# OPTIMIZATION OF THE HCR GEARING FROM PITTING DAMAGE POINT OF VIEW

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Pitting damage as a result of contact stress on the gears teeth flanks is one of the most important problems needing to be solved in the process of gearing design and calculation. According to current valid standards, such calculations can be resolved with a high level of reliability for all the usual gearing types. However, suitable calculations for HCR gears have not been adequately researched to date. It has been identified that in HCR gears some different process of pitting formation occurs during the gear's operation. In this article, the authors present original results of the HCR gearing research and describe a new method for finding optimal solutions for $h^*_{a1}$, $h^*_{a2}$ and $x_1$, using a Generalized Particle Swarm Optimization Algorithm.

**KEYWORDS**

HCR gearing, GPSO algorithm, contact, ratio coefficient, pitting, slip ratio, optimizing of the geometric parameters

## 1 INTRODUCTION

The HCR gearing is nowadays commonly used in the automotive gearboxes. Advantage of using such gears just in the transport vehicles transmissions is that this art of gearing has, with comparison to standard involute teeth profiles, low noise and also low load distribution along the path of contact during the whole teeth mesh. Moreover, in order to get a further reduction of the vibration and teeth load, HCR gear profiles can be optimized. [Sato 1983] found that HCR gears are less sensitive with respect to manufacturing errors. In particular, such kind of gears allows larger tolerance in the tip relief length. Moreover, they found that, in the absence of pressure angle error, the best contact ratio should be about 2. [Kahraman 1999] published an experimental work on HCR gear vibration; they found that the best behavior is obtained with an integer contact ratio, even though other specific non integer (rational) contact ratios can minimize the amplitude of some specific harmonics of the static transmission error. It is important to note that in [Kahraman 1999] HCR gears were obtained by modifying the outside diameter; the other geometric parameters, e.g. the number of teeth, were left unchanged. The main indicator of HCR gearing, which differs from the commonly used standard involute profiles, is higher contact ratio, at least two pair of teeth in contact, see Fig.1.

The best conditions for decreasing in noise is caused by $\varepsilon_\alpha$=2 because there are always two pairs of teeth in contact, which

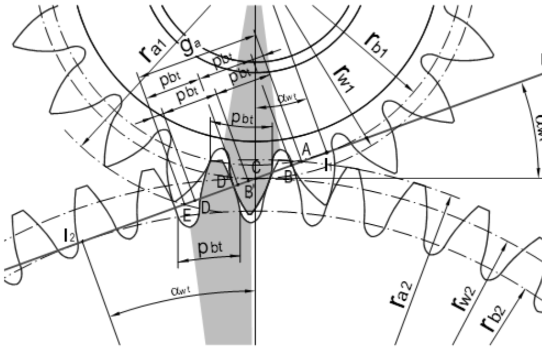

**Figure 1.** Geometry of involute HCR gearing

means when one pair of teeth go out from the contact, another pair of teeth is just coming in contact and applied force is considerably smaller and not varied since it is divided on two pairs of teeth. These favorable characteristics of the HCR gears should be reflected in increase of its resistance to contact fatigue damage - pitting, which is one of the main requirements for the design of the gears used e.g. in automotive transmissions. Creation of fatigue damage of the teeth flanks by pitting directly depends on the gear load. But from pitting damage point of view it is required to get contact ratio

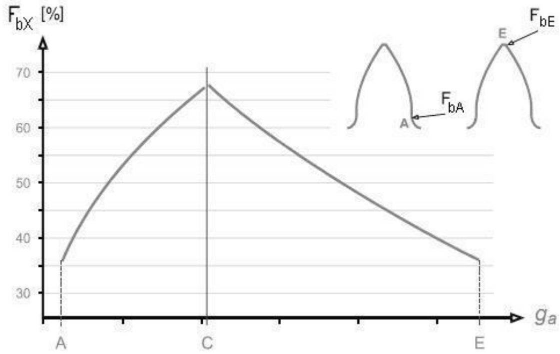


**Figure 2.** Shape of the curves representing the load along the path of contact in one pair of HCR gearing teeth

coefficient as high as possible. Workload at the three pair engagement divides between 2, respectively 3 pairs of teeth sides instead of one, respectively 2 pairs of sides (standard gearing), so its value decreases, see Fig.2.

## 2 PITTING IN THE HCR GEARING

According to current knowledge, creation and character of the pitting in the HCR gear is some different from the standard involute profiles or C-C gearing. The main reasons are significantly higher slides, see Fig. 3, longer engagement and different load distribution between the teeth in HCR gearing, see Fig. 4 and C-C gearing, see Fig. 5, similar load distribution it is also on involute gears. The area damaged by pitting is in the case of HCR gears more situated under the pitch cylinder, is more solid, the pitting is "more progressive", oval shaped and usually affects larger area than pitting generated in standard involute gears see Fig.6 and for C-C gearing see Fig. 7. The shape and location of the pitting in the HCR profiles is clearly shown in the Fig.8 [Veres 2012]. Due to the larger measurement delays at the beginning and the end of the engagement are the profiles significantly more prone to the

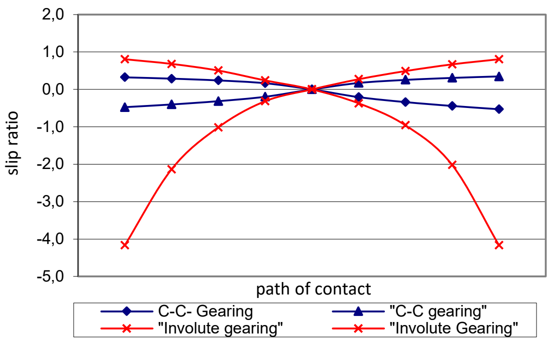


**Figure 3**. Slip ratio of involute HCR and non-involute C-C gearing along the contact path

creation of the temperature scuffing, which is clearly shown also in the Fig.9.

Profit from a more favorable load distribution along the engagement is partially eliminated by less favorable course of the values of the reduced radius of curvature along the meshing, see Fig. 9 for HCR gearing and see Fig. 10 for standard involute gearing [Moravec 2003], [Veres 2011]. Due to the longer contact line is its value in the peripheral areas lower, which of course leads to higher temperature scuffing and also to higher values of the Hertz pressure in contact area. It is clear shown on the Fig.6 where are shapes of contact stress curves along the path of contact for HCR gearing with various geometrical parameters plotted. It is clear to see that the contact stress of HCR gearing is strong depends on its geometry parameters. Therefore it is useful to optimize the HCR gearing

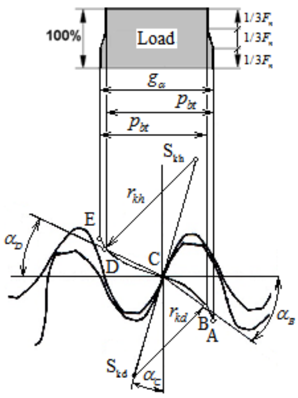


**Figure 4**. Allocation $F_n$ along mesh in C-C gearing

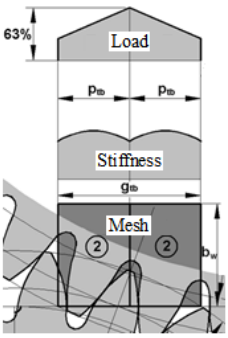


**Figure 5**. Allocation $F_n$ along mesh in HCR gearing

just from this point of view [Rackov 2013].

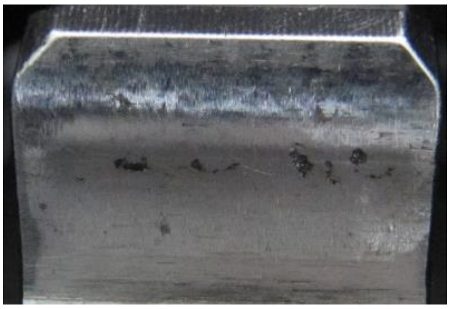

**Figure 6.** Pitting in the standard involute gearing

**Figure 7**. Pitting in the C-C gearing

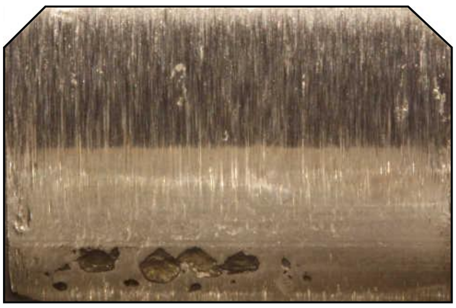

**Figure 8.** Pitting in the nonstandard involute gearing (HCR)

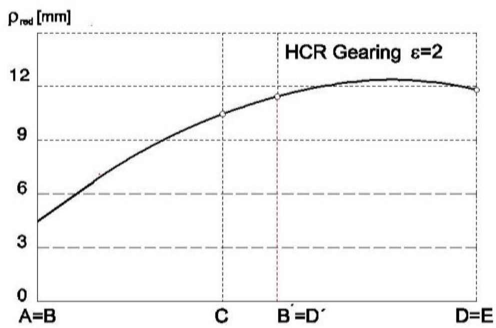


**Figure 9.** Mean contact radius of curvature along the contact path of HCR gearing

## 3 HCR GEARING GEOMETRY OPTIMIZATION AND ITS RESULTS

For optimizing of HCR geometry was used a new method called Generalized Particle Swarm Optimization Algorithm (GPSO) [Shi 1999] [Schutte 2005], [Kanovic 2011]. The GPSO algorithm was implemented in MATLAB. Using GPSO algorithm, solution of HCR value is obtained in a very short time, less than one second. This solution is very accurate, and it goes till $10^{-15}$ accuracy. Calculated obtained results are presented further. Based on preliminary theoretical considerations optimization task with main objective functions:

$$\sigma_{HX} = \sqrt{\frac{F_{b_{nx}}}{\rho_r \, \pi . b} \cdot \frac{1}{\left( \frac{1-\frac{1}{\mu_1^2}}{E_1} + \frac{1-\frac{1}{\mu_2^2}}{E_2} \right)}} = \min \qquad 1$$

$$\varepsilon_\alpha = \frac{g_a}{p_{bt}} = \frac{\sqrt{r_{a1}^2 - r_{b1}^2} + \sqrt{r_{a2}^2 - r_{b2}^2} - a_w . \sin \alpha_{wt}}{p_{bt} . \cos \alpha_{wt}} = 2 \text{ or max}$$

was defined [Kuzmanovic 2012]. It is clear, that above equations can be expressed as functions of pinion and wheel addendum coefficients and addendum modification factor of pinion $\left(h_{a1}^*, h_{a2}^*, x_1\right)$. Than as optimization parameters of this optimization task we can assume addendum $h_{a1}$, $h_{a2}$, and addendum modifications coefficients $x_1$ a $x_2$. Generally we can assume also $\alpha_n$ but this is not advisable because this would mean decrease of value $\alpha_n$, what means also decrease of gearing resistance against fatigue failure in tooth dedendum [Rackov 2014]. For given value of centre distance $a_w$ is known $x_c$ and expressly defined relation between $x_1$ and $x_2$.Than the objective functions can be express in the form:

$$\sigma_{HX} = f\left(h_{a1}^*, h_{a2}^*, x_1\right) = \min \qquad 2$$

$$\varepsilon_\alpha = f\left(h_{a1}^*, h_{a2}^*, x_1\right) = 2$$

or

$$\varepsilon_\alpha = f\left(h_{a1}^*, h_{a2}^*, x_1\right) = \max \qquad 3$$

with constrains of minimum top land width $s_a \geq 0{,}4 m_n$, elimination of manufacturing and mesh interferences and slip ratio on begin and the end of mesh equalization. Results of such defined optimization task are shown on Fig. 11. All displayed points represent solutions convenient to mentioned constrains conditions.

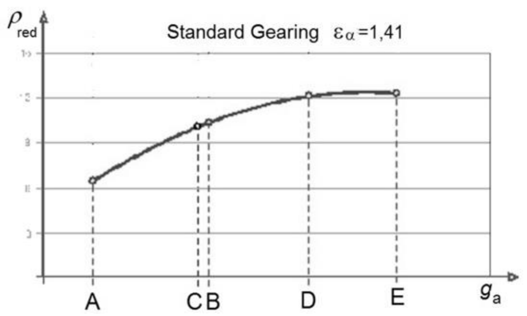


**Figure 10.** Mean contact radius of curvature along the contact path of standard involute gearing

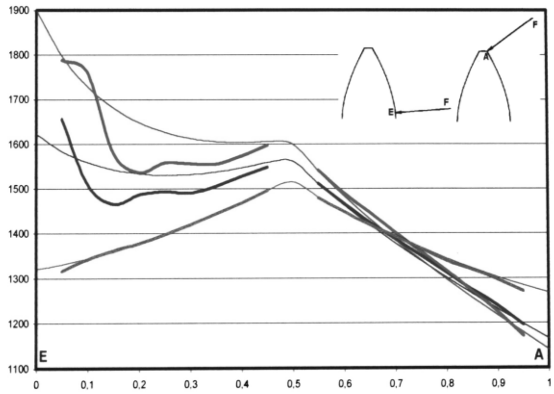


**Figure 11.** Contact stress of HCR gears along the contact path for various geometry characteristics of gearing

## 4 CONCLUSIONS

According to obtained results and their analysis it is possible to state that the optimization of HCR gearing geometry from pitting damage point of view is important task in the process of the transmissions design.

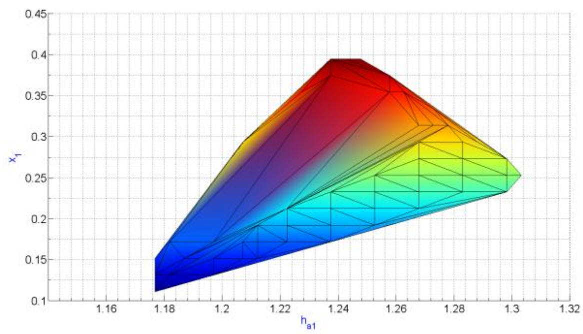


**Figure 12.** Optimal values $h_{a1}$, $x_1$ for maximum contact load capacity depending on $\varepsilon_\alpha$

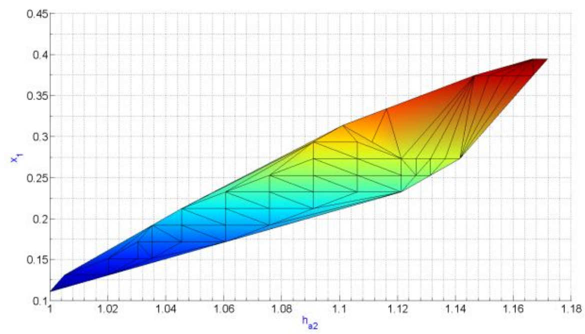


**Figure 13.** Optimal values $h_{a2}$,$x_1$ for maximum contact load capacity depending on $\varepsilon_\alpha$

Results of such optimization task for concrete transmissions parameters ($a_w$=144mm, $z_1$=21, $z_2$=51, $m_n$=4mm) are displayed on the Fig.12 for $h_{a1}^*$, $x_1$ , on the Fig. 13 for $h_{a2}^*$, $x_1$ and for $\left(h_{a1}^*, h_{a2}^*, x_1\right)$ on the Fig. 14. Optimization results that full meeting the requirements stated in the objective function and in the all constrains demonstrate that the whole process to find the optimal vector $\left(h_{a1}^*, h_{a2}^*, x_1\right)$ is limited by low number of suitable combinations of the optimizing parameters.

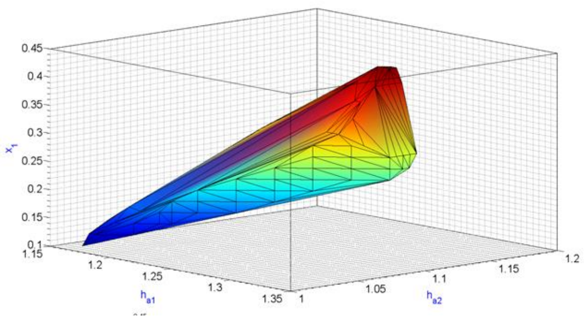


**Figure 14.** Optimal values $h_{a1}$, $h_{a2}$, $x_1$ for maximum contact load capacity depending on $\varepsilon_\alpha$


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