Influence of Hobbing Tool Generating Scallops on Root Fillet Stress Concentrations

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This paper discusses a specific example regarding parallel-sided splines manufactured with a finish hobbing process and their effects on generating root fillet stress concentrations. To estimate the value of the stress concentrations, finite element analysis (FEA) was conducted on the components for two unique hobbing tool designs. The FE results are compared to actual component field service histories.

Introduction

While designing gear and spline teeth, the root fillet area and the corresponding maximum tensile stress are primary design considerations for the gear designer. Root fillet tensile stress may be calculated using macro-geometry values such as module, minor diameter, effective fillet radius, face width, etc. However, the cutting tool geometry and manufacturing process parameters can create microgeometry features, which can greatly influence the actual tensile stress in the root fillet area.

This paper will discuss a specific example regarding parallel-sided splines manufactured with a finish-hobbing process (Fig. 1). Hobbing is a tooth generating process, and the root fillet geometry is solely determined by the geometry of the hob cutter rack form. Other hob cutter features — such as the number of threads and number of gashes — also influence the generated hob scallops in the fillet area. For this discussion, stress concentrations caused by root fillet generating scallops were observed on shafts.

To estimate the value of these root fillet stress concentrations, two methods were used: an ISO 6336-3 stress correction factor for notches in fillet areas and a finite element analysis method. Both methods for estimating the stress correction factor were performed on components for two unique hob tool designs. FEA results will be used to verify the ISO 6336-3 method can be applied to parallel-sided splines.

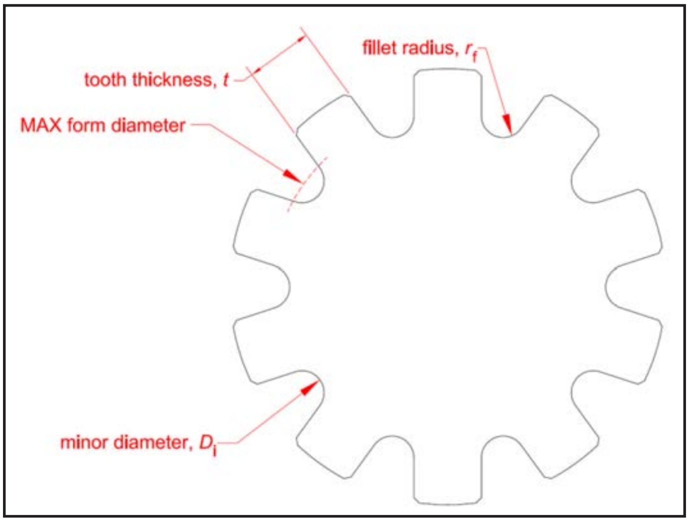

Figure 1 Parallel-sided external spline.

Background

The scope of this study is a parallel-sided spline that is finish-hobbed prior to heat treatment. Multiple applications over a long period of time have proven the spline's design intent and demonstrated reliability. However, there was an observed difference between different suppliers in terms of demonstrated reliabilities within specific vehicle applications. Components from all suppliers met the drawing requirements in terms of specified spline geometry, heat treatment, and other dimensional requirements. To further explain the reliability differences between suppliers, this project was initiated.

For one particular part number that uses this parallel-sided spline specification, multiple samples from different suppliers were obtained. Supporting documentation relative to the cutting tool design for each supplier was obtained as well. After comparing the different samples and looking for differences between the hardware and cutting tool information, it was observed that the generated fillet radius was different between suppliers at the micro-geometry level. All suppliers met the drawing requirement of a minimum fillet radius (*rf*) at a macro-level. In particular, the height and radius of the hob tool generating scallops are unique between the two samples. A comparison of a root fillet area for Supplier A and Supplier B is shown below in Figure 2.

Additional clues for the difference between reliabilities were revealed with metallurgical examination. Crack origination points were found within the fillet area. Furthermore, the initiation points corresponded to small radii related to the hob generating scallops.

Analysis

To quantify the effect of the hob generating scallops, an initial estimation of the increase tensile stress was made per ISO 6336-3:2006, section 7.3 — "Stress correction factor for gears with notches in fillets."

$$Y_{Sg}=\frac{1.3\ Y_S}{1.3-0.6\sqrt{\frac{t_g}{\rho_g}}} \tag{1}$$

Where:
t_g defect depth (mm)
ρ_g defect radius (mm)

$Y_S = 1.0$ as the baseline tensile stress
Y_{Sg} stress correction factor

For the supplier comparisons, initial values for stress correction factor Y_{Sg} were calculated based on root scans of multiple hardware samples. The geometric measurement of hardware was taken directly from the printed root scan, and values for defect radius ρ_g and defect depth t_g were drawn. Generating scallops were present and consistent along the entire axial length of the spline. A circle was drawn with a template and overlaid with the defect radius for simplicity, and this circle diameter is considered as $2 \times \rho_g$. An example of the printed root scan and measurement of the geometry is shown in Figure 4.

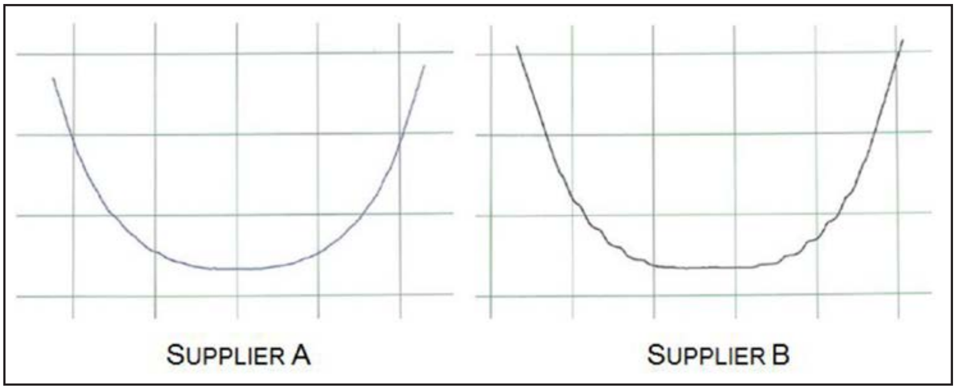

Figure 2 **Measured fillet radius comparison.**

After proper scaling from the printed output, the values for Y_{Sg} were calculated (Table 1).

Table 1 **ISO 6336-3 stress correction factor (Y_{Sg}) from measured hardware.**

	Y_{Sg}
Supplier A	1.10
Supplier B	1.31

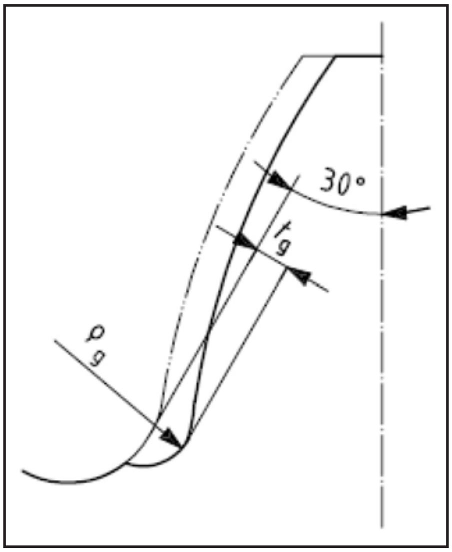

Figure 3 **ISO 6336-3 fillet notch geometry details.**

Initial calculations of the ISO stress concentration factor, calculated from measured hardware, directionally correlate to the experienced reliabilities of known field hardware.

For correlation to each supplier's hob tool design, the ISO 6336 method was used with CAD design data per the hob tool manufacturer's roll-out. The CAD data was assumed as nominal design data for the hobbing tools themselves, and each hob tool vendor directly supplied the appropriate "roll-out" geometry for the workpiece. These CAD roll-outs were then used to estimate values for the defect depth, defect radius, and defect location for each of the suppliers (Fig. 5).

A summary of the stress correction factor calculated by CAD hob roll-out geometry is shown in Table 2.

Table 2 **ISO 6336-3 stress correction factor (Y_{Sg}) from hob tool CAD model.**

	Y_{Sg}
Supplier A	1.12
Supplier B	1.51

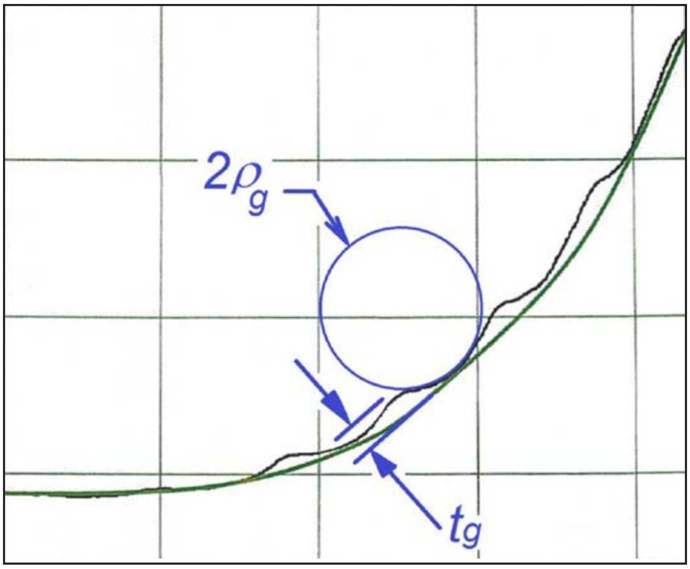

Figure 4 **Root scan with defect measurement.**

The correlation between actual measured hardware and theoretical CAD geometry leads to similar trends — but not an absolute agreement. For Supplier A, the Y_{Sg} value calculated from the hob tool CAD geometry is slightly higher (+2.2%) than direct hardware measurements. For Supplier B, however, the Y_{Sg} value calculated from the hob tool geometry is much higher (+ 15%) than the direct hardware measurements. Actual measured hardware includes effects of the carburizing process, shot cleaning/blasting, and any manufacturing variation(s) that may explain the difference between theoretical and measured fillet geometry.

The ISO methodology, however, lacks the ability to accurately account for the fillet geometry in the following ways:

Multiple fillet notch features, such as hob generating scallops

Any notch location other than 30 degrees from the tooth centerline

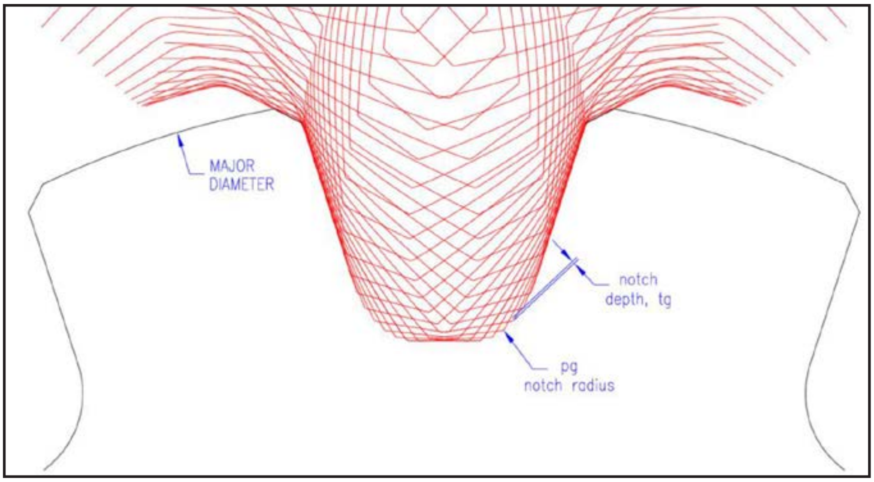

Figure 5 Example: hob cutter rollout, per CAD.

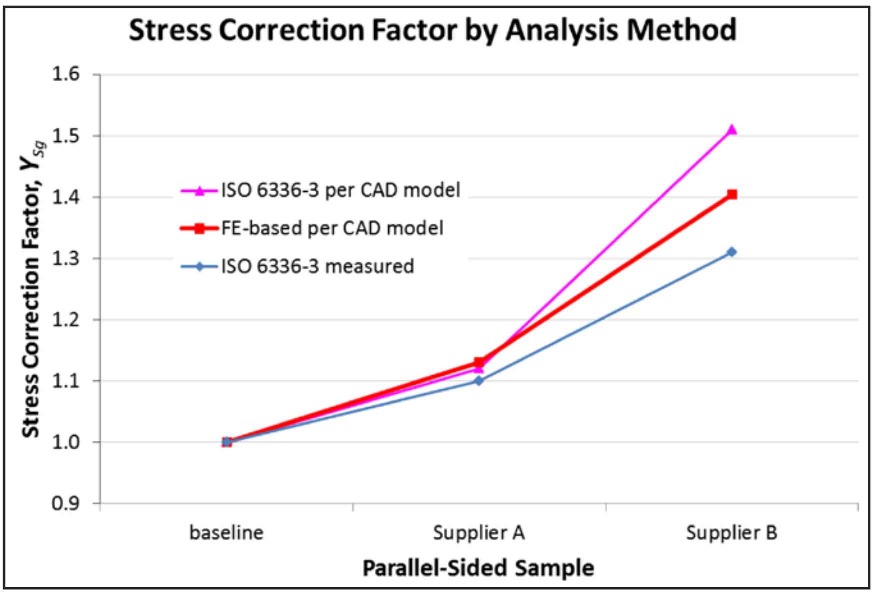

Figure 6 Stress correction factor as function of analysis method.

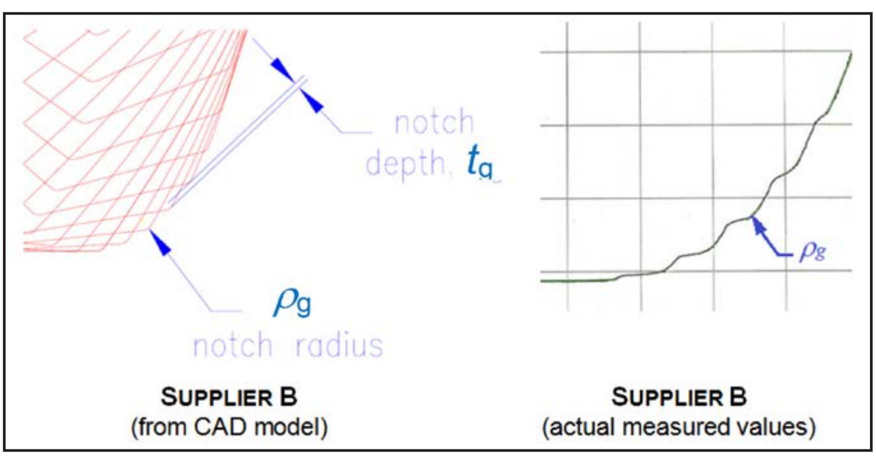

Figure 7 Supplier B fillet details.

To account for these two factors a different approximation methodology is needed. A finite element (FE) method was chosen to represent the geometry for the as-hobbed condition, and the geometry inputs for this FE model were taken directly from the hob tool manufacturer's CAD rollouts. The FE analysis was completed for hob tool designs from Supplier A and Supplier B and compared to a baseline FE model without generating scallops. In this way an FE-based stress correction factor could be calculated as a variation above a baseline tensile stress state. The results of the calculated stress correction factors are shown in Figure 6.

While comparing the three different analysis methods, it can be seen that there is good agreement among stress correction factors for "Supplier A" (within 3%). The stress concentration factors for Supplier A are acceptable in terms of component reliability.

However, for "Supplier B" samples the stress correction factor Y_{Sg} varies when comparing the measured parts and CAD-based geometry. This variation is driven primarily by the defect radius ρ_g, since the defect depth t_g of the measured part correlates within 5% of the CAD model. As stated previously, the actual measured hardware includes effects of the carburizing process, shot cleaning/blasting, and manufacturing variations such as hobbing tool wear, which may influence the measured fillet geometry (Fig. 7).

Stress correction factors calculated with the ISO and FEA methods diverge for the "Supplier B" samples, as Y_{Sg} values increase above 1.13. For Supplier B samples the ISO 6336-3 method over-predicts stress values by 8% when compared to the FE results. Efforts to estimate the stress concentration factor using other methods were evaluated, but found to be overly conservative and did not correlate to observed field service histories (Refs. 2–3). Additionally, the referenced notch geometries and locations were not representative of the specific geometry.

Improved State

To reduce the stress concentration factor due to hob generating scallops, the approach was to re-design the hobbing tool to make the individual generating scallops smaller in height and to increase the radius of the notch. Specifically, the generating scallops can be made shorter by simply having more of them: i.e., increasing the outside diameter and adding more gashes to the hob tool. Reduced tool life can be a concern due to the reduced tooth length, but the added number of gashes adds more teeth to the tool.

Overall, the effect on tool life for the new hob design yields a tool life improvement of approximately 20%. Specifically, the number of gashes of the hob tool was increased 1.5x by increasing diameter and reducing tooth length.

Increasing the tip radius of the hob tool must be done while still preserving the maximum form diameter of the workpiece (Fig. 1). Feasible hob design options were considered by working with a trusted cutting tool supplier, and the end result is a tool radius that reduces the stress concentration factor while still meeting the maximum form diameter requirements of the workpiece (Fig. 8).

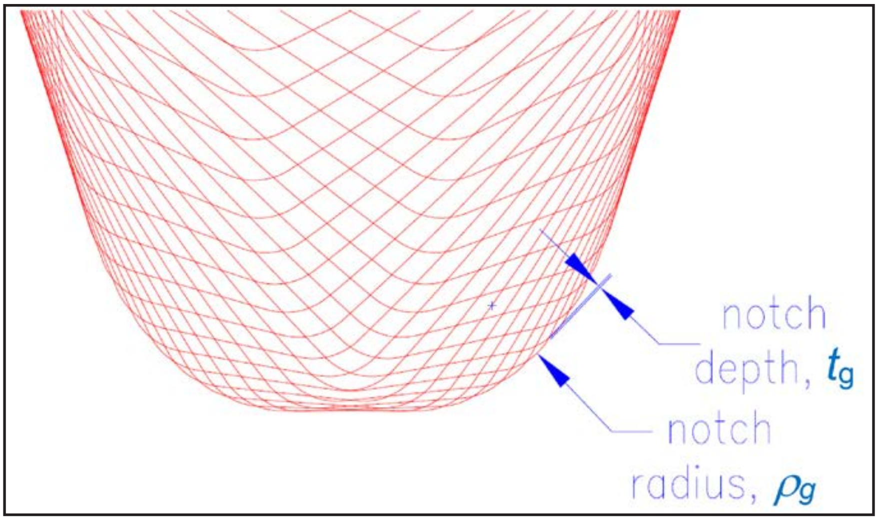

Figure 8 Improved state fillet geometry.

For the improved state, the stress correction factor was re-calculated for Supplier B using both the ISO and FE methods. Overall, the stress correction factor was reduced to the point that it is now equal or superior to the value for Supplier A. For Supplier B, the stress correction factor Y_{Sg} was reduced by solely revising the hob tool design. The Y_{Sg} values displayed in Figure 9 are based on CAD rollouts for each supplier's hob tool design and the FE analysis method.

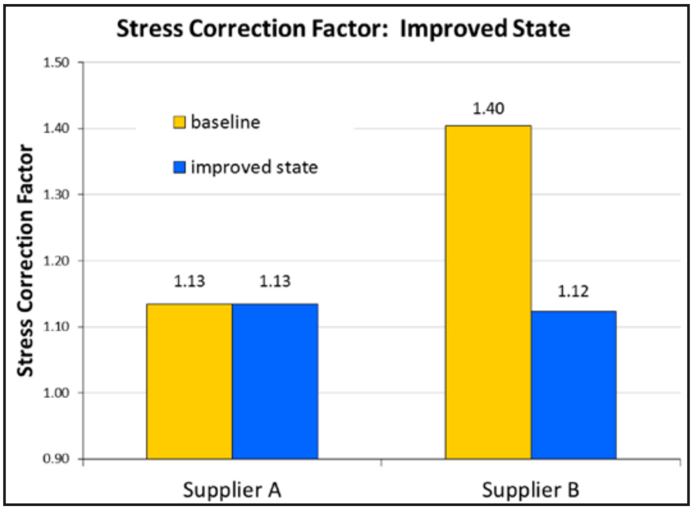

Figure 9 Improved state stress correction factor.

Conclusion

In the design and production of gear and spline teeth, deliberate and clear definition of the root fillet area can prevent unintended variation in component reliabilities. Simply stated, dimensions like minor diameter, maximum form diameter, or equivalent fillet radius may meet the design envelope intent, but it leaves fillet geometry options open for other variations to be produced — some to the benefit and others to the detriment of component reliability.

For this specific case study, the effects have been shown of two different hob cutter designs on the ISO 6336-3:2006 stress correction factor Y_{Sg} for a parallel-sided spline. Furthermore, a stress correction factor was also determined via the use of FE methodology in an attempt to establish correlation between the ISO and FE methods. The FE method further refined the ISO method by including multiple hob generating scallops in their various fillet area locations. It is also shown that for values of Y_{Sg} above 1.15, the predicted stress values using FEA are lower than the ISO predictions.

ISO 6336-3:2006 is conservative when stress correction factor $Y_{Sg} > 1.15$

This conservative result may or may not be the same when applied to an involute spline

In summary, the fillet generating scallops can be optimized by deliberate hob tool design, such that a stress correction factor $Y_{Sg} = 1.12$ can be achieved.

References

1. ISO 6336-3 — Section 7.3. Stress Correction Factor for Gears with Notches in Fillet, 2006.
2. Pilkey, Walter D. *Stress Concentration Factors*, John Wiley & Sons, New York, 1997, p. 105.
3. Ristić, Daniela. "Numerical Stress Concentration Analysis of a Driven Gear Tooth Root with Two Fillet Radius," *Scientific Technical Review*, Vol. LIX, No. 3–4, 2009.

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