Optimizing the tooth root strength of sintered gears for a manual automotive transmission

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Abstract

Tooth root bending fatigue is one of the failure mechanisms of gears. Thus by decreasing the stresses in the tooth root the strength of the gears can be increased. Here the PM technology is more flexible than traditional machining of gears, since the tooth root can be designed into whatever shape desired. In this paper it's investigated how the tooth root of PM Gears can be optimized to reduce stresses. By two different methods, using a CAD software and a gear design software it's demonstrated that bending stresses can be decreased with as much as 30% for gears in a six speed automotive gearbox.

Introduction

The market of high strength transmission gears presents a huge potential for growth of PM steels. Through various demonstration cars Höganäs AB has demonstrated that it is possible to use sintered steels in automotive transmissions. At the same time, to take the full advantage of these materials it's important to not only work with material and process selection, but also with the design of the gears. Some design features that are difficult, and expensive, to introduce with conventionally machined gears come for free with PM. One such feature is the shape of the tooth root, which for machined gears is restricted by the motion of the cutting tool. PM does not have these limitations.

In principle the root of a sintered gear can have any shape, as long as it does not interfere with the mating gear. However, the optimal shape to reduce the tooth root stresses must somehow be determined. One possibility is to use the optimization functionality available in many finite element packages. For instance, in [1] a numerical procedure for tooth root optimization of gears is described. The advantage of such procedures is that it gives the mathematical optimum within the set boundaries.

Some gear design packages also contain routines for designing non-standard roots. As an example KISSsoft [2] can replace the standard shape with an elliptical root. One big advantage with such a setup is that the program can also analyze stresses and check the meshing for interference. The limit is that the possible shapes are often limited to i.e. ellipses.

In [3] it was shown how a manual six speed transmission, called M32, can be redesigned for PM gears. As a part of this work the gears were optimized to give high strength in tooth root bending fatigue. But the optimization was done with the intention of machining prototypes from blanks. In [4] a methodology to optimize tooth roots of PM gears was demonstrated for a research gear. In this paper this methodology is applied to the six speed manual transmission from [3] and it is demonstrated how tooth root stresses can be further decreased.

Tooth root optimization

For this paper gear pairs 1, 4 and 6 were chosen for the root optimization, the methodology for the other gears would be the same, and the results similar. Table 1 gives the basic gear data for the analyzed gears.

Table 1. Summary of gear data

		1st	4th	6th
Normal module	m_n [mm]	2.2	1.64	1,77
Number of teeth - input	z_1	11	50	42
Number of teeth - output	z_2	47	53	31
Pressure angle	α	18°	16.25°	16.25°
Helix angle	β	31.25°	32.25°	31.5°

The first step in the root optimization was done by determining the stresses for the original root design for a machined gear. The model used for the stress analysis is shown in Figure 1. A section of three teeth was cut out, and a unit force was applied to the flank in the pitch point, tangent with the base circle. The calculations were then done using a finite element model in 2D plane stress of the tangential plane of the gear. Geometry modifications and calculations were done using Creo Parametric and Creo Simulate [5].

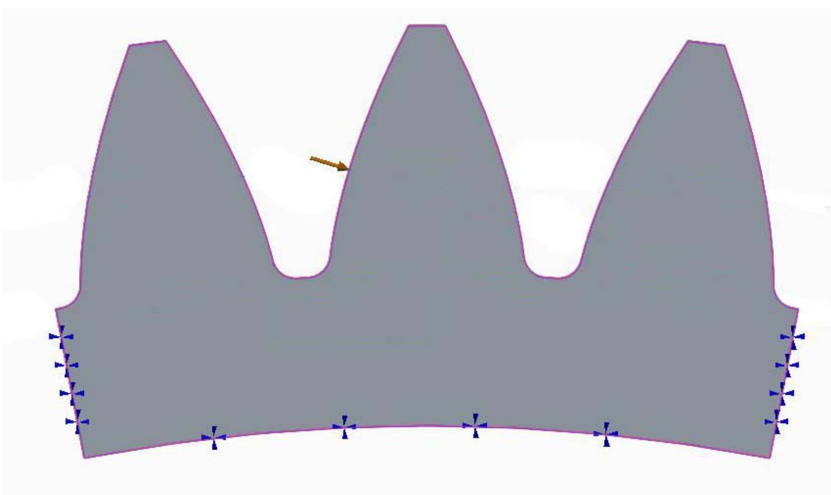

Figure 1. Model for root stress calculations.

When the reference stress level had been determined a small root modification was introduced, by replacing the root with a spline function. Care was taken to keep the modification below the lowest point of contact on the gear flank, not to interfere with the meshing of the gear pair. The spline could then be adjusted to give a smooth transition, at the same time as the curvature in the critical section was minimized to reduce the stress concentration. By iterating stress analyzes with gradual modifications of the tooth root, stresses could be reduced compared to the reference geometry. Root modifications with this procedure were kept small in order to make sure there was no interference with the mating gear. An example of the modified geometry for 4th output gear is shown in Figure 2, marked “spline”, other gears are similar.

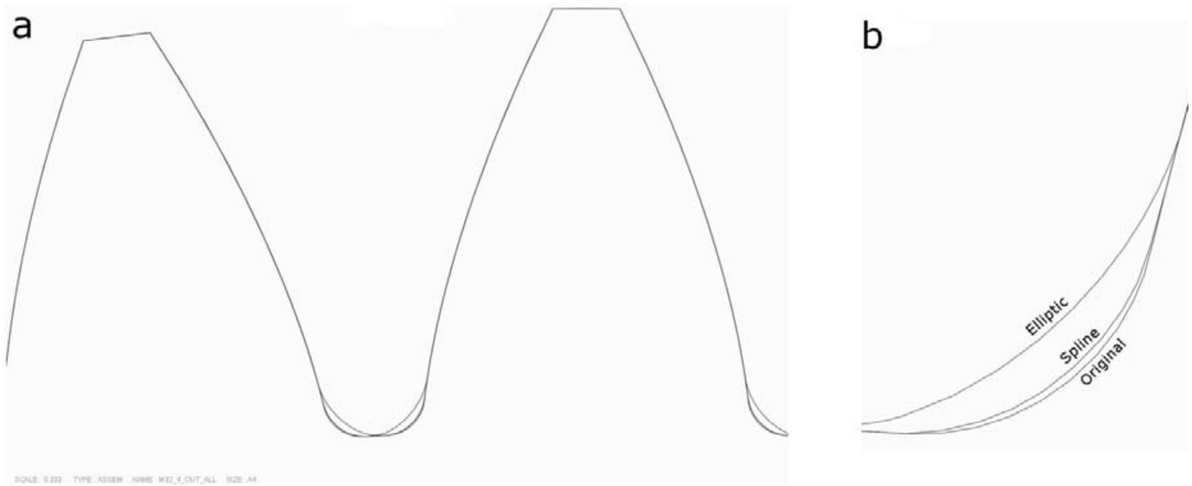

Figure 2. Illustration of the modified tooth roots, 4th gear output, a. overview and b. detail of root.

A second step of root optimization was done by using the built in functionality of KISSsoft to make elliptic roots, the result for the 4th output gear is shown in Figure 2, marked “elliptic”. Here the tooth root was replaced by an ellipse segment that is tangent to the tooth flank and root bottom. A big advantage of making the modifications in a gear design software is that interference can be checked using the program. Figure 3 shows the meshing of gear pair 4, along with the original and two optimized gear profiles. Because of a more efficient check of the meshing, the modifications can usually be bigger and give a higher degree of optimization. This is seen in Figure 2, where the elliptic modification adds significantly more material to the tooth root. The elliptic root were also exported to Creo and calculated in the same way as the other geometries.

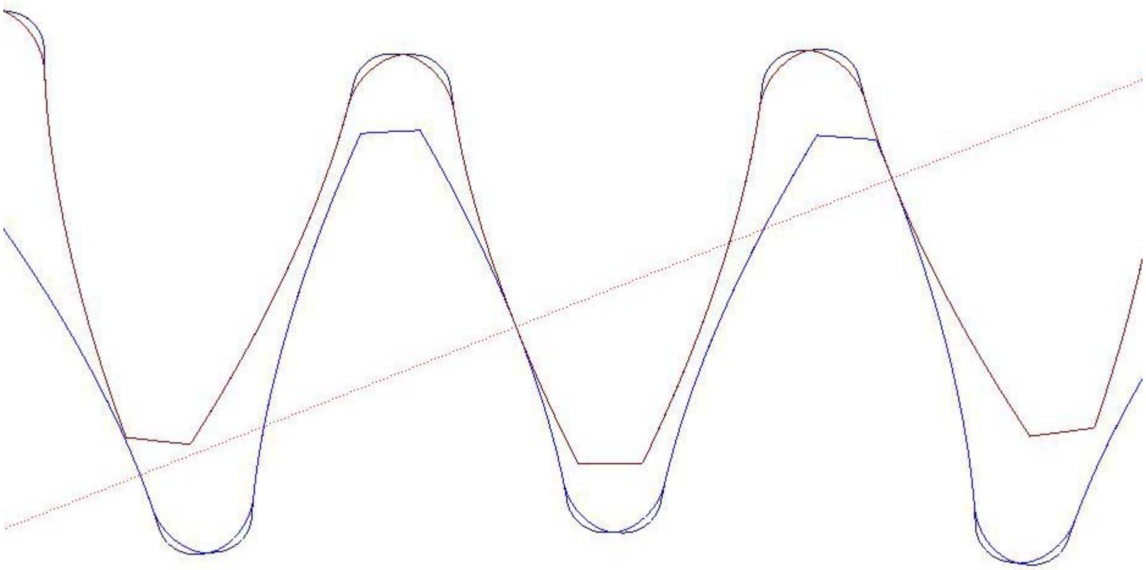

Figure 3. Meshing of 4th gear pair.

Results and Discussion

The results of the stress analyses are presented in Table 2. Since calculations were done for a unit load the results are presented relative to the original root shape. As can be seen from the table the splines give reductions of up to 7% in root stresses, but no reduction was possible for gear pair 1 with this methodology. Elliptic roots give consistently higher stress reductions, with as much as 30% for 6th output gears. For the first gear pair the reduction is significantly less, with only 4%, which is consistent with the difficulty to reduce stresses with the spline modification for this gear. Figure 4-Figure 6 show the resulting maximum principal root stresses for the different gears, note that the same color map was used for the different root shapes, allowing stresses to be compared. In Figure 4 the spline roots were excluded since they gave no improvement in stresses.

Table 2. Summary of stress analysis, relative values.

Root form	1st input	1st output	4th input	4th output	6th input	6th output
Original	1	1	1	1	1	1
Spline	1	1	0.96	0.94	0.93	0.93
Elliptic	0.92	0.96	0.82	0.76	0.83	0.70

It is clear that the elliptical roots in this study give a much higher stress reduction, which is the result of more material added, as seen in Figure 2. However, in general the splines present a more flexible root shape, and should be able to reduce stresses at least as much as the ellipses. The limitation here was that only a small modification was allowed with the spline to make sure meshing was not influenced.

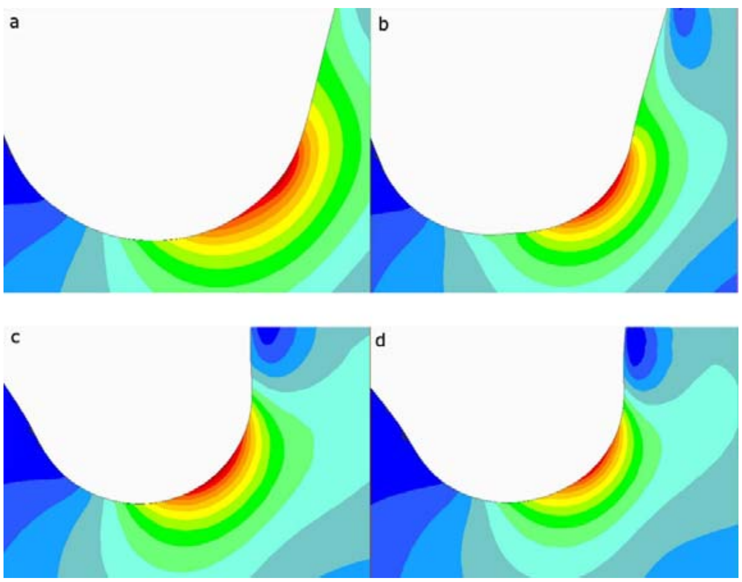

Figure 4. Resulting root stresses from FE calculation 1st gear pair, a. input original, b. input elliptic, c. output original and d. output elliptic.

Making a tooth root optimization using splines is a flexible method that can be applied using standard CAD software. With the methodology it's possible to design more or less any root shape desired. One drawback with the technique is that meshing can be difficult to check. This can impose a restriction that limits the amount of stress reduction possible as was the case in this study. In principle this restriction can be overcome by assembling the gear pair in the CAD software and checking the meshing with the mating gear. This was not tested here. The other limitation is that the process of iterating modifications and calculations by hand can be time consuming.

The elliptic roots possible in KISSsoft are less flexible, but still a powerful tool to optimize tooth roots in sintered gears, as seen here with stress reductions up to 30%. Using such functionally, incorporated in many gear design software also gives other advantages, such as checking the meshing. Often it's also possible to do the stress analysis directly in the gear software, greatly speeding up the design process.

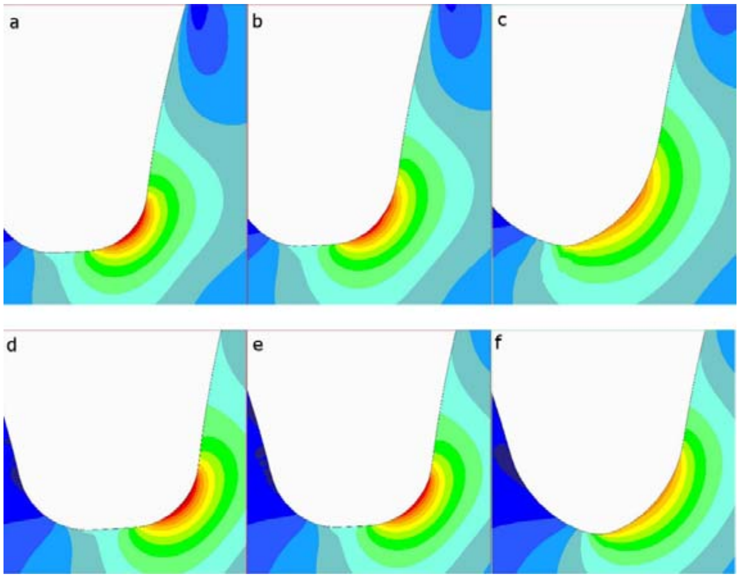

Figure 5. Resulting root stresses from FE calculation 4th gear pair, a. input original, b. input spline, c. input elliptic, d. output original, e. output spline and f. output elliptic.

A final possibility, not tested in this paper, is to use methods of structural optimization and apply it to gears. In [1] a procedure of tooth root optimization using such an approach is given. This is the most advanced option and should be able to give the highest degree of optimization. Still, in setting up the optimization problem the issue of interference with the mating gear must be addressed.

The results from the simulations clearly show that there is a big potential for optimizing the tooth roots of sintered gears to reduce the stresses compared to the same gears manufactured by machining. Even smaller modifications can in some cases give close to 10% lower stresses. For the gearbox analyzed here the elliptic modifications gave up to 30% reduction in stresses in a gear that was optimized for PM, but with a conventional root design. However, not all gear geometries can be improved to such an extent. For the 1st gear pair in the M32 gearbox the reduction in stresses compared to the original design was less, since this design was already able to incorporate a big root radius. Still, it was possible to add some improvement of the strength.

Conclusions

It has been demonstrated how different techniques can be used to optimize the tooth root of sintered gears, for a six speed manual automotive transmission, in order to reduce the stresses and improve the strength. The decrease in stresses, compared to the standard machined design, depend on the gear geometry, but up to 30% lower stresses were found. These design modifications are often difficult to include in machined gears, but come for free with the PM technology. It is thus suggested that root optimization is routinely employed when making PM gear designs.

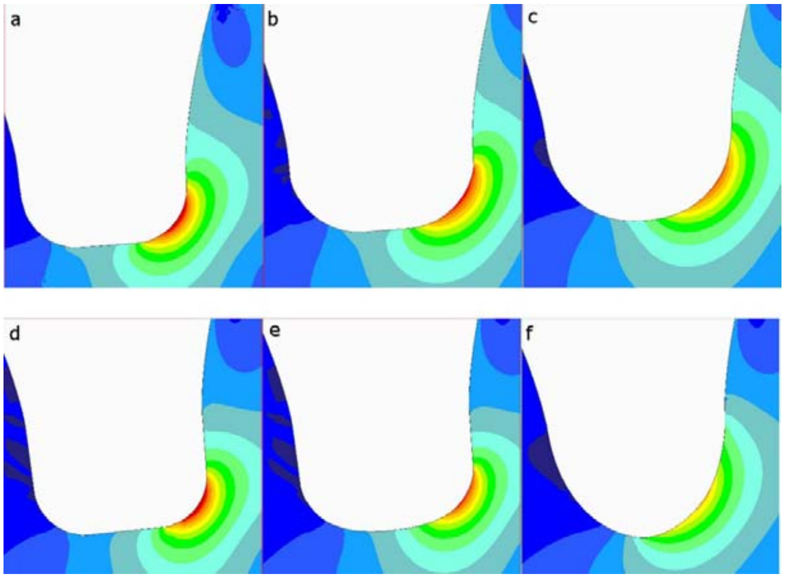

Figure 6. Resulting root stresses from FE calculation 6th gear pair, a. input original, b. input spline, c. input elliptic, d. output original, e. output spline and f. output elliptic.

References

[1] Kapelevich A. and Shekhtman, *Tooth fillet profile optimization for gears with symmetric and asymmetric teeth*, Gear Technology September/October 2009, pp. 73-79

[2] KISSsoft AG, *KISSsoft Release 03-2012*

[3] Flodin A. and Karlsson P., *Automotive transmission design using full potential of powder metal*, Proceedings of PM2012, Yokohama, Japan, 2012

[4] Flodin A. and Andersson M., *Tooth root optimization of powder metal gears – reducing stresses from bending and transient loads*, Proceedings of PM2012, Yokohama, Japan, 2012

[5] PTC, *Creo 2.0*