

Tribological behaviour of nitrided and nitrocarburized carbon steel used to produce engine parts

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Abstract

Purpose – The purpose of this study is to select a proper surface treatment to enhance wear resistance of engine camshafts. The camshaft is a relevant part of a diesel engine which works under torsion, fatigue and wear efforts. They are usually manufactured by casting, forging or machining from forged bar of low alloy steels, and in most cases, the machined surfaces are quenched and tempered by induction heating. After that, in many cases, to withstand the efforts imposed on the active surfaces and improve tribology and fatigue properties, the industry used for decades, thermochemical technologies such as salt bath or gaseous nitriding and nitrocarburizing processes.

Design/methodology/approach – This paper studied the effects of plasma nitriding and plasma nitrocarburizing, on the tribological behaviour of the steel SAE 1045HM3 proposed to produce camshafts. After the plasma treatments, the change in surface roughness was measured; the modified layers were studied by X-ray techniques and its thickness by optical microscopy. The diffusion zone was evaluated by Vickers microhardness determinations. Tribology tests were performed by pin-on-disc configuration using WC ball as a counterpart.

Findings – Results show that plasma nitrided samples present the best tribological behaviour compared with the nitrocarburized ones; also, the influence of the roughness produced by the thermochemical processes appears to be important.

Practical implications – Although both the plasma treatments have been applied for many years, and also reported separately in the scientific literature, there was no information comparing these two treatments for carbon steels, and also, there is not much about tribology in lubricated conditions of nitrided and nitrocarburized carbon steels. In fact, it is not proved that the porosity of the nitrocarburized layer is beneficial for wear resistance in lubricated conditions. In this paper, it was proved that at least in the tested conditions, it is not.

Originality/value – Gas or plasma nitrocarburizing is usually recommended for this kind of applications, although the modified layer is porous. This paper attempts to prove that nitriding could be better than nitrocarburizing, even with a thinner white layer.

Keywords Tribology, Wear, Surface engineering, Steels, Low alloy steel, Plasma assisted diffusion, Nitrocarburizing, Nitriding

Paper type Research paper

1. Introduction

Components like crankshafts and camshafts for combustion engines are made from low alloy steels, and require high wear and fatigue resistance and also a low friction coefficient of the active surfaces. For decades, industry has applied low temperature thermochemical treatments, such as ferritic gas nitriding and ferritic salt bath nitriding and nitrocarburizing (ASM, 1994; Pye, 2003). These technologies produce a case-hardened surface by the introduction of nitrogen, carbon and, in some cases, oxygen and sulphur. The physical metallurgy of the transformed zone (case) has been extensively

studied (Bell *et al.*, 2000; Chiu *et al.*, 2002; Hoffmann and Mayr, 1999; Podgornik and Hogmark, 2006) and, in general, is formed by two layers, the external is commonly known as the white layer or compound layer, underneath of which is a thicker one, called the diffusion layer. The core or base material under the diffusion layer should not suffer any change in its physical or mechanical properties during the thermochemical treatment.

About 40 years ago, technology based on the application of plasma generated by glow discharge started to be applied by the industry because of its advantages, mainly: it is environmentally friendly, it has a low energy consumption and

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presents high flexibility, allowing a better adjustment of the case-hardened properties compared to other technologies (Lampe *et al.*, 2003; Quing *et al.*, 2000; Celik *et al.*, 2005).

Plasma nitriding and plasma nitrocarburizing are processes that take place inside a vacuum chamber at pressure in the range of 1 to 10 hPa. The load to be treated is the cathode of a DC power circuit. The vacuum system is a dynamic one, so it is possible through the flow control of nitrogen (N_2) gas, hydrogen (H_2) gas and a carbon-carrier gas (CH_4) to generate plasma of the desired characteristics. In this way, the reaction between the plasma and the surface of the work load can be controlled to define the composition and characteristics of the entire case (Li and Manory, 1999).

The general description of the process comprises the following: chamber evacuation; heating of the load to the process temperature; glow discharge process and cooling. In the equipment used in this work, the heating at the beginning of the process is performed by electrical resistances, and later on, the glow discharge power provided by a DC-pulsed power supply keeps the temperature at the set point.

Concerning the characteristics of the case-hardened zone, this is formed by one or two layers. Its structure and properties have been investigated for years, in relation to their fatigue, corrosion and tribological properties (Karakan *et al.*, 2003; Quing *et al.*, 1999); nevertheless, there is not a clear conclusion about the more convenient composition, thickness and morphology of the layers that constitute the case.

In plasma nitriding, the case is formed by the white layer, usually Fe_4N (γ' nitrides) and $Fe_{2-3}N$ (ϵ nitrides). Underneath is the diffusion layer that contains nitrogen in solid solution with nitride precipitates (Bell *et al.*, 2000). In the nitrocarburizing process, the case is formed by the white layer, usually with a high proportion of epsilon-type nitrides and carbonitrides $Fe_3(C,N)$ and the diffusion layer. It is well known that the shape, concentration, distribution and composition of the precipitates in the diffusion layer determine some mechanical properties, particularly hardness and fatigue resistance. Concerning the tribology behaviour of the part, the white layer has a paramount importance, especially its constitution, thickness, morphology and its roughness.

Nitrocarburizing is usually recommended for carbon steels, as they do not have enough constituents to form nitrides such as other medium alloy steels. So carbon is added in the process to enhance the formation of a hard compound zone. Nitrocarburized steels usually present a porous structure in the outermost surface layer, especially when the process has been carried out in saline media (ASM, 1994; Pye, 2003; Bell *et al.*, 2000). It is assumed that this apparent drawback is indeed a beneficial issue because it can retain lubricant, and elastically nitrocarburized parts would present a good wear resistance in lubricated conditions. However, we could not find information available in scientific papers, as well as literature about nitriding of carbon or low alloy steels for tribological purposes, even though this treatment is carried out at a significantly lower temperature and certain advantages can arise, such as a monophasic nitride structure in the compound layer and the retaining of the core hardness.

In the past, several researchers evaluated the influence of surface characteristics on the tribological processes for camshaft applications. Alamsyah *et al.* (1989) identified the

effect of different manufacturing processes on the wear performance of AISI A10 (milled and ground) and AISI 4,140 (nitrided plus bead blasted) in a cam-follower lubricated tribosystem. They concluded that the pitting and scuffing wear damage was reduced by the post-machining ion nitriding and bead blasting.

Later, İpeka and Selcuk (2005) reported the wear mechanisms observed on a camshaft made of AISI 1,040 hardened by induction, and identified that the maximum damage occurred in the cam tip due to abrasive and adhesive wear. However, this study was made under dry conditions.

Although the plasma nitrocarburizing and ion nitriding treatments are known and applied since many years in the industry, no information has been found in the literature about comparing these two treatments for very low chromium alloy steels, and discuss about advantages and drawbacks of each one. It is intended to prove in this work that nitriding can be also suitable for AISI 1045HM3 low alloy steel, regarding certain applications where sliding wear conditions will arise.

The purpose of the present paper is to determine the influence of plasma treatments, on the wear and frictional behaviour under sliding lubrication conditions of AISI 1045HM3 low alloy steel. The topographical characteristics and the present phases of tribosurfaces due to the thermochemical process are analyzed, and these results are correlated with their effect on the tribological process.

2. Experimental work

2.1 Material

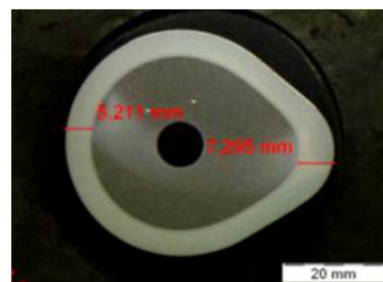
The steel used was a SAE 1045HM3 in the form of annealed bar stock 57.10 mm in diameter; the composition is presented in Table I.

Disc samples with 50-mm outside diameter, 12.6-mm inside diameter and 5-mm thickness were machined. The samples were quenched and tempered to obtain a martensitic structure of 620 HV (56.2 HRC), similar to the case hardness obtained by induction hardening in the actual camshaft production. As we can see in Figure 1, the induction case-hardened thickness spans in a range between 5 and 7 mm. The heat-treated samples were rectified to an average roughness (R_a) of 0.8 μm .

Table I Chemical composition of the steel samples

C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.45	0.78	0.25	0.010	0.003	0.12	0.17	0.05	0.24

Figure 1 Cross-section of a camshaft showing the induction case hardened



Two groups of samples were selected, one for plasma nitriding and the other for nitrocarburizing. Nitrocarburized samples were labeled as “NC” and nitrided samples as “N”. A third group, named “QT”, was composed of conventionally heat-treated samples. The parameters used in the plasma treatments are shown in Table II.

2.2 Microstructural characterization

Hardness was assessed by means of the Vickers technique. For surface hardness, 50-g load was used ($HV_{0.05}$), and the result was the mean value of ten measurements in two samples for each treatment. To evaluate the surface microstructure, samples were cut, embedded in acrylic resin, grounded with emery paper and polished with 1- μm diamond paste. After that, they were etched with Nital reagent (3.5 per cent nitric acid in ethanol). Optical microscopy was used for evaluating the resulting microstructures. Hardness profiling along the case depth were performed using 25-g load in the cross-sectioned samples, after polishing and without etching.

X-ray diffractometry was performed to identify the present phases in the material. An X-ray diffractometer in the Bragg Brentano configuration was used, using $\text{CuK}\alpha$ radiation ($\lambda = 1.5405 \text{ \AA}$) at an acceleration potential of 40 kV. The diffraction angle ranged from 20° to 120° , with a 0.02° step at a speed of $0.06^\circ/\text{min}$.

2.3 Sliding wear tests

Pin-on-disk tests were used for the characterization of the wear behaviour of the samples. Specimens were tested under two sets of conditions, named *as-received* and *polished*. The *as-received* specimens were kept with the same roughness parameters that were obtained after the thermochemical treatments, while the second batch of specimens was polished using abrasive SiC papers up to 320 grit.

All specimens were ultrasonically cleaned with toluene for 5 min before and after each test. A 5-mm diameter WC ball (50 per cent W/50 per cent C and $R_a = 0.05 \mu\text{m}$) was used as the counter body to ensure that wear developed, mainly in the steel disks. Roughness parameters were determined using an ALICONA IF-EDGEMASTER 3D optical 3D roughness measurement system based on focus variation with an 80 nm resolution. The parameters that were taken into account were the average roughness (R_a) which gives an overall idea of the state of the surfaces and R_z and R_t for assessing the influence of local protuberances, because in the *as-received* stage, wear was localized in these local peaks.

The sliding speed in the pin-on-disk tests was set at 0.06 m/s, while the sliding distance was 500 m for the *as-received*

Table II Plasma surface treatments parameters

Parameter	Nitriding (N)	Nitrocarburizing (NC)
T ($^\circ\text{C}$)	490	565
Time (h)	15	8
Pressure (Pa)	600	400
Voltage (V)	600	650
N_2 (%)	25	67
H_2 (%)	75	31
CH_4 (%)	–	2
Pulse time, ON (μs)	75	75

stage and 28,500 m for the *polished* stage. The applied normal load was 10 and 40 N.

This experimental setup was chosen because when *as-received* specimens were tested, the thermochemically treated ones showed signs of severe asperity wear, while quenched and tempered samples exhibited very low wear. To avoid penalizing nitrided and carbonitrided specimens and to assess the influence of roughness, a second stage of tests was carried out with specimens having an equated level of roughness. However, at this stage, the severity of the tests had to be increased due to the absence of wear in the thermochemically treated specimens with the initial setup (10 N normal load – 500 m of sliding distance).

During the test, the friction force was continuously measured and logged with a data acquisition system. Tests were performed using a low-viscosity, additive-free paraffinic petrolate bath, with a cinematic viscosity of 17 cSt at 40°C . All the experiments were performed under ambient laboratory conditions (approximately 25°C , 65 per cent relative humidity). Wear surfaces were analyzed by means of optical Microscopy, while wear scar depth was determined in at least ten different positions using the optical 3D measurement system previously mentioned. Wear rate was estimated from these values as the average of at least three valid results. Additionally, EDS spectra were collected from both inside and outside the wear tracks to determine the presence of oxide or transfer layers in the disk surfaces using a Philips SEM XL 30 CP microscope with an embedded EDS system.

The lubrication regime was estimated using the Hutchings (1992) theory for ball-on-plane sliding conditions, accordingly to equation (1). This theory assumes that both Reynolds hydrodynamic lubrication and Hertz elasticity are valid. This equation compares the lubricant film thickness (h) with the composed surface roughness (σ) of the tribopair to assess the position of the system in the Stribeck's curve:

$$h = 1.79 \times \alpha^{0.49} \times (\eta_0 V)^{0.68} \times R'^{0.47} \times W^{-0.07} \times E'^{-0.12} \quad (1)$$

where:

h = Lubricant film thickness (m).

α = Coefficient of oil viscosity. According to Hutchings (1992) α approximately equals to $(0.6 + 0.965 \times \log(\eta_0)) \times 10^{-8}$

η = Oil viscosity at atmospheric pressure and test temperature (cP)

V = Sliding velocity (m/s).

R' = Equivalent contact radius (m), defined as: $1/R' = (1/R_1 + 1/R_2)$.

W = Applied normal load (N).

E' = Equivalent elastic modulus (GPa), defined as: $1/E' = ((1 - \nu_1^2)/E_1) + ((1 - \nu_2^2)/E_2)$.

In equation (1), the following values were used for the steel: $\nu = 0.3$ and $E = 200 \text{ GPa}$, and for the WC ball: $\nu = 0.24$ $E = 680 \text{ GPa}$ (Shackelford *et al.*, 1994).

The composed surface roughness is defined as $\sigma = (R_{a1}^2 + R_{a2}^2)^{1/2}$. If $h/\sigma < 1$, then there is asperity interaction and, therefore, metallic wear.

3. Results and discussion

3.1 Hardness and microstructure

From the microhardness measurements carried out on the surface of NC samples, $830 \pm 50 \text{ HV}_{0.05}$ was obtained and $790 \pm 50 \text{ HV}_{0.05}$ for N samples. Although the obtained surface hardness values were similar, the hardness profiles (Figure 2) shows that the NC sample (in red) presented a steeper profile, while the N one (in black) is smooth and reaches a smaller penetration. It can also be observed that the core hardness decreased after the plasma treatments to $360 \pm 10 \text{ HV}$ in the N samples and $300 \pm 10 \text{ HV}$ in the NC ones. The hardness profile is usually related to the carbon and nitrogen concentration; in fact, it is proportional to the amount of N or C in solution in the Fe-lattice (Bell *et al.*, 2000; Celik *et al.*, 2005; Li *et al.*, 2008; Woehrle *et al.*, 2012). In this case, the term “core” refers to the induction-hardened zone of several mm showed in Figure 1. Core hardness

Figure 2 Depth hardness profiles of nitrided and nitrocarburized samples

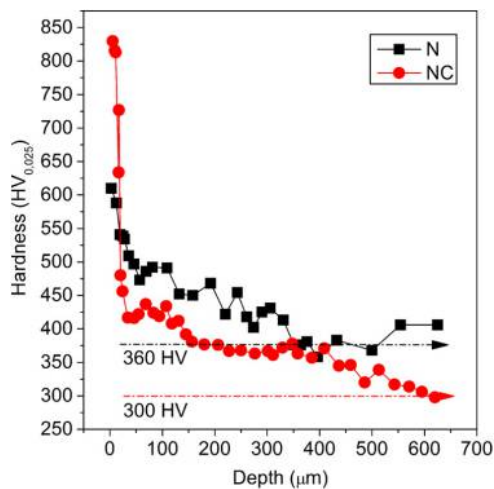
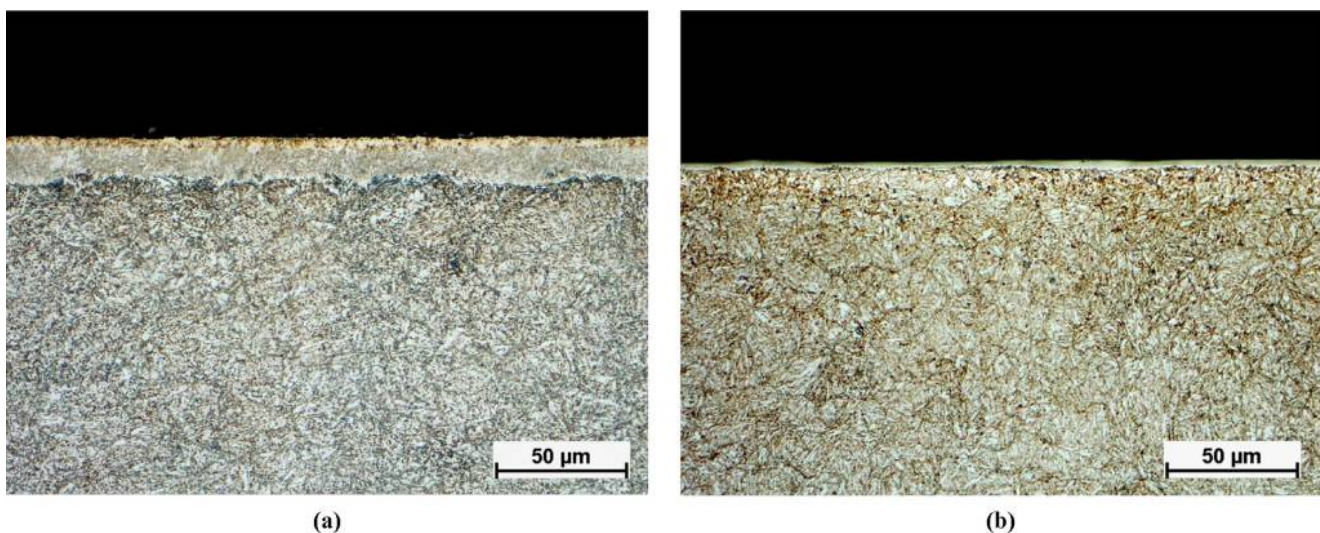


Figure 3 Cross-sectional OM micrograph of: (a) NC sample, where the porous layer is observed in the outer zone of the white layer and (b) N sample



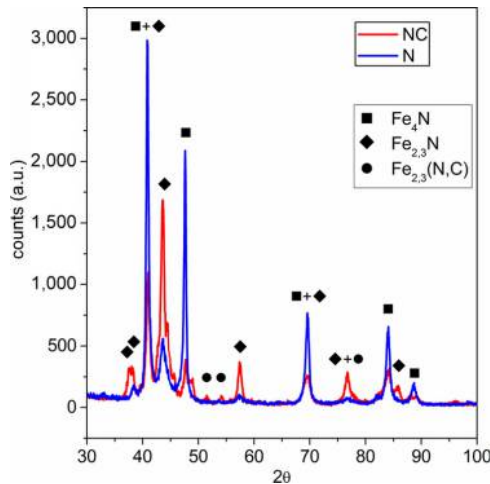
decreases because the processing temperature in both cases, nitriding and nitrocarburizing, is almost 200°C higher than the tempering temperature in the last stage of the induction heat treating, and the longer the treatment, lower the core hardness. Therefore, a compromise solution was selected between core hardness and surface hardness, because time and temperature allow the diffusion of carbon and nitrogen.

The optical micrographs in Figure 3 show the appearance of the modified layers for samples NC and N. It can be seen that the white layer is thinner for the nitrided sample.

The total thickness of the nitrided and nitrocarburized layers (including the diffusion zone) was measured through the hardness profile presented in Figure 2, as indicated by the DIN 50 190-3 standard. This standard defines the depth of the nitrided layer as the distance from the surface where the hardness reaches a value of 50 HV over the core hardness.

For the NC sample, the average white layer thickness is $15.6 \mu\text{m}$ and the diffusion layer thickness is $430 \mu\text{m}$, while for the N sample, the thickness of the white layer thickness was $3.5 \mu\text{m}$ and the diffusion layer was $330\text{-}\mu\text{m}$ thick. These last measurements were taken from the micrographs showed in Figure 3.

X-ray diffraction (XRD) analysis of the two treated samples was carried out to determine the compound phases generated by nitriding or nitrocarburizing in the near surface. In Figure 4, both spectra are superimposed, with the signal of Fe-alpha (typical from the base material). In the nitrided sample (in blue), Fe_4N nitrides were observed with high intensity, being the predominant phase, but even a weaker signal from $\epsilon\text{-Fe}_{2,3}\text{N}$ could be detected. On the contrary, in the nitrocarburized sample (in red), the predominant phase is $\text{Fe}_{2,3}\text{N}$ epsilon nitrides. Fe_4N nitrides and also Fe carbonitrides were present. No peaks of Fe-alpha coming from the base material were detected. This ϵ phase is usually the outer one, as it is formed with addition of nitrogen or carbon to the previously formed Fe_4N , as the surface is the zone with major N and C concentration (Chen *et al.*, 2013; Wells and Bell, 1983). It can be hard but it is porous and fragile, as it can be observed in a micrograph of the NC sample (Figure 3(a)). The porous phase is formed because nitrogen is

Figure 4 XRD patterns of nitrided (N) and nitrocarburized samples (NC)

pushed away from interstitial sites by carbon, and nitrogen atoms move to lower energy zones like grain boundaries. At this time, two atoms can combine to form a gas molecule, which is not stable enough and escapes, leaving a pore in the structure (Celik *et al.*, 2005; Li and Manory, 1999).

3.2 Wear behaviour results

Table III displays the roughness parameters before and after polishing the specimens. Roughness increased after both treatments, especially in the NC samples, probably due to the porous nature of the outer layer shown in Figure 3(a). This has been reported as a usual phenomenon in nitrocarburized steel (Pye, 2003).

It can be seen that roughness values equated for all three groups of specimens after polishing; thus, results could be considered independent of surface topography. Additionally, the variation of the thickness of the white layer after and before surface polishing, along with the wear rate and mean coefficient of friction in each case are presented. White layer thickness was evaluated after polishing to determine the influence of material removal. In this regard, it is important to highlight that the white layer of both N and NC specimens was not significantly diminished by polishing.

In all cases, the h/σ coefficient was comprised between 3.6×10^{-5} and 6.5×10^{-5} ; therefore, the lubrication regime is

considered to be marginal, with a high level of asperity interaction.

3.2.1 Wear behaviour of specimens with as-received surfaces

As stated before, in the first stage, the sliding wear tests were carried out during 500 m on the specimens without modifying their surface characteristics. In Table III, it can be seen that the thermochemically treated specimens had higher roughness values, this difference being more marked in the case of the total roughness (R_t) value. Roughness variations after thermochemical treatments had been reported by several authors; although in the majority of the cases, the analysis has been restricted to R_a values, such as the work of Çetin *et al.* (2007), who measured a R_a increase from 0.02 to 0.18 μm while studying plasma nitrided AISI 420 steel. Less marked increments were reported by Tek *et al.* (2002), going from 0.01 to 0.05 μm of R_a after plasma nitriding.

In our case, the higher value of R_t in N and NC specimens means that they had more prominent and singular peaks, which are prone to severe plastic deformation and subsequent break-off due to elevated contact stresses (Kapoor *et al.*, 1994; Xie and Williams, 1996). This kind of damage has also been observed by Lei *et al.* (1997), who reported asperity flattening when high contact pressure and low speed were applied in simulated make-up process of petroleum connections using a lubricated cross-cylinder friction test.

This phenomenon is more evident in the case of NC specimens, as it can also be appreciated in the OM images (Figure 5(c)). As a consequence, the wear volumes values in this first stage were higher for both thermochemically treated specimens, as well as the COF values (Figure 6), in comparison with QT specimens.

Although the nitrided phases were intensely studied, their effects on the tribological processes in low alloy steels are somewhat controversial. According to Karaoğlu (2002), who studied the plasma nitrided AISI 5,140 under dry sliding, the mixed-phased compound layer ($\gamma' + \epsilon$) is extremely brittle and increased the wear rate of the material.

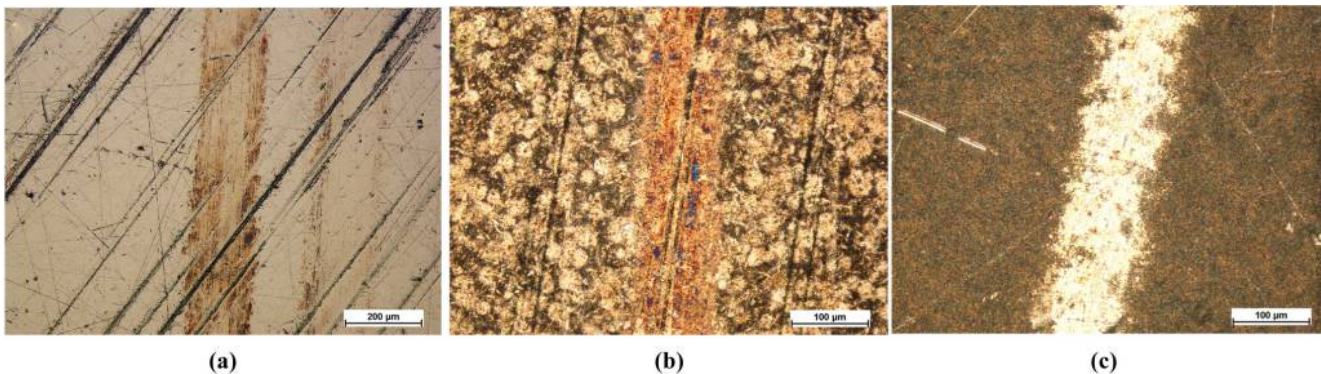
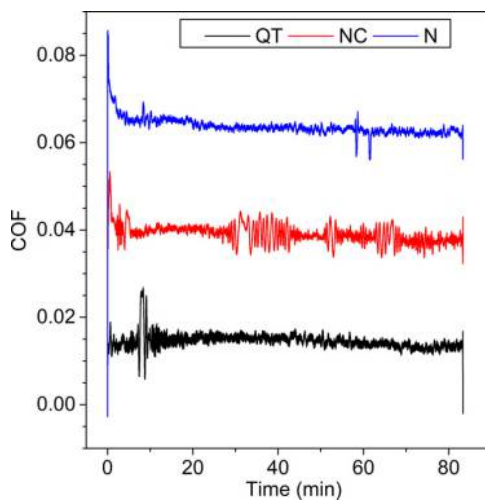
On the other hand, Heydarzadeh Sohi *et al.* (2010) studied the wear performance of AISI 4140 steel under different nitrocarburizing conditions, and reported that a lower wear rate was observed in samples with a compound layer formed by a high amount of ϵ phase and trace of γ' .

In our case, even though the thermochemically treated samples in the as-received condition showed different

Table III Quantitative results of the wear tests

Treatment	Load (N)	Sliding distance (m)	White layer (μm)	COF	Initial roughness (μm)			Wear rate ($\text{mm}^3/\text{N}\cdot\text{m}$)
					R_a	R_z	R_t	
As received								
QT	10	500	–	0.018 ± 0.004	0.10 ± 0.003	1.07 ± 0.016	1.40 ± 0.12	NA ^a
NC	10	500	15.6 ± 1.7	0.039 ± 0.007	0.21 ± 0.011	1.46 ± 0.12	2.04 ± 0.22	$1.20\text{E-}05 \pm 1.1\text{E-}06$
N	10	500	5.5 ± 0.1	0.063 ± 0.007	0.17 ± 0.009	1.45 ± 0.09	2.07 ± 0.19	$9.92\text{E-}06 \pm 5.4\text{E-}07$
Polished								
QT	40	3,000	–	0.072 ± 0.012	0.22 ± 0.05	1.44 ± 0.04	1.79 ± 0.03	$4.83\text{E-}06 \pm 7.3\text{E-}07$
NC	40	28,500	14.4 ± 1.1	0.071 ± 0.006	0.19 ± 0.04	1.46 ± 0.05	1.69 ± 0.04	$1.10\text{E-}07 \pm 2.2\text{E-}08$
N	40	28,500	3.6 ± 0.5	0.057 ± 0.007	0.15 ± 0.04	1.28 ± 0.07	1.65 ± 0.04	$1.16\text{E-}07 \pm 2.8\text{E-}08$

Note: ^aNot available: the wear rate was too low to be determined

Figure 5 Top-down OM images of wear tracks after the test at 1 N**Figure 6** Evolution of the friction coefficient (COF) during tests of as-received specimens

hardness levels and their compound layers were not the same in terms of the phase fractions, no significant difference in the wear rate could be inferred (Table III).

The wear damage of the QT specimen was too low to be determined and the rubbed surface only showed a slight triboxide formation on the wear track (Figure 5(a)), but damage could not be appreciated using both OM and the optical roughness measurement microscope.

In this stage, the frictional behaviour was characterized by very low COF values during the evolution of the tests, with a slight running-in period in N and NC specimens (Figure 6). This phenomenon is related to the high interaction between asperities that diminishes after some degree of asperity wear. After that, both thermochemically treated samples exhibited some variation in the friction force that can be attributed to the breaking off of local asperities followed by stabilization in the friction coefficient.

3.2.2 Wear behaviour of samples with polished surfaces

On the basis of the remarkable difference in the wear rate between QT and the thermochemically treated samples tested at 10 N load, we decided to equate the roughness levels of the specimens before testing. Additionally, the load level was increased up to 40 N.

The obtained results showed that both N and NC samples had a similar performance, with wear rate values being one order of magnitude lower in comparison to QT specimens (Table III).

Due to the severe contact stress conditions, tests in the QT samples (Figure 6(a)) were interrupted at 3,000 m sliding distance, whereas the thermochemically treated specimens exhibited shallower wear tracks than those present in the QT samples, even after 28,500 m sliding (Figure 6(b) and (c)).

The wear results obtained are similar to those documented by other researchers (Ro and Kreuz, 1965; Rowe and Dickert, 1967) who reported wear coefficients ranging from 5×10^{-7} to $5 \times 10^{-10} \text{ mm}^3 \text{ mm}^{-1} \text{ N}^{-1}$ under similar test conditions.

According to Karaoglu (2002), the surface hardness is the most effective factor with respect to wear rate. In that work, samples nitrided for four hours, with a hardness of 226 HV higher than specimens nitrided for one hour, had five times less weight loss than the latter. However, we could not appreciate a difference between N and NC samples, even though the latter was 210 HV harder than N specimens.

Regarding the dominant wear mechanisms, the analysis of SEM images of the worn surfaces of the QT samples (Figure 7(a)) shows signs of plastic deformation, especially at the edges of the track; therefore, the wear occurred by a combination of plastic deformation and moderated oxidative damage. In the case of N-NC specimens, no plastic deformation can be appreciated (Figure 7(b)). Therefore, the wear mechanism was slight oxidative wear, as it is supported by the EDS analysis shown in Table IV and OM images presented in Figures 8(b) and (c). Those observations are similar to the ones reported by Heydarzadeh Sohi *et al.* (2010).

The EDS spectra showed no peaks corresponding to tungsten or cobalt; therefore, we assume that no transfer layers developed during the tests or conventional and thermochemically treated specimens. The ZAF standardless quantification analysis of measurements taken from the wear track and the untested surface revealed that the oxygen signals were stronger in the track; thus, in addition to the OM images (Figures 5 and 8), we infer that oxide layers are being formed in it. Figure 5 shows an EDS spectrum of a QT specimen tested with 40 N of normal load and 3,000 m of sliding distance. In Table IV, a comparison of the estimated atomic concentration of oxygen between the track and the untested

Figure 7 Top-down SEM images of wear tracks after the test: (a) QT and (b) N sample. Both in the polished condition

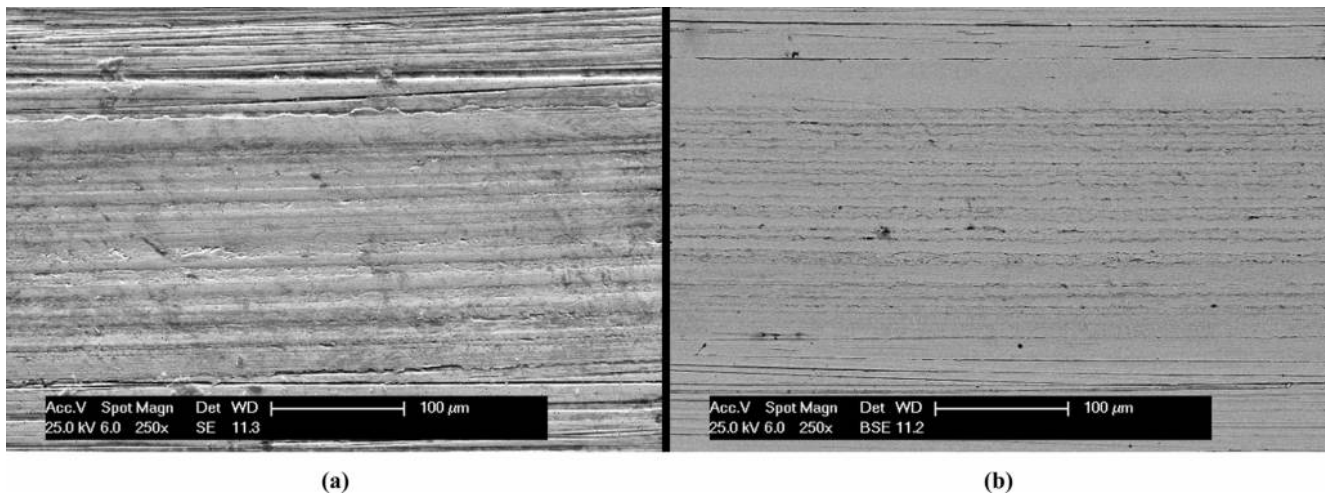


Table IV Estimated atomic concentration (atomic %) of oxygen in tested samples

Sample	Atomic concentration (atomic %)	
	Wear track	Untested surface
QT	7.99	4.61
C	7.44	4.16
NC	4.48	3.63

surface for the three groups of samples tested after polishing is presented (Figure 9).

The friction values are consistent with those obtained by Fu *et al.* (1998), who reported values ranging from 0.05 to 0.08 for AISI 410 plasma nitrided tested under boundary lubrication at 25 N. According to Batchelor *et al.* (1986), frictional temperatures in lubricated wear are much lower than in dry conditions, so when metals slid in boundary lubricated conditions, reactions between the metal and the oil or impurities and additives in the oil greatly improve the possibilities of protective film formation on the metal surface.

Regarding the evolution of the friction coefficient, it can be seen in Figure 10(a) that QT samples had an initial COF value similar to those observed in thermochemically treated specimens

Figure 9 EDS spectra of the wear of a QT specimen tested at 40 N and 3,000 m sliding distance

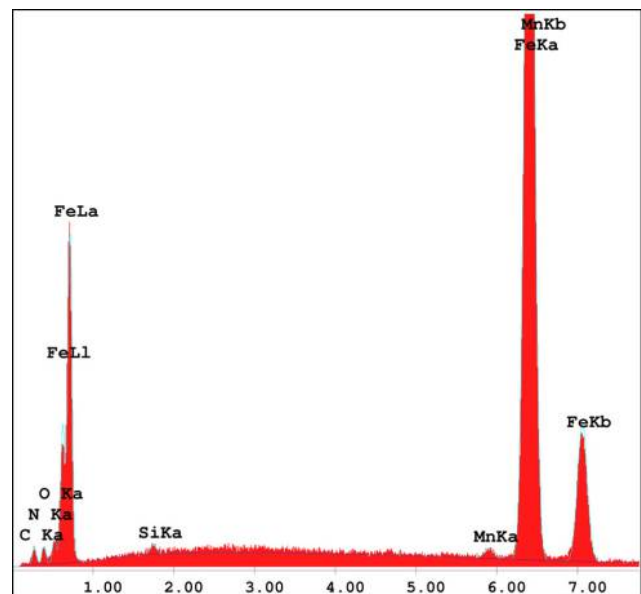


Figure 8 Top-down OM images of wear tracks after the test

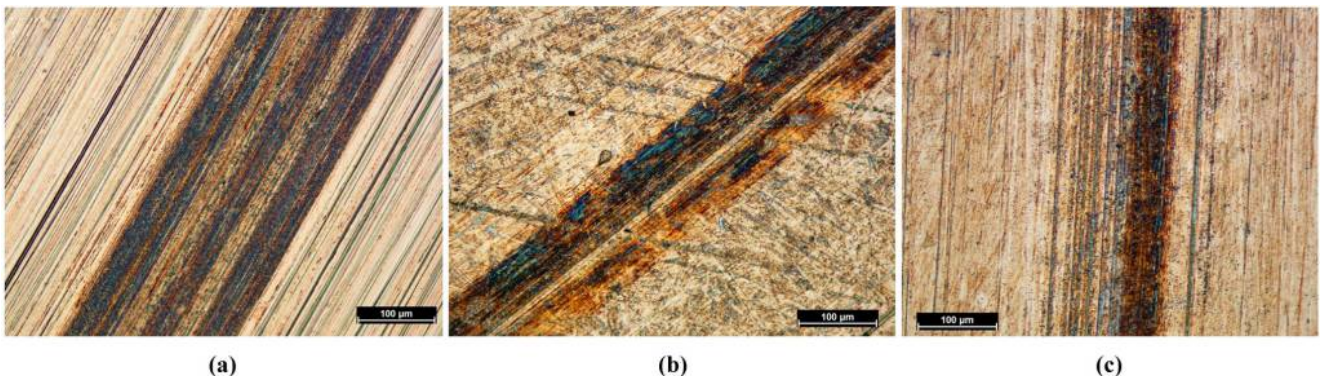
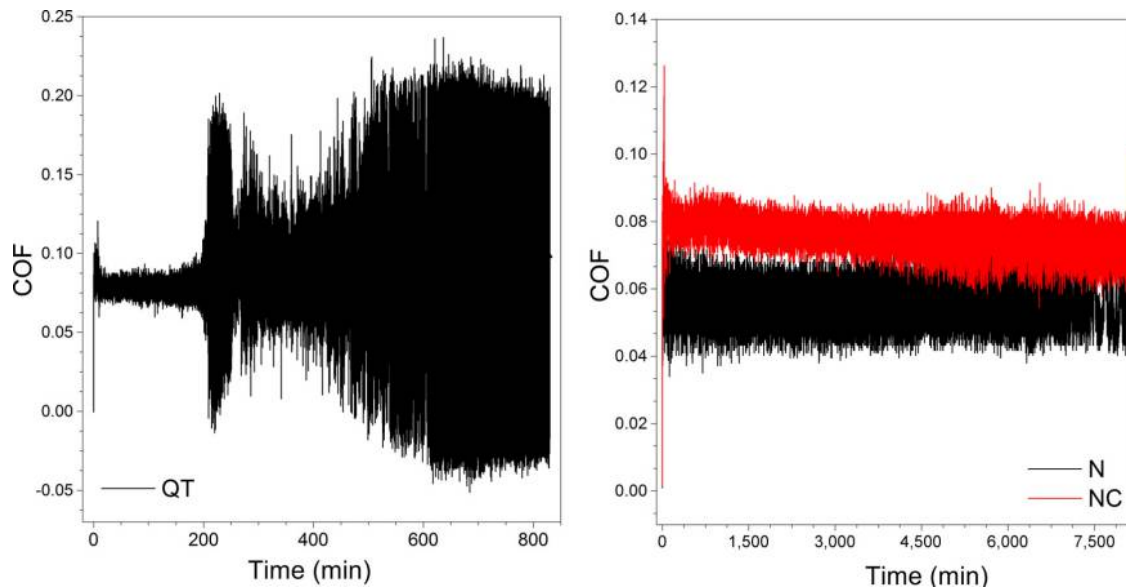


Figure 10 Evolution of the friction coefficient (COF) during tests of polished specimens of (a) QT specimen and (b) N and NC specimens

(Figure 10(b)) below 0.08, but after the running-in period, moderate oxidative wear started to develop which generated sudden variations in the friction force as oxide layers were forming and detaching from the surface. This behaviour is in strong agreement with the one described by Blau (2008, p. 186) and with the mild-oxidational wear model proposed by Stott (1998; Stott and Jordan, 2001).

The friction coefficient of the thermochemically treated specimens showed no significant variations along the duration of the tests (Figure 10(b)), with a slight decrease in the average value for NC samples towards the test progressed. This can be attributed to the formation of thin oxide layers, as it can be seen in Figures 8(b) and (c). It should be noted that N specimens showed lower values of friction than the NC ones, opposing the as-received behaviour (Figure 6).

4. Conclusions

From the present study of the tribological behaviour of plasma nitriding and nitrocarburizing of SAE 1045HM3 steel, the following can be concluded:

- The nitriding process promotes a less marked reduction of the hardness underneath the white layer; this is important from the standpoint of the load bearing capacity of the case.
- A low roughness level is more important than the thickness of the white layer. The nitrided samples, even though they had a thinner compound layer, had the same tribological performance than nitrocarburized specimens. Thermochemically treated materials showed wear rates one order of magnitude lower than the quenched and tempered material.
- The porous layer in the nitrocarburized layer did not improve wear resistance under lubricated conditions. Thus, the plasma nitriding treatment should be preferred over the nitrocarburizing one, because it generates a more homogeneous and monophasic compound layer, and a less marked core hardness reduction.

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