SHORT CRACK FATIGUE BEHAVIOUR OF NITRIDED AND SHOT PEENED STEELS

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ABSTRACT

The execution of shot peening of steels after nitriding is a compound treatment that has been not sufficiently investigated to assess how and when it can be useful to improve the fatigue beahviour of components. In this paper the fatigue threshold of two nitrided and shot peened steels is investigated by means of experimental rotating bending fatigue tests carried out on specimens containing a micro-hole, acting as a pre-crack. Due to the dimension of the pre-cracks, they were considered as short crack. After a critical discussion of the results in terms of residual stress, micro-hardness and inclusion rate, a fracture mechanics based approach is proposed to predict the fatigue threshold value of the stress intensity factor of nitrided and shot peened steels. The results are in good agreement with the experiments.

KEY WORDS

Nitriding, shot peening, residual stress, FWHM, fatigue threshold (ΔK_{th}).

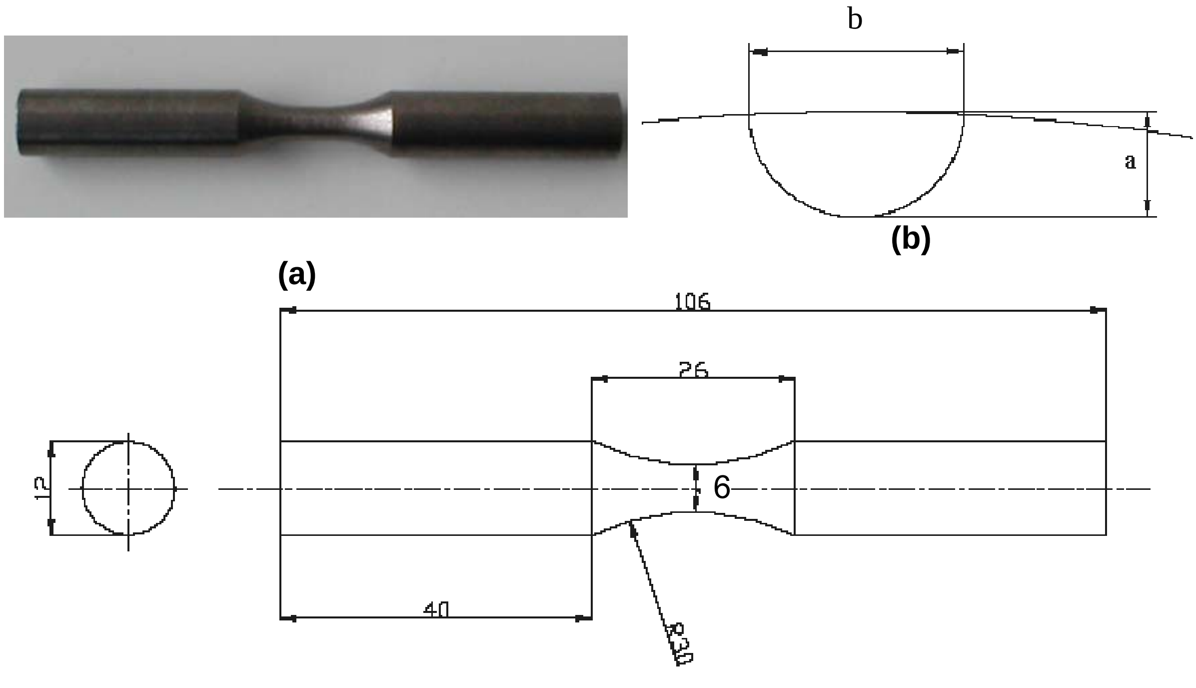
INTRODUCTION

The need of improving performances and the necessity of a more rational use of materials is making popular the use of surface treatments to improve the mechanical behaviour of structural and machine elements.
Among these treatments, shot peening (K.J. Marsh, 1993) is one of the most widely used, due to its ability in increasing the resistance to fatigue, fretting, rolling contact fatigue, stress corrosion cracking... The improved fatigue strength due to shot peening is mainly related with the residual stress induced by the action of the impact of the shot flow against the metallic surface. Shot peening is generally 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 (J.O.Almen, P.H. Black,1963), due to the fact that gears are one of the most important field of application of shot peening.
Less investigated and applied is the case of shot peening execution after nitriding: this is usually attributed to the fact that nitriding is able by itself to give adequate hardness and fatigue strength. In literature it is not possible to find a general approach able to predict the behaviour of nitrided and shot peened components and the results refers to particular cases making difficult their application to wider situations.
The effect of shot peening on a low-alloy steel was analysed and the synergetic effect of the very hard layer by nitriding and of the residual stress field induced by shot peening was evidenced (D. Guanhua, H. Jawen, H. Naisai, 1991). Z. Jingpu

(1994) analysed the effect of shot peening on contact fatigue behaviour of 40Cr steel after a compound heat treatment that includes nitriding and the different failure modes under different pressure values are underlined. From the S-N curves included in this paper, it is evident that shot peening has a positive effect on the fatigue behaviour of nitrided elements. Ohsawa and Yonemura (1984) studied the improvement of shot peening on gas-nitrided elements. In this paper, it was concluded that shot peenings using both glass beads and steel shots were able to increase the rotating bending fatigue limit of aprox. 20%. Also the influence of the peening media and parameters on surface roughness was investigated.
The fatigue strength of a shot-peened nitrided low-alloy steel was investigated (D. Croccolo, L. Cristofolini, M. Bandini, 2002) and the choice of the peening parameters was optimized by means of design of experiments.
Aim of the present paper is to investigate the fatigue threshold behavior of nitrided and shot peened steels and to evaluate the factors that mainly affects the modified fatigue behaviour of the steels after shot peening. Two low-alloy steels with different mechanical characteristics were considered. Rotating bending fatigue tests were executed with this aim (C. Colombo, M. Guagliano, L. Vergani, 2005): the specimens has a blind micro-hole acting as a pre-crack, where fatigue crack propagation started. In this way it was possible to analyze the behavior of the nitrided and shot peened layer of material with respect of crack propagation, to evaluate the threshold value of ΔK of the surface layer of material and to relate it with residual stress distribution, measured by means of an X-Ray diffractometer, and with micro-hardness values. SEM observations were executed on broken and unbroken specimens and the presence of arrested cracks was detected on these latter. In some tests the fatigue crack started from an internal inclusion.
On the basis of the discussion of the experimental results, a modified version of the ΔK_{th} formula presented by Murakami (2002) and by Murakami and Endo (1994) for short cracks, previously proposed by the authors (I. Fernández Pariente, M. Guagliano, 2007) is applied. The additional hardening of the surface layer with material by shot peening is considered a function of the width of the diffraction peak measured during the residual stress measurement. The agreement with the experimental results is satisfactory.

MATERIALS AND EXPERIMENTS

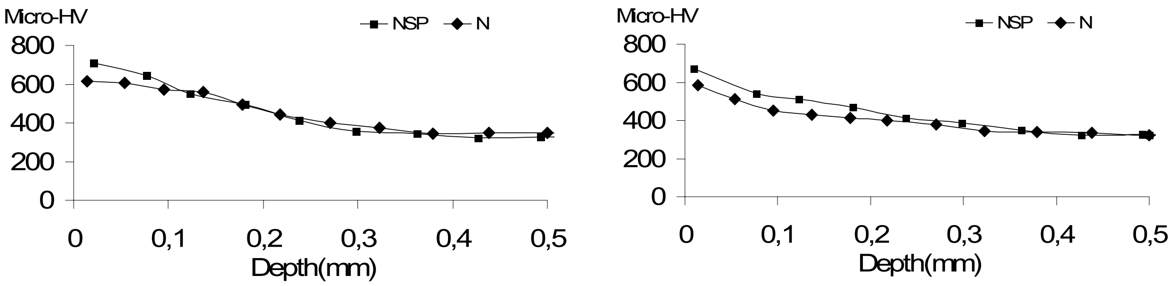
Two different low-alloy steels were considered: the first one is the steel 42CrMo4 UNI EN 10083 (UTS=1100 MPa, Yield Strength=950 MPa, Elastic Modulus E=206˙000 MPa, Elongation A=10%; chemical composition: C=0.4%, Mn=0.6%, Si=0.15%, Cr=1.1%, Mo=0.2%, P<0.035%, S<0.035%). The second is the steel 39NiCrMo3 (UTS=1053 MPa, Yield Strength=940 MPa, Elastic Modulus E=206˙000 MPa, Elongation A=20%).
Sandglass specimens for the rotating bending fatigue tests were machined as showen in Fig. 1a and Fig. 1c.
In the minimum section of these specimens, a micro-hole was obtained by controlled electro-erosion, in order to avoid the modification of the residual stress field induced by shot peening. The shape of the micro-hole is semi-elliptical (see Fig. 1b) with an axes ratio equal to 2 and a nominal value of the depth equal 0.15 mm (±0.02mm). The dimension of the micro-holes is enough small to completely fall into the hardened layer of material. These micro-holes act like a pre-existent defect and were machined to have a preferential site for fatigue crack initiation. In this way it is also possible to observe the evolution of a crack starting from this point, that is to say that it is possible to observe if the run-out specimens have some non-propagated crack started from the micro-hole.



(c)

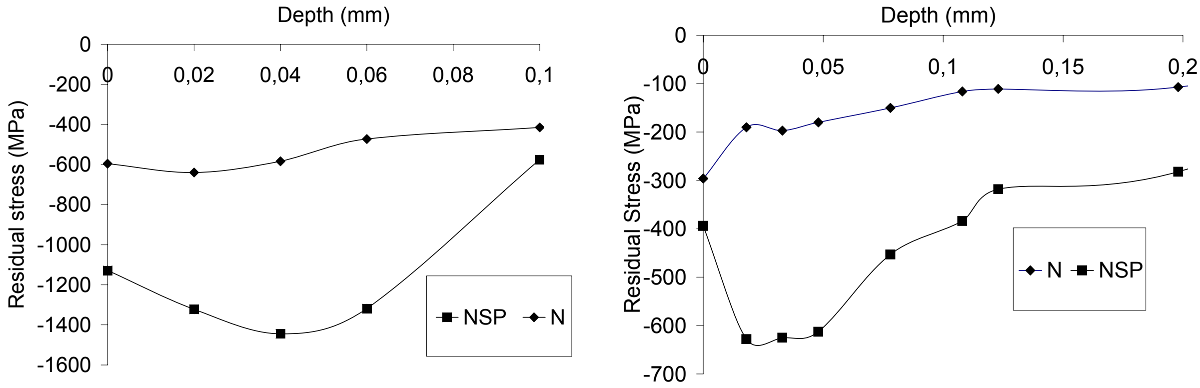
Figure 1 - (a) Specimen used for the rotating bending fatigue tests; (b) Particular of the micro-hole (b/a=2). (c) Specimen geometry

The white layer was not removed. The geometry of the micro-hole allows researchers to consider it as a crack, according to the Murakami's theory (Y. Murakami, 2002), and to elaborate the results by using fracture mechanics concepts. For each material two series of specimens were considered: the first includes specimens previously gas nitrided (temperature T=520°C, duration of gas nitriding = 50 h), the second includes nitrided and shot peened ones (shot used:S170, Almen Intensity (16-18 A).
Rotating bending fatigue tests were carried out, being the aim to assess their fatigue limit. For every series 15 specimens were considered. The tests were stopped after 3E+06 cycles, and the specimens not broken after this number of cycles were considered run-out.
Micro-hardness was measured on one specimen of all the four series by using a test force of 0.981N. In Fig.2 the micro HV in-depth trend is shown: it is possible to observe that shot peening does not strongly influence the values of micro-hardness. The sub-surface layer of material was characterized also by measuring the residual stresses by means of a AST XStress 3000 X -ray diffractometer (radiation Cr Kα, {211} diffraction planes of the αFe phase, irradiated area 1mm^2, sen$^2\psi$ method, 11 angles of measurement). As regards the in-depth measures, they required the removal step by step of thin layers of material: this operation was performed by using an electro-polishing facility. The results of the in-depth residual stress measures were corrected by using the method described by Moore and Evans (1958).
In Fig. 3 it is possible to observe the measured trends of the longitudinal residual stresses for the four series of specimens: the strong changing induced by shot peening with respect of nitriding can be noted.
The X-ray diffraction measurements allowed researchers also to determine the full width at half maximum (FWHM).This quantity is related to the grain distortion, to the dislocation density and to the so called type II micro residual stresses (I.C. Noyan, J.B. Cohen, 1987) and can be assumed as an index of the hardening of the material.



(a) (b)

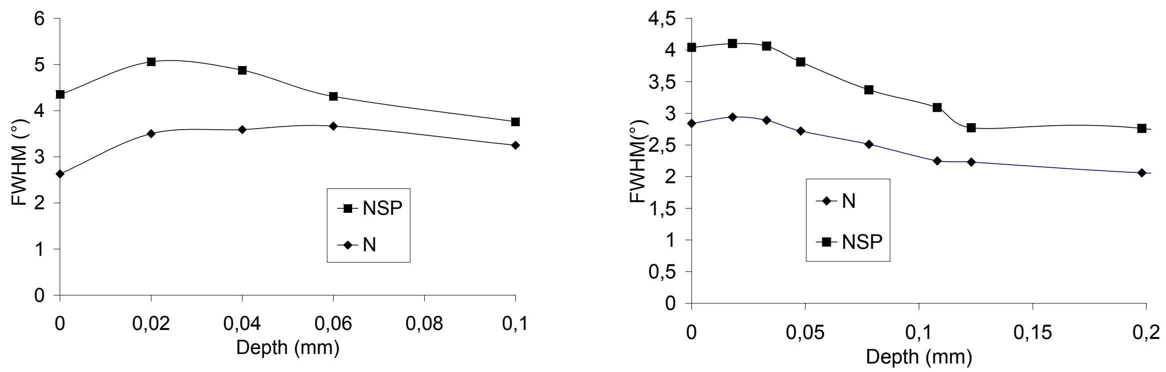
Fig. 2 – In-depth micro hardness trend: (a) 42CrMo4, (b) 39NiCrMo3



(a) (b)

Fig. 3 - In-depth residual stress profile: (a) 42CrMo4, (b) 39NiCrMo3 (N=nitrided, NSP=nitrided and shot peened).

In Fig. 4 the in-depth trend of FWHM is shown: it is clear the strong influence of shot peening also on this quantity, not only in the proximity of the surface but also in depth. From the results of these measurements and the ones regarding micro-hardness, FWHM seems a more accurate hardening index, related only to the surface where the measure is done. On the contrary, micro-hardness involves a finite thickness of material.



(a) (b)

Fig. 4 - In-depth FWHM profile: (a) 42CrMo4, (b) 39NiCrMo3 (N=nitrided, NSP=nitrided and shot peened).

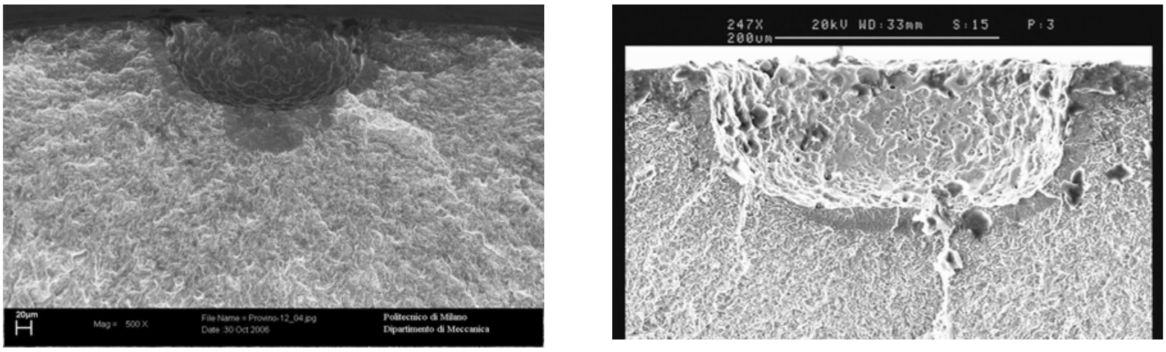
RESULTS

The results were elaborated by using the stair-case procedure. In Table 1 the final results of the fatigue tests are shown: it is evident the improvement induced by shot peening. The specimens made of the steel 42CrMo4 fractured from the micro-hole, while a part of the 39NiCrMO3 specimens started from an internal inclusion.

Tab. I – Fatigue limit experimentally determined by means of the stair-case procedure

	42CrMo4		**39NiCrMo3**	
	Nitrided	**Nitrided+shot peened**	**Nitrided**	**Nitrided+shot peened**
Fatigue limit σ_w (MPa)	±480	±834	±379	±724

In Figure 5 some micrographs of the cracked section are shown: they were taken on run-out specimens after brittle fracture in liquid nitrogen.



(a) (b)

Figure 5 – Two arrested cracks after fatigue tests: (a) 42CrMo4, (b) 39NiCrMo3.

FATIGUE LIMIT PREDICTION

Due to the dimension of the defects considered, the prediction of the fatigue threshold of the N and NSP specimens has to take into account the peculiar behavior of the “short crack” Among the different approaches that is possible to use, the authors (I. Fernández Pariente, M. Guagliano, 2007) showed that as regards nitrided and shot peened specimens it is possible to use a modified version of the formula by Murakami. In fact, hardening induced by shot peening in a very thin layer of material cannot be taken into account by the hardness measurement but by the full width at half maximum (FWHM). The following formula for nitrided and shot peened steels is derived from the one expressed in terms of ΔK_{th} recently proposed and successfully applied:

$$\sigma_w = \frac{1.43 \cdot (HV + 120)}{\sqrt{area}^{1/6}} \left(\frac{1 - R_{\Delta K}}{2} \right)^{\alpha} \left(\frac{FWHM_{NSP}}{FWHM_N} \right) \tag{1}$$

with $\alpha = 0.226 + HV \cdot 10^{-4}$, R is the stress ratio in terms of the stress intensity factor range, ΔK) and HV is the measured hardness. For the only nitrided specimens the terms in R and FWHM are omitted.

By applying this formula to the cases considered in this paper the results included in Table II are obtained: it is noted that they are close to the experimental results, thus confirming also in the case of the nitrided and shot peened steel 39NiCrMo4 the applicability of the proposed formula.

Tab. II – Fatigue limit predictions obtained by using Eq. (1).

	42CrMo4		**39NiCrMo3**	
	Nitrided	**Nitrided+shot peened**	**Nitrided**	**Nitrided+shot peened**
Fatigue limit σ_w (MPa)	±471	±795	±397	±689

CONCLUSIONS

The fatigue behavior of two low-alloy steels nitrided and nitrided plus shot-peened including short defects (acting as pre-cracks) was investigated. Hardening and residual stresses induced by shot peening were experimentally investigated: in particular it was found that hardening is better described by the measurement of the FWHM of the diffraction peak than by hardness measurement.
The results of the fatigue tests were interpreted in the light of the fracture mechanics concepts and show that the improved fatigue behavior is only partially due to the residual stress induced. A modified Murakami formula able to predict the fatigue limit of the nitrided and shot peened steels in presence of small defects is proposed. It include the ratio between the FWHM of the nitrided and shot peened steel and the one of the nitrided steel to take into account hardening due to shot peening. The prediction are satisfactory for both materials.

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