THE CARRYING CAPACITY OF TiCN COATING ON CONVEX-CONCAVE (C-C) GEARINGS

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DOI : 10.17973/MMSJ.2018_12_2018107

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This paper discusses the possibility of increasing the surface load capacity in C60E steel gearings by applying selected thin coatings. It describes the effect of tribological characteristics, such as friction coefficient, wear, adhesion and hardness of TiCN coating on convex-concave gearing (C-C). The average thickness of TiCN is 3.3µm. Delamination of the TiCN coating was recorded at a load of approximately 50 N. The friction coefficient of TiCN was 0,18. The nano-hardness of the TiCN coating was 41.8 GPa. The results of the tests on C-C gearings on the Niemann tester show that the TiCN coating deposition occurred at load level 7 and the scuffing evaluated for surface roughness occurred at load level 12. For comparison on the uncoated C-C gearing with the Biogear S 150 oil used, scuffing evaluated for surface roughness occurred at the 5th load level. From the same test it is clear that the load capacity of gearings is influenced by hardness and thickness of coatings. The complete removal of the coating was preceded by gradual thinning. After its removal, the wear continued on the softer substrate, where the traces after milling filled-up with the substrate metal.

KEYWORDS

Convex-concave gearing, TiCN coating, friction coefficient, wear, adhesion, hardness, Niemann´s test, Biogearfrom

1 INTRODUCTION

Increasing the load capacity and durability of gearings is one of the problems that can be solved by design modification (changing tooth geometry), or technologically (using new materials or technologies).

The design of gearings, or derivation of geometric dependence, is almost exclusively based on the "technological method", where the shape of the production tool, which is actually one member of the gearing, determines the correct mating flanks of the mating gear. At the same time, the gearing design must meet the requirements of the basic principle of gearing, where no production or operating interference is permitted. The design of gears is based on the specific requirements for gears. The mating teeth profile forming the shape constraint must be designed to allow continuous mesh in a constant gear ratio. For a specifically defined teeth profile of the pinion, a unique tooth profile of the mating flanks of the wheel is also determined, and, therefore also the shape of the path of contact. In the case of C-C gearing, the path of contact is made up of circular arcs whose centre of curvature may have a different position relative to the central line O1 – O2 (Fig. 1) . This means that, depending on the basic geometric parameters, it is possible to classify the individual types of planar gearings [Bošanský 2012], as well as the shape of the tooth profile curve.

Based on these parameters, several types of gearings can be recognized in practice. The most frequently used type is the involute gearing. The path of contact has the shape of circular arcs with a radius ∞, which forms a line: as in Fig. 1.

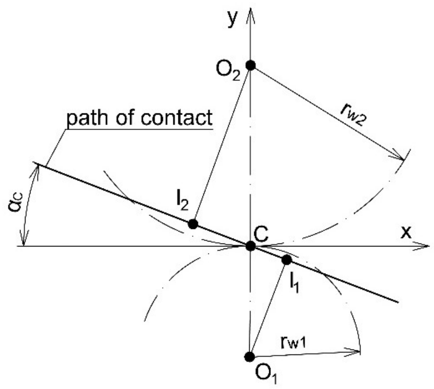

Figure 1. Characteristics of the path of contact defining involute gearing

The theory behind the convex-concave gearing design [Bosansky 2015] is based on the mesh parameters (the lower the contact pressures, the lower the slip ratio, and the higher the contact load capacity) [Kopiláková 2012], where the path of contact is composed of circular arcs, Fig. 2.

The surface tooth load bearing capacity is affected by the magnitude of the contact pressures, as well as by the slip ratio. The comparison of involute and C-C gearings in terms of slip ratio is shown in Fig. 3. The C-C gearing has a significantly lower slip ratio in comparison with the involute gearing, especially on the pinion and wheel.

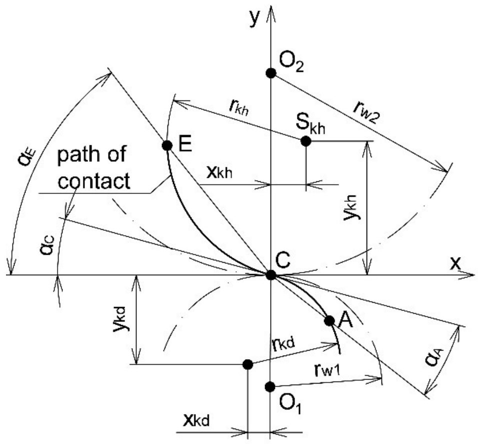

Figure 2. Characteristics of the path of contact defining convex-concave gearing

The torque generates power contact in gearings, which involves high pressure values at the contact points between the tooth

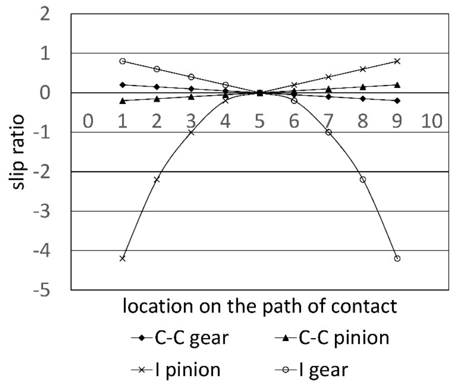

Figure 3. The slip ratio convex-concave and involute gearing on the path of contact

flanks. The magnitude of this pressure is an important indicator for the surface damage of the tooth flank and thus also for the life of gearings, so that it is important to know their size, or the radius of the tooth curvature at the contact point $\rho_{1,2}$. In the case of involute gearing, higher contact pressures are achieved, (the mesh of tooth flank is concave-concave – Fig. 4). In the C-C gearing, lower contact pressures are caused by the convex-

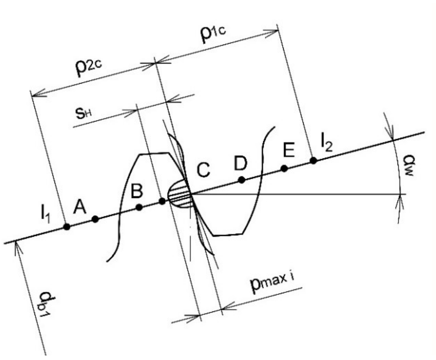

Figure 4. Two teeth in mesh and the magnitude of contact pressure in involute gearing

concave mesh of the tooth, as shown in Fig. 5. Computational

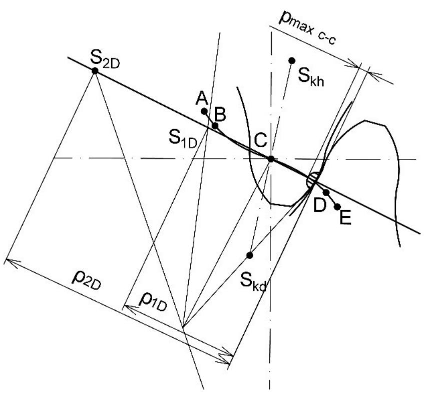

Figure 5. Two teeth in mesh and size of contact pressure in C-C gearing

simulation of convex - concave and involute gearings from the point of view of contact pressures was made using ANSYS software. The contact pressure analysis shows that C-C gearing has even 25% lower pressure in contact teeth than involute gearing. [Bošanský 2012]. These facts showed up in the Niemann´s test to scuffing, where the Bioger S 150 oil used where for the C-C gearing was critical 7th load and on an involute gearings the 5th load stage[]. The technological approach to increasing the load capacity of gearings includes various sophisticated technologies, including chemical and heat treatment methods [Rusnak 2005]. The application of hard thin coatings on steel parts most often increases wear resistance [Nowak 2012], corrosion [Sosa 2017], as well as combined stress [Yang Li 2017]. In particular, several technologies such as PVD, CVD, PACVD and others for the surface application of hard thin coatings have been used in the past few years with the development of material engineering to increase the load capacity of gearings. From previous experiments [Vanya 2012] it is clear that deposition of hard thin coatings on the surface of the tooth flank is one way of increasing load capacity, which also increases the load capacity of gearings for the required lifetime [Bobzin 2015].

The present paper describes the properties of two surface coatings identified in laboratory conditions (Niemann´s test) and their influence on the load capacity of C-C gearing under operating conditions.

2 MATERIALS AND METHODS

Experimental samples and gears were made of C60E steel containing 0.57-065% C, 0.5-08% Mn and 0.15-0.4% Si. This steel is suitable for hardening and surface hardening. It is used to produce less loaded toothed gears, pins, spindles and machine parts with increased demands for abrasion resistance. Titanium carbonitride (TiCN) is characterized by a friction coefficient of 0.3, high hardness (37 GPa) and abrasion resistance, and high toughness as well. Therefore it is suitable for intermittent load. Nitrogen is used to improve adhesion to the substrate. The TiCN coating was applied by Arc (Ion-Plating) using arc at a cathode voltage of 100V, substrate temperature 420 ° C for one hour.

On 30 mm diameter circular samples the thickness of the deposited coating and its chemical composition was determined by SEM and EDX analysis respectively. The adhesion of the coatings to the substrate was monitored by a scratch test by means of a CSEM REVETEST test device. The scratch tests were carried out at a constant speed of the moving sample and at a constant increase in normal force from 1 - 100 N. During the test, the acoustic emission signal dependence of the normal force was recorded. The influence of the coefficient of friction on normal force was also determined by this device. The nanohardness of the coatings was determined at 20mN, 2,5mN and 0,5mN loads. The depth of penetration of the Berkovich indentor into the sample was also observed.

Tribological evaluation of the thin coatings was performed on CSM Instrumental equipment by the Ball on Disk method. The counterpart was the Al_2O_3 ball. Tests were performed dry at 1N load and a sample rate of 80 mm/s on a 100 m track. The wear and friction coefficient were determined from the tribological characteristics. The wear was measured by the material weight loss and the friction coefficient from the frictional and normal force fraction.

Gear tests were performed on machined C-C teeth with roughness approximately 1.1µm. However, for the application of the coatings, the minimum roughness of the flank of the tooth is approximately 0.5µm. Since the teeth are non-standard, special devices which were not available during the experiments, should be used to achieve the required roughness of the teeth. For this reason, the tested gears have to be run in soft state [Misany 2015] to achieve the required roughness. Subsequently, the surface of the teeth was quenched by the laser and tempered at 450 ° C. The objective was to obtain the desired surface hardness of the flank of the tooth (in substrate) preventing deformation of the deposited coating due to high contact pressures (Hertz's teeth pressures). The load capacity of the sealing coatings was determined by FZG test on Niemann's tester [FZG Test]. The wheels were tested under increasing torque (1st to 6th grade -2,5 Nm to 128,8 Nm). The criterion for completing the test is to achieve a weight loss of 10 mg. The test gears were lubricated with the OMV Biogear S 150 ecological lubricant, which is suitable for use in agricultural machinery [Rusnák 2009].

3 RESULT AND DISCUSSION

The thickness of the TiCN coating has an average value of 3.3μm, as seen in Fig. 6. The identified elements correspond to the coating designation. In Fig. 7 there are trace of the scratch

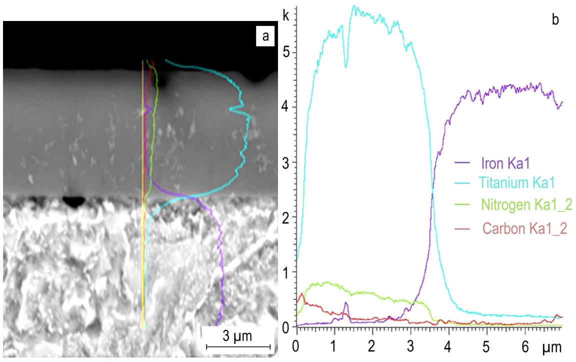

Figure 6. Microstructure and distribution of elements in the TiCN coating on C60E base materials; EDS a) TiCN coating on substrate, b) layout of Elements TiCN coating and substrate

test.

The acoustic emission signal, plotted in Fig. 8, the TiCN coating shows a stronger acoustic emission signal as a consequence of a gradual delamination at the edge of the scratch. When the

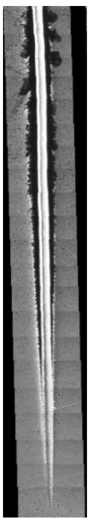

Figure 7. Traces of scratch tests on TiCN coating

indentor penetrates deeper, the acoustic emission signal due to the generation of stresses at greater depths decreases and the damage is more gradual. Delamination of the coatings was recorded approximately at a load of 50N, which compares to

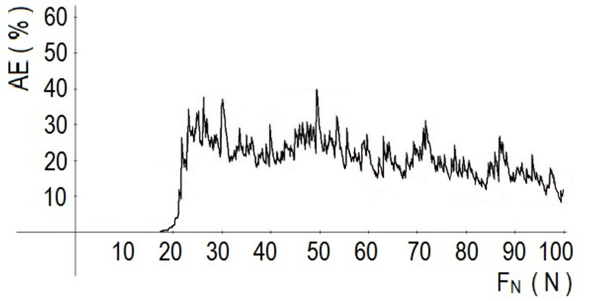

Figure 8. The acoustic emission signal on C60E substrate with TiCN coating

the value stated in the guidelines and is considered to be satisfactory.

The friction coefficient during the scratch test is shown in Fig. 9. The friction coefficient on samples with the TiCN coating

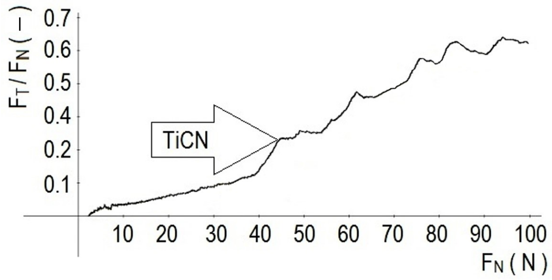

Figure 9. Change of friction coefficient on TiCN coating during a scratch test

increases faster, corresponding to delamination at the edge of the scratch and penetrating into deeper coatings. When the indentor penetrates to a certain depth, reaching the substrate, the friction coefficients level out for the TiCN coating at a normal force greater than 68 N.

With a further increase in load, only friction coefficients for C60E steel substrate have been recorded.

The coating may peel as a result of a step change of chemical composition at the substrate-coating interface. The removal of the negative influence on the tribological characteristics due to the step change between the substrate and the coating can be achieved by chemical-thermal treatment of the surface coatings.

Surface hardness was determined at Berkovich indentor load values of 20 mN, 2.5 mN and 0,5 mN. The identical nano-hardness of 4.1 GPa was measured at the highest load due to penetration of the indentation into the substrate on both coatings. For this reason, Fig. 10 shows the depth of indentation only at the loads of 2.5 mN and 0.5mN. Indentation curves for TiCN coating on C60E substrate at load 2.5m N is clear from Fig. 11. Fig. 12 shows the arithmetic average of the five measurements on TiCN coating. The maximum divergence from the average values was less than 10%, so the average values can be considered as correct. The nano-hardness of the TiCN coating was 41.8 GPa. In Fig. 13 is loss of volumes from the surface of TiCN coating on the C60E substrate.

The friction coefficients of the coating depending on the length

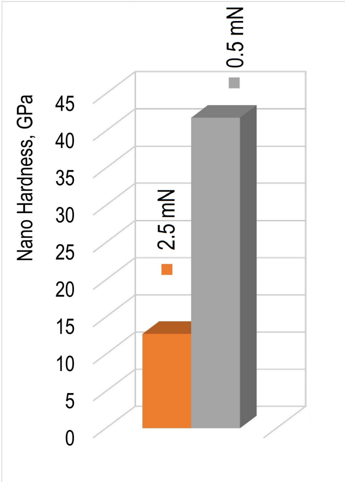

Figure 10. Nanohardness values of TiCN coating on C60E substrate at different load values

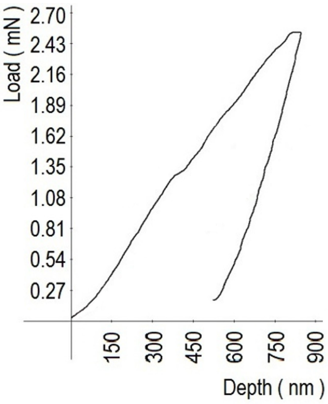

Figure 11. Indentation curves for TiCN coating on C60E substrate at load 2.5mN

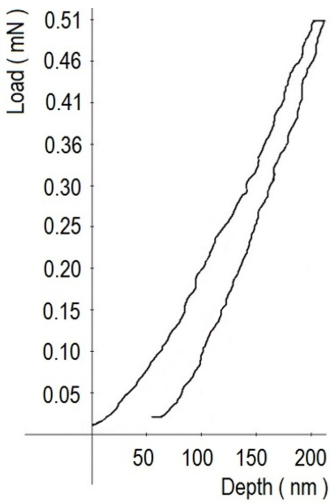

Figure 12. Indentation curves for TiCN coating on C60E substrate at a load of 0,5mN

of the sliding path that are shown in Fig. 14. On TiCN surface was stabilized approximately after 10 m. The Ball on Disk friction coefficient is more versatile in terms of the way of loading the gears compared to scratch tests. C-C convex-concave gearing is a special type of gearing, which is different

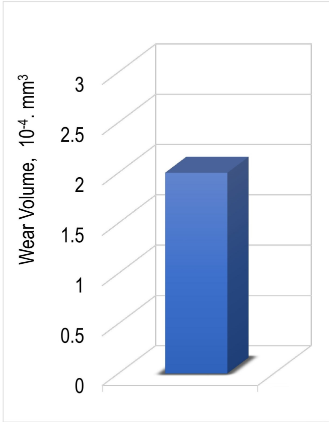

Figure 13. Loss of volumes from the surface of TiCN coating on the C60E substrate

Figure 14. Friction coefficient versus sliding distance for TiCN coating

in the shot from the involute gearing, since there is a reduction of touch pressure in the shot of the teeth and thus increases their load carrying capacity, Fig.5.

Due to their different geometry, it is not possible to use in their manufacture standard tools for involute gearing, but special milling tools, where their accuracy is important. However, the test wheels were produced with a roughness of only about Ra = 1,2 µm. Since for the application of hard thin coatings the surface of the tooth flanks should have a lower roughness (0.5µm), it was necessary to run of the wheel so that the roughness can be reduced to the Ra = 0,6 µm limit. The C-C convex-concave gearing set was tested on a Niemann's tester (FZG test) , where the teeth are gradually loaded from 1st to 12th load stage. The TiCN coating loading capacity was worn after the 7th load stage.

In Fig. 15 is a cross-sectional view of the TiCN-coated tooth section. The thickness of the applied coating is 3.3µm, which is in line with the thickness measured on the samples for scratch tests. The TiCN coating is at the top of Fig. 15, wear was due to a decrease in its thickness. The thinned coating was successively pushed into the substrate and gradually eliminated.

In Fig. 16 b-d is cross section of a tooth with Ti, N and Fe planar distribution respectively (EDS maps). Nitrogen, and titanium, Fig. 16 b, c are only in the surface coatings. In Fig. 16, there is an interface between a portion of the wear surface of the side of the coated and uncoated tooth. Residues of the applied coating on the right side, Fig. 16, are apparent from surface element analysis, Fig. 16 b - c. Fig. 16 shows a different mechanism of wear of the coating and the substrate.

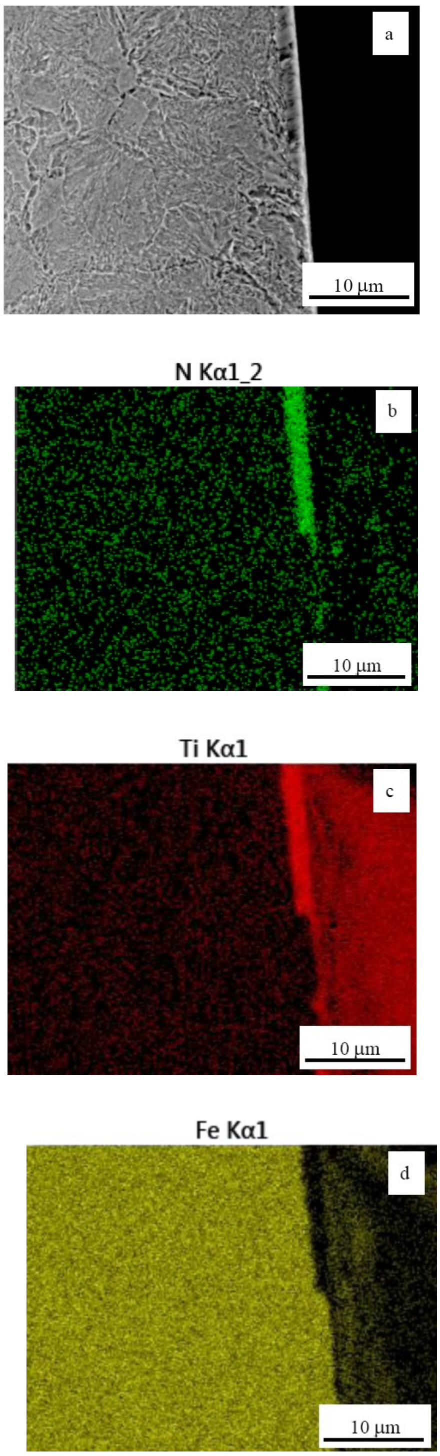

Figure 15. a) Cross section of a tooth with a TiCN coating (SEM),b) N distribution (EDS map), c) Ti distribution (EDS map), d) Fe distribution (EDS map)

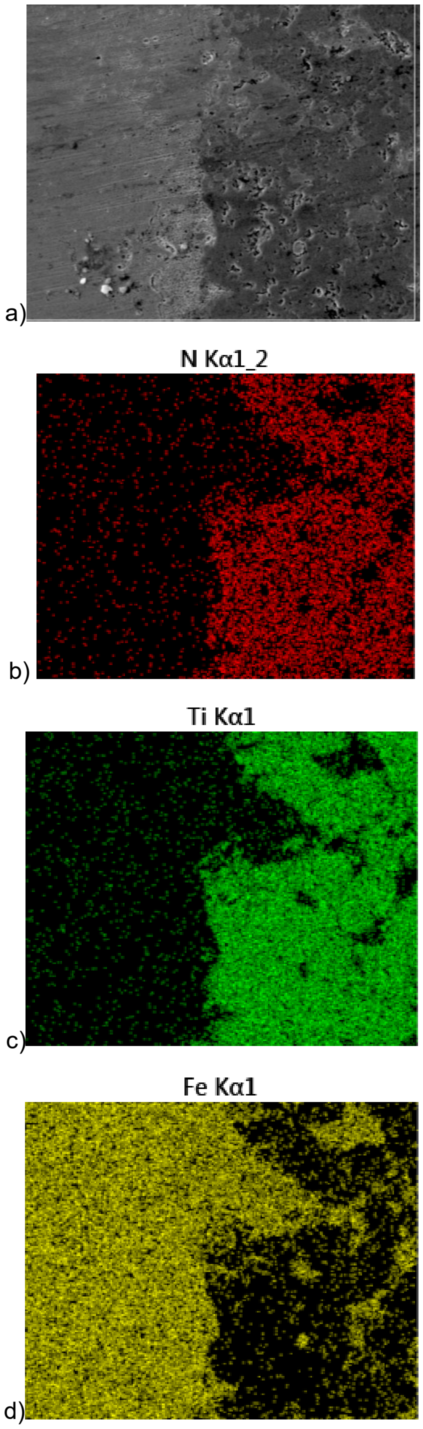

Figure 16. a) Surface of worn tooth - removed part of the TiCN coating and TiCN coating (SEM), b) N distribution (EDS map), c) Ti distribution (EDS map), d) Fe distribution (EDS map)

The coatings were gradually removed from the hard coating. The softer substrate was worn-out so that the steel material was removed from the protrusions of the unevenness and then filling-up depressions. However, account must always be taken of the fact that the use of lubricant also influences significantly the stated load capacity.

The resistance of TiCN coatings can be improved by increasing the substrate hardness, e.g. after quenching tempering at lower temperatures. It slows down the coating force into the substrate, which prevents it from being removed and substrate wear is slowed down.

4 CONCLUSION

Tribological tests under laboratory conditions were performed according to the required standards. The TiCN of 3.3 µm. Under laboratory conditions, tribological tests were performed on small samples to compare the adhesion of the coating to the C60E steel substrate. The influence of the load on the friction coefficient was evaluated. The Niemann test showed different values of the load capacity of both tested gearings (TiCN coating on the gear wheels a non coated gear wheels) when the Biogear S 150 organic lubricant was used. The gearing with the TiCN coating seized up after the at the 6th load stage and non coated gearing seized up after the at the 5th load stage.

From the point of view of prediction of load-capacity, the decisive hardness and thickness of the coatings have been demonstrated. The reason is that in terms of Hertz theory, in the case of C-C gearing, better results occur due to smaller contact pressures on the teeth. The lower specific slip, contact pressure and the application of the chosen type of oil in C-C gearing allows the use of coatings with a higher friction coefficient. In the case of involute gear teeth it is therefore preferable to select the application of multi-coating with a lower friction coefficient. An increase in the load capacity of the coatings can also be achieved by increasing the hardness of the surface of the base material. By tempering the substrate at 200 – 220 °C, greater hardness of the base material is obtained, thereby slowing down the wear of the coating on the surface of the teeth. Greater hardness will also slow down substrate wear after the applied coating is removed.

ACKNOWLEDGEMENTS

This work was supported by the Grant Agency of the Ministry of Education of the Slovak Republic within the project VEGA 1/0394/16 Study of the possibilities of preparation and application of composite materials from waste wood and plastics and the project VEGA 1/0227/15 Study of tribological characteristics of the new high hardness coatings on the materials suitable for gearings and Regional Center University Research Park Slovak University of Technology in Bratislava, Faculty of Mechanical Engineering.

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