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TRIBOLOGICAL ASPECTS OF SINTERED STEEL GEAR IN APPLICATION WORM-AND-GEAR SET

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Abstract: *Due to the low manufacturing costs, worm-and-gear set with the combination of a steel worm and a gear are used almost exclusively in automotive auxiliary drive units such as window lifters, seat adjustments and windscreen wipers. Worm-and-gear sets are a simple and compact way to achieve a high speed gear ratio. Tribological aspect of worm-and-gear set is very complex while there can occur different damage forms such as: wear, pitting or scuffing. The conditions, under which a damage form occurs, are not fully elucidated. In this paper are shown experiments that have been carried out with gear made of sintered steel Fe1.5Cr0.2Mo with different treatment methods.*

Keywords: *sintered steel, gears, worm-and-gear set, wear, pitting, scuffing*

1. INTRODUCTION

Crossed helical gears are used, for example, in automotive auxiliary drive units such as window lifters, seat adjustments, windscreen wipers, and also in home appliances. The trend towards increased comfort in motor vehicles has led to the utilization of more than a hundred servo-drives in luxury class automobiles. Important advantages of the crossed helical gears are their easy and inexpensive design, good noise performance and high ratio that can be realized in one step.

The use of gear wheels made of sintered metal can increase the load capacity of crossed helical gears. As in the case of plastic gear wheels, the large scale production of sintered metal gear wheels requires a special tool and no additional post-production costs.

Hochmann [1] determines the load capacity of material pair steel/steel with grease. The tested gears with grease have lower load capacity than tested gears with oil. Crossed helical gears have different transmission conditions, therefore, these results cannot be used.

The lubricating film thickness, pitting and scuffing load capacity correlate significantly with the base oil viscosity of grease. The addition of a special synthetic graphite as solid lubricant shows increased wear in this research. The base oil viscosity is a decisive factor for calculating the lubricating film thickness of grease, as well as for calculating the pitting load capacity according to DIN 3990 [2]. Performance data of tested lubricants is available for calculating scuffing and pitting load capacity according to DIN 3990. This data takes into account the influence of grease.

2. CHEMICAL COMPOSITION

The material combination steel/sintered metal has been investigated only in few research projects. Researchers from the company Höganäs AB, Sweden [3] investigated sintered metal Astaloy Mo (Fe0.85Mo) and Astaloy CrL (Fe1.5Cr0.2Mo).

Table 1. Chemical composition of sintered steel Fe1.5Cr0.2Mo (%)

element	measure point 1	measure point 2	measure point 3	measure point 4	measure point 5
C	0,254	0,243	0,238	0,253	0,273
Si	0,054	0,047	0,043	0,057	0,053
Mn	0,163	0,161	0,161	0,161	0,161
P	0,009	0,009	0,009	0,009	0,009
S	0,001	0,001	0,001	0,001	0,002
Cr	1,521	1,517	1,526	1,51	1,509
Ni	0,026	0,026	0,026	0,026	0,026
Mo	0,21	0,208	0,209	0,211	0,21
Cu	0,066	0,066	0,067	0,067	0,067
Al	<0,001	0,002	<0,001	<0,001	<0,001
Ti	<0,001	<0,001	<0,001	<0,001	<0,001
V	0,008	0,008	0,008	0,008	0,008
Nb	0,007	0,007	0,007	0,006	0,006
W	0,015	0,015	0,016	0,014	0,013
Co	0,007	0,007	0,007	0,007	0,007
Zr	0,002	0,002	0,002	0,002	0,001
N	0,0248	0,0235	0,0243	0,0244	0,0283
B	0,0003	0,0003	0,0003	0,0003	0,0003
Mg	0,0003	0,0003	0,0003	0,0003	0,0001
Ca	0,0055	0,0042	0,0024	0,0071	0,0063
As	0,002	0,002	0,002	0,002	0,002
Sn	<0,001	<0,001	<0,001	<0,001	<0,001
Pb	0,0021	0,0023	0,0023	0,0018	0,0018
Bi	0,002	0,002	0,003	0,002	0,002
Ce	0,002	0,002	0,002	0,002	0,002
Zn	0,003	0,003	0,002	0,003	0,003

The basic raw material for sintered steel is iron powder. The iron powder is mixed with different metal powders by using special alloy mixing techniques. A homogeneous powder mixture is important for uniform cross-sectional properties within the part. Copper increases the strength and yield strength, but decreases the elongation at break. Nickel improves the strength and relieves the weldability. Cu-Ni compound limits the volume and dimensional changes during the sintering process. Carbon (graphite) in small amounts increases the strength and hardness and improves subsequent heat treatment. Phosphorus improves the strength and elongation, but causes high sintering shrinkage.

An analysis of chemical composition of sintered material (Table 1) shows a small variation between individual samples. The chromium content is within the limits of 1.509 and 1.526%, which differs from the reference value of 0.6 to 1.7%. Molybdenum, as the second influential element, occurs in a concentration of 0.208 to 0.211% and it also differs from the reference value of 4 to 5.5%. Manganese content (0.161%) is significant and good wear resistance can be expected from such a sintered material [4]. The basis for all the tested materials is the iron-based powder Fe1.5Cr0.2Mo. The material variants are shown in Table 2. A detailed description of the additional treatment methods is given in [5].

Table 2. Material variants of the sintered steel

	Additional treatment	Density [g/cm³]	Temperature of sintering [°C]	Dimensional change A [%]
S1	without	7.50	1120	0.16
S2	case hardening	7.49	1120	0.16
S3	case hardening + shot peening	7.49	1120	0.16
S4	pyrohydrolysis	7.50	1120	0.16
S5	sinter-hardening	7.43	1120	0.16
S6	2% copper addition	7.43	1120	0.64

3. TEST CONDITIONS

The practical tests were carried out by using five test benches with a center-to-center distance of 30 mm. The transmission of the asynchronous motor was mounted on the test bench and the output torque was applied via a magnetic particle brake. On each test bench, the engine and the gearbox, as well as the gearbox and the brake, were connected with gear coupling. The measurement of the output torque was made on transmission with a torque gauge bar via a slip ring transmitter. The speeds and output torques were controlled independently for each test bench. The test bench for crossed helical gears and the position of the measuring points is shown in figure 1. The data of the test gear pair are given in table 3.

Table 3: Data of the test gear pair [6]

Parameters	Data
Centre distance	30 mm
Module	1.252 mm
Transmission ratio	40
Pressure angle	20
Wheel material	Fe1.5Cr0.2Mo
Worm material	16MnCr5
Speed	1500 – 10000 min^{-1}
Torque	12-36 Nm
Synthetic oil	Klüber GH6 1500
Mineral oil	Optigear BM 1500
Grease:	Klübersynth G34-130

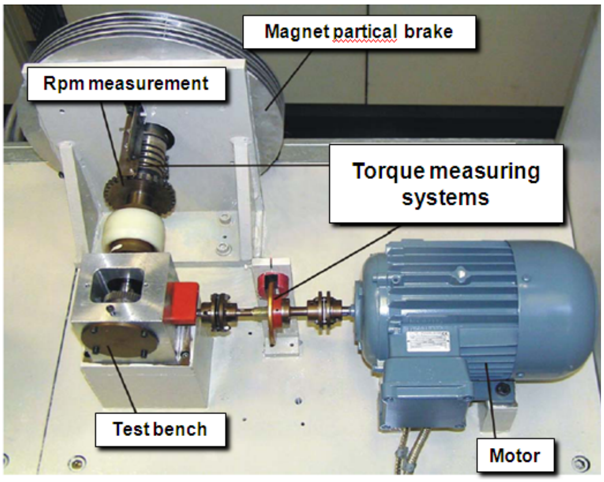


Figure 1. Test bench

4. LUBRICATION

For the sake of comparison, lubrications tests were done under same parameters and with different lubricants: synthetic oil, mineral oil and grease.

4.1. Synthethic oil

Synthetic oil made by Klüber company (Klübersynth GH6 15000) was used in tests. This oil can withstand high scuffing load capacity and has good wear protection. Furthermore, the oil reduces friction and has a flat viscosity-temperature behaviour. This oil is based on polyglycol and it is mainly used in transmissions with the material combination of steel/steel.

The additive GH6 reduces the friction coefficient and wear, especially for worm gears with the material combination steel/bronze. Very low wear intensities for worm gears can be achieved with this oil. Klübersynth GH6 oil with a viscosity of ν_{40} = 1500 mm^2/s was used for testing. Table 4 shows the characteristics of used lubricants.

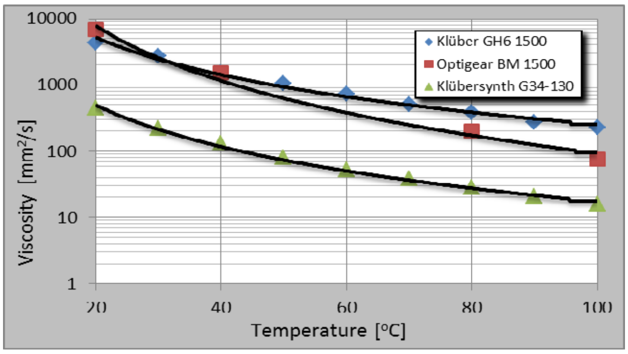


Figure 2. Viscosity-temperature behaviour for used lubricants

4.2 Mineral oil

Castrol Optigear BM 1500 was used in the experiment as the mineral oil with the same viscosity as Klübersynth GH6 1500. High performance gear oil Castrol Optigear BM contains the mineral oil-based additive package MICROFLUX Trans (MFT). This combination of load-active agents and additives adjusts to varying loads and actively prevents wear. Difficulties in the run-in phase can be reduced and problems with wear, material fatigue on surfaces (pitting) and micropitting can be avoided.

Table 4: Data of lubricants

Parameter	GH6 1500	BM 1500	G34-130
Temperature Range [°C]	-20 to 160	-10 to 90	-30 to 130
Density (20°C) [g/cm^3]	1.08	0.93	0.87
Kin. base oil viscos. DIN 51562 ν_{40} [mm^2/s]	1500	1507	150
Kin. base oil viscos. DIN 51562 ν_{100} [mm^2/s]	231	75.6	16
Consistency class DIN 51818, NLGI (grease)			0

4.3 Grease

Klübersynth G34-130 grease for small gears was used in the grease tests. Klübersynth G34-130 is grease based on synthetic hydrocarbon oil. Other ingredients are mineral oil and lithium soap as special polyureas, which serve as consistency factors. The grease has good anti-wear properties and can be used with the combination of steel and plastic.

Figure 2 presents the dependence of kinematic viscosity on temperature for the selected lubricants. The oils Klüber GH6 1500 and Castrol Optigear BM 1500 have the same viscosity at the temperature of 40°C. At higher temperatures, the viscosity of mineral oil Castrol Optigear BM 1500 is smaller than the synthetic oil Klüber GH6 1500. Lubricants dependence on the viscosity is very important at low temperatures. They should still be flowable at high temperatures and very viscous at extremely high temperatures. The best oil in this sense is the Klüber GH6 1500 oil.

5. HERTZIAN CONTACT STRESS

The Hertzian contact stress has a significant influence on the wear rate and the width of the wear surface. The Hertzian contact stress in the crossed helical gears can be determined as the Hertzian contact stress of globoid wheel. It should be taken into consideration that the Hertzian contact stress on the crossed helical gear depends on the width of the wear surface. Therefore, a correlation between the width of the wear surface b_V and the dimensionless ratio p_m^* [5] is introduced. The Hertzian contact stress by the dimensionless parameter of the average Hertzian contact stress $p_{m,V}^*$ is taken into account. The new Hertzian contact stress σ_{Hm} can be calculate for the average Hertzian contact stress $p_{m,V}^*$ according to Equation 1, depending on the output torque T_2, the E-Module E_{red} and centre distance a_s.

$$\sigma_{Hm} = \frac{4}{\pi} \cdot \sqrt{\frac{p_{m,V}^* \cdot T_2 \cdot 1000 \cdot E_{red}}{a_s^3}} \qquad (1)$$

According to the tests for sintered steel Fe1.5Cr0.2Mo with sintered-hardening (S5), the value of E-Module is $E_2 = 203759$ N/mm^2. Therefore, for the material combination of worm made of 16MnCr5 and wheel made of sintered steel Fe1.5Cr0.2Mo, the value of the reduced E-Module is $E_{red} = 227288$ N/mm^2.

The Hertzian contact stress that depends on the width of the teeth $p_{m,V}^*$ can be calculated using Equation 3. The ratio of the width of the globoid wheel b_{2H} to the width of wear surface b_v takes into consideration the increase of the Hertzian contact stress with decreasing width [6].

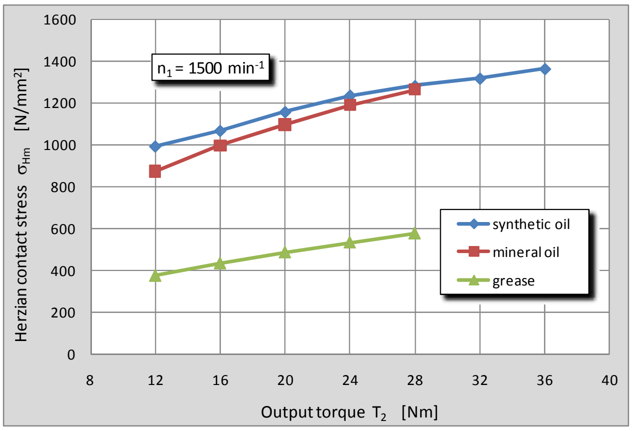
$$p_{m,V}^* = \left(\frac{b_{2H}}{b_v}\right)^{0,8614} \cdot p_m^* \qquad (2)$$

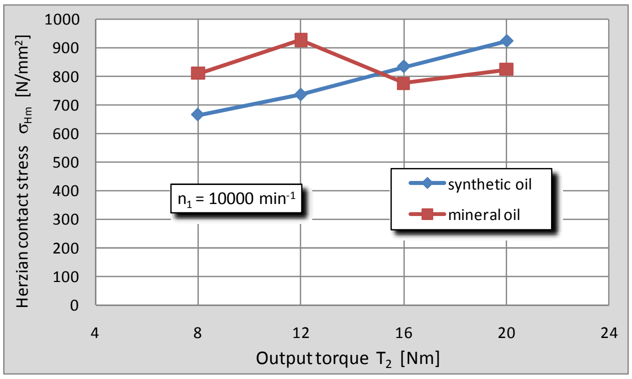
Figure 3 shows the resulting Hertzian contact stress of all tests with different lubricants and $n_1 = 1500$; 5000 und 10000 min^{-1}. In the first load step output torque is 12 Nm, each next step output torque T_2 is increased by 4 Nm, and the time duration of load level is set at 40 hours.

Higher torques leads to the increase in pressure.

There is no great difference in pressure values of Hertzian contact stress for lubrication with mineral and synthetic oil for the rotation speed $n_1 = 1500$ min^{-1} or sliding velocity $v_{gs} = 0.76$ m/s. For grease lubrication, the Hertzian contact stress is on average half the size in relation to mineral and synthetic lubricating oil.

There is great difference in pressure values of Hertzian contact stress for lubrication with mineral and synthetic oil for the rotation speed $n_1 = 5000$ min^{-1} or sliding velocity $v_{gs} = 2.53$ m/s. The values of Hertzian contact stress with synthetic oil are for about 65% higher compared to lubrication with mineral oil. Hertzian contact stresses for lubrication with synthetic oil goes up to 1400 N/mm^2.





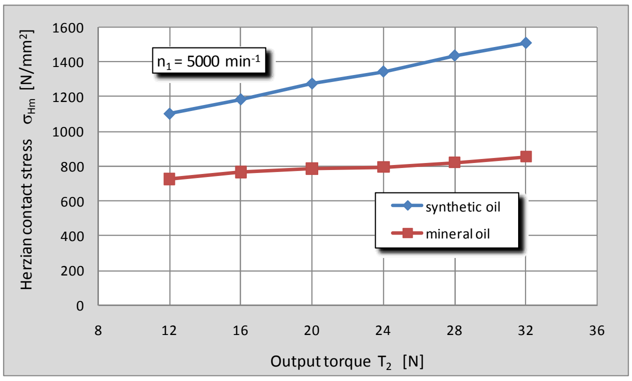


Figure 3. Hertzian contact stress σ_{Hm} for duration of the experiment with different lubrication and $n_1 = 1500$; 5000 and 10000 min^{-1}

For the rotation speed $n_1 = 10000$ min^{-1} or sliding velocity $v_{gs} = 5.05$ m/s up to the number of load changes $N_L = 0{,}9\times10^6$ values of Hertzian contact stress are greater for mineral oil lubrication as compared to synthetic lubricating oil. Then it comes to the sharp increase of wear rate and to reduction of pressure. Lubrication with synthetic oil has a smaller increase of wear rate and smaller reduction of pressure.

Based on the foregoing analysis, it can be concluded that the Hertzian contact stress depends on the choice of lubricant. Synthetic lubricating oil is the most favourable from the aspect of wear, and in terms of achieving hydrodynamic lubrication. Optimal lubrication conditions were obtained for the rotation speed of $n_1 = 5000$ min^{-1} or sliding velocity $v_{gs} = 2.53$ m/s.

6. DAMAGE TYPES

6.1. Wear

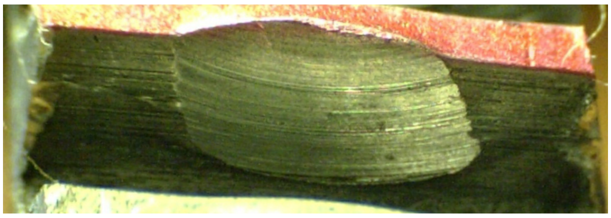


Figure 4. Wear on wheel tooth surface without additional treatment for $T_2 = 36$ Nm; $t = 260$ h; $n_1 = 5000$ min^{-1}

tribological system are: the gear wheel (basic body), the worm (opposed body) and the lubricant (intermediate component).

Experiments with wheels with different additional treatments provide basic knowledge of sintered gears load capacity. Worm and wheel are in contact in a point. During operation, a change in the tooth flank of the wheel appears due to wear. The worm forms on the tooth flank of the wheel, a wear surface that has a shape that is identical to worm gear flank. Wear progress widens the wear surface, which leads to a lower Hertzian pressure in the tooth contact. After a certain period of operation under intensive wear progress, the steady state occurs, where a necessary oil layer exists, so that the wear progress is minimal. Figure 4 shows the form of wear damage on tooth surface of wheel made from material without additional treatment.

Figure 5 compares all experiments with wheels of different material variants after a trial of 100 h and an output torque of 20 Nm. The maximum wear, $\delta_{wn} = 115$ μm, occurred on material S2 – material with case hardening. The minimum wear, $\delta_{wn} = 7.8$ μm, occurred on S5 – sinter-hardening. Figure 4 shows the wear width of the wear surface on wheel from material S4 - “pyrohydrolysis” and S5 sinter-hardening for different speeds. The

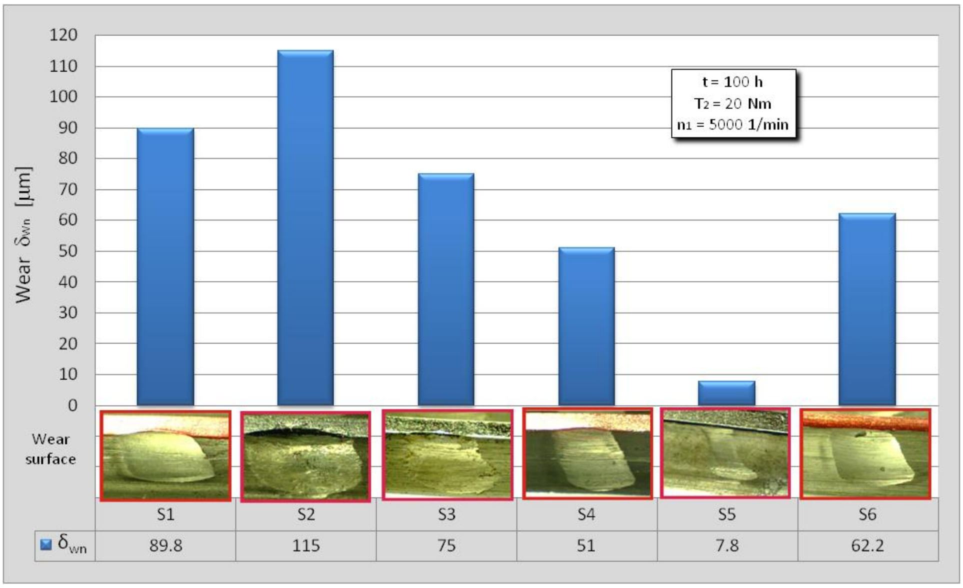


Figure 5. Wear δ_{wn} for all trials with different material variants [6]

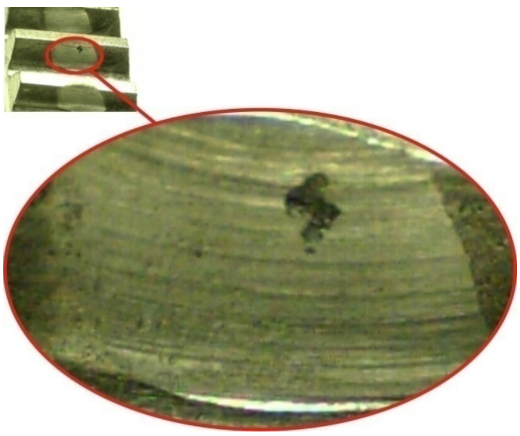
The wear describes the continuous loss of material from the surface of the basic body which has a relative movement with respect to a solid, liquid or gaseous mating with which it is in contact [7]. Wear has exclusively mechanical causes. Different from hardness or tensile strength, wear is not a specific material property but a system property which depends on the particular tribological system. In our case, the elements of the

smallest wear width occurred at input speed $n_1 = 5000$ min^{-1}. The reason for this is that the best experimental conditions, with regard to lubrication and wear, are at this input speed.

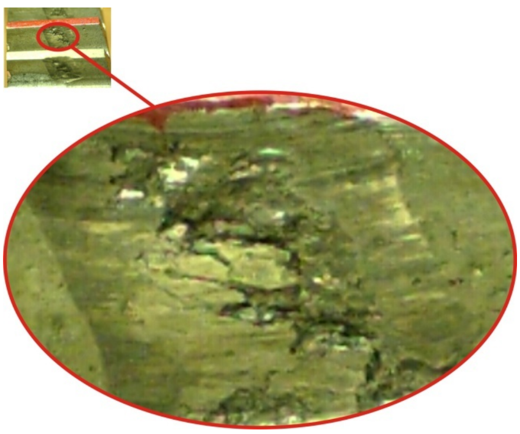
6.2. Wear

A large pressure on surface does not lead to a sudden failure of drive, but over the time, small holes (pits) emerge in the shape of shell on tooth flank. Pit peak always points in the sliding direction. This damage occurs through a cyclic fatigue due to repeated elastic and plastic deformations of the surface. The holes occur only after a sufficiently large number of overrollings (from ca. $5x10^4$ load cycles). If only initial pitting is present, the situation is not dangerous. Destructive pitting destroys the flank and causes failure due to noise and fatigue. The pitting occurred on wheels made from materials S4, S5 and S6 by an output torque of 16 and 32 Nm after the trial time period of 120 h to 240 h.

Figure 6 shows initial and destructive pitting on tooth flank of wheel. In trials with material S1 – without additional treatment, initial pitting ocurred under input speed $n_1 = 5000\ min^{-1}$ and output torque of 20 Nm. In trials with material S5 – sinter-hardening, destructive pitting occurred under input speed $n_1 = 5000\ min^{-1}$ and output torque of 20 Nm and mineral oil.



Initial pitting: without additional treatment
$T_2 = 20$ Nm; t = 120 h; $n_1 = 5000\ min^{-1}$
Lubricant: synthetic oil

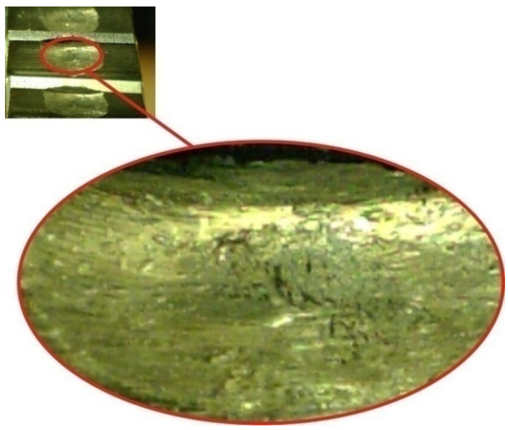


Destructive pitting: sinter-hardening variant
$T_2 = 20$ Nm; t = 120 h; $n_1 = 5000\ min^{-1}$
Lubricant: mineral oil

Figure 6. Pitting on wheel tooth surface [6]

6.3. Scuffing

There is a difference between cold and warm scuffing. Both damage types are caused by the lack of lubricant in contact between teeth. Cold scuffing is relatively rarely seen. It occurs mainly at low speed (< 4 m/s) and between teeth that are having relatively high hardness and rough quality of contact surfaces. Warm scuffing occurs due to great pressure and high sliding velocity between tooth flanks. Under such a load, combined effects occur which lead to the increase in temperature that disrupts the lubricant film between tooth flanks, making the contact between tooth flanks direct and dry. This can cause a short local welding of the flanks which damages both flanks. Warm scuffing is characterized by strip-shaped bands in the direction of the tooth height, and with the strongest expression in the tooth addendum and tooth root. Scuffing on high-speed gears increases the temperature and tooth forces, eventually leading to shaft fracture due to high damage on tooth flanks.



Variant with case hardening
$T_2 = 20$ Nm; t = 160 h; $n_1 = 5000\ min^{-1}$
Lubricant: synthetic oil

Material with 2% copper addition
$T_2 = 28$ Nm; t = 160 h $n_1 = 5000\ min^{-1}$
Lubricant: synthetic oil

Figure 7. Scuffing on tooth flanks of wheel for different material variants [6]

Figure 7 shows the scuffing on wheel tooth flanks for different material variants. With exception of S1, scuffing occurred on all material variants. On wheels made from materials S2 and S3, under load of $T_2 = 16$ Nm and $T_2 = 20$ Nm, the phenomenon of scuffing and significant increase of wear surface and gear forces were observed. Under output torque of $T_2 = 28$ Nm, and input speed $n_1 = 5000\ min^{-1}$ scuffing occurred for S4 and S6. Gear loads rose and, suddenly, the failure of worm shaft occurred. On material variant S6 "2% copper addition", scuffing occurred on tooth root in trials with input speed $n_1 = 5000\ min^{-1}$ and output torque of $T_2 = 28$ Nm, and a very short running time of ca. 10 minutes. Scuffing also occurred on wheel tooth flanks with speed $n_1 = 5000\ min^{-1}$ and output torque of $T_2 = 36$ Nm for material variant S5 sinter-hardening.

7. MAXIMUM OUTPUT TORQUE

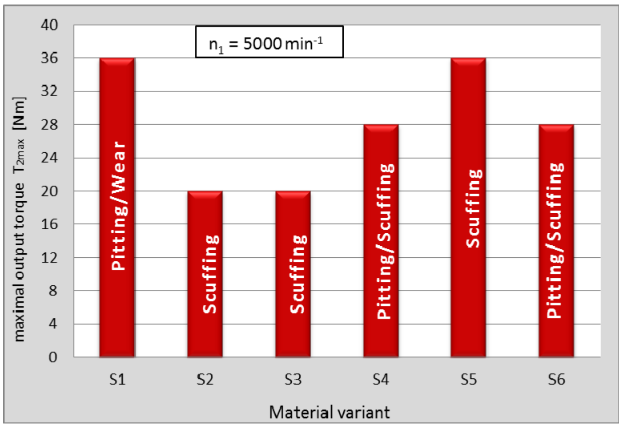


Figure 8. Comparison of maximum transmissible torque with critical damage type for different materials and input speed $n_1 = 5000\ min^{-1}$ [8]

Figure 8 shows maximum transmissible torque, as well as the type of critical damage, in a bar chart. With an output torque of $T_2 = 20$ Nm, materials S2 (case hardening) and S3 (case hardening and shot peening) were damaged due to scuffing. Materials S4 (pyrohydrolysis) and S6 (2 % copper addition) were damaged by pitting when output torque was $T_2 = 24$ Nm, and by scuffing at the value of $T_2 = 28$ Nm. Without an additional treatment, S1 had the most critical wear and some pitting at output torque of $T_2 = 28$ Nm. The wheels S5 (sinter-hardening) had the greatest load carrying capacity, its maximum transmissible torque being 32-36 Nm, and the scuffing being the most dangerous damage form in this case.

8. CONCLUSIONS

The research in this paper shows that tribological parameter of worm-and-gear has great influence on working characteristics in exploitation conditions. The material characteristics like microstructure, wear load capacity and damage types of molded parts can be significantly influenced by additional treatments for sintered steel.

The Hertzian contact stress of teeth in contact depends on the choice of lubricants. The smallest wear occurred in experiments with synthetic oil when Hertzian contact stresses were largest. Synthetic oil can resist the pressures of 1400 N/mm^2 at sliding velocity $v_{gs} = 2.53$ m/s.

All experiments with different material variants show that additional treatments have significant influence on wear. Under identical experimental conditions, the maximum wear δ_{wn} occurred in the trials with wheels of material variant with case hardening (115 μm) and the minimum with wheels with sinter-hardening (7.8 μm).

The pitting was observed in wheels of material variants S4, S5 and S6 by output torque from 16 to 32 Nm. The initial pitting on the tooth flank occurred on material variant without additional treatment (trials with $T_2 = 20$ Nm; t = 120 h; $n_1 = 5000\ min^{-1}$; lubricant: synthetic oil). Destructive pitting on tooth flank occurred in material variant sinter-hardening ($T_2 = 20$Nm; t = 120h; $n_1 = 5000\ min^{-1}$; lubricant: mineral oil).

With exception of S1, scuffing occurred on all material variants. The scuffing was the critical type of damage for wheels from material variants S2 and S3 under the output torque of $T_2 = 20$ Nm with $n_1 = 5000\ min^{-1}$ and by S5 under the output torque of $T_2 = 36$ Nm. For wheels of material variant S6, scuffing occurred for trials with $n_1 = 5000\ min^{-1}$ and output torque of $T_2 = 20$ Nm. For wheels of material variants S4 and S6, the critical type of damage was the combination of pitting and scuffing.

Lubrication with synthetic oil is the most favorable from the aspect of wear and in terms of achieving hydrodynamic lubrication. Optimal working lubrication was obtained for the rotation speed $n_1 = 5000\ min^{-1}$ or sliding velocity $v_{gs} = 2.53$ m/s.

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