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THE EFFECT OF LOW-FRICTION PVD COATINGS ON SCUFFING AND PITTING RESISTANCE OF SPUR GEARS

WPŁYW NISKOTARCIOWYCH POWŁOK PVD NA ZACIERANIE I PITTING WALCOWYCH KÓŁ ZĘBATYCH

Key words:

scuffing, pitting, spur gears, PVD coatings

Słowa kluczowe:

zatarcie, pitting, walcowe koła zębate, powłoki PVD

Summary

Recently, it was reported that low-friction coatings deposited on steel substrates exhibit excellent behaviour under scuffing conditions. However, a factor still limiting the scope of the application of the coatings is their poor performance under conditions of cyclic contact stress, which leads to accelerated fatigue

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failures (pitting). Two PVD coatings were tested: WC/C and MoS_2/Ti. For the complex testing of gears, a back-to-back gear test rig, denoted as T-12U, was used. Two methods were applied: scuffing shock test (S-A10/16,6R/120) and the gear-pitting test (PT C/10/90).

Steel gears coated with low-friction coatings exhibit excellent behaviour under scuffing conditions. The resistance to pitting wear of coated steel gears depends on not only the coating material but also on which steel gear is coated.

INTRODUCTION

The durability of heavily loaded gears depends on two phenomena: scuffing and rolling contact fatigue (pitting) **[L. 1]**. For many engineering materials, further improvement of their properties through a modification of their microstructure, chemical composition, and phase composition is practically impossible. In this situation, the life of machine components can be extended by the modification of its surface layers using new technologies, i.e. thin hard coatings **[L. 2]**. Many kinds of deposition processes, such as physical and chemical vapour deposition (PVD, CVD), have been developed, and the tribological properties of the coated surfaces vary with the deposition process and the alloyed elements. It is well known that thin hard coatings deposited on the surface of machine components improve scuffing resistance of non-conformal contacts **[L. 3]**. One of the most important characteristics of these coatings is the fact that their thickness, usually in the range from 1 to 5 µm, is located in the field of the dimensional tolerances of typical machine elements. That is why it can be deposited on existing parts. However, a factor still limiting the scope of the application of most coatings is their poor performance under conditions of cyclic contact stress, which leads to accelerated fatigue failures (pitting).

Comprehensive research on rolling contact fatigue indicates that PVD coatings like TiN, CrN – although optimised for tool application do not display a satisfactory fatigue life **[L. 3]**.

Recently, it was reported that low-friction coatings like WC/C (a-C:H:W type) and MoST (MoS_2/Ti) exhibit excellent behaviour under scuffing conditions **[L. 4, 5, 6]** and promising behaviour in cone-three balls pitting tests **[L. 7]**.

However, a factor still limiting the scope of the application of some coatings is their poor performance in pitting gear tests, and the application of a WC/C coating on both gears leads to accelerated fatigue failures (pitting) **[L. 7]**.

The newest investigations indicate that, in many applications, it is the most beneficial to coat only one of the contacting surfaces instead of both **[L. 8, 9]**. This aspect of the application of low-friction coatings on gears in respect to scuffing and pitting resistance was tested.

Four material combinations of gears were tested: wheel and pinion uncoated, wheel and pinion coated, wheel coated and pinion uncoated, as well as wheel uncoated and pinion coated.

COATINGS AND LUBRICANTS

Two PVD coatings were tested: WC/C and MoS_2/Ti. The WC/C coating was deposited using the PVD process by reactive sputtering **[L. 10]**. The WC/C (Tungsten Carbide/Carbon) coating also denoted as a-C:H:W or W-DLC is a DLC type representing a-C:H:Me group. This coating is comprised of hard tungsten carbide particles in a softer amorphous carbon matrix. The coating consists of an elemental Cr adhesion layer adjacent to the steel substrate, followed by an intermediate transition region consisting of alternating lamellae of Cr and WC and a hydrocarbon layer doped with W. The detailed design of the WC/C coating is depicted in **Fig. 1**.

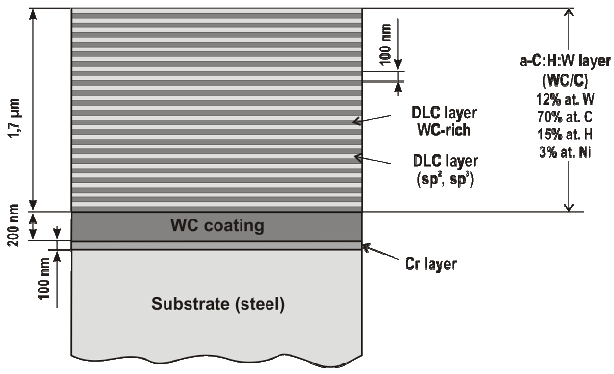


Fig. 1. Design of the WC/C coating
Rys. 1. Budowa powłoki WC/C

The MoS_2/Ti coating was deposited by DC Magnetron Sputtering using a CFUBMSIP process (closed field unbalanced magnetron sputter ion plating).

The coating procedure starts with ion cleaning followed by a 70 nm Ti layer, a 200 nm MoS_2/Ti multilayer, a 900 nm MoS_2/Ti (non-multilayer), and the last step of a 50 nm layer of MoS_2 for coloration. The detailed design of the coating is depicted in **Fig. 2**.

The coatings were deposited on original FZG Gear Types A10 and C-PT. The number of pinion teeth is 16, and wheel 24. The A10 test gears were made of 20MnCr5 steel. They were carburized; case hardened, tempered and Maag criss-cross ground according to FVA Information Sheet No. 243 Status June 2000. The C-PT test gears were made of 16MnCr5 steel. They were carburised, case hardened, tempered and ground according to FVA Information Sheet No. 2/IV, 1997 specifications.

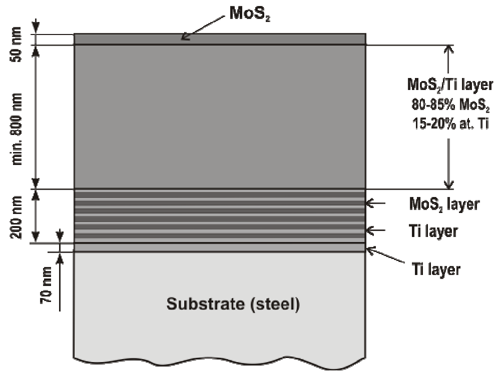


Fig. 2. Design of the MoS_2/Ti coating
Rys. 2. Budowa powłoki MoS_2/Ti

The test gears were lubricated using mineral automotive gear oil of API GL-5 performance level and 80W/90-viscosity grade.

THE SCUFFING AND PITTING GEAR TESTS

For the complex testing of gears, a back-to-back gear test rig, denoted as T-12U, was used.

The scuffing shock test method (S-A10/16,6R/120) is described in details in **[L. 4]**. In the used gear scuffing shock test, the load is not increased in stages from the lowest value, but the expected failure load is applied to an unused gear flank (hence, the name: “shock test”). The failure load stage (FLS) is determined.

Test conditions of the method used are summarised in **Table 1**.

Table 1. The conditions of gear scuffing shock test method
Tabela 1. Warunki badań dla metody szokowej zacierania kół zębatych

Parameter	Value
test gear type	FZG, type A10 (width of pinion face 10 mm)
motor rotational speed	3000 rpm
circumferential speed	16.6 m/s
direction of motor rotation	“reversed” (R)
run duration	7 min. 30 sec.
maximum load stage	12
maximum loading torque	535 Nm
maximum Hertzian stress	2.6 GPa
initial lubrication oil temperature	120ºC (uncontrolled after starting the run)
type of lubrication	dip lubrication (oil quantity ca. 1.5 dm^3)

The gear pitting test method (PT C/10/90) is described in FVA Information Sheet. No. 2/IV, 1997 and in **[L. 8]**. Test conditions are summarised in **Table 2**.

Table 2. The conditions of gear pitting test method
Tabela 2. Warunki badań pittingu kół zębatych

Parameter	Value
gear type	C-PT, face width 14 mm
rotational speed	1450 rpm
lubrication	dip lubrication
No. of valid runs	min. 2
Running in	
duration, h	2
torque, Nm	135 (6^{th} Load Stage)
oil temperature, °C	60 (uncontrolled during running in)
Test run	
duration	Until pitting criterion is reached, maximum $40x10^6$ Load Cycles at Pinion, Single run – 7 h
torque	372 Nm, 10^{th} Load Stage
max. Hertz contact pressure, GPa	1.8
oil temperature, °C	90 (controlled)

The gear-pitting test is performed on a pair of lubricated test gears until a damaged area of tooth flanks reaches the failure criterion. For every test run, a new gear flank and fresh lubricant were used. Each gear pair was tested on both flanks. After running in and after certain load cycle intervals, the test procedure was interrupted, and test gears were inspected for damage. The inspection interval was 7 operating hours. If the damaged area of tooth flanks reached the failure criterion, the test run was stopped. The total test time of each run was limited to 300 operating hours (about 40 million load cycles at pinion). The failure criterion was a pitting area on an individual tooth of at least 4% of the active flank (about 5 mm^2).

The failure probability of 50% (LC_{50}) was calculated on the basis of the Weibull distribution of pitting lifetimes at 2 or 3 runs and the pitting area of the last two inspections, according to FVA Information Sheet No. 2/IV, 1997.

RESULTS FROM SCUFFING TEST

Failure load stages (FLS) obtained for the tested material combinations are presented in **Figure 3**.

For both coatings, the best resistance to scuffing is observed when both gears are coated. Even at the highest possible load (12^{th} load stage), no significant wear marks were noted on the teeth.

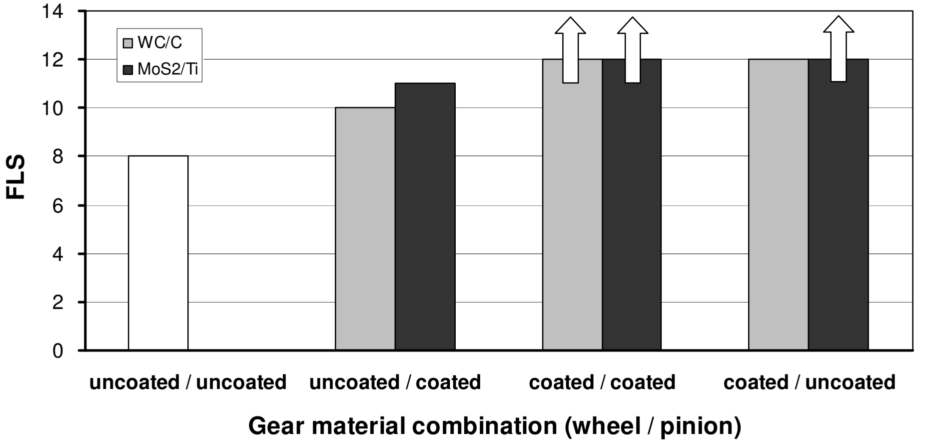
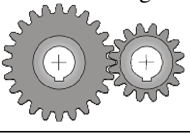
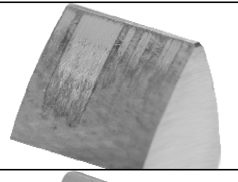
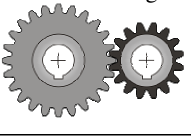
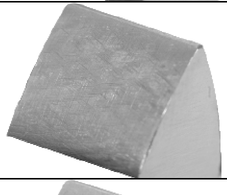
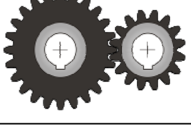
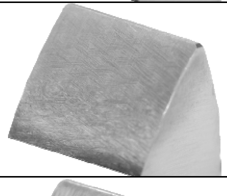
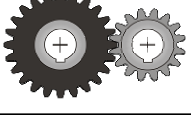
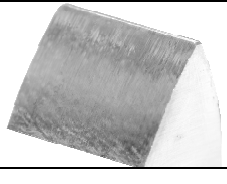


Fig. 3. Scuffing resistance for various wheel/pinion combinations
Rys. 3. Odporność na zacieranie różnych wariantów skojarzeń kół z powłokami

Table 3. Modes of the wear of the test pinion at particular load stages for the tested material combinations with the WC/C coating
Tabela 3. Zdjęcia zużycia koła zębatego małego przy poszczególnych stopniach obciążenia dla różnych wariantów skojarzeń kół z powłoką WC/C

8th Load stage 	A_p = 703 mm^2 W_w - not measured	
11th Load stage 	$A_p \approx 0$ W_w = 338 mg	
12th Load stage 	A_p = 6 mm^2 W_w = 145 mg	
12th Load stage 	A_p = 318 mm^2 W_w = 3 mg	

When the pinion is uncoated and the wheel is coated with the WC/C coating, the resistance to scuffing is slightly higher than in the case when the pinion is coated and the wheel is uncoated.

Modes of the wear of the test pinion at critical load stages for the tested material combinations with the a-C:H:W coating, together with the total area of failures on the pinion (A_p), and wear of wheel (W_w) as well as the photographs of the wear that appeared most often on the pinion teeth are presented in **Table 3**.

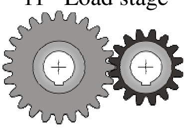
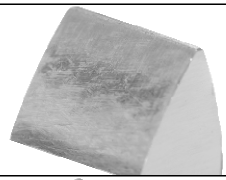
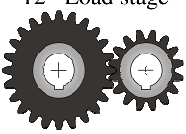
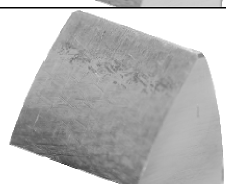
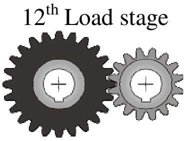
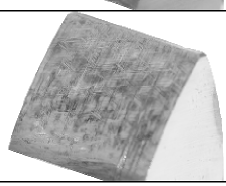
When one or both gears are WC/C-coated, only scratches and scoring predominate on the pinion teeth.

When the pinion is coated and the wheel uncoated, excessive wear of wheel occurs. Typical of "the action" of the WC/C coating, the uncoated gear undergoes the process of polishing through the rubbing by the hard coating. This process is discussed in **[L. 7]**.

Modes of the wear of the test pinion at critical load stages for the tested material combinations with the MoS_2/Ti coating, together with the total area of failures on the pinion (A_p), and wear of wheel (W_w) as well as the photographs of the wear that appeared most often on the pinion teeth are presented in **Table 4**.

Table 4. Modes of the wear of the test pinion at particular load stages for the tested material combinations with the MoS_2/Ti coating

Tabela 4. Zdjęcia zużycia koła zębatego małego przy poszczególnych stopniach obciążenia dla różnych wariantów skojarzeń kół z powłoką MoS_2/Ti

11th Load stage 	$A_p = 109\ mm^2$ $W_w = 25\ mg$	
12th Load stage 	$A_p \approx 0$ $W_w = 16\ mg$	
12th Load stage 	$A_p \approx 0$ $W_w = 9\ mg$	

For the material combinations with the MoS_2/Ti coating, the pinion wear was more severe than for WC/C coating. Additionally, unlike for the material combinations with the WC/C coating, in the case of MoS_2/Ti, the uncoated gear does not undergo the process of polishing through the rubbing by the hard coating.

RESULTS FROM PITTING TEST

The results from pitting tests obtained for gear material combinations with coatings are summarised in **Figure 4**.

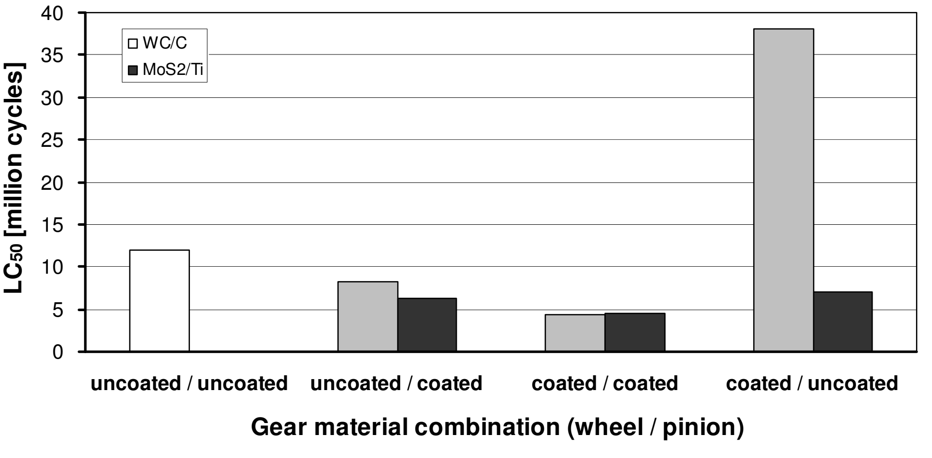


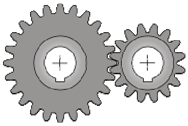
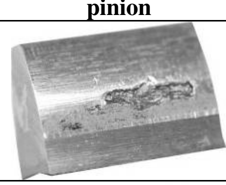
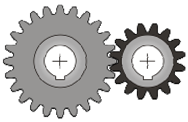
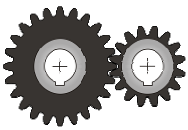
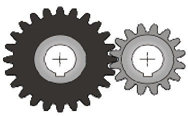
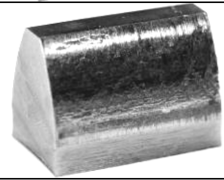
Fig. 4. The LC_{50} lives for various wheel/pinion combinations
Rys. 4. Trwałość LC_{50} różnych wariantów skojarzeń kół z powłokami

The WC/C coating can have either a positive or a negative effect on the rolling contact fatigue. The test results indicate that the resistance to pitting depends on which gear is coated. The highest durability was achieved for the WC/C coated wheel and the uncoated pinion. The most damaged surfaces on the tested gears are presented in **Table 5**.

The MoS_2/Ti coating always exerts a negative effect on the rolling contact fatigue. Similar to a WC/C coating, the resistance to pitting wear depends on which gear is coated. For the coated /coated pair, a significant decrease in the fatigue life is observed in comparison to the uncoated gears. A higher LC_{50} life was obtained for the coated wheel/uncoated pinion than for the uncoated wheel / coated pinion.

Table 5. The most damaged surfaces on pinion after the specified number of load cycles (WC/C coating)

Tabela 5. Wygląd najbardziej zużytego zęba koła małego po określonej liczbie cykli zmęczeniowych (powłoka WC/C)

Wheel/pinion	No. of load cycles	The most damaged surfaces on pinion
	7.1 x 10^6	
	4.7 x 10^6	
	8.5 x 10^6	
	40.6 x 10^6	

SUMMARY

The performed test proved that gears coated with low-friction coatings exhibit excellent behaviour under scuffing conditions. For the two coatings tested (WC/C and MoS_2/Ti), the best resistance to scuffing/scoring (FLS > 12) is observed when both gears are coated; however, the WC/C coating gives a slightly better protection against severe wear than MoS_2/Ti – only scratches instead of scoring are observed for WC/C.

The presented results indicate that the resistance to pitting of coated gears depends on not only the coating material but also on which gear is coated. While the MoS_2/Ti coating always has a negative effect, the WC/C coating can have either a positive or a negative effect on the rolling contact fatigue.

The application of coating on both gears, which is very effective in overcoming scuffing problems, or on the gear with a lower number of teeth, always decreases resistance to pitting.

Therefore, to increase both scuffing resistance and the fatigue life of gears, one should apply the WC/C coating and deposit it on the gear with the higher number of teeth, leaving the smaller one uncoated.

A general rule was summarised in **Fig. 5**. The resistance to pitting wear of coated gears depends on not only the coating material but also on which gear is coated.

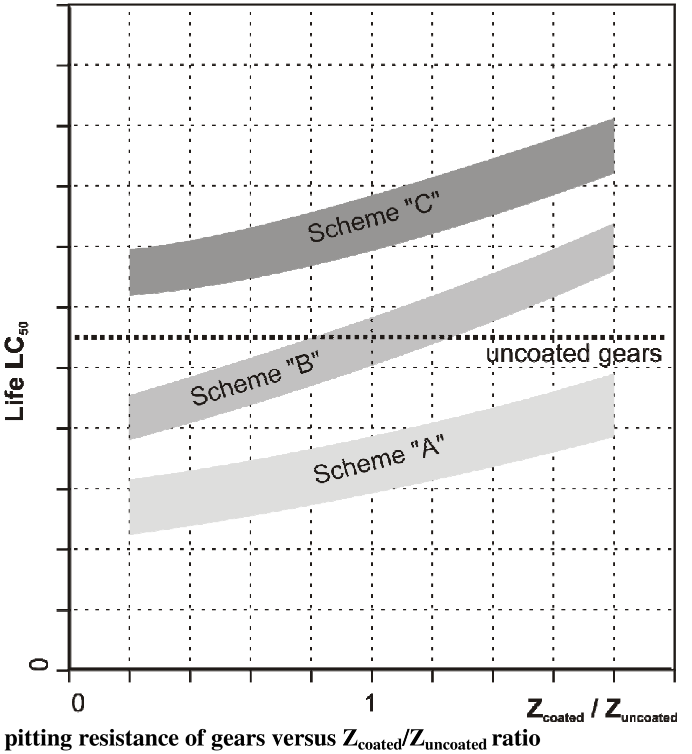


Fig. 5. The pitting resistance of gears versus $Z_{coated}/Z_{uncoated}$ ratio
Rys. 5. Zależność odporności na zużycie przez pitting od stosunku $Z_{coated}/Z_{uncoated}$

The maximum pitting resistance is achieved when the coating is deposited on the gear with the higher number of teeth to obtain a higher ratio of the number of coated teeth to the number of uncoated teeth ($Z_{coated}/Z_{uncoated}$). The three possible situations illustrated in **Fig. 5** are as follows:

- Scheme "A" (hypothetical) is related to single coatings used presently in tool applications (e.g. TiN, CrN).
- Scheme "B" is based on the research results and concerns WC/C low-friction coatings.
- Scheme "C" (hypothetical) is the most desired, but it is still unachievable and requires the development of a new generation of coatings.

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Streszczenie

Najnowsze badania wskazują, że stalowe koła zębate pokryte powłokami niskotarciowymi wykazują znacznie większą odporność na zacieranie niż koła stalowe bez powłok. Jednakże czynnikiem limitującym stosowanie

tychże powłok na koła zębate jest ich niewystarczająca odporność na powierzchniowe zużycie zmęczeniowe – pitting.

W pracy przeprowadzono badania dla dwóch powłok WC/C i MoS_2/Ti. Kompleksowe badania kół zębatych przeprowadzono z wykorzystaniem stanowiska pracującego w układzie mocy krążącej oznaczonego T-12U, stosując metodę zacierania szokowego (S-A10/16,6R/120) oraz metodę badania pittingu (PT C/10/90).

Przeprowadzone badania dowiodły, że stalowe koła zębate pokryte powłokami niskotarciowymi wykazują dobrą odporność na pitting. Ponadto dowiedziono, że odporność na pitting zależy nie tylko od rodzaju powłoki, lecz także od tego, które koło stalowe zostało pokryte.