Powder Metal through the Process Steps

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Powder metal (PM) gears normally sell due to the lower cost and their relatively high mechanical performance. The reason behind the lower cost is that most of the machining is omitted due to the net-shape forming process. So how net-shape are powder metal gears? In this article some hard-to-find information about the tolerances through the manufacturing steps will be presented.

The powder metal gear manufacturing processes are quite different from traditional-cut gears. The hard finishing process is identical, but heat treatment and prior processes are very different. For cut gears, the tolerances given by each process are well known — but for powder metal gears this is not common knowledge.

The powder metal process for the analyzed gear in this article is:

Compaction-sinter-case carburize-and grinding (threaded wheel)

Experimental background:

- Material composition: Astaloy Mo + 0.3% C-UF4 + 0.65% lube HD
- 10 gears were individually marked and measured as:
  - ¤ Green
  - ¤ Sintered
  - ¤ Case hardened
- Compaction pressure: 700 MPa, green density: 7.21 $g_{/}cm^3$
- Sintering conditions: 1,120°C, 30 min 90/10 N_2/H_2 in a laboratory belt furnace Cremer CBS25-115/e; the gears were placed on flat Al_2O_3 trays during the sintering
- Case hardening by gas carburizing and oil quenching; carburizing at 920°C, Cp 1%, 40 min.; tempering at 180°C, 30 min
- Gears were finish ground by gear maker Swepart using a Reishauer threaded wheel gear grinder
- The ground gears were measured both by a Zeiss DuraMax 5/5/5 coordinate measurement machine (CMM) equipped with software "*GEAR PRO involute*" and by a Klingelnberg P40
- The green, sintered and case hardened gears were only measured by the Zeiss DuraMax 5/5/5
- Zeiss reports quality class for all parameters; only Klingelnberg reported quality class for lead profile parameters
- As compacted gears (and by that also the sintered and heat treated gears) have 0.1 mm grinding stock or protuberance added to the involute
- For measurement of the involute profile and lead profile, the highest number of four measured teeth is presented as a "worst-case scenario"
- In the measurement by the Zeiss "*GEAR PRO involute*," the same four teeth (front, left, back and right from the pressing direction) were measured after each processing step

Figure 1 PM-optimized pinion used in the investigation.

The compacted gear geometry is the 4:th drive gear in a 6-speed manual transmission (Fig. 1).

The right flank has a helix angle modification of-60 µm, which causes problems for the Zeiss CMM but is correctly handled by the Klingelnberg (Fig. 2). The traces in Figure 2 are the desired end result in the lead direction after grinding.

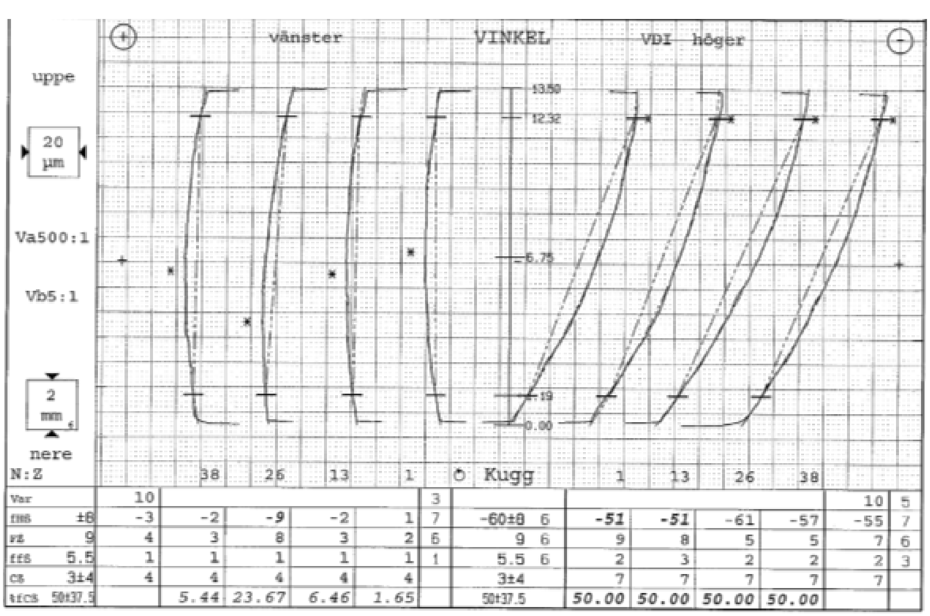

Figure 2 Measurement chart from the Klingelnberg P40; a 3 ± 4 µm lead crowning is also introduced by the grinding.

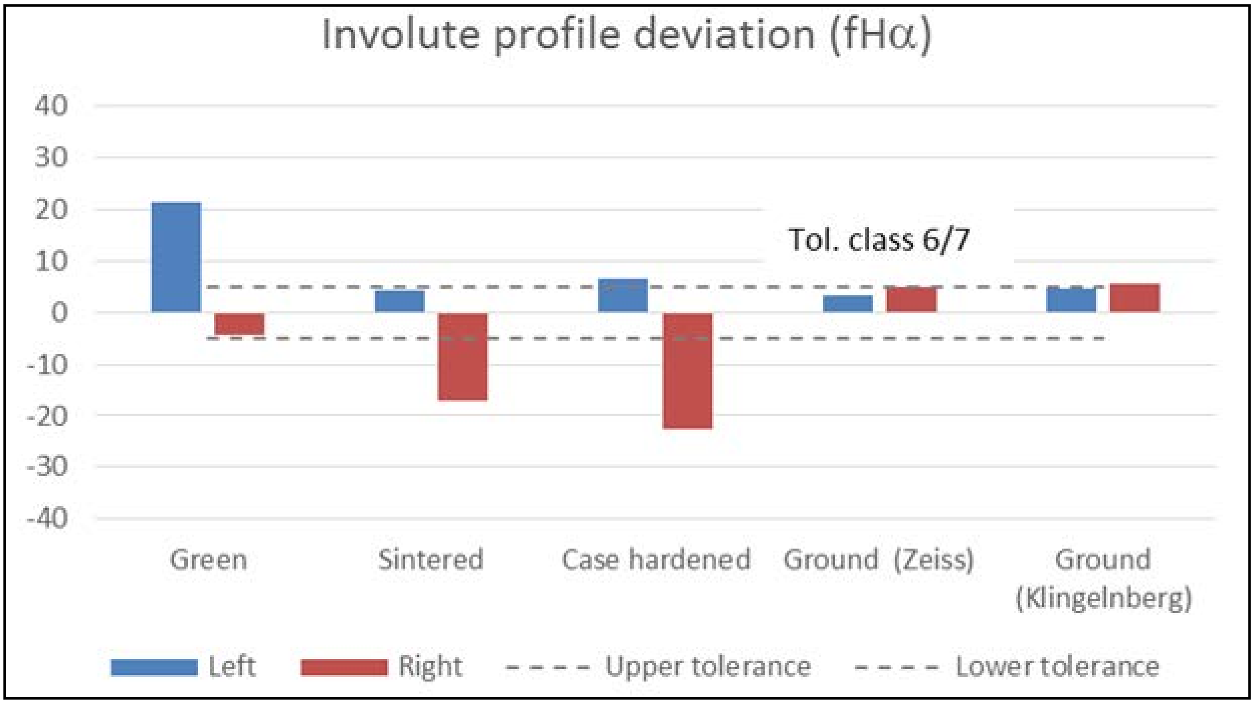

Figure 3 Involute profile deviation.

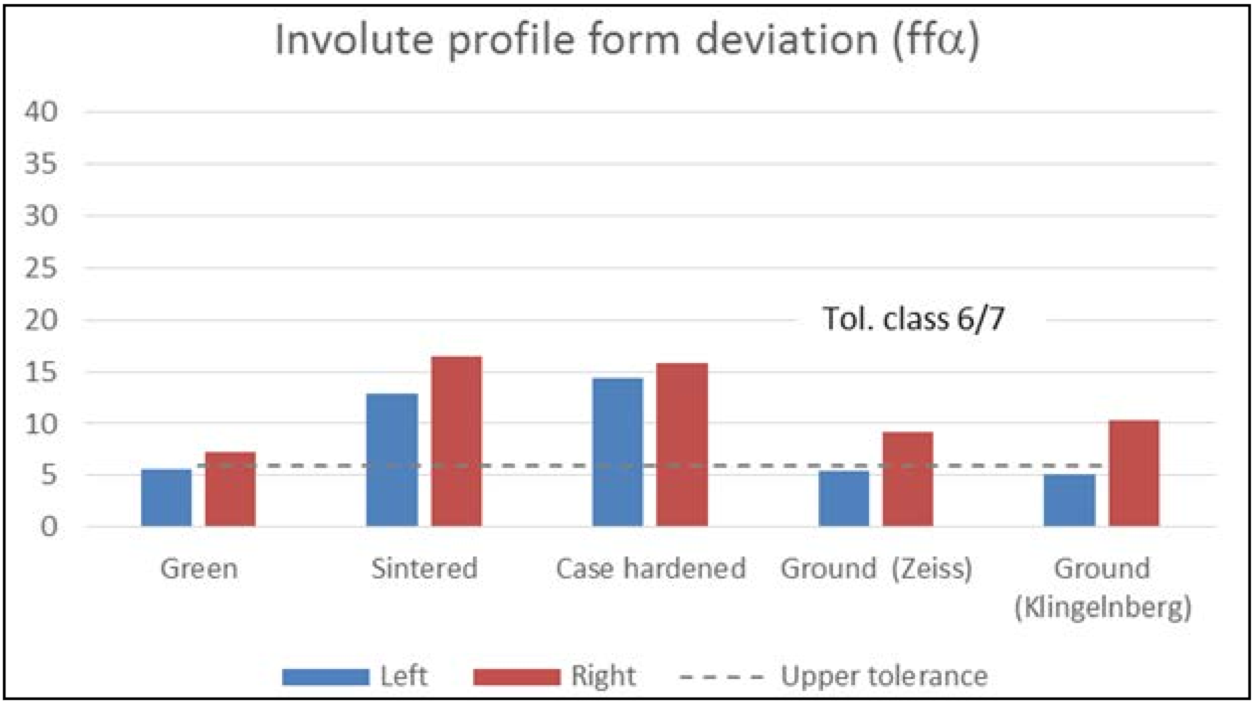

Figure 4 Involute profile form deviation looks at the waviness of the surface; in this case the data is misrepresenting the waviness since powder particles got stuck on the surface before sintering.

Result

The presented results use the ISO nomenclature. The worst results are presented in the following graphs, from 4 teeth on each of the 10 gears. This means that data in the bar diagrams are averaged over 10 gears; the worst of the teeth from every gear is selected. The numbers are chosen as a worst-case scenario so that an overly positive picture of the results are presented.

Involute Deviation

The involute profile deviation demonstrates a large movement going from green to sintered, while subsequent case carburizing does not change the shape nearly as much (Fig. 3).

The involute profile form deviation is very good in the green state, but the sintering deteriorates the profile significantly. The reasons for that are complex, but, for example, stress relieving and phase transformations are two influencers.

However, in this study it is actually powder particles that stuck to the flank,

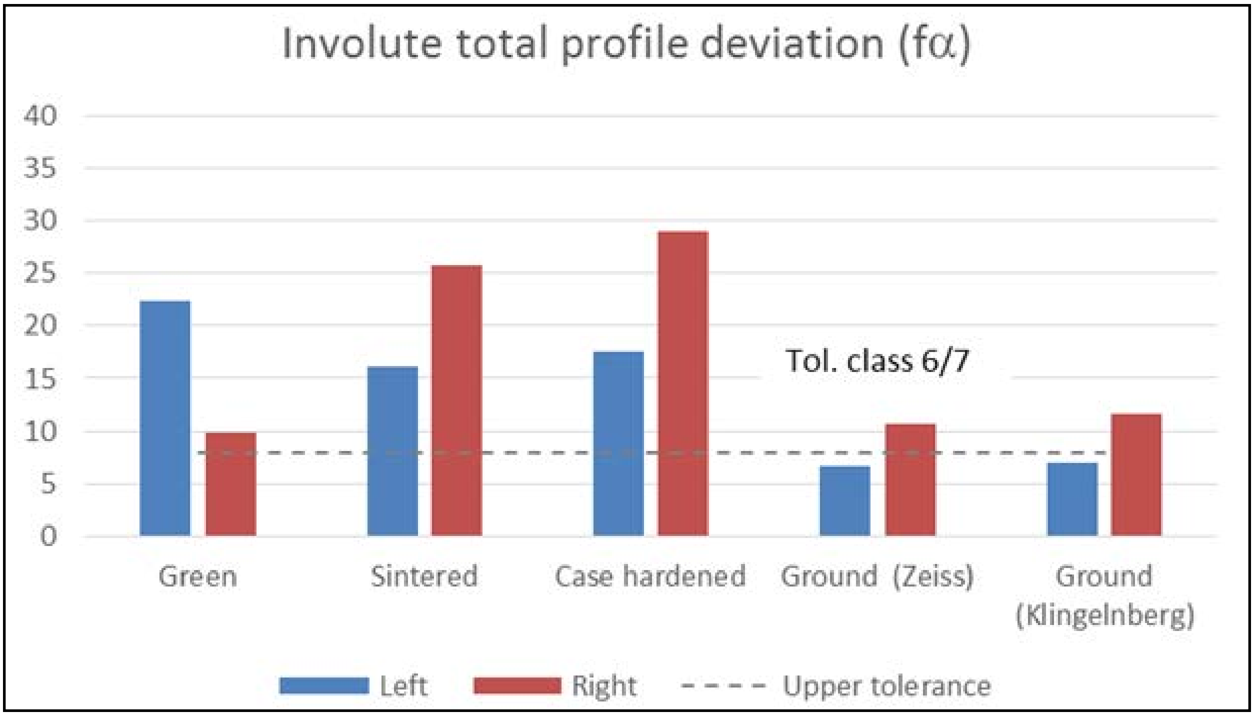

Figure 5 **Involute total profile deviation is the combined angular error and waviness error in Figures 3 and 4.**

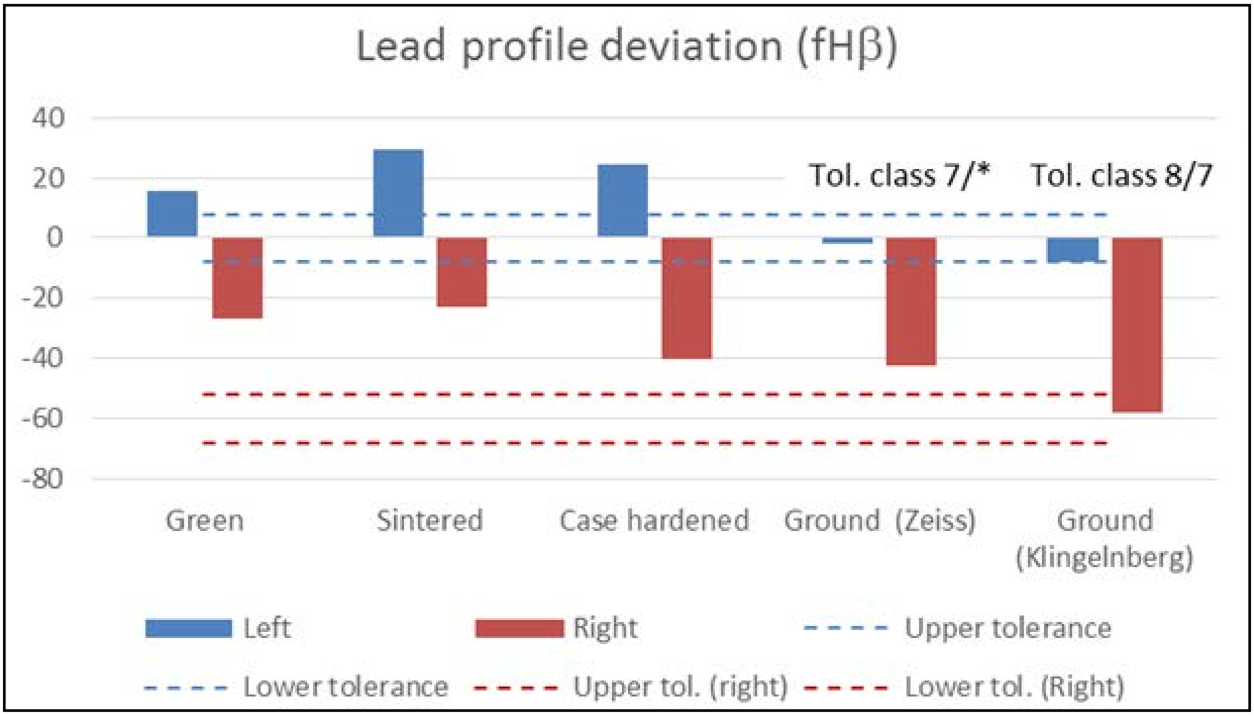

Figure 6 **Lead profile deviation.**

and the ball tip probe is bouncing off those particles. The carburizing does very little to the deviation, and any geometric changes that are contributed by the carburizing are masked by those powder particles on the surface. The right flank is actually out of tolerances after grinding — which can be remedied and should not be blamed on the material.

These two deviations are combined into the total profile deviation and displayed n Figure 5.

The errors on the profile form deviation influence the result in Figure 5, since it overshadows the profile error or waviness error.

Lead Deviation

The lead profile deviation parameter is the equivalent to the involute profile deviation error but in the lead direction. The right flank has a 60 μm modification which is not captured correctly by the Zeiss machine so the reader has to disregard that bar in Figure 6. The Klingelnberg can handle this modification and after grinding the teeth are within tolerances.

Figure 7 depicts the lead profile form deviations. Here as well is the result

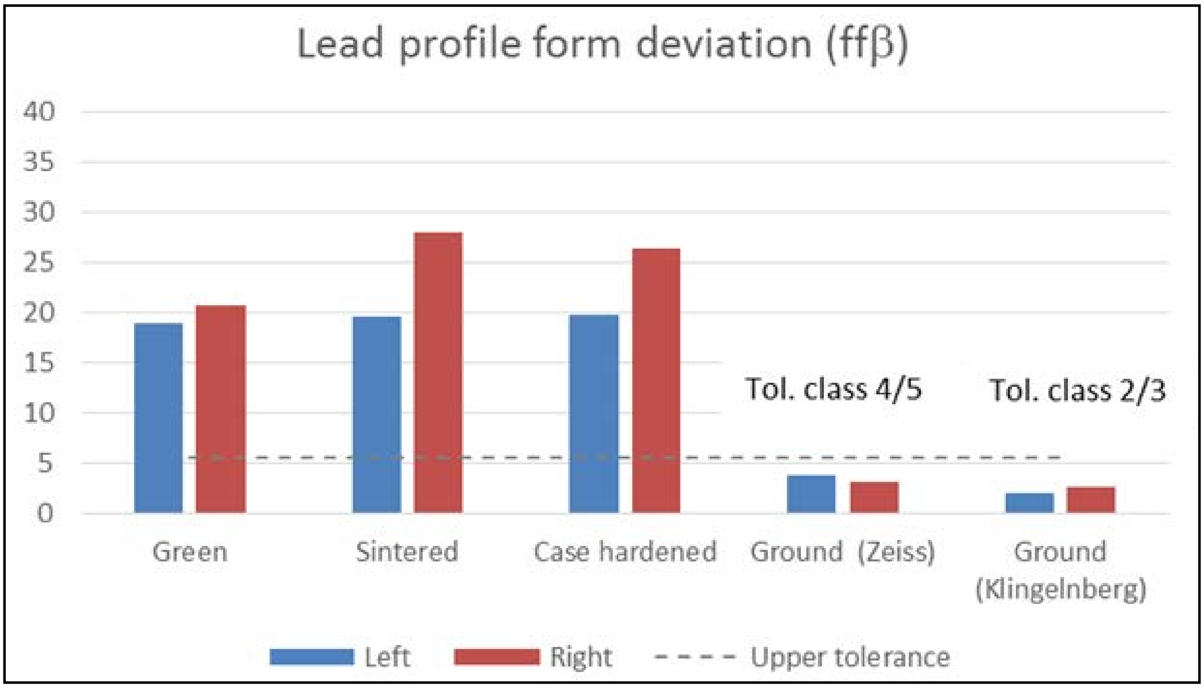

Figure 7 Lead profile form deviation; the poor geometry in green, sintered and case hardened is an artifact created by powder particles stuck on the flanks.

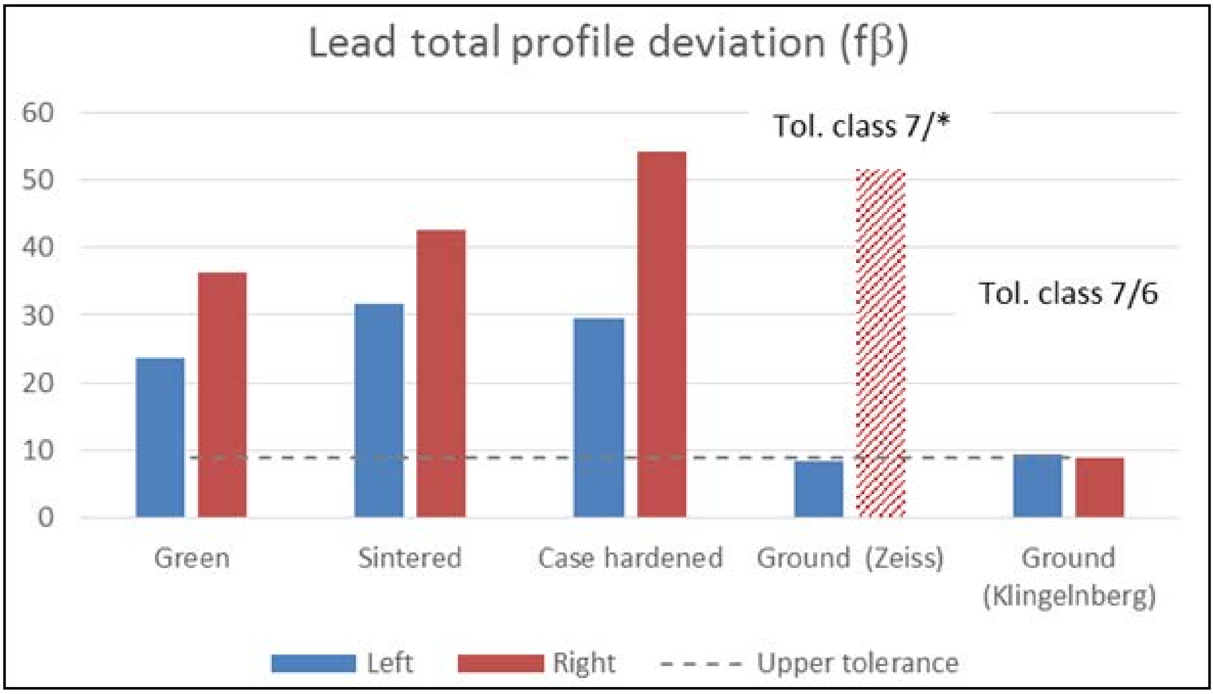

Figure 8 Lead total profile deviation; within tolerances after grinding; deviations before grinding are partly due to powder particles stuck on the flank and not the actual error in the lead profile.

influenced by residual powder grains on the flanks. After grinding the profiles are within tolerance.

When lead profile form and profile deviation are combined the total lead profile error is formed. In Figure 8 it can be seen that after grinding the profile is within specification. The bar measured by the Zeiss is hatched since it is incorrect.

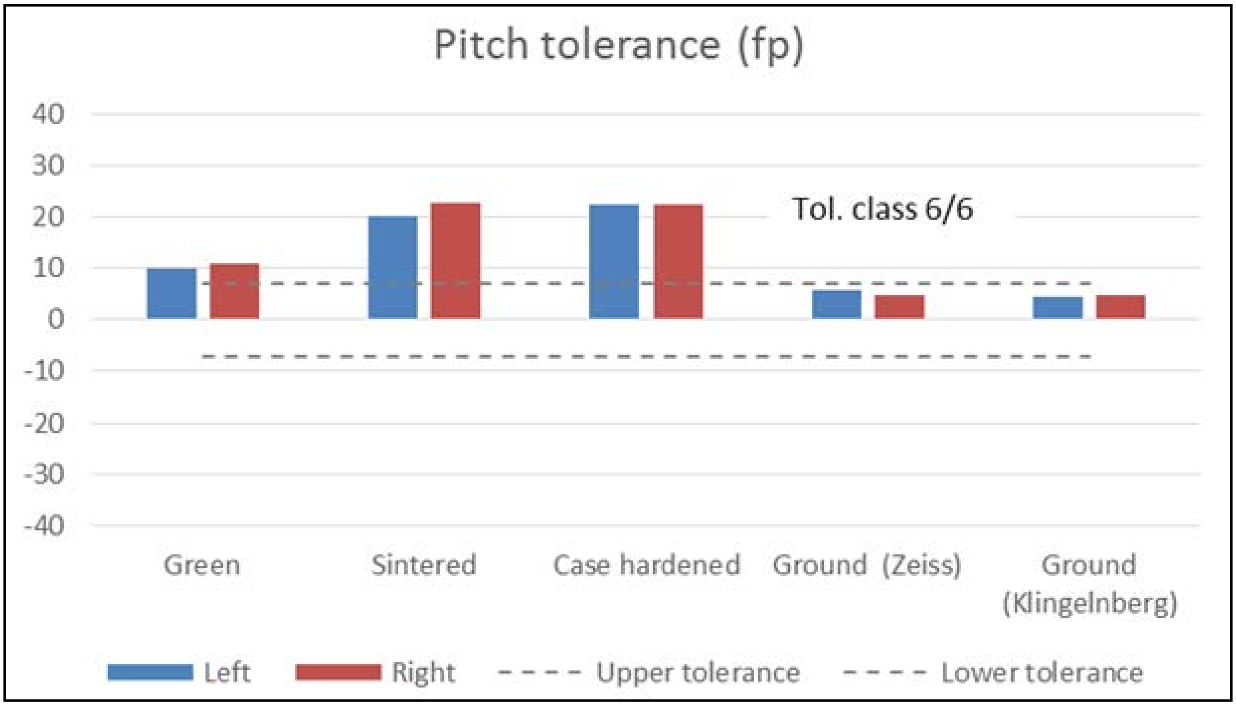

Figure 9 **Maximum single pitch deviation.**

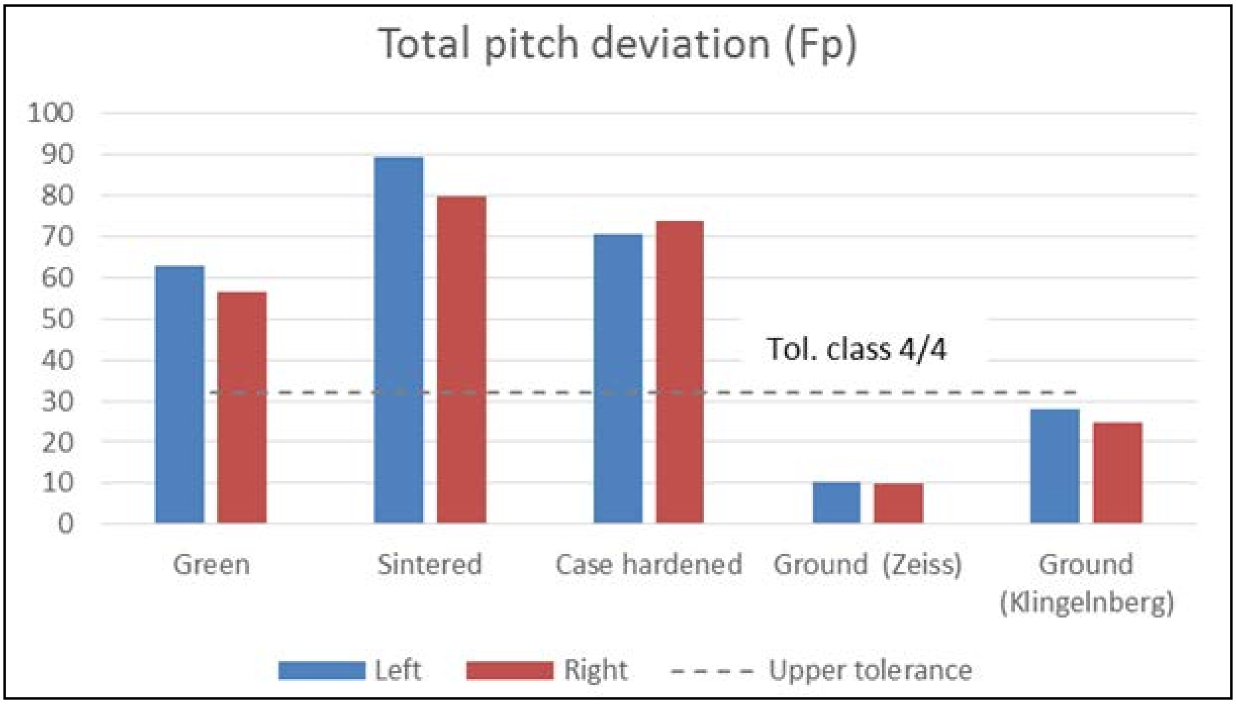

Figure 10 **Total pitch deviation.**

Pitch Deviation

The maximum single-pitch deviation is shown (Fig. 9). In the green state the deviation is very small; it grows predominantly during sintering and then less so in the following case carburizing process. After grinding, the gears are within tolerances. The total or cumulative pitch deviation is depicted in Figure 10; it follows the same pattern as the pitch tolerance in Figure 9.

The adjacent pitch deviation which measures the biggest pitch error between 2 teeth on the gear is shown in figure 11. The same trend as before can be seen with the biggest step in error being caused by the sintering process. Again, the grinding operation saves the day.

Runout

Radial runout and powder metal gears require some extra explanation. In a PM compaction tool there are a number of different parts. Since there is clearance in the radial direction between the different parts — or punches — there will be some play, and during the compaction stroke the different parts will be pushed in different directions. Here the worst-case scenario is that all the parts are pushed in one direction and the clearances line up radially — creating a large runout. In the gear under investigation (Fig. 1) there

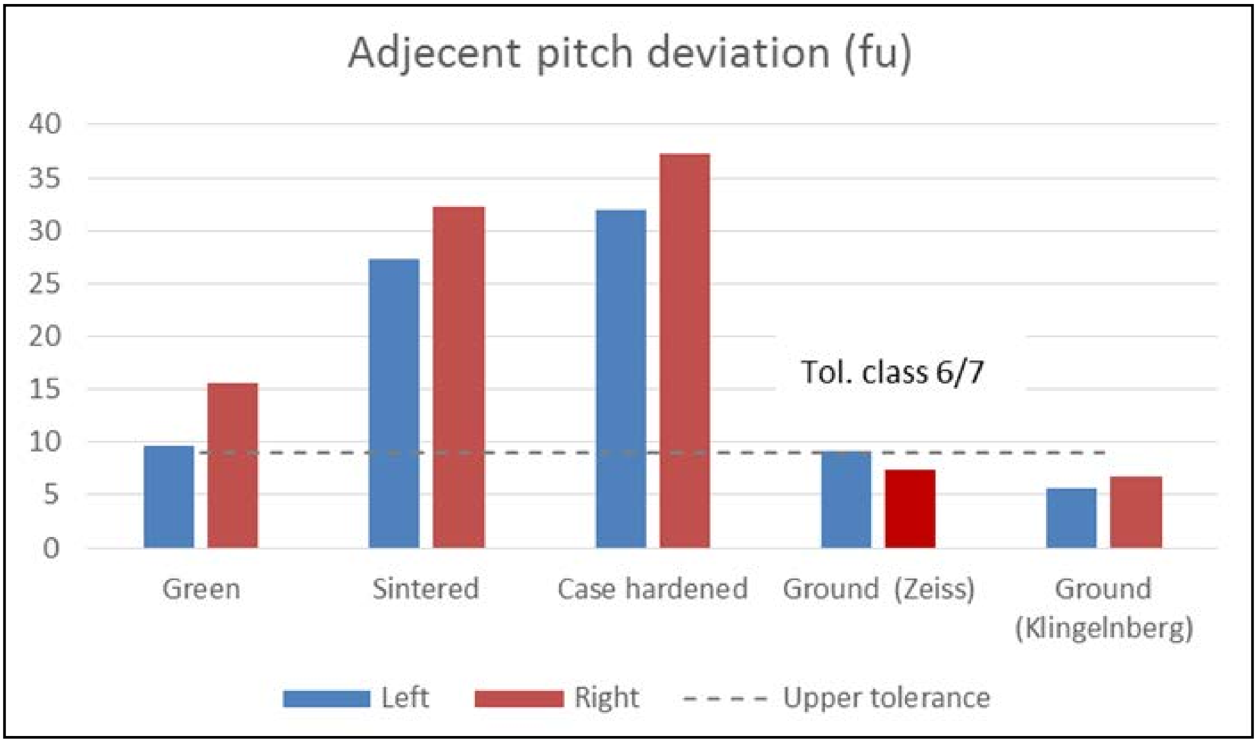

Figure 11 Adjacent pitch deviation.

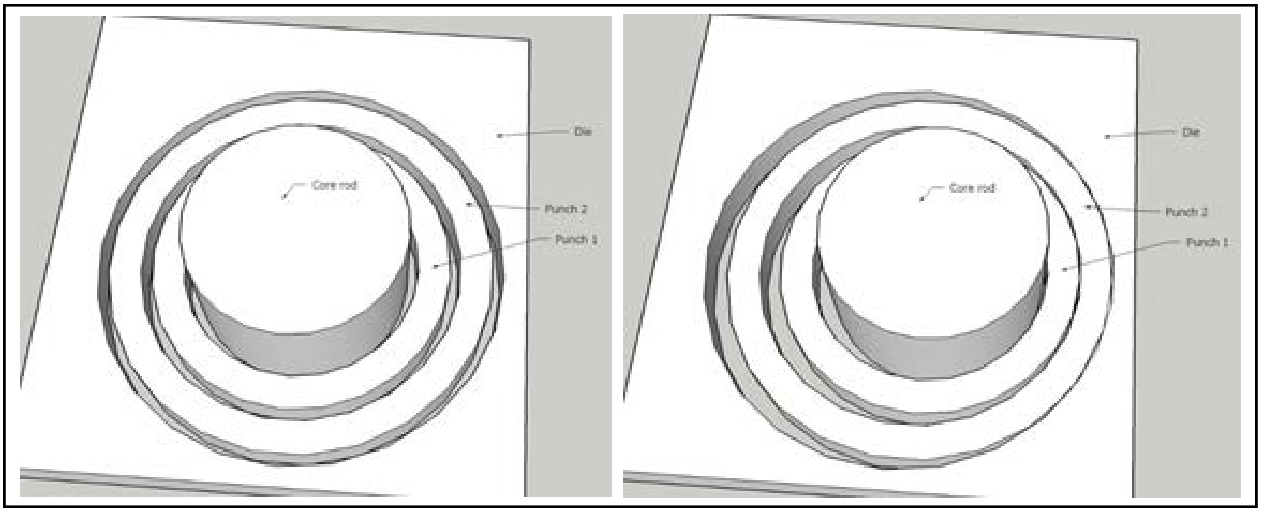

Figure 12 Left: simple tool with concentric part; right: clearances stacked in one direction.

are 3 punches plus the core rod forming the spline. This is a very advanced tool, as it creates the sum of 4 clearances—plus elastic spring-back and plastic deformation of the particles—as the theoretical run out. A very simple tool consisting of only one punch and no core rod will then have significantly less radial run-out since it will consist of only the clearance between the one punch and the die (Fig. 12). In (Fig. 12, left) is a simple tool with core rod, 2 punches and a die. All tool parts are concentric, with tool clearances of course greatly exaggerated. In (Fig. 12, right) we see a worst-case where all the clearances line up and the core rod is offset with the sum of clearances creating runout and spacing errors in the measurement protocols. The maximum stacked clearance in the tool is 65 µm.

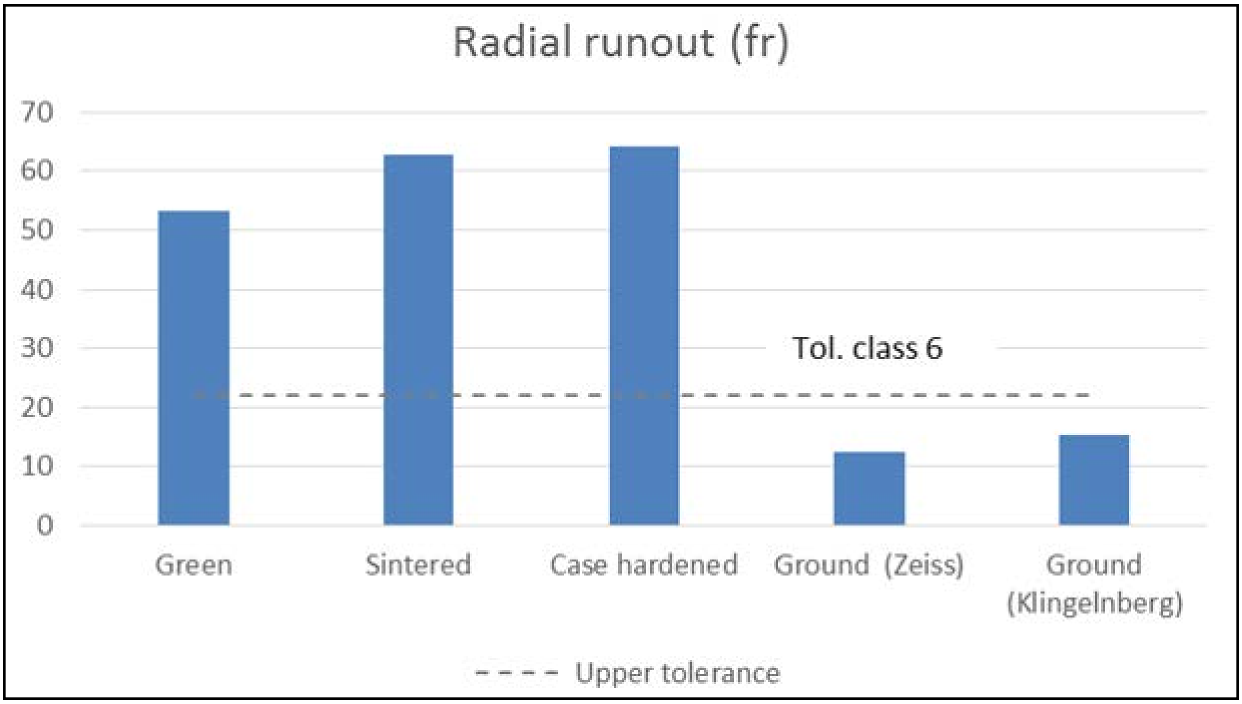

Figure 13 **Radial runout.**

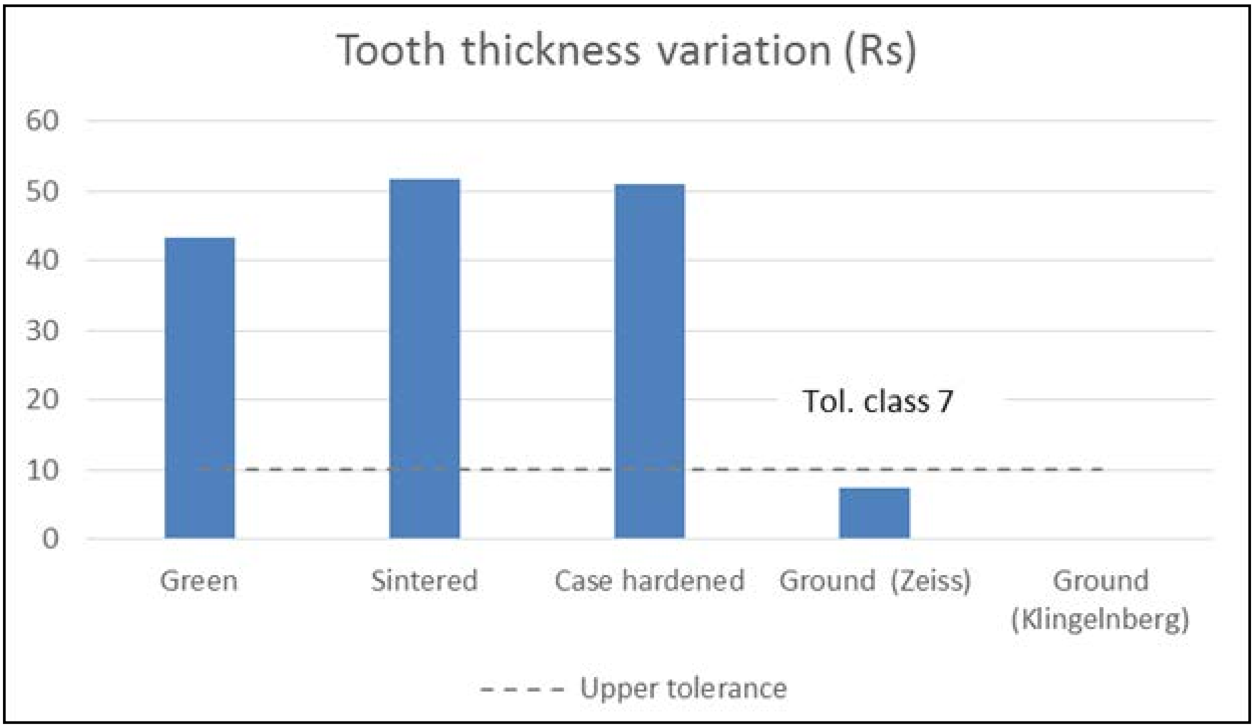

Figure 14 **Tooth thickness.**

Radial Runout

The radial runout follows the previous pattern of deterioration, with heat and the biggest drop in tolerance coming from the sintering (Fig. 13). However, the grinding will return the runout to within tolerances. One important fact is that this gear has a compacted internal spline and therefore can't be ground in the bore. Thus the runout is never worse than what can be repaired in the grinding. If that wasn't the case, then the net-shape capability of powder metal forming the spline would not be useful.

The tooth thickness deviation is also connected to the runout and how centered the bore is on the gear (Fig. 14).

The tooth thickness shows a similar development through the process steps, as the runout with an initially large discrepancy between actual and nominal value. With a simpler tool using less punches, the actual and nominal values would be closer.

The tip diameter changes as well during heat treatment. This parameter will also be influenced by the runout. As can be seen (Fig. 15) the diameter will be within specification after grinding. If the tip diameter is too low or too high,

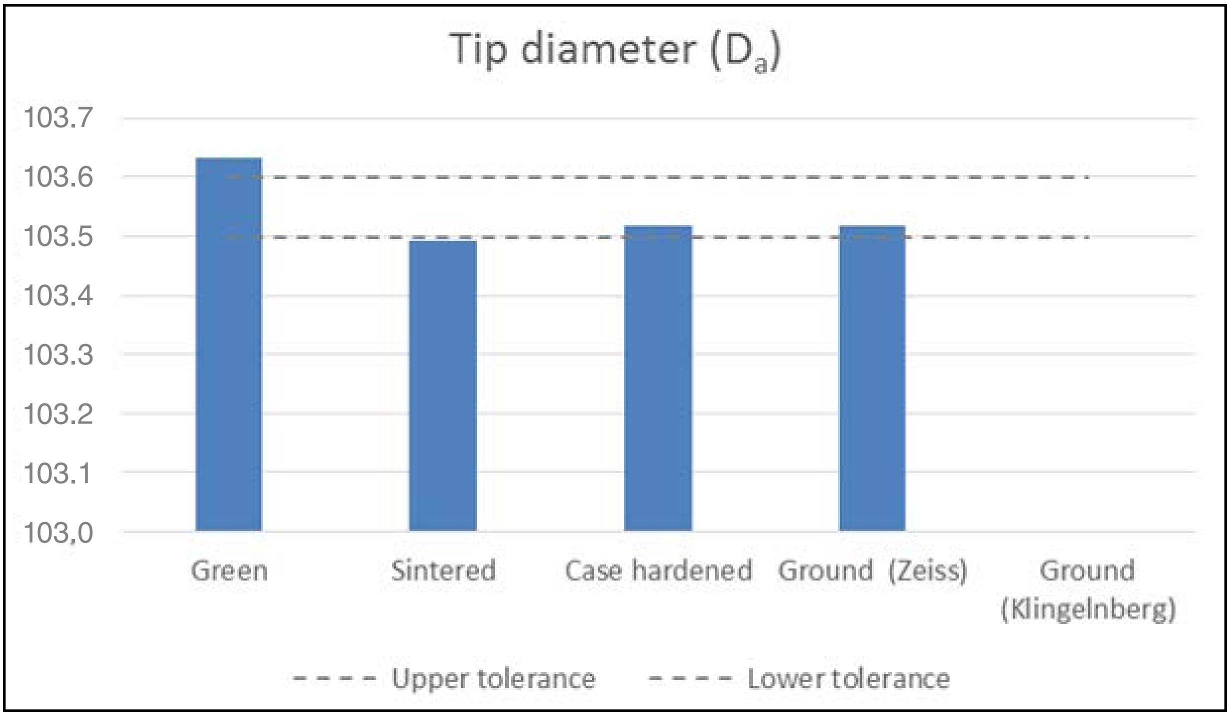

Figure 15 Tip diameter; not measured in the Klingelnberg.

there are ways to shrink and grow a part slightly in the sintering furnace. How this is done is not part of this paper, but one question that might come up is: If a die is cut and the gears turn out too small by a couple of tens of microns, does the die have to scrapped? The answer to that is no, there are ways using the material and sintering to correct such problems. Improving the runout without grinding is more difficult; it can be improved, but it can't be fixed all together.

Summary and Conclusions

An automotive gear in a 6-speed manual transmission has been manufactured using powder metal manufacturing technology. The tool consisted of 3 upper and 3 lower punches, plus a core rod and a die. The tool can be considered to be very advanced and, due to the number of punches and the core rod, it is also a tool where higher deviations can be expected. The goal of the investigation was to determine the tolerance classes after each manufacturing step, and if the deviation could be remedied with the final grinding without grinding the bore where a spline has been net-shape-compacted.

The findings are that the tolerances deteriorated predominantly in the sintering step. The case carburization using conventional oil quenching contributes further to the deviation — but not as much as the sintering. In some cases the case carburize process reduces the deviation, but no conclusions should be made from those observations where that occurred. The final grinding of the flanks returns the tolerances back to ISO 6-7 which is the nominal value. The data presented is taken as a combined worst case out of 10 gears. A combined low pressure sintering and case carburizing process using a controlled step quench is known to further reduce the deviations (Ref. 1).

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References

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