CONTRIBUTION TO THE STUDY OF HCR GEARING PROPERTIES FROM WARM SCUFFING DAMAGE POINT OF VIEW

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Abstract: The issue of design and dimensioning of HCR gearing, particularly of the gearings with an internal engagement, it nowadays, especially in the design of hybrid cars drives, highly topical. This kind of gearing has many advantages in operation, but at the same time it is more complicated in stage of its design and load capacity calculation. Authors in this contribution present some results of temperature scuffing research of internal and external HCR gearing. There are given the equations for calculation of warm scuffing resistance of both external and internal HCR gearing derived according to the integral temperature criterion.

Key words: HCR gearing, warm scuffing, flash temperature, integral temperature criterion

1. INTRODUCTION

Nowadays, the highly loaded gears transmissions are still increasingly designed with the High Contact Ratio (HCR) gearing (Fig.1). We can observe this new trend during our analysis of the constructional solutions of components, which transmit the power output in the transport vehicles, mainly in passenger car gearboxes. It results from the demand to reduce the unladen weight of vehicle, however the transmitted power output should be retained the same or bigger. This leads to the search of new options to minimize the size of gearing and thus the size of gearwheels too.

Reducing the dimensions of the gear leads to its bigger heat load caused by reduction of the material’s volume for the transfer of heat energy which is formed in the teeth meshing. Increased thermal stress gear may give rise to warm scuffing of teeth flanks. The tendency to scuffing damage is besides the heat stress depended on the gear load, the peripheral speed, the gearing geometry, the quality of teeth flanks and on the properties of the lubricating oil.

Damaging of the teeth flanks by scuffing can lead, when crossing the limit criteria, up to the shutdown such gear, what is possible even after a short time of operation. In the case of the gearings with internal engagement, although are applied advantageous properties of the convex-concave meshing, but in the extreme cases of the gearing with HCR profiles it is possible also here to expect this type of teeth flanks damage, and therefore is the study of scuffing reasonable even for this type of gearing. The HCR gearing has even another advantage – the advantage of low noise in the case of properly chosen value length of path of contact (εg≈2). This predetermines usage of HCR gearing in passenger automotive gearboxes. The design of this profile is more complicated compared to the design of standard profile (Fig.2), because of the bigger danger of emergence of interferences in the mesh, low topland width and undercut of teeth.

Fig.1. Internal gearing and pinion with HCR profile of teeth flanks

Fig.2. Internal gearing and pinion with standard profile of teeth flanks

Problems with the teeth geometry proposal can be solved directly during its designing. The teeth designing is more complicated from the strength characteristics point of view, mainly because of the missing extensive...
experimental testing results and even non-existing, or more-precisely not-sufficient support of the standardized calculation procedures.

On the basis of extensive experiences in experimental testing of the HCR gear endurance with external engagement from the point of the contact strength view, was the second HCR gear testing broaden to the gearing with internal engagement, mostly from the point of resistance to the thermal gear scuffing ϵα≥2. It is related mainly to the solution of the hybrid car drives problems during division of the power flow, in which are almost solely used planetary gear (2k+r) with annulus ring, and therefore is the study of internal engagement in this context very important.

2. WARM SCUFFING OF GEARING WITH EXTERNAL AND INTERNAL ENGAGEMENT

In general, the danger of the damage of the teeth flanks caused by warm scuffing is bigger in the case of gearing with external engagement than in the internal one. It is related to the positive influence of the convex-concave meshing of the internal gearing in comparison to the convex-convex meshing of the external gearing. On the other hand, in the case of the HCR internal gearing, the negative effect is caused by the longer path of contact, what also means the higher values of the tangential velocities at the beginning and at the end of meshing. The higher values of local flash temperature comes up from this conditions and with them comes also a higher probability of the warm scuffing occurance. According to Blok (flash temperature criterion) it is possible to express the flash temperature at any point of meshing along the contact path by the formula

\[ T = 0.62 \mu_s \left( \frac{F_n}{b} \right)^{0.75} \left( \frac{E_r}{\rho_r} \right)^{0.25} \frac{|v_{t1}-v_{t2}|}{(\lambda_1 \rho_{a1} \rho_{a2} + \lambda_2 \rho_{a2})^{1/2}} \]  

(1)

Where is:

- \( \mu_s \) friction coefficient in tooth engagement at point X
- \( F_n \) normal force
- \( \sigma_{a} \) working transverse pressure angle
- \( E_r \) reduced wheels materials modulus of elasticity
- \( \rho_r \) reduced radius of curvature at that point of mesh
- \( v_{t1,2} \) tangential velocity at the X profile point
- \( \lambda_{1,2} \) coefficients of thermal conductivity of wheels materials
- \( \rho_{m1,2} \) specific densities of wheels materials

There are not has been published any relevant results of the valuation of the internal HCR gearing resistance against the warm scuffing damage. Nowadays we use the normalized calculation of load capacity of the involute gearing to the thermal scuffing derived according to the integral temperature criterion. However, this is valid only for standard profiles. For HCR gearing is necessary to extrapolate particular factors, which have substantial influence on the designation of the integral temperature value and in this way it is possible to extend the validity of this criterion, even on the gearing with \( \epsilon_{\alpha} \geq 2 \).

HCR gearing is different from the standard profiles in different load distribution along the contact line and, of course, there are here also bigger tangential velocities at the beginning and at the end of the meshing. If we analyze relation (1) more deeply, it is evident, that from the geometric parameters point of view, the main influence on the resistance to scuffing of the teeth have the values of the tangential velocities and the value of reduced radius of curvature. The values of these parameters are shown in the Fig.3 to Fig.6 both so for the standard gearing as and for the HCR gearing (both external and internal according to parameters in Tab.1 to Tab. 3).

If we take into account Blok’s intensity of local flash temperature of standard and HCR gearing with
comparable geometric characteristics, it is apparent, that these temperatures are bigger for HCR gearing and it is valid same for internal or external engagement. At the Fig.7 are plotted Blok’s local flash temperatures along the contact path for gearing loaded by $M_{k}=1000$Nm, and of the peripheral speed $v_p=12$ m.s$^{-1}$, for the standard gearing with $\varepsilon_{\alpha}=1.6$ (Tab.1), HCR gearing with $\varepsilon_{\alpha}=2$ (Tab.2) and for the internal HCR gearing with $\varepsilon_{\alpha}=2$ (Tab.3). It is obvious, that values of local flash temperatures are much smaller for the internal gearing than for the external one,

but here we have to take into account the fact, that the internal gearing can be loaded by bigger torque and then even internal gearing damage, caused by warm scuffing, can be decisive for its draft.

### Table 1. Parameters of standard external profile

<table>
<thead>
<tr>
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<th>pinion</th>
<th>wheel</th>
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<tr>
<td>number of teeth</td>
<td>$z_1=21$</td>
<td>$z_2=51$</td>
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<tr>
<td>module</td>
<td>$m_n=4mm$</td>
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<tr>
<td>addendum factor</td>
<td>$h_{a1}=1.00$</td>
<td>$h_{a2}=1.00$</td>
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<td>addendum modification factor</td>
<td>$x_1=+0.40$</td>
<td>$x_2=-0.40$</td>
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<tr>
<td>helix angle</td>
<td>$\beta=0^\circ$</td>
<td></td>
</tr>
<tr>
<td>pressure angle</td>
<td>$\alpha_t=20^\circ$</td>
<td></td>
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</tbody>
</table>

### Table 2. Parameters of HCR external profile

<table>
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<th>pinion</th>
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</thead>
<tbody>
<tr>
<td>number of teeth</td>
<td>$z_1=21$</td>
<td>$z_2=51$</td>
</tr>
<tr>
<td>module</td>
<td>$m_n=4mm$</td>
<td></td>
</tr>
<tr>
<td>addendum factor</td>
<td>$h_{a1}^*=1.30$</td>
<td>$h_{a2}^*=1.29$</td>
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<tr>
<td>addendum modification factor</td>
<td>$x_1^*=0.40$</td>
<td>$x_2^*=-0.40$</td>
</tr>
<tr>
<td>helix angle</td>
<td>$\beta=0^\circ$</td>
<td></td>
</tr>
<tr>
<td>pressure angle</td>
<td>$\alpha_t=20^\circ$</td>
<td></td>
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</tbody>
</table>

### Table 3. Parameters of HCR internal profile

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<th></th>
<th>pinion</th>
<th>wheel</th>
</tr>
</thead>
<tbody>
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<td>$z_2=-73$</td>
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<tr>
<td>module</td>
<td>$m_n=4mm$</td>
<td></td>
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<tr>
<td>addendum factor</td>
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<td>$h_{a2}^*=1.1837$</td>
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<td>addendum modification factor</td>
<td>$x_1^*=0.4218$</td>
<td>$x_2^*=-0.407$</td>
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<tr>
<td>helix angle</td>
<td>$\beta=0^\circ$</td>
<td></td>
</tr>
<tr>
<td>pressure angle</td>
<td>$\alpha_t=20^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

3. TEMPERATURE CRITERION

The main goal of the authors of the study is to extend the validity of integral temperature criterion (according to Winter and Michaelis) even on the HCR gearing and
Fig.10. Simplified courses of the load and flash temperature values along the path of contact for standard gearing

\[ \vartheta_{\text{sl,1}} = \vartheta_{\text{sl}} + 2.2 \vartheta_{\text{BE}} X_\varepsilon \]  \hspace{1cm} (2)

The value of local flash temperature \( \vartheta_{\text{BE}} \) at the meshing point E will be determined from the equation (1) for specific parameters of the end point E, which is in the meshing of the pinion head. For the calculation and projection of the graphs, we had to take into account the course of the loading and tangential velocity along the meshing line according to Fig.10 and Fig.11.

Basically the main difference between the calculation of the integral temperature intensity for standard and HCR gearing is determination of factor of load distribution \( X_\varepsilon \).

Relations for \( X_\varepsilon \) are determined as a part of the area under the course curves of the local flash temperatures along the meshing (Fig.7) and local flash temperatures at the point \( E_{c=1} \) multiplied by the length of the meshing line (equivalent areas). For the standard involute gearing with parameters according to the tab.1 applies.

\[ X_\varepsilon = \frac{1}{2 e_1 e_2} \left[ 0.18(\varepsilon_1^2 + 0.7 \varepsilon_2^2) + 0.82 \varepsilon_1 + 0.52 \varepsilon_2 - 0.3 \varepsilon_1 \varepsilon_2 \right] \]  \hspace{1cm} (3)

Where \( \varepsilon_1 \) and \( \varepsilon_2 \) are the pinion, resp. wheel contact ratio coefficients.

For the HCR gearing was on the same way derived equation for \( X_\varepsilon \) in the form

\[ X_\varepsilon = \frac{1}{2 e_1 e_2} \left[ 0.204 \varepsilon_1^2 + 0.123 \varepsilon_2^2 + 4.106 \varepsilon_1 + 2.122 \varepsilon_2 - 0.543 \varepsilon_1 \varepsilon_2 - 0.54 \right] \]  \hspace{1cm} (4)

4. CONCLUSION

According to the above mentioned theoretical considerations were evaluated properties of tooth gears according to Tab. 1 to Tab.3 (Tab.4) against scuffing damage, and the results obtained for the externally toothed wheels were also experimentally verified. From Tab.4 it can be seen that the value of the integral temperature at HCR external gearing is significantly higher than for external standard profiles. In this case, the calculated temperatures are valid for the pinion's revolution \( n_1 = 720 \) 1/min. The limit integral temperature of scuffing for oil PP 80, which was measured at our department, is about 308 °C. This means that the HCR external gearing does not have sufficient temperature safety against thermal scuffing, which has to be greater than 1.4. It is clear, that the internal gearing is more resistant against warm scuffing damage, but also for this gearing with HCR profile is needed always check its load capacity from this point of view. When comparing the properties of gears according to Table 1 to Table 3, it is necessary to take into account that the wheels with external teeth were designed for lifetime tests on contact fatigue (without to take in account the scuffing), and gears with internal engagement were designed specifically so to achieve so low resistance against warm scuffing damage as it is possible from point of view of geometric parameters of gearing.
The results from the brief analysis of the warm scuffing problematic of the HCR gearing state, that this kind of gearing is significantly prone to the scuffing damage of the teeth flanks. In our tests of the HCR gearing on contact fatigue occurred warm scuffing damage already after a short gearbox running, what had caused impossibility to continue the experiment. Tests were carried out on the experimental equipment with closed power flow (aw=144mm) which has similar construction as standard FZG rig (Fig.13). Test wheel had parameters according to table 2 (Fig.14). On the Fig.15 is shown part of test wheel with progressive scuffing damaged teeth flanks, which occurred after few minutes during realization of experimental tests of HCR gearing on contact fatigue (pitting). In this specific case we solved this problem by replacing the original lubricating oil PP 80 with hypoid gear oil PP 90H, thereby scuffing problems were eliminated. Based on these conclusions is clear that the design of HCR gearing, whether they be standard profile (tab.1), External HCR profile (tab.2) or Internal HCR (tab.3)

![progressive scuffing](image)

**Fig.14. Tooth flank of testing wheel damaged with progressive scuffing**

![initial signs of pitting](image)

**Fig.15. Testing and technological gears used in the experimental rig acc. to Fig.16.(aw=144mm, gearing geometry parameters according to Table 2.)**

**Table 4. Calculated integral temperature parameters**

<table>
<thead>
<tr>
<th></th>
<th>standard profile (tab.1)</th>
<th>External HCR profile (tab.2)</th>
<th>Internal HCR (tab.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_e</td>
<td>0,19</td>
<td>0,52</td>
<td>0,26</td>
</tr>
<tr>
<td>ΔB[°C]</td>
<td>139,1</td>
<td>163,0</td>
<td>48,2</td>
</tr>
<tr>
<td>ΔT[°C]</td>
<td>128,1</td>
<td>256,5</td>
<td>97,6</td>
</tr>
</tbody>
</table>

![Experimental rig with closed power flow](image)

**Fig.16. Experimental rig with closed power flow (aw=144mm, testing wheel according to Table 2.) (external gearing)**
external or internal, it is always necessary to envisage the possibility of the occurrence of warm scuffing. Testing of internal gears requires structural modifications on the experimental equipment. These modifications of experimental rig with closed power flow are evident from Fig. 16.

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REFERENCES


