INFLUENCE OF SHOT PEENING ON THE FATIGUE BEHAVIOUR OF A GAS-NITRIDED LOW-ALLOY STEEL

Inés Fernanez Pariente[a], Mario Guagliano[b]

[a] *Dip.to Ciencia de los Materiales, Universitad de Oviedo, Campus de Viesques, edificio de Energia - Gijón (Espana), e-mail: inesfp@uniovi.es.*
[b] *Dip.to di Meccanica, Politecnico di Milano, via La Masa, 34 – 20156 Milano, e-mail: mario.guagliano@polimi.it.*

SOMMARIO
Lo studio dell'efficacia della pallinatura applicata ad elementi precedentemente nitrurati non è stato trattato adeguatamente in letteratura e non ancora chiaro se, in quali circostanze ed in che misura, la pallinatura possa incrementare le prestazioni di componenti nitrurati sollecitati a fatica. Nella presente memoria è proposto un approccio per valutare l'influenza della pallinatura sul comportamento a fatica di elementi nitrurati. L'approccio si basa sui concetti della meccanica della frattura. Provini lisci in cui è stato praticato un microforo, con funzione di pre-criccatura, sono stati sollecitati a fatica flessionale rotante. I valori di microdurezza e degli sforzi residui misurati sono stati messi in relazione ai risultati delle prove di fatica. Elaborando i risultati delle prove è anche stato possibile ricavare i valori della soglia di propagazione del materiale nitrurato e pallinato. E', infine, proposta una formula per la determinazione del ΔK_{th} di acciai basso legati nitrurati e pallinati.

ABSTRACT
The effectiveness of the application of shot peening after nitriding for improving the fatigue strength of high-performance steel components has not been adequately treated in literature, and it is not clear if shot peening can really and drastically increase mechanical performances of nitrided elements. In this paper an approach to assess the influence of shot peening on nitrided components is presented. It is based on fracture mechanics concepts. Smooth specimens with a micro-hole acting as a pre-crack were fatigue tested. The values of micro-hardness and of the residual stresses were measured and related to the experimental results. By elaborating the results it was possible to determine the threshold values of the stress intensity factors of the nitrided and shot peened material. A formula to predict the value of ΔK_{th} of shot peened and nitrided steels is proposed.

1. INTRODUCTION
The ever more pronounced trend in developing mechanical systems with improved performances, lightness and reliability is pushing researchers and companies to develop more resistant materials and to apply surface coatings or surface treatments able to modify the mechanical characteristics of the sub-surface layer of material, thus enabling the improvement of the strength of the materials in different service situations. If the attention is focussed on fatigue, one of the most widely used surface treatment to enhance the strength of components under cyclic load is shot peening. It consists in "bombing" a surface with a shot flow with an energy able to cause plastic deformation of a thin layer of material under the surface. The result is the introduction of a compressive residual stress field near the surface and hardening of the same layer of materials. These effects, especially the first one, are the responsible of the improved fatigue behaviour of the shot peened parts; the improvement is more pronounced in the case the treated parts are notched, due to the severe gradient of the applied stress.

It is possible to find many studies and researches about shot peening and its application to steels, and a relevant part of these ones considers carburized and shot peened steels [i.e. 2, 3]. The case of nitriding and shot peened is less investigated and applied and it is usually attributed to the fact that nitriding is able by itself to give adequate hardness and fatigue strength and also to the fact that, in high-cycle fatigue applications, crack in nitrided elements starts form an internal inclusion, thus preventing to make effective the residual stresses induced by shot peening.
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 on contact fatigue behaviour 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 the S-N curves included in that paper, it is evident that shot peening has a positive effect on the fatigue behaviour of nitrided elements. Oshawa et al. [6] studied the improvement of shot peening on gas-nitrided elements. 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 optimised by means of design of experiments. The results suggest that the effectiveness of shot peening on nitrided components is related to the inclusion rate and to the typical inclusion dimension of the steel; however no reliable relation can be found if the strength of the nitrided and shot peened layer of material is not known.
This is the topic of this paper, where rotating bending fatigue tests were carried out on specimens including a micro-hole (with controlled depth) acting as a crack [8]. The tests allowed to analyse the behaviour of the nitrided layer with respect of crack propagation and to assess the threshold value of ΔK of the nitrided layer and its variation with respect of the residual stress distribution. Residual stresses were measured by means of an R diffractom eter, before and after the test, together with micro-hardness measures. SEM observations were executed on broken and unbroken specimens and the presence of arrested cracks was detected on these latter.
The test results were interpreted on the basis of the experimental measures and observations and a formula to determine the fatigue threshold of nitrided and shot peened steels is proposed.

2. EXPERIMENTAL ANALYSIS

The material considered is the steel 42CrMo4 (UTS=1100 MPa, ield Strength=950 MPa, Elastic Modulus E=206000 MPa, Elongation A=10%). In Fig. 1 a it is possible to see the sandglass geometry of the specimens that were fatigued by means of rotating bending tests. In Fig. 1b it is possible to note the geometry of the microholes that were electro-eroded in the minimum section of every specimen. All the specimens were gas nitrided (temperature T=520℃, duration=50 h). The specimens were then peened with an Almen intensity equal to 16A. The holes act as pre-crack and their dimension is short enough to completely fall into the treated layer, that is to say that the behaviour of the microholes can be related to the fatigue strength of the nitrided layer.

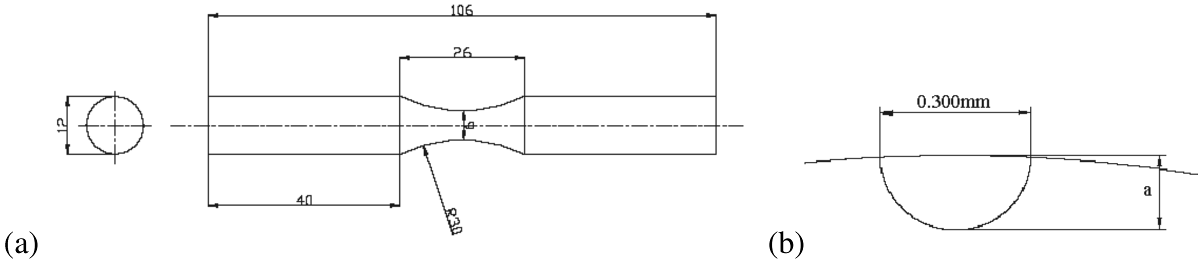


Fig. 1: a) Specimen used for rotating bending fatigue tests: a) Specimen geometry b) Particular of the micro-hole (a=0.12mm).

In Fig.2 the in-depth trend of the microhardeness is shown: it is possible to know that shot peening influence ust the surface value.

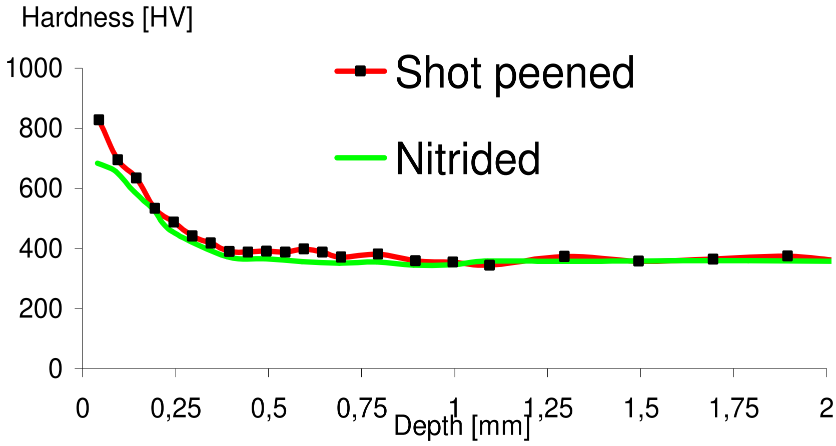
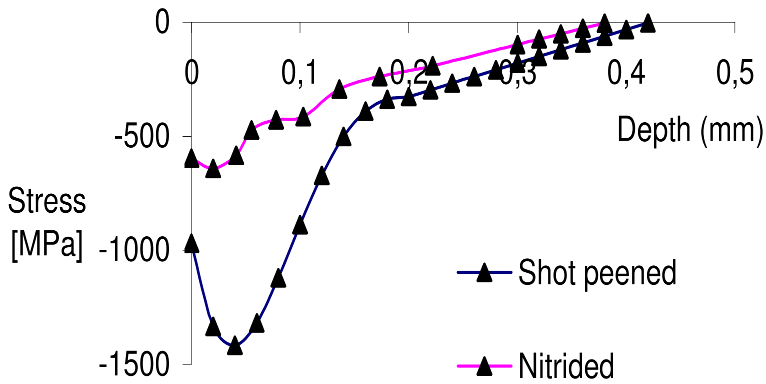


Fig. 2: Microhardness in-depth trend of nitrided (Nitrided) and nitrided+shot peened (Shot Peened) specimens.

In Fig. 3a the in-depth trend of residual stresses measured by means of a AST Stress 3000 diffractometer (radiation Cr, target Feα, irradiated area 1mm^2, sen$^2\psi$ method, 11 angle of measurement) is shown. In Fig. 3b the in-depth trend of the full width of the diffraction peak at half maximum (FWHM): this quantity is related to the hardening of the material and to the dislocation density. It is clear that for both, residual stresses and FWHM there is a remarkable difference between the nitrided and the nitrided and shot peened specimens.



(a)

Fig. 3: Residual stress in-depth trend (a) and FWHM in-depth trend (b).

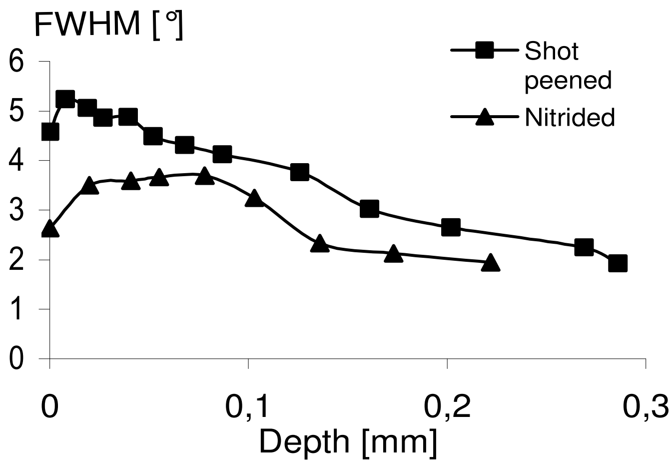
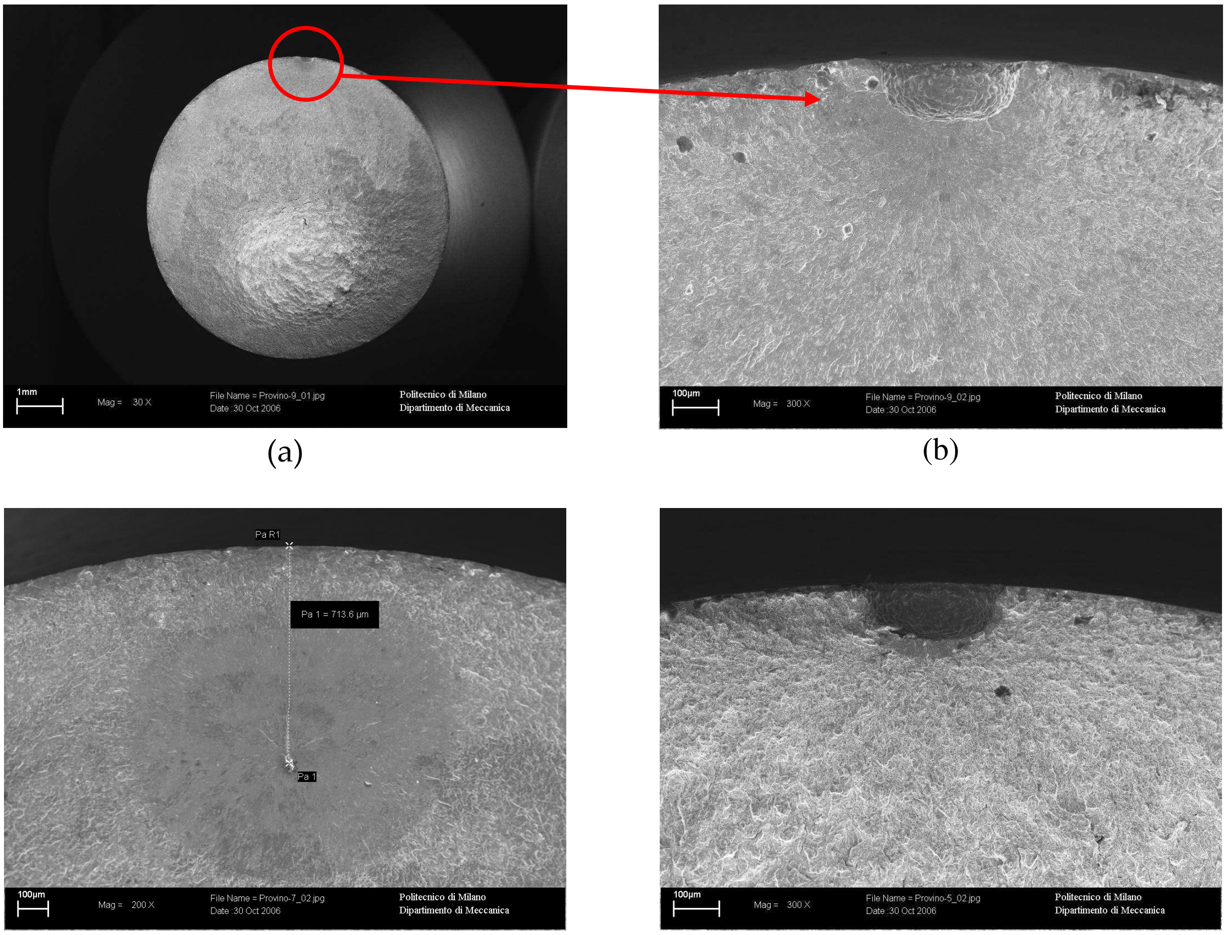


Fig. 3: FWHM in-depth trend.

As regards the fatigue tests, the stair case procedure was followed for determining the fatigue limit after 3 million cycles. The resulting fatigue limit was 850 MPa. Almost all the propagating cracks started from the micro-hole. Also in the run-out specimens, after having broken them in liquid nitrogen, non-propagating cracks were found. One example of them is shown in Fig. 4d, together with a crack started from an internal inclusion (Fig. 4c) and with a propagated crack (Fig.4a and Fig. 4b).



(a) (b) (c) (d)

Fig. 4. SEM images showing: (a) and (b) a propagated crack started from a microhole, (b) a propagated crack started from an internal inclusion, σ=860MPa (c) an arrested microcrack started from the microhole, σ=840MPa.

3. FATIGUE THRESHOLD ASSESSMENT

After having performed all the experimental tests and measurements described in the previous paragraph, it is possible to verify if the results found fit well with the equations usually utilized to predict the fatigue threshold of a material. It is possible to use different approaches, and all them assume that, due to the small dimension of the crack considered, the threshold depends not only of material properties but also on the crack dimension (we are in the field of short cracks). Among the different approaches [12, 13], in this paper the one by Murakami is considered [10, 11]. This approach has many advantages with respect of other models: it is simple to apply, it is based on a great amount of experimental data and it allows to treat also cracks or defects with arbitrarily crack front. In fact, the stress intensity factor of a crack is related to the $\sqrt{area}$ of the crack and not to the shape of the crack itself. The size and not the shape of microcracks is important. Indeed the case considered in this paper fits well with the cases considered by Murakami: in fact, the presence of non-propagating cracks emanating from the micro-holes makes possible to assimilate the micro-hole plus the non- propagated crack to a crack with $\sqrt{area}$ equal to the one of both, the microhole plus the non-propagated crack. Also the dimension of the cases considered lies inside the upper limit of validity of the formulas proposed by Murakami (for $\sqrt{area}$ more than 1mm, the value of ΔK_{th} is constant and equal to the one of the long cracks). Murakami suggests, for fatigue cycles with R=-1 and for steels, the following formula to calculate ΔK_{th}:

$$\Delta K_{th} = 3.3 \cdot 10^{-3}(HV + 120)\left(\sqrt{area}\right)^{1/3} \tag{1}$$

that is valid for microhardness 700 HV. It is poss ible to note that this formula does not requires the knowledge of residual stress value and refers only to the applied stress (ΔK_{th} is the due only to applied stress and it is expressed in $MPam^{1/2}$). The formulas valid for R ($=\sigma_{min}/\sigma_{max}$), stress ratio of the fatigue cycle, is equal to -1.

If R is different the formula must be modified:

$$\Delta K_{th} = 3.3 * 10^{-3}(HV + 120)\left(\sqrt{area}\right)^{1/3}\left(\frac{1-R}{2}\right)^{\alpha} \tag{2}$$

with α=0.226+HV·10^{-4};

If we apply (1) to the cases considered in this paper we obtain ΔK_{th}= 445 $MPamm^{1/2}$. It is possible to note that (1) is unable to meet the experimental results. This is not strange, since (1) has been determined by considering surface hardened steels (case hardened, carburized, nitrided) but not shot peened steels, that have, due to the presence of a strong compressive residual stress field near the surface, a peculiar behavior. In this case it is possible to consider Eq.(2), where the stress ratio R includes the presence of the residual stresses and the applied ones. In the case considered in this paper the residual stresses used for the calculation of R are the ones measured after the end of the test: In fact, by looking at the data in references [14] it is possible to write that the relaxation takes place in the first fatigue cycles, and, consequently, that the final ones are the values contributing to the improved behavior of the shot peened specimens. The results obtained by using (2) is the following one:

ΔK_{th}= 517 $MPam^{1/2}$

Also in this case the experimental results does not fit well with the predictions suggested by Murakami. Indeed, the present analysis presents many different points with respect of the study by Murakami. In fact, Eq. (2) is referred to fatigue cycles with R≠-1, not to fatigue tests that consider the presence of residual stresses. In this latter case, if we consider the presence of surface defects (that can be assimilated to cracks), the definition of R is not trivial: the presence of the crack suggests that it is more correct to define R as the ratio between the effective minimum value of K and its effective maximum one, including the presence of residual stresses, that is to say:

$$R_{\Delta K} = \frac{K_{\min}}{K_{\max}} = \frac{K_{appl-\min} + K_{res}}{K_{appl-\max} + K_{res}} \tag{3}$$

If this definition of $R_{\Delta K}$ is used in (2), we obtain:

ΔK_{th}= 552 $MPamm^{1/2}$ (series NSP)

This result is more similar to the experimental one even if it is still far from an accurate prediction of the experimental results.
Shot peening does not only introduce a compressive residual stress field in the surface layer of material, but causes also a strong distortion of the material grains in the layer of material immediately under the surface[14] and an increment of the dislocation density. From a macroscopical point of view this means that shot peening is able to induce hardening in a thin layer of material. The mechanical parameter usually used to quantify hardening is the value of microhardness (HV), that also in the Murakami approach is considered. But, as concern the nitrided and shot peened specimens

considered in this analysis, the HV measures showed that there is not a substantial difference between the HV values of nitrided and nitrided plus shot peened specimens. That is to say that microhardness is not able to reveal the microstructural modifications induced by the impact of the shots against the treated surface. On the other hand, the -Ray diffr action measures showed an evident difference of the results concerning the nitrided and the nitrided and shot peened series of specimens. And not only as regards the residual stress trends (that have been already discussed) but also for the FWHM in-depth values. This last quantity is related to the grain distortion and to the dislocation density and, even if its values have not a direct physical relation with hardening status of a surface, it can be used to compare the state of different surfaces. The advantage of FWHM as index of surface hardening is that its measures refers only to the surface (the depth of penetration of the -Ray beam is really negligib le) and does not include a finite thickness of material, like microhardness does. So, it can be thought to use it for developing criteria to predict fatigue strength of surface treated materials, ust to disti nguish the effect of the surface treatment (i.e.: shot peening) from the fatigue behaviour of the not-surface treated material. This idea is not completely new, in fact it was successfully used in [19] for the development of a fatigue strength evaluation approach for shot peened materials, based on Dang Van criterion. In this study, FWHM is used to complete the Murakami formula for determining the value of ΔK_{th} of nitrided and shot peened steels (SP), by differentiating their behaviour from the one of only nitrided ones (N), this latter thing being not possible by using the HV values. The proposed modified formula is the following one:

$$\Delta K_{th} = 3.3 * 10^{-3} (Hv + 120)\left(\sqrt{area}\right)^{1/3} \left(\frac{1 - R_{\Delta K}}{2}\right)^{\alpha} \left(\frac{FWHM_{SP}}{FWHM_{N}}\right) \tag{4}$$

where all the symbols have the meaning previously defined.

Due to the fact that this parameter has not a direct physical meaning and to the nature of RD measures, the use of single values of FWHM can be affected by not negligible errors. To minimize this effect the average value of the FWHM along the crack depth were used: in this way it is possible to obtain a more stable value, less influenced by single measurements conditions and imperfections.
By using this modified formula the following results are obtained:

ΔK_{th}= 725 MPamm$^{1/2}$

This values are really closed to the ones that were calculated from the experimental tests results (ΔK_{th}= 745 MPamm$^{1/2}$) and are a first validation of the possibility to use FWHM values to characterize the mechanical characteristics of a treated surface in view of defining fracture mechanics based approaches for fatigue strength prediction.

4. CONCLUSIONS

The fatigue threshold behaviour of a nitrided and shot peened steel was investigated by means of hardness, residual stress measurements and by carrying out rotating bending fatigue tests of pre-cracked specimens. The results were compared with the Murakami's formula and result was not satisfactory. These latter formula was modified by considering the ratio of the FWHM between the nitrided and shot peened material and nitrided one and by modifying the definition of R in terms of the stress intensity factor range: in this case the results were comparable with the experimental one. The proposed formula seems to correctly describe the peculiar fatigue threshold behaviour of nitrided and shot peened materials; further experiments are necessary to generalize it.

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