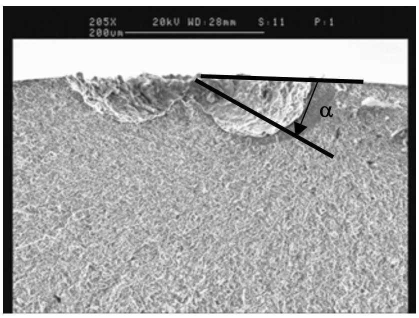


Fig.4 An interrupted crack found in a 12A100 nitrided and peened run-out specimen, $\sigma_a$=760 MPa.

A first approximation value of the threshold stress intensity factor $\Delta K_{th}$ is evaluated by the values obtained by the analyses related to the N specimens. In particular in the case of stress applied $\sigma_a$=380MPa the specimen broke, while if the stress applied is $\sigma_a$=360MPa the specimen run out. The corresponding stress intensity factor determined by the numerical analyses is a tentative threshold value for the nitrided specimens, in particular $\Delta K_{th}$=7.6

MPa$\sqrt{m}$ . The same calculations can be performed for the a 12A specimens, that in the case of $\sigma_a$=760MPa did not fracture, while with $\sigma_a$=780MPa broke. The corresponding stress intensity factor is $\Delta K_{th}$=11.0 MPa$\sqrt{m}$ , that is significantly higher that in the case of the nitrided specimens.

A simple model based on the weight function technique [8] is on course of development, and the results will be compared with the ones obtained with the FE ones. I case of satisfactory agreement it the WF function approach will be used as simple and fast method, to predict the fatigue crack growth behavior of nitrided and shot peened elements.

## 4. CONCLUSIONS

Tests carried out on cracked nitrided and shot peened specimens are presented. The following results are found:

a) the fatigue behavior is strictly correlated with the residual stress pattern;
b) the location of the crack initiation point can lay on the surface or at an internal inclusion, depending on the applied strees and on the position of the inclusion with respect of the residual stress field;
c) the values of the effective stress intensity factors calculated allow to interpret the experimental results.

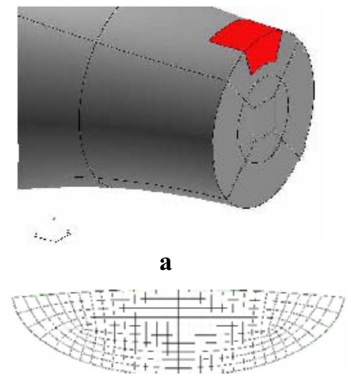

Fig.5: a) Specimen finite element model; b) particular of the mesh of the submodel of the cracked zone.

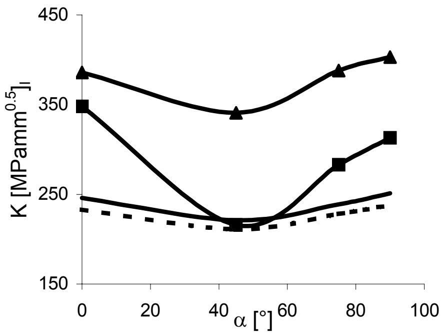


Fig.6 K values along the crack front: –▲– specimen 12A100, broken, $\sigma_a$=780MPa; —■— specimen 12A100, run-out, $\sigma_a$=760MPa; —specimen N, broken, $\sigma_a$=380MPa; ---specimen N, run-out, $\sigma_a$=360Mpa.

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