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Mechanical characterization of a new low carbon bainitic steel for high performance crankshaft

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Abstract

In the actual automotive environment, the need to increase the performances of materials is requiring extra engineering efforts. The possibility to develop new materials is very important. Indeed alternative solutions in terms of material choice allow designers to optimize their projects and keep low costs of production. Dealing with potential alternatives to traditional quenched and tempered steels for high stressed components, as just seen in previous work, bainitic grades could be a valid solution. This is particularly true if the mechanical performances are kept without compromise the economic savings of bainitic grades. So a detailed evaluation of the mechanical properties of these steels needs a further deepen also for applications requiring case hardening treatment. The scope of this article is to introduce and show the characterization phase of a new bainitic low carbon content for a high-performance crankshaft application. In details, a long-life fatigue resistance staircase test is performed after a gas nitriding treatment and the results are compared to the untreated material. The increment of the fatigue resistance is quantified and can be utilized by structural engineers to develop and optimized their projects. Moreover, the case hardened depth and microhardness profiles are collected and evaluated in terms of nitriding effectiveness (nitrogen diffusion).

Keywords: mechanical component, material selection, crankshaft, steel, nitriding, fatigue;

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1. Introduction

Bainitic grades are utilized in several automotive applications. This is done because of the advantages in terms of costs and time if compared to traditional quenched and tempered steels. In fact, the potential of the bainitic grades consists into the possibility to reach high mechanical characteristics without passing through several heat treatments as in quenched and tempered steels. Moreover, also the fatigue performance must be quantified in order to completely analyze the bainitic grades compared to high strength steels. The use of this information could be useful in materials selection (Cavallini et al. (2013), Giorgetti et al. (2017)) for the identification of the better solution in many industrial applications (e.g. Eco-design: Giorgetti et al. (2016)). This is particularly true in contexts in which the materials are highly stressed and the loads is time dependent. An example of this type of components is the crankshaft for an internal combustion engine.

So dealing with fatigue in high stressed components, it will be interesting, as discussed in article by Citti et al. (2018), to evaluate the fatigue limit of typical bainitic steel considering not only the untreated material but also the nitriding as a case hardening treatment. The nitriding process allows developing elevated fatigue performances necessary for high stressed mechanical components. Indeed nitriding treatment for traditional steels allows adding 50% or more onto fatigue resistance to the untreated material as shown by several authors (Sun and Bell (1991), Genel et al. (2000), Limodin et al. (2006)). This increment of the fatigue limit is due to compressive residual stresses on the nitrogen diffusion layer, below the actually applied stress onto the component itself.

The aim of this article is to study the behavior of a bainitic steel after a traditional gas nitriding process in terms of nitrogen diffusion and fatigue limit increment compared to the untreated material. The method for the investigation of the long life fatigue is the rotating bending.

2. Experimental work

A bainitic steel low carbon has been used in this study. In table 1 is shown the chemical composition of the steel. The steel was received in vacuum air remelted bars of 80 mm diameter after a pseudo forging treatment at 1000°C for 45 mins. and air cooling to room temperature. Smaller squared section raw bars were cutout from main bars at equal distance from the center (Fig.1). Finally, onto these smaller bars, a stress relief heat treatment at 550°C for 8 hours was carried out. From this condition, specimens were machined and the nitriding heat treatment into a static gas oven for 72 hours at 515°C was carried out too.

Table 1. Chemical composition of steel tested.

	C%	Mn%	Si%	Cr%	S%	Ni%	Mo%	Cu%	Others%	Fe%
Steel tested	0,16	1,48	0,97	1,43	0,05	0,18	0,14	0,23	0,17V	bal.

Fig. 1. Squared raw bar (16x16x150mm) for preparation of a specimen.

In figure 2 a simplification of the heat treatments cycle is reported considering also the nitriding phase.

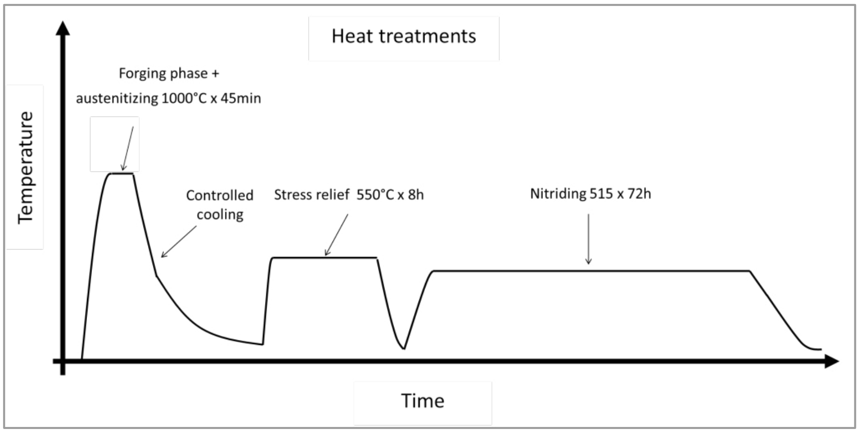

Fig. 2. Scheme of the heat treatments cycle performed onto the specimens.

The static mechanical properties (ISO 6892-1) of the material at core after the heat treatments cycles are collected in Table 2. The machine utilized for the tensile test is a Galdabini Quasar 200 equipped with extensometer in strain control.

Table 2. Mechanical characteristics of steel after heat treatments cycle.

Norm	Proof strength Rp0,2 [MPa]	Tensile strength Rm [MPa]	Percentage elongation A%
ISO 6892-1	952	1124	18

The specimens for the rotating bending fatigue are realized following similar machining phases for an engine crankshaft. For the nitrided specimens the resistant section was firstly ground and then nitrided. A final grinding (0,05 mm material removal) plus polishing was carried out at the end of the nitriding heat treatment. Identical machining operations were performed also for the not nitrided specimens (untreated specimens). The final surface roughness values achieved on specimens are comparable with the surface roughness values of a typical crankpin. In figure 3 is shown the technical drawing of the finished specimen before bending test. In Table 3 are shown the average and standard deviation of the final roughness parameters measured on the specimens after final polishing.

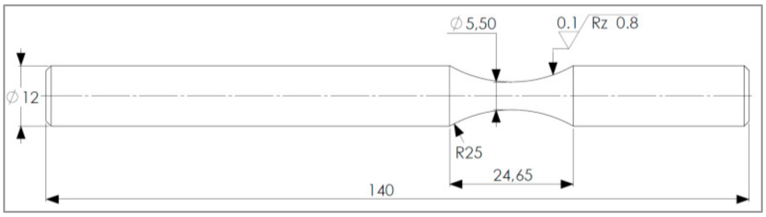

Fig. 3. Technical drawing of the finished ground and polished specimen.

Table 3. Roughness parameters measured on the calibrated zone of samples.

	Ra [µm]	Rz [µm]	Std. dev. Ra	Std. dev. Rz
Untreated specimens	0,09	0,76	0,016	0,174
Nitrided specimens	0,10	0,79	0,021	0,206

Each specimen was cleaned and degreased in heptane solvent before the tests.

For the evaluation of the nitriding process, hardness profile curves on specimens were carried out. The nitriding depth profiles were realized by interpolation of micro Vickers hardness indentations by 0,5 kg load for 15 sec.

Rotating fatigue tests were performed on a single point bending test machine at a frequency of 50Hz in the air. In figure 4 are shown a scheme of the machine and of the clamping system for the specimen.

The method followed for the identification of the fatigue limit at 10^7 cycles was the staircase method at constant step of load variation. There was no observation of heating effects on the specimens during fatigue testing and pure rotating bending conditions were maintained properly.

The specimens at the end of the tests were sectioned and by optical micrographs metallurgical considerations were carried out about nitriding heat treatment process.

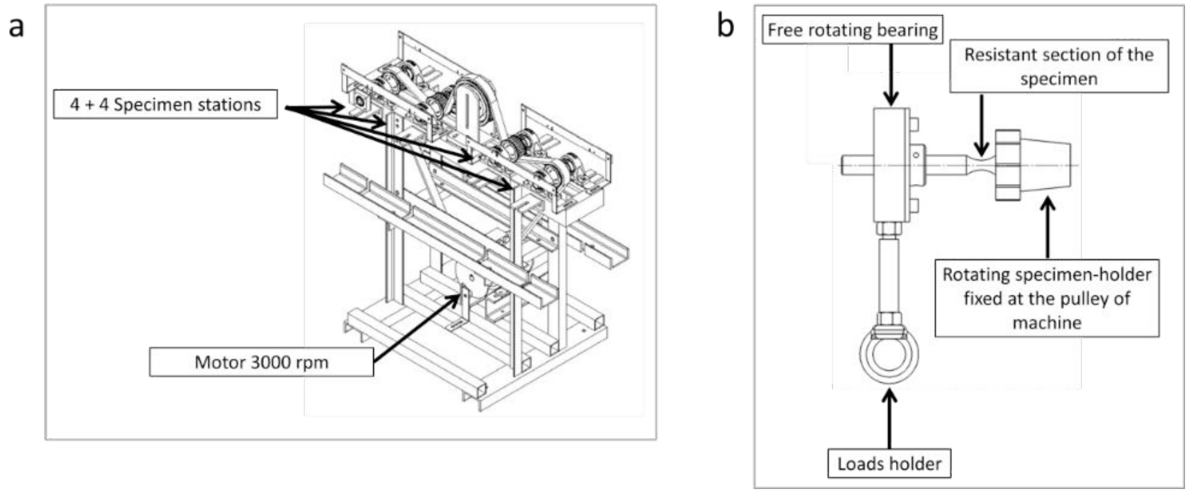

Fig. 4. (a) scheme of the eight stations rotating fatigue machine; (b) clamping system for the specimen.

3. Results and discussion

Metallographic cross sections were done both for the untreated and for the nitrided specimens. The microstructure of the material was analyzed after etching by Nital 2%. At core of the nitrided steel, the microstructure results homogenous (Fig. 5) and no variations are detect compared to the untreated steel. This confirms that the heat treatments cycle was properly set up.

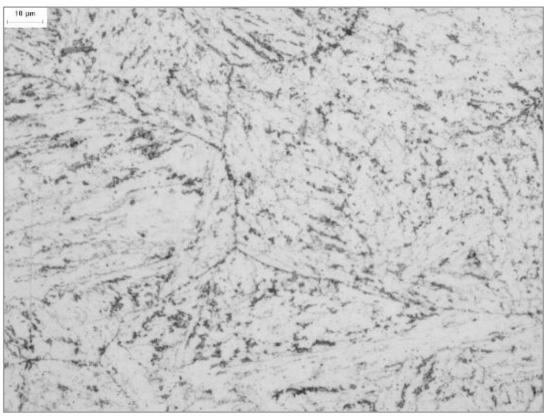

Fig. 5. core microstructure example of nitrided and untreated specimen 500x.

As known the gas nitriding process generally performed between 500° and 580°C generates a compound layer also called “white layer” of intermetallic compounds (nitrides and carbonitrides: γ_Fe_4N phase or ε_-Fe_2N phase). This layer is very brittle, and its debris could potentially interpose between mechanical components such as crank pins and bearings generating failure. For this reason, in such applications it is removed.

Deeply into the steel, typically for a depth of 0,1–0,5 mm the nitrogen diffuses generating a modified structure or “diffusion zone”. This region is made up of stable nitrides generated by the thermochemical reaction of the nitrogen with the steel.

So, differently from the core, the microstructure nearby the surface edge of the nitrided steel is deeply modified. In figure 6 is shown the microstructure of a nitrided specimen in a transversal section where the final grinding and polishing were omitted. In details in figure 6a is possible to distinguish the compound layer (thickness 13 μm) developed in this steel and the diffusion zone below. Moreover, some nitriding lamellae developing from the compound layer are detected and not closed net is formed at grain boundaries (Fig. 6b).

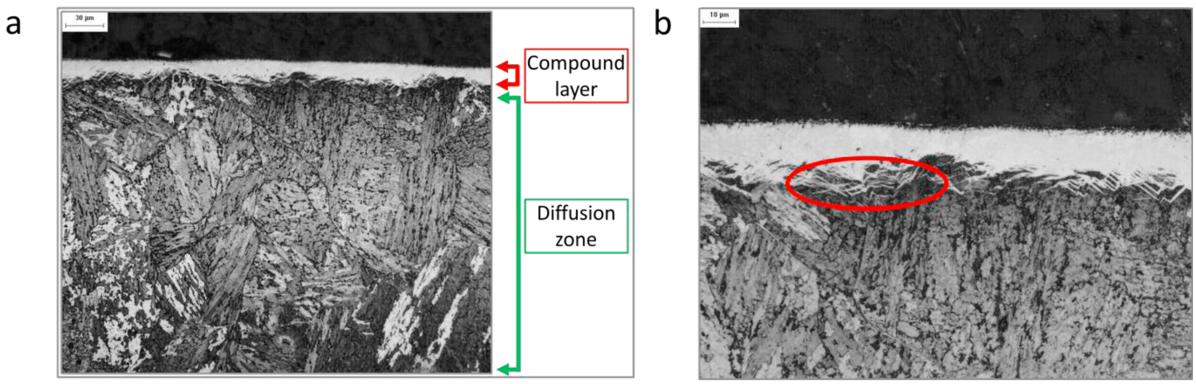

Fig. 6. (a) compound layer and diffusion zone 200x; (b) compound layer detail with nitriding lamellae generated 500x after Nital 2% etching.

The main advantage in terms of fatigue resistance, in particular in bending stressed applications, given by the nitriding process consists into the generation of a compressive state below the surface due to the diffusion of nitrogen and the lattice deformation.

In figure 7 are shown two curves of the nitriding depth profiles of the specimens. Two transversal sections per specimen were analyzed. The first one in the ground and polished section and the second one in a raw part of it without final grinding and polishing operations. The standard deviations of the measurements per each single indentation are added into the graph too. The two curves show a constant shift of about 0,05 mm due to the final grinding and polishing. This constant shift demonstrates that the final grinding was properly carried out and that no grinding burns happened during machining operations.

About the evaluation of the nitriding heat treatment, four reference depths of the nitriding case were established. They were set at 525 Vickers, core plus 100 Vickers, core plus 50 Vickers and finally core plus 10% core hardness Vickers. In Table 4 are reported the value of the core hardness and the values of depths at the various reference points. The nitriding depth measured could be compared with traditional nitrided quenched and tempered steels as reported by Bell et al. (1982).

Table 4. Core hardness and nitriding depth measurements at various references.

	Core HV	Depth 525 HV	Depth core + 100 HV	Depth core + 50 HV	Depth core + 10% hardness HV
Not ground zone	375	0,41 mm	0,43 mm	0,48 mm	0,50 mm
Ground and polished zone		0,36 mm	0,39 mm	0,43 mm	0,46 mm

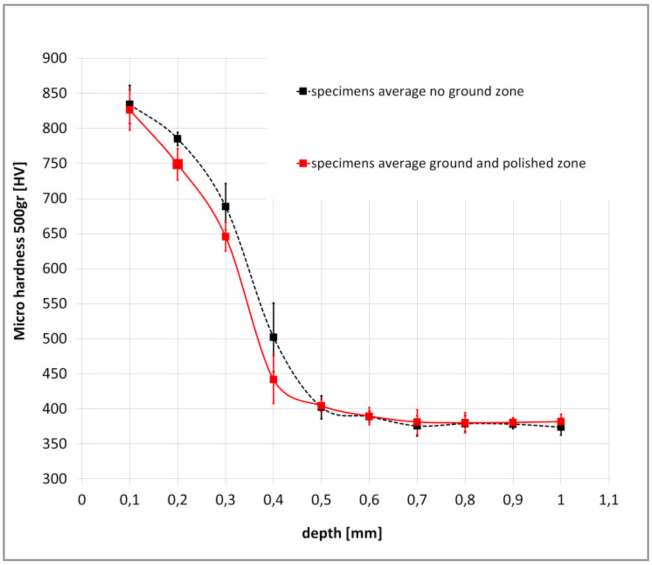

Fig. 7. Nitriding depth curves for the ground and polished section (red line) and for the not final ground section (black dashed line).

The staircase method as UNI 3964 suggests was carried out using 20 specimens in order to evaluate the final fatigue limits. The procedure of the staircase consists into a sequential series of tests performed at constant steps of load variations (25MPa) until all the specimens are tested. The single test consists into a fail/not fail (runout) test. If the specimen tested fails, the following specimen is loaded at an inferior level of stress determined by a single step variation otherwise an increment of load is done. When all specimens are tested the fatigue limits respectively at the 10th 50th and 90th percentile of survival can be computed.

Taking into account the following parameters

$A = \sum_{i=0}^{i_{max}} n_i$, $B = \sum_{i=0}^{i_{max}} in_i$ and $C = \sum_{i=0}^{i_{max}} i^2 n_i$

the average (50th percentile) stress μ is computed as

$$\mu_{50} = S_0 + s \cdot \left(\frac{B}{A} \pm 0{,}5\right) \tag{1}$$

In previous equations i is an integer denoting the stress level, with i_{max} corresponding to the highest stress level in the staircase. If the majority of specimens failed, then the lowest stress level at which a survival occurs corresponds to the i = 0 level and mi corresponds to the number of specimens which survived each stress level. The next highest stress level would be the i = 1 level, and the stress level one above that would be i = 2, etc. If the majority of specimens survived, then the lowest stress level at which a failure was observed is denoted as the i = 0 level and ni corresponds to the number of specimens which failed at each stress level. S_o is the stress value corresponding to the i = 0 stress level. s is the step size. The plus sign in the equation (1) is used when failures are the majority event, while the minus sign is used if runout is the majority event.

About standard deviation this is computed as

$$\sigma = 1{,}62 \cdot s \cdot \left(\frac{A \cdot C - B^2}{A^2} + 0{,}029\right) \tag{2}$$

if

$$\frac{A \cdot C - B^2}{A^2} \geq 0{,}3$$

or,

$$\sigma = 0{,}53 \cdot s \tag{3}$$

if

$$\frac{A \cdot C - B^2}{A^2} \leq 0{,}3$$

Then, utilizing the formulas (1), (2) or (3), the 10^{th} and 90^{th} percentiles of survival can be computed easily applying the formulas

$$\mu_{10} = \mu + \sigma \cdot 1{,}28 \quad (4)$$

and

$$\mu_{90} = \mu - \sigma \cdot 1{,}28 \quad (5).$$

Using this approach, it is possible to analyze the data from the complete staircase performed onto the untreated specimens. In figure 8 is shown the complete staircase of the untreated specimens where the white circles represent runout cases (number of cycles > 10^7 cycles), while black circles represent the failure cases. In Table 5 are detailed, per each specimen, the number of cycles to the failure and the values of bending stress applied.

It is important to notice that the maximum number of cycles counted with a failure of the specimen is 3,4 10^6; it means that the fatigue knee of the material for the S/N curve is reached and that it is quite close to the typical reference value of 2 10^6 cycles for the infinite life of specimens.

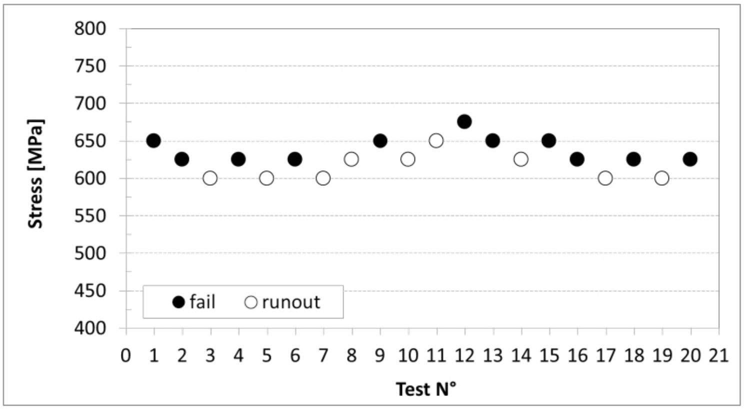

Fig. 8. Complete staircase results of untreated specimens.

Table 5. Stress and cycles per each test of the staircase of the untreated specimens.

Test n°	Stress [MPa]	Cycles	Test n°	Stress [MPa]	Cycles
1	650	607.859	11	650	runout
2	625	436.748	12	675	361.883
3	600	runout	13	650	3.429.555
4	625	2.358.303	14	625	runout
5	600	runout	15	650	568.986
6	625	2.972.062	16	625	369.231
7	600	runout	17	600	runout
8	625	runout	18	625	523.837
9	650	138.095	19	600	runout
10	625	runout	20	625	991.105

Then, applying the formulas (4 and 5), it is possible to compute the 10^{th} and 90^{th} percentile of survival for the untreated specimens staircase. In Table 6 are reported the calculated limits which can be directly utilized for the design of components realized with the steel here analyzed.

Table 6. Fatigue limits reached by untreated specimens after staircase fatigue test.

	10^{th} of survival [MPa]	50^{th} of survival [MPa]	90^{th} of survival [MPa]
Fatigue limit	652	626	601

It is important to notice that the ratio between Rm and the 50th fatigue limit is high above 50% (56%). This value is in line with high performance quenched and tempered steel families reported by several studies (Yakura et al. (2017), Zhou et al. (2012)).

About nitrided specimens, the starting bending stress applied for the beginning of the staircase was set at a value of 950 MPa because in literature (Genel 2000) the potential of increment of the fatigue limit due to nitriding is found to be up to the 50% of untreated material fatigue limit, here considered.

Unfortunately, the expectations about this increment have not been confirmed by the experiments made and a series of failures were collected during the staircase record particularly for the first specimens. In figure 9 are shown the results per each nitrided specimen tested and in Table 7 are reported the details of the number of cycles before specimens get fail per each single test.

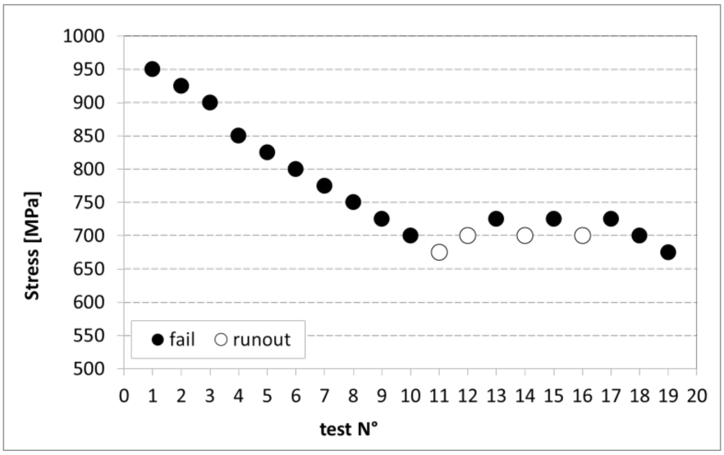

Fig. 9. Complete staircase results of nitrided specimens.

Table 7. Stress and cycles per each test of the staircase of the nitrided specimens.

Test n°	Stress [MPa]	Cycles	Test n°	Stress [MPa]	Cycles
1	950	342.883	11	675	runout
2	925	315.987	12	700	runout
3	900	502.502	13	725	2.316.421
4	850	1.805.298	14	700	runout
5	825	1.779.669	15	725	5.668.272
6	800	1.397.384	16	700	runout
7	775	3.995.105	17	725	1.793.493
8	750	6.864.826	18	700	7.310.471
9	725	3.053.342	19	675	5.358.816
10	700	7.368.754			

The results of the staircase performed onto the nitrided specimens can then be used to compute the 10th, 50th and 90th percentiles of survival applying equations (1), (4) and (5). In Table 8 are reported the calculated values of the three limits.

Table 8. Fatigue limits reached by nitrided specimens after staircase fatigue test.

	10th of survival [MPa]	50th of survival [MPa]	90th of survival [MPa]
Fatigue limit	723	706	690

Taking into account the 50th percentile of survival of the untreated specimens, the increment of the nitriding fatigue reached by the steel analyzed is about 13%. This value appears quite low if compared with other quenched and tempered steels after the nitriding heat treatment. In fact, as just previously underlined, nitriding onto traditional quenched and tempered steels shift the fatigue limit at very higher levels: more than 30% of the basic material (Genel et al. (2000), Forrest (1968)).

Moreover, a collective graph of all the results is shown in Figure 10 to view the S/N curves for the stress levels and cycles to failure of both the untreated and nitrided specimens. The two curves highlight a different behavior of the two families of steels. In particular, notice that in several cases the number of cycles measured at the failure of the nitrided specimens is in the range between 4 10^6 and 10^7 cycles, while no more than 3,4 10^6 cycles with failure were detected for the untreated specimens. This means that the knee of the S/N curve for the nitrided specimens is shifted at a higher number of cycles than the untreated steel. This could be a symptom of later initiation of fatigue cracks due to nitriding as suggest by Terent'ev et al. (2006)).

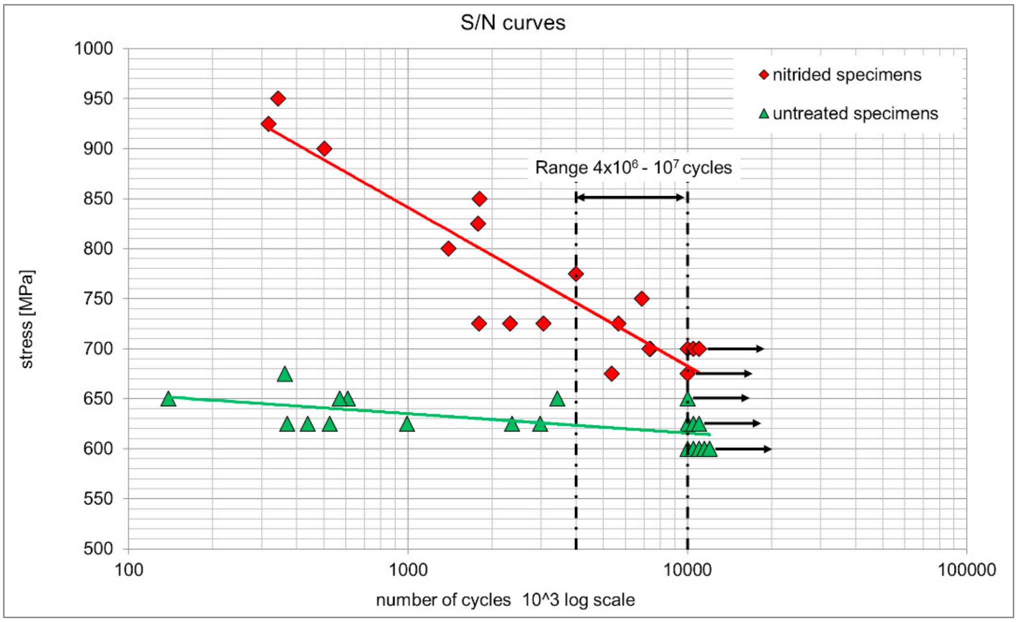

Fig. 10. S/N curve of untreated and nitrided specimens.

4. Conclusions

The steel analyzed is a typical bainitic grade with high mechanical characteristics that can substitute the traditional quenched and tempered steels in such projects which require high fatigue resistance property as automotive engines. The untreated material has got excellent fatigue results considering its mechanical properties (> than 50% of Rm). Moreover the fatigue crack propagates about 30% of the resistant section.

The gas nitriding technique utilized to increase the fatigue property of this steel demonstrates good results about the nitrogen diffusion, but the expected values of fatigue results are against this fact. The fatigue limit increment compared to the untreated specimens is about 13%. Moreover during the staircase test of the nitrided specimens a series of specimens broke in high cycles range (more than 4 millions) differently from the untreated specimens. This behavior could be associated with an increased embrittlement of the material which must be confirmed by fractography. Further investigations must be undertaken by looking also at the heat treatments cycle modification in order to increase the advantage in fatigue limit given by the nitriding treatment.

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