High performance sintered steel gears for use in transmissions and machinery – a critical review

High performance sintered steel gears meet wrought steel gears!

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Abstract

Except for high–end gear applications in automotive and aerospace transmissions, high performance sintered steel gears meet wrought steel gears in respect to gear strength and geometrical quality. The performance increase has to thank advances in powder metallurgy in last two decades such as selective surface densification, new materials and lubricants for high density–, warm– and warm die pressing. This review lists results of a decade with high performance sintered steel gear prototypes development at Höganäs AB in Sweden.

1. Introduction

Mechanical power transmissions and machinery of today meet hard demands on sustainable production, low cost, compact size, low weight, highly efficient and quiet operation, long useful service life and when it ends – full recycling. Comparing powder metallurgy (P/M) or simply called sintered gears with machined wrought steel gears, there is no doubt that the latter have reached ultimate levels in gear strength, geometrical and material quality. In contrast, the sintered steel gears have reached very high levels in gear strength, geometrical and material quality but offer highly sustainable production, low total cost and full recycling for a range of applications in automotive, agricultural, construction, power tools and home appliances industry.

A compromise, machined–sintered gears is also possible by so called clever blank–concept. Here the gears blanks are manufactured by pressing and sintering, selective surface densification, hardening and then send for hard finishing in order to acquire the final geometrical quality. By this concept, one is allowed to raise the level of production sustainability by pressing geometrical features in press direction and eliminating waste of material as machining chip and acquire high gear strength, material and geometrical quality.

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Both sintered and sintered–machined gears are complying important global trends on improvements in production sustainability. To provide an illustration for this, Table 1 lists results of recently published study by Metal Powder Industry Federation (MPIF). The analysis was done on a truck transmission notch segment but the numbers for gears will not be too much different. In comparison to machining, the P/M gear manufacturing will for sure keep double raw material utilization, almost negligible material loss, and half of the energy used.

Table 1: A side by side comparison of a truck transmission notch segment manufacturing steps by Metal Powder Industries Federation (MPIF) [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

2. High performance sintered gears

P/M entered gear applications through sintered pump gears in 1940' [2]. Since that time P/M has advanced in developing pressing technologies for high density such as selective surface densification from early 1980' [3], warm compaction in 1980' [4], new high density lubricants and warm die compaction from 1990' [5], fully pre–alloyed chromium steel powder grades such as Astaloy CrM, –CrL and from 2000' [6] and recently Astaloy CrA™ and high density powder solutions, such as Hipaloy™, from 2000'[7].

Today it is readily possible to achieve spur and helical P/M gears with sintered density exceeding 7.2 g/cm^3 in single pressing – single sintering process by warm– and warm die compaction, exceeding 7.4 by double press double sinter (DPDS) process, exceeding 7.5 g/cm^3 by high density powder solutions and fully densified, 7.8 g/cm^3, gear tooth flank and/or root surface by for example gear rolling [3, 8, 9], shot peening or Densiform® process [10].

However, gears in several transmission and machinery applications have been found to fit application demands based on experience. Often, there is neither load capacity calculation nor experimental verification of the main gear design parameters and therefore any change of the design and/or manufacturing process is connected with a lot of questions and uncertainties. A particular uncertainty is present when a conversion to sintered gears is discussed, due to reasons such as low market share of sintered gears, ca 3 % according to AGMA in 2009 [11], presence of pores in the material, rather low presence of powder metallurgy in material courses for mechanical designers and premature failures of earlier sintered components due to their low strength.

3. Results of high performance sintered steel gear development at Höganäs AB

For a decade high performance sintered steel gear have been extensively investigated development at Höganäs AB in order to screen feasibility of use of new technologies in powder metallurgy to sintered gears. That included among others techniques surface densification by gear rolling, burnishing, shot–peening and their combinations, high density pressing, warm compaction and warm die pressing techniques together with new low chromium alloyed, fully pre-alloyed steel powder grades and new generations of powder mixes with powdered lubricant and lubricant coated on the steel powder. Sintered materials of interest were for the low Cr and Mo alloyed fully pre–alloyed steel powders with good hardenability. Sintered materials to be mentioned here are [12]:

– Astaloy CrL, i.e. Fe–1.5Cr–0.2Mo, fully pre-alloyed Cr powder grade, relatively insensitive to price fluctuations of Mo as alloying element, with 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 exceed the level of 7.4..7.5 g/cm^3. Otherwise, vacuum or low pressure gas carburizing had to be used [13].

– Astaloy 85Mo and Astaloy Mo, i.e. Fe–1.5Mo respective Fe-0.85Mo, fully pre-alloyed Mo powder grade, relatively sensitive to price fluctuations of Mo as alloying element, with high hardenability,

– Distaloy HP, i.e. Fe–1.5Mo fully pre-alloyed Mo powder grade diffusion alloyed with 4 Ni and 2 Cu, Distaloy DC i.e. Fe–1.5Mo fully pre-alloyed Mo powder grade diffusion alloyed with 2 Ni, and Distaloy AE, i.e. plain iron grade powder diffusion alloyed with 1.75 Ni, 0.5 Mo and 1.5 Cu. Distaloy grades are very robust powder grades with high hardenability developed for components with density of up to 7.3 g/cm3 advisable by using warm– or warm–die compaction.

– Fe–Cu–C materials such as Fe–1.5Cu–0.4C are basic sintered materials for low to moderate performance sintered components. These materials were not tested but are mentioned here due to historical reasons.

Important to mention is how sintered density affects hardening. To illustrate, a common cold pressing density level for machinery gears in powder metallurgy is 6.9 to 7.1 g/cm^3, for warm– and warm die pressing is 7.2 to 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 to 7.1 g/cm^3 have fully connecting pore system and it allows deep penetration of gases in carburizing atmosphere and the soaking times are few times shorter comparing to wrought components. A problem which may appear is that carburization from unwanted surfaces must be prevented which may include additional costs for carbon inhibiting mask and its removal after hardening. Increasing sintered density, this problem may be less pronounced, but when reaching sintered densities of over approximately 7.4..7.5 g/cm^3, the sintered components start behaving like wrought components during carburization [13].

Avoiding further details of powder metallurgy and surface densification technology in order to let this review focus on achieved results (the details are of course found in respective references) Figure 1, Figure 2 and Figure 3 present achieved gear pitting resistance, gear tooth root strength and respective RCF-roller resistance. The figures are done to overview prototype specimens, their testing method, wrought references, and manufacturing techniques with achieved results. The prototype gears are described with manufacturing route, material composition and sintered density level.

P/M gear pitting resistance, see Figure 1, was experimentally evaluated in a force square or back–to–back test rig with closed power loop [14]. Sintered Fe–1.5Cu–0.4C gears were reported in a classic gear book [15] to have gear pitting resistance of 400 MPa (no details about sintered density given). ISO 6336 declares gear tooth root strength of 1000 MPa for case hardened low alloyed wrought steels manufactured in material quality MQ (a common,, good gear quality). Own tests with case hardened Astaloy Mo+0.2C, 7.3 g/cm^3 sintered gears indicated equal, 400 MPa, pitting resistance level. First when gear sintered density reached 7.6 g/cm^3 level, pitting resistance approached level of 1000 MPa. Surface densification by means of shot–peening 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 gave rise to adhesive wear failure. However, additional burnishing, i.e. gear rolling in order to smooth the surface and partly correct the tooth profile [9,3] pushed up gear pitting resistance to 1200 MPa level. Radial gear rolling [3] achieved deeper densification, DD= 0.3 mm, but equal level of pitting resistance. A sintering after the rolling, so called re-sintering, gave additional 100 MPa in pitting resistance likely due to the additional homogenization of the material structure.

By looking on the plot of contact stresses vs. tooth flank depth for reference Hertzian stress of 1500 MPa and wrought steel (full dense) material in Figure 1, one see that the Von Mises stress knee has a maximum at 0.06 mm depth and that magnitude of all contact stress components drop below 500 MPa below 0.3 mm – recommended case hardened depth in ISO 6336. Results here showed that already a surface densification of 0.15 mm applied on high core density sintered gears resulted in pitting resistance levels of 1200 MPa or 20 % increase. Deeper densification, to 0.30 mm, combined with re-sintering after rolling resulted in a 30% increase in the pitting resistance. These findings need a further investigation.

P/M gear tooth root strength, Figure 2, was experimentally evaluated by using a high–frequency linear pulsator of resonance type and applying testing requirements from ISO 6336 [16] and DIN 3990 [17]. Again, sintered Fe–1.5Cu–0.4C gears were reported the classic gear book [15] to have gear tooth root strength of 500 MPa (no details about sintered density given). ISO 6336 declares gear tooth root strength of 1000 MPa for case hardened low alloyed wrought steels manufactured in material quality MQ (a common, good quality) and having core hardness of at least 30 HRC. However, ISO gear tooth root strength data were generated by testing of gears with module of 3 to 5 mm, and comparing to relatively small modules of 1 to 3 mm which occurs more frequently in gear practice of today, an increase in gear tooth root strength of case hardened gears of 23% when decreasing the module from 3 to 1.5 mm was observed by Jeong [18] and agree well with results of own testing. Testing results in Figure 2 should be therefore compared to 1300 and not to 1000 MPa. So showed case hardened sintered gears with density of 7.3 and 7.6 g/cm^3, tooth root strength of 400 MPa and 800 MPa respectively. Application of shot–peening raised the tooth root strength to 1100 MPa level. To note here that a selective root shot–peening produces 0.15 mm densification depth as well an orange peel surface finish but benefits with the densified depth are large than losses 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 tooth strength 1000..1200 and 1100..1300 MPa respectively. Astaloy CrL gears normally exceed the strength of Astaloy 85Mo gears for equal manufacturing route, but here low pressure carburization was not optimal [13]. Gas carburized, gear rolled 7.5 g/cm^3 core dense Astaloy CrL+0.2C gears with densification depth of 0.3 mm, reached 1200 MPa and if additionally shot-peened after common CQT, the gear tooth root strength increased up to 1400 MPa.

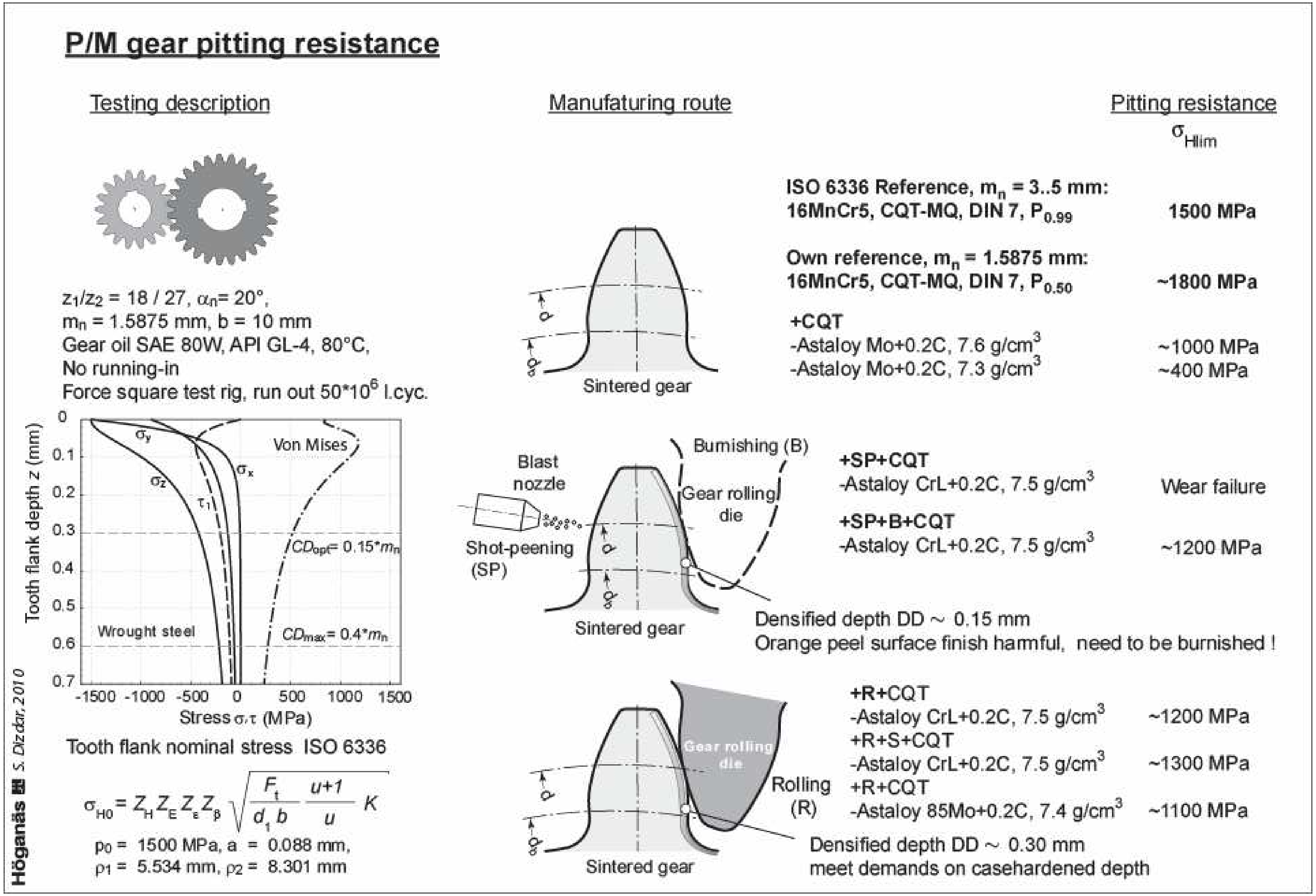

Figure 1. P/M gear pitting resistance.

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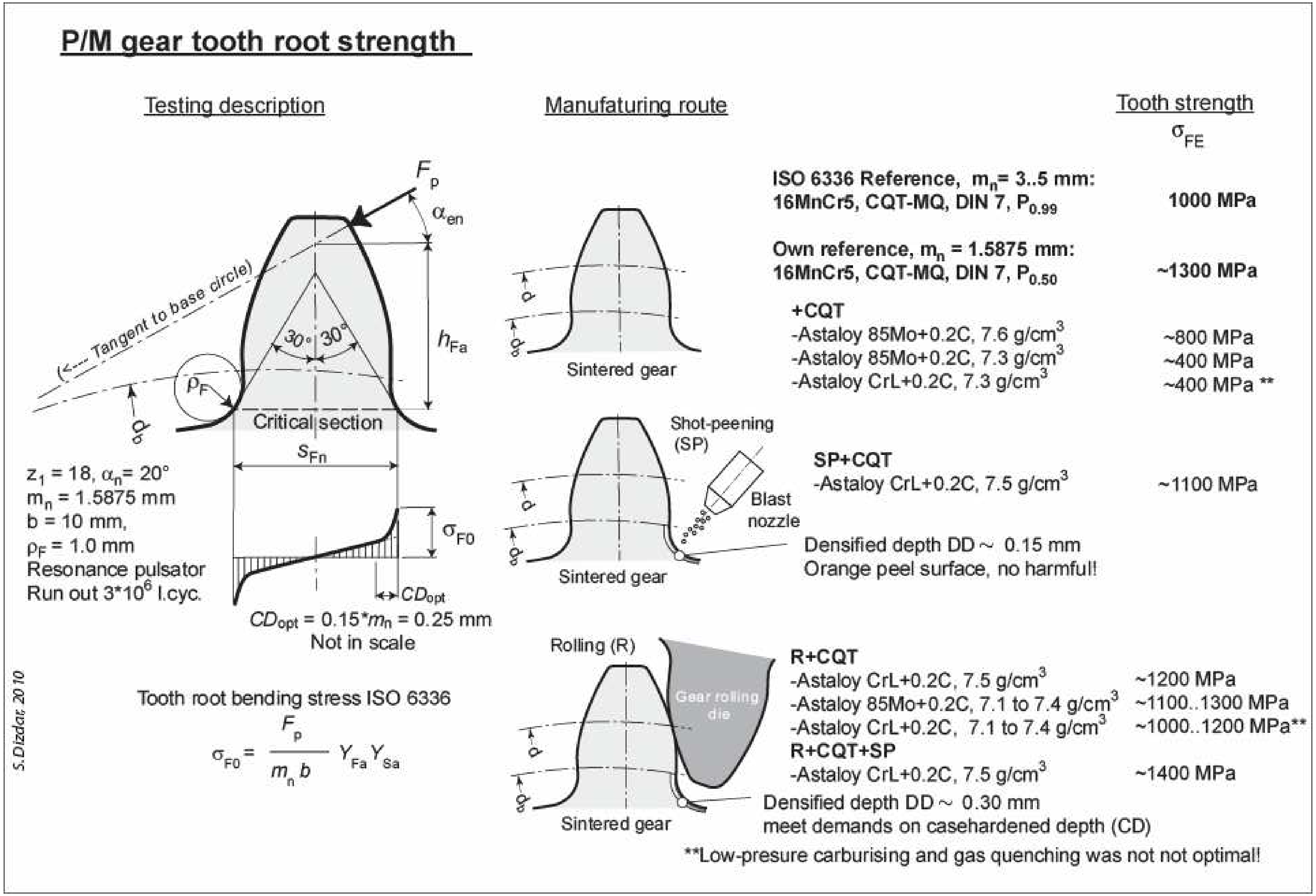

Figure 2. P/M gear tooth root strength.

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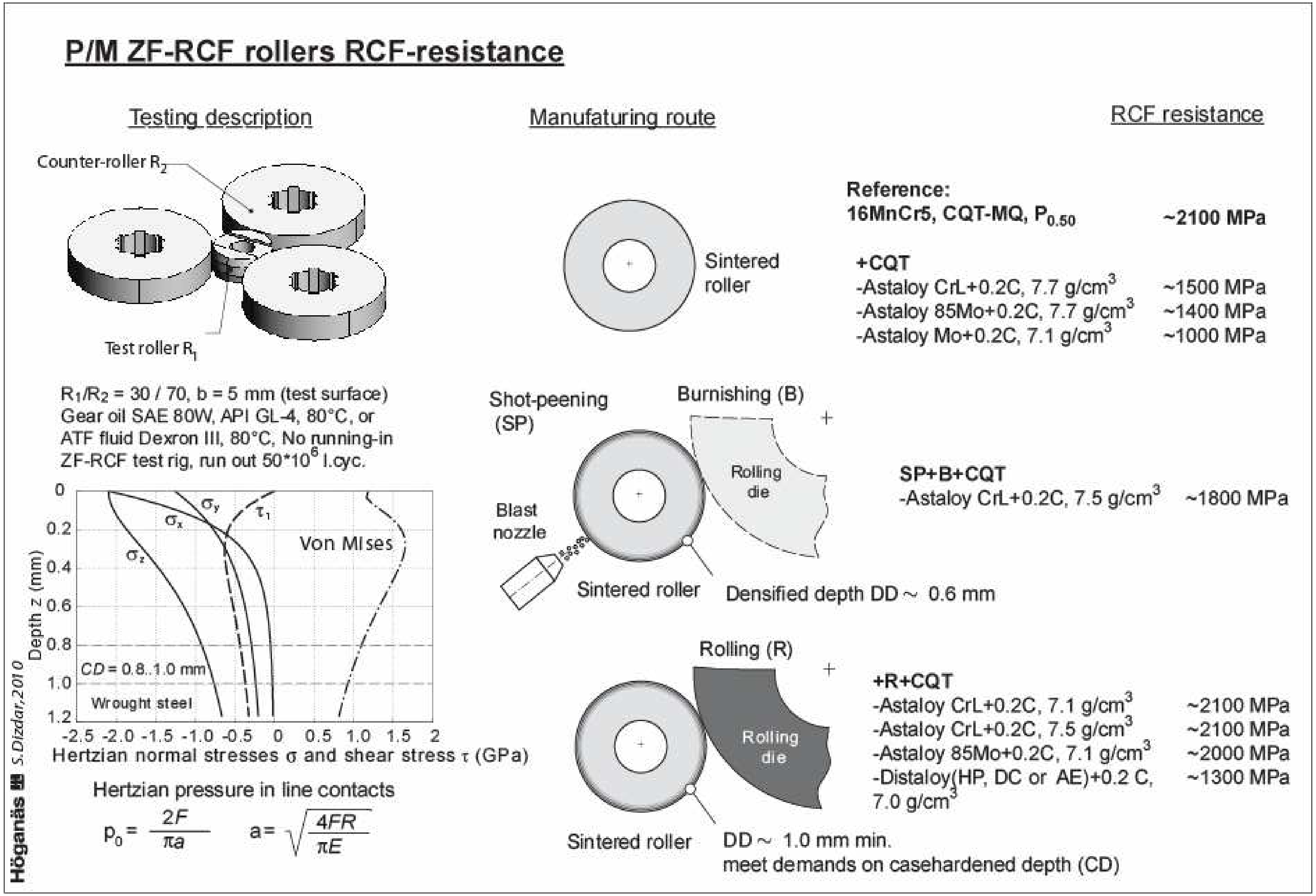

Figure 3. RCF resistance of P/M rollers.

RCF resistance of P/M rollers, Figure 3, was experimentally evaluated by using ZF-RCF test rigs through external testing on contract. As known, this type of testing gives a general picture of RCF for a severity of rolling–sliding contact applications including gears and bearings. However, the achieved testing results are useful for ranking of materials/processes but cannot be directly transferred to gears. RCF–resistance of 2100 MPa for 16MnCr5 rollers case hardened to 1.0 mm in case depth was used as the reference. Case hardened sintered rollers with density of around 7.0 g/cm^3 reached close to 1000 MPa. Increasing the roller's sintered density to 7.6 or 7.7 g/cm^3 by high density pressing, RCF-resistance raised up to 1500 MPa. It appears that any further increase in the RCF-resistance, a surface densification technique has to be used. 7.5 g/cm^3 sintered rollers densified to 0.6 mm depth by shot–peening and burnishing the RCF resistance reached 1800 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 2100 MPa. The reason for this is likely that high magnitudes of all contact stress components stand inside 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 [20]. By gear rolling quality of sintered gears can be improved to quality 6 to 7 for all deviations suggested in DIN 3961 to have 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 good question is if 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 [19]. However, the pressing die and the rolling die geometry can compensate for it. A high core density is of benefits 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 the surface roughness as defined for machined surfaces cannot be fully applied here. However, using the machined surface roughness approach, until some agreement on surface roughness for sintered surfaces, average surface roughness R_a 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 [3,19] and what is even smother than for ground teeth.

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

Table 2: A brief comparison of some 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 ($P_{0.50}$)
Tooth root bending	1000 ($P_{0.99}$) 1300 ($P_{0.50}$) – m_n=1.5875 mm	1100..1300 ($P_{0.50}$)
Gear quality	DIN 7	DIN 7-8
Surface finish	R_a< 0.25 µm	R_a< 0.20 µm

4. Conclusions

High performance sintered low alloyed Cr and Mo steel gears meet wrought machined gears for a severity of applications in transmissions and machinery except high–end ones in automotive and aerospace applications. In production sustainability, the sintered gears clearly exceed wrought machined gears. Taking into account the gear size transferability issue, following conclusion were reached:

–Pitting resistance of sintered steel gears reached over 70% of the wrought steel reference,
–Gear tooth root strength of sintered steel gears prototypes met the wrought steel reference,
–RCF-roller resistance of sintered steel gears prototypes met the wrought steel reference.

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 and show that sintered gear pitting performance is already enough high for a severity of high demanding gear applications.

Gear quality achieved by gear rolling of sintered gears reached DIN 6 to 7 (8) quality, which can be kept after case hardening if compensated by press/rolling die for top small teeth ness during case hardening. Surface roughness of gear sintered rolled gears is even smoother than surface roughness of the ground gears.

The key for achieving a high performance sintered steel gears is in surface densification depth equal to demanded case hardened depth in combination with a properly high core density for a particular gear application. 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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