Nitriding duration reduction without sacrificing mechanical characteristics and fatigue behavior: The beneficial effect of surface nano-crystallization by prior severe shot peening

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1. Introduction

Gas nitriding is a case hardening process whereby nitrogen is introduced into the surface of a solid ferrous alloy by holding that at a suitable temperature (below Ac1, for ferritic steel) in contact with nitrogenous gas, usually ammonia [1]. As a result released nitrogen atoms either chemically react with or diffuse between iron atoms and a case hardened surface is generated. The hardened case itself is sub-divided into compound and diffusion layers. Due to its considerable improvement in wear, corrosion and fatigue resistance, nitriding has become a well-accepted thermo-chemical process which is widely applied for high performance transmission shafts and gears, bearings, extruder screws, forging dies, injectors, crankshafts, camshafts and so on.

It has been well-known for a long time that kinetics of diffusion phenomena is highly dependent on time. Nitriding is not an exception. A clear beneficial effect of nitriding duration on resultant mechanical characteristics such as, the surface micro-hardness value [2–5], the thickness of the hardened layers [2–5], pitting corrosion resistance [2], forging die durability [6], dynamic load-ability [5], wear resistance [5] and fatigue behavior [7–9] has been reported in the literature. Therefore, prolonging nitriding may seem to be the first choice to obtain a better performance. It is accompanied, however, by the high energy cost of processing at high temperature. There is yet another alternative based on the fact that diffusion along grain boundaries is much more enhanced in comparison with the diffusion through grains. This justifies the idea of application of a prior mechanical treatment aimed to generation of defects, interfaces, increasing dislocation densities and possibly developing new micro-structure like sub-grains and eventually new grain boundaries.

For instance transformation of the coarse-grained into a very fine grained structure by high pressure torsion enhanced thickness of the nitrided layer and increased surface hardness in the subsequent radio frequency plasma nitriding of stainless [10].

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Dislocation density increment and strain induced transformation of austenite to martensite obtained by shot peening [11] were mentioned to provide faster diffusion for the subsequent plasma nitriding of stainless steel leading to twice thicker nitrided layer than not peened specimens under the same plasma nitriding condition [12]. Prior shot peening could also improve corrosion and wear resistance of gas nitrided 316L austenitic steel [13]. Generation of nano-structured surface layers through a prior surface mechanical attrition (SMAT) applied on pure iron enhanced nitrogen diffusion such that subsequent nitriding was feasible even at much depressed temperature (300 °C) [14]. Moreover, a nitrided layer twice as thick as that on a coarse-grained sample was developed on a SMAT iron sample under the same gaseous nitriding conditions [15].

Shot peening is actually a surface mechanical treatment generally applied to improve fatigue behavior of metallic parts. During the process small spherical peening media (shots) are accelerated in various kinds of peening devices to hit the surface of work piece with energy able to cause plastic deformation, compressive residual stresses and work hardening in the surface layers [16]. While a lot of attention was devoted in the last four decades to understand how residual stresses are developed during the process [17,18], it has not been a long time that shot peening was recognized as potential process to produce surface nano-crystallization. The common aspect is to use special combinations of peening parameters to multiply the kinetic energy of the shot impacts in order to generate a large number of defects, dislocations and interfaces (grain boundaries) on the surface layer of treated part and consequently transform its microstructure into ultra-fine grains or nano-structure [19]. The process in this case is called severe shot peening rather than shot peening in order to put the emphasis on the fact that it is amide to generate ultra-fine grained or nano-structured surface layers.

Based on this literature review most studies on the application of a severe plastic deformation prior to nitriding were done on stainless steel. Most recently the present authors investigated the effect of combination of severe shot peening and nitriding on the fatigue limit of a high strength low alloy (HSLA) steel [20]. The study was accomplished to shed light first on the applicability of this combination on HSLA steel and more importantly to find whether or not fatigue limit can be benefitted by this combination as much as surface hardness and case depth most often can. Based on the result, although prior severe shot peening caused up to three times deeper compound layer and produced deeper compressed layer, it was not able to further improve the fatigue limit of nitrided specimen. Local fatigue strength calculation revealed that the combination did improve the local fatigue strength up to 300 μm in depth. However, since fatigue cracks initiated below the hardened case (below 500 μm), the improvement was not seen in the final fatigue behaviour of the specimen. Therefore, the present study was designed to affirm even if the improvement did not contribute in the fatigue behaviour of smooth specimen; it exists and can be exploited in the form of nitriding duration reduction. Notwithstanding the high temperature required to perform nitriding, its duration reduction without affecting resultant mechanical characteristic and fatigue behaviour would be of great technological and scientific importance. To this end severe shot peened plus 7.5 h nitrided specimens are examined and compared with 15 h nitriding from the previous study. The treated specimens have been characterized by optical and scanning electron microscopy (OM and SEM) observation, residual stress measurement using X-ray diffraction (XRD), micro-hardness tests and surface roughness measurement. The specimens have been tested through rotating bending fatigue tests performed at room temperature. SEM observations of the fractured surfaces were applied to illustrate the failure mechanism.

2. Materials and methods

The material used in this study was high strength low alloy steel ESKYLOS6959 (equivalent to DIN 35NiCrMoV12-5 or AISI 4340). This class of steel is mostly used in the ground vehicle applications. Its chemical composition is summarized in Table 1. Mechanical properties evaluated through tension test are the following: 878 MPa yield stress, 1010 MPa UTS and 17.7% elongation at break. 12 Rotating bending fatigue test specimens were machined from a forging that had been quenched from 880 °C in water and then tempered at 635 °C for 5 h. The specimen geometry is presented in Fig. 1.

Specimens were subjected to severe shot peening followed by a nitriding in an industrial unit. Processing temperature and time during nitriding were 510 °C and 7.5 h respectively. Indeed the standard cycle of nitriding in the industrial unit is performed in the same temperature but for 15 h. The standard cycle of the pervious study [20] was applied. However, duration was deliberately reduced by 50% in the present study. Standard steel shots S230, using an air blast machine were employed to conduct severe shot peening. The shot peening intensity measured on "Almen A" strip was 18A. Shot peening was performed with 1000% coverage to ensure surface layers are severely deformed. The experimental assessment included OM and SEM observation of the cross section, micro-hardness measurement from surface towards depth, XRD measurement of residual stress carried out step by step by removing a very thin layer of material using an electro-polishing device, surface roughness measurement and eventually rotating bending fatigue test. The results of the in-depth residual stress measurements were corrected by using the method described in [21] to take the effect of layer removal into account. The details of the experimental procedure are excluded in this paper for the sake of brevity and readers are referred to [20] for more information. The results will be given under the label of SSP + N−7.5 h for the present samples. The corresponding results of nitriding on the same sample and in the same atmosphere and temperature but for 15 h from the previous study [20] were also added under the label of N−15 h to affirm the improvement that can be obtained by prior severe shot peening.

3. Results

3.1. Micro-structure

Overall view of the cross section by OM in Fig. 2 shows formation of a very thin compound or white layer of few microns on the top surface. The constituents of this hard and brittle layer are Υ' (Fe_4N) and ε ($Fe_{2-3}N$) phases [22]. Beneath the compound layer the so-called diffusion zone with dispersed needle shape precipitates of Υ' in ferritic matrix as well as the solid solution of nitrogen in ferrite exists.

Formation of compound layer is more evident from the SEM image of the cross section shown in Fig. 3. Depth of compound layer was measured to be in the range of 4–6 μm after nitriding for 15 h. Performing severe shot peening prior to nitriding caused the same deep compound layer to be created even if the subsequent nitriding duration was shortened to 7.5 h. This is due to the very dense structure and fine grained surface layer generated by severe plastic deformation during severe shot peening. This can be realized by the SEM image taken from the surface of severe shot peened specimen, illustrated in Fig. 4. By severe shot peening much more defects and interfaces are generated in the surface layers through repeating impingements. With the proceeding of collisions, some areas approach to the critical condition of nano-crystallization and grain fragmentation below 100 nm occurs [19].

Table 1
Chemical composition of steel grade 1.6959 used in this study (wt%).

C	Mn	Si	Cr	Mo	Ni	V	Fe
0.3–0.4	0.4–0.9	0.15–0.55	1–2	0.35–0.9	2.5–4.5	0.05–0.25	Balance

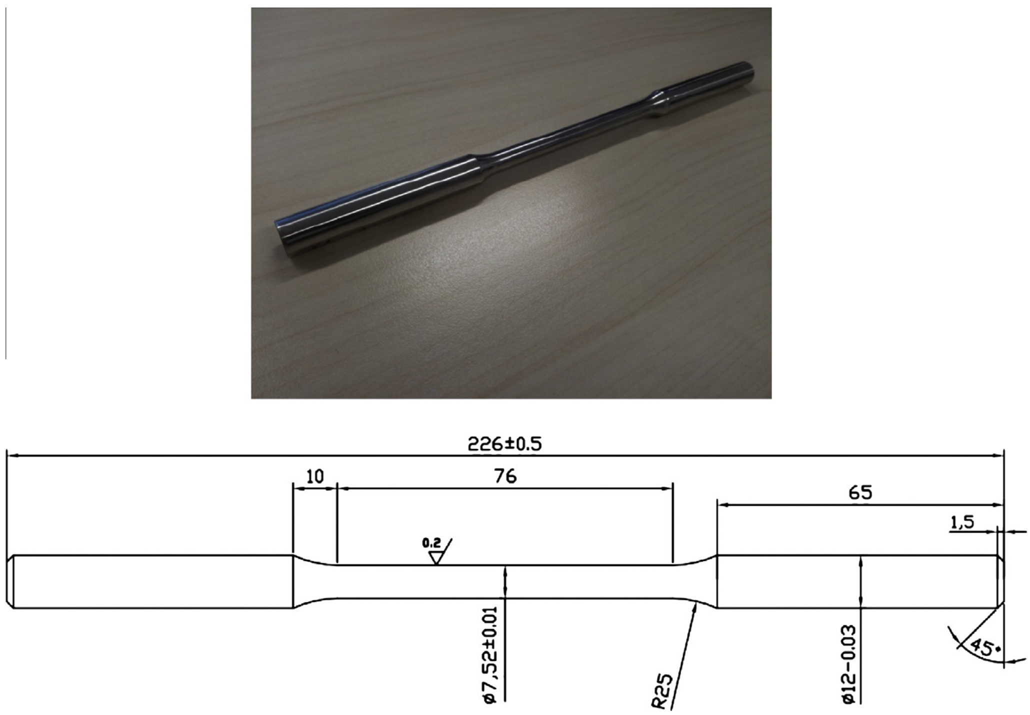

Fig. 1. The detailed specimen geometry used for rotating bending fatigue test. All dimensions are given in mm.

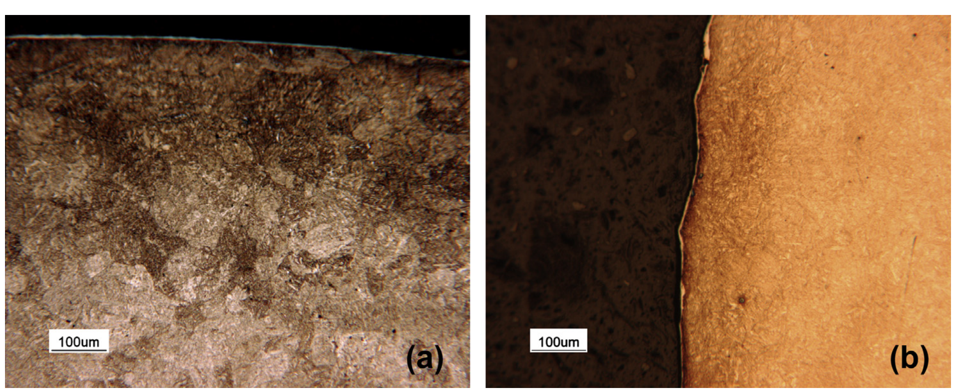

Fig. 2. Cross sectional optical microscopy of (a) N−15 h and (b) SSP + N−7.5 h specimens.

3.2. Hardening

Fig. 5 depicts the variation of micro-hardness from the treated surface to the bulk material. Maximum value of micro-hardness was measured at the surface of both treated specimens and then it gradually diminished to micro-hardness of the base material. Definition of case depth after nitriding is a matter of convention. Technically it is defined to be the depth at which the hardness is 100 HV more than core hardness [23]. A hardness value of 10% above the core hardness has been also used in the literature to characterize the case depth after nitriding when the fatigue characteristics are regarded [24,25]. Therefore, both values were superimposed in the graph. According to the first criterion the case depth produced after nitriding at 15 h was measured to be approximately 500 µm, while the case depth after severe shot peening and nitriding at 7.5 h is approximately 400 µm. According to the second criterion the case depth nitriding at 15 h is approximately 290 µm, while the case depth after severe shot peening and nitriding at 7.5 h is approximately 200 µm. It is clear that regardless of the convention, the case depth of SSP + N−7.5 h is not as deep as the case depth of N−15 h. However, it is interesting to note that the same surface micro-hardness was obtained for both treatments.

The width of the diffraction peak at half of the maximum (FWHM), measured by XRD, can be also assumed as an index of hardening. FWHM is able to reflect more aspects of surface work hardening which cannot be revealed by micro-hardness values [26,27]. The in-depth FWHM distribution of both treated

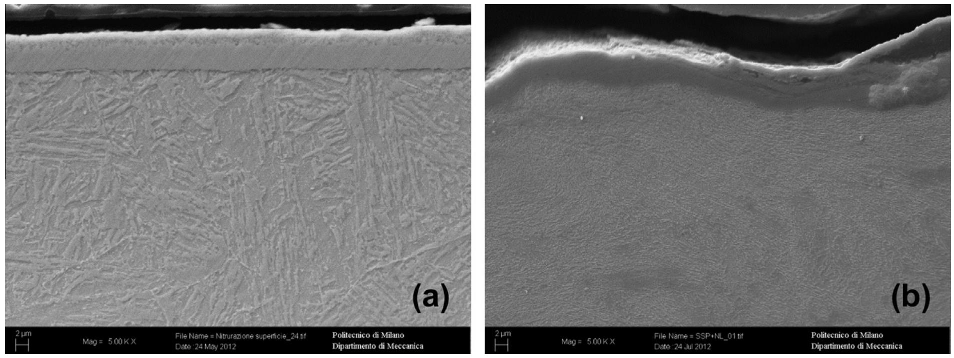

Fig. 3. Cross sectional scanning microscopy of (a) N−15 h and (b) SSP + N−7.5 h specimens.

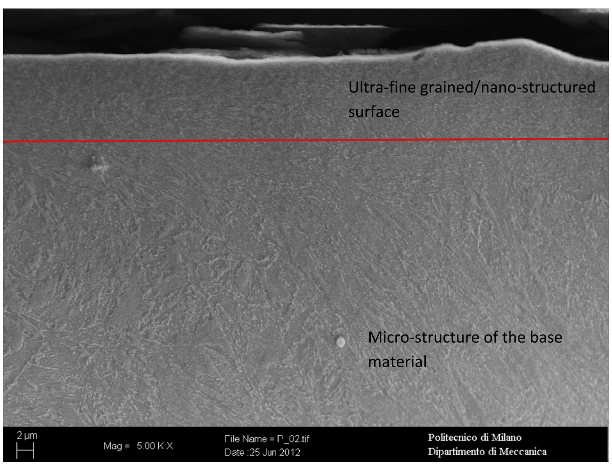

Fig. 4. Cross sectional scanning microscopy of severe shot peened specimen.

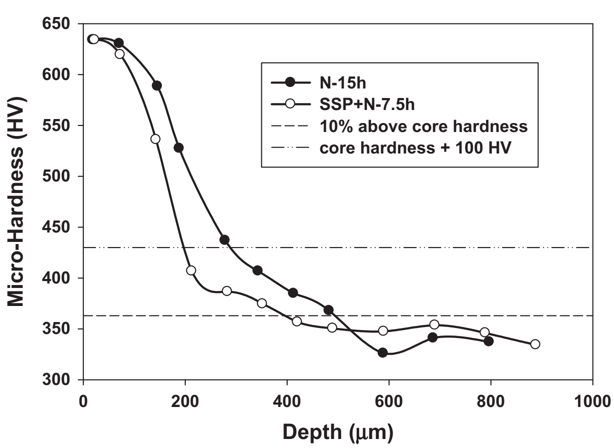

Fig. 5. In depth micro-hardness distribution of the treated specimens.

specimens is illustrated in Fig. 6. It is clear from the distribution that both treatments are able to produce hardened layers. The amount of FWHM at the surface of SSP + N−7.5 h specimen is appreciably higher than the corresponding surface value of the N−15 h specimens, even if shorter time was applied in the former case. This is due to ultra-fine grained/nano-structured surface layers generated after severe deformation and accumulation of plastic strains by repeated impingements during severe shot peening.

The effectiveness of excellent properties generally induced by surface nano-crystallization processes highly depends on the thermal stability of the generated ultra-fine grained/nano-structured

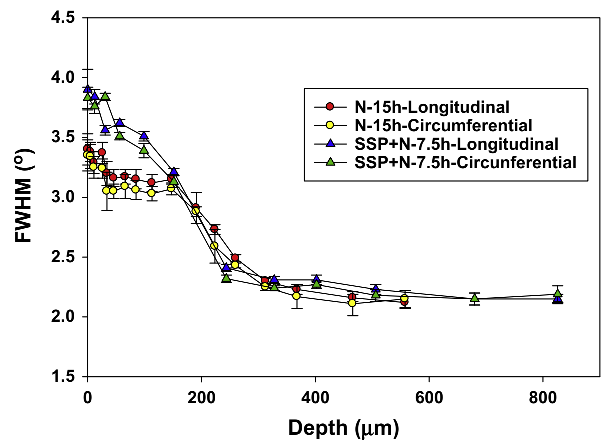

Fig. 6. In depth FWHM distribution of the treated specimens.

layers. By increasing the temperature, grain coarsening might occur which in turn tends to decrease the hardness. The higher level of surface FWHM for SSP + N−7.5 h specimens, clearly affirms that ultra-fine grained structure generated by severe shot peening was quite stable after being subjected to 510 °C for 7.5 h during subsequent nitriding.

3.3. Residual stress

In depth longitudinal and circumferential residual stress distribution of both treated specimens is depicted in Fig. 7. Nitriding and its combination with severe shot peening generated equi-biaxial compressive residual stress state. From the surface up to 150 μm in depth, slightly higher compressive residual stresses were developed for the SSP + N−7.5 h treated specimens with respect to the N−15 h treated specimen. The increment of compressive residual stress for the hybrid treatments is more evident below 150 μm in depth up to to 680 μm where it vanishes. For instance, the increment of compressive residual stress by application of prior severe shot peening at the depth of 245 μm is nearly 65%. It is also worth noticing that the by application of prior severe shot peening depth of compressed layer increased by 22% even if the nitriding duration had been shortened by 50%.

3.4. Surface roughness

Table 2 shows the surface roughness parameters of all treated specimens. The parameters are based on the definition of ISO 4287 [28]. The arithmetic-mean value (R_a) is most often considered as the representative parameter of surface roughness. Nitriding

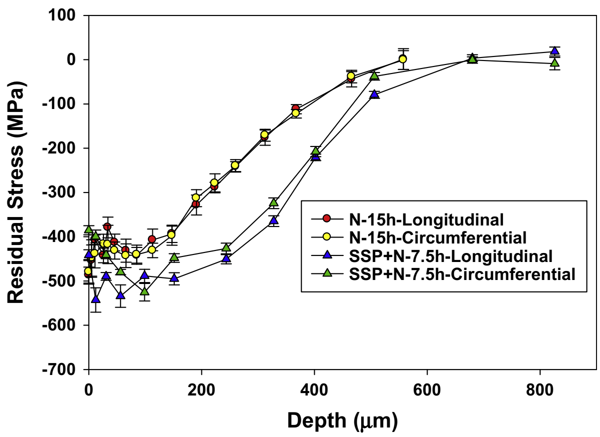

Fig. 7. In depth residual stress distribution of all surface treated specimens.

Table 2
Surface roughness parameters of as-received and surface treated specimens.

Treatment	l_r (mm)	l_n (mm)	R_a (μm)	R_q (μm)	R_z (μm)	R_t (μm)
AR	0.8	4	0.07	0.10	0.62	0.82
N−15 h	0.8	4	0.59	0.76	4.37	5.04
SSP + N−7.5 h	0.8	4	4.72	5.93	23.67	32.96

increased the R_a value of as-received specimens from 0.07 to 0.59 μm. The roughness increment by nitriding can be attributed to the formation of pores at the top of the compound layer which can be seen from Fig. 3a. The R_a value for the case of SSP + N−7.5 h is eight times bigger than the corresponding value for the only nitrided specimen. This is a well-recognized side effect of the shot peening process especially when severe parameters are applied. The rough surface generated by severe shot peening can be clearly observed in the OM and SEM image shown in Figs. 2b and 3b respectively.

3.5. Fatigue limit

Fig. 8 shows the fatigue limit for as-received and both surface treated specimens. Fatigue limit of as-received specimen was 491 MPa. Nitriding significantly increased the fatigue limit of specimens by 51.3%. It is interesting to note that severe shot peening plus nitriding, notwithstanding the 50% duration reduction, was able to come up with the same level of fatigue limit or even with some slight improvement (54.7% with respect to the fatigue limit of the as-received specimens).

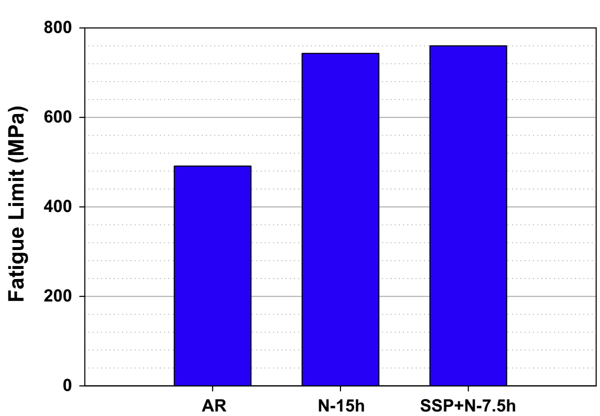

Fig. 8. Fatigue limit of as-received and surface treated specimens.

3.6. Fractography

The fractured surface of both treated specimens was examined by SEM observation to assess the effect of different surface treatments on fatigue crack initiation and propagation. Fig. 9a and b shows the fractured surface of a nitrided and severe shot peened plus nitrided specimen respectively. The final fracture in both cases resulted from initiation and propagation of a subsurface, so-called "fish eye" crack. It should be noted that fish eye crack feature has been observed in all broken specimens. The same fracture mechanism for nitrided specimen has been also reported elsewhere [29,30]. Although in rotating bending loading condition, surface layers are exposed to higher levels of applied stress than the subsurface layers, fatigue crack has not originated from the surface but beneath the hardened layer produced by nitriding.

4. Discussion

Kikuchi et al. [31] applied fine particle peening prior to gas nitriding of austenitic stainless steel and showed that hybrid treatment could further improve the fatigue strength as compared to nitriding only. Based on the result of the pervious study [20] nitriding at 15 h improved the fatigue limit by 51.3%. No further improvement in fatigue limit was obtained by the combination of severe shot peening and nitriding at 15 h. The two conclusions at the first glance may seem contradictory. But it is worth noticing that improvement in the former case occurred for notched specimen while no change in the latter case was found for smooth specimen. It was demonstrated that the combination did improve the local fatigue strength in the subsurface layer up to 300 μm. But since the critical site of crack initiation was located at the depth of 500 μm or even deeper, the local fatigue strength improvement could not contribute to increase the fatigue limit. If the same experiment was applied for notched specimens an increase in fatigue limit would have been expected. Because the critical site of initiation for notched specimens is always on the surface where, as shown, is benefitted by the hybrid treatment. In the present study combination of severe shot peening with nitriding at 7.5 h was assessed. 50% reduction of duration was deliberately decided to affirm the fact that even for smooth specimens the improvement by hybrid treatment can be actively exploited and indeed it is in the form of duration reduction. According the available reports on the effect of nitriding duration on fatigue limit [7,9], an absolute progress in fatigue limit is obtained with prolonging nitriding. The reason is that effective depth increases with the process time. A deep nitrided case helps to move the crack initiation site further toward the core, thus a higher bending stress at the surface is required to create a sufficiently high stress in the subsurface to initiate a fatigue crack [24]. What was shown here by comparing the results for N−15 h and SSP + N−7.5 h is that 50% duration reduction did not come up with less fatigue limit as expected in the literature. This is undoubtedly due to the beneficial effect of prior severe shot peening.

In conventional nitriding of coarse-grained steel, nitrogen diffusion in the Fe lattice dominates. In the nano-crystalline structures, on the other hand, nitrogen mostly diffuses along grain boundaries with much faster diffusivity because of much smaller activation energy (approximately half) compared with that for the lattice diffusion [14]. A clear and well-defined micro-structure change can be observed from the SEM image illustrating the surface of severe shot peened specimen (Fig. 4). Ultrafine grained/nano-structured surface layer up to 10–12 μm was generated after sever shot peening. Such a structure provided facilitated nitrogen diffusion through dense structure and generated fine grained layers for the subsequent nitriding. There is generally a direct correlation

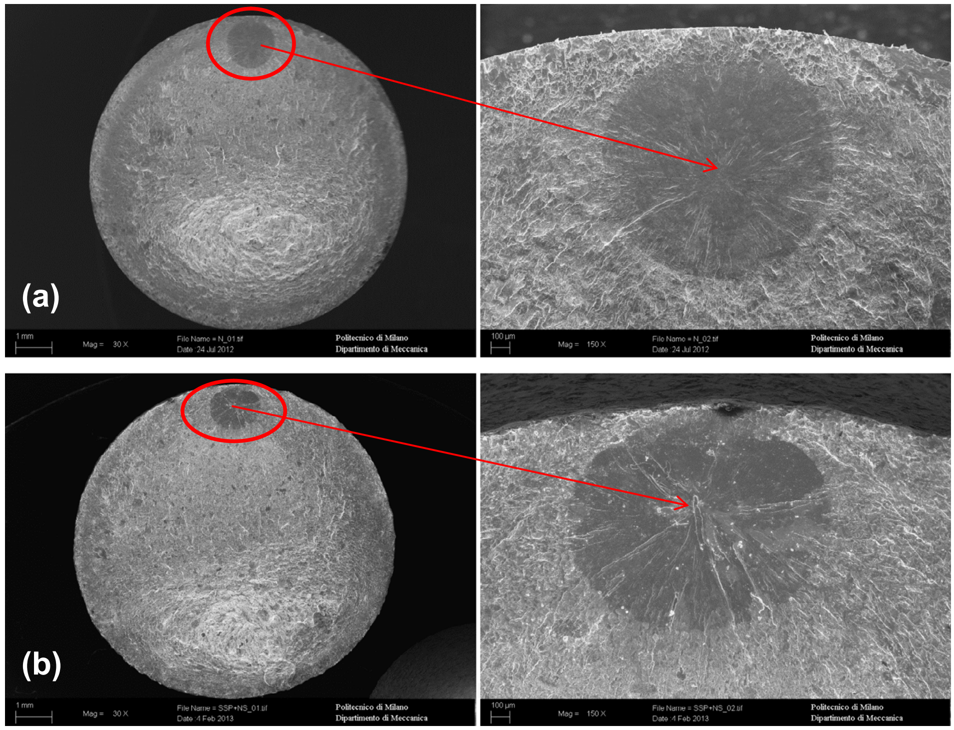

Fig. 9. SEM fractography of surface treated samples: (a) N−15 h and (b) SSP + N−7.5 h.

between nitrogen concentration and increased surface micro-hardness in the nitriding process and micro-hardness profiling scaled fairly well with the nitrogen concentration [32–34]. A precise look at the micro-hardness distribution (Fig. 5) affirms that the resultant micro-hardness at the very top surface for N−15 h and SSP + N−7.5 h is quite the same. Furthermore, the depth of compound layer, shown in the SEM image of Fig. 3 is quite the same for both specimens. These two confirm that the ultrafine grained/nano-structured surface layers generated after sever shot peening increased the kinetic of nitrogen diffusion in such a way that the nitriding with 50% time reduction ended up with the same micro-hardness and thus nitrogen concentration in the affected zone. Micro-hardness difference for both treated specimens is not appreciable up to 70 μm by going further in depth, nonetheless, a clear deviation between the two micro-hardness distributions appears. This is due to the fact that severe shot peening was able to refine the micro-structure up to a limited depth after which the advantages of refined micro-structure cannot be taken in the subsequent nitriding. Eventually, as can be seen in the micro-hardness distribution, the hardened layer in the N−15 h specimens is deeper than SSP + N−7.5 h specimens. This is also affirmed by the OM observation shown in Fig. 2.

Rotating bending fatigue tests demonstrated that the same level of improvement can be obtained by application of severe shot peening before nitriding while nitriding duration is reduced. In both N−15 h and SSP + N−7.5 h specimens, fatigue cracks initiated form the sub-surface layers below 500 μm in depth for all broken specimens. It is well accepted that extrusion and intrusion pile up is responsible for crack initiation on the surface during fatigue. However, in both treated specimen extrusion and intrusion process is very limited by surrounding hard material and they could not be easily piled up [35]. This behavior is even more interesting in the case of severely peened specimens where surface roughness is 8 times bigger than only nitrided specimens. The surface micro-hardness increased sufficiently by subsequent nitriding that despite the presence of high surface roughness and potential sites of crack initiation, the initiation site shifted to the sub-surface layers. Furthermore, highly distorted structure of surface layer of severely peened and nitrided specimens in comparison with only nitrided ones, which can be clearly realized from the FWHM distribution and SEM image, could play a positive role to prevent the initiation of fatigue cracks from the surface.

Crack initiation most likely occurs where applied stress exceeds the local fatigue strength which generally lies in the sub-surface layers below the hardened case. Local fatigue strength is a function of compressive residual stress and micro-hardness for a given material. In the present work, although the depth of hardened layer is not exactly the same for both specimens, the same average crack initiation depth was found in both cases. This can be attributed to the fact that, as shown in Fig. 7, deeper compressive residual stress was created for SSP + N7.5 h. In another word, slightly shallower hardened layer of SSP + N7.5 h was compensated by slightly deeper compressed layer so that the final crack initiation site and fatigue limit is the same for both specimens.

5. Conclusions

The effect of surface nano-crystallization by prior severe shot peening aimed to shorten subsequent nitriding on micro-structure, hardening, residual stress, surface roughness, fatigue and fracture behavior of low alloy steel was investigated. The following conclusions can be drawn on the basis of obtained results:

- Ultrafine grained/nano-structured surface layer up to 10–12 μm was successfully generated by sever shot peening. Such a structure provided facilitated nitrogen diffusion through dense structure and generated fine grained layers during subsequent nitriding. In comparison with the only nitrided specimen, performing severe shot peening prior to nitriding caused the same deep compound layer to be created even if the nitriding duration was shortened by 50%.

- In comparison with the only nitrided specimen, the same surface micro-hardness was obtained by application of prior severe shot peening despite 50% reduction of the subsequent nitriding duration.
- The higher level of surface FWHM for severe shot peened plus nitrided specimens with respect to only nitrided ones, clearly affirm that ultra-fine grained structure generated by severe shot peening was quite stable after being subjected to 510 °C for 7.5 h during subsequent nitriding.
- Nitriding and its combination with severe shot peening generated equi-biaxial compressive residual stress state. Higher compressive residual stresses and deeper compressed layer were developed for the combined severe shot peened and nitrided specimens with respect to the only nitrided specimen.
- Nitriding at 15 h significantly increased the fatigue limit of specimens by 51.3%. It is interesting to note that severe shot peening plus nitriding, notwithstanding the 50% nitriding duration reduction, was able to come up with the same level of fatigue limit or even with some slight improvement to 54.7%.
- Diffusion layer for nitriding at 15 h was deeper than severe shot peening plus nitriding at 7.5 h. This is due to the fact that severe shot peening was able to refine the micro-structure up to a limited depth after which the advantages of refined micro-structure cannot be taken in the subsequent nitriding. This deficiency, however, was completely compensated by deeper compressed layer in the combined treatment and eventually fatigue behavior was almost identical.
- Based on the results demonstrated in this paper, nitriding duration can be successfully reduced without losing improvements in mechanical characteristics and fatigue behavior if a suitable prior severe shot peening, aimed to surface nano-crystallization, is performed.

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References

[1] ASM Handbook. vol 04. Heat Treating: ASM, International. 1991.
[2] Fossati A, Borgioli F, Galvanetto E, Bacci T. Glow-discharge nitriding of AISI 316L austenitic stainless steel: Influence of treatment time. Surf Coat Technol 2006;200:3511–7.
[3] Rahman M, Hashmi MSJ. Effect of treatment time on low temperature plasma nitriding of stainless steel by saddle field neutral fast atom beam source. Thin Solid Films 2006;515:231–8.
[4] Wang L, Ji S, Sun J. Effect of nitriding time on the nitrided layer of AISI 304 austenitic stainless steel. Surf Coat Technol 2006;200:5067–70.
[5] Hosseini SR, Ahmadi A. Evaluation of the effects of plasma nitriding temperature and time on the characterisation of Ti 6Al 4V alloy. Vacuum 2012;87:30–9.
[6] Castro G, Fernández-Vicente A, Cid J. Influence of the nitriding time in the wear behaviour of an AISI H13 steel during a crankshaft forging process. Wear 2007;263:1375–85.
[7] Li CX, Sun Y, Bell T. Shot peening of plasma nitrided steel for fretting fatigue strength enhancement. Mater Sci Technol 2000;16:1067–72.
[8] Mubarak Ali M, Raman SGS. Effect of plasma nitriding environment and time on plain fatigue and fretting fatigue behavior of Ti-6Al-4V. Tribol Lett 2010;38:291–9.
[9] Genel K, Demirkol M, Çapa M. Effect of ion nitriding on fatigue behaviour of AISI 4140 steel. Mat Sci Eng A 2000;279:207–16.
[10] Ferkel H, Glatzer M, Estrin Y, Valiev RZ. RF plasma nitriding of a severely deformed high alloyed steel. Scripta Mater 2002;46:623–8.
[11] Ji SJ, Wang L, Sun JC, Hei ZK. The effects of severe surface deformation on plasma nitriding of austenitic stainless steel. Surf Coat Tech 2005;195:81–4.
[12] Shen L, Wang L, Wang Y, Wang C. Plasma nitriding of AISI 304 austenitic stainless steel with pre-shot peening. Surf Coat Tech 2010;204:3222–7.
[13] Hashemi B, Rezaee Yazdi M, Azar V. The wear and corrosion resistance of shot peened-nitrided 316L austenitic stainless steel. Mater Design 2011;32:3287–92.
[14] Tong WP, Tao NR, Wang ZB, Lu J, Lu K. Nitriding iron at lower temperatures. Science 2003;299:686–8.
[15] Tong WP, Liu CZ, Wang W, Tao NR, Wang ZB, Zuo L, et al. Gaseous nitriding of iron with a nanostructured surface layer. Scr Mater 2007;57:533–6.
[16] Farrahi GH, Lebrun JL, Couratin D. Effect of shot peening on residual stress and fatigue life of a spring steel. Fatigue Fract Eng M 1995;18:211–20.
[17] Al-Hassani STS. Mechanical aspect of residual stress development in shot peening. First International Conference on Shot Peening ICSP1. Paris: 1981. p. 14–7.
[18] Guagliano M. Relating almen intensity to residual stresses induced by shot peening: a numerical approach. J Mater Process Technol 2001;110:277–86.
[19] Guagliano M. Severe shot peening to obtain nanostructured surfaces: processes, properties and application. In: Baiker S. editor., Wetzikon: Metal Finishing News. 2012.
[20] Hassani-Gangaraj SM, Moridi A, Guagliano M, Ghidini A, Boniardi M. The effect of nitriding, severe shot peening and their combination on the fatigue behavior and micro-structure of a low-alloy steel. Int J Fatigue (2013), http://dx.doi.org/10.1016/j.ijfatigue.2013.04.017.
[21] Moore MG. Evans WP. SAE Technical Papers: Mathematical correction for stress in removed layers in X-ray diffraction residual stress analysis; 1958.
[22] Hassani-Gangaraj SM, Guagliano M. Microstructural evolution during nitriding, finite element simulation and experimental assessment. Appl Surf Sci 2013;271:156–63.
[23] UNI 11153-2. Measurement of thickness of hardened surface layers on ferrous parts. Nitriding and Ferritic Nitrocarburizing. 2006.
[24] Bell T, Loh NL. The fatigue characteristics of Plasma Nitrided three Pct Cr–Mo steel. J Mater Eng Perform 1982;2:232–7.
[25] Ashrafizadeh F. Influence of plasma and gas nitriding on fatigue resistance of plain carbon (Ck45) steel. Surf Coat Technol 2003;174–175:1196–200.
[26] Farrahi GH LJ. Surface hardness measurement and micro-structural characterisation of steel by X-ray diffraction profile analysis. J Eng 1995;8:159–67.
[27] Fernandez Pariente I, Guagliano M. About the role of residual stresses and surface work hardening on fatigue ΔKth of a nitrided and shot peened low-alloy steel. Surf Coat Technol 2008;202:3072–80.
[28] ISO 4278. Geometrical product specifications (GPS) – surface texture: profile method- terms, definitions and surface texture parameters. 1st ed. 1997.
[29] Guagliano M, Vergani L. Effect of nitriding on low-cycle fatigue properties. Int J Fatigue 1997;19:67–73.
[30] Limodin N, Verreman Y, Tarfa TN. Axial fatigue of a gas-nitrided quenched and tempered AISI 4140 steel: Effect of nitriding depth. Fatigue Fract Eng M 2003;26:811–20.
[31] Kikuchi S, Nakahara Y, Komotori J. Fatigue properties of gas nitrided austenitic stainless steel pre-treated with fine particle peening. Int J Fatigue 2010;32:403–10.
[32] Corredor LH, Chornik B, Ishizaki K. Correlation study of hardness and nitrogen concentration in nitrided steel by Auger electron spectroscopy. Scr Metall 1981;15:195–9.
[33] Alphonsa I, Chainani A, Raole PM, Ganguli B, John PI. A study of martensitic stainless steel AISI 420 modified using plasma nitriding. Surf Coat Technol 2002;150:263–8.
[34] Zagonel LF, Figueroa CA, Droppa Jr R, Alvarez F. Influence of the process temperature on the steel microstructure and hardening in pulsed plasma nitriding. Surf Coat Technol 2006;201:452–7.
[35] Hussain K, Tauqir A, Ul Haq A, Khan AQ. Influence of gas nitriding on fatigue resistance of maraging steel. Int J Fatigue 1999;21:163–8.