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Analysis of the HCR Gearing from warm Scuffing Point of View

The issue of design and dimensioning of HCR gearing, particularly of the gearings with an internal engagement is 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 the stage of its design and load capacity calculation. Authors present in this contribution some results of warm 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

Keywords: HCR, 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.2). 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.

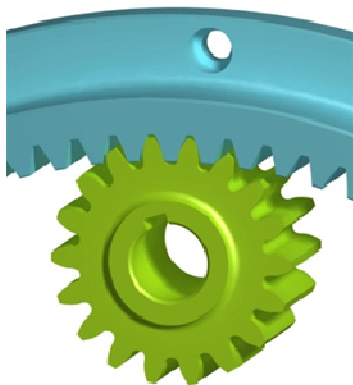


Figure 1. Internal gearing with standard profile of teeth flanks

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, besides the heat stress depends on the gear load, the peripheral speed, the gearing geometry, the quality of teeth flanks and on the properties of the lubricating oil. Damage of the teeth flanks by scuffing can lead, when crossing the limit

criteria, up to the shutdown of that gear, what is possible even after a short time of operation.



Figure 2. Internal gearing with HCR profile of teeth flanks

In the case of the gearings with internal engagement, although advantageous properties of the convex-concave meshing are applied, but in the extreme cases of the gearing with HCR profiles it is possible to expect this type of teeth flanks damage.

The study of scuffing is therefore 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 ($\varepsilon_\alpha \approx 2$) [1]. 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.1), because of the bigger danger of emergence of interferences in the mesh, small top-land width and undercut of teeth [1], [2].

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 [3], 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 [7], the next HCR gear testing was extended by

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the gearing with internal engagement, mostly from the point of resistance to warm scuffing $\varepsilon_\alpha \approx 2$.

It is related mainly to the solution of the hybrid car drives problems with 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.

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 come up from these conditions and with them come also a higher probability of the warm scuffing occurrence. 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 (1) [6].

There not have been yet published any relevant results of the valuation of the internal HCR gearing resistance against the warm scuffing damage [4]. 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. In this way it is possible to extend the validity of this criterion, even on the gearing with $\varepsilon_\alpha \geq 2$.

$$g_{Bl} = 0,62 \mu_X \cdot \left(\frac{F_n}{b} \right)^{0,75} \left(\frac{E_r}{\rho_{rX}} \right)^{0,25} \cdot \frac{|v_{t1X} - v_{t2X}|}{\sqrt{\lambda_1 \cdot \rho_{m1} \cdot c_1 \cdot v_{t1X} + \lambda_2 \cdot \rho_{m2} \cdot c_2 \cdot v_{t2X}}} \quad (1)$$

2. WARM SCUFFING OF GEARING WITH INTERNAL ENGAGEMENT

HCR gearing is different from the standard gearing in different load distribution along the contact line. Of course, there are also bigger tangential velocities at the beginning and at the end of the meshing. If we analyse 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 of reduced radius of curvature. The values of these parameters are shown in the Fig.3 to Fig.6 both for the standard gearing 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. 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 torque $T_{kl} = 1000$ Nm, and of the peripheral speed $v_o = 12$ m/s, for the standard gearing with $\varepsilon_\alpha \approx 1,6$ (Tab.1), HCR gearing with $\varepsilon_\alpha \approx 2$ (Tab.2) and for the internal HCR gearing with $\varepsilon_\alpha \approx 2$ (Tab.3).

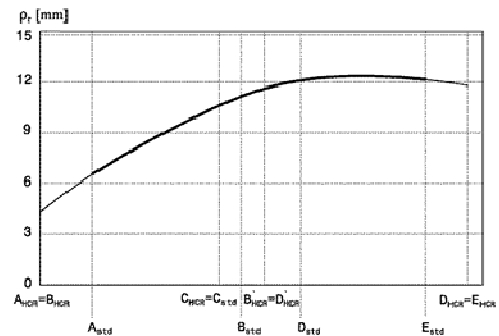


Figure 3. Values of ρ_r along the path of contact of external HCR and standard gearing

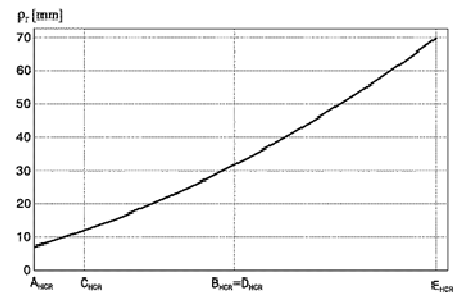


Figure 4. Values of ρ_r along the path of contact of internal HCR gearing

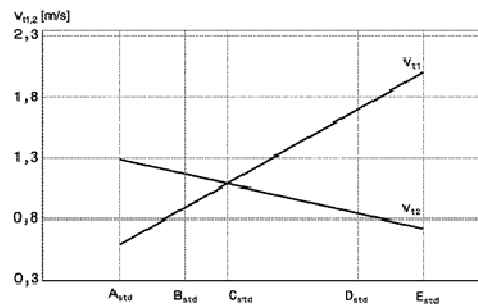


Figure 5. Tangential velocities of standard gearing with external engagement

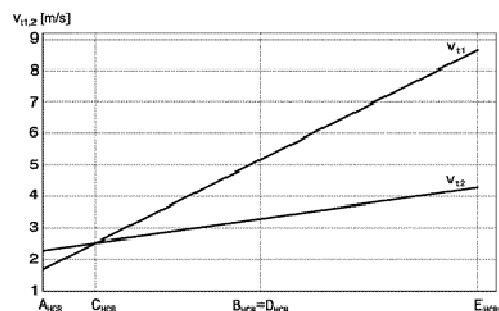


Figure 6. Tangential velocities of HCR gearing with internal engagement and $\varepsilon_\alpha = 2$

It is obvious that values of local flash temperatures are much smaller for the internal gearing than for the external one (because of ρ_r values, see Fig. 3 and 4).

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.

3. INTEGRAL 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 check it out by experimental testing according to FZG methodology. In case of internal gearing testing it will be made on adapted experimental rig with closed power flow. The value of the integral temperature of mating gears flanks, we can express by relation (2) [6]:

$$g_i = g_{ol} + 2,2g_{BIE}X_\varepsilon \quad (2)$$

where g_{ol} is oil temperature.

Table 1

parameter	pinion	wheel
number of teeth	$z_1=21$	$z_2=51$
module	$m_n=4$ mm	
addendum factor	$h_{a1}^*=1,00$	$h_{a2}^*=1,00$
addendum modification factor	$x_1=+0,40$	$x_2=-0,40$
helix angle	$\beta=0^\circ$	
pressure angle	$\alpha_t=20^\circ$	

Table 2

parameter	pinion	wheel
number of teeth	$z_1=21$	$z_2=51$
module	$m_n=4$ mm	
addendum factor	$h_{a1}^*=1,30$	$h_{a2}^*=1,29$
addendum modification factor	$x_1=+0,40$	$x_2=-0,40$
helix angle	$\beta=0^\circ$	
pressure angle	$\alpha_t=20^\circ$	

Table 3

parameter	pinion	wheel
number of teeth	$z_1=21$	$z_2=73$
module	$m_n=4$ mm	
addendum factor	$h_{a1}^*=1,2385$	$h_{a2}^*=1,1837$
addendum modification factor	$x_1=0,4218$	$x_2=0,407$
helix angle	$\beta=0^\circ$	
pressure angle	$\alpha_t=20^\circ$	

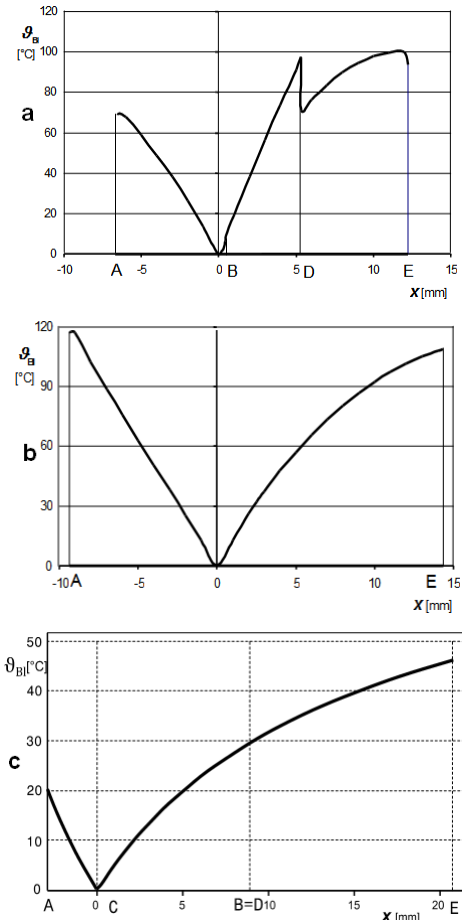


Figure 7. Courses of local flash temperatures along the contact path of external involute standard gearing (a), HCR external gearing $\varepsilon_\alpha \approx 2$ (b), and of internal HCR gearing $\varepsilon_\alpha \approx 2$ (c)

The value of local flash temperature g_{BIE} at the meshing point E will be determined from the equation (1) [6] 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. 8.

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_ε .

Relation for X_ε (4) is determined from the condition of equality of the area below the flash temperature curve along the path of contact (Fig.7) and area of rectangle with side equal to contact line length g_a and product of g_{BIE} and X_ε what can be expressed in form:

$$\int_0^{g_a} g_{Bl} dg_a = g_{BlE} \cdot g_a \cdot X_\varepsilon \quad (3)$$

For the standard involute gearing with parameters according to the Tab.1 applies [5], [6]:

$$X_\varepsilon = \frac{1}{2\varepsilon_1 \varepsilon_\alpha} \left[0,18 \left(\varepsilon_1^2 + 0,7\varepsilon_2^2 \right) + 0,82\varepsilon_1 - 0,52\varepsilon_2 - 0,3\varepsilon_1 \varepsilon_2 \right] \quad (4)$$

Where ε_1 and ε_2 are the pinion, resp. wheel contact ratio coefficients.

For the HCR gearing was on the same way derived equation (5) for X_ε in the form

$$X_\varepsilon = \frac{1}{2\varepsilon_1\varepsilon_\alpha} (0,204\varepsilon_2^2 + 0,123\varepsilon_1^2 + 4,106\varepsilon_1 + 2,1222\varepsilon_2 - 0,543\varepsilon_1\varepsilon_2 - 0,54) \quad (5)$$

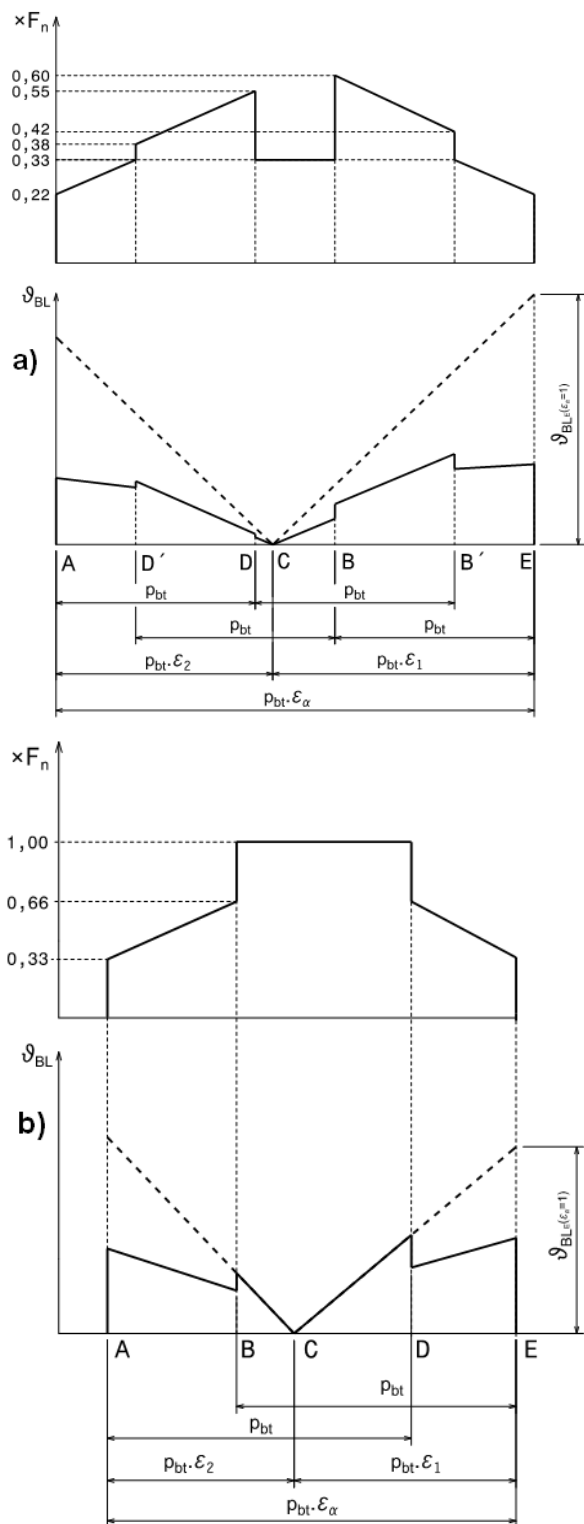


Figure 8. Simplified courses of the load and flash temperature values along the path of contact for standard (a) and HCR (b) gearing with $\varepsilon_\alpha \geq 2$ – according Tab.1 and Tab.2 in Figure 7

4. CONCLUSION

According to the above mentioned theoretical considerations were evaluated properties of tooth gears against scuffing damage according to Table 1 to 3 (Tab.4), and the results obtained for the externally toothed wheels were also experimentally verified [7]. From Table 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 $n_I=720$ 1/min. The limit integral temperature of scuffing for oil PP 80 (SAE 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 warm 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 gearing with HCR profile is needed always to check its load capacity from this point of view.

The results from the brief analysis of the warm scuffing problematics 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. In this specific case we replaced the original lubricating oil PP 80 (SAE 80) with hypoid gear oil PP 90H (SAE 90), thereby scuffing problems were solved. Based on these conclusions is clear that in the case of HCR gearing design, whether that be external or internal, it is always necessary to envisage the possibility of the occurrence of warm scuffing.

Table 4

Parameter	External standard profile (Tab.1)	External HCR profile (Tab.2)	Internal HCR profile (Tab.3)
X_ε	0,19	0,52	0,26
$\vartheta_{BLE}[^\circ\text{C}]$	139,1	163,0	48,2
$\vartheta_l[^\circ\text{C}]$ ($\vartheta_{ol}=70^\circ\text{C}$)	128,1	256,5	97,6

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NOMENCLATURE

F_n	normal force $F_n = \frac{2T_{k1}}{d_1 \cos \alpha_{wt}}$
\mathcal{G}_{Bl}	flash temperature (acc. to Block)
μ_x	friction coefficient in tooth engagement at point X
α_{wt}	working transverse pressure angle
b	face width, resp. length of the contact teeth surfaces
E_r	reduced modulus of elasticity of the wheels

	materials
ρ_{rx}	reduced radius of curvature at mesh point
$v_{t1,2X}$	tangential velocity at the X profile point
	coefficients of thermal conductivity of
$\lambda_{1,2}$	wheels (pinion – index 1 and wheel – index 2) materials
$\rho_{m1,2}$	specific densities of wheels materials
d_1	pinion pitch diameter
$c_{1,2}$	correction factor

АНАЛИЗА ПРЕНОСНИКА СА ВЕЛИКИМ КОЕФИЦИЈЕНТОМ КОНТАКТА СА АСПЕКТА ТОПЛОГ ЗАРИБАВАЊА

Вереш М., Крајчовић А., Немчекова М.

Проблем пројектовања и димензионисања преносника са великим коефицијентом контакта, нарочито преносника са унутрашњим спрезањем, данас је веома актуелан, посебно у пројектовању погона хибридних аутомобила. Овај тип преносника има много предности у функционисању, али је истовремено компликованији за пројектовање и израчунавање капацитета оптерећења. У овом раду аутори приказују резултате истраживања топлог заривавања код преносника са унутрашњим и спољашњим назубљењем са великим коефицијентом контакта. Дате су једначине за израчунавање отпорности на топло заривавање код преносника са спољашњим и унутрашњим назубљењем са великим коефицијентом контакта, које су изведене на основу интегралног критеријума за температуру.