ASPECTS OF THE INFLUENCE OF SOME HEAT TREATMENT SURFACES WITH NITROGEN ON THE FATIGUE PHENOMENA TYPICAL OF HERTZIAN LINE CONTACT

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ABSTRACT

As we know, in the case of some bearings or gears, there are rolling or rolling-sliding line contacts. This kind of contacts, close to the punctiform contact types, belongs to the hertzian contact category. Even for constant loads, the rolling motion produces a variable superficial efforts state, characterized by normal and tangential-shear stress under impact.

The intricacy of studying this kind of contacts is further increased by the presence of lubricant; it therefore depends on several more factors such as: the load, the speed, the rolling-sliding ratio, the lubricant quality, the surface topography and whether the contacts are absolute or incomplete elasto-hydrodynamic, or elasto-plastic hydrodynamic. The wear behaviour of plasma nitrided low alloy steel has been investigated under dry rolling contact with sliding traction.

Particular attention was paid to subsurface shear behaviour during the wear process and to prediction of the load bearing capacity of the nitrided specimens. In order to further improve the tribological properties and load-bearing capacity of the low-alloy steel, a duplex plasma surface-engineering technique has been developed.

KEY WORDS: EHD line contact, rolling-sliding, surface fatigue, plasma nitriding, duplex treatment.

1. INTRODUCTION

We generally speak of a rolling line or punctiform contact, irrespective of the whether the samples are loaded or not and lubricated or not. The hertzian rolling contact cases are characterized by contact microsurfaces and higher pressures in the contact zone. Therefore, surface deformation must be considered.

The appearance and evolution of fatigue phenomena have been explained by using the space stress condition state and the theoretical models of Hertz and Boussinesq.

Wear of plasma nitrided steels usually occurs in a mild way compared to that of unnitrided steels. After nitriding, a thin compound layer and a relatively thick diffusion zone are produced on the component surface. The compound layer, supported by the diffusion zone, improves resistance to seizure and/or scuffing; the diffusion zone improves the fatigue strength and load bearing capacity.

On the other hand, plasma-assisted PVD of ceramic coatings, such as ion plating of thin (1-10 μm), hard titanium nitride (TiN) coatings, owing to their unique physical, mechanical and metallurgical properties, offers superior tribological properties to the component. Obviously, the remarkable properties of the thin coatings are exhibited only when the integrity between the coating and the substrate is maintained during service.

A duplex plasma surface-engineering technique, combined plasma nitriding and PVD of ceramic coatings, has recently been developed in an attempt to further improve the tribological performance and load-bearing capacity of low-alloy steel.

2. THEORETICAL CHARACTERIZATIOON OF THE ROLLING LINE CONTACT IN DRYCONDITIONS

In order to simplify the testing methods, the line contact modelling is carried out with two wheels (discus). For instance, if we study the gear teeth contact (on the evolvent flank) in the gear pole, the equivalent wheel radii Re_1 and Re_2 will be $Rr_1 \sin\alpha$ and $Rr_2 \sin\alpha$, where α represents the gear angle and Rr_1, Rr_2 represent the gear rolling circle radii.

If we consider two wheels of the same size, made of the same steel, under an applied normal force Q, they will be elastically deformed in the contact zone. The contact is realised on a rectangular surface of 2b width and L length (L - length of the rectangular microsurface contact) – see Fig. 1.

The applied force is supposed to generate only elastic deformations in the contact zone.

Because of microsurface appearance in the contact zone – A, the Q/A ratio represents the pressure contact:

$$P = \frac{Q}{A} \tag{1}$$

The Q/L ratio represents the uniform repartition of the normal force q on the measured length (typical force - q).

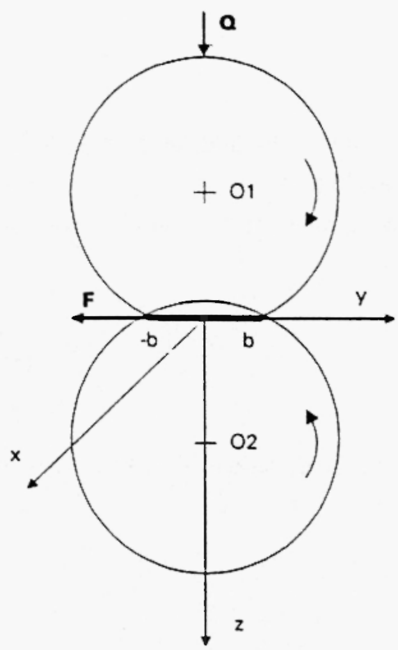


Fig. 1: The hertzian linear contact between two identical wheels, in dry conditions.

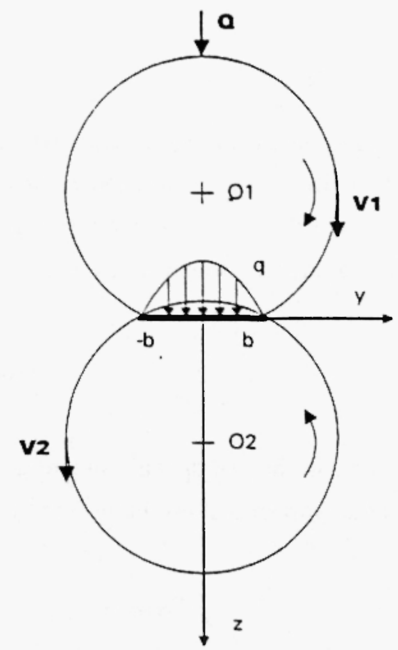


Fig. 2: The hertzian typical force distribution, q, on the contact width - 2b.

$$q = \frac{Q}{L} \tag{2}$$

To simplify the analysis, it is reasonable to assume a plane stress condition (yoz). Thus, the typical force q distribution on the width contact 2d will be a hertzian distribution (see Fig. 2). According to the Boussinesq theory, the wheels might be considered as two elastic semispaces due to the microsurfaces appearing in the contact zone.

Considering the plane problem (yoz), the wheels can be modelled through to semiplanes limited by the contact segment 2b. Thus, on the contact segment 2b, there are normal compressive stress axes, σ_z and σ_y, along with oz and oy axes. The maximum values of this stress are in the central point O (middle of the 2b segment). The most important stress is σ_z, which is produced by the normal typical force q.

According to Fig. 2, there is a pure rolling motion, when the speed wheels are equal ($v_1 = v_2$), in the same direction. In this case, when the sliding motion does not exist, the oy and oz axes can be considered principal normal axes. On these axes, the normal σ_z and σ_y stresses become σ_3 and σ_2.

As a result of the elasticity theory, it has been found that the maximum shear tangential stress appears on the bisectrix line between the oz and oy axes. These show a pulsating behaviour.

$$\tau_{45(yz)\max} = \frac{\sigma_3 - \sigma_2}{2} \tag{3}$$

It is known from photoelastic studies that the maximum amplitude value is reached at z=0.786b depth, on the oz axis, below the surface. Here, $\tau_{45(yz)max} = 0.31\sigma_3$ (see Fig. 3).

Without the oz axis, according to plane stress conditions, if the normal and tangential stresses are known (along two directions), we have:

$$\tau_{max} = \sqrt{(\sigma_z - \sigma_y)^2 + 4\tau_{zy}^2} \tag{4}$$

where τ_{zy} is the orthogonal tangential stress component along the oy direction. This stress has an alternate symmetrical evolution (see fig. 4).

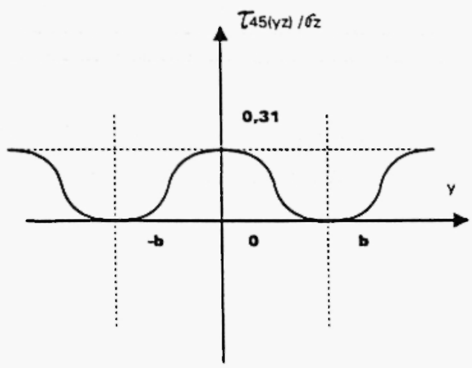


Fig. 3: The maximum amplitude of 45(yz) tangential shear stress, for z=0.786b depth.

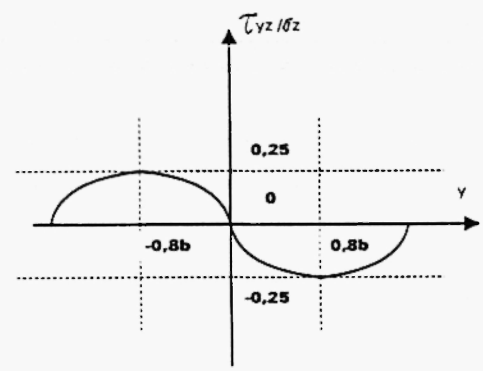


Fig. 4: The maximum amplitude of yz orthogonal shear stress, for z=0.5b depth.

The maximum amplitude value is reached at z = 0.5b and y = 0.8b, on one side and on the other side of the oz axis; here, $\tau_{zy\,max} = 0.25\sigma_2$ (see Fig. 5).

The equation (4) is used when a rolling-sliding motion exists. Figure 6(a) presents the normal stress variation, σ_3 and σ_2, and the tangential shear stress variation τ_{45mmax}, in the pure rolling motion case.

When a frictional-tangential force is superimposed on the contact region (rolling-sliding motion case), the tangential shear stress τ_{45yz} value is increased (τ_{45yz} *=0.36 σ_z for $\mu = 0.3$) and its maximum amplitude value approaches the surface. As a result of many theoretical studies, it is thought that the shear tangential stress below the surface is very important for the fatigue phenomena, when the friction coefficient is $\mu < 0.25$. When the friction coefficient $\mu > 0.25$, the surface shear tangential stress is important.

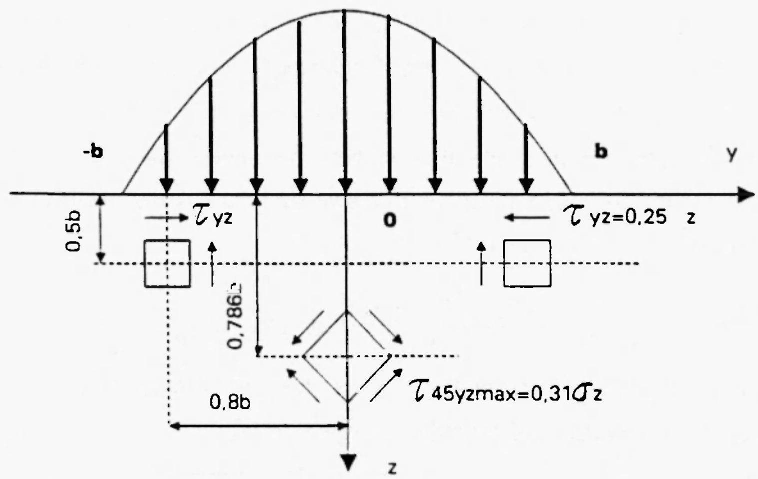


Fig. 5: The maximum shear tangential stress zone below the micro-surface contact.

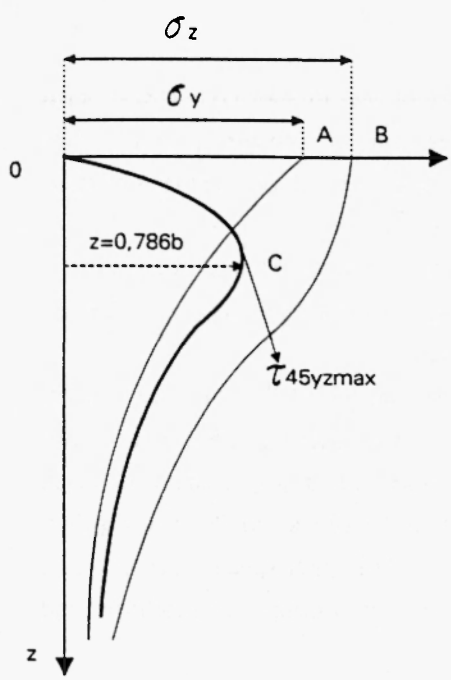


Fig. 6a: The variation of σ_z, σ_y and $\tau_{45yz\ max}$ stress for the pure rolling motion case.

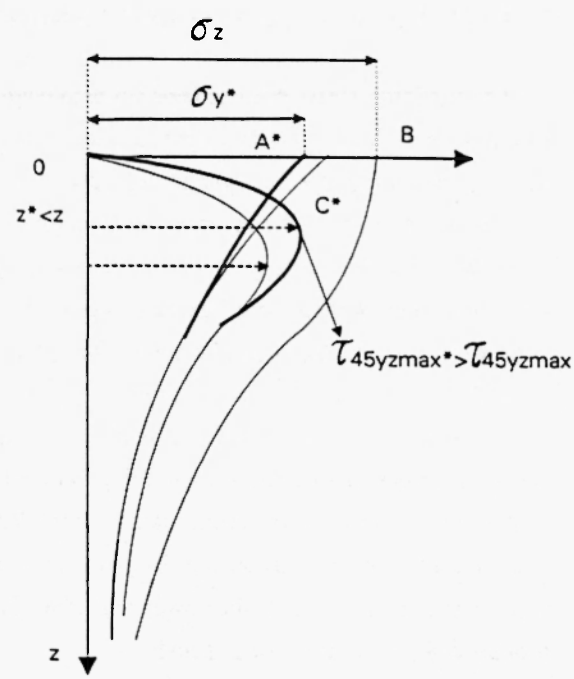


Fig. 6b: The variation of σ_z, σ_y and $\tau_{45yz\ max}$ stress for the rolling-sliding motion case.

The heat treatment surfaces, such as nitriding, at the rolling surface contact reach a very important residual compressive stress in the thick case. It has been found that the residual compressive stress is beneficial in forestalling shear and fracture in the nitriding case, except for the very near surface zone where the shear stress is increased (≅ 10 μm). The hardness and thickness of the superficial case prevent plastic deformation in the subsurface. This superficial residual compressive stress σ_R has a direction parallel to the contact surface (along the oy axis), σ_{yR}.

In the pure rolling motion case, and after the heat treatment surfaces have been achieved, the τ_{45yz} tangential stress depends on the residual compressive stress σ_{yR}. Thus, according to equation (3), the new value of the maximum tangential shear stress τ_{45yz} is:

$$\tau'_{max} = \frac{\left[\sigma_3 - \left(\sigma_2 + \sigma_{2R}\right)\right]}{2} \quad \text{or} \quad \tau'_{max} = \tau_{max} - \frac{\sigma_{2R}}{2} \tag{5}$$

In the case of the rolling-sliding motion, because tangential forces appear on the contact surface, the following expression is obtained according to equation (4):

$$\sigma_{max} = \sqrt{\left[\sigma_z - \left(\sigma_y + \sigma_{yR}\right)\right]^2 + 4\tau_{zy}^2} \tag{6}$$

3. TRIBOLOGICAL AND METALLURGICAL ASPECTS

The nitriding treatment has been used to engineer the surfaces of various steel components, such as crank-shafts and gears to improve wear resistance and fatigue strength. Sometimes, this kind of parts operate under special dynamic conditions and need a high-tenacity moulding. These conditions can be provided by a low alloy steel, such as En40B, hardened and tempered.

Referring to the latest specialty references, the paper attempts to make a presentation regarding the wear behaviour of three heat treatment surfaces. These are plasma nitriding, TiN coating (PVD) and duplex treatment concerning plasma nitriding followed by TiN coating.

En40B steels are very often used in gear or crank-shaft manufacture. The wear behaviour of En40B treated steel has been investigated under dry rolling contact with applied sliding traction /4/. Wear tests were carried out at room temperature and normal atmospheric humidity, using a SAE type machine (two wheels in a rolling contact line). The normal load of 200 kg was applied via a spring. Each specimen wheel was 50 mm in diameter and 10 mm thick /4/. The upper specimen rotated at a surface speed of 0.9 m/s, the lower specimen at 1 m/s. Wear test specimens were machined and ground to $R_a = 0.6$ μm surface finish.

4. ASPECTS OF THE PLASMA NITRIDING HEAT TREATMENT

Initially the test material was hardened and tempered and its mean hardness was 310 HV. The En40B steel was characterized by the following composition (wt%): 0.27 C; 0.08 Si; 0.50 Mn; 0.18 Ni; 3.21 Cr; 0.5 Mo /2/. The test specimens were compared for four initial states: unnitrided, nitrided at 420°C for 10 h, nitrided at 500°C for 2.5 h, nitrided at 500°C for 10 h and nitrided at 500°C for 35 h /4/. The *in situ* plasma nitriding conditions were: p = 3mbar, 25% N_2 + 75$ H_2.

5. ASPECTS OF THE SUPERFICIAL WEAR STRENGTH OF THE PLASMA NITRIDED SAMPLES

Figure 7 shows the variation of the hardness profile with time and temperature. Figure 8 summarises the wear curves obtained for various specimens. The accumulated wear was measured

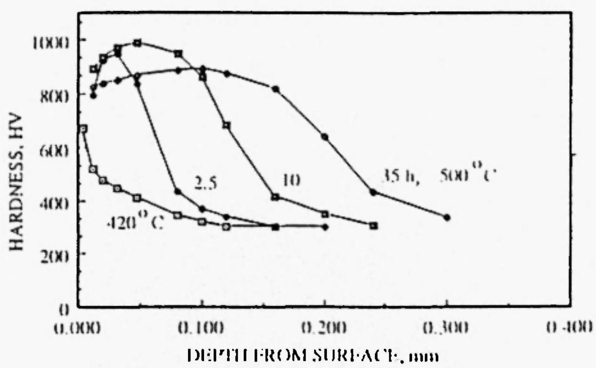


Fig. 7: Hardness profiles of specimens nitrided at 500°C for 2.5 and 3.5 h and at 420°C for 10 h.

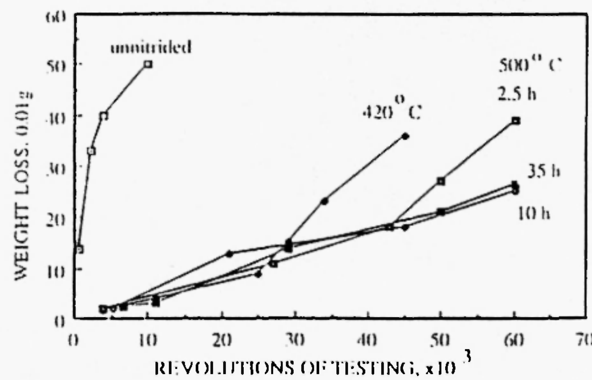


Fig. 8: Wear curves for unnitrided and nitrided specimens.

using a balance accurate to 0.001g /4/. Examination of the metallographic sections, following different working periods, gives a conclusive picture of the superficial zone where the fatigue micro-cracks start /3/.

Microsections parallel to the rotating direction and normal to the surface revealed that a shear or plastically deformed zone, ≅ 200 μm in thickness, had developed near the surface in the unnitrided steel case /3,4/ (Fig. 9 a,b).

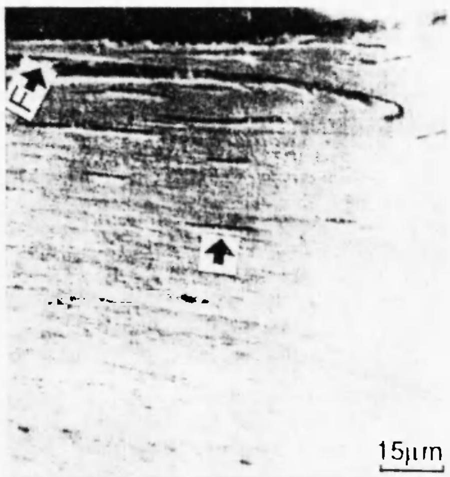
The test specimens nitrided at 500° for 2.5 h displayed cracking in the nitrided case. Also, shearing of the matrix just beneath the nitrided case was observed as indicated by the elongation of the non-metallic inclusions (see Fig. 10). Specimens nitrided at 500°C for 2.5 h and at 420°C for 10 h showed identical results.

When the test specimens were plasma-nitrided at 500°C for 10 and 35 h to produce strong, thick layers on the surfaces, the wear resistance of the steel was substantially improved. Shearing was limited to a near surface zone, 10 μm thick /4/ (see Fig. 11). As a result, oxidation wear dominated the wear process. Therefore, it is necessary that the substrate have sufficient strength to support the oxide films formed during the wear process by frictional heating /10/.

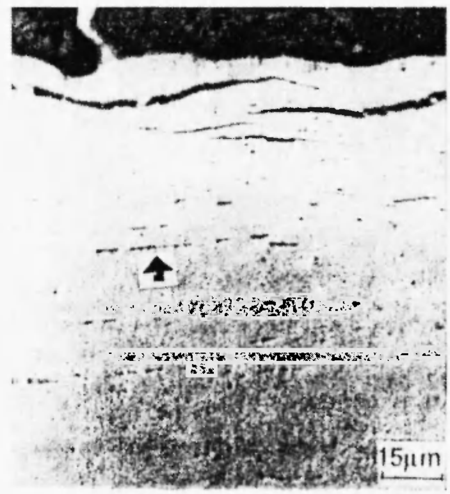
Fig. 12 shows the shear yield strength profiles of nitrided specimens and the shear stress profile induced by the applied normal load of 200 kg and the frictional tangential force of 0.6 x 200 kg /4/.

Fig. 13 represents the effect of residual stress on the shear stress profile induced during pure rolling contact with Q = 200 kg load and F = 0; τ'_{max} results from both the applied force and residual

Fig. 9: Metallographic sections of worn unnitrided specimens (tested under 200 kg load for 20,000 revolutions).



9.a. Upper wheel cut parallel to rotation direction /9/.



9.b.: Upper wheel cut normal to rotation direction /9/.

Fig. 10: Metallographic section of worn specimen nitrided at 500°C for 2.5 h (after 60,000 revolutions) /4/.

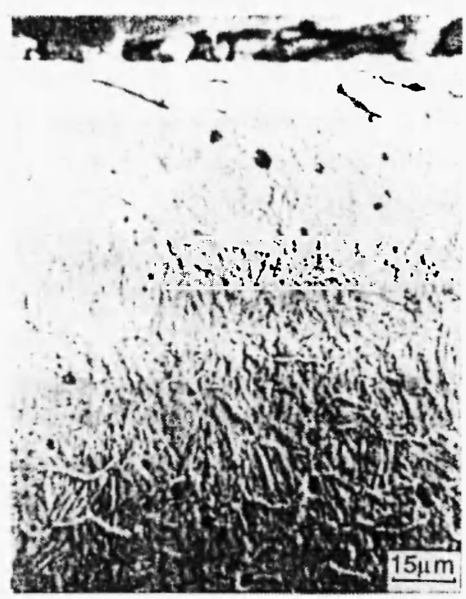


Fig. 11: Metallographic section of worn specimen nitrided at 500°C for 35 h (after 80,000 revolutions) /4/.

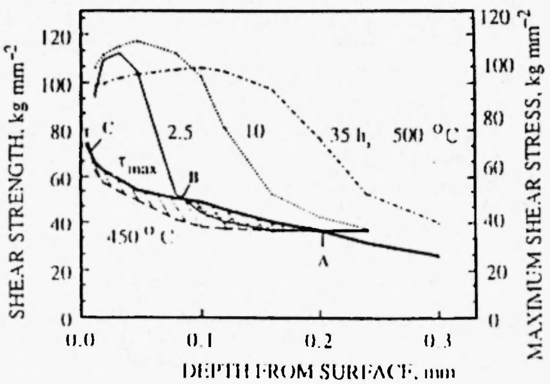


Fig. 12: Shear yield strength profiles of nitrided specimens and shear stress profile.

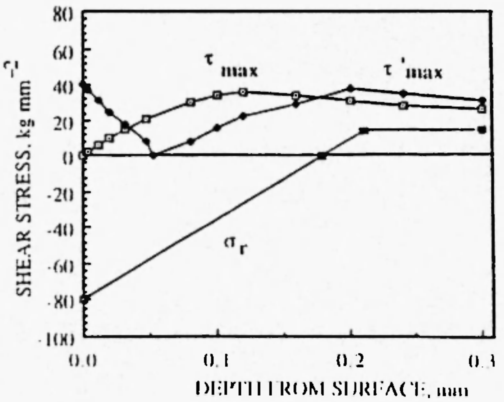


Fig. 13: Effect of residual stress on the shear stress profile.

stress /9/.

Under a pure normal force, the shear stress on the contact surface is zero. It increases with increasing distance from the contact until a peak value is reached at z = 0.786b. Under the influence of residual-compressive stress σ_R, the shear stress in the near surface zone is increased. Further into the subsurface, the shear stress is reduced until the unnitrided core is reached, where the tensile residual stress increases the resultant shear stress.

6. CHARACTERIZATION OF PVD - TiN TREATED En40B STEEL

TiN coating of the test samples was carried out by employing a commercial Balzers ion plating process at 500°C (measured using an infrared pyrometer) /2/. Prior to coating, the sample surfaces were cleaned and modified by dry micro-blasting (R_a = 0.4).

Experimental results demonstrated that the "TiN coating - nitrided substrate" combination can be optimised by proper process control and the composite possessed superior metallurgical and mechanical properties over the nitrided steel and the "TiN coating - unnitrided steel" composite /3/.

Figures 14a and 14b show the TiN coatings deposited on the nitrided surface with and without a compound (iron nitride) layer, respectively. In the case where the iron nitride layer formed during nitriding was not removed prior to coating (using a slight grinding process), a "black" layer about 1.5 μm thick was observed between the TiN coating and the iron nitride layer in the composite (Fig. 14a).

When the iron nitride layer was removed or the specimen was bright-nitrided prior to coating, no "black" layer was observed in the composite /3/ (Fig. 14b).

Microhardness measurement revealed that the "black" layer had a relatively low hardness (400-500 HV). In conjunction with the X-ray diffraction results, which showed that the "black" layer

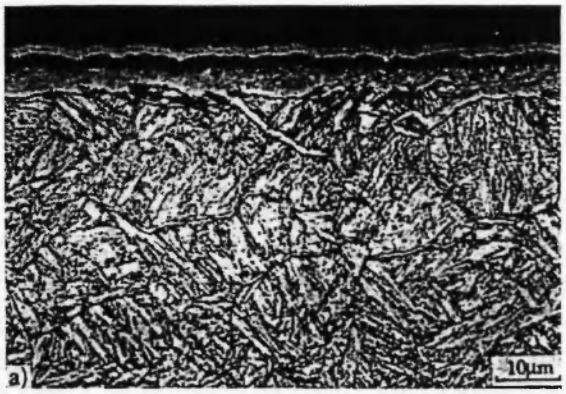


Fig. 14a: The compound iron nitride layer was not removed prior to coating /3/.

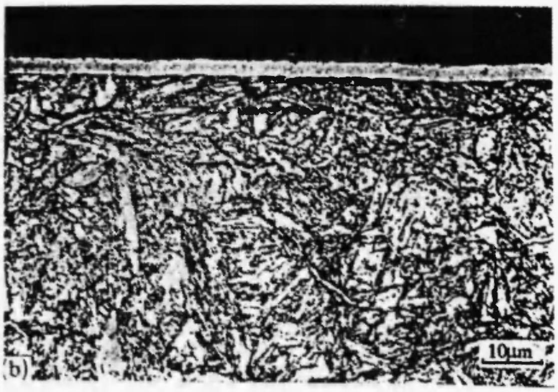


Fig. 14b: The compound iron nitride layer was removed prior to coating /3/.

comprised mainly α-Fe, it can be concluded that the "black" layer was the product of decomposition of the outer part of the iron nitride layer during the ion-plating process, which led to the transformation of Fe_4N and $Fe_{2\text{-}3}N$ to α-Fe. It should be noticed that the "black" layer deteriorates the coating-substrate adhesion. It should therefore be eliminated.

7. ASPECTS OF THE WEAR BEHAVIOUR AND LOAD-BEARING CAPACITY OF THE COATED LAYERS

The tests were carried out under the same conditions as the plasma nitriding, but the normal load was varied. Tests of the load-bearing capacity of "TiN coating" were carried out under the typical conditions of Fig. 16. Figure 15 shows the wear curves obtained under an applied load of 50 kg.

Figure 16 shows the wear volume-applied load curves for various specimens. The wear volume of the as-nitrided specimen increased gradually with increasing applied load. Nevertheless, for each investigated TiN coating-substrate composite system there existed some critical load above which the coating failed catastrophically, leading to an abrupt increase in the wear rate by several orders of magnitude /1/.

The "TiN-unnitrided substrate" combination had the lowest load-bearing capacity among all the combinations tested, obviously owing to the relatively low strength of the unnitrided substrate. When a TiN coating was deposited on a nitrided surface, the coated composite exhibited much higher load-bearing capacity than the TiN coating on the unnitrided substrate, with the "TiN-nitrided case" combination having the highest load-bearing capacity.

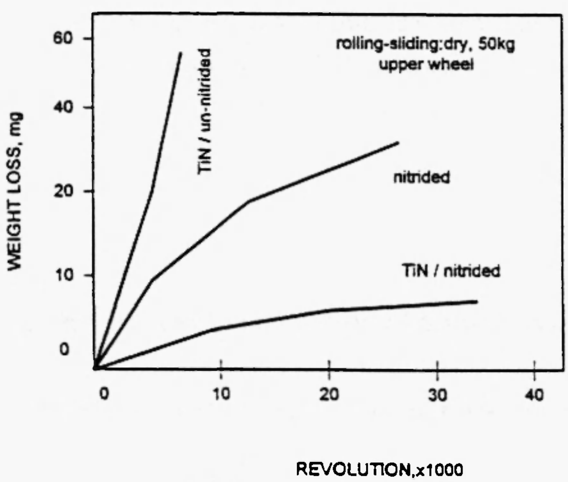


Fig. 15: Wear curves generated for the nitrided and TiN coated samples under a load of 50 kg. The lower wheels were plasma-nitrided in all the tests.

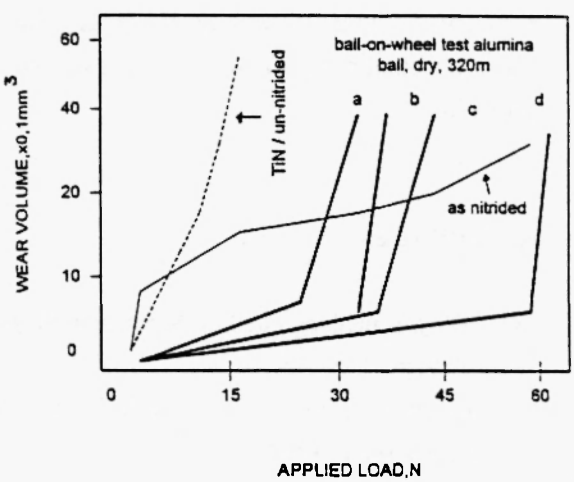


Fig. 16: Wear volume applied load curves for various coating-substrate combinations: a. TiN-black layer (1.5 μm thick); b. TiN-black layer (0.9 μm); c. TiN-iron nitride; d. TiN nitrided case combination /4/.

8. CONCLUSIONS

Plasma nitriding substantially improves the wear behaviour of low-alloy steels. The degree of improvement depends on the depth and strength of the nitrided case.

In the rolling-sliding line contact case, the wear of the unnitrided steel is caused by intense shear deformation at the surface and in the subsurface. Shallow case nitrided steel cannot bear the applied load effectively; shearing occurs in the case/core transition zone or even in the nitrided case. Increasing the nitrided case depth and strength effects an increase in the load-bearing capacity, so that wear occurs in a mild mode.

The surface modification of low-alloy steel via plasma surface engineering substantially improves the fatigue and wear behaviour as well as the load-bearing capacity of the steel. It is anticipated that the TiN coating deposited on the nitrided surface would have no influence on the fatigue behaviour of the composite. Eventually, the fatigue strength only depends on such properties as depth and residual stresses of the nitriding case.

On the other hand, a thin ceramic coating (TiN) deposited on the nitrided surface provides superior wear resistance that cannot be obtained by either individual plasma nitriding or PVD ceramic coating on the unnitrided surface.

It is essential to control the plasma-nitriding, surface preparation and ion-plating processes so that a composite with a TiN coating of high hardness, a sufficiently thick nitrided case and a "TiN-nitrided case" combination is produced, ensuring that the wear resistance and load-bearing capacity are optimised.

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