Mechanics Transport Communications

ISSN 1312-3823 (print)
ISSN 2367-6620 (online)
volume 23, issue 3, 2025

Academic journal http://www.mtc-aj.com **article № 2760**

ON DETERMINING THE WEAR RESISTANCE OF DIFFUSION LAYERS

Ilia Zumbilev
zumbilev@mail.bg

Technical University of Sofia – Branch Plovdiv, BULGARIA

Abstract: *The present study aims at making a geometrical and force analysis of the kinematic scheme of a test stand for determining the wear resistance of nitrided and carbonitrided layers by means of a rotating sphere.*

Based on the obtained results, it was established that the tilt angle of the sample with respect to the rotating sphere (α) can reach up to 55° and depends on the distance between the sample and the rotating shaft. The wear resistance of the diffusion layers was studied, locating the sample at an angle α = 30°.

The results show the positive influence of the processes of ion nitriding and carbonitriding on wear resistance. Depending on the angle of location, the modes of carbonitriding the chemical composition of the sample and its wear resistance vary in different limits.

Key words: *wear resistance, kinematic scheme, diffusion layers*

1. INTRODUCTION

Wear resistance is an important operational parameter of coatings, which predetermines their wide application in industry. The coatings, formed on the surface, are most frequently with low thickness (electroplating and varnish coatings, and diffusion layers, are between 2 and 600 μm thick, PVD and CVD coatings – between 0.5 и 10 μm) which requires higher accuracy when determining their wear resistance.

The main factors, having an impact on wear resistance, can be divided into technological. constructive and operational [1,2]. The technological factors include the structural and the chemical, physical and mechanical properties, while the constructive ones are the contact scheme, the macro- and micro- geometry of the friction surfaces, the lubrication scheme etc. The operational factors are the relative sliding speed, relative load, temperature mode and lubrication. The surface layer, formed during friction, is characterized by increased free energy, physical and chemical activity, and also by certain mechanical properties. It is the layer, on which the mechanism of contact interaction and the level of destruction from friction depend. When the materials rub, the so-called frictional anisotropy occurs, i.e. the coefficient of friction depends on the orientation of the rubbing surfaces with respect to the different crystallographic planes. It has been established that the adhesion, and the coefficient of friction depend on the type of the crystal lattice. Materials with hexagonal lattice have a reduced adhesion, a small coefficient of friction and higher wear resistance compared to the metals, whose crystal lattice is either body-centered (BCC) or wall-centered (WCC). It has been proved that with the decrease of the coefficient of linear expansion and of the Jung modulus E of the materials, their wear resistance increases [2, 3, 5].

Different weight methods have been used to determine the wear resistance of thin coatings, such as Pin on Disc, Cylinder on Disc I Taber Test. However, a common disadvantage of these methods is that despite of determining the worn mass of the coatings by means of high accuracy electronic scales (of 1x10 -5g order), an error in measuring appears, which often exceeds 10%. With the existing devices of the companies BAQ – kaloMAX NT and CSM instruments – CALOTEST, used for determining the wear resistance of thin coatings, a significant problem is to establish the angle between the sample and the hard roller in the scheme hard roller – plane [8, 9].

This work aims at making a geometrical and force analysis of the kinematic scheme of a test stand for determining the wear resistance of nitrided and carbonitrided layers by means of a rotating sphere.

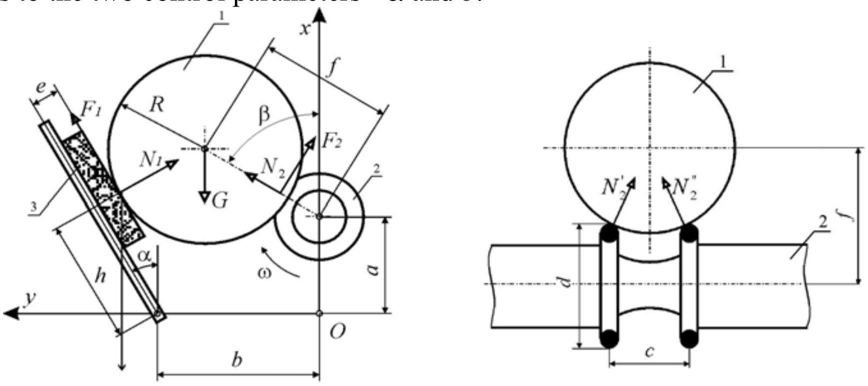
2. EXPERIMENTAL

Geometrikal and force analysis of the kinematic scheme of the stand

By its very nature, in the proposed kinematic scheme of operation on the stand (Fig. 1), the sample (3) is rigidly fixed and oriented with its coating up. A steel sphere (1) is placed on the rotating shaft (2), and driven by it. The sphere, while rotating in place, performs abrasive friction by sliding at one point on the test coating, wearing it away. The compressive force of the sphere on the coating during wear is constant and is determined solely by the weight of the sphere, with no additional external load applied.

The design parameters in the given scheme, which cannot be changed are [9]:

- *a* – height of the axis of the driving roller;
- *d* – diameter of the driving shaft;
- *c* – distance between the driving parts of the shaft;
- *e* – distance between the plane, passing through the axis of rotation of the plate and the surface of the sample. This parameter is considered conditionally constant, since its change can be accounted for by adjustments to the two control parameters - α and *b*.



a b

Fig. 1. Diagram of the working mechanism of the stand for determining wear resistance [9]

The control parameters in the proposed scheme can be: α – tilt angle of the sample relative to the vertical; b – distance between the vertical plane, passing through the axis of the rollers and the axis, relative to which the plate, fixing the sample, rotates; R – radius of the sphere. It changes discretely and a sphere with a diameter of 30 mm is considered in the present work.

The objective of the geometrical analysis of the mechanism is to determine the following parameters: the distance between the axis of the plate movement and the point of contact between the sample and the sphere – h; the angle between the plane, passing through the axis of the driving rollers and the vertical – β; the distance between the axis of rotation of the rollers and the center of the sphere – f.

The following ratios are derived to determine the listed parameters:

(1) $$\sin(\alpha-\beta)=\frac{R+e-(a\sin\alpha+b\cos\alpha)}{f}$$

(2) $$h=a\cos\alpha-b\sin\alpha+f\cos(\alpha-\beta)$$

(3) $$f=\frac{d}{2}+\sqrt{R^2-\left(\frac{c}{2}\right)^2}$$

Fig. 1a shows the load of the mechanism, where the active force is the weight of the sphere denoted by G.

Sliding occurs at the point of contact between the sample and the sphere and the frictional force is proportional to the normal force N_1 with a coefficient of sliding friction μ_1.

There is no sliding at the points of contact between the drive shaft and the sphere, and the traction forces are determined by the condition of the angular velocity of the sphere being constant:

(4)

$$F_2 = F_2' + F_2'' = F_1 \frac{2R}{\sqrt{4R^2 - c^2}}$$

The limiting value of the frictional force at rest is proportional to the normal force with a proportionality factor μ_2.

The conditions for equilibrium of the sphere involve the sum of the two normal forces, which is conventionally denoted as N_2:

$$N_2' = N_2'' = N_2 \frac{R}{\sqrt{4R^2 - c^2}}$$

(5)

The following condition must be fulfilled in order to avoid sliding between the surface of the sphere and the rollers:

$$F_2 < N_2 \frac{2\mu_2 R}{\sqrt{4R^2 - c^2}} \Rightarrow F_1 < \mu_2 N_2$$

(6)

From the equilibrium conditions of the sphere (Fig. 1), the following correlations for the normal forces at the two contact points are obtained:

(7) $$N_1 = G \frac{\sin\beta}{\cos(\alpha - \beta) + \mu_1 \left[1 - \sin(\alpha - \beta)\right]}$$

(8) $$N_2 = \frac{N_1}{\sin\beta}\left[\cos\alpha - \mu_1\left(\sin\alpha - \cos\beta\right)\right]$$

When determining the dependence of the normal force N_1 on the control parameters and the range, in which they can change, the following restrictions are used [9].

The dependence below must be satisfied to have a solution to (1):

(9) $$\frac{R + e - \left(a\sin\alpha + b\cos\beta\right)}{f} \le 1$$

Fig. 2b shows the permissible ranges of the control parameters for 30 mm diameter of the sphere. In the admissible area (1), different values of the normal force N_1 are indicated, and to the right of the graphs, their values in N.

From Fig. 2 it can be noted that as the diameter of the steel sphere increases, the value of the normal force N1 increases (0.7-2.4 N).

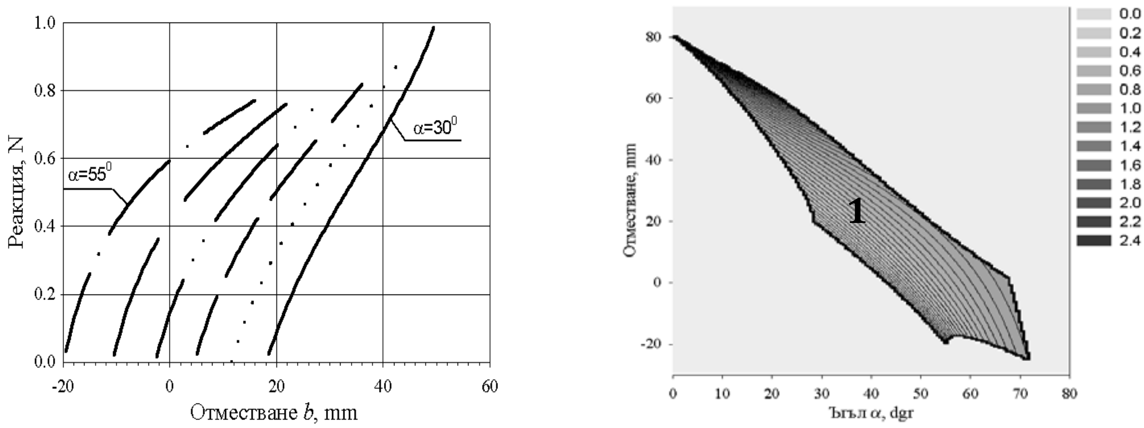
The results of the dependence between the normal force and the displacement b (at fixed values of the tilt angle of the sample, which changes every 50mm), are given in Fig. 2a. It can be seen from them that the greater the displacement of the sample b relative to the rotating shaft, the smaller the angle of inclination. It also depends on the diameter of the steel sphere. The smaller its diameter, the smaller the angle of inclination of the test sample, reaching the value of 20°,

Wear resistance of the layers

All wear tests of the base material and the layers were carried out under the same conditions, namely: revolutions of the stand shaft – 700 rpm; 30 mm in diameter steel sphere, made of heat-treated bearing steel 100Cr6, DIN17350, with 2-µm-thick TiN coating and hardness HV=21GPa; sphere revolutions – 373 rev/min; angle of location of the sample α = 30°; test time 3 min; abrasive material - diamond paste with size of the particles 0.25 µm.

The degree of wear is determined by the worn volume of the layer V_{wear}. For this purpose, the diameter d of the obtained wear imprint in the layer is measured by means of a metallographic microscope with a suitable magnification x 200. For the worn volume of the layer V_{wear}, expressed by the radius of the used sphere R and the radius of the worn section r, the following dependence is obtained:

$$V^{wear} = \pi \left[\left(R - \sqrt{\left(R^2 - r^2\right)}\right) \right]^2 . \left[\mathbf{R} - \frac{R - \sqrt{\left(R^2 - r^2\right)}}{3} \right], mm^3, \quad V^{wear} = \frac{V_{core}^{wear} - V_{layer}^{wear}}{V_{core}^{wear}} .100\%$$



a) b)

Fig. 2. Diameter of the sphere 30 mm

Materials and metallographic research

Armco iron (99.8%) was the material, subjected to testing. Test samples with dimensions 15 x 15 x 10 mm were made of it. The test samples were ground to surface roughness Ra = 0.63 µm.

Then they were nitrided and ion-carbonitrated in the "Ion-20" installation under the modes, given in Table 2. Ammonia (NH3) and corgon gas (82% Ar and 18%CO2) were used as saturating gases. The temperature of treatment was 550°C.

To clarify the morphological features of the nitrided and carbonitrided layers metallographic analysis was made. A microscope – Axioskop – was used to determine the structure and thickness of the obtained layers.

The thickness of the nitrided and carbonitrided layer is determined by the depth to which a microhardness, equal to the core plus 50, is achieved. The microhardness measurement for the obtained layers was carried out with a Leitz microhardness tester with a load of 0.98 N (100 g), by the Vickers method. The sections for examination were developed with a 3% solution of nitrogen acid in ethyl alcohol.

3. RESULTS FROM AND DISCUSSION ON THE WEAR RESISTANCE TESTS

The maximum surface hardness HV0.1 and the total thickness of the carbonitrided layer δ_{tot} were determined by measuring the microhardness of the ion nitrided and carbonitrided steel in-depth. With the help of a metallographic microscope, the thickness of the combined zone δ_{cz} was determined. The obtained results are given in Table 1.

Depending on the mode of carbonitriding, the wear resistance of the test samples varies within different limits. The results in Table 1 show the positive influence of the process of ion carbonitriding on the wear resistance of Armco iron.

After ion-carbonitriding of Armco-iron under the following mode: temperature 550°C, treatment duration 2h, ammonia pressure P1= 350Pa, corgon pressure P2 = 350Pa, a smaller wear depth h= 4.2µm and worn layer volume V_{wear} = 0.000813mm3 were obtained – Table 1. The resulting carbonitrided layer has a microhardness of 540HV0.1 and a combined zone thickness of 4µm.

During the test with Armco-iron, the sphere penetrated to a depth of 4.2µm into the carbonitrided zone, and this depth is approximately equal to its thickness. The greatest achieved increase in Armco-iron wear resistance, reaching up to 52%, was only observed with a specific mode of treatment out of all modes of ion-carbonitriding.

Table 1. **Armco - iron wear results**

$P1_{NH3}$, Pa	P2, corgon, Pa	P_{total} Pa	τ_{tot} h	$HV_{0.1}$	δ_{cz} µm	δ_{tot}. µm	r mm	h µm	V_{wear}, mm 3	V_{wear} %
360	40	400	2	430	6	220	0.400	5,3	0,0013401	23
280	120	400	4	480	7	280	0.410	5,3	0,001211	30
400	-	400	2	380	6.5	260	0.390	5.1	0,0013401	23
350	350	700	2	540	4	210	0,355	4,2	0,0008313	52
-	-	-	-	80	-	-	0.428		0,0017410	-

P1- ammonia pressure,Pa
P2- corgon pressure,Pa
Ptotal- total pressure,Pa
HV- surface hardness,
δcz- thickness of the combined zone area, µm
r - radius of the worn section ,mm
h - depth of the worn section, mm
V^{wear} - the worn volume of the layer, mm^3
δtot- total thickness of the carbonitrided layer, µm

This can be explained by the high hardness of the layer and the large amount of carbon dissolved in the ε-carbonitride, which has a hexagonal lattice and a lower coefficient of friction than the other phases. The uniform distribution of carbon and nitrogen in the combined zone also has a positive effect (Fig. 3 b)

In the diffusion zone of the formed carbonitrided layer, separations are observed (Fig. 3a), which are smaller in size and in greater amount than those obtained at 90% NH3 and 10% of corgon and larger, but in a smaller amount when carbonitriding with 50% NH3 and 50% of corgon. This is probably due to the diffusion of carbon also in the diffusion zone of the carbonitrided layer.

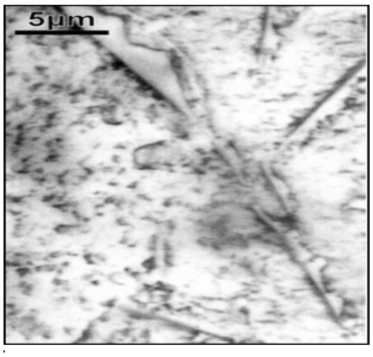
For all modes of Armco-iron ion-carbonitriding the formed layers have a higher surface microhardness than those, obtained after ion-nitriding. In all modes of ion-carbonitriding, higher wear resistance of Armco-iron is observed than after its ion-nitriding. This can be explained by the deposition of a larger amount of carbon on the surface, which probably leads to the formation of a hexagonal ε-carbonitride.

The existence of a large concentration difference between the carbon, deposited by the plasma, and the existing carbon in the technical iron (0.02% C), leads to the deposition of a larger amount of carbon on the surface and an increase in the diffusion of nitrogen in depth, as a result of which increased amount of carbonitride separations are observed in the diffusion zone.

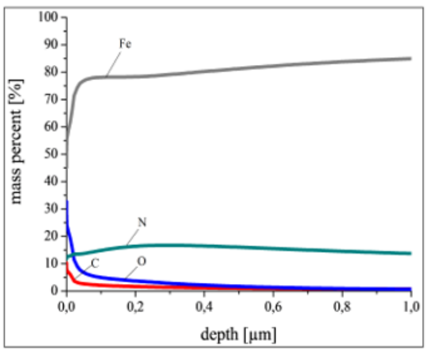
4. CONCLUSIONS

On the basis of the conducted study, the following conclusions can be drawn up:

- It has been found that the tilt angle of the sample relative to the rotating sphere reaches up to 55° and depends on the distance between the test sample and the rotating shaft.
- It has been proven that the constructed stand can be used in determining the wear resistance of nitrided and carbonitrided layers.
- It has been found that, for the same tilt angle (α), the increase in the diameter of the sphere leads to a decrease in the distance between the sample and the rotating shaft (b),



a)



b)

Fig. 3. Microstructure (*a*) and distribution of carbon (C) and nitrogen (N) in-depth after carbonitriding of Armco - Fe P1NH3 = 350Pa, P82% Ar + 18% CO2 = 350 Pa (*b*)

REFERENCES:
[1] T. LAMPE: Plasmawärmebehandlung von Eisenwerkstoffen in stickstoff-und kohlenstoffhaltigen Gasgemischen, VDI-Verlag GmbH, Düsseldorf (1985).
[2] P. FISHER-CHATTERJEE, W.EYSELL: Nitrieren und Nitrocarburieren, Sindeifingen, Expert Verbag, (1994).
[3] W.SEDEL: Werkstofftechnik. Carl Hanser Verlag, Munchen, (2005).
[4] D. PYE: Practical Nitriding and Ferritic Nitrocarburizing, ISBN, ASM International Materials Park, Ohio (2003).
[5] A. ZJUMBLLEV, I ZJUMBLLEV: Influence of the Nitrided Zone Over the Wear Resistance of Ion-Nitrided Steels. Proceedings fo the 25th ASM International Heat Treating Conference, Indianapolis, Indiana, September 14–17, 2009, USA, pp. 47-54.
[6] F.CZERWINSKI: Heat Treatment—Conventional and Novel Application, Janeza: InTech, (2012).
[7] Y. KAYALI: Wear and Corrosion Behaviour of Borided and Nitrided M2 High Speed Steel, Journal of the Balkan Tribological Association, 19 (3), pp.340–353 (2013).
[8] F.LOFLERL: Methods to investigate mechanical properties of coatings, Thin Solid Films 339 (1999) p. 181-186.
[9] A. ZJUMBLLEV, D. RUCHEV: Geometrical and force analysis of a stand for testing coatings. Journal of the Technical University of Plovdiv "Fundamental Sciences and Applications", Vol. 16, 2011, pp. 61-64.