High-Performance Sintered-Steel Gears for Transmissions and Machinery: A Critical Review

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Management Summary

Except for higher-end gear applications—found in automotive and aerospace transmissions, for example—high-performance, sintered-steel gears match wrought-steel gears in strength and geometrical quality. The enhanced P/M performance is due largely to advances in powder metallurgy over last two decades, such as selective surface densification, new materials and lubricants for high density and warm-die pressing. This paper is a review of the results of a decade of research and development of high-performance, sintered-steel gear prototypes at Höganäs AB.

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Introduction

The mechanical power transmissions and machinery of today are designed and manufactured to meet the difficult demands of sustainable production, low cost, compact size, low weight, high efficiency, quiet operation, long service life and—when it ends—full recycling. And when comparing powder metallurgy (P/M)—sintered gears—with wrought steel gears, there is no doubt the latter have attained the best-possible levels in gear strength, geometry and material quality. In contrast, while sintered-steel gears have also reached very high levels in gear strength, geometry and material quality, they also offer highly sustainable production, low total cost and full recycling for a range of applications in the automotive, agricultural, construction, power tools and home appliances industries.

Another method for making machined-sintered gears is the so-called blank concept. Here the gear blanks are manufactured by pressing and sintering, selective surface densification and hardening, and are then sent for hard finishing to attain final geometrical quality. With this concept, production sustainability is enhanced by pressing geometrical features in the press direction and eliminating material waste, while also providing high gear strength and material and geometrical quality.

Both sintered and sintered-machined gears are in step with global trends toward improvements in production sustainability. Table 1 lists results of a recently published study by the Metal Powder Industry Federation (MPIF); the analysis was done on a truck transmission notch segment, but the numbers for gears will not much vary. In comparison to machining, P/M gear manufacturing will certainly reduce raw material needs—due to very limited material loss—and at half the energy used.

High-Performance Sintered Gears

P/M entered gear applications through sintered pump gears in the early 1940s (Ref. 2). Since that time P/M has advanced in developing pressing technologies for high density such as selective surface densification (Ref. 3); warm compaction (Ref. 4); high-density lubricants and warm-die compaction (Ref. 5); fully pre-alloyed chromium steel powder grades such as Astaloy CrM, Astaloy CrL (Ref. 6) and, most recently, Astaloy CrA and high-density powder solutions, such as Hipaloy (Ref. 7).

Today it is readily possible to produce spur and helical P/M gears with a

Table 1—Side-by-side comparison of truck transmission notch-segment manufacturing steps by Metal Powder Industries Federation (MPIF) (Ref. 1)

Manufacturing technology	Finished part weight (g)	Raw material utilization (%)	Material loss (g)	Manufacturing steps	Energy used (kWh/piece)
P/M	300	95	16	6	1.243
Machining	312	40..50	260	17	2.847

sintered density exceeding 7.2 g/cm^3 by virtue of:

- Single-pressing/single-sintering process with warm- and warm-die compaction.

It is possible to exceed 7.4 g/cm^3 by virtue of:

- Double-press/double-sinter (DPDS) process.

It is possible to exceed 7.5 g/cm^3 by virtue of:

- High-density powder solutions and fully densified, 7.8 g/cm^3 gear tooth flank and/or root surface by, for example, gear rolling (Refs. 3; 8–9), shotpeening or Densiform process (Ref. 10).

However, gears for several transmission and machinery applications have been found to fit application demands based on what may be called trial and error. Often, there is neither load capacity calculation nor experimental verification of the main gear design parameters available; therefore any change of the design and/or manufacturing process is connected with many questions and uncertainties. A particular uncertainty develops when a conversion to sintered gears is discussed, due to reasons such as the low market share of sintered gears—approximately 3%, according to AGMA in 2009 (Ref. 11)—the presence of pores in the material; a rather low presence of powder metallurgy in material courses for mechanical designers and premature failures of earlier sintered components due to their low strength.

High-Performance Sintered-Steel Gear Development

For some time now, high-performance sintered steel gears have been extensively investigated by Höganäs AB in order to screen the feasibility of using new technologies in powder metallurgy for sintered gears. That included, among others techniques, surface densification via gear rolling; burnishing; shotpeening; high-density pressing; warm compaction and warm-die pressing techniques, together with new low-chromium-alloyed, fully pre-alloyed steel powder grades and a new generation of powder mixes with powdered lubricant and lubricant coated on steel powder. Sintered materials of interest were for the low Cr- and Mo-alloyed, fully pre-alloyed steel powders with good hardenability. Sintered materials of note are (Ref. 12):

- ***Astaloy CrL (Fe alloyed with 1.5% Cr, 0.2% Mo).*** Fully pre-alloyed Cr powder grade; relatively impervious to price fluctuations of Mo as alloying element; very high hardenability and strength already at sintered densities such as 7.0 g/cm^3. Gears made of this material can be gas-carburized as common if core-sintered density exceeds the level of 7.4–7.5 g/cm^3; otherwise, vacuum- or low-pressure-gas-carburizing is required (Ref. 13).
- ***Astaloy 85Mo(Fe alloyed with 0.85% Mo) and Astaloy Mo (Fe***

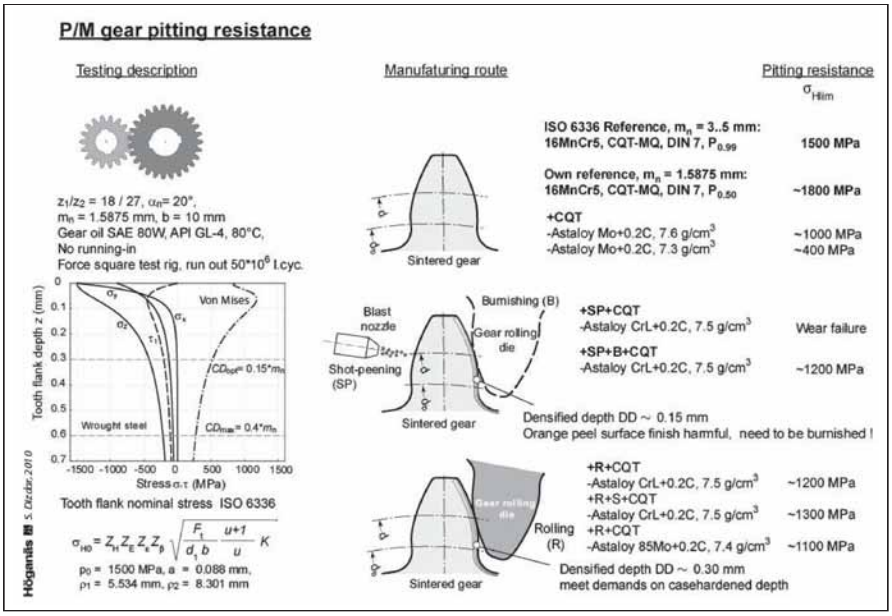

Figure 1—P/M gear pitting resistance.

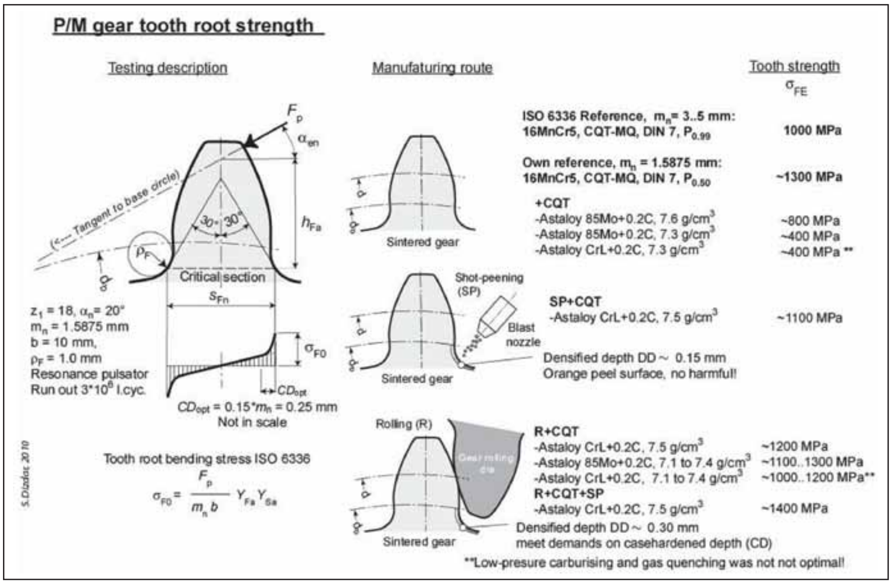

Figure 2—P/M gear tooth root strength.

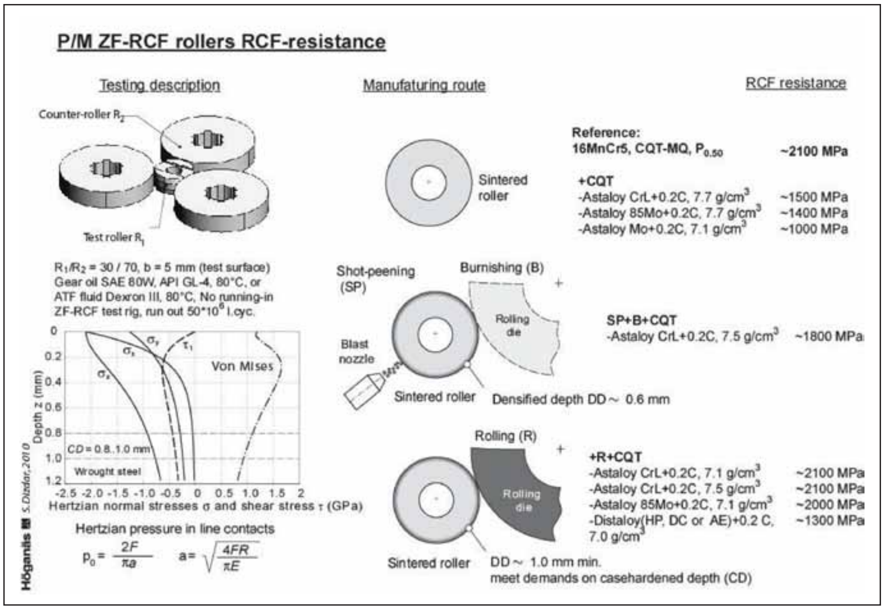

Figure 3—Rolling contact fatigue (RCF) resistance of P/M rollers.

alloyed with 1.5% Mo). Fully pre-alloyed Mo powder grade; relatively sensitive to price fluctuations of Mo as alloying element; high hardenability.

- ***Distaloy HP (Fe alloyed with 1.4% Mo, 4.0% Ni, 2.0% Cu).*** Fully pre-alloyed Mo powder grade diffusion alloyed with nickel and copper.
- ***Distaloy DC (Fe alloyed with 1.5% Mo, 2.0% Ni).*** Fully pre-alloyed Mo powder grade diffusion alloyed with nickel.
- ***Distaloy AB (Fe alloyed with 1.75% Ni, 0.5% Mo and 1.5% Cu*).** Plain iron grade powder diffusion alloyed with nickel, molybdenum and copper. Distaloy grades are very robust powder grades with high hardenability developed for components requiring density of up to 7.3 g/cm^3; use of warm- or warm-die compaction recommended.
- ***Basic sintered materials (Fe alloyed with 1.5% Cu, 0.4% C).*** Basic sintered materials for low-to-moderate-performance sintered components.

It is important to explain how sintered density affects hardening. To illustrate, a common cold-pressing density level for machinery gears in powder metallurgy is 6.9–7.1 g/cm^3; for warm- and warm-die pressing: 7.2–7.3 g/cm^3; and for high-density pressing and double-pressing: double-sintering (DPDS) is up to 7.7 g/cm^3. Sintered materials with densities lower than approximately 7.0–7.1 g/cm^3 have a fully connective pore system that allows deep penetration of gases in a carburizing atmosphere; and, soaking times are shorter compared to wrought components. A problem that may arise is carburization of unwanted surfaces—it must be prevented, which may include additional costs for a carbon-inhibiting mask and its removal after hardening. Depending upon sintered density, this problem may be less-pronounced, but when reaching sintered densities of over 7.4–7.5 g/cm^3, the sintered components start behaving like wrought components during carburization (Ref. 13).

But our focus here is documented results (see references). In addition, Figures 1–3 detail the current gear pitting resistance, gear tooth root strength and respective rolling contact fatigue (RCF) roller resistance existent in sintered gears. These figures provide an overview of prototype specimens—e.g., their testing method, wrought references and manufacturing techniques with achieved results. The prototype gears are described with manufacturing process, material composition and sintered density level.

P/M gear pitting resistance (Fig. 1) was experimentally evaluated in a force-square—or back-to-back—test rig with closed power loop (Ref. 14). Sintered gears (Fe alloyed with 1.5% Cu and 0.4% C) were reported in a classic gear book (Ref. 15) to have a gear pitting resistance of 400 MPa (no details about sintered density available). ISO 6336 declares a gear tooth root strength of 1,000 MPa for case-hardened, low-alloyed wrought steels manufactured in material quality—or MQ, a common, good gear quality. Tests with case-hardened Astaloy Mo+0.2C, 7.3 g/cm^3-sintered gears indicated an equal, 400 MPa pitting resistance level. When gear-sintered density reached a 7.6 g/cm^3 level, pitting resistance approached a level of 1,000 MPa. Surface densification by means of shotpeening applied to the Astaloy CrL+0.2C, 7.5 g/cm-sintered gears resulted in a densified layer of 0.15 mm (DD = 0.15 mm means that full density dropped to 98 % relative density at 0.15 mm depth), but caused an orange peel-like surface finish that led in turn to adhesive wear failure. However, additional burnishing, i.e.—gear rolling in order to smooth the surface and partly correct the tooth profile (Refs. 9; 3)—boosted gear pitting resistance to a 1,200 MPa level. Radial gear rolling (Ref. 3) achieved deeper densification—DD = 0.3 mm—at equal level of pitting resistance. A post-rolling sintering—or "re-sintering"—provided an additional 100 MPa in pitting resistance, likely due to the additional homogenization of the material structure.

By looking at the plot of contact stresses vs. tooth flank depth—and for reference, a Hertzian stress of 1,500 MPa and wrought-steel (full-dense) material in Figure 1, it can be seen that the Von Mises stress knee has a maximum at 0.06 mm depth and that the magnitude of all contact stress components drops below 500 MPa at less than the 0.3 mm case depth recommended in ISO 6336. Results showed that a surface densification of 0.15 mm applied on high-core-density sintered gears resulted in pitting resistance levels of 1,200 MPa—*a 20% increase*. Deeper densification—to 0.30 mm—combined with re-sintering after rolling—resulted in a 30% increase in pitting resistance. To be clear, however, these findings require further investigation.

P/M gear tooth root strength (Fig. 2) was experimentally evaluated by using a high-frequency, resonance-type linear pulsator and applying testing requirements from ISO 6336 (Ref. 16) and DIN 3990 (Ref. 17). Again, sintered Fe–1.5Cu–0.4C gears were reported in the classic gear book (Ref. 15) to have a gear tooth root strength of 500 MPa (no details about sintered density given). ISO 6336 declares a gear tooth root strength of 1,000 MPa for case-hardened, low-alloyed wrought steels manufactured in material quality (MQ—a common, good quality) and having a core hardness of at least 30 HRC. However, ISO gear tooth root strength data were generated by testing gears with a module of 3–5 mm and comparing them with relatively small modules of 1–3 mm—a more frequent occurrence in gear manufacturing today. A 23% increase in the gear tooth root strength of case-hardened gears when decreasing the module from 3–1.5 mm was observed by Jeong (Ref. 18), and aligns well with our own test results. The results in Figure 2 should therefore be compared to 1,300—not 1,000 MPa; results also included case-hardened sintered gears with a density of 7.3 and 7.6 g/cm^3, and a tooth root strength of 400 MPa and 800 MPa, respectively. Shotpeening raised the tooth root strength to a 1,100 MPa level. It should be noted here that selective root shotpeening produces 0.15 mm densification depth as well an orange peel surface finish, but benefits of the densified depth are greater than losses associated with a rough surface finish. Application of gear rolling to 7.1–7.4 g/cm^3-dense Astaloy CrL+0.2C and Astaloy 85Mo+0.2C gears—with densification depth of 0.3 mm—resulted in a tooth strength of 1,000–1,200 and 1,100–1,300 MPa, respectively. Astaloy CrL gears normally exceed the strength of Astaloy 85Mo gears, but in this case low-pressure carburization was not optimal (Ref. 13). Gas-carburized, gear-rolled, 7.5 g/cm^3 core-dense Astaloy CrL+0.2C gears, with a densification depth of 0.3 mm, reached 1,200 MPa; if also shotpeened after common carburize-quench-temper operations, gear tooth root strength increased to 1,400 MPa.

The RCF resistance of P/M rollers (Fig. 3) was experimentally evaluated by using ZF–RCF test rigs through external testing on contract. As known, this type of testing reveals a general picture of RCF for a severity of rolling-sliding contact applications, including gears and bearings. However, while the achieved testing results are useful for ranking of materials/processes, they cannot be directly transferred to gears. RCF resistance of 2,100 MPa for 16MnCr5 rollers case-hardened to 1.0 mm in case depth was used as the reference. Case-hardened sintered rollers with a density of around 7.0 g/cm^3 reached close to 1,000 MPa. Increasing the roller's sintered density to 7.6–7.7 g/cm^3 by high-density pressing elevated RCF resistance to 1,500 MPa. It appears that to increase RCF resistance, a surface-densification technique must be used. 7.5 g/cm^3-sintered rollers—densified to 0.6 mm depth by shotpeening and burnishing the RCF resistance—reached a 1,800 MPa level. Both 7.1 and 7.5 g/cm^3 -sintered rollers—densified to deeper than 1.0 mm by radial rolling—met the reference RCF resistance of 2,100 MPa. The likely reason for this is that high magnitudes of all contact stress components stand inside a fully densified surface layer.

P/M gears with sintered density of 7.1 g/cm^3 manufactured by using pressing-sintering hardening routes usually achieve gear quality no higher than DIN 10 (Ref. 20). But by gear rolling, the quality of sintered gears can be improved to quality 6 to 7 for all deviations suggested in DIN 3961 having general or particular importance for uniformity of rotation, load capacity and noise reduction of gears. Quality DIN 8 can be more appropriate to envelop all teeth deviations, but of course the real question is whether all the teeth deviations need to achieve a certain quality. A subsequent case-hardening can make the teeth "top-small," and so lower the tooth profile quality to quality DIN 10 (Ref. 19). However, the pressing die and the rolling die geometry can compensate for it. A high core density is of benefit when trying to achieve high gear quality, since high (core) density techniques produce less density gradients in the gear teeth.

Surface roughness of sintered gears is a particular question. Sintered components in general achieve so-called stratified surfaces, including deep surface pores; and surface roughness, as defined for machined surfaces, cannot be fully applied here. However, using the machined surface roughness approach—until consensus is reached on acceptable surface roughness for sintered surfaces—the average surface roughness Ra is normally smoother than 0.8 µm for sintered gear flanks over 7.1 g/cm^3 in density, and smoother than 0.2 µm for gear rolled flanks (Refs. 3; 19). And that is even smother than for ground teeth.

A very brief summary of the all testing results is listed in Table 2.

Conclusions

High-performance-sintered, low-alloyed Cr and Mo steel gears are equal to wrought-machined gears for a number of difficult applications in transmissions and machinery—excepting the high-end ones in automotive and aerospace. In production sustainability, the sintered gears clearly exceed wrought-machined gears. Taking into account the gear size transferability issue, the following conclusions were reached:

- Pitting resistance of sintered-steel gears reached over 70% of the wrought-steel reference (standard)
- Gear tooth root strength of sintered-steel gear prototypes met the wrought-steel reference (standard)
- RCF roller resistance of sintered-steel gear prototypes met the wrought-steel reference (standard)
- Sintered low-alloyed Cr steels, such as Astaloy CrL for gear applications, reached 70% gear pitting and 100% RCF resistance of reference wrought-steel gears. These are important and very encouraging results showing that sintered-gear pitting performance is already of sufficient severity resistance for demanding gear applications.
- Gear quality achieved by gear rolling of sintered gears reached DIN 6–7 quality, which can be maintained after case hardening if compensated by use of a press-rolling die for top-small teeth during case hardening. The surface roughness of gear- sin-

Table 2—Brief comparison of guide values for gear strength and quality

	DIN 16MnCr5, m_n= 3..5 mm -machined, CQT, ground -manufact. quality MQ (ISO 6336)	P/M Astaloy CrL, m_n=1.5875 mm -pressing, sintering, shot-peening / gear rolling, CQT
Pitting	1500 ($P_{0\ 99}$)	1800 (P0.50)
Tooth root bending	1000 ($P_{0\ 99}$) 1300 (P0.50) — m_n=1.5875 mm	1100..1300 (P050)
Gear quality	DIN 7	DIN 7-8
Surface finish	R_a< 0.25 pm	R_a< 0.20 pm

tered rolled gears is even smoother than that of the ground gears.

- The key for achieving high-performance, sintered-steel gears is in making the surface densification depth equal to a required case-hardened depth, in combination with a properly high core density for a particular gear application. An increase in core density positively affects case-hardening and, if exceeding 7.4–7.5 g/cm^3, makes case-hardening of sintered steels as simple as case-hardening of wrought steels.

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