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Original Research Article

A new scuffing shock test method for the determination of the resistance to scuffing of coated gears

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ABSTRACT

An improvement in the scuffing resistance of toothed gears is achievable by e.g. the deposition of thin, hard coatings onto the gear teeth. However, the testing of the scuffing resistance of coated gears requires the application of specialised test methods.

This paper presents a new test method, designed by the authors, called “gear scuffing shock test for coatings”. This method is based on the test method denoted as FZG S-A10/16,6R/110 developed at the Technical University of Munich. Because the FZG test method is dedicated exclusively to lubricating oils, its application for testing coated gears required introducing significant modifications.

The developed method has been verified during the testing of the scuffing resistance of gears coated with the low-friction a-C:H:W coating and composite low-friction MoS_2/Ti coating. Various material combinations were tested: coating–coating (both gears coated), coating-steel, steel-coating, and for reference steel–steel (both gears uncoated). Mineral, automotive gear oil of API GL-5 performance level, and SAE 80W-90-viscosity grade was used for lubrication.

It has been shown that this test method can be successfully applicable to test the scuffing resistance of coated gears—it has a resolution good enough to differentiate between the tested material combinations.

1. Introduction

The verification of the quality of newly developed gear oils and new techniques of surface engineering of the tooth surface of gears requires that gear testing should be used. The most often used is a unique complex of gear test methods developed in the Gear Research Centre (FZG) at the Technical University of Munich. Approximately, 500 FZG gear test rigs are used around the world [1].

The most often used and popular gear tests for lubricating oils are performed using the FZG A/8,3/90 scuffing test method. Unfortunately, this method makes it impossible to differentiate between gear oils having very good extreme-pressure (EP) properties, from the point of view of the resistance to gear scuffing [2]. This is why various scientific centres have developed their own test methods [2–5].

Recognising the problem of the low resolution of A/8,3/90 scuffing test, the FZG has developed a new method called “scuffing shock test”, denoted as S-A10/16,6R/90 or S-A10/16, 6R/110 (S—*shock*), depending on the initial temperature of the tested oil (90 or 110 °C). The new test method is described in detail in the literature, e.g. [6–11]. The scuffing shock test is

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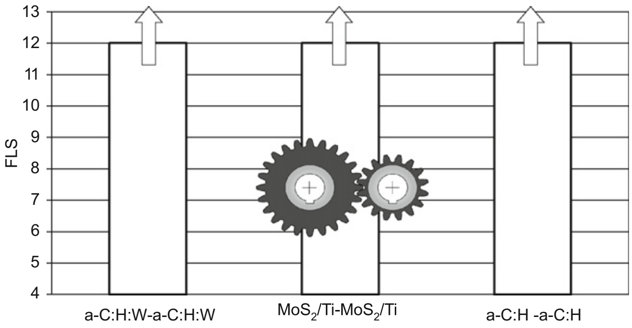


Fig. 1 – Failure load stages (FLS) obtained for the tested coatings (both gears coated)—FZG A/8,3/90 test method; data compiled from [15–17].

carried out under much severer conditions compared to the A/8,3/90 test. This is a result of the reduced face width of the small gear (pinion), doubling rotational speed, higher initial temperature of the tested oil, reversing the direction of rotation, and starting the test at once with a load at which the failure is expected, hence the name "shock test". Shock loading prevents the test gears from running-in and in turn increases their susceptibility to scuffing, which increases the method resolution.

Nowadays, one of the research directions in numerous scientific centres in the world is an improvement in the scuffing resistance of toothed gears, achievable by the deposition of thin, hard, low-friction coatings onto the gear teeth, e.g. the a-C:H:W or MoS_2/Ti coatings [12–14]. For the last several years, intensive research work has also been performed on this subject in the Tribology Department of ITeE-PIB. Until now, the FZG A/8,3/90 gear scuffing test method has been used most often in various scientific centres, which, like in the case of testing gear oils, exhibits too low resolution to differentiate between the coated gears from the point of view of their resistance to scuffing [15–17]—Fig. 1.

To solve this problem, in the Tribology Department of ITeE-PIB, research was undertaken to apply the FZG scuffing shock test for coated gears to differentiate between their resistance to scuffing. Because the FZG test method is dedicated exclusively to lubricating oils, its application for testing coated gears required introducing significant modifications—a unique test method has been developed, being the subject of this paper.

2. New test method

2.1. *Idea of the method*

The main difference between the test method designed by the authors and the gear scuffing shock test S-A10/16,6R/110, developed by FZG, is a rise in the initial oil temperature to 120 °C, adoption of another failure criterion related to wear of the wheel (big gear), and resigning from the criterion of invalidation of the test results when wear of the wheel exceeds 20 mg.

The test is performed on a pair of lubricated test gears with a coating (it can be applied on one or both the gears), run under the conditions mentioned below, at a constant rotational speed, and at the initial temperature of the lubricating oil identical for all the runs—until a failure load stage (FLS) is determined, i.e. such a load at which at least one of the failure criteria is met. 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"). Any time the change of the load requires the unused gear flank, so before the subsequent run the test gears should be disassembled and reversed or replaced with new ones.

Test conditions according to the developed method:

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 s
maximum load stage	12
maximum loading torque	535 N m
maximum Hertzian stress	2.6 GPa
initial lubrication oil temperature	120 °C (uncontrolled after starting the run)
type of lubrication	dip lubrication (oil quantity ca. 1.5 dm^3).

After starting the run the oil in the test chamber is heated by the heaters and due to friction. The oil temperature is allowed to rise freely. No cooling system is used in the test.

After run completion at a given load stage, the failures on the pinion teeth should be noted using the symbols from Table 1.

The runs are performed until the failure load stage (FLS) has been determined, which reflects the resistance of the test gears to scuffing. The FLS is such a load at which at least one of the failure criteria has been met and, and when at the load stage lower by one, neither of the failure criteria has been met. The failure criteria are specified in Table 2.

When there is significant decohesion of the coating due to poor adhesion to the surface, the run should be invalidated.

When both test gears are uncoated, a standardised test method S-A10/16,6R/110, developed by FZG should be used. However, to compare the results with the new test method, it

Table 1 – Modes of wear of the test pinion (small gear).

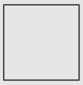
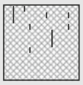
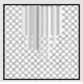
Mode of wear	Symbol	Appearance
Polishing	W	
Scratches	R	
Scoring	B	
Scuffing	Z	

Table 2 – Failure criteria according to the new test method.

Measured quantity	p–w[a] steel-coating	p–w coating-steel	p–w coating–coating
Total area of failures on the pinion (A_p)	$>$ 100 mm^2		
Wear (mass loss) of the wheel (W_w)	$>$ 200 mg		

[a] “p” —pinion (small gear) and “w”—wheel (big gear).

Table 3 – Comparison of the FZG gear scuffing tests and the method designed by the authors.

	Gear scuffing test FZG A/8.3/90	Gear scuffing shock test FZG S-A10/16,6R/110	New gear scuffing test
Purpose of test	Testing lube oils	Testing lube oils	Testing coatings
Test gear type	FZG A-type (pinion and wheel width 20 mm)	FZG A10-type (pinion width 10 mm, wheel width 20 mm)	FZG A10-type
Test materials	20MnCr5	20MnCr5	20MnCr5, but at least one gear coated
Motor rotational speed	1500 rpm	3000 rpm	3000 rpm
Circumferential speed	8.3 m/s	16.6 m/s	16.6 m/s
Direction of motor rotation	“Normal”	“Reversed” (R)	“Reversed” (R)
Run duration	15 min.	7 min 30 s	7 min 30 s
Maximum load stage	12	12	12
Maximum loading torque	535 N m	535 N m	535 N m
Maximum Hertzian stress	1.8 GPa	2.6 GPa	2.6 GPa
Loading type	Stepwise, from load stage 1	Shock (i.e. starting with a load at which the failure is expected)	Shock
Initial lubrication oil temperature	90 °C	110 °C	120 °C
Temperature stabilisation during the run by cooling	No	No	No
Type of lubrication	Dip lubrication	Dip lubrication	Dip lubrication
Failure criterion	$A_p \geq$ area of one pinion tooth ($\approx$200 mm^2)[a]	$A_p >$ area of one pinion tooth ($\approx$100 mm^2)	$A_p >$ area of one pinion tooth ($\approx$100 mm^2), or $W_w >$ 200 mg[b]
Criterion of invalidation of the run	None	$W_w >$ 20 mg (if FLS is not reached)	Significant decohesion of the coating

[a] A_p—total area of failures on the pinion.
[b] W_w—wear (mass loss) of the wheel.

is necessary to start a run at the initial oil temperature of 120 °C rather than 110 °C.

If the failures are observed only within 1 mm from the tooth addendum, they are only scratches, or the failures are so small that the original criss-cross-grinding pattern is still intact, they should be neglected when calculating the total area of the failures.

To better explain the differences between the “old” FZG gear scuffing test A/8.3/90, scuffing shock test S-A10/16,6R/110 and the new test method designed by the authors, the test conditions according to each method and the failure criteria are specified in Table 3.

2.2. Test gears

A photograph of the FZG A10 scuffing test gears employed in the test according to the developed method is shown in Fig. 2.

The A10 test gears are made of 20MnCr5 steel. They are carburised, case hardened, tempered, and Maag criss-cross ground. The effective face width of the pinion is 10 mm and

Fig. 2 – Photograph of the FZG A10 scuffing test gears.

the wheel 20 mm. The number of pinion teeth is 16 and wheel 24. The gears are identical to the ones used to perform tests according to the FZG S-A10/16,6R/110 method.

2.3. *Test equipment*

For the complex testing of gears, a back-to-back gear test rig, denoted as T-12U, was designed in the Tribology Department of ITeE-PIB in Radom. Its photograph is presented in Fig. 3 and kinematic schemes—in Fig. 4.

Fig. 3 – Photograph of the T-12U gear test rig.

The T-12U test rig is equipped with a control-measuring system, which consists of measuring transducers (such as thermocouple and speed transducer) and the controller (Fig. 3).

During runs, the following quantities are measured: rotational speed, lubrication oil temperature, motor current load, time, and the number of motor revolutions. The measured values are displayed on the controller.

The test rig is mounted on the concrete base equipped with vibration-dumping feet.

The T-12U gear test rig is a back-to-back rig (Fig. 4) where the test gears 2 and 3, located in the test chamber 5 are connected by two shafts to the slave gears, located in the chamber 9. The front shaft 8 has two parts. Between them there is the load clutch 7. To apply the loading torque between the meshing gears, before the run one part of the shaft (the left part of the front shaft 8) is fixed to the base with the lock-pin via the clutch and its support. A round-shaped loading lever 12 is placed on the right part of the clutch 7, and then the weight hanger 13 is suspended and appropriate number of weights 14 put on it. They give a static loading torque by twisting the shafts, which is measured indirectly—using the torsion angle indicator 6. When the load has been applied, the two halves of the clutch 7 are firmly fixed against each other with the bolts. Then, the lock-pin is removed to close the safety cover. During the run the loading torque "circulates" between the gears. In the back-to-back solution the motor 11 must overcome only the friction between gears, rolling bearings, and some minor components of friction (friction against seals, internal friction in the oil). Thus, the whole design is very simple and compact.

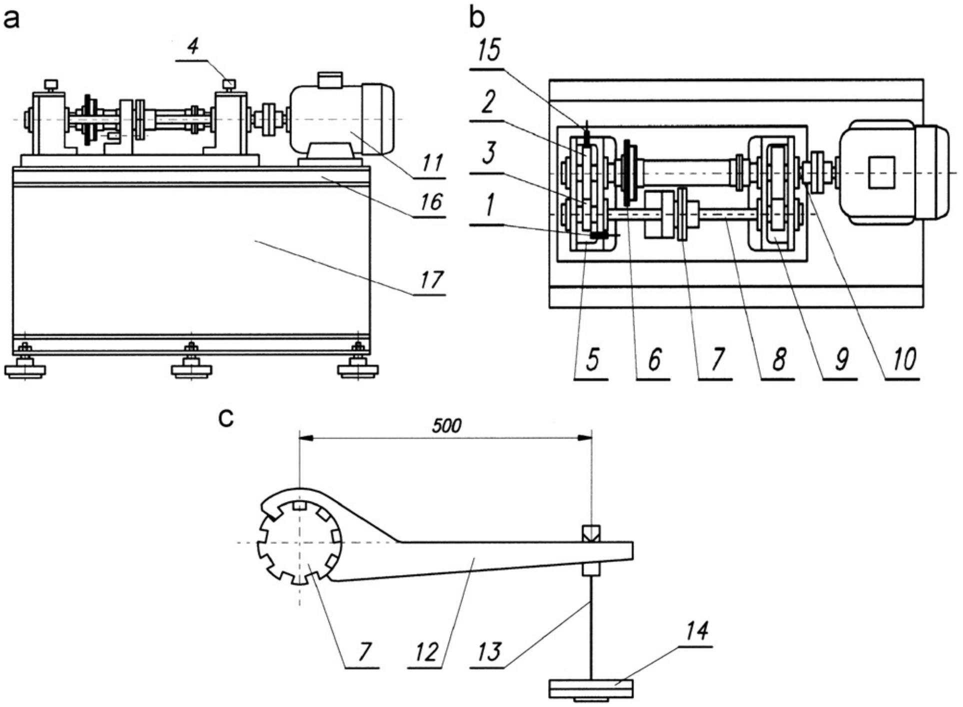


Fig. 4 – Kinematic schemes of the T-12U gear test rig: (a) front view, (b) top view, (c) loading equipment; 1—thermocouple, 2—test wheel, 3—test pinion, 4—vent, 5—test chamber, 6—shafts torsion angle indicator, 7—load clutch, 8—front shaft, 9—slave chamber, 10—drive clutch, 11—electric motor, 12—loading lever, 13—weight hanger, 14—weights, 15—heaters, 16—frame, and 17—concrete base.

An AC squirrel-cage motor 11 of the nominal rotational speed of 3000 rpm is used to drive the rig. It is controlled by the frequency converter, which enables to change the rotational speed within a wide range.

In the gear scuffing shock tests the test gears are dip lubricated. In the test chamber where test gears are located there are two heaters 15 to heat up the lubricating oil. The thermocouple 1, with the measuring point inserted in the lubricating oil, is to measure the oil temperature. A PID controller is used to protect against overheating of the lubricating oil.

The motor 11 of the machine is automatically stopped when the preset time elapses. The required time is set on the controller panel. Additionally, the operator can read out the number of motor revolutions to confirm the correct duration of the run. The number of motor revolutions is displayed on the controller panel (Fig. 3) connected to the speed transducer.

In the T-12U machine the friction torque can be measured indirectly—by measurement of the motor current load, which can be assumed to be proportional to the friction torque.

The test rig has a special support–on the side cover of the test chamber 5–for mounting vibration transducers (accelerometers) to enable the operator to monitor the level of vibrations along different axes. However, now there is no possibility to automatically stop the motor when the vibration level is very high. This feature (together with other features like direct measurement of the friction torque) will be included in a new test rig, denoted as T-12UF, being developed at present.

Additional equipment includes a mass comparator for a very precise determination of the mass loss (wear) of the wheel.

2.4. *Test materials*

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

2.5. *Statistical analysis*

To check statistical differences between the results obtained, the uncertainty of measurement was assessed—for the gear scuffing tests performed under "shock" conditions. This was done according to the procedures specified in the document EA-4/16 G:2003—binding in the accredited laboratories meeting the requirements of ISO/IEC 17025:2005.

In the statistical analysis of the quantitative results of experiments researchers most often use either the standard deviation, or confidence intervals calculated for a level of confidence of 95%. They are calculated on the base of experimental results taking into account the results of at least three runs.

The uncertainty of measurement includes not only the statistical assessment of experimental data, expressed by e.g. the standard deviation, but also the data from "non-statistical" sources, e.g. certificates of calibration of the measuring instruments, accuracy of measurement by a given operator, accuracy of calibration of the measuring channels, etc. All these data build up the so-called "budget of uncertainty", being the base for the calculation of the standard uncertainty. Then, the expanded uncertainty is calculated by multiplication of the standard uncertainty by a coverage factor $k=2$, which for a normal distribution provides a level of confidence of approximately 95%. In the paper, for simplification the expanded uncertainty is called "uncertainty of measurement". Once it has been calculated, the test result y and the uncertainty of measurement (expanded uncertainty) U should be reported as $y \pm U$.

As a normal practice, the uncertainty of measurement is given in relation to the average value of the measurement. For the gear scuffing tests performed under "shock" conditions, the respective formula is expressed as follows:

$$U = 0.45 + 0.06 \times \mathrm{FLS} \tag{2.1}$$

where U is the uncertainty of measurement (expanded uncertainty) and FLS is the failure load stage.

According to ILAC-G8:03/2009, if the uncertainty intervals expressed by U do not overlap each other, one can say that the compared results are statistically different.

3. Results and discussion

3.1. *Material combinations with the a-C:H:W coating*

Failure load stages (FLS) obtained for the tested material combinations with the a-C:H:W coating are presented in Fig. 5. The coated gear is dim grey coloured and the uncoated one is light grey coloured. The assessed uncertainties of measurement for each result obtained are also shown in the Fig. 5.

Fig. 5 shows that the new test method makes it possible to differentiate between the tested material combinations. 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.

When the pinion is uncoated and the wheel is coated with the a-C:H:W coating, the resistance to scuffing is slightly higher than in the case when the pinion is coated and the wheel is uncoated. The probable reason is that there is a transfer of graphite (solid lubricant) from the a-C:H:W coated gear to the teeth of the uncoated one, which is more effective for the wheel coated than in the opposite situation, because the area of the coated steel surface of the wheel (big gear with 24 teeth) is greater than in the case the coating is deposited on the pinion (small gear having only 16 teeth). One must have in mind, however, that the difference in the scuffing resistance of the two material combinations is not statistically significant, because the measurement uncertainties overlap each other.

In comparison to the case of the both gears uncoated, when the a-C:H:W coating is deposited on one or two gears, much

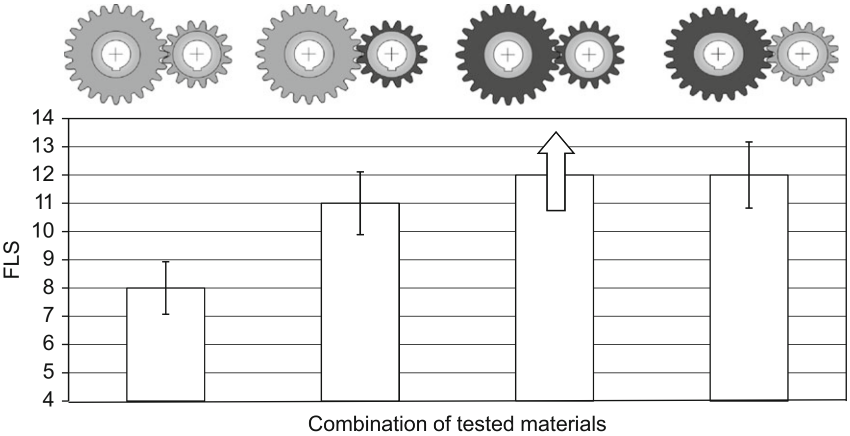


Fig. 5 – Failure load stages (FLS) obtained using the new test method for the tested material combinations with the a-C:H:W coating.

higher resistance to scuffing is observed. This is a result of a smaller affinity in the different materials than when both of them are identical (i.e. steel–steel). Yet another phenomenon can be attributed to it. When one of the mating materials (coating) is much harder than the other one (steel), or when two very hard materials are in contact (coating–coating) there is a reduction in the tendency to adhesive bonding, hence scuffing.

Although in the name of the developed method the word "scuffing" is used, and for simplification the phrase "resistance to scuffing" is employed, one should have in mind that the failure criteria specified in Table 2 may be met when another form of severe wear, namely scoring, occurs. This will be explained on the basis of the results compiled in Table 4. The table presents the symbolic modes of the wear of the test pinion at particular load stages for the tested material combinations with the a-C:H:W coating—the mode of wear that appeared most often on the pinion teeth was taken into account. The photographs of the most often appearing mode of wear of the pinion at the highest load stage are also shown in the table. Grey cells in the table denote the failure load stage (FLS). Below the symbols of the wear modes, the total area of failures on the pinion (A_p) and wear of wheel (W_w) are given. The used symbols of wear were presented earlier in Table 1.

As can be observed in Table 4 for the tested material combinations, three modes of wear appear most often on the pinion teeth—scratches, scuffing, or scoring.

When one or both gears are a-C:H:W-coated, only scratches and scoring predominate on the pinion teeth.

Scratches appear as shorter or longer fine lines in the sliding direction of the tooth flanks. If only scratches predominate on the coated pinion teeth, i.e. the measured total area of failures is very small then it is the wear of the wheel (mass loss) that may be decisive for the identification of the failure load stage (FLS).

Scoring appears on the uncoated pinion, when the wheel is coated with the a-C:H:W coating—Table 4. On the basis of CEC L-07-95 standard, it can be adopted that scoring marks run in the same direction as scratches. They occur singly or in zones as light, medium or deep grooves continuing towards the tip of the tooth and having a rougher appearance than the criss-cross-grinding pattern—Fig. 6.

What is typical of "the action" of the a-C:H:W coating, the uncoated gear undergoes the process of polishing through the rubbing by the hard coating. This can be seen in Fig. 7.

The role of such polishing is to be explained in further experiments planned by the authors.

Scuffing is observed only when the two gears are uncoated—Table 4. Like scoring, scuffing is one of the most dangerous modes of gear wear. According to CEC L-07-95 standard, scuffing marks occur as single, fine marks or strips, or areas covering a part or all of the flank width. They appear as dull areas with the roughness much greater than the original criss-cross-grinding pattern shown in Fig. 6. In this case the grinding pattern is no longer visible.

The difference between scuffing and scoring is that scuffing originates from the adhesive bond creation between the mating surfaces, which are then sheared, and scoring results from mechanical abrasion of the surface by the very hard wear particles under conditions of a very high load.

3.2. *Material combinations with the Mos$_2$/Ti coating*

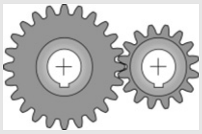
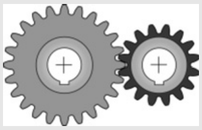
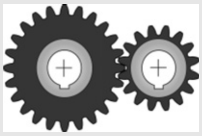
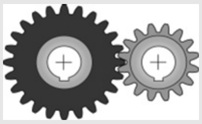
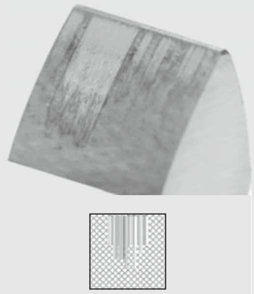
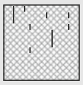
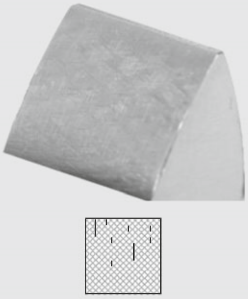
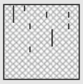
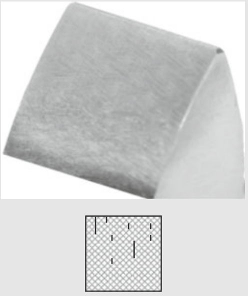
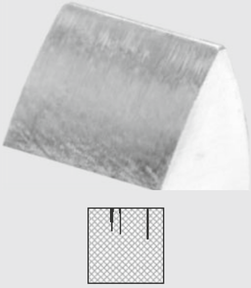
Failure load stages (FLS) obtained for the tested material combinations with the MoS$_2$/Ti coating are presented in Fig. 8.

Fig. 8 shows that the best resistance to scuffing is observed when both gears are coated with the MoS$_2$/Ti coating, or when the uncoated pinion meshes the coated wheel.

Like in the case of the a-C:H:W coating, when only the wheel is MoS$_2$/Ti-coated, the resistance to scuffing is higher than in the situation when only the pinion coated. The probable reason is that there is more effective transfer of MoS$_2$ (solid lubricant) from the MoS$_2$/Ti-coated wheel to the teeth of the uncoated pinion than in the opposite situation, because the area of the coated steel surface of the big gear (wheel) is greater than in the case when the coating is deposited on the small gear (pinion).

In comparison to the case when both gears are uncoated, a much higher resistance to scuffing is observed when the MoS$_2$/Ti coating is deposited on one or two gears.

Table 4 – Modes of the wear of the test pinion at particular 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); grey cells—the failure load stage (FLS).

Load stage				
7	 $A_p = 26\ \text{mm}^2$ $W_w = 1$ mg			
8	 $A_p = 703\ \text{mm}^2$ W_w - not measured			
9				
10		 $A_p \approx 0$ $W_w = 180$ mg		
11		 $A_p \approx 0$ $W_w = 338$ mg	 $A_p = 5\ \text{mm}^2$ $W_w = 76$ mg	 $A_p \approx 0$ $W_w = 2$ mg
12			 $A_p = 6\ \text{mm}^2$ $W_w = 145$ mg	 $A_p = 318\ \text{mm}^2$ $W_w = 3$ mg

The respective mechanisms of this behaviour were described earlier.

Table 5 presents the symbolic modes of wear of the test pinion at particular load stages for the tested material combinations with the MoS_2/Ti coating. Like in the case of the a-C:H:W coating, the mode of wear that appeared most often on the pinion teeth was taken into account. The photographs of the most often appearing mode of wear of the pinion at the highest load stage, are also shown in the table. Grey cells in the table denote the failure load stage (FLS). Below the symbols of the wear modes, the total area of failures on the pinion (A_p) and wear of wheel (W_w) are given. The used symbols of wear were presented earlier in Table 1.

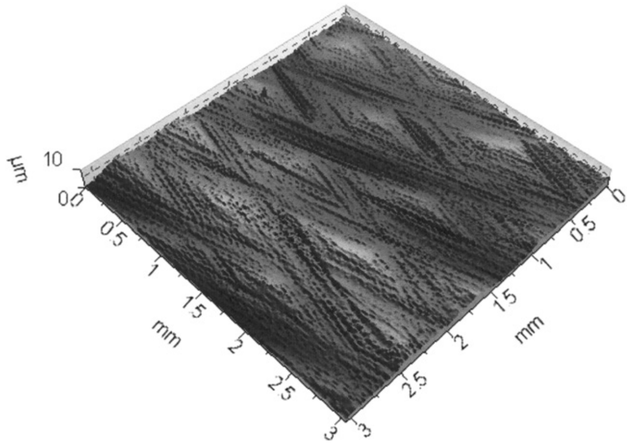


Fig. 6 – Original criss-cross-grinding pattern on the test gear teeth—stylus profilometry image.

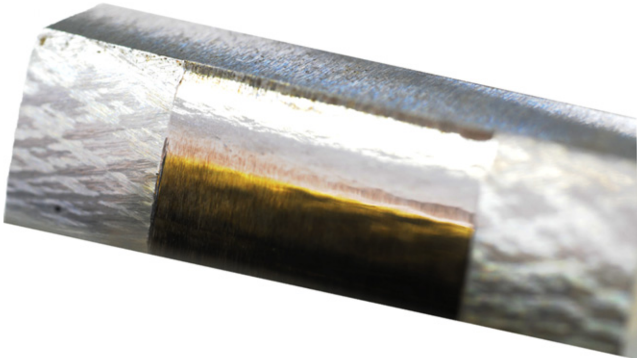


Fig. 7 – Photograph of the tooth of the uncoated wheel, polished by the a-C:H:W-coated pinion.

As can be observed in Table 5 for the tested material combinations, two modes of wear appear most often on the pinion teeth—scuffing or scoring. When one or both gears are coated, only scoring predominates on the pinion teeth.

When the pinion is coated and the wheel is uncoated, and when both the gears are coated, identical results were obtained for the two investigated coatings—FLS values are respectively 11 and higher than 12 (Figs. 5 and 8). Therefore, the main measurement of the resistance to scuffing/scoring makes it impossible to differentiate between these two situations. Under these circumstances, the analysis of the modes of wear at particular load stages can give additional, valuable information. In the case of the material combinations with the a-C:H:W coating, the predominating mode of wear of the pinion was only scratches. For the material combinations with the MoS_2/Ti coating, the pinion wear was much severer, and scoring instead of scratches could be met most often. Thus, the a-C:H:W coating provides a better protection against severe wear than MoS_2/Ti. The reason for this behaviour is not related to the coating nanohardness—for a-C:H:W it is 1081 HV (lower) and for MoS_2/Ti it is 1500 HV (higher). What is more—unlike for the material combinations with the a-C:H:W 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. To explain these phenomena, further analyses are necessary and planned by the authors in the near future.

4. Summary and conclusions

The analysis of the values of the failure load stage (FLS), reflecting the resistance to scuffing, shows that the developed gear scuffing shock test for coatings makes it generally possible

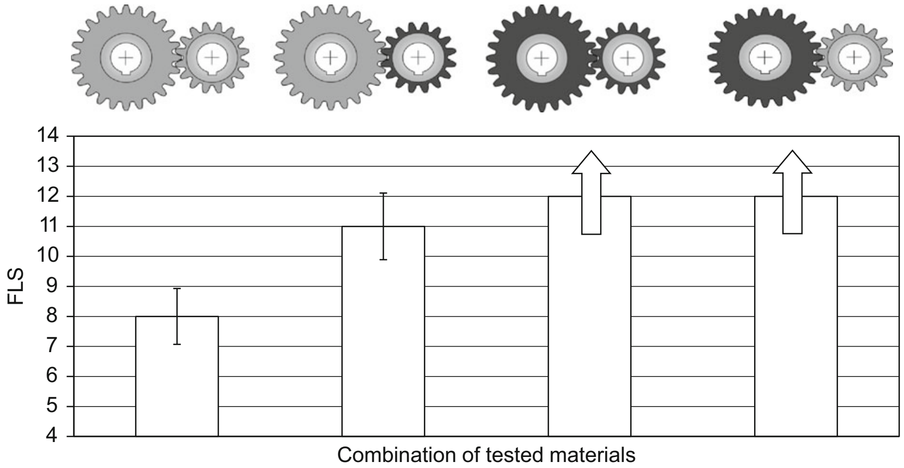
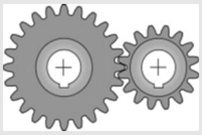
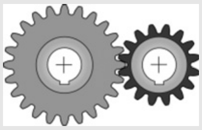
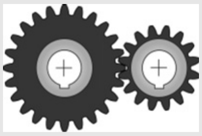
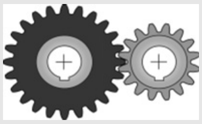
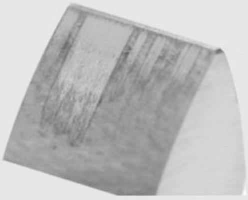
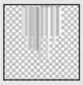
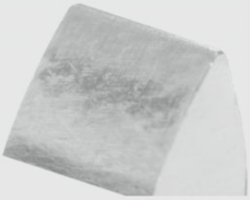
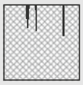
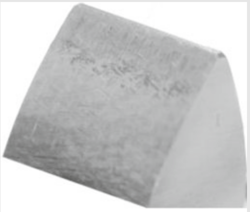
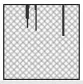
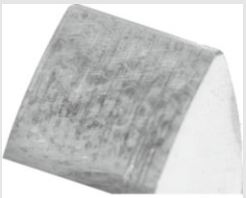


Fig. 8 – Failure load stages (FLS) obtained using the new test method for the tested material combinations with the MoS_2/Ti coating.

Table 5 – Modes of wear of the test pinion at particular 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); grey cells-the failure load stage (FLS).

Load stage				
7	 $A_p = 26\ mm^2$ $W_w = 1\ mg$			
8	  $A_p = 703\ mm^2$ W_w - not measured			
9				
10		 $A_p = 32\ mm^2$ $W_w = 11\ mg$		
11		  $A_p = 109\ mm^2$ $W_w = 25\ mg$	 $A_p \approx 0$ $W_w = 16\ mg$	 $A_p \approx 0$ $W_w = 9\ mg$
12			  $A_p \approx 0$ $W_w = 16\ mg$	  $A_p \approx 0$ $W_w = 9\ mg$

to differentiate between the tested material combinations—coating–coating (both gears coated), coating-steel, steel-coating, and also steel–steel (both gears without a coating). Thus, the new test method has a sufficient resolution; however, in some cases, apart from the analysis of only FLS values, analysis of the predominating modes of wear at particular load stages is recommended and may give additional, valuable information. For the two coatings tested (a-C:H:W and MoS_2/Ti), the best resistance to scuffing/scoring (FLS > 12) is observed when both gears are coated; however, the a-C:H:W coating gives a slightly better protection against severe wear than MoS_2/Ti—only scratches instead of scoring are observed for a-C:H:W.

In the case when one or both the gears are coated, two modes of wear occur most often on the pinion teeth—scratches and scoring. Scuffing is observed only when the two gears are uncoated.

The following conclusions can be drawn:

- The presented new gear scuffing shock test for coatings has been successfully verified by the testing of thin, hard coatings deposited on the gears, therefore it can be implemented in the laboratories of the R&D centres devoted to surface engineering and the engineering of advanced materials intended for modern toothed gears.
- If the coating is intended for application on gears, from the point of view of the highest achievable resistance to scuffing/scoring, it is recommended that both meshing gears are a-C:H:W-coated.
- Although the T-12U gear test rig has been effectively employed in the performed research, it is suggested that its research capacities should be extended by the measurement and computer acquisition of the friction torque, which will make it possible to investigate, as postulated by gear transmissions manufacturers, the possibility of the reduction of friction between the meshing teeth by the application of a low-friction coating. At present, a new version of the T-12U test rig, denoted as T-12UF, is being developed within the framework of the strategic programme executed at ITeE-PIB in Radom, and the planned deadline of this work is in the end of 2012. For the safety reasons, the new machine will have the possibility to automatically stop the motor when the vibration level is extremely high, owing to the implementation of a vibration monitoring system connected to a switch-off device.

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