Damage Types of Crossed Helical Gears with Wheels from Sintered Steel

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Abstract:
Sintered steel appears to be a very effective material for wheels in crossed helical gears. High demands are set on gears made from sintered steel regarding wear, fretting, tooth fracture and pitting load capacity. This report shows results of iron-based sintered material Fe1.5Cr0.2Mo in case of crossed helical gears concerning wear resistance and other damage types under different speed, torque and lubricants. As material variants, samples with additional treatment, such as pyrohydrolysis, case hardening, shot peening, sinter-hardening, and 2% copper addition are used.

Key words: Sintered steel; Gears; Transmission; Wear

1. Introduction

Crossed helical gears are used, for example, in automotive auxiliary drive units such as window lifters, seat adjustments, windscreen wipers, and 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.

In these applications, combinations with pinions or worms made of steel, and gear wheels made of plastic are often used. The gear wheels are made by injection molding at low cost in large quantities. Due to the low carrying capacity of gear wheels made of plastic, they can transfer only small torque. Otherwise, size of the transmission is relatively large.

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

The work by Wendt [1] is the first one focusing on the study of load capacity for crossed helical gears with material combination steel/sintered metal. As sintered metal, he used Fe1.5Mo0.3C with material density of 6.9 and 7.2 kg/dm³. His work provides approximate equations for the calculation of safety factors for tooth damage such as pitting and wear. He also verified that increased material density leads to an increased wear resistance.

The load capacity of mechanical parts depends on failure limits. Stress analysis determines the stress in materials and the deformations of structure and examines whether a failure can be prevented with adequate safety. The factors of safety for failure limits should not be too high in order to exploit materials and to achieve cost-effective solutions. Failure limits depend, apart from load, material and design, on influences such as lubricants,
temperature, corrosion and wear. To meet these requirements, detailed information on failure limits is needed. Here, a detailed study of the wear load capacity, the overall efficiency and oil sump temperature for the gear wheels with Fe1.5Cr0.2Mo sintered steel with different treatment methods is carried out in 160 wear tests.

2. Chemical composition of sintered steel and material variants

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

Tab. I. Chemical composition of sintered steel Fe1.5Cr0.2Mo (%)

<table>
<thead>
<tr>
<th>element</th>
<th>measure point 1</th>
<th>measure point 2</th>
<th>measure point 3</th>
<th>measure point 4</th>
<th>measure point 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.254</td>
<td>0.243</td>
<td>0.238</td>
<td>0.253</td>
<td>0.273</td>
</tr>
<tr>
<td>Mn</td>
<td>0.163</td>
<td>0.161</td>
<td>0.161</td>
<td>0.161</td>
<td>0.161</td>
</tr>
<tr>
<td>Cr</td>
<td>1.521</td>
<td>1.517</td>
<td>1.526</td>
<td>1.51</td>
<td>1.509</td>
</tr>
<tr>
<td>Mo</td>
<td>0.21</td>
<td>0.208</td>
<td>0.209</td>
<td>0.211</td>
<td>0.21</td>
</tr>
</tbody>
</table>

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 (Tab. 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 [3]. The basis for all the tested materials is the iron-based powder Fe1.5Cr0.2Mo. The material variants are shown in Tab. II. A detailed description of the additional treatment methods is given in [5].

Tab. II. Material variants of the sintered steel Fe1.5Cr0.2Mo

<table>
<thead>
<tr>
<th>Additional treatment</th>
<th>Density [g/cm³]</th>
<th>Temperature of sintering [°C]</th>
<th>Dimensional change A [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 without</td>
<td>7.50</td>
<td>1120</td>
<td>0.16</td>
</tr>
<tr>
<td>S2 case hardening</td>
<td>7.49</td>
<td>1120</td>
<td>0.16</td>
</tr>
<tr>
<td>S3 case hardening + shot peening</td>
<td>7.49</td>
<td>1120</td>
<td>0.16</td>
</tr>
<tr>
<td>S4 pyrohydrolysis</td>
<td>7.50</td>
<td>1120</td>
<td>0.16</td>
</tr>
<tr>
<td>S5 sinter-hardening</td>
<td>7.43</td>
<td>1120</td>
<td>0.16</td>
</tr>
<tr>
<td>S6 2% copper addition</td>
<td>7.43</td>
<td>1120</td>
<td>0.64</td>
</tr>
</tbody>
</table>
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 Fig. 1. The data of the test gear pair are given in Tab. III.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre distance</td>
<td>30 mm</td>
</tr>
<tr>
<td>Module</td>
<td>(1.252 mm)</td>
</tr>
<tr>
<td>Transmission ratio</td>
<td>40</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>20</td>
</tr>
<tr>
<td>Wheel material</td>
<td>Fe1.5Cr0.2Mo</td>
</tr>
<tr>
<td>Worm material</td>
<td>16MnCr5</td>
</tr>
<tr>
<td>Speed</td>
<td>1500 – 10000 min⁻¹</td>
</tr>
<tr>
<td>Torque</td>
<td>12-36 Nm</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Oil: Klüber GH6 1500</td>
</tr>
</tbody>
</table>

4. Damage types

4.1. Wear

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 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. Fig. 2 shows the form of wear damage on tooth surface of wheel made from material S1 (without additional treatment).

**Fig. 3.** Wear $\delta_{wn}$ for all trials with different material variants

**Fig. 4.** Material: S4 “pyrohydrolysis” and S5 - sinter-hardening for $T_2 = 20$ Nm; $t = 120$ h; lubricant: synthetic oil Klübersynth GH6 1500
Fig. 5. Wear surfaces on wheel of material S5 – sinter-hardening with different lubricants and $T_2 = 28 \text{ Nm}; t = 200 \text{ h}; n_1 = 1500 \text{ min}^{-1}$

Fig. 3 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, $\delta_{\text{wn}} = 115 \mu m$, occurred on material S2 – material with case hardening. The minimum wear, $\delta_{\text{wn}} = 7.8 \mu m$, occurred on S5 – sinter-hardening. Fig. 4 shows the wear width of the wear surface on wheel from material S4 - “pyrohydrolysis” and S5 sinter-hardening for different speeds. The smallest wear width occurred at input speed $n_1 = 5000 \text{ min}^{-1}$. The reason for this is that the best experimental conditions, with regard to lubrication and wear, are at this input speed. Fig. 5 shows the wear width of the wear surface at wheel from material S5 with different lubricants for input speed $n_1 = 1500 \text{ min}^{-1}$. The wear width $b_w$ of grease lubricant is higher than oil for about 50%.

4.2. Pitting

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. $5 \times 10^4 \text{ load cycles}$). 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.
Fig. 6. Initial pitting on wheel tooth surface from different material variants

Fig. 6 shows initial pitting on tooth flank of wheel with different material variants. In trials with material S1 – without additional treatment, initial pitting occurred under input speed $n_1 = 5000 \text{ min}^{-1}$ and output torque of 36 Nm. In trials with material S5 – sinter-hardening, initial pitting occurred on wheel tooth flank under input speed $n_1 = 5000 \text{ min}^{-1}$ and output torque of 16 Nm and only with mineral oil.

Fig. 7 shows destructive pitting on tooth flank with different material variants. In trials with material S5 – sinter-hardening, destructive pitting occurred under input speed $n_1 = 5000 \text{ min}^{-1}$ and output torque of 20 Nm and mineral oil. In trials with material S4 – “pyrohydrolysis”, destructive pitting occurred after at least 180 h under input speed $n_1 = 5000 \text{ min}^{-1}$ and output torque of 28 Nm.

Fig. 7. Destructive pitting on wheel tooth flank with different material variants

4.3. 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 ($< 4 \text{ m/s}$) 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.

Fig. 8. Scuffing on tooth flanks of wheel for different material variants

Fig. 8 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 S4 “pyrohydrolysis”, scuffing occurred on tooth root in trials with input speed $n_1 = 5000$ min$^{-1}$ and output torque of $T_2 = 16$ 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. On trials with input speed $n_1 = 10000$ min$^{-1}$ scuffing also occurred under smaller output torque.

4.4. Scoring

Compared with worm materials, the wheel sintered material has lower hardness. In trials, damage also occurred on the harder opposite body. Scoring was observed in circumferential direction of wheel tooth flanks and on wear wheel surface. This damage on worm caused increased wear on the wheel, which could lead to early failure of transmission.

The grooves are caused by abrasive wear particles of worm, which are released due to the high Hertzian pressure in tooth contact. The wear particles in the continued operation on the wheel surface cause greater scoring damage. The contamination of the oil by wear particles from the wheel also speeds up the progression of scoring.
The scoring occurred on all sliding velocities and generally more at higher torques. For material S4 “pyrohydrolysis”, high scoring on tooth flank was observed at input speed $n_1 = 1500 \text{ min}^{-1}$ and output torque of 24 Nm. Fig. 9 shows a damaged wheel tooth flank of material variant S4 with $n_1 = 1500 \text{ min}^{-1}$, $T_2 = 32 \text{ Nm}$ and synthetic oil.

5. Maximum output torque

Fig. 10 shows maximum transmissible torque, as well as the type of critical damage, in a bar chart. With an output torque of $T_2 = 20 \text{ Nm}$, 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 $T_2 = 24 \text{ Nm}$, and by scuffing at the value of $T_2 = 28 \text{ Nm}$. Without an additional treatment, S1 had the most critical wear and some pitting at output torque of $T_2 = 28 \text{ Nm}$. 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.
6. Summary

The material characteristics like microstructure, hardness, wear load capacity and damage types of molded parts can be significantly influenced by additional treatments for sintered steel. This report gives an analysis of damage types of sintered steel that are improved through various additional treatments. The most common damage types of gear tooth flanks are wear, pitting and scuffing.

The analysis of wear progress for all experiments with different material variants shows that additional treatments have greater influence on wear. Under identical experimental conditions, the maximum wear \( \delta_{\text{wn}} \) occurred in the trials with wheels of material variant S2 – case hardening (115 \( \mu \)m) and the minimum with wheels with S5 – sinter-hardening (7.8 \( \mu \)m).

The experiments with different input speeds (1500, 5000 und 10000 min\(^{-1}\)) show that the smallest wear width of wear surface occurs at input speed \( n_{1} = 5000 \text{ min}^{-1} \). The lubricants have very significant influence on wear. The wear width \( b_{v} \) of grease lubricant is higher than oil for about 50%.

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 S1 – without additional treatment (trials with \( T_{2} = 36 \text{ Nm}; t = 250 \text{ h}; n_{1} = 5000 \text{ min}^{-1} \); lubricant: synthetic oil) and S5 – sinter-hardening (\( T_{2} = 16 \text{ Nm}; t = 60 \text{ h}; n_{1} = 5000 \text{ min}^{-1} \); lubricant: mineral oil). Progressive pitting on tooth flank occurred in material variant S4 – “pyrohydrolysis” (\( T_{2} = 28 \text{ Nm}; t = 180 \text{ h}; n_{1} = 5000 \text{ min}^{-1} \); lubricant: synthetic oil) and S5 – sinter-hardening (\( T_{2} = 20 \text{ Nm}; t = 120 \text{ h}; n_{1} = 5000 \text{ min}^{-1} \); lubricant: mineral oil).

With exception of S1, scuffing occurred on all material variants (S2, S3, S4, S5, and S6). The scuffing was the critical type of damage for wheels from material variants S2 and S3 under the output torque of \( T_{2} = 20 \text{ Nm} \) and by S5 under the output torque of \( T_{2} = 36 \text{ Nm} \). For wheels of material variant S5, scuffing occurred for trials with \( n_{1} = 5000 \text{ min}^{-1} \) and higher output torque and for trials with input speed \( n_{1} = 10000 \text{ min}^{-1} \) at smaller output torque. For wheels of material variants S4 and S6, the critical type of damage was the combination of pitting and scuffing.

The scoring occurred at all sliding velocities and mostly at higher torques. For material variant S4 “pyrohydrolysis” and at \( n_{1} = 5000 \text{ min}^{-1} \), by torque greater than 24 Nm, a very strong damage on tooth flanks due to scoring was observed.

Finally, it can be concluded that the variant with the additional treatment “sinter-hardening” has the best wear resistance.

7. References

7. DIN 50320, 12/1979
Садржај: Синтер-челик се показао као веома погодан материјал за израду зупчаника завојних преносника. Од ових зупчаника захтева се висока носивост у односу на хабање, заривање, лом зупца у подножју и у односу на питање. У раду су приказани резултати истраживања облика оштећења и граничних стања бокова зубаца зупчаника од од Fe1,5Cr0,2Mo синтер-челика са различитим завршним обрадама. При томе су вариране бројеви обртаја, обртни моменти и средства за подмазивање. Од поступака завршне обраде примењени су цементација, сачмарење, третман воденом паром, додатак 2% бакра и отвардњавање синтер топлотом.
Кључне речи: синтеровани челик; зупчаник; облици оштећења; гранична стања