ESTABLISHING OF ROLLING - FRICTION COEFFICIENT, FOR HERTZIAN CONTACTS BETWEEN STEEL BALLS AND DIFFERENT KINDS OF THERMOCHEMICAL TREATED STEEL SURFACES

Daniel MUNTEANU

Transilvania University of Brasov
muntean.d@unitbv.ro

ABSTRACT

It is known that for the ball displacement guide paths, the necessary start-moving force of the mobile half-couple is higher than the displacement-motion keeps force.Within the frame of this work, it has been designed and manufactured special pairs of rolling-motion couples, made from 5115AISI case-hardening steel and 4140 AISI heat treatable steel. After that, some of them (in the first blend) were carburized (at 925^{o}C) and others carbonitrided (at 890^{o}C) in gaseous conditions. The rolling - friction tests supposed different arrangements of the half-couples and balls. In order to establish the rolling - friction coefficients for all the thermochemical treated surfaces, a typical method such as the inclined plane slope, was used. Taking into account each kind of superficial treatment category, generally, it has been observed smaller values of equivalent friction coefficient for the carburized surfaces in comparison with the carbonitrided ones. For low - temperature superficial treatments category, a little bit smaller values of equivalent friction coefficient for the nitocarburized surfaces in comparison with the nitrided ones were obtained. The non-treated surfaces have been characterized, in all the cases, by minimum friction coefficient values in comparison with the treated ones. In comparison, the results clearly show a difference between the equivalent friction coefficient values registered for carburized/carbonitrided and nitrided/nitrocarburized surfaces. Thus, in the first case, these values were smaller than in the second case.

KEYWORDS: Steel, Carburizing, Nitriding, Rolling-friction coefficient

1. Introduction

There are several practical applications, including bearings and gears, in which rolling or rolling-sliding punctiform or line contacts are developed. In mechanics, this kind of contacts belongs to the hertzian contacts category. Even for constant loads, the rolling motion produces a variable superficial state of efforts characterized by normal and tangential - shear stresses under impact. The intricacy of researching this kind of contacts is further increased by the presence of lubricant [1]. Thus, for the study it must be considered several factors such as: the load, the speed, the rolling - sliding ratio (if the sliding exists), the lubricant presence and quality, the surface topography, etc.

Owing to the high temperature of carburizing, which could lead to the grain's increasing and

Generally, contact micro surfaces and higher pressures in the contact zones characterize the hertzian rolling contact cases. Therefore, surface deformations must be considered. The appearance and evolution of surface fatigue phenomena have been theoretically explained in literature using the *space stress state condition* and the models of Hertz and Boussinesq [1,2,3].

In this kind of contacts, wear process of hardened steel surfaces usually occurs in a mild way, in comparison with the unhardened surfaces. For instance, in the case of ball - bearings manufacturing, generally are used two steel categories: hypereutectoid steels with chromium and low carbon alloyed steels for carburizing and carbonitriding. Many practical cases, especially for impact stress conditions, showed better mechanical behaviour for bearings manufactured from carburized steels.

deformations appearance, in certain cases the carburizing process has been replaced with nitrocarburizing. Thus, the process temperature became lower.

The steels for bearing manufacturing, especially in the rolling contact surfaces, have to be able to support the strong alternating stresses, which are caused by the compressive forces between balls (rolls) and rolling guide paths.

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, 2, 3, 4]. Depending of the rolling - surface qualities and rolling body dimensions too, this wave could be more or less important in size. Its appearance has an important role in rolling motion because it leads to a rolling - friction moment developing. This moment is in opposite with the rolling motion and plays an important role, not only for the motion but also for the start - moving.

The paper tries to establish an equivalent friction coefficient value for different types of hertzian contacts (ball on carburized, carbonitrided, nitrided and nitrocarburized plane steel surface) for rolling start - moving conditions.

2. Theoretical and experimental background

The rolling - friction process is characterized through a typical friction torque which gives a specific rolling - friction moment M_{rf}. Figure 1 presents a schematic arrangement of a ball rolling motion on a plane surface.

Very often, the practical physical explanations of the rolling - friction process takes into account the plastic deformations appearance in the contact zone [1]. If we consider a rolling contact in which the ball is harder than the rolling plane surface, on the contact zone will appear an indentation cup.

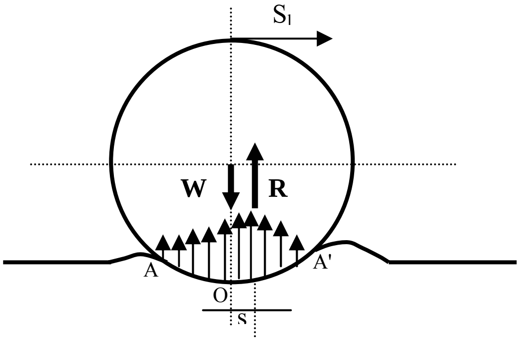

Fig. 1 *Schematic arrangement of a hertzian punctual contact, in plane coordinates; W – ball weight, R – result of typical force-reaction distribution on the contact zone AA', s – the moment arm, S$_l$ – the ball linear speed.*

This phenomenon leads to a specific material accumulation, not only in front of the contact (where is more important) but also behind the contact (figure 1).

Thus, the reaction force *R* on the AOA' section is given by infinity of elementary forces. The general force - moment of these elementary forces in relate of 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, *R,* give the moment M_{rf}, which is in opposite with the rolling sense of the ball [1,4]. The practical researches showed that for equilibrium state, the value of this moment must be lower than a certain maximum value, as follows:

$$M_{rf} \le s \cdot R \tag{1}$$

In relation (1), *s* represents the rolling - fri coefficient. In comparison with the sliding friction coefficient μ which is dimensionless, the rolling - friction coefficient *s* has a little dimension, very difficult to measure. It represents the maximum displacement distance of the normal reaction *R* support relatively to the theoretic contact point *O* (fig. 1).

For static equilibrium conditions, when the rolling body (ball or role) is not moving and the rolling plane surface is in a perfect 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 initiation, because rolling - friction coefficient *s* is difficult for measure, the friction phenomenon can be evaluated considering *the equivalent (conventional) sliding - friction coefficient* μ_0 *at start* [5].

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 force, which keeps the displacement-motion. The start-moving force is equal to the normal load *W* = *R* multiplied by the equivalent friction coefficient μ_0.

Thus, in order to establish the static friction coefficients for all the samples, a typical method such as the inclined plane slope was used. This system [5] may estimate the friction coefficient value, based on some typical linear size measurements. Thus, correlation between the friction angle α and the

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

friction coefficient μ is:

At the same time, a plane inclines the friction couple that is in a rest state, with variable angles, until the sliding phenomenon appears in the couple. The angular value α_{limit} = α_0 where the sliding appears, is in direct correlation with the static sliding - friction coefficient μ_0 at start according with:

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

3. Experimental arrangements

In order to estimate the equivalent friction coefficient, it has been designed and manufactured special pairs of rolling-motion couples, from E 410 Bohler, Austrian designation, (≈ 5115AISI) case-hardening steel with the following chemical composition: 0.17%C, 0.30%Si, 1.20%Mn, 0.90%Cr and V 320 Bohler, Austrian designation, (≈ 4140AISI) heat-treatable steel with the following chemical composition: 0.41%C, 0.30%Si, 0.70%Mn, 1.10%Cr, 0.20%Mo.

Each half-couple has a parallelepiped form, with 141x100x15 mm. Some of these half-couples have plane (flat) friction surfaces and others have by threes identically longitudinal V-guide paths on the rolling - friction surface.

The relative motion between the half-couples has been achieved with three identically balls, and the point contacts in three different contact zones. The rolling - friction tests supposed different arrangements of the half-couples and balls. Through different changes of the half-couple (plate), each lower plate will become consecutively fixed plate and each upper plate will become mobile plate. Thus, the role of the lower plate and upper plate is replaceable. The upper plate is moving in relate of the lower one by means of bearing balls with different sizes. At each test, all the balls, which form the couple, have to be the same sizes. The minimum number of balls is three, of which two on the edge paths and one on the center path.

It has been used different sizes of identically balls, with 8, 10, 12, 15.9, 18, 19.8, 22, 25 and 26 mm in diameter, made from high speed steel (AISI M2) hardened and three times tempered, characterized by 64 HRC and R_a = 0,06 μm. Each rolling-friction couple was fixed, in a perfect horizontal position of start, on the plateau of a special tribosystem.

In order to establish the rolling - friction coefficients for all the thermochemical treated surfaces, a typical method such as the inclined plane slope, was used. Help of a variable-dropping plane inclines the rolling couple (which is in a horizontally-rest state) the rolling phenomenon appearances in the couple. The angular value $\alpha_{limit} = \alpha_0$ where the rolling appears, is in direct correlation with the equivalent sliding - friction coefficient μ_0 at start.

After that, the samples manufactured from E 410 steel were carburized (at 920°C) and others were carbonitrided (at 860°C) in gaseous conditions, using an endothermic atmosphere completed by 8% CH_4 for carburizing and an endothermic atmosphere completed by 8% CH_4 and 5% NH_3 for carbonitriding. In both cases, the carbon potential in the furnace chamber was kept at 0,9% and the maintaining period at the treatment temperature 7 hours. After the thermochemical treatments, the samples were first case hardened (from 830°C) using oil like quenching agent, and second low tempered (at 180°C).

At the same time, the samples manufactured from V 320 steel were hardened (from 840°C) using oil like quenching agent, and high tempered (at 585°C). After that, the samples were polished and it has been a roughness of Ra = 0.1μm.

Some of samples were gas - nitrided (at 520°C, for 15 hours in $NH_3 + N_2$ atmosphere with ammonia dissociation grade α = 25%) and others were gas - nitrocarburized (at 560°C, for 7 hours in endothermic gas + NH_3 atmosphere).

The hardness values were estimated using a special device Akashi MVK 4-E type, with 0,05 daN load. The roughness values of the surfaces were also established, based on profilometer method, using a Tallysurf 4 (Taylor-Hobson) type profilometer.

4. Experimental results and discussion

Table 1 presents the average experimental values from roughness and Vickers hardness for all the samples manufactured from E 410 case-hardening steel, after removing of extreme values for each kind of measurement.

Table 1.*Roughness and Hardness values of sample surfaces (E 410 case-hardening steel).*

Sample surfaces	Roughness values R_a [μm]	Hardness $HV_{0.050}$
Untreated	0.43	238
Carburized	0.32	816
Carbonitrided	0.36	832

The same characteristics are shown in table 2 for the samples manufactured from V 320 heat-treatable steel.

Table 2. *Roughness and Hardness values of sample surfaces (V 320 heat-treatable steel).*

Sample surfaces	Roughness values R_a[μm]	Hardness $HV_{0.050}$
Just hardened and tempered (+ polished)	0.11	238
Nitrided	0.48	756
Nitrocarburized	0.38	788

The rolling-friction coefficients established by the inclined plane slope method are shown in Table 3.

Table 3. *Average values of rolling - friction coefficient* μ_0 *for different kind of couples (A, B, C, D, E, F) and for different ball measurements.*

Balls diameter [mm]	**Average values of rolling - friction coefficient μ**					
	A	B	C	D	E	F
8	0.0021	0.0024	0.0021	0.0024	0.0023	0.0026
10	0.0019	0.0022	0.0020	0.0024	0.0022	0.0023
12	0.0020	0.0022	0.0021	0.0022	0.0022	0.0023
15.9	0.0020	0.0023	0.0023	0.0024	0.0023	0.0025
18	0.0022	0.0023	0.0022	0.0023	0.0024	0.0025
19.8	0.0019	0.0021	0.0022	0.0023	0.0023	0.0024
22	0.0016	0.0017	0.0017	0.0022	0.0019	0.0022
25	0.0014	0.0016	0.0015	0.0018	0.0017	0.0020
26	0.0013	0.0014	0.0014	0.0016	0.0014	0.0017

where A, B, C, D, E, F, G were the following couples:

A: Carburized half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
B: Plane carburized half-couple (fixed) – Balls – Plane untreated half-couple;
C: Carbonitrided half-couple with longitudinal V-guide paths on the rolling (fixed) - friction surface – Balls – Plane untreated half-couple;
D: Plane carbonitrided half-couple (fixed) – Balls – Plane untreated half-couple;
E: Untreated half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
F: Plane untreated half-couple (fixed) – Balls – Plane untreated half-couple.

For the nitrided and nitrocarburized samples, the rolling-friction coefficients established by the inclined plane slope method are shown in Table 4, where A', B', C', D', E', F', G' were the following couples:

A': Nitrided half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
B': Plane nitrided half-couple (fixed) – Balls – Plane untreated half-couple;
C': Nitrocarburized half-couple with longitudinal V-guide paths on the rolling (fixed) - friction surface – Balls – Plane untreated half-couple;
D': Plane nitrocarburized half-couple (fixed) – Balls – Plane untreated half-couple;
E': Untreated half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
F': Plane untreated half-couple (fixed) – Balls – Plane untreated half-couple.

Figures 4, 5 and 6 present, for carburized, carbonitrided and thermo-chemically untreated samples, the dependencies between rolling – friction coefficient and couples characterized through different ball sizes (three identical balls). The graphic dependencies denote, for all cases, that increasing the ball diameters in rolling – friction couples leads to a slightly decreasing of the friction coefficient values. Nevertheless, all friction tests revealed the same behaviour for a little tendency of increasing friction coefficient in the middle of ball sizes interval (e.g. 15,9 – 18 mm in diameter). This phenomenon is very difficult to explain but it is possible a little deviation from balls spherical shape in this interval.

For all three graphic represented cases, smaller friction coefficient values were observed for couples which in a half-couple is represented by V-guide paths on the rolling (fixed) - friction surface. This is very important if we are thinking that in these cases, the contact is produced in three points for each ball, two on the V-guide paths and one on the other plane half-couple. Anyway, this aspect could be appear due to the smaller width of the rolling paths in comparison with whole plane surfaces. Thus, the effect of front resistant wave could be reduced because it is developed only on the limited width.

Figures 7, 8 and 9 present, the same dependencies for nitrided, nitrocarburized and thermo-chemically untreated samples.

The graphic dependencies of these kinds of surfaces, denote that increasing the ball diameters in rolling – friction couples leads to a slightly decreasing of the friction coefficient values. Like for the first groups of samples (carburized and carbonitrided), it has been registered a little increasing friction coefficient in the middle of ball sizes interval (e.g. 15,9 – 18 mm in diameter).

In comparison, for nitrided and nitrocarburized surfaces, slightly lower values for friction coefficient were registered in the couple plane – balls – plane types. These results could conclude the importance of the guide paths during the rolling motion. The establishing of rolling-friction coefficient μ_0, lead to the conclusion that the lowest coefficient values generally characterize the carburized surfaces and the highest the untreated surfaces.

Table 4. *Average values of rolling - friction coefficient μ_0 for different kind of couples (A', B', C', D', E', F') and for different ball measurements.*

Balls diameter [mm]	Average values of rolling - friction coefficient μ					
	A'	B'	C'	D'	E'	F'
8	*0.0033*	0.0032	*0.0034*	0.0026	*0.0024*	0.0023
10	*0.0034*	0.0033	*0.0033*	0.0027	*0.0022*	0.0019
12	*0.0032*	0.0030	*0.0033*	0.0028	*0.0021*	0.0018
15.9	*0.0035*	0.0035	*0.0034*	0.0032	*0.0023*	0.0022
18	*0.0034*	0.0033	*0.0033*	0.0030	*0.0025*	0.0023
19.8	*0.0034*	0.0032	*0.0030*	0.0027	*0.0021*	0.0020
22	*0.0033*	0.0031	*0.0022*	0.0018	*0.0018*	0.0016
25	*0.0030*	0.0023	*0.0023*	0.0015	*0.0017*	0.0013
26	*0.0031*	0.0022	*0.0021*	0.0016	*0.0013*	0.0012

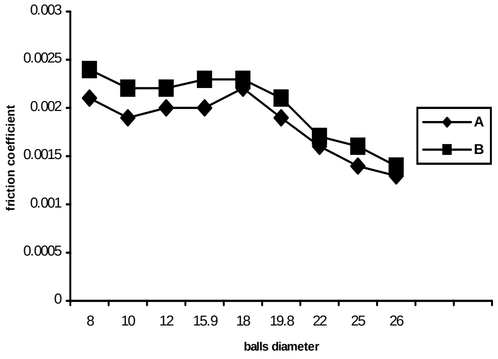

Fig. 4: *The rolling-friction coefficient μ_0 (average values) for different ball sizes.*
A: Carburized half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
B: Plane carburized half-couple (fixed) – Balls – Plane untreated half-couple;

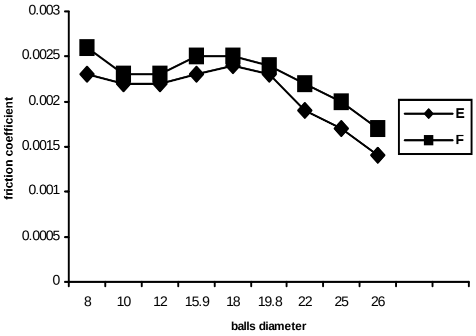

Fig. 6: *The rolling-friction coefficient μ_0 (average values) for different ball sizes.*
E: Untreated half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
F: Plane untreated half-couple (fixed) – Balls – Plane untreated half-couple.

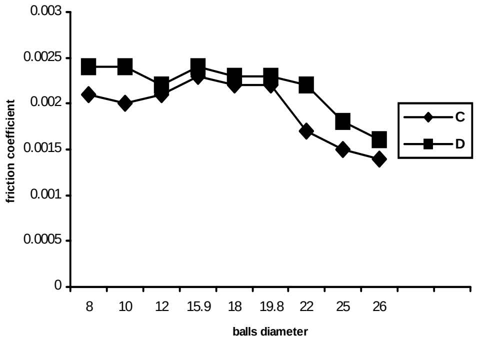

Fig. 5: *The rolling-friction coefficient μ_0 (average values) for different ball sizes.*
C: Carbonitrided half-couple with longitudinal V-guide paths on the rolling (fixed) - friction surface – Balls – Plane untreated half-couple;
D: Plane carbonitrided half-couple (fixed) – Balls – Plane untreated half-couple;

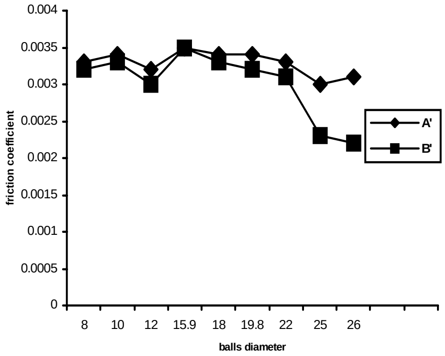

Fig. 7: *The rolling-friction coefficient μ_0 (average values) for different ball sizes.*
A': Nitrided half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple;
B': Plane nitrided half-couple (fixed) – Balls – Plane untreated half-couple;

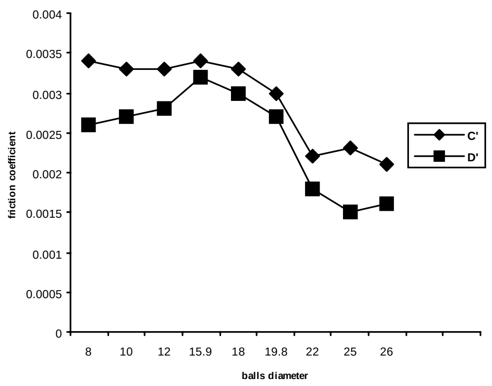

Fig. 8: *The rolling-friction coefficient μ_0 (average values) for different ball sizes. C': Nitocarburized half-couple with longitudinal V-guide paths on the rolling (fixed) - friction surface – Balls – Plane untreated half-couple; D': Plane nitrocarburized half-couple (fixed) – Balls – Plane untreated half-couple;*

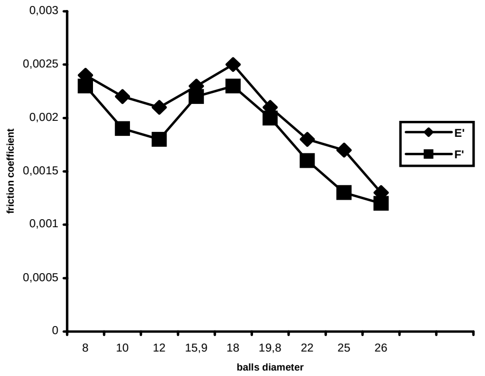

Fig. 9: *The rolling-friction coefficient μ_0 (average values) for different ball sizes. E': Untreated half-couple with longitudinal V-guide paths on the rolling - friction surface (fixed) – Balls – Plane untreated half-couple; F': Plane untreated half-couple (fixed) – Balls – Plane untreated half-couple.*

Referring to this, and according with roughness and hardness measurements from Table 3, it is very difficult to have a clear conclusion about the main influence on rolling-friction coefficient. Anyway, both surfaces (carburized and carbonitrided) are able to decrease the friction coefficient, maybe a little more the carburized ones, but the registered differences could appear owing the roughness differences (smaller in the case of carburized surfaces).

At the same time, both surface treatments achieved on the samples contribute to the superficial hardness enhancement and to the minimizing hertzian deformations on the rolling paths. For this reason, if we consider the surface deformations on the treated rolling paths almost the same, with increasing of ball diameters and weight too, the contact pressures become higher. These increased pressures are able to flattening the roughness and to start the balls earlier. At the same time, with increasing the surface hardness, the "material micro-wave" from the contact zone on the rolling path (in front of it, in the moving sense) becomes smaller and this aspect leads to an earlier ball start moment.

Regarding the rolling-friction coefficient μ_0 of nitrided and nitrocarburized samples, we can observe also almost the same values for all the cases. However, in this case, the high experiments precision revealed that the lowest coefficient values generally characterize the untreated surfaces and the highest the nitrided ones. (see Table 4). Anyway, both surfaces (nitrided and nitrocarburized) are able to increase the friction coefficient, maybe a little more the nitrided ones, but the registered differences could appear also owing to the roughness and hardness differences (smaller in the case of non-treated surfaces).

In comparison, the results clearly show a difference between the equivalent friction coefficient values registered for carburized/carbonitrided and nitrided/nitrocarburized surfaces. Thus, in the first case, these values were smaller than in the second case; this conclude that, besides roughness value, the compund zone developed on the top of nitrided/nitrocarburized surfaces increasing the rolling - friction coefficient. At the same time, the increased values of rolling-friction coefficient in these last cases (nitrided and nitrocarburized paths) could also appear owing to the little bit smaller values of hardness in comparison with carburized and carbonitrided ones.

5. Conclusions

Generally, it has been observed smaller values of equivalent rolling-friction coefficient for the carburized and carbonitrided samples in comparison with the nitrided and nitrocarburized ones..

Using longitudinal V-guide paths on the rolling - friction surfaces, for carburized and carbonitrided rolling surfaces, it could be reached friction conditions better then on the plane rolling – friction surfaces. In these cases, the untreated surfaces were characterized by friction coefficients higher than the treated ones.

In comparison, for nitrided and nitrocarburized rolling surfaces, using longitudinal V-guide paths on the rolling - friction surfaces it could be reached friction conditions lower then on the plane rolling – friction surfaces. Generally, for these cases, it hasve been observed the smallest values of equivalent friction coefficient for the non-treated surfaces in comparison with the nitrided and nitrocarburized ones.

The minimum rolling-friction coefficient (at start) values were registered, in all the cases, when the contacts have been achieved with balls of maximum diameter (26 mm).

Regarding surfaces topography, carburizing seems to develop smaller roughness values. In fact, we could say that starting from the same untreated substrate roughness (R_a = 0.538 μm) both surface treatments lead to decreasing the final roughness. Anyway, the roughness decreasing after carburizing is a little higher than after carbonitriding, nitrocarburizing and nitriding. This could be contribute to a little decreasing of the friction coefficient and, if the final polishing is not taking into account (like in this work), this aspect is very important for some practical applications that imply hertzian contact.

The results clearly show a difference between the equivalent rolling-friction coefficient values registered for carburized/carbonitrided and nitrided/nitrocarburized surfaces. Thus, in the first case, these values were smaller than in the second case; this conclude that, besides roughness value, the compund zone developed on the top of nitrided/nitrocarburized surfaces increasing the rolling - friction coefficient.

With increasing the surface hardness, the “material micro-wave” from the contact zone on the rolling path (in front of it, in the moving sense) becomes smaller and this aspect leads to an earlier ball start moment and also to the decreasing of rolling-friction coefficient.

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