IGS to Increase Wind Gearbox Torque Density

Ruben Carranza Fernandez and Thomas Tobie

Introduction

To increase cost efficiency in wind turbines, the wind industry has seen a significant rise in power density and an increase in the overall size of geared components. Current designs for multimegawatt turbines demand levelized cost of energy (LCOE) reduction, and the gearbox is a key part of this process.

It is feasible to reach beyond the current industry limit of 200 Nm/kg torque density barrier with a combination of technology, improved design, optimized materials, and surface engineering (Fig. 1).

Since fatigue failures nearly always occur at or near the surface, where the stresses are greatest, the surface condition strongly affects the gear life. Consequently, an improved surface condition effectively avoids major redesign or increased material cost due to an increase in part size.

Additional finishing methods such as shot peening (SP) and superfinishing (SF) significantly increase the gear load capacity, but these effects have not yet been adequately considered in the current ISO 6336 standard or in any other gear standards.

The combination of SP followed by SF will be described here as an "improved gear surface" (IGS).

Defining SP

The objective of SP is to induce compressive residual stresses in the near-surface layer of a part. This occurs by a propelled stream of spherical shots, often called media. Each impact of the shot media has the effect of leaving a small hemisphere or dimple and compressive residual stresses that occur from localized yielding of the base material at the point of shot impact.

SP is a controlled process, and according to ISO 6336-5 (Ref. 1), the recommended minimum control should be based on SAE AMS 2430 (Ref. 3), SAE AMS 2432 (Ref. 4) or SAE J 2441 (Ref. 5). SP should not be confused with mechanical cleaning operations or shot blasting.

There are four main parameters to specify and control SP: media hardness, media size, intensity, and coverage.

Defining SF

SF is a polishing process that removes surface roughness peaks due to a relative movement between the workpiece and an abrasive media in a vibrating barrel (bowls or tubes). The reduction in roughness depends on the initial roughness and processing time.

SF can be subdivided into mechanically and chemically accelerated processes.

Combined Effect of SP + SF (IGS)

SP can be detrimental to surface durability due to an increase in surface roughness. It may therefore be required to refinish the tooth flanks to achieve the specified surface finish and texture, as stated in ISO 6336-5 (Ref. 1).

Post-SP processes are allowed, but, in general, can alter the residual compressive stress obtained by SP.

SF reduces the surface roughness without significantly changing the residual stress state below the surface because of the small amount of material removed. Therefore, SF allows preservation of the compressive residual stresses induced by an SP process and improves flank surface roughness requirements.

Case Study Measurements and Results

An estimation of the torque density increase using SP followed by an SF process is studied in this paper based on surface and residual stress measurements for a multimegawatt case-carburized planet wheel gear of material 18CrNiMo7-6 with material

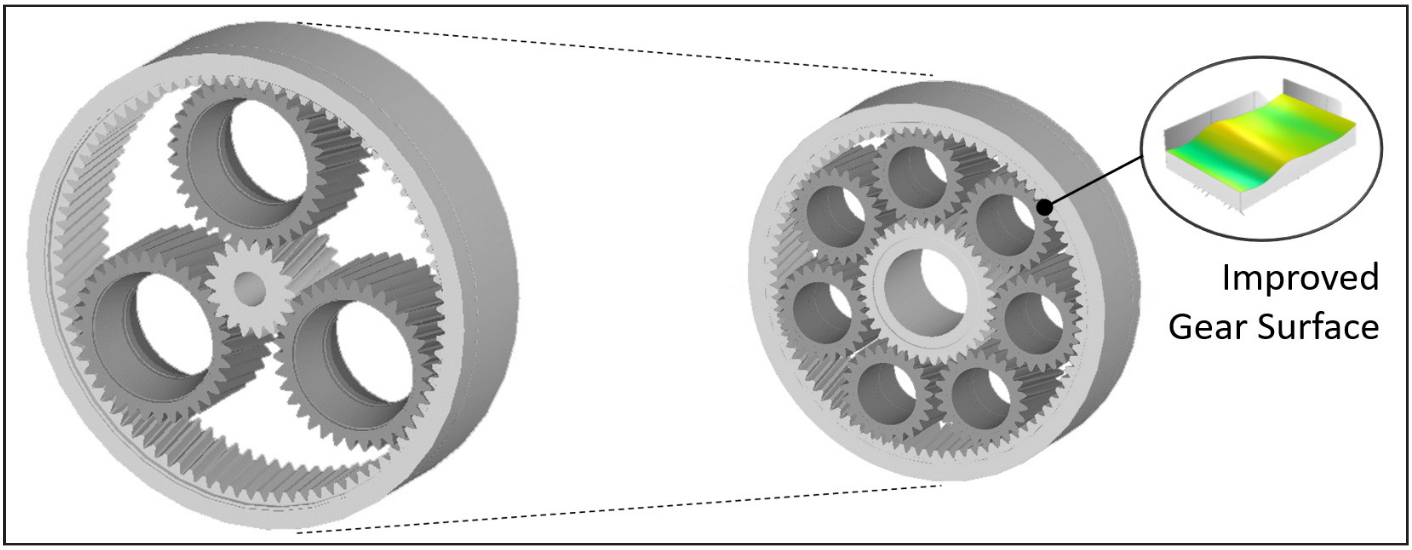

Figure 1 Gearbox torque density increase.

quality grade MQ-a according to ISO 6336-5 (Ref. 1) and gear module m_n=20.5 mm.

For these investigations, a standard ground finished planet gear wheel was divided into three sectors. Different surface conditions were then applied to compare the expected results regarding bending and pitting (contact) fatigue strength in a case study (Fig. 2).

Sector 1 is the reference part, with standard flank grinding as the finish condition. The tooth root is unground, and the shot blasting intensity has been deliberately increased to show its influence. The amount of retained austenite is slightly above the standard to show an SP effect.

Sector 2 followed a standard SP process (S330H/0.45 mmA/100% coverage) on the flank and root (Fig. 3).

Sector 3 follows a double SP process with modified intensity and coverage parameters. Afterward, a chemically accelerated superfinish process was applied to achieve an Rz flank value below 1 µm (Fig. 4).

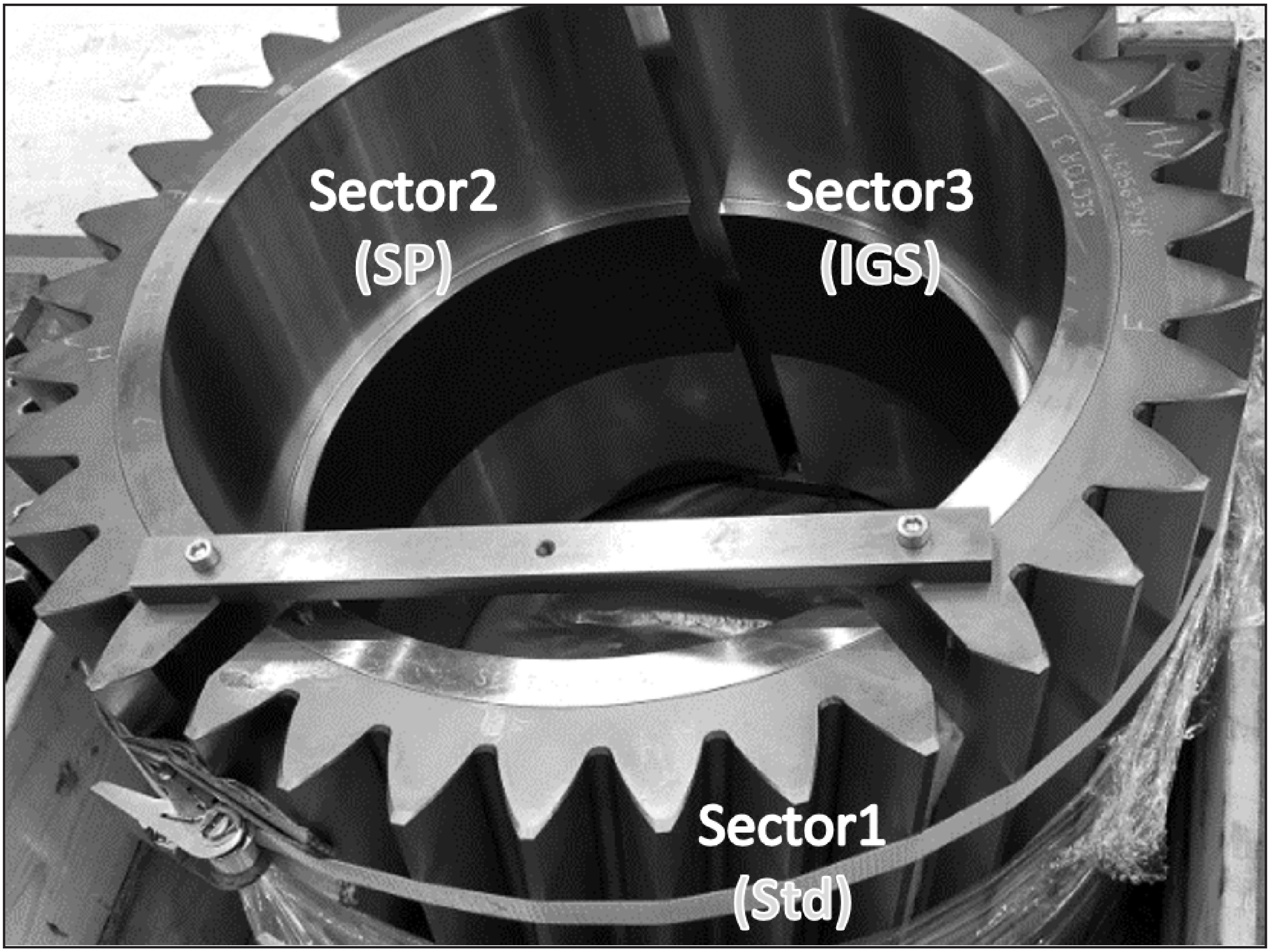

Figure 2 **In the case study, a gear was divided in three sectors, and each sector received a different surface finishing process.**

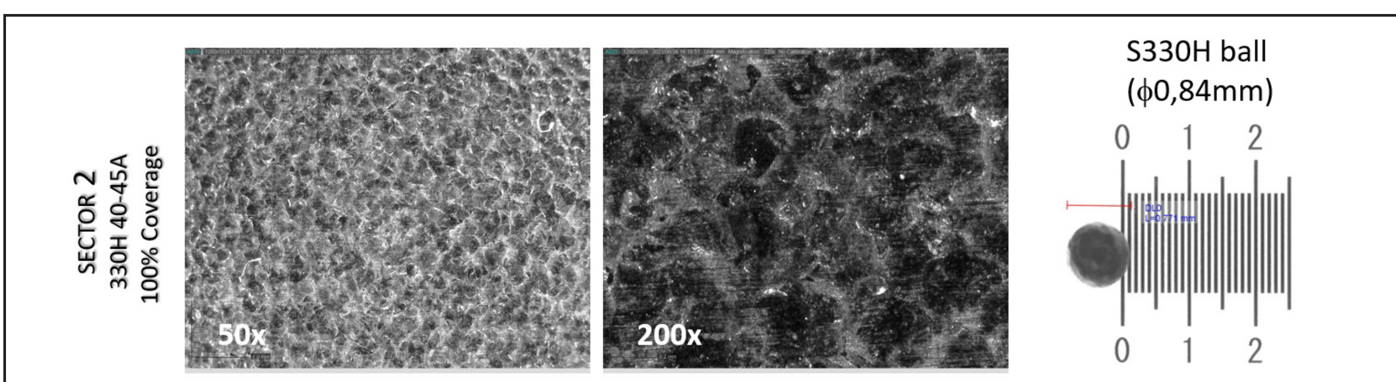

Figure 3 **Almen strip Sector 2.**

Figure 4 Chemically accelerated process applied on Sector 3.

Roughness was measured in three sectors, according to ISO-4288 (Ref. 6) over the three parts in the root and flank areas using three different profilometers (173 measurements).

To better understand the surface topography, an optical calibrated profiler based on confocal and interferometry techniques was also used over gear replicas (Fig. 6). A good correlation between both techniques was obtained, aligned with other reported experiences (Ref. 34).

This optical technique is an easy way to contrast root roughness measurements in areas and directions where standard profilometers cannot reach.

Optical measurements (Figs. 7, 8) clearly show that SP effectively changes topography and removes grinding marks, as observed in other papers (Ref. 31). The SF process in Sector 3 creates an isotropic surface condition.

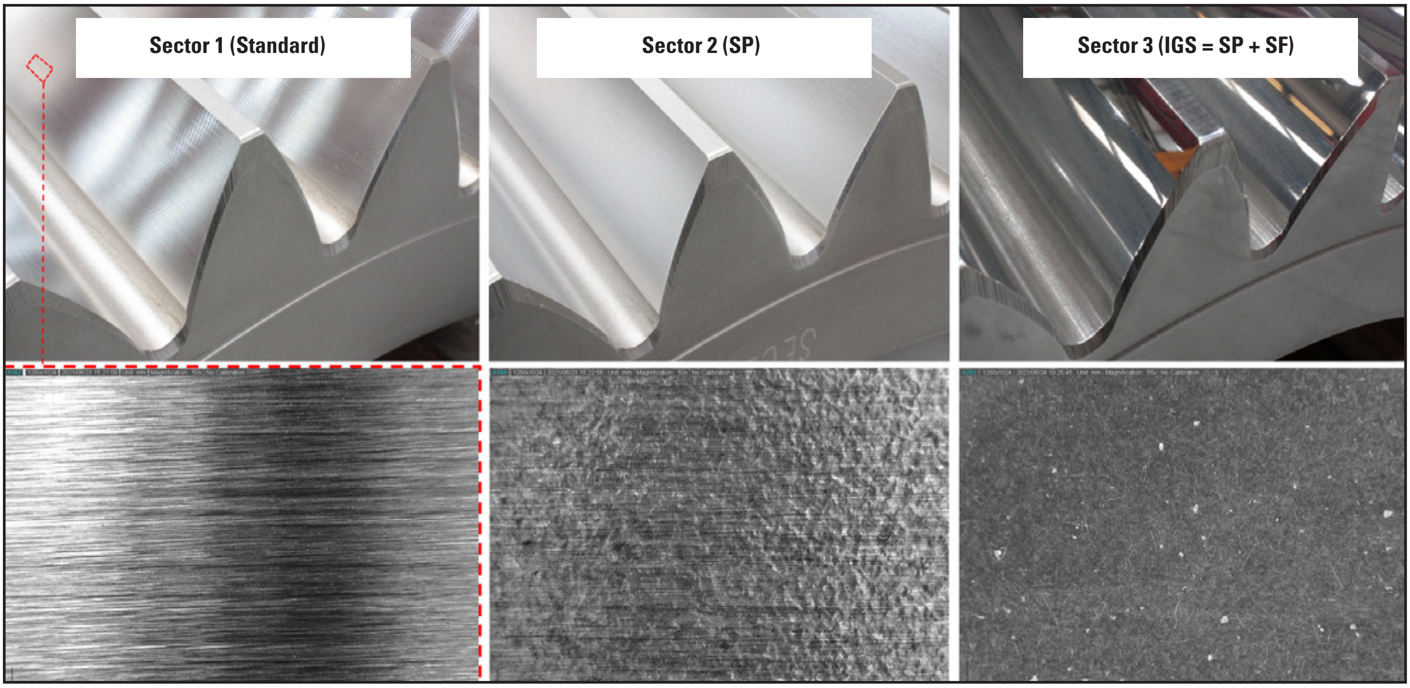

Figure 5 Microscope 50X flank surface images comparison, Sectors 1–3.

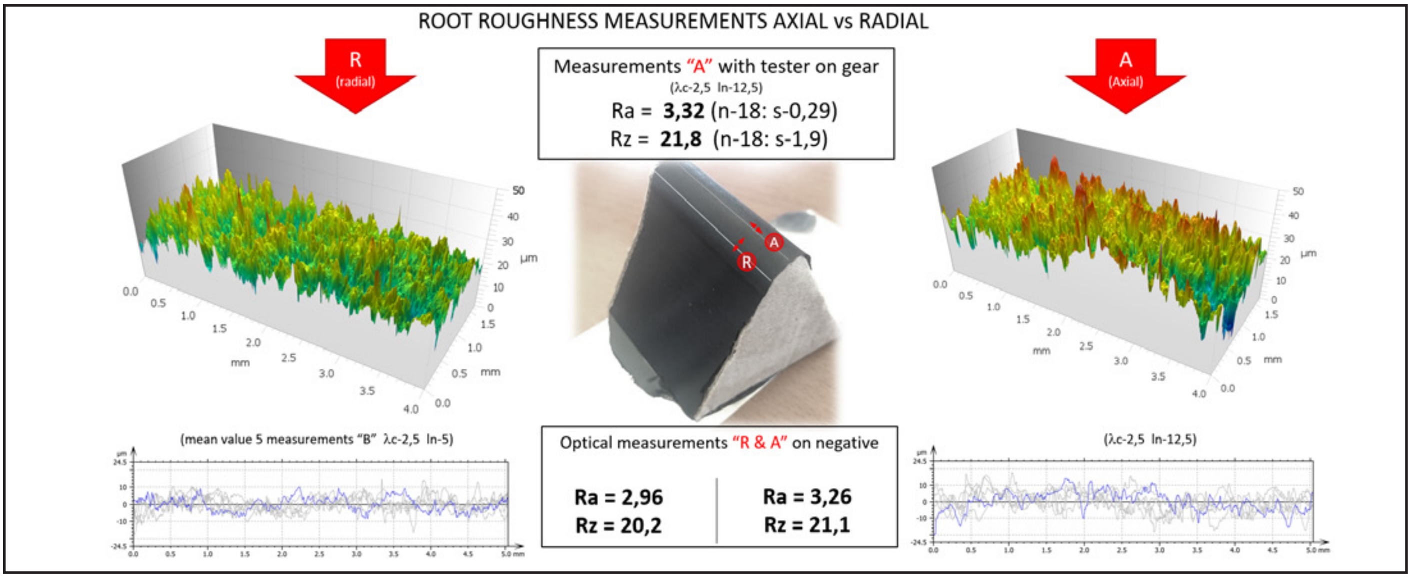

Figure 6 Gear replicas for optical roughness measurements.

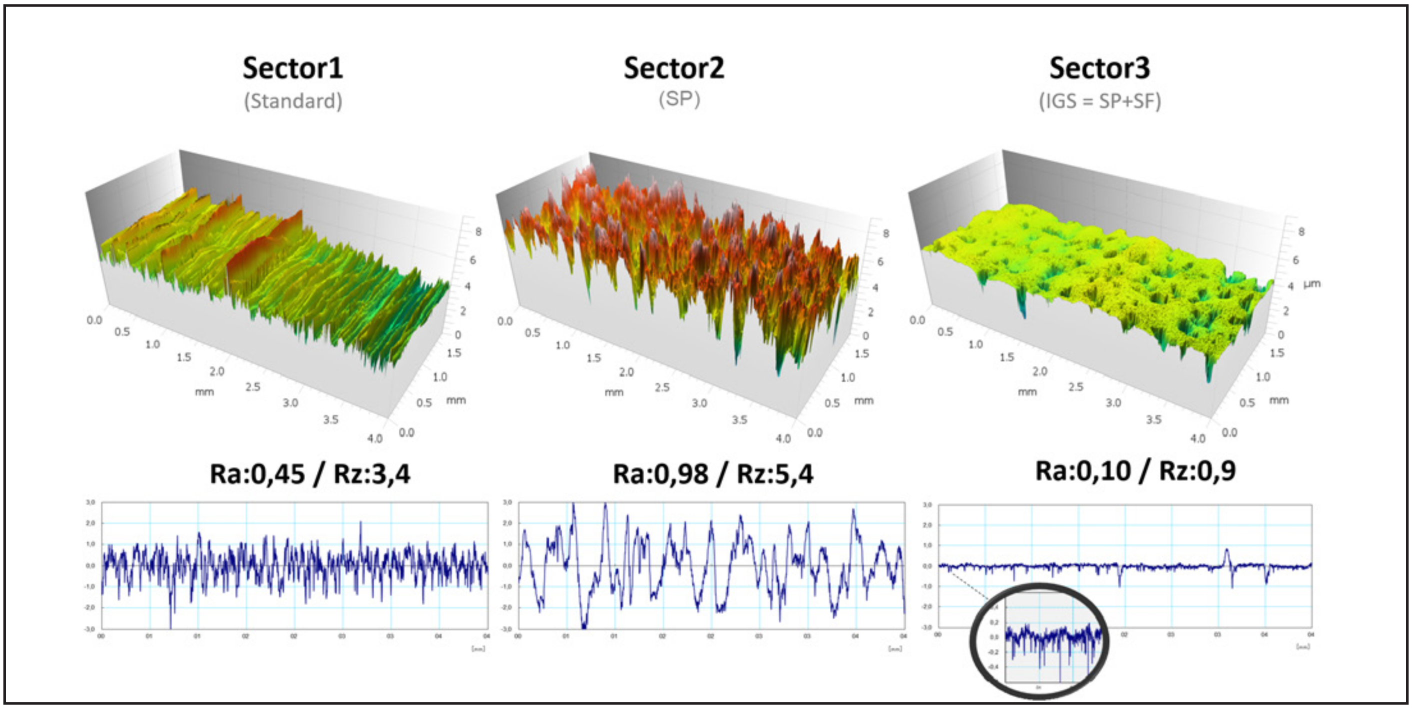

Figure 7 Gear flank roughness, Sectors 1–3.

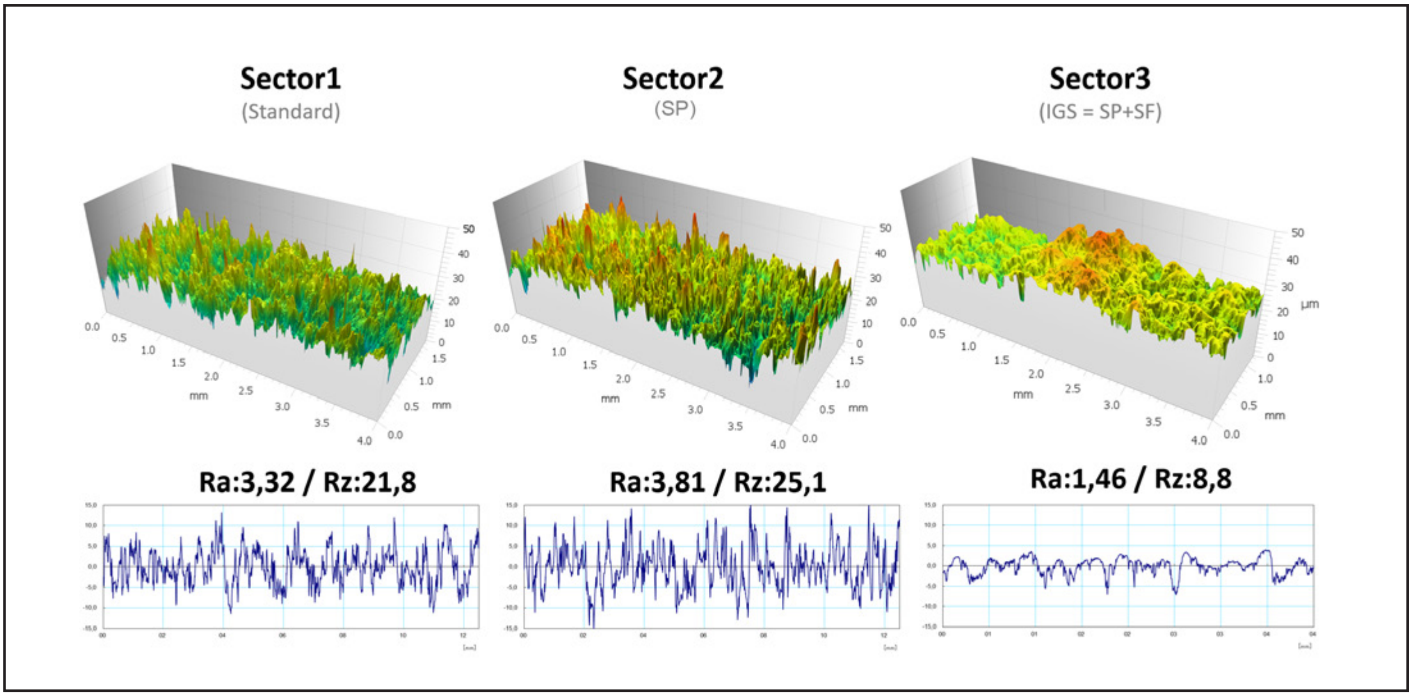

Figure 8 Gear root roughness, Sectors 1–3.

Mean results are summarized in Figure 9 and compared to part drawing specifications.

The Sector 1 flank is aligned with specification, while the root is rougher than the standard due to an intense shot blasting process.

Sector 2 is aligned with the SP expected flank influence, with an increase in Rz of 59% vs. Sector 1. Root roughness is almost not modified compared to Sector 1 due to the previously mentioned intense blasting.

Sector 3 superfinish corrects and improves the prior SP process, achieving Rz values at the flank surface less than 1 μm. SF reduces the peaks of this rough condition in Sector 3 root, but only in a limited way.

Residual stress measurements, retained austenite quantification and hardness measurements were also performed over the three sectors. The results are summarized in Figure 10.

Retained austenite evaluation was performed according to ASTM E 975-13 (Ref. 7). The X-ray energy-dispersive diffraction method was used, with a continuous spectrum of the tungsten anode, linked to elaborated software that rebuilt the theoretical diffraction patterns of any mixture. This technique allows 15 reflections of the ∝ phase (martensite) and 18 reflections of

Gear Root

	Rz	Ra
Sector1	21,8	3,32
Sector2	25,1	3,81
Sector3	8,8	1,46

Gear Flank

	Rz	Ra
Sector1	3,4	0,45
Sector2	5,4	0,98
Sector3	0,9	0,10

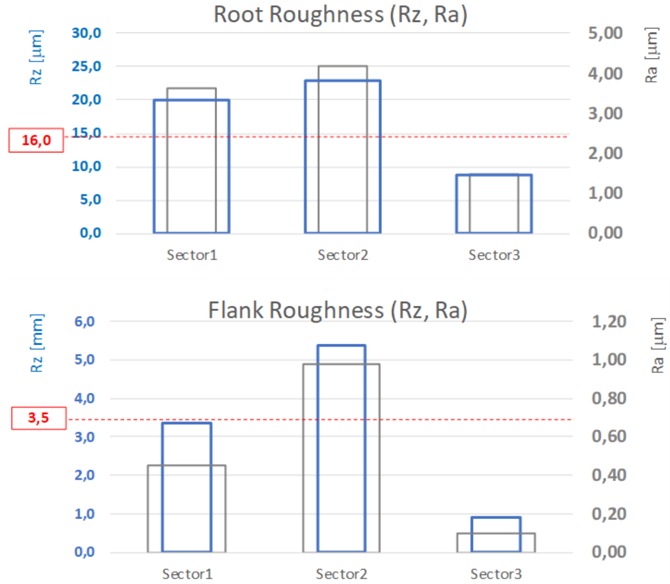

Figure 9 Roughness Ra and Rz results for Sectors.

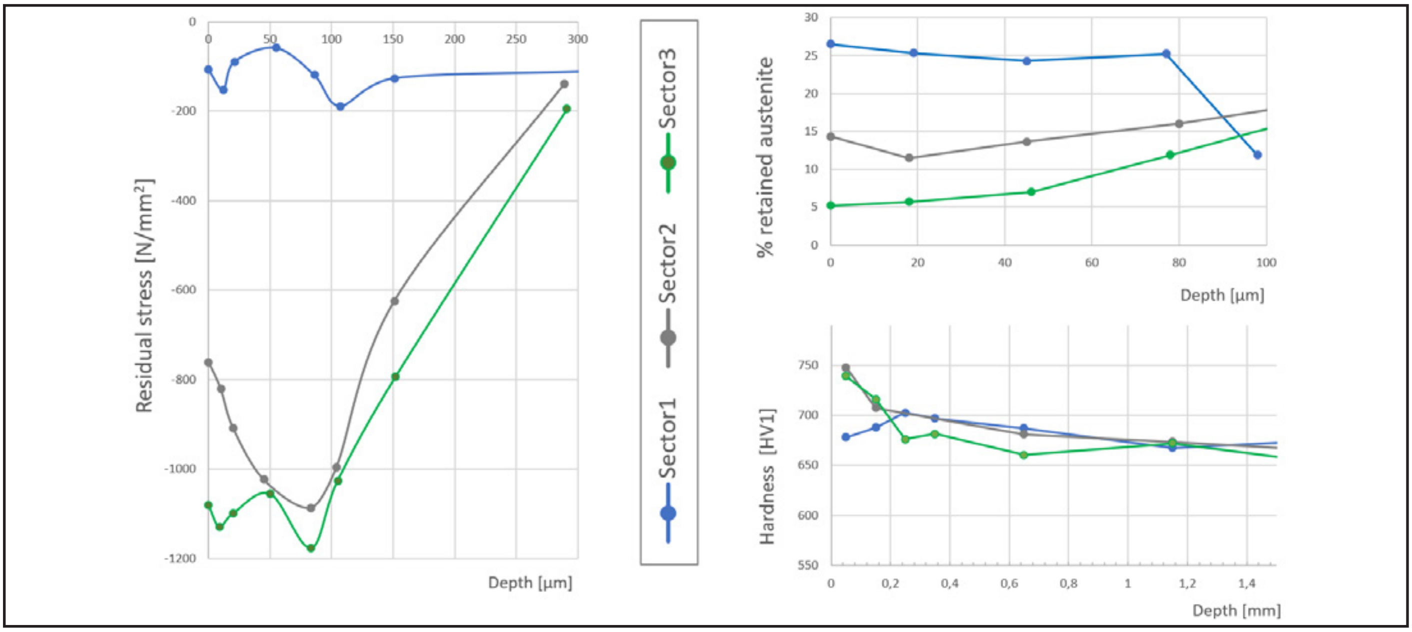

Figure 10 Residual stresses (axial direction), retained austenite and hardness [HV1] over gear sectors in the flank region.

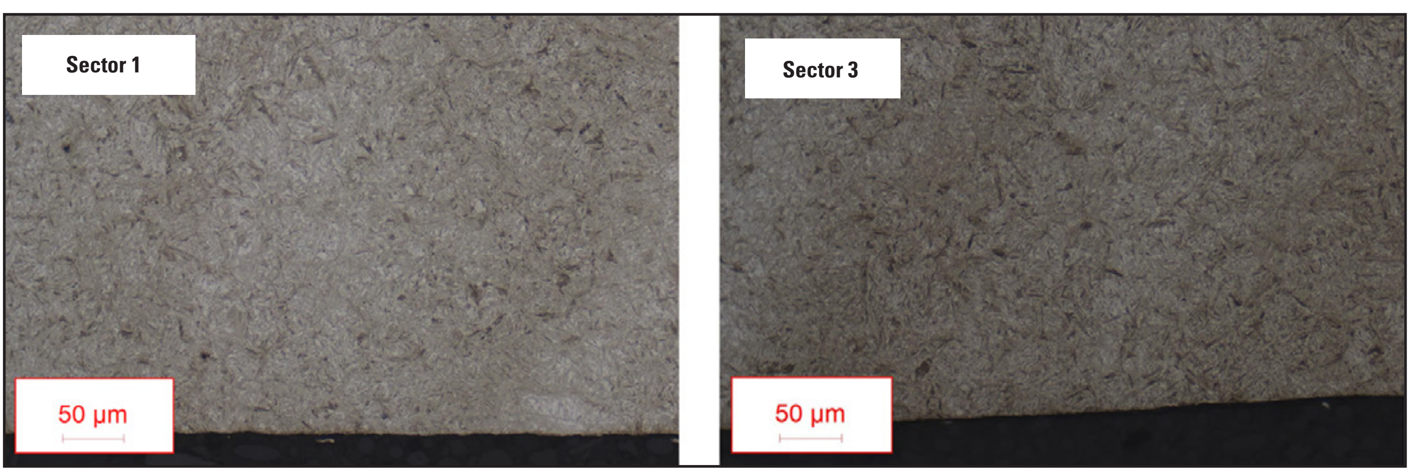

Figure 11 Micrograph comparison between Sector 1 and Sector 3 (same etching).

the γ phase (austenite) in the energetic field of 12 keV to 40 keV for an angular value fixed at θ=18.25°. Material removal was done by chemical attack.

Residual stress analysis was carried out by X-ray diffraction following the EN 15305 standard test method (Ref. 8). Metal removal was performed by electrochemical polishing, and the depth was controlled by a profilometer.

A hardness Vickers profile was carried out according to NF EN ISO 6507-1 (Ref. 9) on a cross-section of the tooth flank.

The results are aligned with expectations based on previously referred investigations.

The residual stress in Sector 1 is based on the heat treatment process and is affected by gear flank grinding and the high percentage of retained austenite in this part.

Sector 2 SP results are aligned with AGMA 938 (Ref. 2) and Stenico (Ref. 21) results for 18CrNiMo7-6 material, both in maximum value and penetration.

The Sector 3 results show an improvement in the maximum value and penetration depth compared with Sector 2 because of applying a double SP process with higher intensity and coverage in the first phase process, followed by a fine particle second process that increased the surface values.

Retained austenite is transformed into martensite due to SP in Sectors 2 and 3. The percentage of transformation is affected by SP intensity. A comparison of the micrographs of Sector 1 and Sector 3 (Fig. 11) clearly shows retained austenite transformation in Sector 3 near the surface due to SP.

Figure 12 shows bending and pitting fatigue safety margins of Sectors 1–3 compared to drawing specifications, calculated following ISO 6336 standard Method B (in blue).

An assessment of expected results is also done based on references ("Empirical" in Fig. 12).

According to ISO 6336, by applying IGS, an improvement of 1.14 and 1.11 in bending and pitting safety, respectively, should be expected compared to standard conditions (root fillet blasted, not ground; tooth flank ground).

Based on experimental investigations, additional improvement should be expected above 1.2 for pitting and bending fatigue.

Bending fatigue improvement has a potential scatter conditioned mainly on material cleanliness. Since wind power standards are quite exigent on this topic, a maximum value of 590 N/mm² for $\sigma_{F\ Lim}$ is considered feasible (Ref. 38). Additional bending improvement has been referred to using an optimized SP process, but the size effect and subsurface high cycle failures are recommended to be conservative. A closer approach to a real bending safety margin increase seems only possible following high cycle endurance tests on gears that are as close as possible to real size and cleanliness conditions.

Pitting improvement was calculated using Koenig et al. (Ref. 26) formulae to include the IGS effect.

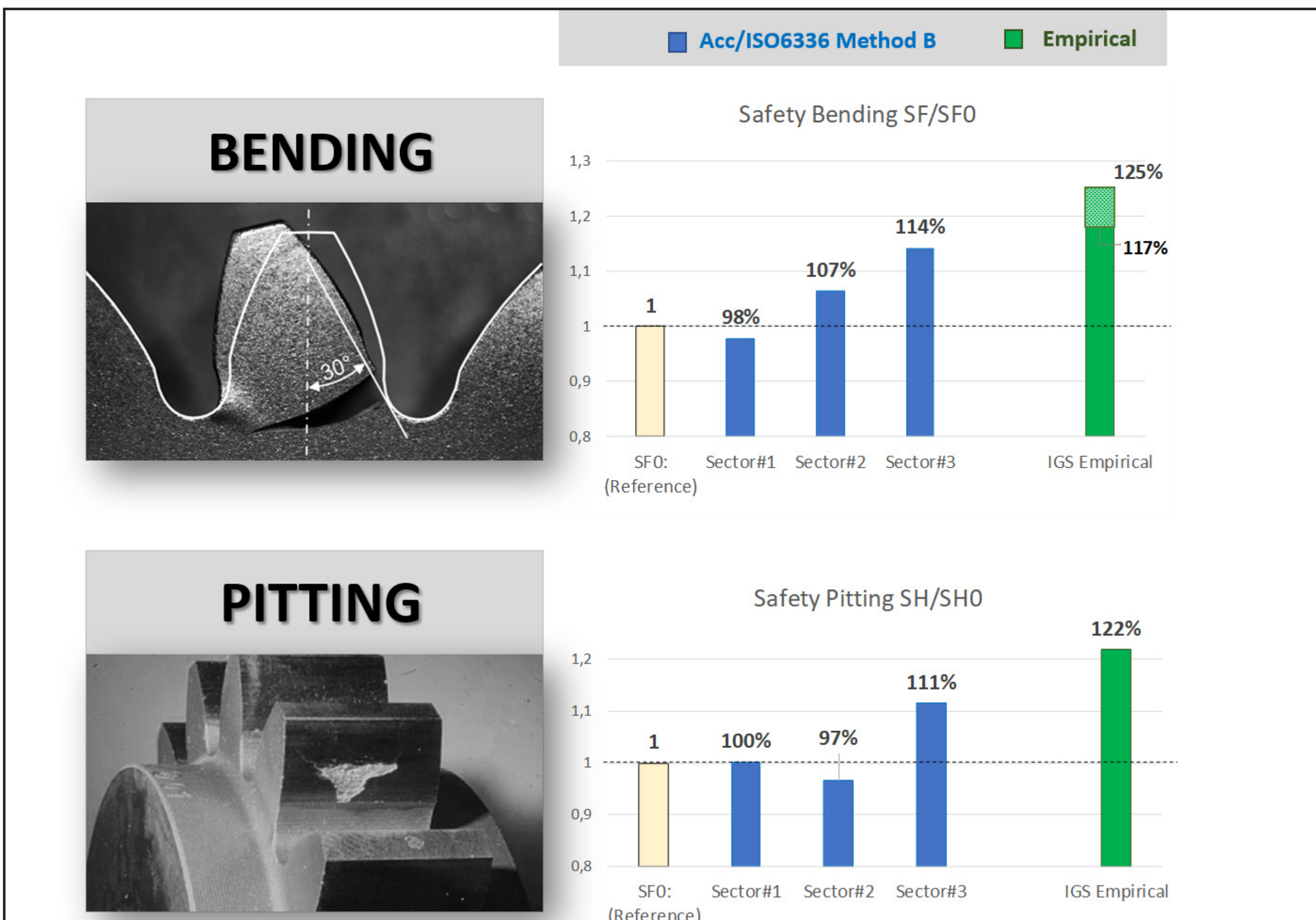

Figure 12 Bending and pitting fatigue safety margins compared to standard.

IGS benefits on micropitting, scuffing, wear and gearbox efficiency are not calculated here but should be considered as an additional benefit of this process.

Conclusions

The increased demand for wind power transmissions and mass reduction to improve LCOE leads to gear designs close to their load-carrying capacity limits. A good option to increase gear torque density is SP followed by SF.

To date, the calculation methods according to ISO 6336 Method B (Ref. 2) are based on investigations with conventionally ground gears and are mainly based on mn=5 mm studies. Gears with increased compressive residual stresses via SP and shallow surface roughness due to SF are not yet considered, or adequately considered, in the standard.

A case study for a wind gearbox planet wheel m_n=20.5 mm is analyzed. The measured results are aligned with other experimental studies, and based on those references, potential increases of safety margins above 1.2 both for pitting and bending strength have been assessed.

The bending strength numbers of ISO 6336 are conservative but valid due to subsurface high cycle fatigue failures and should only be increased if experimental investigations preclude such subsurface failures.

High cycle fatigue testing of gear samples that are as close as possible to wind gear parts, following Method B (Ref. 1), would be needed to confirm and certify such predictions.

Other IGS benefits, such as micropitting, scuffing and wear risk reduction, and gearbox efficiency, should also be considered and confirmed by testing on gear parts as close as possible to wind gear modules.

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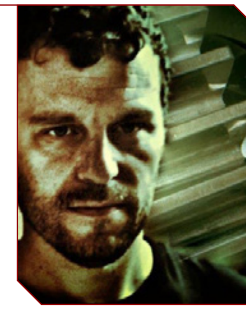

Ing. Ruben Carranza Fernandez is developer and head of wind gearbox refurbishment business at Gamesa. He has worked in the quality, manufacturing and engineering departments of the gearbox unit over the last 20 years. Since 2008 he has also been manager of the Siemens Gamesa wind gearbox repair center in Spain.

Dr.-Ing. Thomas Tobie is head of the department “Load Carrying Capacity of Cylindrical Gears” at the Gear Research Center (FZG), Technical University of Munich. He is specialized in the fields of gear materials, heat treatment, gear lubricants, gear strength and gear testing with focus on all relevant gear failure modes like tooth root fracture, pitting, micro-pitting, scuffing and wear as well as subsurface initiated fatigue failures. Dr. Tobie is an active member of several national and international working groups of DIN, ISO, IEC and CEC and author of numerous papers in scientific journals and at conferences.