Chapter

Testing of the Resistance to Scuffing of Spiral Bevel Gears: Test Rig, Method, and Results of Verification Testing

Waldemar Tuszynski, Marek Kalbarczyk, Bartosz Kiser, Michal Michalak, Remigiusz Michalczewski, Jerzy Mydlarz, Witold Piekoszewski, Marian Szczerek and Jan Wulczynski

Abstract

In spite of long-term development of the technology of bevel gear production, the automotive industry reports various operational demands such as the need of the size and mass reduction of gears without lowering their durability and reduction of friction leading to a decrease in the energy losses and a decrease of the tendency to scuffing. What is more expected, EU regulations may impose the use of new generation gear oils (ecological-friendly) providing the proper operational properties of the transmission. In view of these demands, a new, bevel gear test rig and scuffing test method have been developed at ITeE-PIB. The idea resulted from a necessity to improve reliability of tests—popular gear tests are run mostly on spur gears having the tooth geometry significantly different than bevel gears. The test rig, test method, and results of verification testing are presented. The effect of various gear oils and the deposition of a low-friction coating on the resistance to scuffing were investigated. It is shown that the new test rig fulfils the research requirements and that the new test method has a good resolution.

Keywords: bevel gear, test rig, scuffing, gear oil, coating

1. Introduction

1.1 Types of automotive drivetrains

In modern motor vehicles, like cars, lorries, and buses, the design of the drivetrain depends on the function of a given vehicle. For small- and medium-sized cars, the automotive engineers pay attention to design such a drivetrain that occupies as small space as possible. In this case, the motor and gearbox are located crosswise in the front part of the vehicle; thus, it is the front wheels that are driven, and the functionality of the transmission, differential, and associated components of the driven axle is integrated into one assembly called the transaxle. This design is very compact; however, it limits the maximum motor power to approximately 150 kW, which is a result of offloading the front wheels when the vehicle accelerates.

A diagram of the described drivetrain is shown in **Figure 1** [1]. In this and the next few figures, the rectangle with the four circles represents the motor and its cylinders.

In the vehicles of a higher class, being larger in size, the criterion of the compactness of the drivetrain is not so important. In such vehicles, as well as in vans and lorries, the so-called classic drivetrain is employed. In this case, the motor is located longitudinally in the front part of the vehicle, and the rear wheels are driven (**Figure 2**) [1].

In the solution portrayed in **Figure 2**, the driving torque is transmitted from the motor via the clutch, gear box, and drive shaft to the axle with a final drive, differential, shafts, and finally to the wheels.

In motor vehicles having the classic drivetrain, during acceleration, the back wheels are loaded; thus, the problem of the adherence of the driven wheels to the

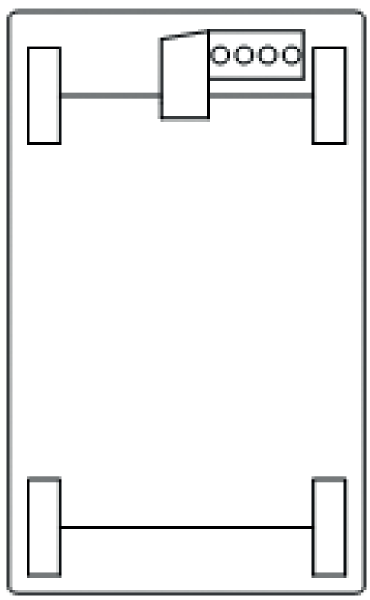


Figure 1.
Diagram of a transverse drivetrain [1].

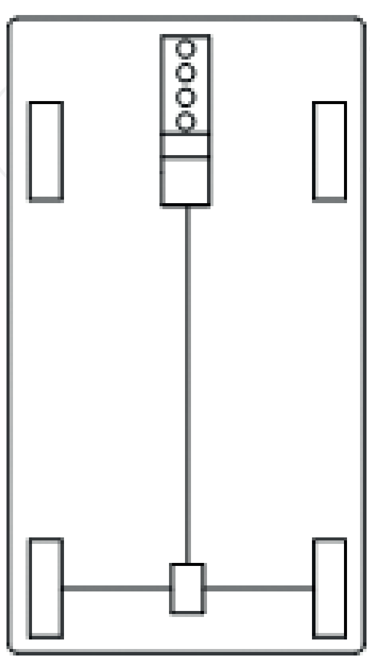


Figure 2.
Diagram of a classic drivetrain [1].

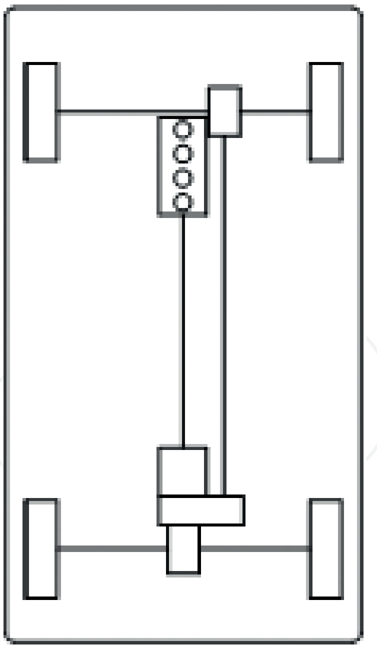


Figure 3.
Diagram of a drivetrain with all wheels driven [1].

road does not limit the motor power. It is very important in high-class cars (e.g. BMW, Mercedes), as well as in lorries.

The highest acceleration and off-road functionality are exhibited by vehicles having all wheels driven. In such vehicles, the number of final drives equals the number of the driven axles. A scheme of the "state-of-the-art" drivetrain used in, e.g. Nissan GT-R sports vehicles, is presented in **Figure 3** [1].

Unique features of this design are two driving shafts. The first one transmits the driving torque from the motor to the gearbox. Then, the torque is transmitted to the rear axle final drive (transaxle). The second driving shaft transmits the torque from the gearbox via the distribution box to the final drive of the front axle. This sophisticated design makes it possible to uniformly load both axles and achieve a neutral vehicle behaviour when turning.

Another example of a drivetrain that drives all the vehicle wheels is a famous Willys-Overland used by the US Army during the World War II. Its numerous "clones" are still produced in the world. It is interesting that its original version Willys-Overland is still employed by the Indian Army. The described drivetrain is shown in **Figure 4** [1].

The drivetrain shown in **Figure 4** is equipped with two axles. The driving torque produced by the motor is transmitted from the gearbox via the distribution box to the two driving shafts and then to the front and rear axles.

1.2 Final drives

A typical axle consists of the final drive, differential, and half shafts, which transmit the driving torque to the wheels.

The final drive is to transmit the driving torque to the wheels, at the same time, reducing the transmitted rotational speed, very often changing its direction, and increasing the driving torque. In most cases, the final drive consists of a pair of toothed gears.

The final drive can be one-stage, two-stage, and multistage, depending on the number of the reduction gears. Concerning the simplest, one-stage final drives for the automotive purposes, four of these types are applied (**Figure 5**) [2].

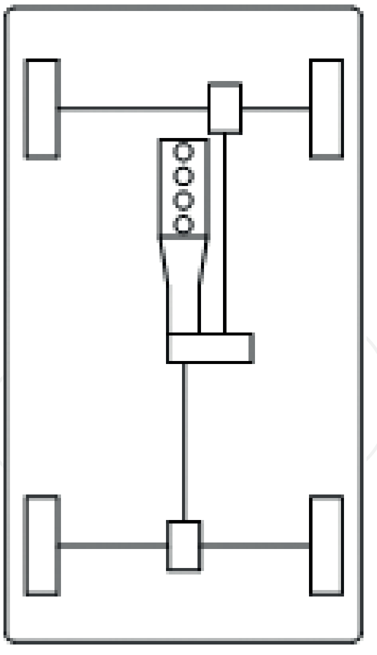


Figure 4.
Diagram of a drivetrain with all wheels driven used in the Willys-Overland off-road vehicles [1].

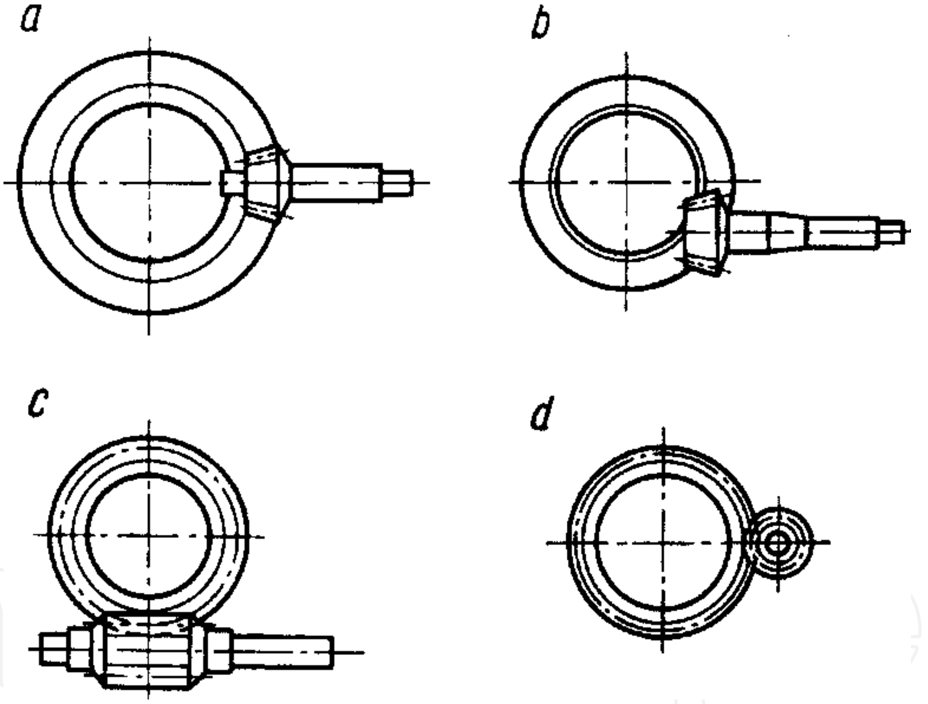


Figure 5.
The typical, one-stage final drives produced by the automotive industry: (a) spiral bevel gears (offset = 0), (b) hypoid gears (offset >0), (c) worm gears, and (d) helical gears [2].

A hypoid gear is a type of a spiral bevel gear whose axis does not intersect with the axis of the meshing gear. This is why the distance between these axes, called the offset, is higher than 0. In spiral bevel gears, the offset is exactly 0.

Spiral bevel gears or hypoid gears are used in the final drives of the drivetrains shown in **Figures 2–4**, while in the drivetrain presented in **Figure 1**, helical gears constitute the final drive.

Although nowadays, in vehicles, practically only helical gears (e.g. in the drivetrain from **Figure 1**) or hypoid gears (e.g. in the drivetrain from **Figure 2**) are used, spiral bevel gears are still very important, because they are broadly applied in lorries, special vehicles, and buses, where the axle size and the noise emission are

Figure 6.
Scuffed area on the tooth flank of a spiral bevel gear.

of minor importance but the gear efficiency is a priority. For example, spiral bevel gears are employed for the final drives in the drivetrain of the Willys-Overland off-road vehicles (**Figure 4**); their "clones" are still produced throughout the world.

It should be emphasised here that spiral bevel gears are used not only in motor vehicles. It can be estimated that, in case of, e.g. speed reducers with bevel-shaped gears, spiral bevel gears are applied in 90% of such devices, leaving only 10% to hypoid gears.

In spite of long-term development of the manufacturing technology and service of spiral bevel gears, there are still problems related to friction. The following problems, coming from excessive friction in such gears, still exist: an increase in the oil temperature followed by a rise in the tendency to scuffing. A typical scuffed area on the flank of the spiral bevel gear tooth is shown in **Figure 6**.

For the purpose of research on spiral bevel gears, the authors have developed a new test rig and a method for testing scuffing of such gears. The new testing machine and the test method will be a subject of the body of this chapter.

1.3 Automotive gear lubrication

Comprehensive characteristics of the automotive gear oils were provided in the former authors' chapter, being a part of the book [3]. Generally, the characteristics of the automotive gear oils were based on the source document provided by the American Petroleum Institute (API) [4].

However, to help the reader to analyse the data in this chapter, the authors decided to repeat information given in the book [3].

As in the book [3], emphasis was put on the classification of manual transmission fluids (MTF), i.e. automotive gear oils, excluding oils for automatic transmissions, called the automatic transmission fluids (ATF) and excluding oils for off-road vehicles (e.g. tractors). For simplification, manual transmission fluids (MTF) will be called the equivalent name—"automotive gear oils"—that will be used throughout the text.

There are two different classifications of automotive gear oils.

The first one specifies lubricant service designations or the "performance levels" of automotive gear oils. These have been provided by the American Petroleum Institute (API) [4]. The API classification divides automotive gear oils into seven performance levels. Four performance levels are in current use, three are not. The reason for the performance level not to be in current use results from changes of manufacturers' recommended tests or the unavailability of test equipment, and it does not mean that such products have been withdrawn from the market.

The API classification is described in **Tables 1** and **2**.

API service designation	Application areas and short characterisation
GL-1	Manual transmissions operating under such mild conditions that straight petroleum or refined petroleum oil may be used satisfactorily Not satisfactory for many passenger car manual transmissions GL-1 oils may contain oxidation and rust inhibitors, defoamers, and pour depressants. Friction modifiers (FM) and extreme pressure (EP) additives shall not be used in GL-1 oils
GL-4	Axles with spiral bevel gears operating under moderate to severe conditions of speed and load or axles with hypoid gears operating under moderate speeds and loads GL-4 oils may be used in selected manual transmission and transaxle applications where MT-1 lubricants are unsuitable GL-4 oils contain up to 4% of extreme pressure (EP) additives
GL-5	Gears, particularly hypoid gears, in axles operating under various combinations of high-speed/shock-load and low-speed/high-torque conditions GL-5 oils contain up to 6.5% of extreme pressure (EP) additives
MT-1	Nonsynchronised manual transmissions used in buses and heavy-duty lorries API MT-1 does not address the performance requirements of synchronised transmissions and transaxles in vehicles and heavy-duty applications API MT-1 oils provide protection against the combination of thermal degradation, component wear, and oil seal deterioration, which is not provided by lubricants in current use meeting only the requirements of API GL-1, 4, or 5

Table 1.
API service designations (performance levels) of automotive gear oils in current use, according to the source document—API Publication 1560 [4].

API service designation	Application areas and short characterisation
GL-2	Automotive worm-gear axles operating under such conditions of load, temperature, and sliding velocities that lubricants, satisfactory for API GL-1 service, will not suffice GL-2 oils contain antiwear or film strength improvers specifically designed to protect worm gears Currently, it is very difficult to find products designed as “GL-2” in the automotive market
GL-3	Manual transmissions operating under moderate to severe conditions and spiral bevel axles operating under mild to moderate conditions of speed and load GL-3 oils provide load-carrying capacities exceeding those satisfying API GL-1 but below the requirements of API GL-4 oils GL-3 oils are not intended for axles with hypoid gears They contain up to about 3% of antiwear (AW) additives
GL-6	Hypoid gears designed with a very high pinion offset Their EP properties are typically better than of GL-5 oils GL-6 oils contain up to 10% of extreme pressure (EP) additives

Table 2.
API service designations (performance levels) of automotive gear oils not in current use, according to the source document—API Publication 1560 [4].

Apart from the designations from **Tables 1** and **2**, there is also one denoted as API GL-5(LS) or GL-5+. Gear oils that meet the requirements of this class contain special additives, called friction modifiers (FM), preventing the stick–slip phenomenon under conditions of limited slip (LS). As such, GL-5(LS) oils are intended for lubrication of limited slip differentials.

To reduce the number of various gear oils in the market and, in turn, simplify oil selection, many lubricant manufacturers implement more universal (“multi-class”) gear oils. In this group, gear oils denoted as API GL-4/GL-5 or GL-4+ predominate.

SAE viscosity grade	Maximum temperature for viscosity of 150,000 cP [°C]	Kinematic viscosity at 100°C, cSt [mm^2/s] Minimum	Kinematic viscosity at 100°C, cSt [mm^2/s] Maximum
70 W	−55	4.1	—
75 W	−40	4.1	—
80 W	−26	7.0	—
85 W	−12	11.0	—
80	—	7.0	<11.0
85	—	11.0	<13.5
90	—	13.5	<18.5
110	—	18.5	<24.0
140	—	24.0	<32.5
190	—	32.5	<41.0
250	—	41.0	—

Table 3.
Automotive gear oil viscosity classification according to the source document—SAE J306:2005 [5].

The second classification was provided by the Society of Automotive Engineers (SAE) [5]. It is a viscosity classification. It divides automotive gear oils into 11 grades based on their rheological properties (**Table 3**).

For lubrication of automotive gears, multiviscosity grade oils are mostly employed, e.g. SAE 80W-90. This designation means that such an oil meets the requirements of both low-temperature (SAE 80W) and high-temperature grades (SAE 90).

1.4 Scuffing

The comprehensive analysis of the scuffing phenomenon was provided in the former authors' chapter, being a part of the book [6]. However, to help the reader analyse this chapter, the authors decided to extract the most important information and present it here.

1.4.1 Some definitions of scuffing

Despite long tradition of research on scuffing, its terminology has not been systemised so far. The term scuffing has many synonyms, e.g. seizure, scoring, galling, and seizing.

The variety of terms presented here makes interpretation of literature data difficult. Additionally, many terms are very often used as equivalents, e.g. scuffing and seizure.

The lack of consensus on the origin of scuffing as well as its symptoms is reflected by numerous definitions of the phenomenon. Some of them associate scuffing with wear, the others—with friction. The former are the definitions given or quoted by, e.g. Enthoven and Spikes, Dyson, Ludema, and Sadowski. Among the latter, one can classify the definition given by Nosal.

Enthoven and Spikes [7] have quoted the definition suggested by the Organisation for Economic Co-operation and Development, characterising scuffing as "localized damage caused by the occurrence of solid-phase welding between sliding surfaces, without local surface melting".

Dyson [8] has adopted the definition presented by The Institution of Mechanical Engineers: scuffing is “gross damage characterized by the formation of local welds between the sliding surfaces”.

Ludema [9] has considered scuffing to be “a roughening of surfaces by plastic flow whether or not there is material loss or transfer”.

Sadowski [10] has interpreted scuffing as “an interference of stabilised wear and a boundary example of such wear”.

However, according to Nosal [11], scuffing is “a collection of phenomena taking place in the sliding pair, localized mainly deep inside the surface layer, producing an increased and unstabilised friction which is likely to result in seizure”.

1.4.2 What does initiate scuffing?

Practical lubrication in most of the sliding pairs, e.g. high-speed toothed gears, is neither a purely hydrodynamic (HD) nor an elastohydrodynamic (EHD) process. Despite either HD or EHD, film supports most of the loading applied to the tribosystem elements, collisions between the highest surface asperities cannot be excluded. Therefore, besides fully lubricated friction, dry and boundary friction may also appear. Their common action is called the mixed friction or mixed lubrication [12].

The lubricating film, being produced at mixed friction, compared to such created at fully lubricated friction, is significantly thinner. Collisions of surface asperities give rise to a local load increase, then the lubricating film collapses, and scuffing takes place. It is a serious practical problem, because scuffing can appear in tribosystems creating apparently good conditions for lubrication.

A kinetic model, proposed by Nosal [11], presents scuffing to be a sequence of the following phenomena: collapse of the lubricating film ⇨ removal of oxides layers in microareas of contact, leading to direct metal–metal contacts ⇨ appearance of adhesive bonds due to a temperature increase or plastic deformation ⇨ development of adhesive bonds deeper and deeper inside the surface layer ⇨ shearing of adhesive bonds, tearing out and transfer of metal particles from one element onto the other, due to their relative movement ⇨ rapid development of the above phenomena ⇨ macroscopic range of destruction (scuffing).

The kinetic model of scuffing assumes that the transition from stabilised friction to scuffing requires some time, rejecting the idea that it takes place very rapidly, i.e. during $t \to 0$.

Scuffed areas on the tooth flank of a spiral bevel gear were presented earlier in **Figure 6**.

It is very important to differentiate between the terms scuffing and scoring. Scuffing has a physical nature and is a result of shearing adhesive bonds, which appear between the rubbing surfaces. Scoring has a rather mechanical nature and appears at very high loads. Under such conditions abrasion of the surface takes place—by the action of the very hard wear particles [13].

1.5 Some reasons for the bevel gear testing

In spite of long-term development of the technology of bevel gear production, the automotive industry reports various operational demands. The main one concerns the need of the size and mass reduction of gears without lowering their durability. The second demand relates to the reduction of friction, leading to the decrease in heat emission, lowering the energy losses, and above all, resulting in a decrease of the tendency to scuffing. The abovementioned effect can be achieved by the deposition of a thin, hard, and low-friction coating on the operating surface of the gears, although the present-day research is limited to spur gears [14–22].

The third important aspect is environmental protection, which is addressed by the use of new generation gear oils (ecological-friendly) providing the proper operational properties of the gear. In addition, the new EU law requirements, concerning the biodegradability of lubricants in various fields, are expected to be implemented soon. This is why numerous research investigations are now being conducted, which consider the application of ecological oils for various technological areas [23–26].

Apart from the demands mentioned above, an equally important issue is the diversification of automotive gear oils in respect to API GL performance levels. Present research concerns the simple specimens [27–29], such as the four-ball tribosystem, as well as spur gear investigation [30, 31]. However, there is a striking lack of research performed in this direction on spiral bevel gears.

The mentioned demands could be fulfilled only by a new tribotester, intended for testing bevel gears. There are some tribotesters of this type. The first one is the hypoid/bevel gear test rig [32, 33] developed in the Gear Research Centre (FZG) at the Technical University of Munich. The second one is the test rig [34] designed at NASA Glenn Research Center. This machine is intended for aeronautics purposes. However, these test rigs are not widely available.

Poor availability of bevel gear test rigs is probably the reason why most of the publications in this area focus on the two aspects:

- Optimisation of the geometry of bevel gears, optimisation of the conditions of meshing teeth of bevel gears, as well as improvement of the production technology—by using the tools of mathematical modelling [35–38]

- Case studies, focusing on the explanation of operational causes of bevel gear scuffing, surface fatigue wear (pitting), and teeth breakage in various vehicles, machines, and devices, i.e. lorry transmission, turbojet gearboxes, or in the transmissions of industrial conveyors [39–41]

In spite of the test rig, for the investigation of bevel gears, a necessary factor is the usage of proper test methods. Unfortunately, a review of the most common standards indicates that there is a complete lack of any standardised methods for testing scuffing of bevel gears. The existing standards concern the means of construction calculations for providing the proper resistance to scuffing (ISO/TR 13989-1,2), and it has to be underlined that these calculation methods are treated as controversial. For this reason, the American Gear Manufacturers Association (AGMA) has not published such a method as a standard yet. The lack of research in this area is clearly visible.

In contradiction to the calculation methods, available as standards or computer programmes, the proposals of authorial methods for friction and wear testing of hypoid or bevel gears are presented very rarely in publications [32, 33, 42, 43].

As it was mentioned before, answering to the issues specified above at the Tribology Department of the Institute for Sustainable Technologies (ITeE-PIB), a new test rig for the investigation of bevel gears was developed, and the authorial method for testing scuffing of bevel gears was designed. The testing machine and the test method are the subjects of the chapter.

2. Bevel gear test methodology

2.1 New bevel gear test rig

The kinematic scheme of the developed test rig is presented in **Figure 7**. In the line of testing equipment for tribological research, developed at ITeE-PIB, the bevel gear testing machine is denoted as T-30.

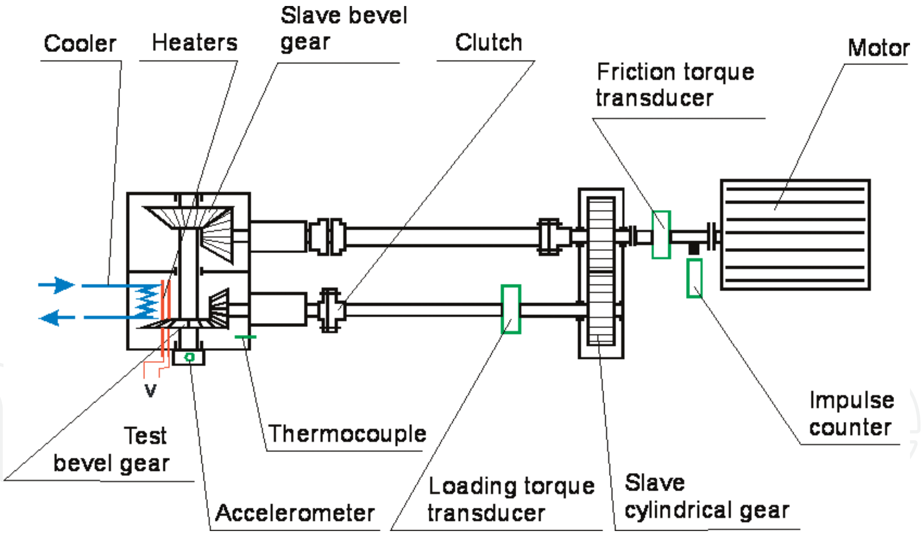


Figure 7.
Kinematic scheme of the T-30 back-to-back bevel gear test rig.

The main part of the T-30 test rig consists of three gears—a test bevel gear, slave bevel gear, and slave cylindrical (helical) gear—and in the figure, all the teeth were presented as if they were straight for simplification. The test bevel gear consists of a pinion and a gear wheel, which are immersed in the investigated oil. Before the test, the test chamber is preheated to the required temperature by means of a heating unit. The test chamber is equipped with cooling channels (in **Figure 7** called the cooler) connected with a heat exchanger working in a closed water circulation system. This construction makes it possible to cool the oil before the gear inspection. Furthermore, it extends the application area of the T-30 test rig for investigation under conditions of constant oil temperature (necessary for surface fatigue testing).

The testing machine is equipped with a circulating power system. After the application of the required load and fixing the shafts and the clutch, the torque circulates in the shaft-gear system. The load (shaft torsion) is applied by means of the lever unit with the number of weights, providing the possibility of obtaining a torque up to 720 Nm. The applied torque and its changes during the test are measured by means of the loading torque transducer.

The measurement of friction torque is realised with the use of a friction torque transducer mounted between the motor and the slave cylindrical gears. The purpose of using friction torque measurement is to make it possible to compare materials from which the test gears are produced from the point of view of a possible friction reduction. The motor is supplied through a power inverter, providing the possibility of speed regulation.

A photograph of the T-30 bevel gear testing rig, equipped with the control and measuring system, is presented in **Figure 8**.

The control system makes it possible to regulate the motor speed to change the lubrication conditions of the tested gear by changing the motion direction, to regulate the temperature of the oil, and to automatically turn off the motor after reaching the required number of test pinion revolutions or after exceeding the selected level of vibrations. The main elements of the control system are mounted in the measuring cupboard (**Figure 8**—left side).

The measuring system (**Figure 8**) consists of a digital amplifier, the set of measuring transducers, and a computer equipped with specialised software. During the test, the following quantities are measured and registered: the loading torque between the gears, the friction torque, the motor speed, the number of test pinion revolutions, the temperature of the tested oil, the level of vibrations, and the test duration.

Figure 8.
Photograph of the T-30 back-to-back bevel gear test rig with its control and measuring system (on the left) and water circulating cooling system (on the right) [44].

The measured signals from the transducers are amplified and transferred to the computer. The specialised software developed at ITeE-PIB makes it possible to display the curves of measured values in relation to test duration. At the end of the test, the measurements are saved on the hard disc, and then research reports can be printed.

The new test rig was designed with the cooperation between ITeE-PIB and Invenio Ltd. and manufactured by ITeE-PIB.

2.2 New bevel gear scuffing test

A simplified scheme of the geometric configuration of the test bevel gears is presented in **Figure 9**.

The pinion and the wheel have a spiral line of teeth. The direction of motion shown in **Figure 9** is defined by the authors as "normal" viewed from the test chamber's front cover, and the wheel rotates counterclockwise. From the same point

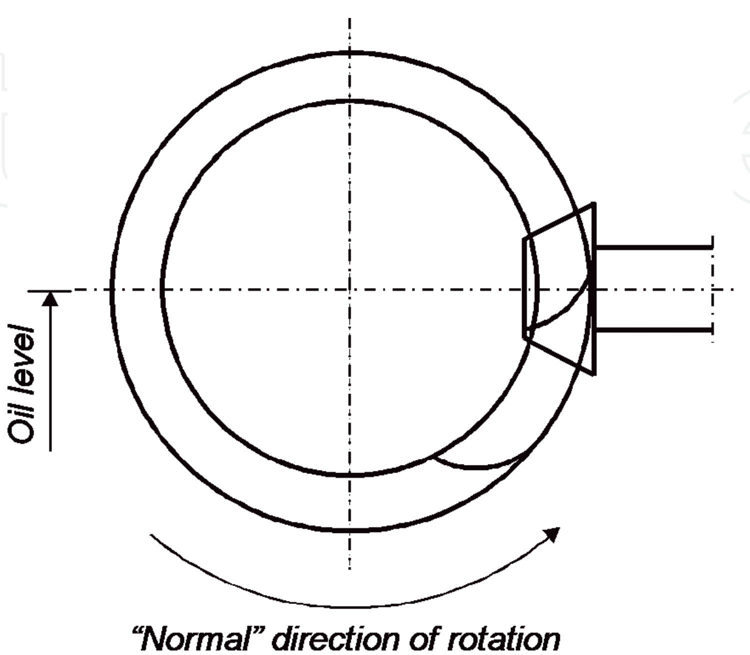


Figure 9.
Simplified scheme of the geometric configuration of the test bevel gears [44].

of view, the pinion is mounted behind the wheel, which was skipped in **Figure 9** in order to simplify the scheme.

Under the load action direction, which results from the test rig construction, the convex flank of the pinion tooth is pressed to the concave flank of the wheel. As a consequence, the convex flank of the pinion is recognised as the investigated one. The pinion and the wheel are immersed in the tested oil up to the level of the gear axis.

The developed test method consists in performing research on the lubricated spiral bevel gears, operating under the conditions presented below, at the constant rotational speed, gradually increasing load, with a starting temperature the same for every test, until the failure load stage (FLS) is reached, which is a basic indicator of the resistance to scuffing, or until the 12th load stage is reached. FLS is the load stage under which the area, which is damaged by polishing, scratches, and scoring, exceeds the area of one pinion tooth ($\geq 450\ mm^2$). Therefore, the FLS is a measure of the anti-scuffing properties of the investigated oil or the scuffing resistance of the coating deposited on one or both test gear elements.

Test conditions

• Type of test gears	Bevel gears with spiral teeth line
• Rotational speed of the motor	3000 rpm
• Average circumferential speed	7.7 m/s
• Single run duration	15 min
• The motion rotational direction	"Normal" (**Figure 9**)
• Min. and max. Load stage	From 1 to 12 (the 13th and 14th stage is allowed)
• Loading torque	From 3 to 535 Nm, gradually increasing
• Hertzian contact stress	From 0.1 to 1.5 GPa
• Oil starting temperature	90°C (not stabilised during the test)
• Type of lubrication	Immersive (approx. Volume of oil: 2 l)
• Level of oil	To the axis of the test gear elements

Depending on the requirements, beside the basic scuffing resistance indicator, which is FLS, for evaluation of anti-scuffing properties, an additional criterion can be used, which is the damage progression of the pinion teeth flanks. For this purpose, during every pinion inspection, apart from the total damaged area, the most common mode of wear is also notified in the report sheet—according to **Table 4**.

When testing a low-friction hard coating deposited on one of the test gears, the coated element "polishes" the uncoated one due to a mild abrasive action of the coating surface. Therefore, polishing areas on the teeth flank of the uncoated gear can be neglected when inspecting test gears for the sings of damage.

2.3 Test spiral bevel gears

The pair of test spiral bevel gears is shown in **Figure 10**.

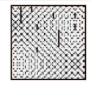
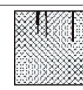
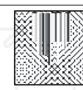
Mode of wear	Symbol	Appearance
Polishing	W	
Scratches	R	
Scoring	B	
Scuffing	Z	

Table 4.
Possible modes of wear of the test pinion.

Figure 10.
Test spiral bevel gears.

The spiral bevel gears were manufactured in a high, fifth grade of precision, defined in DIN 3965. They were made of 18CrNi8 steel. The material was carburised (0.6–0.9 mm in depth). Then it was tempered to achieve the hardness of 56–60 HRC. Machining was performed using Klingelnberg's method.

Technical specifications of the test spiral bevel gears are presented in **Table 5**.

2.4 Oils tested

For the research, the following oils were used: the commercial mineral-based oils of API GL-1 and GL-5 performance level, intended for vehicle mechanical gears, and VG 220 viscosity grade, ecological oil, intended for industrial gears (this oil has been developed at ITeE-PIB). The characteristics of the investigated oils are presented in **Table 6**.

2.5 Materials tested

Two material configurations were tested. The first one consisted of a steel pinion and steel wheel, and the second one consisted of a steel pinion and a-C:H:W coated steel wheel. The photographs of both configurations are presented in **Figure 11**.

The a-C:H:W coating is a multilayer coating. The structure of the coating is presented in **Figure 12**, showing the results of the depth profile quantitative analysis obtained by a glow discharge optical emission spectrometer (GDOES). The reference sample was deposited on the Armco Fe substrate material (technically pure Fe).

As it is shown in **Figure 12**, on the Fe-based substrate, the layer of Cr is deposited to increase adhesion of the tungsten carbide (WC) layer to the substrate. The hard WC is of crucial importance to achieve the high load-carrying capacity, and in case when the outer layer wears out, the WC layer protects the substrate material from abrasive wear.

Description	Pinion	Wheel
Manufacturing process	Klingelnberg	
Material	18CrNi8 steel	
Heat treatment	Case hardening	
Case depth	0.6–0.9 mm	
Surface hardness	56–60 HRC	
Core hardness	33–45 HRC	
Gear quality	5 according to DIN 3965	
Number of teeth	7	18
Normal module	8.70 mm	
Normal pressure angle	20°	
Mean spiral angle	35°	
Shaft angle	90°	
Working tooth flank	Convex	Concave

Table 5.
Main material and geometrical characteristics of the test spiral bevel gears.

Symbol	API GL service designation	Viscosity grade	Type of base oil	Application and short characteristics
GL-1 90	GL-1	SAE 90	Mineral	Manual transmissions operating under such mild conditions that straight petroleum or refined petroleum oil may be used satisfactorily GL-1 oils do not contain any lubricating additives
GL-5 80W-90	GL-5	SAE 80W-90	Mineral	Gears, particularly hypoid gears, in axles operating under various combinations of high-speed/shock-load and low-speed/high-torque conditions GL-5 oils contain up to 6.5% of extreme pressure (EP) additives
Eko VG 200	—	VG 220	Natural (vegetable)—mixture of rapeseed and castor oils	Industrial transmissions and transmissions in machine tools and in machines working especially in the paper industry The oil contains 2% (wt.) of sublimated sulphur, performing as an EP additive

Table 6.
Characteristics of the tested gear oils.

The outer layer is responsible for the interaction with the mating element of the tribosystem. It is a multilayer structure (colloquially named WC/C) that consists of WC-reach DLC layers with DLC interlayers. The presence of nickel is required for technological reasons. Low-friction properties are a result of a high concentration of amorphous carbon (sp^2) in the outer layer.

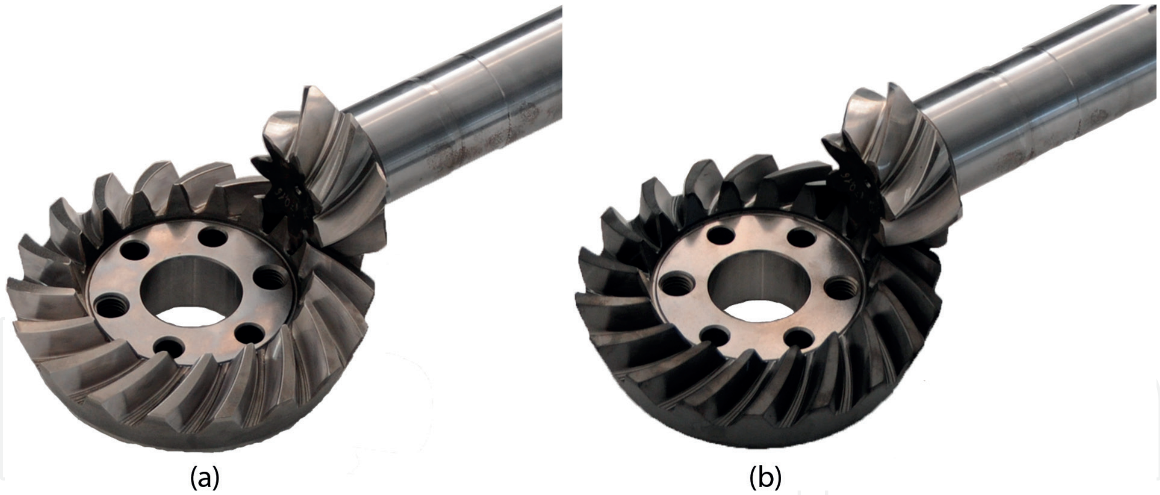


Figure 11.
Material configurations of the test bevel gears: (a) steel pinion, steel wheel, and (b) steel pinion, a-C:H:W coated wheel.

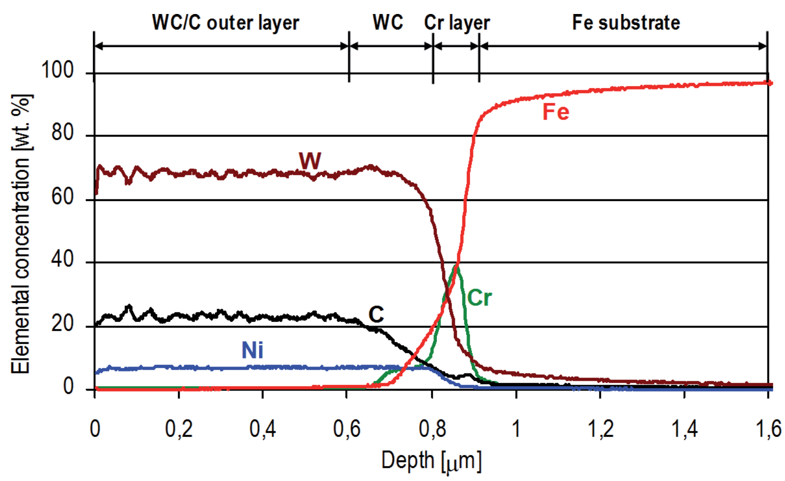


Figure 12.
Structure of the a-C:H:W coating; the results of the quantitative GDOES depth profiling (hydrogen was not analysed).

3. Results of verification testing of the T-30 bevel gear test rig

In **Figure 13**, the FLS values obtained for investigated oils and material configurations are presented. The expected repeatability intervals are added to the bars.

The failure load stage result analysis indicates that the resolution of the scuffing test method is very high—the FLS differences between all the tested cases are statistically significant. It is also of great importance that, for all the tested cases, the 12th load stage was not exceeded. The maximal obtained FLS level is not higher than 10, which is an additional confirmation of the very high resolution of the developed test method.

In the steel pinion/steel wheel configuration, the GL-1 90 oil without additives exhibits low resistance to scuffing (represented by very low—3rd—FLS), whereas the GL-5 80 W-90 oil, with significant concentration of EP additives, makes it possible to reach much higher FLS value (eighth). The Eko VG 220 oil is characterised by an intermediate value of failure load stage, which indicates that it can be used as a lubricant only for bevel gears, which operate under conditions of low and moderate loads, still providing a measurable ecological effect.

According to the facts presented by the researchers [17–22] who performed scuffing tests on spur gears, there is a possibility to improve the resistance to scuffing of gear elements by deposition of a thin, hard coating, i.e. a-C:H:W, on at least one of the gears. This thesis is fully confirmed by the results of the

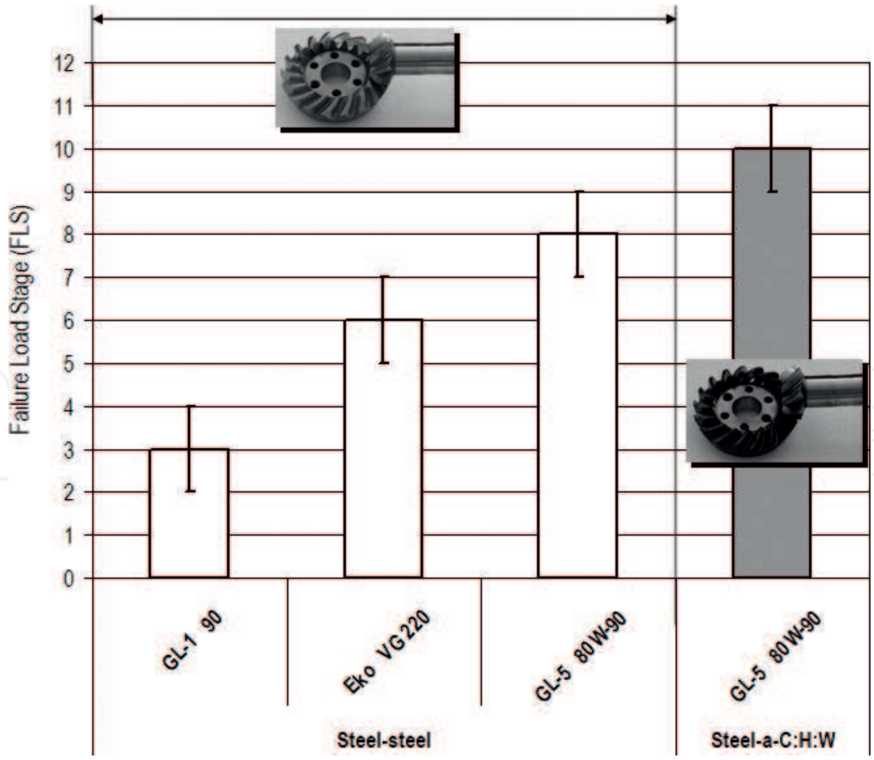


Figure 13.
Failure load stage (FLS) for the tested gear oils and material configurations.

bevel gear scuffing test performed on the configuration of a steel pinion mating a-C:H:W coated steel wheel for which the highest value of FLS was obtained (tenth). This test result indicates that the thin hard coatings represent a very high application potential for scuffing resistance improvement in the area of heavily loaded gears.

As stated before, considering the assessment of the anti-scuffing properties of oils and the resistance to scuffing of various material combinations of gear elements, in particular with coatings, one more important criterion can be used, which is the progression of wear, occurring on the flanks of pinion teeth under stepwise increasing load.

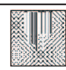
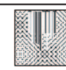
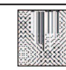
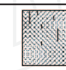
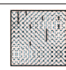
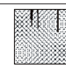
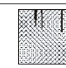
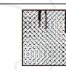
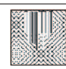
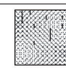
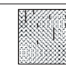
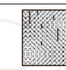
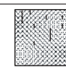
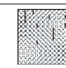
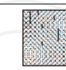
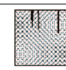
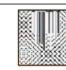
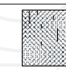
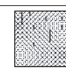
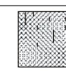
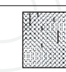
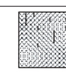
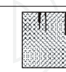
The detailed analyses comprised the modes of wear that occurred on most of the pinion teeth. The results of the analyses are compiled in **Table 7**. Below the symbols of the wear mode, the total damaged area of the pinion teeth is presented, expressed in mm^2. The description of wear modes is provided earlier in **Table 4**.

It can be observed that, as the load increases, the progression of tooth wear is the fastest for the gears lubricated with GL-1 90 oil, because the scuffing is initiated just after the test at the first load stage.

When considering the wear modes during two tests on two different material combinations lubricated with GL-5 80 W-90 oil, the eighth load stage causes the scuffing of the steel-steel pair, while on the steel pinion meshing with a-C:H:W coated wheel, only scoring (in a form of groves) appears. It is because the presence of the coating causes a lower level of affinity than in the steel-steel case. Additionally, the high hardness of the coating, decreasing the tendency to adhesive bonding, significantly mitigates scuffing. As an effect of these factors, the steel-coating material configuration reached a high tenth load stage.

Thus, the additional criterion (i.e. progression of wear on the teeth flanks) constitutes a very useful supplement to the basic criterion, which is the failure load stage, and it can provide additional and valuable information on the damage process of the teeth.

Concerning the coating-steel material combination of bevel gear teeth, it is very difficult to compare the wear results reported in this chapter with the results obtained by other researchers, because such papers are extremely rare. For example,

Load stage	Steel—steel 			Steel—a-C:H:W 
	GL-1 90	**Eko VG 200**	**GL-5 80 W-90**	**GL-5 80 W-90**
1	 216 mm^2	 ≈0	 ≈0	 ≈0
2	 295 mm^2	 7 mm^2	 ≈0	 ≈0
3	 910 mm^2	 16 mm^2	 ≈0	 ≈0
4		 31 mm^2	 ≈0	 ≈0
5		 54 mm^2	 ≈0	 ≈0
6		 1225 mm^2	 70 mm^2	 ≈0
7			 116 mm^2	 72 mm^2

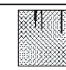
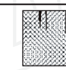
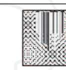
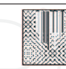
Load stage	Steel—steel 			Steel—a-C:H:W 
	GL-1 90	Eko VG 200	GL-5 80 W-90	GL-5 80 W-90
8			 1575 mm^2	 130 mm^2
9				 164 mm^2
10				 960 mm^2

Table 7.
The wear modes found on the teeth of the test pinion at increasing stages of load; the research was performed using various gear oils and material combinations.

Basiniuk et al. [45] studied the behaviour of coated bevel gears, however, from a point of view of a noise and friction reduction.

The authors plan to continue their research on the coated bevel gears. The aim will be to identify mechanisms of interaction between the surface and the gear oil of different chemistry in the steel-coating and coating-coating friction zones of the meshing teeth. Scientific publications, relating to this aspect, concern mainly testing on simple model specimens. The most recent papers in this field are, e.g. [46–58].

4. Conclusions

Based on the carried out research, the following conclusions can be drawn:

- The developed method for testing scuffing of spiral bevel gears exhibits a good resolution.
- It is possible to improve the resistance to scuffing by the application of a thin, low-friction coating on one of the elements of the spiral bevel gear.

The developed test rig with the test method can be used for the assessment of the anti-scuffing properties of oils intended for bevel gear lubrication and also for the determination of the resistance to scuffing of bevel gears from the perspective of materials used for gears and possibly the tooth surface processing. Thus, they can be applied in R&D industrial laboratories of lubricant producers, manufacturers of devices that contain bevel gears, automotive industry, as well in laboratories of technical universities where the aspects of bevel gear tribology and design are studied and investigated.

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Author details

Waldemar Tuszynski[1*], Marek Kalbarczyk[1], Bartosz Kiser[2], Michal Michalak[1], Remigiusz Michalczewski[1], Jerzy Mydlarz[2], Witold Piekoszewski[1], Marian Szczerek[1] and Jan Wulczynski[1]

1 Tribology Department, Institute for Sustainable Technologies—National Research Institute (ITeE-PIB), Radom, Poland

2 Invenio Ltd, Tychy, Poland

*Address all correspondence to: waldemar.tuszynski@itee.radom.pl

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