Analysis of Shot Peening Influence on Short Crack Fatigue Threshold of Nitrided Steels

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Abstract
Great advance in technology requires each time better materials with better mechanical properties, able to resist high stresses, fatigue, wear. For getting this objective surface treatments are very useful. In terms of fatigue, nitriding and shot peening are known as two of the most effective methods to increase components' strength. In this paper the effect of nitriding plus shot peening on fatigue threshold of a low-alloy steel is investigated by means of experimental rotating bending tests carried out on sandglass specimens containing a micro-hole acting as a pre-crack. Different sizes of micro-hole obtained with different processes were considered to assess the influence of crack dimension on fatigue strength in the field of short cracks. After that a critical discussion of the results in terms of residual stress, micro-hardness trend and fatigue strength is done, bearing out the influence of the defects dimension on the fatigue threshold of nitrided and shot peened low alloy steels.

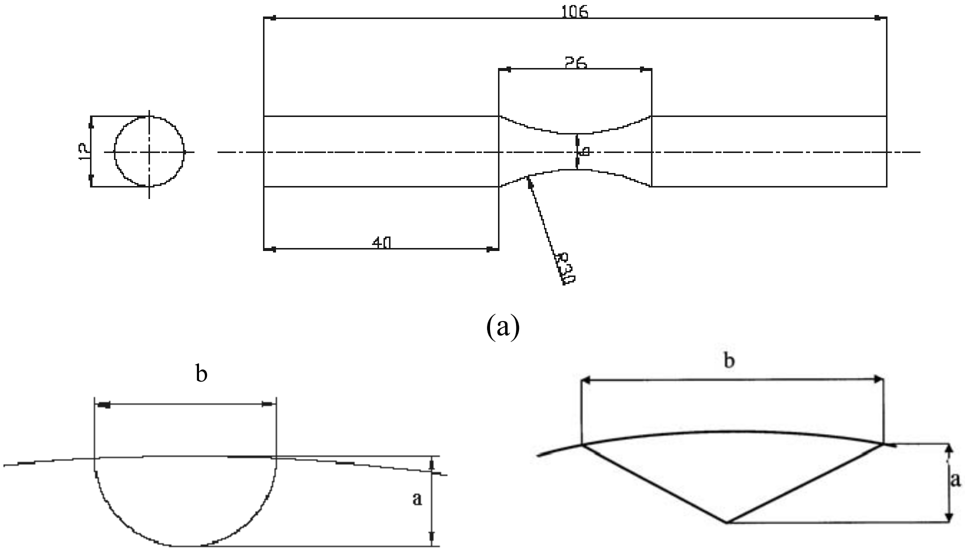
1. Introduction
Fatigue is an important parameter to be considered in the behaviour of mechanical components subjected to constant and variable amplitude loading. In fact, it is well known that 80-90% of fracture accidents are caused by fatigue. Investigation indicates that almost 100% of these fractures start from the sites of stress concentrations at structural discontinuities such as holes, notches, shoulders, cracks, defects, and scratches [1, 2].
There are too many factors which may influence fatigue strength to permit the establishment of a unifying theory. These factors include matters such as the size and shape of surface defects, natural defects and nonmetallic inclusions, chemical composition, etc. Stresses at these structural discontinuities are higher than at other places on structures because of stress concentration, taking place a decrease in fatigue strength. This phenomenon is called 'notch effect'. This effect has a big relationship with the size and shape of holes and notches. Theories based on stress concentration factors and stress distribution or gradient are applicable to notches witch may be seen by the naked eye, that is, notches larger than about 1mm. However, as notch size decreases, these theories become invalid. Previous studies on small defects may be divided into those which mainly considered small notches and small cracks, and those which investigated the influence of

nonmetallic inclusions as equivalent notches or voids [3]. In this work, the influence of the size or artificial defects in a low-alloy steel is studied.
Previously, Murakami has also studied the effect of micro-holes in fatigue strength [4, 5]. He affirms that the fatigue limit of materials containing defects is essentially a crack problem and that there is a very strong correlation between $(area)^{1/2}$ and K_{Imax}, being $(area)^{1/2}$ the square root of the initial defect projected area.
On the other hand, is well known that nitriding and shot peening treatments are widely used for improving the fatigue life of materials [6-8]. Nitriding consists in putting a steel part in an nitrogenous gas, generally ammonia, at temperature (500°C-550°C) and for a time sufficient to obtain the formation of hard compounds while shot peening consists in shooting a metallic surface with a small shots flow under controlled conditions, with an impact energy able to cause plastic deformation of the surface layer of material. The improvement due to nitriding is due to the precipitate formed during this treatment and the formation of a very hard case, while the improvement due to shot peening is related to a refinement of the microstructure [9]. In both cases, the improvement in fatigue strength is because of a compressive residual stress field and strain hardening induced by these treatments [10-12].
In this paper the effect of nitriding plus shot peening on fatigue strength of a low-alloy steel 42CrMo4 is investigated by means of experimental rotating bending tests carried out on three series of sandglass specimens containing an artificial micro-hole acting as a pre-crack. Two different sizes of micro-hole were considered to assess the influence of crack dimension on the fatigue crack propagation strength in the short cracks regime. After that a critical discussion of the results in terms of residual stress, micro-hardness trend and fatigue strength is done, bearing out the influence of the defects dimension on the fatigue threshold of nitrided and shot peened low alloy steels.

2. Material and experimental methodology

The material considered 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%).
Sandglass specimens were machined, being the aim to perform rotating bending fatigue tests, see Fig. 1a. In the minimum section of these specimens, a micro-hole was obtained by controlled electro-erosion (it was possible to obtain a dimensional tolerance equal to ±0.02 mm with respect of the nominal dimensions, see Fig. 1b) and by indentation. These microholes act like a pre-existent defect and were machined to have a preferential site for fatigue crack initiation. The white layer was not intentionally removed even if the application of shot peened accidentally and partially removed it. Two different hole geometries and dimensions were considered: the first hole, call hole A, was obtained by electro erosion and has a semi-elliptical shape, while the second one, called B, has a conical shape and was obtained by indentation. This second procedure locally

influence the residual stress state but it was used since the impossibility to use electro erosion to obtain such a small conical holes.



(b) (c)

Fig. 1 – Geometry of the specimens used for the rotating bending fatigue tests, (a), geometry of hole A (a=0.125mm b=0.28mm) (b), geometry of hole B (a=0.70mm, b=340mm) (c).

Both micro-hole geometries allow researchers to consider the holes as cracks, according to the Murakami's theory [3], and to elaborate the results in terms of fracture mechanics concepts. The dimension of the holes is short enough to completely fall into the hardened case, that is to say that the results of all the tests can be related to the fatigue strength of the nitrided layer. Three different series of 15 specimens were considered. The first series (called N in the following pages of the paper) includes specimens with hole A that were gas nitrided (temperature T=520°C, duration of gas nitriding = 50 h). The second one (NSPA) is formed by specimens with hole B that were gas-nitrided (same parameters of series N) and then shot peened with an Almen intensity equal to 16A. The third one (NSPB) includes specimens with the hole B nitrided and shot peened with the same parameters of series NSPA. The micro-holes were obtained after nitriding and shot peening.

Micro-hardness was measured on one specimen of each series with the help of the device FM-700 Future Tech Corp., under a load of 100g. In Fig.2 the micro HV in-depth trend is shown for the three series of specimens: it is possible to observe that shot peening influences the values till 200μm in depth.

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 Feα 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, thus preventing a strong alteration of the pre-existent residual stress state.

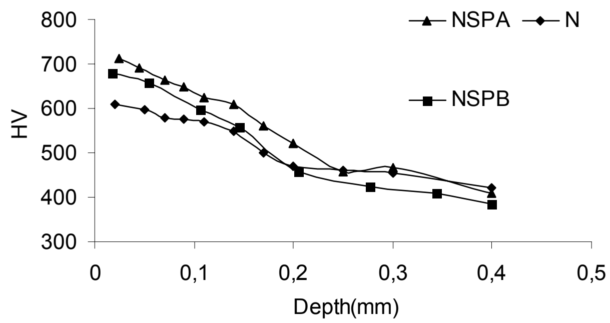


Fig. 2 – Micro hardness in-depth trend.

The results of the in-depth residual stress measures were corrected by using the method described in [13].

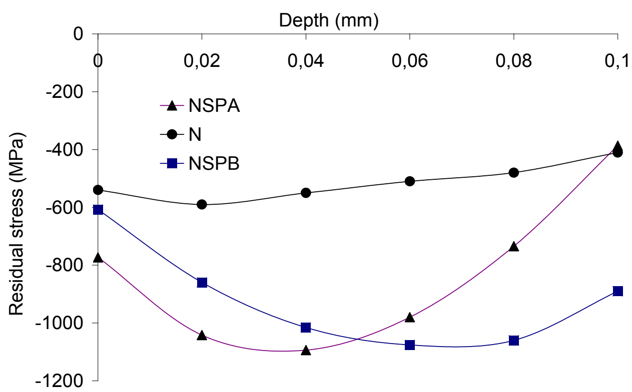


Fig. 3 – Residual stress in-depth trend

In Fig. 3 it is possible to observe the measured trends of the longitudinal residual stresses for the three series of specimens: the strong changing induced by shot peening with respect of only nitriding is observable. The results of the NSPA and NSPB specimens are different because they were nitrided and peened in different times, thus including some little no controlled variation in the processes.

The X-ray diffraction measurements allowed researchers to obtain another important information about the surface state of material: the width of the diffraction peak at half the maximum diffraction (FWHM). This quantity is related to the grain distortion, to the dislocation density and to the so called type II micro residual stresses [14]. It is assumed as an index of the hardening of the material, that is to say that the larger is the FWHM the larger is the hardening of the measured surface.

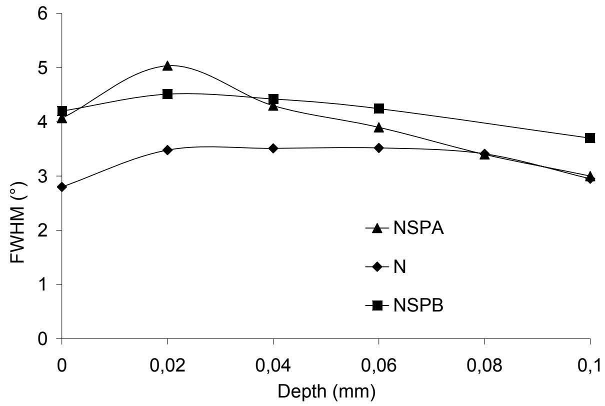


Fig. 4 – FWHM in-depth trend

In Fig. 4 the in-depth trend of FWHM is shown: it is clear the strong influence of shot peening also on this parameter, not only in the proximity of the surface but also in depth. In fact shot peening is able to cause plastic deformation of the surface layer of material due to the plastic deformation associated with the multiple shot impacts.

3. Results

3.1 Fatigue tests

Rotating bending fatigue tests were carried out on the sandglass pre-cracked specimens, 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. The results were elaborated by using the stair-case procedure [15]. In Table 1 it is possible to observe the final results of the fatigue tests: it is evident the improvement induced by shot peening for both the series NSPA and NSPB.
After the fatigue test, all broken specimens presented a fracture started from the micro-hole. This means that the presence of this latter makes the surface the weakest point of the minimum section and that the experimental procedure makes possible to investigate the nitride and shot peened layer of material.

Table 1: Results of the stair-case procedure (3E+06 cycles), R=-1.

Specimen series	**Bending fatigue strength, $\Delta\sigma_{lim}$ [MPa]**	**Notes**
N	±480	The fractures start from micro-holes
NSPA	±850	The fractures begin from micro-holes
NSPB	±770	The fractures begin from micro-holes

3.2 SEM observations

Fracture surface of broken specimens were observed by means of a SE microscope. It is confirmed that fatigue failures started from the surface. In Fig. 5 it is possible to observe some example of the fracture surfaces. The aspect of the crack is the same for both the nitrided and the nitrided and shot peened specimens.

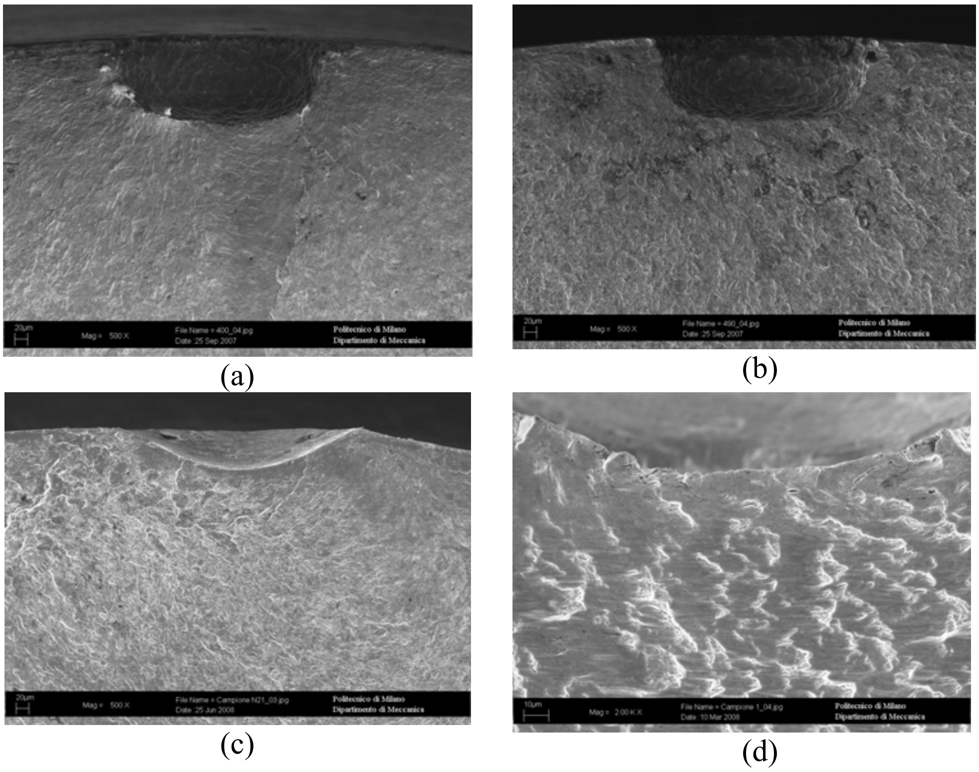


Fig. 5 – SEM Micrographs of the failure sections of the specimens: N (a), NSPA (b), NSPB (c), NSPB magnification factor 2000x (d).

By the observation of Fig. 5(d) it is possible to see that some microcracks are present in the layer just under the hole surface: these cracks were not observed for the other series (with the hole obtained by electro erosion) and could have influenced the fatigue tests results.
On another hand, in Fig. 6 the fracture surface of some run-out specimens (after brittle fracture in liquid nitrogen) it is possible to observe the presence of no-propagated cracks started from the hole.

4. Discussion
The fatigue tests, the experimental measurement of residual stresses and FWHM, the hardness measurement and the SEM observations permitted to do some consideration about the behaviour of the micro-holed specimens. First of all the strong influence of shot peening on the fatigue limit of the pre-cracked specimens can be noted: an increment of more than 50% is noted.

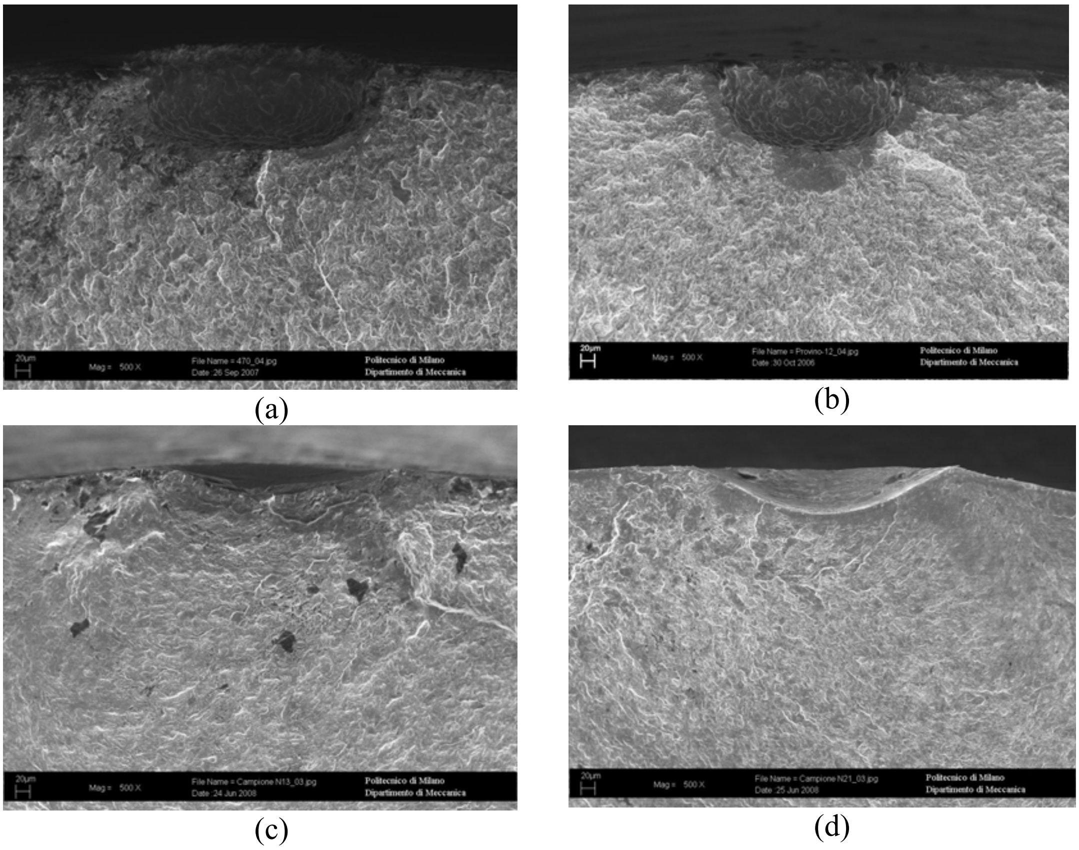


Fig. 6 – SEM Micrographs of the fracture sections of some run-out specimens (after brittle fracture in liquid nitrogen): N (a), NSPA (b), NSPB (c, d).

This result can be interpreted both as the effect of residual stresses and of the surface hardening due to the action of the multiple impacts of the shots. However, not only the shot peened specimens have a significant compressive residual stress state but also the only nitrided ones have compressive residual stress state. On the other hand the trends of the hardening, both in terms of micro-hardness and of FWHM, are really different till a depth about 0.15 mm. This makes possible to confirm the remarkable influence of surface hardening that was noted in [12].
The results (see Table 1) show also that notwithstanding the minor dimension of the hole the NSPB specimens have a lower fatigue limit that the NSPA. This can be interpreted as a consequence of the different surface hardening, as the trend of micro-hardness and FWHM shows. Another factor that can play a role in the obtained results is the fact that the NSPB holes were obtained by mechanical indentation, thus locally modifying the residual stress state and introducing small cracks that make easier the fatigue damage development. In other words, the influence of the way the defect is obtained can be noted.

5. Conclusions

The fatigue crack propagation behavior of a nitrided and shot peened steel was investigated by means of rotating bending fatigue tests carried out on specimens including micro holes acting as pre-cracks. The results showed the great influence of shot peening in improving the fatigue strength of the pre-cracked nitrided steel. The size of the holes of the three different series is small enough to consider the test in the field of the short crack regime: in fact the fatigue limit increases with the crack size. The impossibility to obtain the smaller hole by electro erosion made necessary to use an indenter, preventing a direct comparison of the results regarding the two hole sizes. However in this way it was possible to appreciate the influence of the way a defect is generated on the fatigue behaviour of nitrided shot peened pre-cracked specimens. Further work is on course to determine the fatigue threshold value of the stress intensity factor of the nitrided and shot peened steel as a function of the defect size.

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