Evaluation of Wear in an Automotive Transmission using Powder Metal (PM) Gears

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Abstract

In 2008, Höganäs together with KBE+ redesigned the transmission for the smart fortwo car. The ambition was to create a PM friendly, reduced weight transmission that could be built into the original transmission housing whilst maintaining reliability. The reverse engineering analysis showed that this could be done without sacrificing service life, and with an accumulated weight reduction on the gears of 1 kg. In 2010, this transmission was built into a smart fortwo, driven to the PM World Congress in Florence and exhibited there. Since the congress, the smart car has been used as an everyday driver for eight years and accumulated 200 000 km.

In this paper, an evaluation of the PM gears will be presented. The gears are visually inspected after 200 000 km of real driving. The wear, as well as any other damage to gears and synchronizers will be investigated and discussed. Topography measurements before and after 200 000 km will be shown for quantification of wear, and pictures of the gear flanks will be shown to establish the general condition of the gears. From the design work the stress conditions are known, and from the logging system in the car, information on cycles and load can be estimated to further understand the load history of the gears.

Introduction

Powder metal gears are becoming a reality in power transmissions for passenger cars. There are different manufacturing methods, some are powder forged and others are densified in different ways. There are also those that are just sintered and case hardened without performance boosting processes, like in the GM 4T60E. The evolution has been fueled using various demonstrators and prototypes, from smaller cars like the smart fortwo where Höganäs AB pioneered the work, to subsequent investigations by Getrag, GKN and WZL-RWTH in Aachen on the same transmission. Another challenging demonstrator was the Mitsubishi EVO X rally car that was equipped with Höganäs gears during three years of extreme driving in the world rally series. In this paper the smart car will be further investigated as it reached its planned end of life through regular on-road driving.

Background

Back in 2008 when the smart car transmission was redesigned for powder metal and built by Höganäs AB, Swepart Transmission and KBE+, a logging system was put in place to collect driving data during its lifetime. An onboard PC was connected to the CAN bus and programmed to sample certain driving data available on the bus, saving it on the hard drive for future analysis. The ambition in 2008 was to drive the car for 200 000 km and then examine the gears for any damage and wear if present. This goal was achieved in 2017 without any issues with the PM gears. The car accumulated the mileage mainly through highway miles as a commuter car and the occasional trips to conferences and customers. This becomes very evident when the log is examined and the speed, gear and cycles are plotted in Figure 1. The gears were machined from powder metal slugs and case carburized, then tempered and ground. The material is Astaloy 85Mo with 0.3 %C.

Experimental Procedure

Since the driving data is known from the log and the theoretical stresses have been calculated by using the AGMA method, it is possible to derive where a failure is likeliest to occur. The failure mode can either be a tooth root bending failure or a pitting failure.

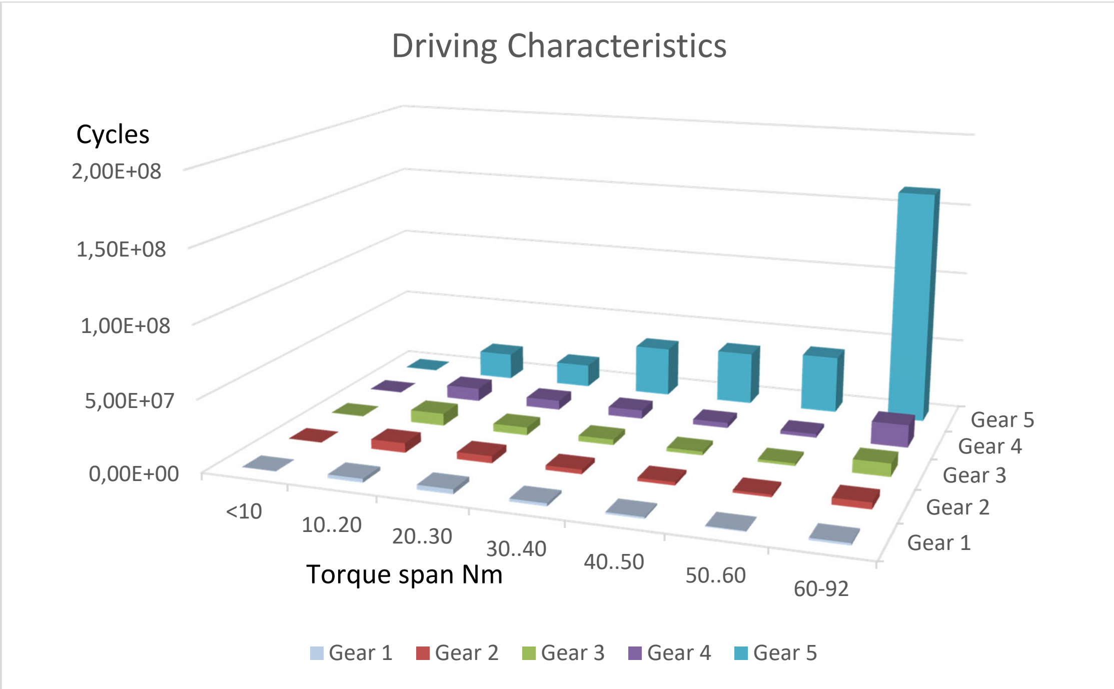


Fig.1. Driving characteristics. Most revolutions for 5:th pinion in every torque span.

As can be seen in Figure 1, almost all the kilometers are accumulated in 5:th gear using 60-92 Nm of torque. The maximum contact stress that each PM gear pair is subjected to is illustrated in table 1.

Table 1

Gear	Stress MPA
3	1275
4	1253
5	1180

From Table 1 it can be seen that the difference in contact pressure is within 95 MPa for gear pairs 3-5, but the number of cycles that the 5:th gear pair is subjected to is more than 17 times higher than for the 3:rd or 4:th gear pair in the high torque (60-92 Nm) region in Figure 1. It is likely that any failure will occur in the 5:th gear pair rather than in 3:rd or 4:th, despite the higher contact stress caused by the vastly higher number of cycles. For this reason the wear analysis, using stylus and SEM, will be focused on the 5:th pinion since it sees the most revolutions at the highest contact stress. The bending stress for gears 3-5 are low and will fail after the surfaces fail, so the bending failure mode will not be considered in this paper.

Results and Discussion

In order to obtain qualitative wear data, the profile of a driving flank from a newly manufactured 5:th drive pinion can be compared before and after 164 000 km of total driving in 5:th gear. In addition, pictures of the flank may be used.

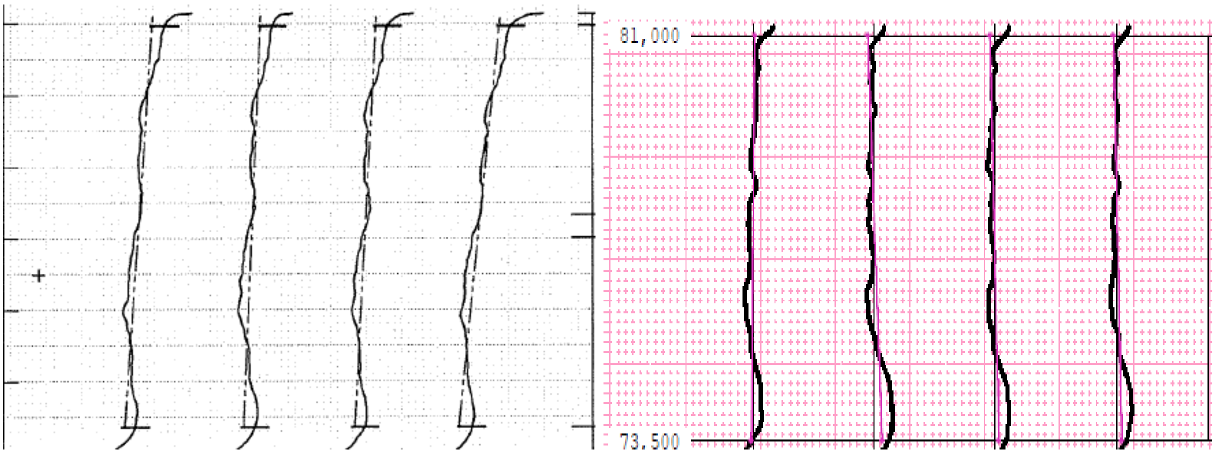


Fig. 2. Flank form. Left: Before running. Right: After running.

Figure 2 shows an attempt to depict the flanks of the gears before and after running. The two measurements were made on different machines. The graph to the left is from a Klingelnberg CMM, and the graph to the left is from a Zeiss. The machines have provided very similar results in previous benchmarking. The same gear teeth at exactly the same positions have not been measured either, but it is the same gear. The ball diameter of the probe is 1.5 mm in both measurements and the evaluation lengths and diameters are the same. As can be seen there are no anomalies created on the teeth surfaces after running, and the wear can be regarded as mild with detectable wear at the root of the pinion. This is normal and is caused by the sliding distance in the root being longer than anywhere else on the tooth surface. It is important to note that the wear depth affecting transmission error and noise is

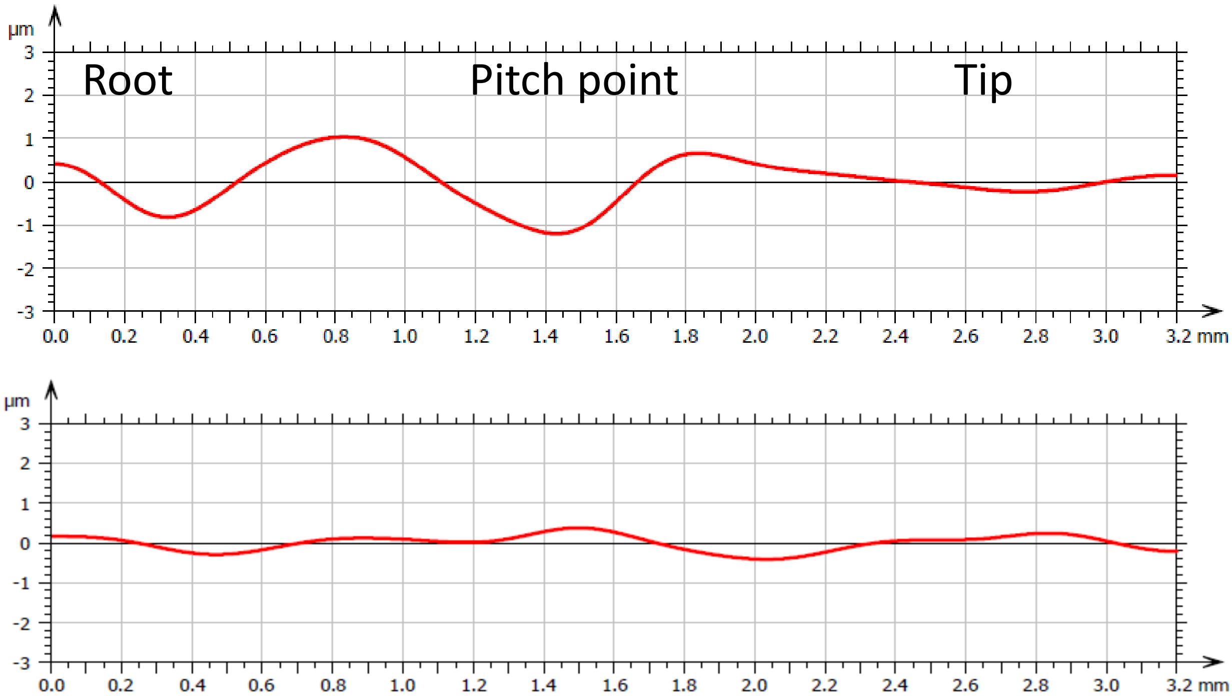


Fig. 3. Waviness on drive side (upper graph) and coast side (lower graph).

just a few microns, and not tens of microns. In addition, no NVH related transmission issues were ever reported from the drivers during its lifetime.

Since the graphs in figure 2 filter out finer details of the surfaces due to the ball diameter and the filters used, the worn surface was also measured using a stylus instrument. This can be seen in Figure 3 and 4.

Figure 3 shows the worn drive side of the 5:th gear with the involute removed by a 4:th order polynomial. A Gauss filter with a cut-off length of 0.8 mm has removed the roughness. The lower graph in figure 3 shows the coast side which can be assumed to be unworn. The waviness amplitude in the upper graph is about 2 microns while it is less than 1 micron in the lower graph. Caution should be exercised when working with filtered graphs, but from a macro point of view there is not a lot of material worn off. Only wear estimates can be made from Figure 2 and 3 and it is not possible to numerically quantify the wear due to the filtering technique used.

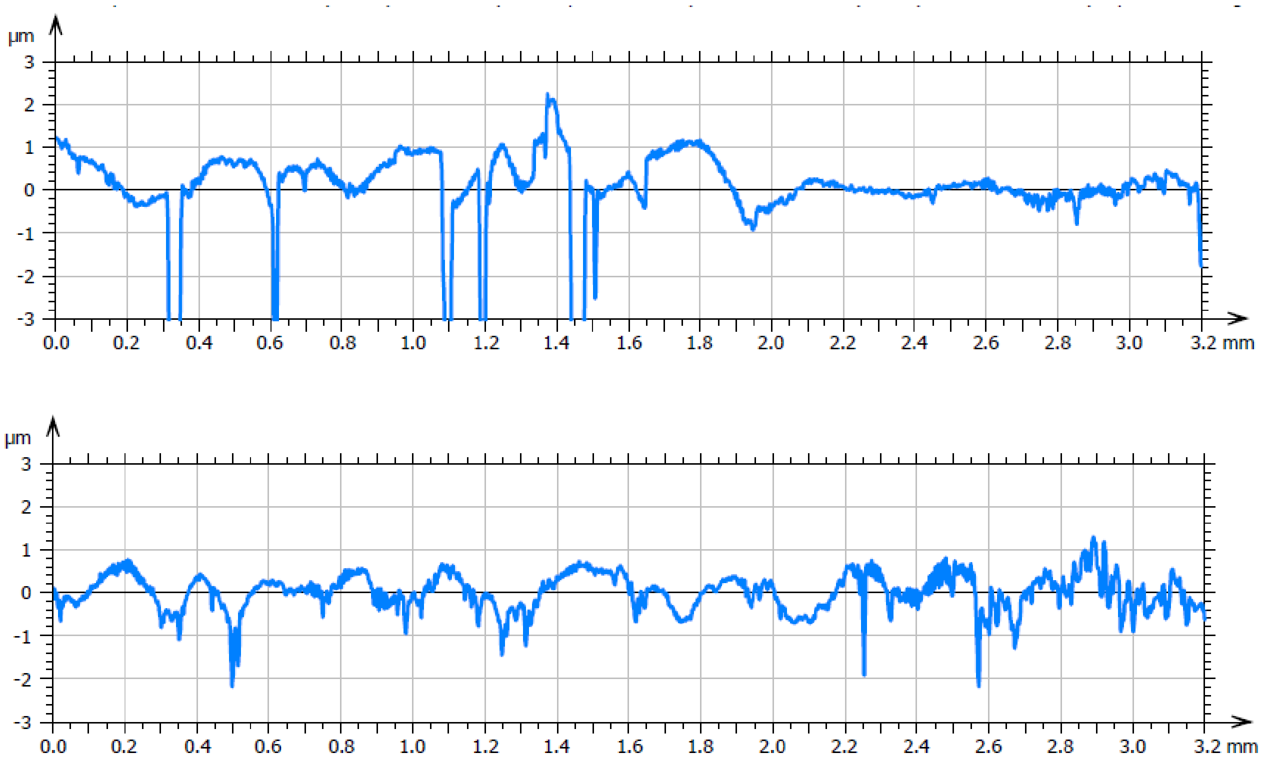
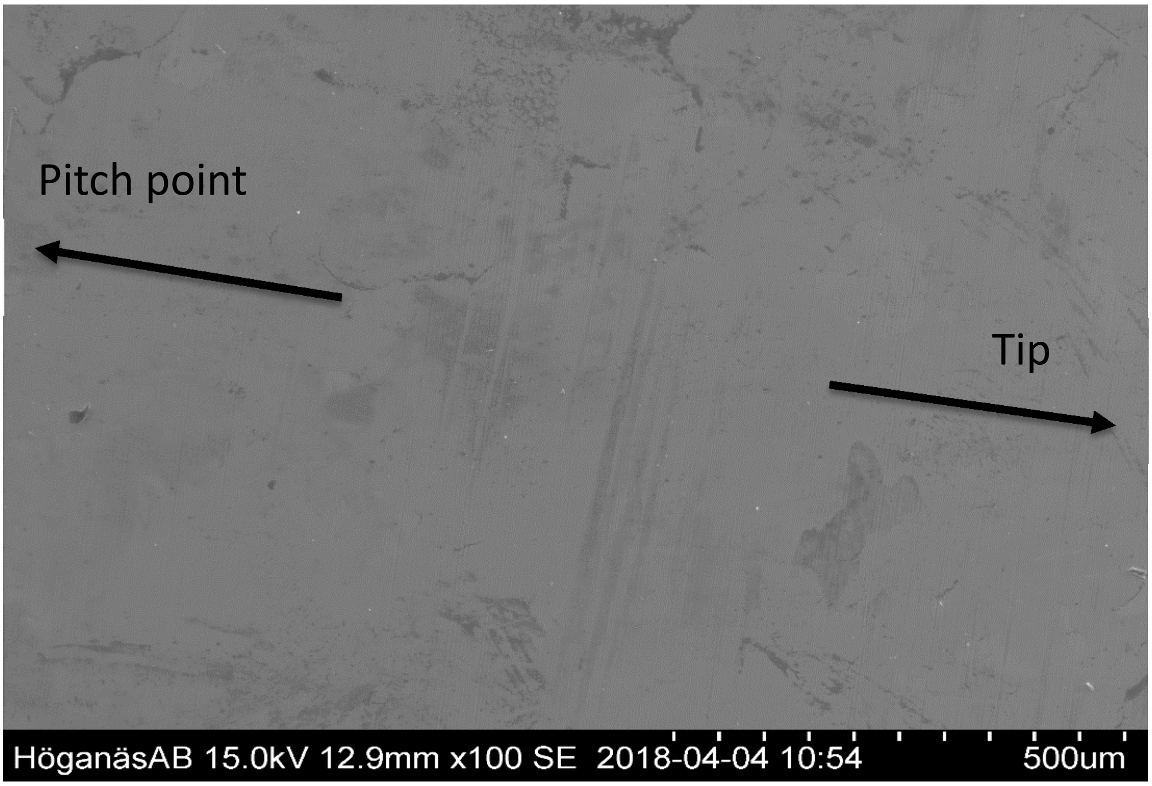


Fig.4. The residual after filtering out the curve in Figure 3. The upper graph is the worn surface and the lower graph is from the coast side so regarded as unworn.

In Figure 4 the surface roughness is presented. The upper graph is the worn surface of the 5:th pinion and the lower graph is the same tooth but on the coast side. The coast side can in this case be considered as unworn. The worn side shows what looks like holes in the surface but only below the pitch point. This is not uncommon for worn ground gears [1]. Above the pitch point the surface roughness has been smoothened and is less rough than the unworn coast side. The asperities from grinding have been worn down to create a smoother finish and the surface has just been worn in. These observations are normal for a pinion [1].

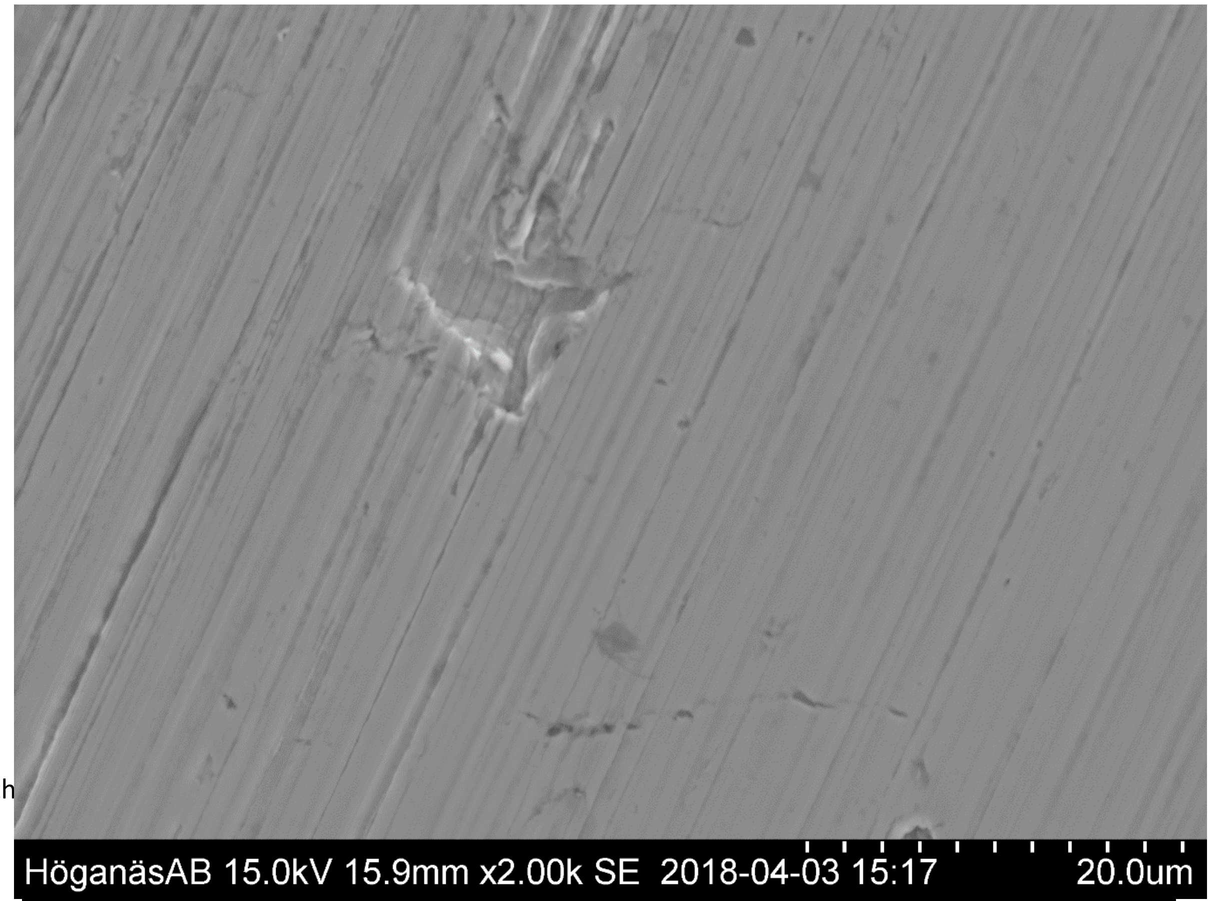
In a SEM it is possible to derive more information from the surfaces. In Figure 5 the area above the pitch point is shown corresponding to 2-3 mm in the upper graph of picture 4. The wear is just through the grinding marks and these are still somewhat visible. Wear depths of



approximately 2-4 µm can be deduced from the roughness graphs in Figure 4. The wear in the root can be expected to be a little deeper as seen in Figure 3 and 4.

Fig. 5. SEM image of the area above the pitch point.
Fig. 6. Reference surface that is unworn. The grinding marks are not aligned in the same direction as in Figure 5.

In Figure 4 there are some deeper holes in the worn surface in the root area where the curve



drops out of the scale. In Figure 7 the SEM zooms in on a dimple just above start of active contact.
Fig. 7. Surface defect below pitch point.

It is interesting to note that it looks like there are grinding marks at the bottom od the defect in figure 7. This implies that the asperities have maybe broken off into several pieces, but no deeper than the deepest grinding marks, or the defect was already there during grinding, or it is not grinding marks at the bottom and there is a pit gradually forming. Either way, the defects on the surface after running is not bigger than the one in figure 7 which is shows how well the surface stood up to the loads and cycles.

In Figure 8 some damage at the start of the mesh is shown. This part of the pinion is often the most susceptible to wear because the contact conditions are not optimal. The models in the software for tip relief have difficulties simulating the conditions here. Figure 9 shows the start of the contact and it is evident that there is hard line contact indicating insufficient relief in the area circled in red. This normally is self balancing due to the wear and the wear rate is very high in the beginning but recedes with cycles. The pit in figure 8 has no cracks around its perimeter indicating that it is not growing due to low load bearing. The load bearing is done by the other gear pair in mesh.

This also demonstrates the pitfalls of using filtered curves like in Figure 3 and 4, since they are not well aligned with what is seen in the microscope. These curves give a qualitative indication of the changes in the surface but can’t be used as they are for absolute wear. Another filtering technique has to be used with a controlled function instead of a best curve fit polynomial.

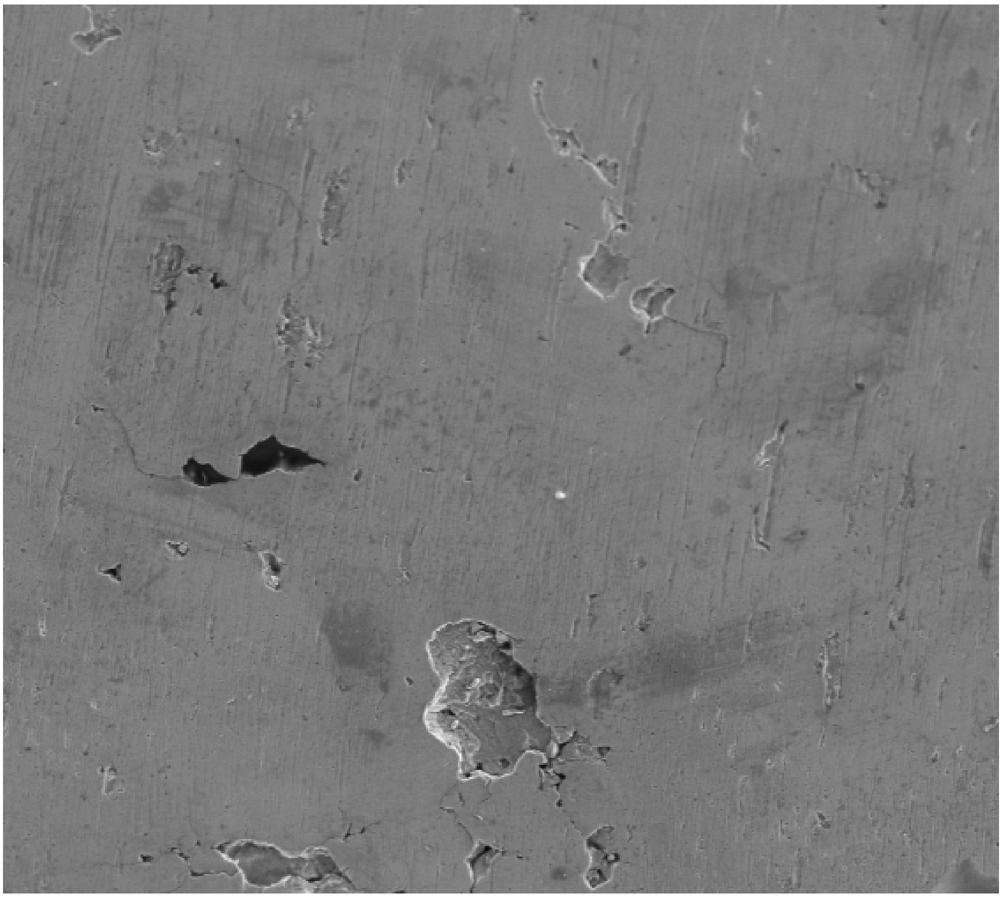


Fig. 8. Deep in the root area some surface damage is deeper than grinding marks.
Fig. 9. Start of contact. Red circled area is severe wear.

Conclusions

A smart fortwo has been equipped with powder metal gear wheels and driven for 200 000 km. The driving behavior has been recorded and used for assessing which gear is most likely to see wear and fatigue. The surfaces have been investigated to better understand the amount of wear the 5:th pinion has accumulated. It was found that the wear depths were mild to moderate over the whole flank, except at the start of active contact. No wear mechanism that could be related to the specific use of powder metal steel could be found. The wear patterns and apparent wear mechanism look the same as found on solid steel [1].

During its service life the car had no issues with its powder metal gears and the gear box was perceived as quiet by drivers. This is also in line with previous findings [2],[3].

References

[1] Flodin A. (1999) *Wear investigation of spur gear teeth,* Lubrication Science Vol. 7. Issue 1. Sept. 2000, pp. 45-60.

[2] Flodin, A. Hirsch, M. (2017) *Wear investigation of finish rolled powder metal gears,* Presented at APMA 2017, The 4th International Conference on Powder Metallurgy in Asia. Apr. 09-11, 2017, Hsinchu, Taiwan.

[3] Henser, J. (2010) Diploma thesis WZL Aachen. Micro Geometry Optimization of PM Gears.