

VIII. Enabling High-Performance PM Gears Through Advance Finishing – Felipe de Sá, M.Sc. (ITA) / Daniel Hinzmann, Dipl.-Ing. (IWF)

Powder metallurgy (PM) gears are often considered suitable only for low-demand applications, largely due to concerns about surface integrity and inherent porosity. This presentation challenges this perception by proposing a framework in which advanced finishing strategies can elevate PM gears to high-performance applications. The approach begins with the premise that surface integrity is not only a barrier, but also an opportunity. If properly understood, it can be engineered to meet demanding functional requirements. Through a combination of experimental surface characterization and simulation of porous materials, the finishing chain is repositioned as a critical enabler rather than a corrective stage. This includes predictive modeling that accounts for the specific mechanical behavior of PM microstructures during surface processing. Non-traditional finishing processes such as abrasive brushing and water-jet peening are highlighted for their potential to selectively improve surface properties without compromising the beneficial core porosity. This work presents PM as a technology for innovation, rather than a constraint, where tailored finishing strategies enable competitive performance levels. The presentation outlines how integrated process knowledge and surface engineering can bridge the gap between the inherent properties of PM and the demands of modern gear applications.

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The Brazilian Gear Conference ITA-WZL 2025

Enabling High-Performance PM Gears Through Advanced Finishing

Felipe de Sá Carneiro, M.Sc. (ITA)

Daniel Hinzmann, Dipl. -Ing. (TU Berlin)

São José dos Campos, August 13th & 14th, 2025

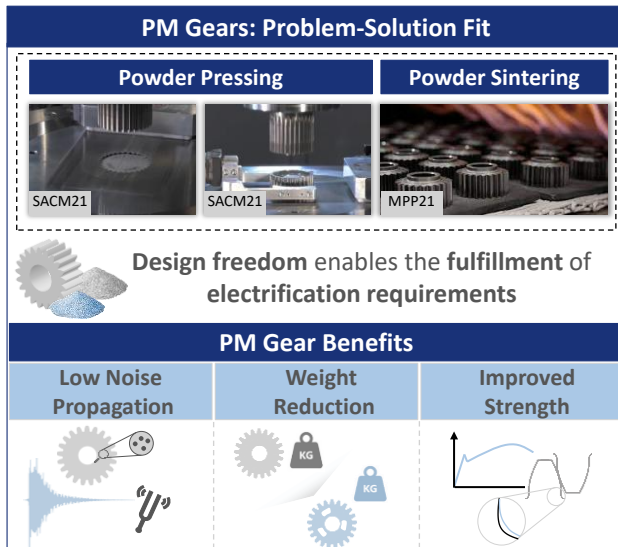
Agenda

1. PM Application Challenges
2. The Surface Densification Analysis
3. Non-Conventional Finishing Processes
4. Summary and Outlook

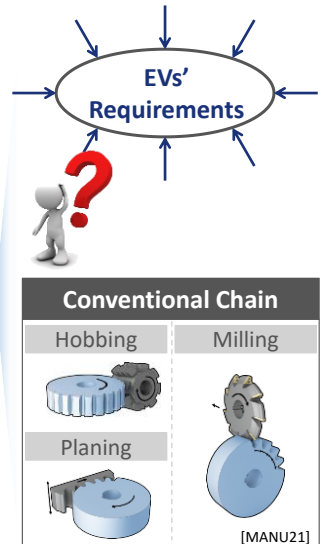


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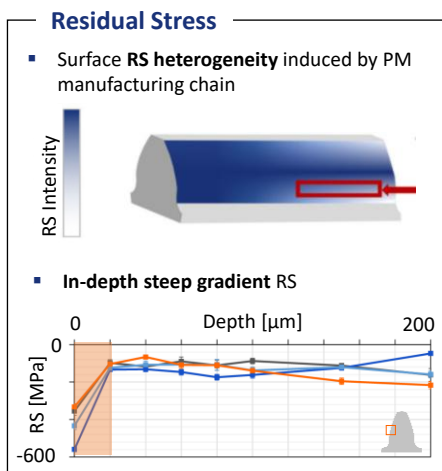
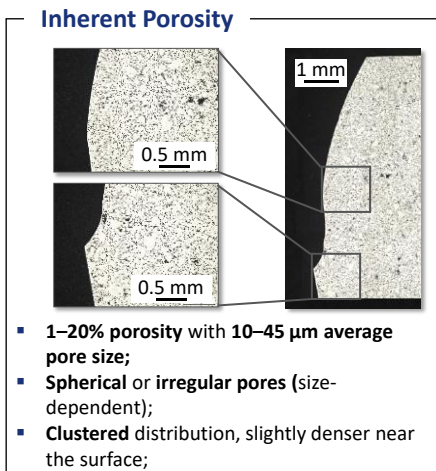


Source: [KLOC15, FREC18]



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The Powder Metallurgy Gear: Surface Integrity State



[Rego, 2016; Robatto, 2017]



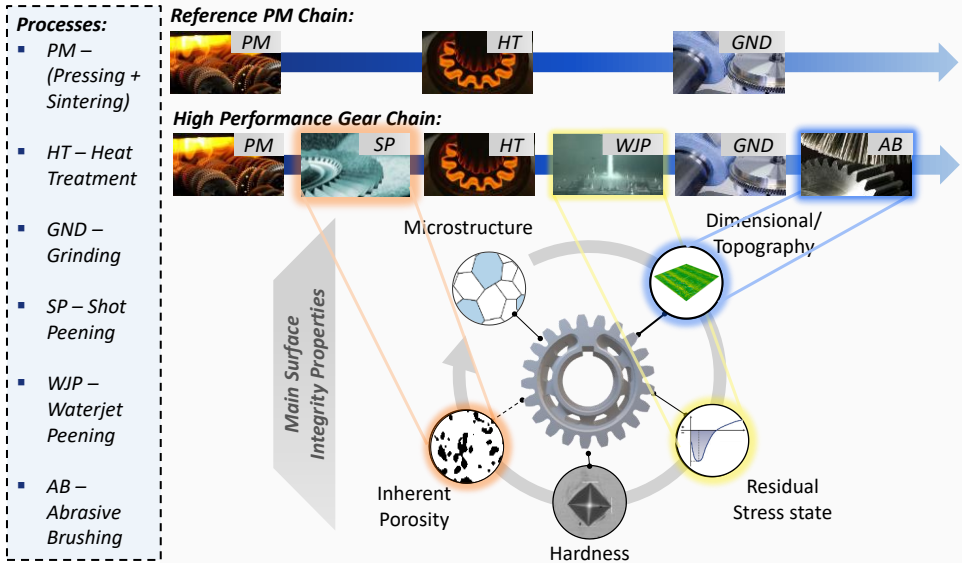
Motivation

Finishing route for PM Gears considering the porosity effect on the surface integrity.



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Proposed High Performance Chain



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Agenda

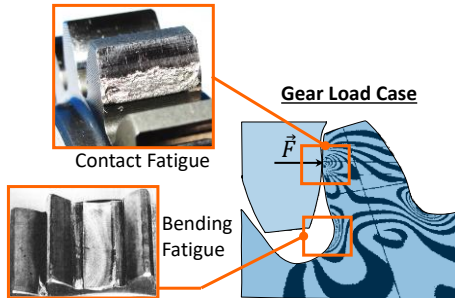
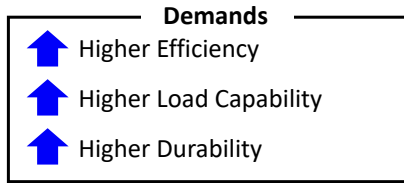
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Selective Densification

Shot Peening

- Well-focused densification jet through the nozzle
- Densification **flexibility** in different geometries
- Densified layer of up to **877 µm**

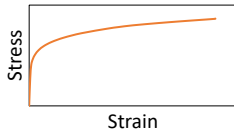
Source: Höganäs AB, Donzella et al. (2011); Rodziňák et al. (2012); Klocke et al. (2013); Criscuolo (2024)



Simulation as a Manufacturing Tool: *Densification Model*



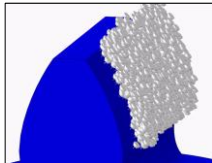
Step 1: Porous Material Modeling



Extracting elastic & plastic **homogenized properties**

$$f(\underbrace{A, B, C, m, n, E, v}_{\text{Bulk Material Properties}}, \underbrace{\rho}_{\text{Porosity Attributes}}, \underbrace{D_{eq.}}_{\text{Homogenized Properties}}) = (\underbrace{A_h, B_h, C_h, m_h, n_h, E_h, v_h}_{\text{Homogenized Properties}})$$

Step 2: Densification Process Modeling



Applying porous material properties to previously developed Shot Peening model by Guimarães (2021)

Step 3: Densification Criterion Definition

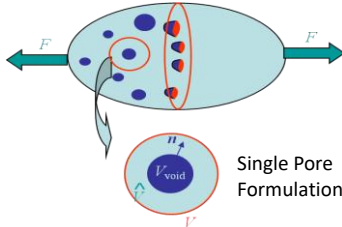


Addressing relative density (RD) numerically through a plastic strain associated criterion





Gurson Model (1985)



$$f(\sigma) = \left(\frac{\sigma_e}{\sigma_y} \right) + 2f_v \cosh \left(\frac{\text{tr}(\sigma)}{2\sigma_y} \right) - (f_v^2) - 1 \leq 0$$

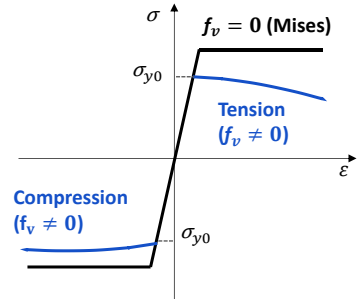
Yield Stress Criterion

Where:

- σ_e is the Mises criterion
- σ_y is the yield criterion for fully dense material
- f_v is the void fraction (porosity).

Uniaxial Behavior of Porous Material

For a perfectly plastic matrix material



Model Assumptions

- Isotropic hardening effects
- Reasonable physical results for low porosity ($f_v < 10\%$)

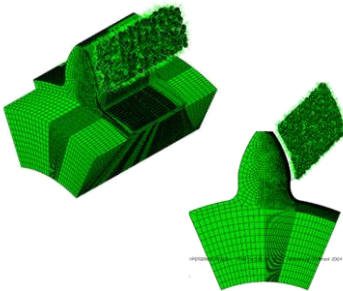


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Simulation as a Manufacturing Tool: Gear Densification Analysis



Shot Peening FEM Setup



Densification Criterion

Empirical statement for pore growth, R/R_0 (McClintock, 1968):

$$\ln \left(\frac{R}{R_0} \right) \approx \epsilon_{eq}$$

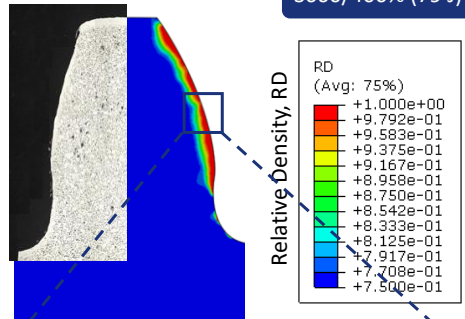
Final nodal density (Carneiro, 2024):

$$\rho_f = 1 - (1 - \rho_0)e^{-3\epsilon_{eq}^{pl}}$$

Peening Condition:

(Media/Coverage)

S660/400% (79 J)



Relative Density (%) per Depth along Flank



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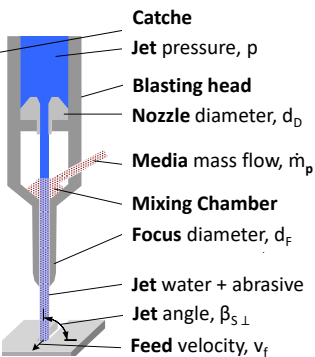
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Waterjet Peening: *Potential of Properties Improvement*



Adaptation of

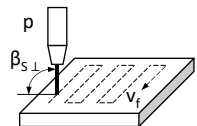
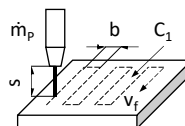
- Residual Stress Profile
- Surface Quality



Residual Stress Adaptation

Shot Peening

- High residual stress close to the surface contributes to
 - Enhanced fatigue strength
 - Improved bending fatigue performance
 - Increased wear resistance
 - Suppression of microcrack propagation
 - Potential for performance enhancement without material substitution
- Influence on resulting residual stress based on interaction of relevant process parameters



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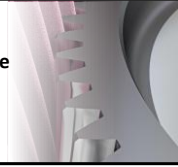
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Adaptation of

- Residual Stress Profile
- Surface Quality



Use case:
Dental implant



Hardened gear
Module 1.5 mm

Residual Stress Adaptation

Shot Peening

- The use of liquid carrier media for shot acceleration enables
 - targeted shot peening of extremely small radii
 - uniformly strengthened surfaces by following parallel processing paths during treatment
 - adaptation of residual stress depth profiles that are unattainable using conventional processing methods
- Applicable in high-performance sectors such as **medical technology, aerospace** and the **automotive industry**.

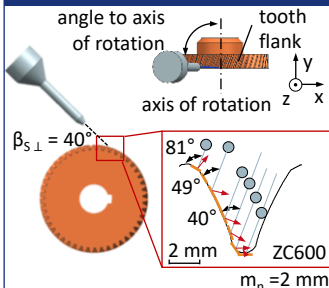


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Waterjet Peening: Residual Stress Improvement



Process Details



■ **Process:**
High velocity
WJP

■ **Material:**
16MnCr5

■ **Tool:**
ZC 600

■ **Process Parameters:**
C = 1 x 98 %
P₁ = 500 bar
P₂ = 1.00 bar
s = 40 mm
d₀ = 0,33 mm
d_f = 1,1 mm
m_p = 150 g/min

Adaptable Property Parameters via High Velocity WJP

Target Values

hardening σ	MPa	> 1.100
depth z	μm	> 80
roughness Rz	μm	< 32

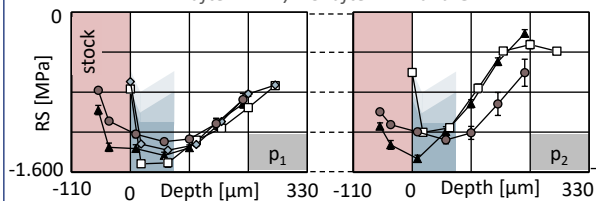


4 mm

Experimental Setup: WJP for Residual Stress Adaptation

- ▲ H gear module $m_n = 2 \text{ mm}$ - $\beta_{s\perp} = 40^\circ$
- HS gear module $m_n = 2 \text{ mm}$ - $\beta_{s\perp} = 40^\circ$, Meas. Pos. 0°
- ◆ HS gear module $m_n = 2 \text{ mm}$ - $\beta_{s\perp} = 40^\circ$, Meas. Pos. 180°
- H reference - analogy component ($\beta_{s\perp} = 60^\circ$)

H: after WJP / HS: after WJP and GND

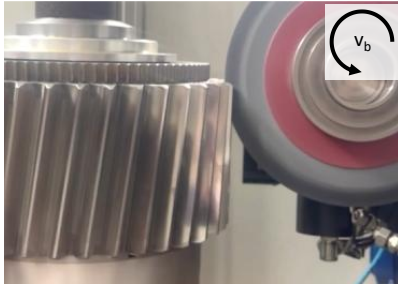


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Adaptation of

- Micro Topography
- Surface Texture



Micro Topography Adaptation

Abrasive Brushing

- Micro topography can be improved regarding peaks of the surface roughness
- Efficient process development based on bi-directional tool path
- Rounding of both front edges due to entry of the brushing tool into the tooth gaps on both sides
- Extended service life and improved performance behavior of machined gear



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Abrasive Brushing: *Topography Improvement*



Process Details



Process

Parameter:

$a_{eb} = 5 \text{ mm}$

$v_b = 20 \text{ m/s}$

□ $v_{f,1} = 800 \text{ mm/min}$

■ $v_{f,2} = 200 \text{ mm/min}$

* Dry Machining

Gear

Geometry:

$z = 39$

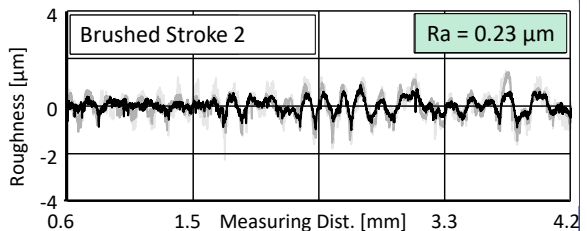
$m_n = 10 \text{ mm}$

$b = 200 \text{ mm}$

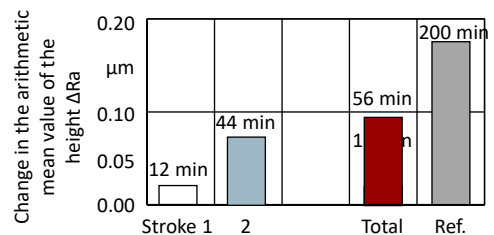
$\alpha = 20^\circ$

$\beta = 7.5^\circ$

Adaptation of Surface Roughness Peaks



Comparison of Abrasive Brushing and Conventional Grinding



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Summary and Outlooks

Summary

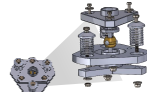
- Tailored finishing chains may enable high-performance PM gears (**Design for PM**)
- Emerging processes like **Waterjet Peening** and **Abrasive Brushing** could help overcome surface integrity challenges
- Simulation tools might support the identification of optimal finishing strategies

Outlooks

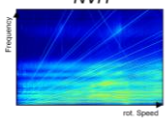
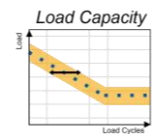
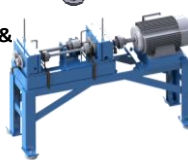
- Development of non-conventional finishing chains for powder metallurgy gears
- Fatigue testing and validation of high-performance hypotheses



Tribology



Fatigue &
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