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ESTABLISHING THE ROLLING - FRICTION COEFFICIENT FOR DIFFERENT CONTACTS BETWEEN BALLS AND TERMOCHEMICALLY TREATED STEEL ROLLING PATHS

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ABSTRACT

Within the frame of this work, the influence of four very well-known and often used thermochemical treatments (carburizing, carbonitriding, nitriding and nitrocarburizing) of steel rolling paths applied on rolling-friction coefficient has been studied. The rolling - friction tests supposed different arrangements of the semi-couples (plates) and intermediary balls. Because of the difficulty in estimating the value (dimension) of the rolling friction coefficient, an equivalent static friction coefficient μ_0 (at the start) was established for all the couples. According to the experimental results of this study, the carburized rolling paths seemed to offer the best conditions for rolling, the initial move appearing at the earliest. In addition, the presence of nitrogen and the possible Fe_xN compounds on the contact rolling surface leads to an increased friction coefficient μ_0. Finally, the study demonstrated that there is a slight tendency for a certain decrease in μ_0 when increasing the intermediary balls diameter.

KEYWORDS: rolling-friction coefficient, rolling-path, steel, ball, carbon, nitrogen

1. Introduction

1.1. Rolling – contact theoretical aspects

Bearings and gears commonly exhibit Hertzian point or line contacts when operated under rolling or rolling/sliding conditions. Even for constant loads, the rolling motion produces a variable superficial state of efforts characterized by normal and tangential-shear stresses.

The difficulty of researching into this kind of contacts is further increased by the presence of lubricants [1]. Thus, in this type of study several factors such as: load, speed, rolling-sliding ratio (if the sliding exists), lubricant presence and quality, surface topography etc. must be considered.

Generally, contact micro surfaces and higher pressures in the contact zones characterize the Hertzian rolling contact cases. Therefore, surface deformations must be taken into account. The appearance and evolution of surface fatigue phenomena have been theoretically explained in the literature using the *space stress state condition* and the models of Hertz and Boussinesq [1-3].

In this kind of contacts, wear processes of hardened steel surfaces usually occur in a mild way, in comparison with the unhardened surfaces. The Hertzian contacts are characterized by the appearance of a typical "material wave" on the rolling guide path, in front of the rolling body (ball or roll) [1-3]. Depending on the rolling-surface qualities and rolling body dimensions as well, this wave could be more or less important in size. Its appearance has an important role in rolling the rolling contacts because it leads to the development of a rolling-friction moment. This moment is in opposition with the rolling motion and plays an important role not only in the motion but also in the start-move.

If we consider a rolling contact in which the ball is harder than the rolling plane surface, an indentation cup on the contact zone will appear. This phenomenon leads to a specific material accumulation not only in front of the contact (where it is more consistent) but also behind the contact (see Fig. 1).

Very often, the practical physical explanations of the rolling-friction process take into account the plastic deformations appearance in the contact zone [1].

In fact, the rolling-friction process is characterized by a typical friction torque which gives a specific rolling - friction moment M_{rf}.

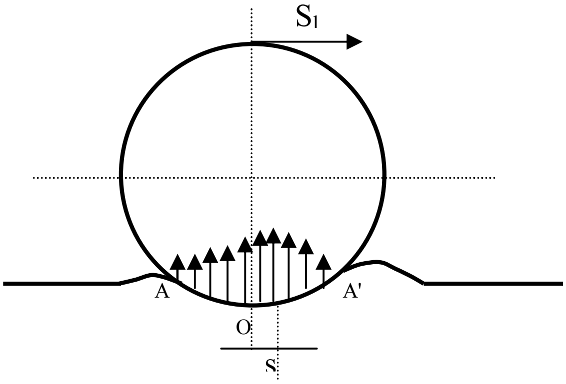


Fig. 1. Schematic arrangement of a Hertzian punctual contact in plane coordinates; W – ball weight, N – result of typical force-reaction distribution on the contact zone AA', s – the reaction force's arm, S_l– the ball's linear speed

According to Fig. 1, the reaction force N on the AOA' section is given by an infinity of elementary forces. The general force-moment of these elementary forces related to the theoretical contact point O is the rolling friction moment M_{rf}. These elementary reaction forces are not symmetrically distributed. Thus, in front of the contact, where more material is concentrated, the reaction forces are stronger. Owing to this reason, the elementary reaction forces result - N, generates the moment M_{rf}, which is opposite to the rolling sense of the ball [1]. The practical research discussed in the literature shows that for an equilibrium state, the value of this moment must be lower than a certain maximum value, as follows:

$$M_{rf} \leq s \cdot N \tag{1}$$

In relation (1), s represents the rolling-friction coefficient. In comparison with the well-known sliding friction coefficient μ which does not have a dimension, the rolling-friction coefficient s has a slight dimension which is very difficult to measure. It represents the maximum displacement distance of the normal reaction support N compared to the theoretical contact point O (see Fig. 1).

For static equilibrium conditions, (if we consider the rolling body harder than plane path support), when the rolling body (ball or role) is not moving and the rolling plane surface is in a perfectly horizontal position, the accumulation of material is symmetrically distributed in front and behind the ball. However, for very little inclinations of the plane support, at rolling-move initiation, because the rolling-friction coefficient s is very difficult to measure, the friction phenomenon can be evaluated considering ***the equivalent (conventional) sliding-friction coefficient μ_0 at the start*** (see Fig. 2).

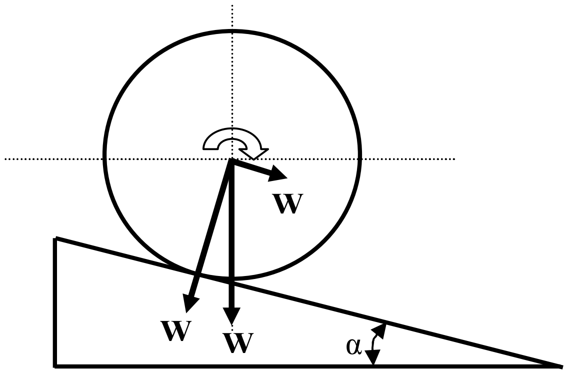


Fig. 2. Schematic arrangement of rolling on an inclined plane (the ball weight and its components on normal and tangential directions)

Thus, it is known that for the ball displacement guide paths, the necessary start-moving force of the mobile half-couple is bigger than the dynamic force which keeps the displacement-motion. In these conditions, the start-moving force can be estimated to be equal to the normal component (W_n) of load W multiplied by the equivalent friction coefficient μ_0 (see Fig. 2).

1.2. Diffusional thermochemical treatments

In practice on the other hand, there are certain applications in which this kind of contacts appears very often. One of the most important contacts refers to the case of bearings. For bearings manufacturing an alternative variant used in terms of materials is the replacement of the traditionally hypereutectoid bearing steels (e.g. AISI 52100 with 1% wt. C and 1.5 wt. Cr) with other cheaper steels in which the percentage of carbon is under 0,3. In order to be able to sustain Hertzian-contact solicitations, these low carbon steels have to be improved on the superficial contact path-regions, by means of various thermochemical treatments. The most important ones are carburizing and carbonitriding.

As it is known, carburizing is the addition of carbon to the surface of low-carbon steels at temperatures generally between 850 and 950 °C, at which austenite, with its high solubility for carbon, is the stable crystal structure. Carbonitriding is a modified form of gas carburizing rather than a form of nitriding. Typically, carbonitriding is carried out at a lower temperature and for a shorter time than gas carburizing which produces a shallower case than the usual one obtained by carburizing [4-11].

In both cases, hardening is accomplished when the high-carbon surface layer is quenched to form martensite so that a high-carbon martensitic case with good wear and fatigue resistance is superimposed on a tough, low-carbon steel core.

These two superficial heat treatment variants are known in the field of heat-treating sector as high temperature thermochemical treatments and they always suppose each time a case hardening by quenching and low tempering.

There are also other practical applications which suppose certain mechanical properties in terms of high toughness for all bulk structure and this aspect supposes the use of heat-treatable steels for parts manufacturing. This means the use of steels with carbon content between 0.3 and 0.6 wt.%. These steels can offer, after the secondary bulk heat treatment, an excellent toughness to the part during dynamic work conditions. Very often, for this kind of steel-parts, in order to improve the superficial friction/wear properties, two successful variants of thermochemical treatments are used: the nitriding and the nitrocarburizing.

Nitriding is a surface-hardening heat treatment that introduces nitrogen into the surface of steel at a temperature ranging from 460 to 550 °C while it is in the ferrite condition. This is a thermochemical diffusion process where nitrogen, carbon, and to a very small extend oxygen atoms diffuse into the surface of the steel part, forming a compound layer at the surface, and a diffusion layer below. Nitrocarburizing is a shallow case variation of the nitriding process [4, 12-16]. Both procedures are performed mainly to provide an anti-wear resistance to surface parts and to improve fatigue resistance.

Although the rolling-friction contact has been studied very often in mechanics, there is not much information about the influence of a certain kind of rolling surface material on the evolution of rolling motion, especially in terms of the rolling-friction coefficient. Because of the difficulty to measure the rolling-friction coefficient, this paper tries to establish an equivalent friction coefficient value (at move-start) for different types of hertzian contacts (ball on carburized, nitrided, carbonitrided and nitocarburized plane steel surfaces) for rolling conditions.

2. Experimental aspects

2.1. The tribosystem

In order to establish the equivalent static friction coefficient value for all the sample combinations, a typical method such as the inclined plane was used. A home-made tribosystem, inclined – plane type (schematically shown in Fig. 3), have been used to estimate the friction coefficient value based on some typical linear size measurements [17-19]. Thus, according to Fig. 3, for a plane-contact area between two bodies (the base one being fixed) the correlation between the friction angle α and the friction coefficient μ is:

$$tg\alpha = \mu \tag{2}$$

The system allows a plane inclination of the friction couple (that is in a rest state), with variable angles, until the sliding phenomenon appears in the couple.

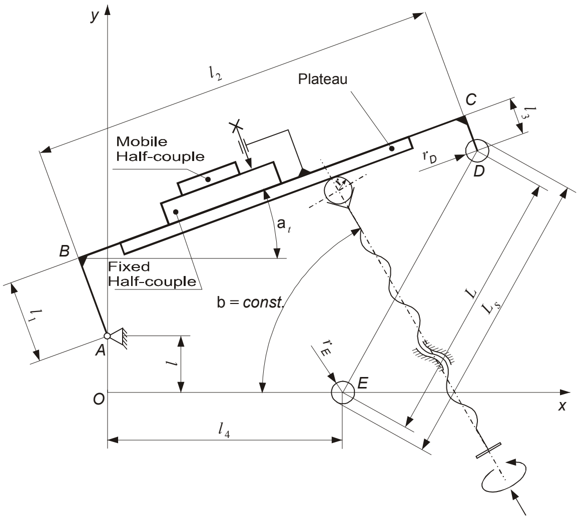


***Fig. 3.** The inclined plane tribosystem based on linear measurements (schematic arrangement)* [17- 19]

According to equation 2, the angular value $\alpha_{limit} = \alpha_0$ where the sliding appears (at the start moment), is in direct correlation with the static sliding-friction coefficient μ_0 at the start, according to:

$$tg\alpha_0 = \mu_0 \tag{3}$$

In order to test different pairs of half-couples on the system plateau it is possible to mount the driving (fixed) semi-couple by means of some clamping claws.

The lowering of the tribosystem driving plate *p* is achieved with a motion screw to which is fitted an inclined axis nut fillet, whose inclination is under 60°. The screw inclines the driving plate *p* through a ball *r*. The ball is situated inside a cone-shaped socket at the head in the screw. The driving plate *p* leans against the ball by means of a plane section which is perfectly parallel to the surface which the fixed semi-couple is placed on. The establishment of the driving plate p slope is given by the L_S size measurement (between the pins D and E which are characterized by r_D and r_E radius – Fig. 3) in accordance with a non-linear function [17-19]:

$$\alpha_0 = 2arctg\frac{-C_2+\sqrt{C_2^2-\left(C_1-L^2\right)^2+C_3^2}}{C_1-C_3-l^2} \qquad (4)$$

where:

$$L = L_S - r_D - r_E$$
$$C_1 = l_2^2 + \left(l_1 - l_3\right)^2 + l_4^2 + l_5^2$$
$$C_2 = 2l_4\left(l_1 - l_3\right) + 2l_2 l_5$$
$$C_3 = 2l_5\left(l_1 - l_3\right) - 2l_2 l_4$$

For practical applications, and for different values of L_s, the non-linear function values can be computer-assisted. Thus, in accordance with the measured length it is possible to find the static friction coefficient directly. The measurement of L_s, has been carried out by means of a digital micrometer.

2.2. The rolling-couples

In order to measure the equivalent friction coefficient (at start) by means of inclined plane method, special pairs of rolling-motion couples have been designed and manufactured (see Figures 5 and 6). In these rolling-motion couple systems, each semi-couple has a parallelepiped form, with 141x100x15 mm (see Fig. 4) and three identical longitudinal parallel V-guide paths on the rolling - friction surface.

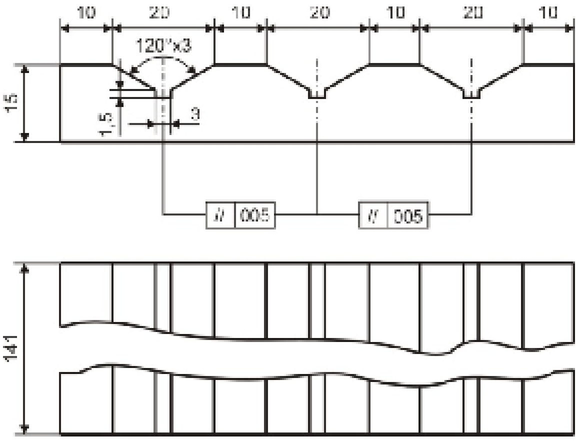


Fig. 4. *The schematic drawing of the semi-couples with longitudinal V-guide paths* [17, 18]

The rolling - friction tests supposed different arrangements of the semi-couples and balls (see Fig. 5a, b). In this configuration, the upper plate is moving on the lower one (stationary) by means of the identical three balls.

Thus, sets of three identical balls of different sizes have been used. They measure 8, 10, 12, 15.9, 18, 19.8, 22, 25 and 26 mm in diameter, are manufactured from ball-bearing steel (AISI 52100) hardened and low tempered and have a final hardness value of 63 HRC and final roughness $R_a = 0.04$ μm.

Fig. 5. (a, b) *Details on the rolling-contact elements: a) the set of 3 identical balls; b) the whole rolling couple*

Each rolling-friction couple was fixed in a perfectly horizontal position of start by means of a horizontal level dial-gauge on the tribosystem base plateau (see Fig. 6).

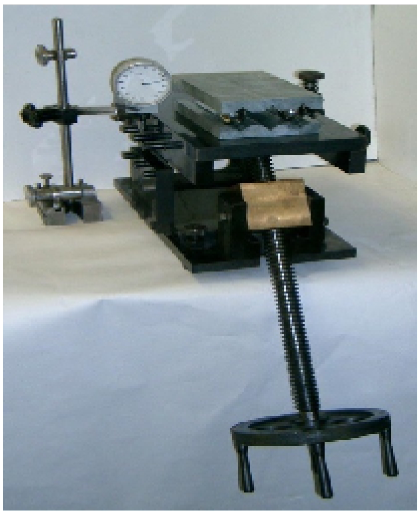


Fig. 6. *The rolling couple arrangement*

2.3. The contact surfaces: steels and thermochemical treatments

The steels used in the manufacture of the rolling-motion couples are: 5115 AISI case-hardening steel (0.17% C, 0.30% Si, 1.20% Mn, 0.90% Cr) and 4140 AISI heat-treatable steel (0.41% C, 0.30% Si, 0.70% Mn, 1.10% Cr, 0.20% Mo).

The lower (stationary) semi-couples were thermochemically treated. It is important to mention here that the upper-mobile semi-couple was the same in all the tests, being manufactured from 4140 AISI heat-treatable steel. This choice was made in order to prevent a possible influence of a small mass difference of the upper semi-couples on the rolling-friction tests. The experimental program supposed 6 couple variants for rolling-friction tests. Table 1 presents the steels used for preparing the six different lower semi-couples and the thermochemical treatments applied of the rolling paths.

Table 1. *The stationary semi-couple types used in the experimental program*

The lower semi-couple	Steel	The type of thermochemical treatment
A.	5115 AISI case-hardening steel	Carburizing
B.	5115 AISI case-hardening steel	Carbonitriding
C.	4140 AISI heat-treatable steel	Nitriding
D.	4140 AISI heat-treatable steel	Nitrocarburizing
E.	5115 AISI case-hardening steel (annealed state)	Without thermochemical treatment
F.	4140 AISI heat-treatable steel (tempered state)	Without thermochemical treatment

The carburizing and carbonitriding procedures were conducted in a gas-tight multi-purpose chamber furnace with an integrated double-walled oil quench bath and a mixture of endothermic atmosphere (90%) and CH_4 (10%), at 920^{o}C for carburizing and a mixture of endothermic atmosphere (85%), CH_4 (10%) and NH_3 (5%), at 870^{o}C for carbonitriding. In both cases, the carbon potential in the furnace chamber was kept at 1.1% and the maintaining period at the treatment temperature (in the main diffusion phase) was 7 hours for each treatment. After the thermochemical treatments, the samples were slowly cooled till 820^{o}C and then case hardened (from 820^{o}C) in oil-like quenching agent.

Finally, both types of samples were low tempered at 180^{o}C for 2 hours.

The gas-nitriding process supposed a single diffusion phase at 530^{o}C, for 20 hours in 50% NH_3 + 50% N_2 atmosphere, NH_3 dissociation rate $\alpha = 25\%$. The gas – nitrocarburizing treatment was conducted at 560^{o}C, for 5 hours in 50% endothermic gas + 50% NH_3 atmosphere, with NH_3 dissociation rate of 40%. Before nitriding and nitrocarburizing, the semi-couples were hardened (from 840^{o}C) in oil like quenching agent and high tempered at 550^{o}C for 2 hours. After tempering, the semi-couples were finely polished.

Two lower plates for each category of treatment type were used for the bottom (fixed) semi-couple. According to the description of this method 10 rolling-friction tests were performed for each variant: 5 in one direction and 5 abeam so that the one-way roughness should not influence the movement of the samples. 120 tests for each couple type and 1080 tests in total were performed for all the samples (taking into account the 9 sets of balls). In each case, the utmost values were eliminated.

The results discussed in section 3 represent these final average values. Before all the tribological tests, the semi-couples and the balls were first degaussed and then alkaline cleaned and wiped. The environmental conditions of the tribological tests were: T = 20.5^{o}C and 63% humidity.

2.4. The friction coefficient (plane contact) – parallel measurements

In order to have enough information on the influence of the surface material nature on the equivalent static friction coefficient value, small parallel parallelepiped samples (PS) were prepared. These samples were used to establish the static friction coefficient (plane on plane) in order to compare the friction tendencies both for rolling/plane and plane/plane contacts. Their dimensions were 20x10x5 mm, they were manufactured from ball-bearing steel (AISI 52100) which was next hardened, low tempered and fine-polished. These PSs were manufactured from the same material (steel) and had the same final hardness value and aproximativelly the same roughness as the balls. These tests were performed for each couple, between the PSs and the flat surface placed between two of the longitudinal V-guide paths and this resulted in the frictional movement being parallel to the longitudinal axis of this V-path. Except for the number of balls, the number of the tests in this case was the same as that in the rolling tests: 60 for all the couples.

2.5. Hardness and roughness measurements

The surface hardness values of the thermochemically treated surfaces were established by means of microhardness-equipment FM-700 at a load of 100 g (HV0.1). The roughness values of the surfaces were also established based on the profilometer method with a TR-220 portable roughness tester.

3. Experimental results and discussion

3.1. Equivalent rolling – friction coefficient

Figures 7, 8 and 9 present the equivalent rolling-friction coefficient values registered for all the couple types considered in the experimental program. The same conclusion is valid if we consider, for each type of rolling-contact couple, the medium value of friction coefficient reported to all ball sizes (Fig. 9a).

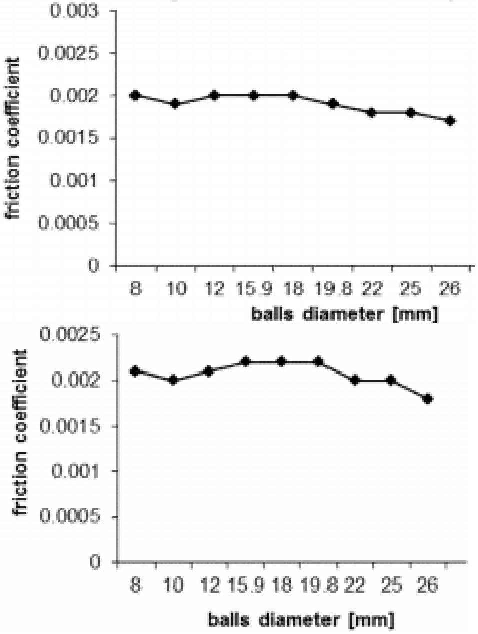
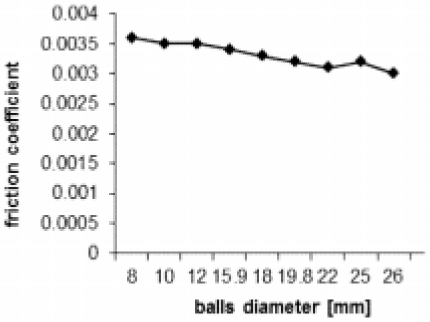


Fig. 7. (a, b) *The equivalent rolling-friction coefficient (average values) for different ball set sizes in contact with carburized (a) and carbonitrided (b) surfaces (A, B variants-Table 1)*



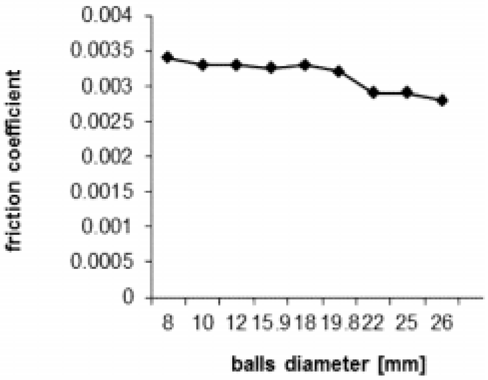


Fig. 8. (a, b) *The equivalent rolling-friction coefficient (average values) for different ball set sizes in contact with nitrided (a) and nitrocarburized (b) surfaces (C, D variants-Table 1)*

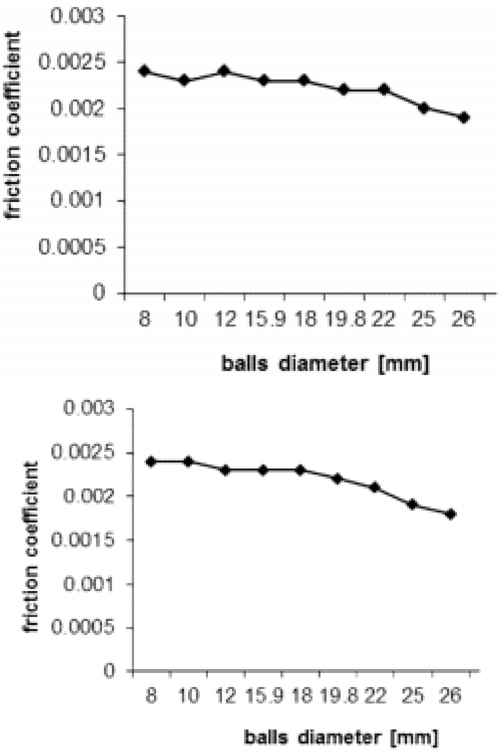


Fig. 9. (a, b) *The equivalent rolling-friction coefficient (average values) for different ball set sizes in contact with uncoated steels, 5115 AISI annealed conditions (a) and 4140 AISI hardened and high tempered (b) surfaces (E, F variants – Ttable 1)*

Although the input of nitrogen is not considerably related to carbon, in the case of high temperature thermochemical treatments like carbonitriding, its presence leads to a slow increasing tendency of the friction coefficient value.

These friction coefficient values are lower but almost comparable to the ones obtained for non-treated steel rolling paths. However, the major advantage for the carburized variants is the path’s hardness, considerably higher in comparison with the non-treated ones.

Regarding the rolling contacts on the nitrided and nitrocarburized paths, here the experimental results revealed the maximum values for the friction coefficient and a visible increase by comparison with the remaining variants.

3.2. Hardness, rolling-surface nature and roughness

Taking into account all the results related to equivalent friction coefficient, there are a few parameters that are worth mentioning and discussed here: firstly, the evolution of rolling-path hardness, secondly the nature of the rolling–path surface-material influenced by the thermochemical treatment and thirdly, the rolling–path surface roughness. All these three aspects have to be correlated to the experimental values registered for equivalent rolling – friction coefficients.

Table 2 presents the average experimental values of roughness R_a and Vickers hardness for all the sample categories, after removing the extreme values for each kind of measurement.

Table 2. *The roughness and micro-hardness ($HV_{0.1}$) values of the rolling-contact surfaces*

Sample surfaces	**Roughness average values** R_a [μm]	**Vickers Hardness (on surface top)** $HV_{0.1}$
Carburized rolling path (5115 AISI)	0.42	796
Carbonitrided rolling path (5115 AISI)	0.46	820
Nitrided rolling path (4140 AISI)	0.58	876
Nitrocarburized rolling path (4140 AISI)	0.52	588
Untreated steel (annealed steate) – 5115 AISI	0.56	348
Untreated steel (tempered state) – 4140 AISI	0.44	393

All hardness values of thermochemically treated paths are normal and comparable to others registered in different experimental or practical procedures involving these kinds of superficial treatments [5-11]. The hardness values registered for the high-temperature diffusion treatments (after case hardening and low tempering processes) are not very different, with a plus for carbonitrided surfaces. This aspect could be explained by taking into account the formation during the carbonitriding process of very hard and dense compounds, Fe(C,N) and Cr(C,N) types, which are known to be harder in comparison with the correspondent carbon compounds Fe-C and Cr-C.

Regarding the hardness, the nitriding process gives the steel surface the maximum value; these aspects are in accordance with other well-known results in terms of nitriding and they could be explained by taking into account the long diffusion time and the development of a very dense and hard compound layers zone (known in the nitriding practical applications as “the white layer”) – Fe_4N (the γ’ compound) and possible $Fe_{2\text{-}3}N$ (the ε compound) [12, 13, 15, 16, 20, 21]. The nitrocarburizing represents a shorter-time process; it usually builds up a thin compound layer on the surface of the steel, which consists essentially of ε - phase iron carbonitride, below which there is a non-consistent diffusion region.

In terms of the nature of rolling – path surface-material, in Fig. 10a, it can be seen that the best rolling-friction behavior is provided by the paths with the highest carbon contents. This reveals the importance of the rolling–surface composition and the solid lubricant effect of carbon. The appearance of nitrogen in the composition of surface–rolling paths is correlated with the increase of the friction coefficient (see Fig. 11a). Here the worst behavior is registered for the nitrided paths where carbon is missing.

According to the roughness results in Table 2 and related to the non-treated steel surfaces, it is clear that the diffusion processes based mainly on carbon lead to the decrease of the surface roughness (R_a from 0.56 to 0.42 for carburizing and 0.46 for carbonitriding). In an opposite sense, the enriching in nitrogen by diffusion increases the steel surface roughness, from 0.44 to 0.58 for nitriding and 0.52 for nitrocarburizing. The presence of carbon close to nitrogen in the diffusion process diminished this tendency of roughness increase. An increase in surface roughness after nitrocarburizing was also observed by Qiang in [22].

Thus, one may conclude than indeed the rolling – path roughness and the rolling - path surface-material nature may play important roles in the variation of the friction coefficient. At the same time, we could conclude that all surface treatments achieved on the samples examined in this study contribute to the superficial hardness enhancement and to the minimizing of rolling path deformations. For this reason, if we consider the surface deformation of the treated rolling paths in the contact region, when the superficial hardness increases the contact area could decrease and the contact pressure could become higher. Although these increased pressures should contribute to flatten the roughness and to start the balls earlier on the treated surfaces, this process is not unfold. In this sense, the nitriding paths case is illustrative. Related to this, Xiao reported in [23] a study on the influence of surface roughness and the pressure distribution on the frictional behaviour in rolling/sliding contacts. He showed that the friction coefficient increases linearly with increasing contact pressure up to a maximum limit above which the friction coefficient is constant. Regarding nitriding, this observation is in accordance with the present experimental work results (maximum friction coefficient for nitriding), where the maximum hardness could explain the minimum deformation of surface rolling – path and the increased contact pressure.

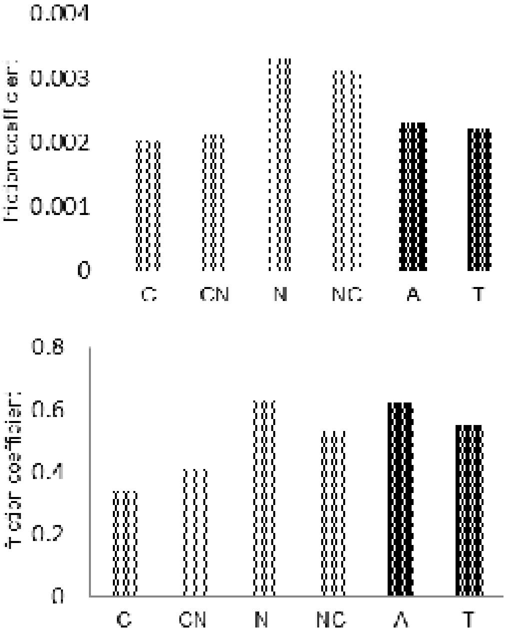


Fig. 10. (a, b) *The medium value of equivalent rolling-friction coefficient for the smallest ball diameter: balls in contact with different thermochemically treated plane rolling paths (a) and the friction coefficient for the plane contact between PSs and the same different plane rolling paths (b); C–carburized, CN–carbonitrided, N–nitrided, NC–nitrocarburized, A–annelead, T–tempered*

According to these aspects, the hardness could not be taken into consideration like a main parameter to explain the variation of the equivalent rolling-friction coefficient. Besides, if the rolling-surface deformations are not taken into account, the increased roughness of the treated surfaces seems to have a strong enough and dominant influence on balls start movement. This is in accordance with the registered values for roughness of carburized (the minimum ones) and of nitriding (the maximum ones) rolling paths and the correspondent friction coefficients (Table 1, see Figures 7a, 8a and 10a). Moreover, in the case of parallel measurements performed with PSs (see Fig. 10b).

In fact, the parallel measurements performed on PSs are in accordance with the ones obtained for the rolling contacts (see Fig. 10b).

However, in this case, there is a very small difference between the friction coefficients registered for non-treated paths and the nitrided ones. At the same time, for this type of plane contact, the lower value of friction coefficient is visible in comparison with the remaining variants. Its variation shows a straight dependence on the steel surfaces particular composition (and consequently their structural features), namely that of C. Besides the solid lubricant role that this carbon could be playing, one must consider that this moderate roughness value could give the contact the best conditions for friction.

4. Conclusions

This work presents an experimental procedure for establishing the rolling–friction coefficient for certain contacts that suppose steel balls and thermochemically treated rolling steel paths. The rolling motions were realised by balls on a steel plateau with longitudinal V-guide paths. The difficulty in measuring the rolling friction coefficient could be avoided if the friction phenomenon is evaluated considering *the equivalent (conventional) sliding-friction coefficient at start.* In order to establish the equivalent friction coefficient value, a typical method such as the inclined plane slope was used.

The best conditions for rolling seem to be provided by the carburized paths while the nitrided paths worsen this movement.

Taking into account our experimental conditions and results, we conclude that both nature (composition) of material and surface roughness are able to influence the equivalent rolling-friction coefficient. Although the non-treated steel paths revealed a good tendency for rolling, it is important to notice the role of superficial hardness and the strengthening of the rolling paths provided by the superficial treatments on the fatigue phenomena typical for Hertzian rolling contacts.

References

[1]. Popinceanu N, Gafitanu M. - *The basic problems of the rolling contact*, Bucharest: Technical Publishing House, 1985.

[2]. Pavelescu D., *Tribotechnics*, Bucharest: Technical Publishing House, 1983.

[3]. Pavelescu D., Tudor A. - *Tribology*, Bucharest: Pedagogical and Didactical Publishing House, 1980.

[4]. *,** http://steel.keytometals.com/articles.

[5]. Munts V. A., Baskatov A. P. - *Rate of carburizing of steel*, Metal Science and Heat Treatment (English Translation of Metallovedenie I TermicheskayaObrabotkaMetalov), 1983, 25, p. 98-102.

[6]. Moiseev B. A., Brunzel Y. M., Shvartsman L. A. - *Kinetics of carburizing in an endothermal atmosphere, Metal Science and Heat Treatment*, (English Translation ofMetallovedenie I TermicheskayaObrabotkaMetalov), 1979, 21, p. 437-442.

[7]. Totten G. E., Howes M. A. H. - *Steel Heat Treatment*, Handbook, NewYork: Marcell Dekker Inc., 1997.

[8]. *Surface Hardening of Steel*, ASM International. Materials Park. Ohio, 2002.

[9]. *ASM Handbook*. ASM International. Materials Park. Ohio, 1991.

[10]. Slycke J., Ericsson T. - *A study of reactions occurring during the carbonitring process*, Journal of Heat Treating, 1981, 2, p. 3-19.

[11]. Slycke J., Ericsson T. - *A study of reactions occurring during the carbonitring process*, Part II. Journal of Heat Treating, 1981, 2, p. 97-112.

[12]. Pye D. - *Practical nitriding and ferriticnitrocarburizing*, ASM International, Materials Park, Ohio, 2003.

[13]. Somers M. A. J., Mittemeijer E. J. - *Layer-grow kinetics on gaseous nitriding of pure iron: Evaluation of diffusion coefficients for nitrogen in iron nitrides*, Metallurgical and Materials Transactions A, 1995, 26, p. 57-74.

[14]. Somers M. A. J., Mittemeijer E. J. - *Modeling the kinetics of the nitriding and nitrocarburizing of iron*, Heat Treating 1997, Proceedings of the 17th Conference ASM International, 1998, p. 321-330.

[15]. Maldzinski L., Liliental W., Tymowski G., Tacikowski J. - *New possibilities for controlling gas nitriding process by simulation of growth kinetics of nitride layers*, Surface Engineering, 1999, p. 15:377-384.

[16]. Sola R., Giovanardi R., Veronesi P., Poli G. - *Improvement of wear and corrosion resistance of ferrous alloys by post – nitrocarburizing treatments*, Metalurgical Science and Technology, 2011, 29-2, p. 14-24.

[17]. Bobancu S., Cozma R., Cioc V. - *Tribology and Inventics - Practical Applications*, Brasov, Transilvania University Publishing House, 2000.

[18]. Cozma R., Bobancu S., Cioc V. - *Equipment and devices for tribological characterizations*, Bucuresti, Matrix Rom, 2005.

[19]. Munteanu D., Vaz F. - *Tribological researches on rolling – friction coefficient for carburized and carbonitrided steel surfaces*, Journal of the mechanical behavior of materials, 2005, 16, p. 407-418.

[20]. Somers M. A. J. - *Thermodynamics, kinetics and microstructural evolution of the compound layer; a comparison of the states of knowledge of nitriding and nitrocarburizing*, Heat Treatment of Metals, 2000, 4, p. 92-102.

[21]. Du H., Somers M. A. J., Agren J. - *Microstructural and compositional evolution of compound layers during gaseous nitrocarburizing*, Metallurgical and Materials Transactions A, 2000, 31, p. 195-211.

[22]. Qiang Y. H., GE S. R., Xue Q. J. - *Microstructure and tribological behaviour of nitrocarburizing - quenching duplex treated steel*, Tribology International, 1999, 32, p. 131–136.

[23]. Xiao L., Bjorklund S., Rosen B. G. - *The influence of surface roughness and the contact pressure distribution on friction in rolling/sliding contacts*, Tribology International, 2007, 40, p. 694–698.