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FRICTION REDUCTION AND IMPROVEMENT OF THE SCUFFING RESISTANCE OF SPIRAL BEVEL GEARS BY A LOW-FRICTION COATING

REDUKCJA TARCIA ORAZ POPRAWA ODPORNOŚCI NA ZACIERANIE KÓŁ ZĘBATYCH STOŻKOWYCH O ZĘBACH ŁUKOWYCH POPRZEZ OSADZENIE POWŁOKI NISKOTARCIOWEJ

Key words:

spiral bevel gear, friction, scuffing, thin coating

Słowa kluczowe:

koło zębate stożkowe o zębach łukowych, tarcie, zacieranie, cienka powłoka

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Abstract

There are many problems in the operation of spiral bevel gears; for example difficult lubrication conditions and high friction between meshing teeth leads to excessively high oil temperature and the risk of scuffing.

Thus, the aim of this work was to check whether by the deposition of a thin, hard, low-friction coating on the teeth flanks of spiral bevel gears it is possible to reduce friction and improve scuffing resistance.

The tribological experiments were carried out using two tribotesters: T-02U Four-ball testing machine and T-30 Bevel gear test rig. Two types of thin, low-friction coatings were tested. The first one was a-C:H:W. The other one was MoS_2/Ti. The coatings were deposited on one or more tested samples (test balls and bevel gears), so the four material combinations were obtained: steel-steel, coating-steel, steel-coating, and coating-coating. For lubrication a commercial, mineral automotive gear oil of the API GL-5 performance level and 80W-90 viscosity grade was used.

The results of the four-ball tests show that the a-C:H:W coating deposited on the teeth flanks is much more effective in friction reduction than MoS_2/Ti.

The deposition of the a-C:H:W coating on the teeth of the spiral bevel gears proves to be very helpful in reducing friction between the meshing gears. The combination of the a-C:H:W-coated pinion meshing the uncoated wheel is the most efficient. Concerning the improvement of the scuffing resistance, two material combinations are the most effective: a-C:H:W-coated pinion meshing the uncoated wheel and the both gears coated.

INTRODUCTION

Bevel gears consist of cone-shaped pinions and wheels with crossing axes (the 0 offset) and are used in those drive trains where there is a need to change the direction of torque transmission (mostly by 90º). It can be estimated that bevel gears are used, for example, in 20–30% of the speed reducers; therefore, in the present-day technology, the importance of bevel gears is high.

In spite of long-term development of the technology of bevel gear manufacturing, the producers of drivetrains equipped with bevel gears report various operational demands. One of the main issues is related to the reduction of friction, resulting in a decrease in the oil temperature and the tendency to scuffing (**Fig. 1**). Such an effect may be achieved by the deposition of a thin, hard, low-friction coating on the tooth flanks of bevel gears; although, the present-day research in this area is limited rather to spur gears **[L. 1–7]**.

Addressing the above demand requires the use of a test rig capable of the friction and wear testing of bevel gears. Worldwide, there are only individual testing machines of this type, i.e. the hypoid (including bevel) gear-testing machine developed in the Gear Research Centre (FZG) at the Technical

University of Munich **[L. 8, 9]**, or the test rig intended for aeronautics, designed at NASA Glenn Research Centre (USA) **[L. 10]**. Such test rigs are not widely available, which is probably why most of the papers concerning bevel gears concentrate on only two aspects. The first is the use of mathematical modelling for the optimization of the profile and meshing conditions of bevel gears teeth, and for the improvement of the production technology **[L. 11–14]**. The second one is limited to case studies, focusing on the explanation of operational causes of bevel gear scuffing, surface fatigue wear (pitting), and teeth breakage in various vehicles and industrial devices **[L. 15–17]**.

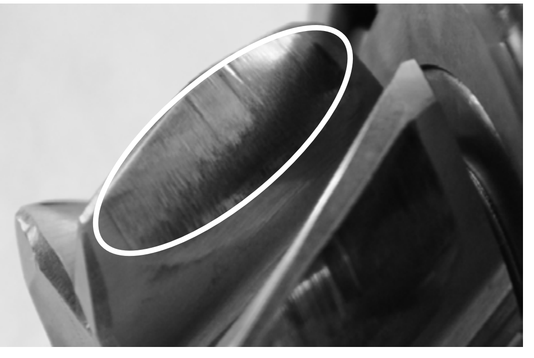

Fig. 1. Scuffed area on the tooth flank of a spiral bevel gear (in the white ellipse)
Rys. 1. Obszar zacierania na zębie koła stożkowego o zarysie łukowym

Apart of the test rig, in the tribological testing of bevel gears, a necessary factor is the usage of proper test methods. Unfortunately, there are no standardised tests, and the proposals of authorial methods for testing bevel gears are rarely presented in publications **[L. 8, 9]**.

At ITeE – PIB in Radom, a new test rig for the tribological testing of bevel gears was developed, and the authorial method for testing scuffing of bevel gears was designed **[L. 18]**. They were used to check potential, beneficial effects of the deposition of low-friction coatings on the teeth of spiral bevel gears, e.g. the friction reduction and scuffing resistance improvement.

EXPERIMENTAL

Test samples and tribotesters

In the four-ball tests, test balls were chrome alloy bearing steel with diameters of 12.7 mm (0.5 in.). Surface roughness did not exceed R_a = 0.032 μm, and hardness was between 60 to 65 HRC.

In the bevel gear scuffing tests, specially designed test, spiral bevel gears (**Fig. 2a**) were used, which were machined in a high, 5th grade of precision (according to DIN 3965), from 18CrNi8 steel, carburised up to 0.6–0.9 mm of depth, and tempered to 56–60 HRC of hardness. Both gear elements were machined by means of Klingelnberg's method. The T-30 Back-to-back bevel gear test rig, designed with the cooperation of the invenio company, and manufactured at ITeE – PIB, was used for the testing – **Fig. 2b**).

a)

b)

Fig. 2. Test spiral bevel gears (a), and T-30 Back-to-back bevel gear test rig (b)
Rys. 2. Testowe koła stożkowe o zębach łukowych (a) oraz urządzenie do badań kół zębatych stożkowych T-30 (b)

Test methods and materials

In the four-ball tests the friction torque was measured, and then the friction coefficient was calculated. The test parameters were the following: applied load = 392 N (40 kG), rotational speed = 500 rpm, run duration = 1 h, and initial oil temperature = 20ºC. Between the top and bottom balls, pure sliding took place.

In the bevel gear scuffing tests, the loading torque was gradually increased from the 1st to the 12th load stage (pinion loading torque was changed from 3.3 up to 535 Nm). After the test run under a particular load stage, the teeth of the pinion were examined for the signs of wear, such as grooves and scuffing. The load stage was then increased up to the moment when the damaged area reached the area of one pinion tooth. The load stage under which the aforementioned criterion was reached is called the "Failure Load Stage" (FLS) and describes the resistance to scuffing of the tested bevel gears. During each run, the friction torque was measured. The other test parameters were as follows: pinion rotational speed = 3000 rpm, single run duration = 15 min, initial oil temperature = 90ºC (not stabilised during the run), dip lubrication with the oil level up the axis of the test gears.

The test samples were coated with the low-friction a-C:H:W coating, and composite low-friction MoS_2/Ti coating. All material combinations were tested: coating-coating (all test samples coated), coating-steel, steel-coating, and steel-steel for reference (all test samples without the coating). In all the cases, mineral, automotive gear oil of API GL-5 performance level and SAE 80W-90-viscosity grade was used for lubrication.

RESULTS

First, the four-ball tests were performed. Friction coefficients obtained for the tested material combinations are presented in **Fig. 3**. The coated ball is dim grey coloured, and the uncoated one is light grey. The confidence intervals for each result obtained are also shown in the figure.

From **Fig. 3**, it can be seen that, in the case of the a-C:H:W coating, its deposition on the top ball or on all the balls significantly reduces the friction coefficient in comparison with the steel–steel tribosystem; although, the scatter of results is relatively high. From the point of view of the friction reduction, the MoS_2/Ti coating is not as effective as the a-C:H:W. Only when the bottom balls are coated, a drop in the friction reduction is observed. Therefore, it is the a-C:H:W coating that was accepted for further testing.

To verify the four-ball results, bevel gear scuffing tests were carried out.

The resistance to scuffing for all the material combinations is presented in **Fig. 4**.

It can be observed from **Fig. 4** that when the a-C:H:W coating is deposited on one or two gears, the resistance to scuffing is significantly improved in comparison with the case of the uncoated gears; for the two material combinations: coated pinion meshing uncoated wheel and both gears coated the resistance to scuffing is the highest.

The comparison between the friction torques for the four tested material combinations and the load stages between 5th and 8th is shown in **Fig. 5**.

Concerning the average values of the friction torque, they were considered for the last four load stages, ending with the 8^{th} load stage, because that stage was the Failure Load Stage (FLS) in the case of the steel-steel material combination. It can be observed that the combination of the a-C:H:W-coated pinion meshing the uncoated wheel gave the considerably lowest friction torque at practically each load stage. Additionally, the a-C:H:W-coated pinion mating the a-C:H:W-coated wheel exhibited lower friction torques but not as low as for the previous situation.

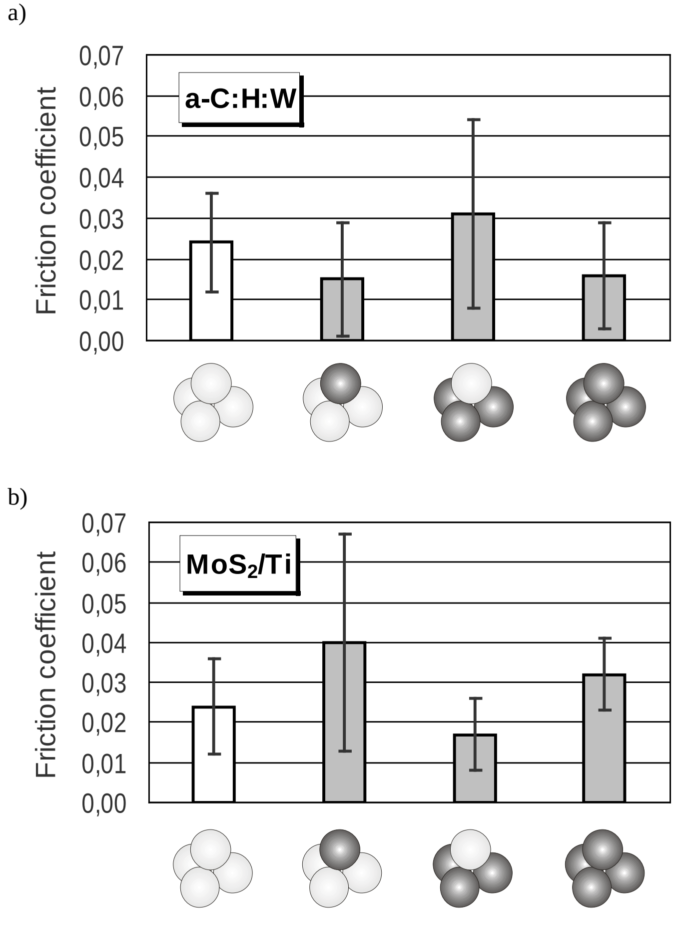

Fig. 3. The chart showing friction coefficients for various material combinations in four-ball tests: a) with a-C:H:W coating, b) with MoS_2/Ti coating

Rys. 3. Współczynnik tarcia dla różnych skojarzeń materiałowych w teście czterokulowym: a) z powłoką a-C:H:W, b) z powłoką MoS_2/Ti

To facilitate comparison of the friction reduction results, the relative reduction in the friction torque for the three material combinations with the a-C:H:W coating (referring to the steel–steel combination) was calculated for the load stages between 5th and 8th – **Fig. 6**.

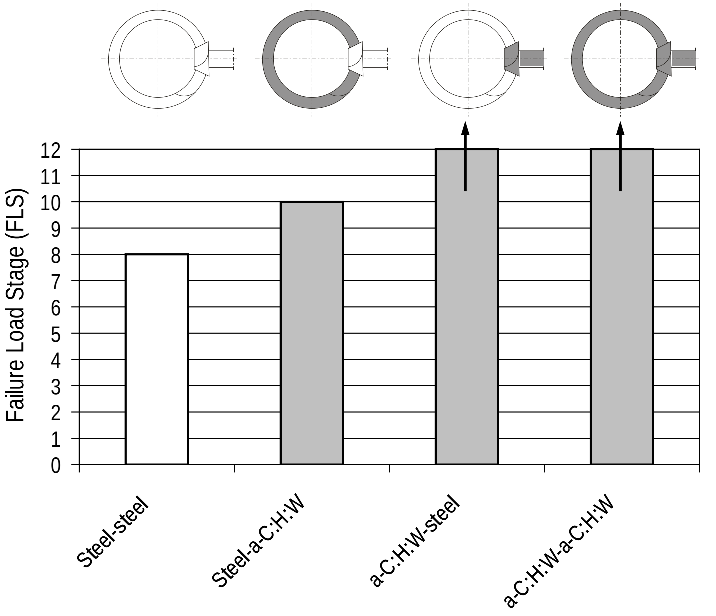

Fig. 4. The chart showing the resistance to scuffing for all the material combinations, measured by the Failure Load Stage (FLS)

Rys. 4. Odporność na zużycie dla wszystkich skojarzeń materiałowych, mierzona stopniem obciążenia niszczącego (FLS)

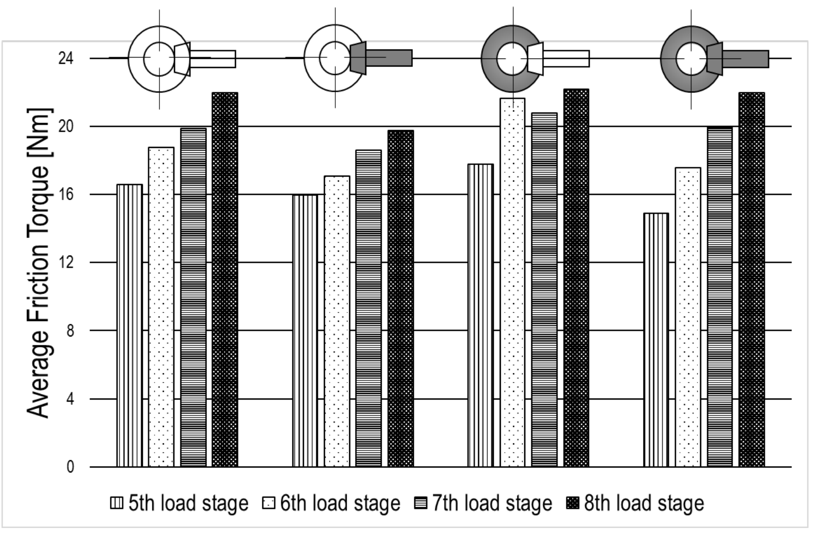

Fig. 5. The chart showing the comparison of the average values of the torque of friction forces for the material combinations with the a-C:H:W coating; results for steel pinion – steel wheel for reference

Rys. 5. Porównanie średnich wartości momentów tarcia dla skojarzeń materiałowych z powłoką a-C:H:W; wyniki dla skojarzenia bez powłoki podano dla odniesienia

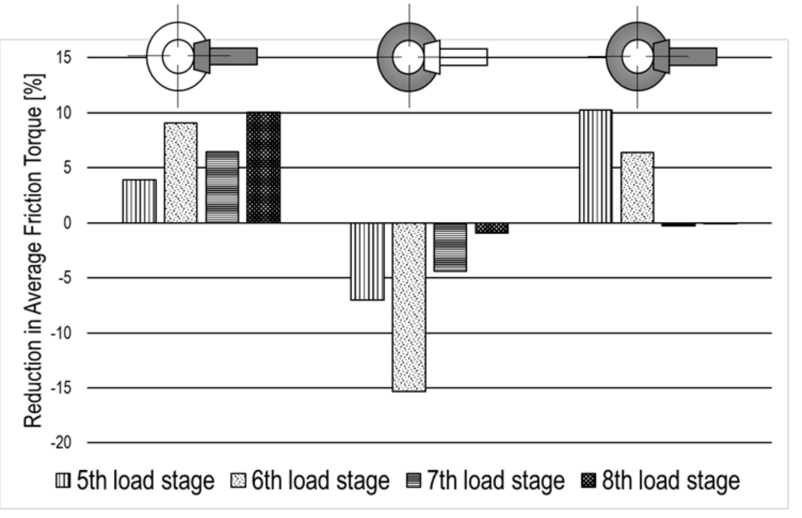

Fig. 6. The chart showing the percentage reduction of the torque of friction forces in relation to the situation of the uncoated pinion meshing the uncoated wheel (steel–steel)

Rys. 6. Procentowy spadek momentu tarcia w odniesieniu do skojarzenia bez powłoki

From **Fig. 6** it can be observed that for the material combination of the a-C:H:W-coated pinion – the uncoated wheel there was a reduction in the friction torque for each of the four considered load stages, even at the level of 10%. For the a-C:H:W – a-C:H:W material combination there was a reduction at the 5^{th} and 6^{th} load stages, but an increase in the torque at the 7^{th} and 8^{th} stages was observed. For the uncoated pinion mating the a-C:H:W-coated wheel there was an increase in the friction torque at each load stage.

Why various material combinations give various resistance to scuffing and friction reduction is to be solved yet. Comprehensive surface analyses of the worn tooth flanks are necessary and are planned, although some preliminary results can be found in **[L. 19]**.

SUMMARY AND CONCLUSION

By the deposition of the a-C:H:W low-friction coating on the teeth flanks of spiral bevel gears it is possible to reduce the tendency to scuffing and the level of friction in comparison with the uncoated gears.

For the two material combinations, coated pinion meshing uncoated wheel and both gears coated the resistance to scuffing is the highest.

The most effective from the point of view of the friction reduction is the combination of the a-C:H:W-coated pinion meshing the uncoated wheel – a significant reduction in the friction torque up to 10% is noticed – in comparison with the case of the uncoated gears. The reason for such a behaviour will be explained in further authors' works.

The results obtained can be used as guidelines by the bevel gear manufacturers to significantly improve the resistance to scuffing and reduce friction between the meshing teeth, without the necessity to look for better gear oils.

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Streszczenie

Istnieje wiele problemów związanych z eksploatacją kół zębatych stożkowych o zębach łukowych, np. trudne warunki smarowania i wysokie tarcie w zazębieniu, prowadzące do zbyt wysokiej temperatury oleju i pojawienia się ryzyka zacierania.

Celem prac było zatem stwierdzenie, czy poprzez osadzenie cienkiej, twardej powłoki niskotarciowej na zębach kół stożkowych możliwa jest redukcja tarcia oraz poprawa odporności na zacieranie.

Do badań tribologicznych użyto uniwersalnego aparatu czterokulowego T-02U oraz urządzenia T-30 do badań kół zębatych stożkowych. Przebadano dwie cienkie powłoki niskotarciowe: a-C:H:W oraz MoS_2/Ti. Zostały one osadzone na jednym bądź więcej elementach testowych (kulki łożyskowe, koła zębate), uzyskując cztery kombinacje materiałowe: stal–stal, powłoka–stal,

stal–powłoka i powłoka–powłoka. Do smarowania użyto handlowego, samochodowego oleju przekładniowego klasy jakościowej API GL-5 i lepkościowej 80W-90, z bazą mineralną.

Wyniki badań czterokulowych pokazały, że naniesiona na zęby koła powłoka a-C:H:W jest znacznie bardziej efektywna w redukcji tarcia niż MoS_2/Ti.

Wyniki badań przekładniowych wykazały, że powłoka a-C:H:W wykazuje skuteczność w redukcji tarcia także kół zębatych stożkowych o zębach łukowych. Najlepsze rezultaty uzyskano dla kombinacji materiałowej pokrytego powłoką zębnika współpracującego z niepokrytym kołem talerzowym.

W przypadku odporności na zacieranie najlepsze wyniki uzyskano dla dwóch kombinacji materiałowych: pokryty powłoką zębnik współpracujący z niepokrytym kołem talerzowym oraz oba koła pokryte powłoką.