The Brazilian Gear Conference ITA-WZL

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BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

XI. Application of the Crack Growth Concept for Calculating the Lifetime of Gear Tooth Root –

Laurenz Roth, M.Sc. (WZL)

Aviation gear units are used to increase the efficiency of aircraft engines. By decoupling the fan and engine stages, the fan diameter can be enlarged and the bypass ratio increased. Aircraft gearboxes quickly reach very high load cycles during their operating life. The predominant damage mechanism is tooth root fracture of the planetary gear under alternating load. To increase power density, steels with high material cleanliness and optimized surfaces by shot peening and superfinishing are used in the aerospace sector. In the literature, sub-sur-face induced fractures occur in shot peened gears in the range of high load cycles, while non-peened gears have their crack origin from the surface. This phenomenon cannot be explained by standard-based calculation approaches of the tooth root load capacity. In the field of fracture mechanics, however, this can be demonstrated for standard specimens with the aid of crack growth tests (compact tension tests) using fracture mechanics equations that derive the lifetime from the crack growth rate. In this report, the applicability of the NASGRO crack growth equation to tooth root fracture was examined. To the end, the gear-specific material properties such as a pronounced hardening depth profile, a residual stress depth profile and the defect size of the material as well as the gear-specific tooth root stress over the rolling contact were taken into account. Subsequently, the crack initiation depths and lifetimes were calculated according to NASGRO for an non-peened case-hardened type C test gear made of different steel purities of 20MnCr5 and compared with test results.

Application of the crack growth concept for calculating the lifetime of gear tooth root

Speaker: Laurenz Roth M.Sc.
Author: Johannes Lövenich M.Sc.

WZL of RWTH Aachen
Prof. Dr.-Ing. Christian Brecher
Prof. Dr.-Ing. Thomas Bergs
Dr.-Ing. Jens Brimmers

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CLEAN AVIATION
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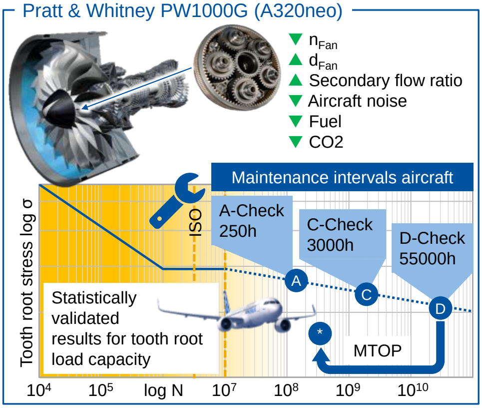
The Brazilian Gear Conference ITA-WZL 2023, October 18th / 19th 2023

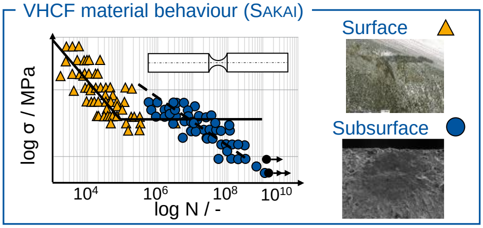
Agenda

Introduction
Problem and motivation

Pratt & Whitney PW1000G (A320neo)



VHCF material behaviour (SAKAI)

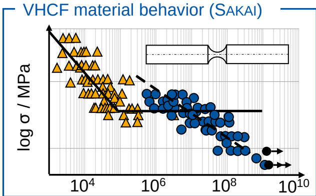


Service lifetime consideration more sensible than fatigue strength level?

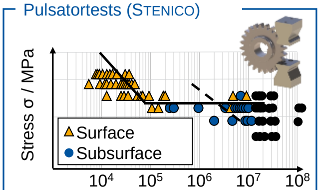
- ▼ ISO 6336: Lifetime factor Y_{NT} at $N = 10^{10}$ of 0.85
- ▲ Weight savings through more accurate calculation
- ▲ Better understanding of damage development

Introduction
Problem and motivation

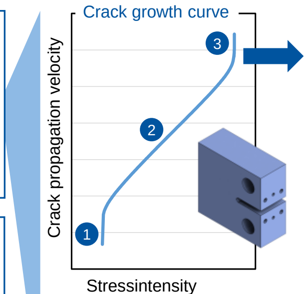
VHCF material behavior (SAKAI)



Pulsatortests (STENICO)



Crack growth curve



Crack growth phases
1. Microcrack
2. Macrocrack
3. Overload break

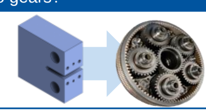
NASGRO equation:

$$\frac{da}{aN} = C \cdot \left[\left(\frac{1-f}{1-R}\right) \cdot \Delta K_I\right]^m \cdot \frac{\left(1-\frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\left(1-\frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

NASGRO equation Lifetime:

$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1-\frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1-\frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

Can the Nasgro equation be applied to gears?



Agenda

1	Introduction
2	**Objective and approach**
3	Transfer of the crack growth equation to gears
4	Application of the crack growth laws to a type C gear
5	Summary and Outlook

Objective
Problem, objective and approach

Problem

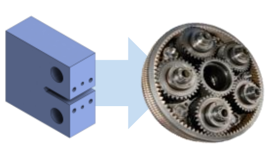
- Sub-surface induced fractures difficult to represent by standard-based approaches
- ISO 6336 calculates fatigue strength level but no lifetime

Objective

Application of the crack growth concept for calculating the lifetime of gear tooth root

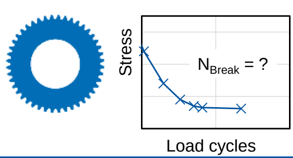
Objective 1

Transfer of crack growth laws to gears



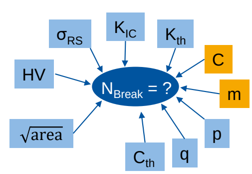
Objective 2

Development of a tooth root lifetime model based on crack growth rate for a type C test gear



Objective 3

Analysis of the influencing factors and evaluation of the lifetime model



Agenda

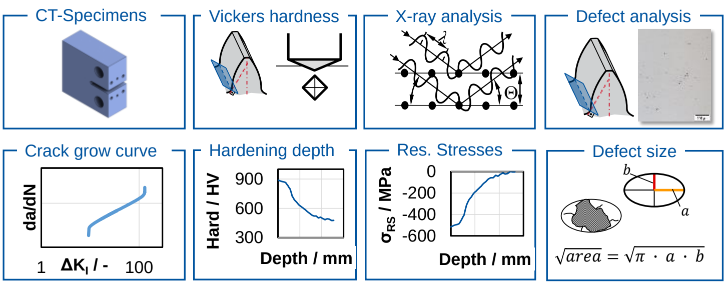
Transfer of the crack growth equation to gears

Material characterization

1. Material characterization
2. Simulation of the stress depth curve
3. Determination of the crack initiation depth
4. Calculation of the lifetime

$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1 - \frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1 - \frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

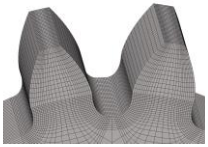
$C, m, K_{IC}, p, q, \alpha, C_{th}$	$K_{th}, \Delta K_I$



Transfer of the crack growth equation to gears
Calculation of tooth root stress in depth

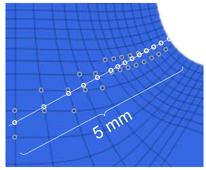
1. Material characterization
2. **Simulation of the stress depth curve**
3. Determination of the crack initiation depth
4. Calculation of the lifetime

Meshing



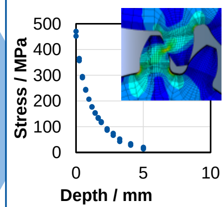
- Local fine meshing in the foot area at depth with STIRAK

Evaluation stress



- Degrees normal to the surface at the level of the 30º tangent

FEM stress curve over depth



Stress intensity ΔK_I

$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1 - \frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1 - \frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

Transfer of the crack growth equation to gears
Structure of the lifetime calculation and the NASGRO equation

1. Material characterization
2. Simulation of the stress depth curve
3. **Determination of the crack initiation depth**
4. Calculation of the lifetime

$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1 - \frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1 - \frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

Threshold ΔK_{th}

At $\Delta K_I > \Delta K_{th}$ crack growth starts

$$\Delta K_{th} = 2{,}77 \cdot 10^{-3} \cdot (HV + 120) \cdot (\sqrt{area})^{\frac{1}{3}}$$

Stress intensity ΔK_I and $\Delta K_{I,\,max}$

$$\Delta K_{stat} = 0{,}5 \cdot \Delta\sigma_{loc} \cdot \sqrt{\pi \cdot \sqrt{area}}$$

$$\Delta K_{growth} = Y \cdot \Delta\sigma_{max} \cdot \sqrt{\pi \cdot a}$$

Transfer of the crack growth equation to gears
Structure of the lifetime calculation and the NASGRO equation

1. Material characterization
2. Simulation of the stress depth curve
3. Determination of the crack initiation depth
4. Calculation of the lifetime

Crack opening fucnction f
- Crack opening effects

$f = A_0 + A_1 \cdot R$

$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1 - \frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1 - \frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

Crack length a
- Initial crack length a_0 Grain size
- Fracture crack length a is determined from fracture surface analyses

Threshold ΔK_{th}

At $\Delta K_I > \Delta K_{th}$ crack growth starts

$\Delta K_{th} = 2.77 \cdot 10^{-3} \cdot (HV + 120) \cdot (\sqrt{area})^{\frac{1}{3}}$

Stress intensity ΔK_I and $\Delta K_{I,\,max}$

$\Delta K_{stat} = 0.5 \cdot \Delta\sigma_{loc} \cdot \sqrt{\pi \cdot \sqrt{area}}$

$\Delta K_{growth} = Y \cdot \Delta\sigma_{max} \cdot \sqrt{\pi \cdot a}$

Fracture Resistance K_{IC}
- Stress intensity at which the overload fracture occurs
- Determination by tests on CT-specimens

Agenda

1	Introduction
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3	Transfer of the crack growth equation to gears
4	**Application of the crack growth laws to a type C gear**
5	Summary and Outlook

Application of the crack growth laws to a type C gear
Calculation of the crack initiation depth

Macro geometry

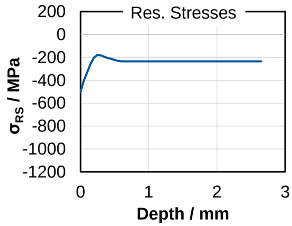
m_n	=	4.5 mm
z_1/z_2	=	16 / 24
x_1	=	0.1817
x_2	=	0.1715
b	=	14 mm
β	=	0°

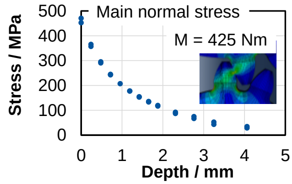
Material data AISI 9310
14NiCrMo13-4

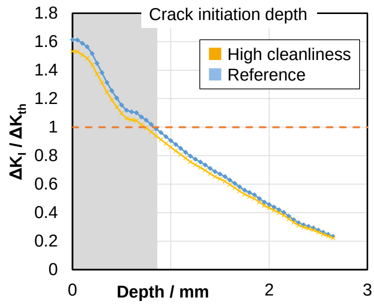
C	=	2.28E-12
m	=	2.945
p/q	=	0.25
C_{th+}	=	1.5
α	=	2.5
σ_{max}/σ_F	=	0.3

Maximal defect size

$\sqrt{area}_{Ref}$	=	89.2 µm
$\sqrt{area}_{clean}$	=	65.2 µm







Conclusion

Fractures start at the surface because there $\frac{\Delta K_I}{\Delta K_{th}}$ is maximal

Application of the crack growth laws to a type C gear
Calculation of the lifetime

Macro geometry

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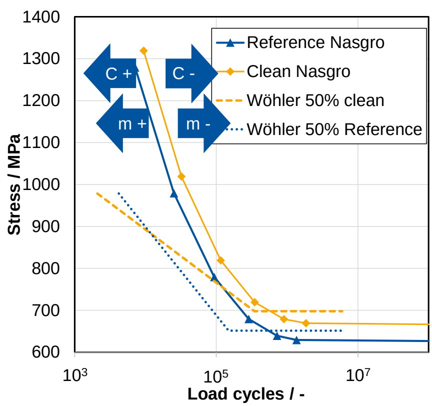


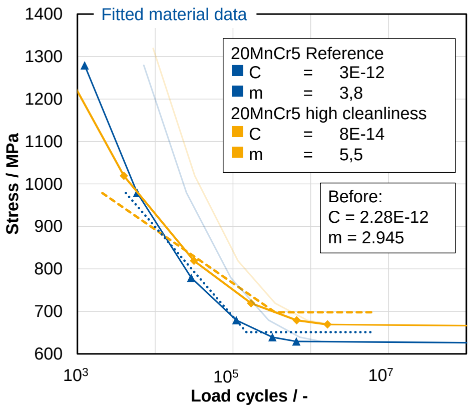
Assumption

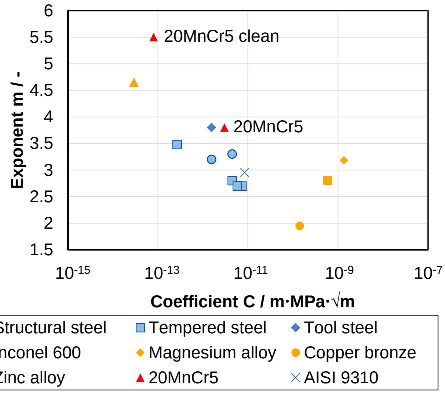
- Material parameters C, m, p, q are taken from case-hardened steel AISI 9310, since no data are available for 20MnCr5

Conclusion

- Fatigue strength levels and difference in purity can be mapped
- Fatigue strength is above the test results
- Adjustment of material data C and m

Application of the crack growth laws to a type C gear
Calculation of the service lifetime - fitting of the material parameters





Agenda

1	Introduction
2	Objective and approach
3	Transfer of the crack growth equation to gears
4	Application of the crack growth laws to a type C gear
5	**Summary and Outlook**

Conclusion
Summary and Outlook

Summary

- Consideration of lifetime in the VHCF range more meaningful than fatigue strength?
- Transfer of the Nasgro equation to gears with gear-specific properties
- Lifetime is covered after fitting the material parameters

Outlook

- Consideration of sub-surface induced fractures
- Experimental validation of the material parameters
- Validation at the WZL VHCF back-to-back test rig in the MatCH4Turbo project

BGC 23

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Aeronautics Institute of Technology,
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RWTH Aachen University (Germany),
Laboratory for Machine Tools and
Production Engineering

IV. Design for Residual Stress: An Artificial Intelligence Approach (DRS:AI)

– *Carla Cunha, M.Sc. (ITA) / André Oliveira, Dr. (Eigendauer)*

Residual stresses are defined as the product of internal deformations that remain in a material even without external loads. As they add to the external forces acting, they can be decisive in the performance of mechanical components. Despite residual stresses' benefits still not being captured by design standards, its normalization is a trend for manufacturing in the coming years. In that regard, Industrial 4.0 concepts such as Artificial Intelligence are the key to making in-situ measurement and control of residual stress states possible and agile. Previous works present the concept of "Design for Residual Stress" (DRS), which demonstrates that the parametrization used in one process largely influences the residual stress state of its subsequent process or step. In this sense, this work presents a methodology for developing intelligent systems supported by the DRS concept to investigate residual stress. The use of Artificial Intelligence (AI) techniques is outstanding against analytical methods, once it can provide agility and solutions capable of extrapolation beyond tight operational envelopes. During the AI development, though, the analytical methods could be extremely helpful by playing a benchmark role to avoid spurious correlations. The development stages of the aforesaid model are presented. The main requirements and challenges regarding the process of creating an artificial intelligence model are highlighted. Lastly, an artificial intelligence approach based on both DRS concept is proposed for online measurement and control of residual stress state.

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THE BRAZILIAN GEAR CONFERENCE
ITA-WZL

CENTRO DE COMPETÊNCIA EM MANUFATURA

The Brazilian Gear Conference ITA-WZL 2023

Design for Residual Stress: An Artificial Intelligence Approach (DRS:AI)

Carla Cunha, M.Sc. *(ITA)*

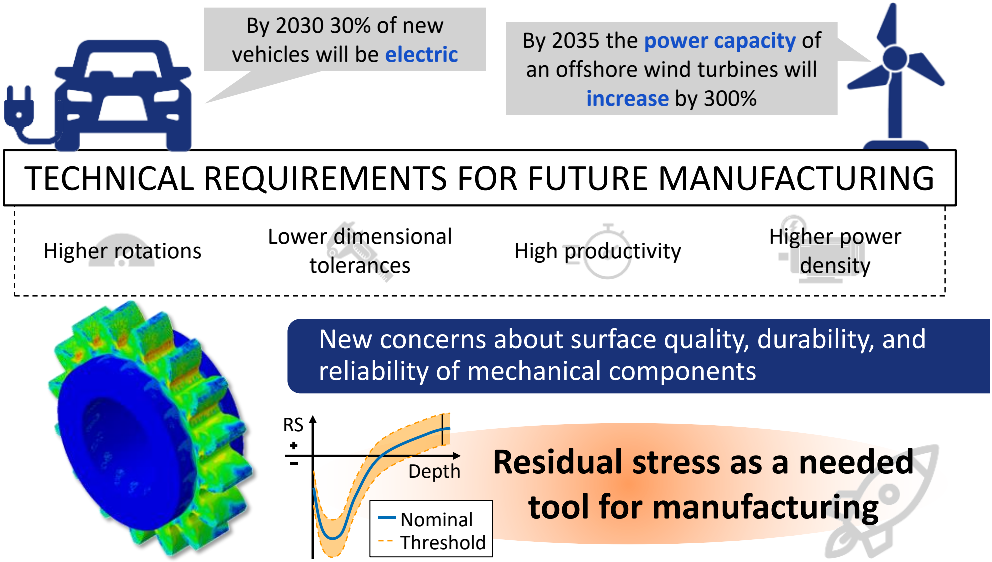
André Oliveira, Dr. *(Eigendauer)*

São José dos Campos, October 18th & 19th, 2023

Agenda

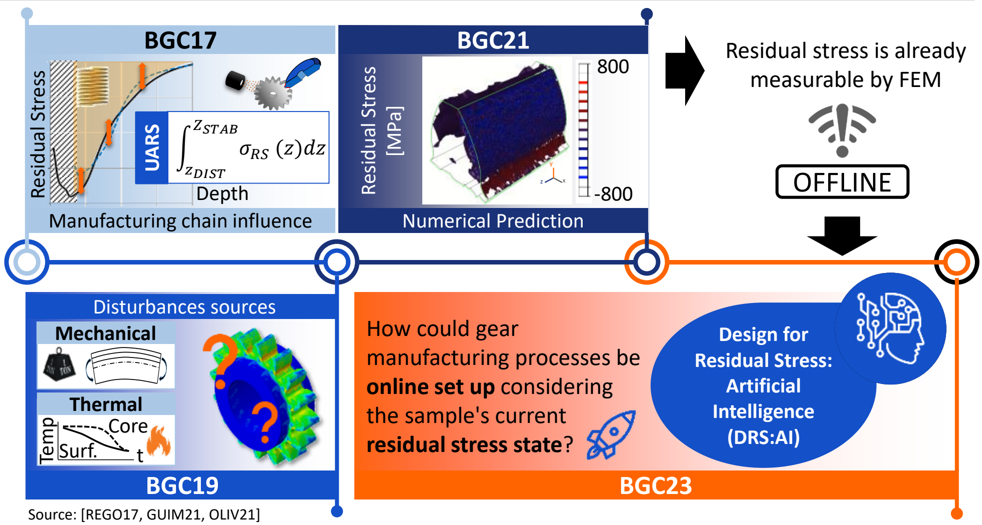
1. Residual Stress in Future Manufacturing
2. Artificial Intelligence as a Tool for Manufacturing
3. Design for Residual Stress: An Artificial Intelligence Application
4. Summary and Outlook

Residual Stress in Future Manufacturing



Design for Residual Stress: *The Evolution of Manufacturing Control*

DRS: Gear design and production chain can be defined with stating Residual Stress as a target



Source: [REGO17, GUIM21, OLIV21]

Residual Stress in-situ Measurement and Control

Measurement?

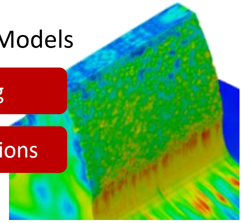
X-Ray Diffraction

- Position-dependent
- Time-consuming
- Destructive testing

Control?

Finite Element Models

- Time-consuming
- Limited applications

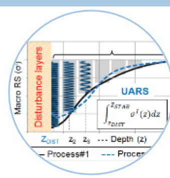


Artificial Intelligence Approach

In-situ measurement and control of RS state: **POSSIBLE & AGILE**

Objective and Approach

Artificial Intelligence Approach + **Desing for Residual Stress Concept**



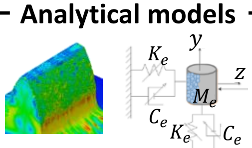
How to create an intelligent system applicable in industrial environment to measure and control residual stress during production?

Development of an approach, supported by **artificial intelligence models** and the **DRS concept**, for **on-line measurement and control of residual stress state**.

Agenda

Artificial Intelligence Definitions

Analytical models



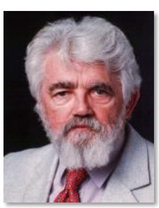
Optimal Solution ✔

Why Artificial Intelligence?

- Agility
- Extrapolation
- Multipurpose
- Highly complex relationships
- Large-scale databases

What is Artificial Intelligence?

"Artificial Intelligence** is the science and engineering of making intelligent machines, especially **intelligent computer programs"

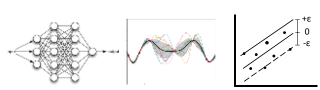


John McCarthy (1956)

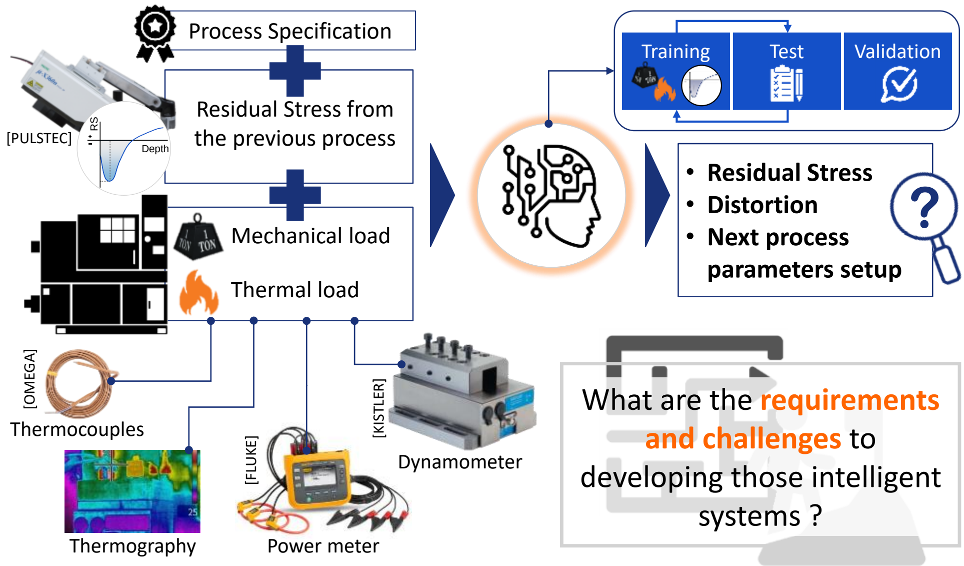
Artificial Intelligence

Machine Learning

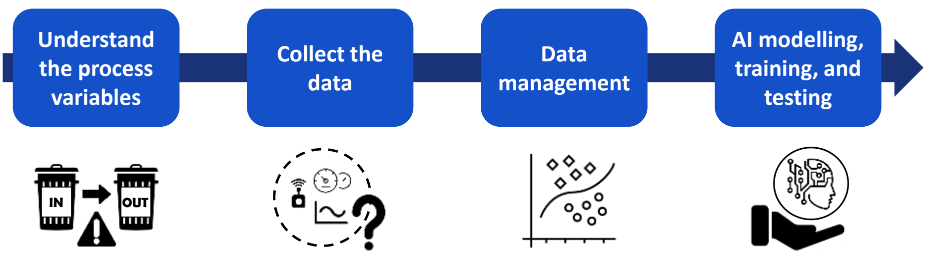
Algorithms



AI Application for Residual Stress Measurement and Control



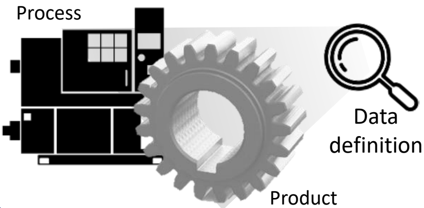
Requirements and Challenges of Artificial Intelligence Applications



Requirements and Challenges of Artificial Intelligence Applications

Understand the process variables → **Collect the data** → Data management → AI modelling, training, and testing

INDUSTRY REQUIREMENTS



SENSORS' CHALLENGES

Complex preparation | Use of cutting fluid | Expensive | Integrity of the workpiece

Requirements and Challenges of Artificial Intelligence Applications

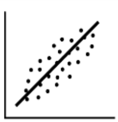
Understand the process variables → Collect the data → **Data management** → AI modelling, training, and testing

Cleaning

Identify outliers

Extract features

Analysis



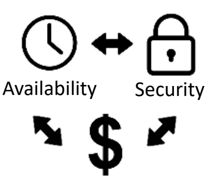
Identify Correlations

Spurious correlations

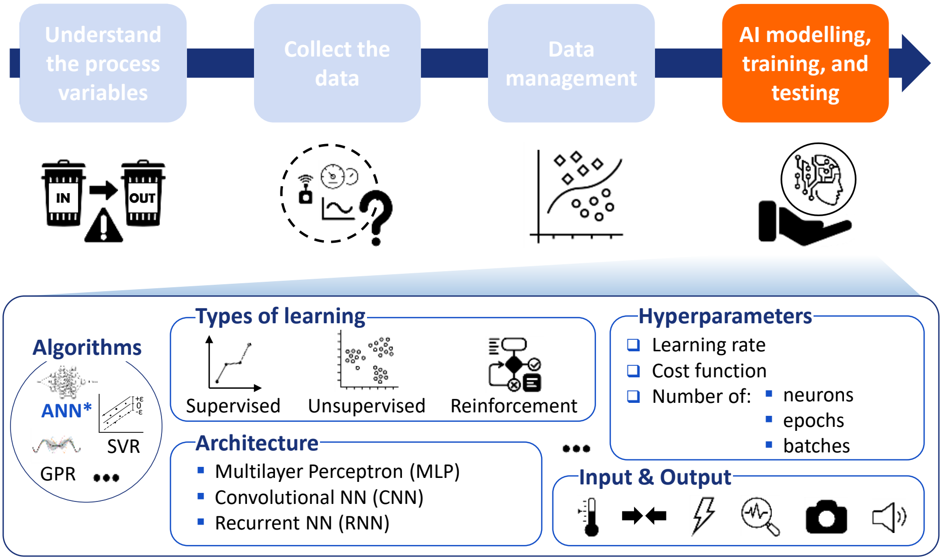
Statistically related is not a guarantee of causally related!

✓ **Finite Element Model support as a solution**

Storage



Requirements and Challenges of Artificial Intelligence Applications



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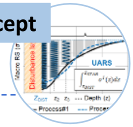
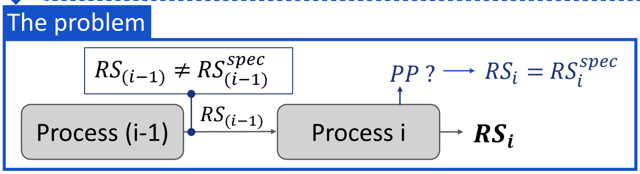
DRS:AI: *An Artificial Intelligence Approach*

Rego (2016): **determined** the influence of $RS_{(i-1)}$ on RS_i

D'Oliveira (2021): **quantify** the influence of $RS_{(i-1)}$ on RS_i

DRS concept



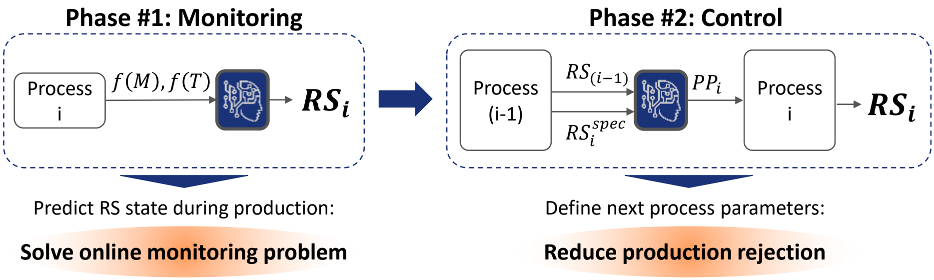


RS: Residual Stress

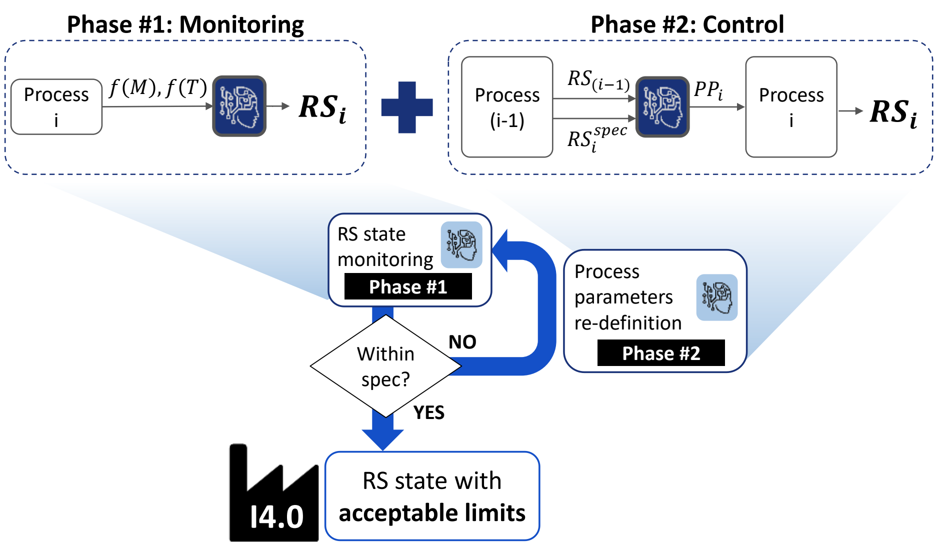
PP: Process Parameters

$f(T)$: Online thermal load

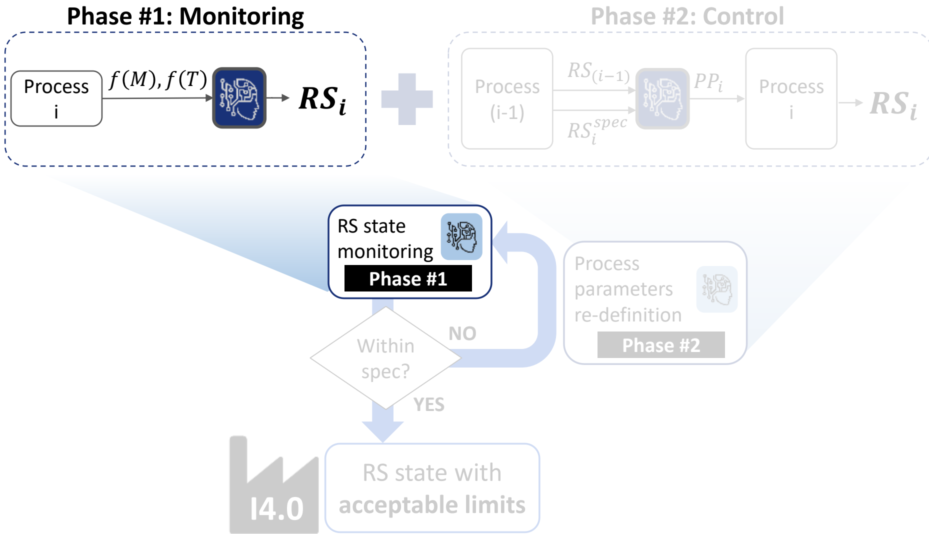
$f(M)$: Online mechanical load



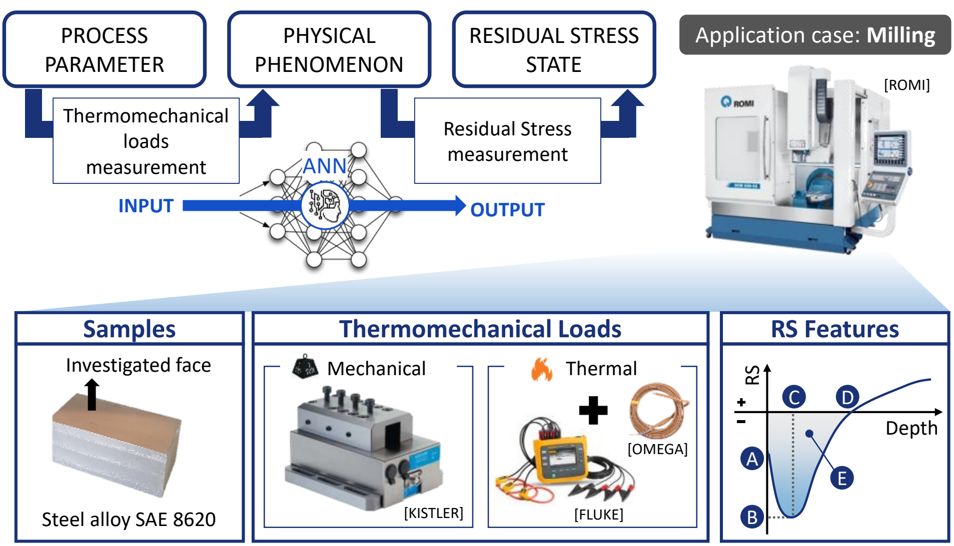
DRS:AI: *An Artificial Intelligence Approach*



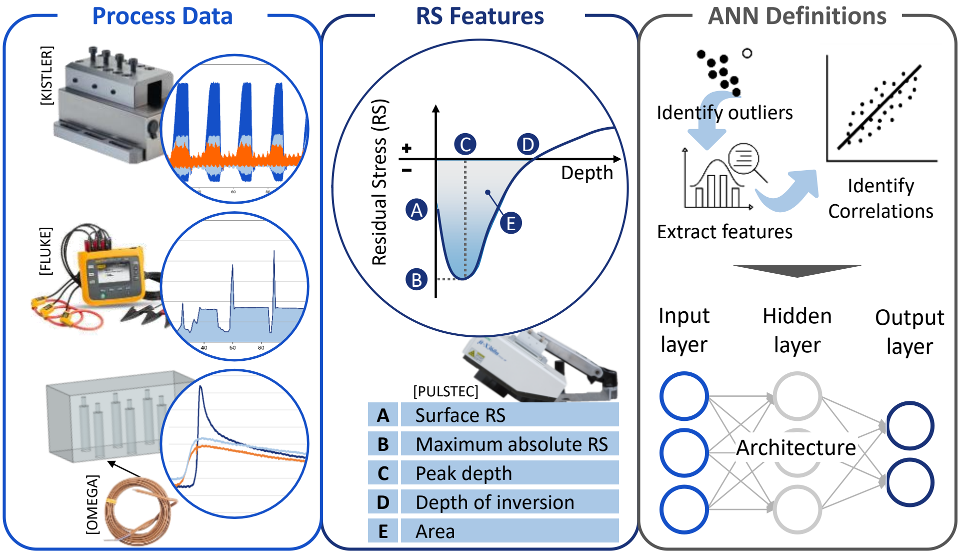
DRS:AI: *An Artificial Intelligence Approach*



DRS:AI – Monitoring: *Structure of an ANN Model*



DRS:AI – Monitoring: *Structure of an ANN Model*



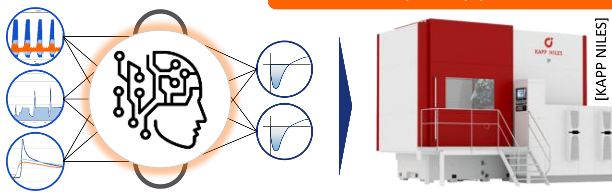
Agenda

1. Residual Stress in Future Manufacturing
2. Artificial Intelligence as a Tool for Manufacturing
3. Design for Residual Stress: An Artificial Intelligence Application
4. **Summary and Outlook**

Summary

- DRS:AI: **Monitoring** and **Control** Phases
- DRS:AI Monitoring: **ANN model structured**
  - ✓ Inputs and Outputs: identified **correlations between thermomechanical loads and residual stress features**.
  - ✓ Residual stress state **prediction using ANN**.

Next Steps: Application on **Profile Gear Grinding**



TU berlin IWF
Fraunhofer IPK

Understand the process variables → Collect the data → Data management → AI modelling, training, and testing

Outlook

! Residual Stresses' benefits **are still not captured** by gear design standards

AGMA ISO ANSI

International Collective Effort

ASM INTERNATIONAL
RS
Residual Stress
ASM Technical Committee

Residual Stress normalization is a **trend for manufacturing** in the coming years

BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

XII. Design for Thermal Power: The Oil Churning Impact on Thermal Behavior –

Rodrigo Metzger, M.Sc. (ITA) / Walmir Navarro, Eng. (WEG CESTARI)

As the load density increases and the gearboxes are downsized, the thermal dissipation capacity becomes a new challenge. Due to the imbalance between generated thermal power and thermal dissipation capacity, new mechanisms for optimizing gearbox cooling are required. This presentation will explore the importance of a method to evaluate the oil churning and the thermal behavior of gearboxes to attend these issues. As an objective, a method of evaluating the oil churning and heat distribution along the gearbox is expected. A back-to-back test-rig is used to evaluate the thermal behavior of gearboxes, using two types of tests. The first test is used to qualitative evaluation of the oil churning using a translucid cover and high-speed cameras. For the second set of tests, the measurement of the thermal distribution of the gearbox is evaluated. Different levels of oil, torque, and speed were tested and compared during the tests to evaluate the heat distribution. Also, a Computational Fluid Dynamics (CFD) model is used for comparison and evaluation of the method. The results shown that rotational speed was the most influential parameter on the oil churning and gearbox temperature. The oil temperature was directly affected by the power losses associated, however, the oil level showed to have an optimum point between power losses and oil temperature that can be further explored. The developed methodology, and the selection of the high-speed and thermal camera were sensitive to the evaluation of the results.

Design for Thermal Power: The Oil Churning Impact on Thermal Behavior

Rodrigo Metzger, M.Sc. *(ITA)*
Walmir Navarro, Eng. *(WEG CESTARI)*

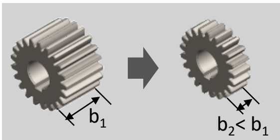
São José dos Campos, October 18th & 19th, 2023

Agenda

1. Introduction
2. Oil Churning Assessment
3. Thermal Behavior Assessment
4. Summary and Outlook

Technological Context

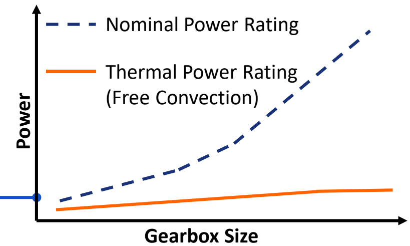
- Continuous trend on **gearbox downsizing** (power density increase)
  - **Reduced capacity on thermal dissipation**



- **Increased power** density by **reducing the mass** of the electric machine (up to 50%)

- Gearbox energy balance:
  - Power & Losses increases cubically with gearbox size: $(Power, Losses)^3$
  - Surface for thermal dissipation increases quadratically with gearbox size: $(Surface)^2$

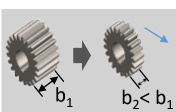
Unbalance of mechanical and thermal power capacities



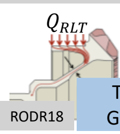
Source: [MART06, MCKI11, BAUE18]

Downsizing: *Thermal Efficiency*

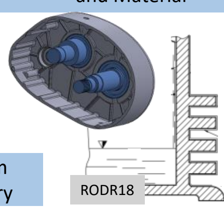
Efficiency Increase Required



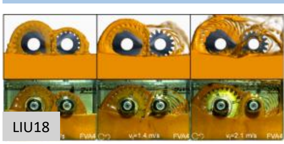
Gearbox Housing Geometry and Material

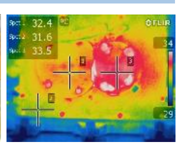


Thin Rim Geometry



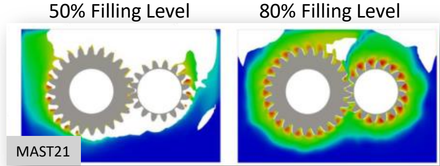
Oil Churning and Thermal Dissipation



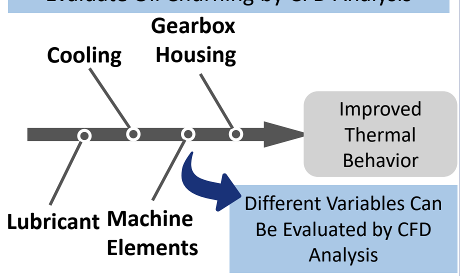


Computational Fluid Dynamics (CFD)

50% Filling Level | 80% Filling Level



Evaluate Oil Churning by CFD Analysis



Source: [HÄGG17, RODR18, MAST21]

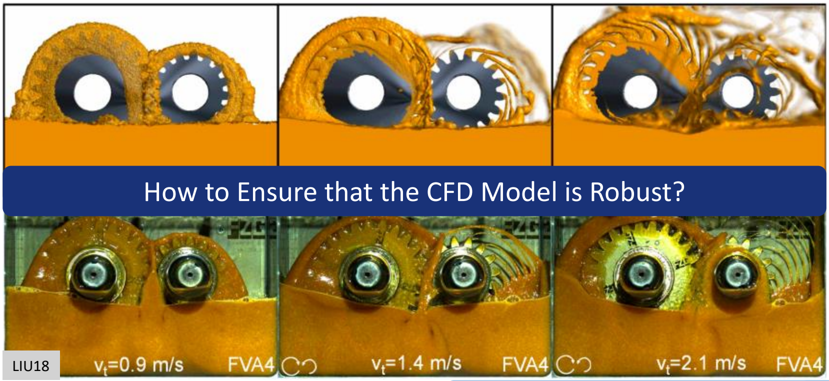
CFD Models Development

Evaluate The Oil Churning

- Visualizing oil churning
- Different oil churning levels

Evaluate The Temperature Behavior

- Reliable thermal data acquisition
- Sensor positioning and acquisition



Source: [LIU18]

Experimental Tests to Evaluate CFD Models

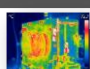
Objective and Approach

Objective

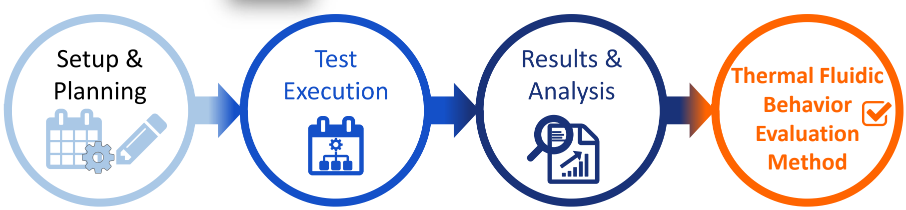
Development of a **Thermal Fluidic Behavior Evaluation Method** Applied to Gearboxes

Approach

Step 1: Evaluate the Oil Churning



Step 2: Evaluate the Temperature Behavior



Agenda

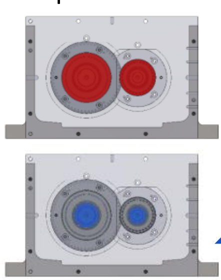
Evaluating Oil Churning

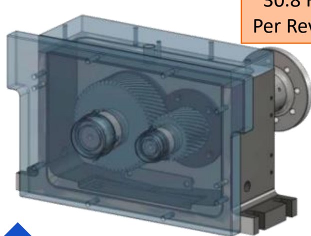
Visualizing Oil Churning

- Transparent Cover

Reference

Proposed

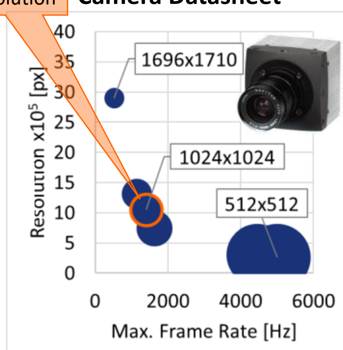




92% Gear Visible Area

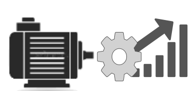
30.8 Frames Per Revolution

High-Speed Camera Datasheet

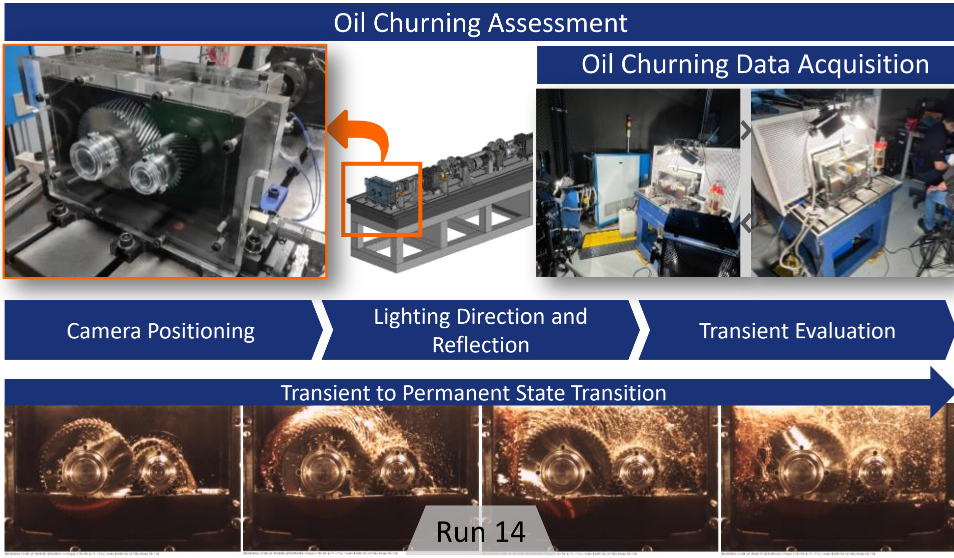


Selected
- Max. Frame rate: 1405
- Resolution: 1024x1024
- Total Frames: 4075

Different Oil Churning Levels | **Design of Experiments (DoE)**

Viscosity	Oil Fill Level	Rotational Speed
Controlled by Temperature		

Test Execution: *DoE 01 – Oil Churning Assessment*



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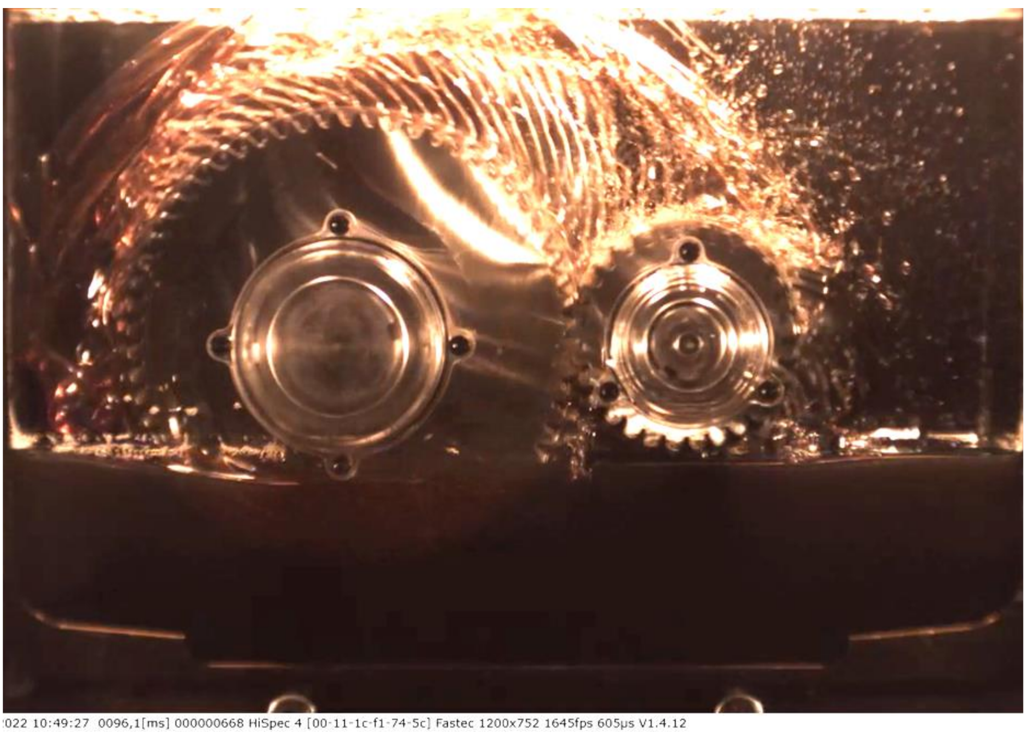
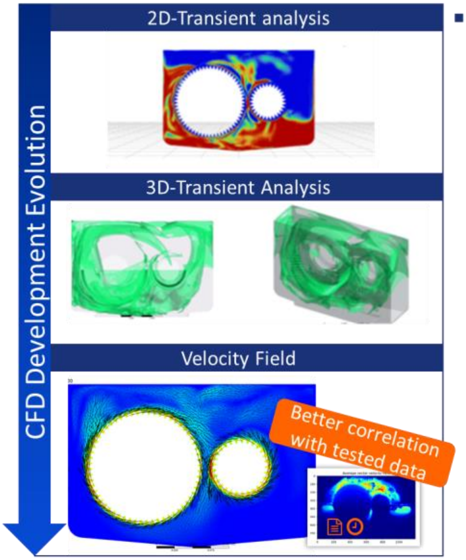
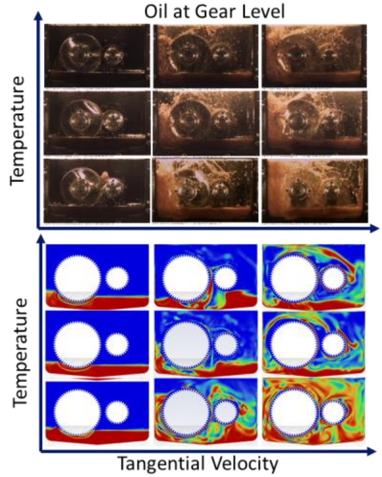


Result & Analysis: *Oil Churning – CFD Model*



- CFD Model vs Experimental Data
  - Experimental data **converged with CFD model**



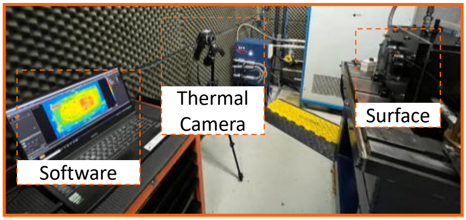
Agenda

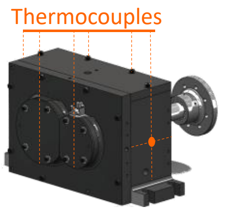
1. Introduction
2. Oil Churning Assessment
3. **Thermal Behavior Assessment**
4. Summary and Outlook

Setup & Planning

Thermal Behavior Setup

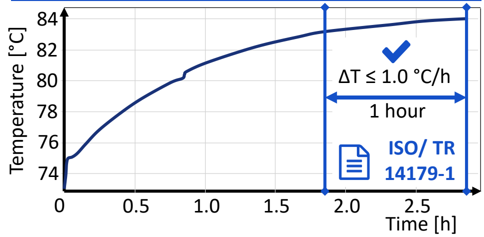
- Thermocouples positioning
- Thermal camera positioning



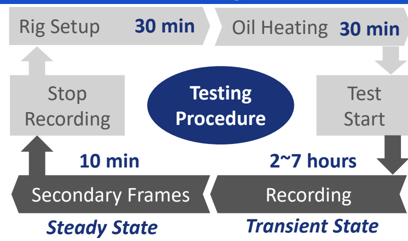


Subiter

Thermal Stabilization

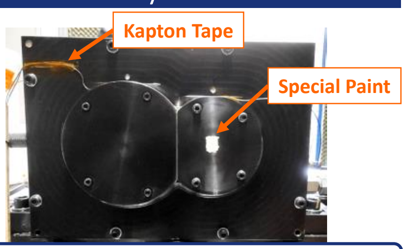


Thermal Testing Procedure

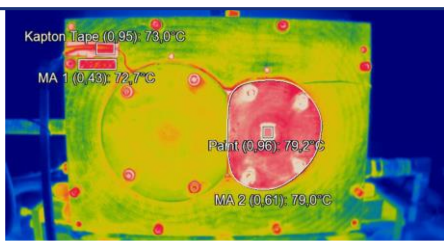


Test Execution: *DoE 02 – Thermal Behavior Assessment*

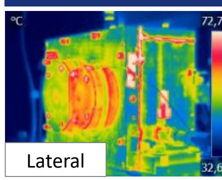
Emissivity Evaluation

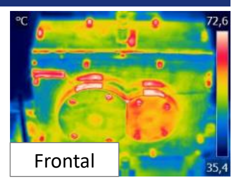


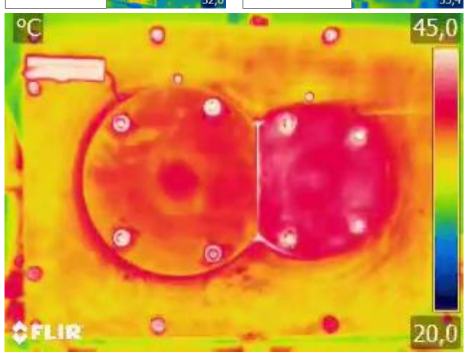
Different Regions and Emissivity



Thermal Camera Results



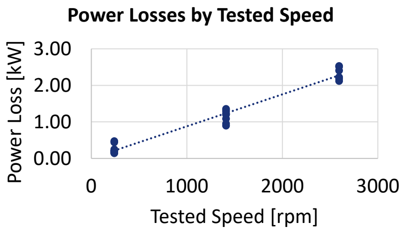


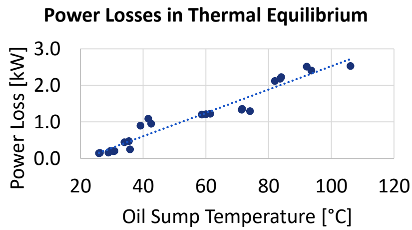


Result Analysis: *Power Losses and Efficiency*

Power Losses & Efficiency

- Speed as most influential parameter in oil churning and temperature
- Power loss increase with oil temperature

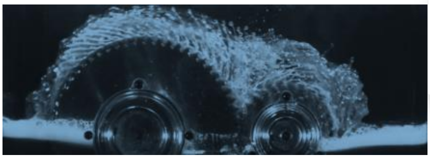


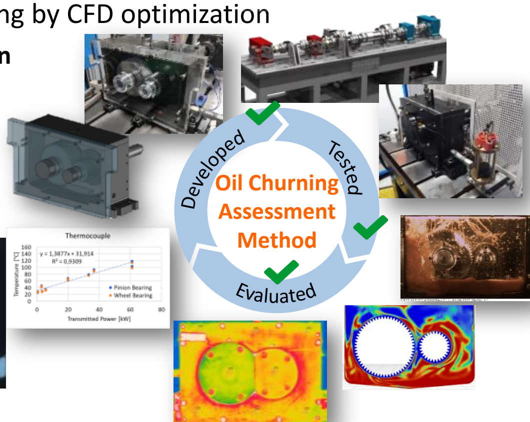


Agenda

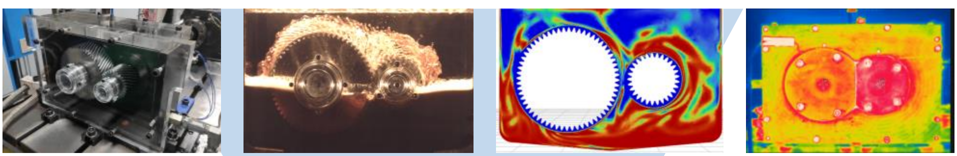
Summary: *Thermal Fluidic Behavior Evaluation Method*

- Thermal fluidic behavior evaluation method **developed**
- **Evaluation of Oil Churning** by image during operation
- Possibility to improve downsizing by CFD optimization
  - CFD for Oil Churning **evaluation developed**
- Gearbox **thermal assessment developed**





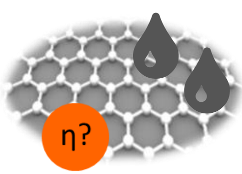
Outlook: *Possibilities*

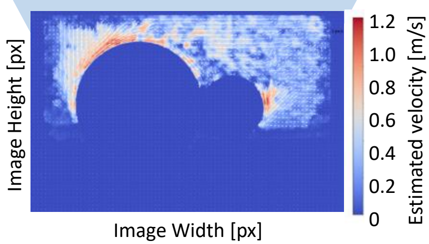


Methodology Evolution: *AI for Oil Churning Quantification*

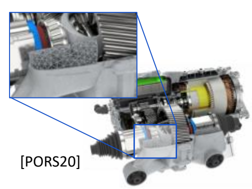
- Application of the methodology did not consider the use of CFD

New Oil Additives





New Design Evaluations (AM)



BGC 23

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VII. Gearing up for Quieter Transmissions: Stiffness-Optimized Gears Through Powder Metallurgy –

Guilherme Santos, M.Sc. (ITA)

The transition to electric vehicles plays a critical role in curbing greenhouse gas emissions, combating climate change, and fostering sustainability. Ongoing research efforts are focused on facilitating a seamless shift from traditional combustion engines to electric motors. Among the key considerations in electric vehicle design is their electric transmission, which must address the challenge of minimizing unpleasant noise, vibration, and harshness (NVH) conditions that arise due to the absence of a combustion engine. This study presents a novel methodology for designing gear pairs with reduced noise characteristics to enhance passenger comfort. The approach involves purposefully introducing slight variations in gear pair stiffness through gear body modifications during gear meshing. By leveraging concepts from Artificial Intelligence (AI), the traditional and time-consuming finite element modeling of gear deflection is circumvented, enabling a more extensive exploration of the design space. The adoption of powder metallurgy manufacturing techniques facilitates the fabrication of complex gear body designs, further enhancing the optimization process. To evaluate and compare the effectiveness of the proposed gear designs, transmission error measurements are conducted. By implementing these advancements, the research aims to contribute to the ongoing development of efficient and quieter electric vehicle transmissions.

The Brazilian Gear Conference ITA-WZL 2023

Gearing up for Quieter Transmissions: Stiffness-Optimized Gears Through Powder Metallurgy

Guilherme Santos, M.Sc. *(ITA)*

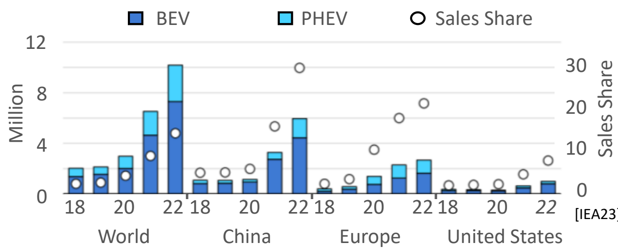
São José dos Campos, October 18th & 19th, 2023

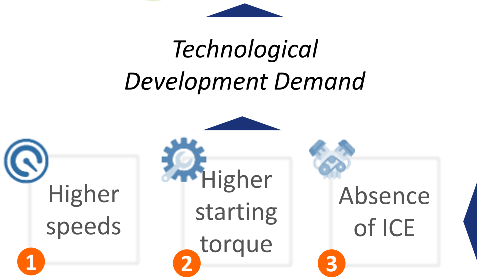
Agenda

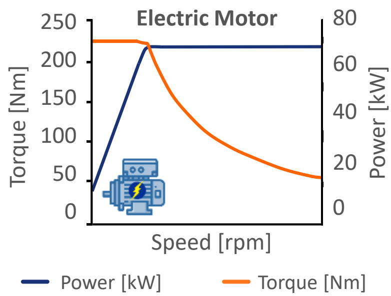
1. Why Quieter is the Way to Go
2. Quieter Designs: Noise Excitation
3. Quieter Designs: Noise Propagation
4. Summary and Outlook

Why Quieter is the Way to Go: *Electric Vehicle Landscape*

Over 26 Million electric cars were on the road in 2022.





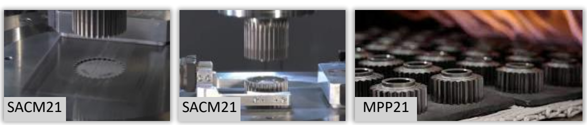


Source: [EV23, IEA23]

Why Quieter is the Way to Go: *Powder Metallurgy Gears*

PM Gears: Problem-Solution Fit

Powder Pressing		Powder Sintering

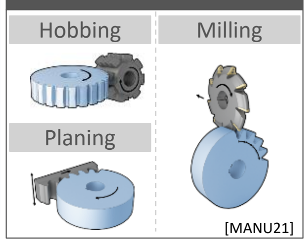


Design freedom enables the **fulfillment** of **electrification requirements**

PM Gear Benefits

Low Noise Propagation	Weight Reduction	Improved Strength

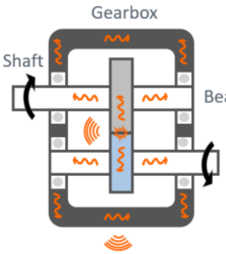
Conventional Chain



Source: [KLOC15, FREC18]

Why Quieter is the Way to Go: *Powder Metallurgy Gears*

Structure-Borne Noise



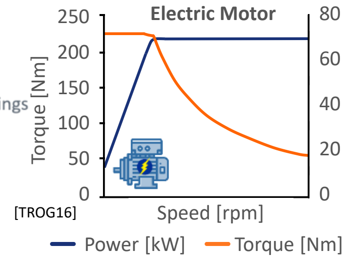
Excitation

Transmission/ Propagation

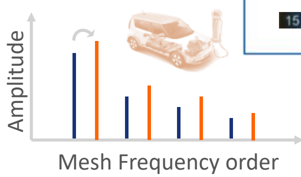
Radiation

Perceived sound ⇔ Transmission operating conditions

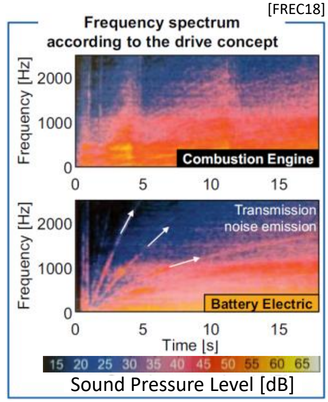
Electric Vehicle Operating Conditions



- Higher mesh frequency
- Challenging microgeometry design



[FREC18]



Source: [BEGA12, TROG16, FREC18]

Agenda

1. Why Quieter is the Way to Go
2. Quieter Designs: Noise Excitation
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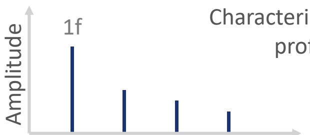
Quieter Designs: *Noise Excitation*

Whine Noise: *tonal sound* that is excited from gears and is characterized by sounds at the gear *mesh frequency* and its *multiples*

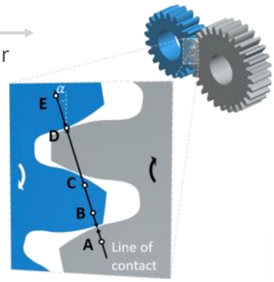


Characteristic whine noise profile in frequency domain

Line of contact = const

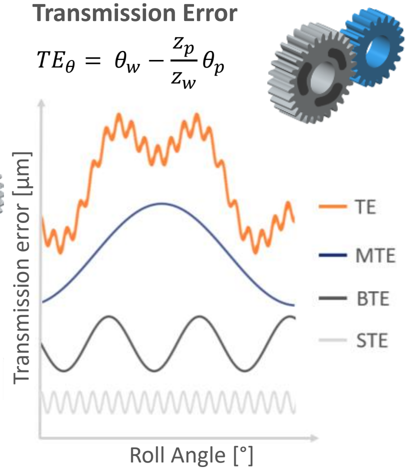
With Velocity constant:

$$\Delta t_{A \rightarrow E} = \text{Const}$$



Transmission Error

$$TE_\theta = \theta_w - \frac{z_p}{z_w}\theta_p$$

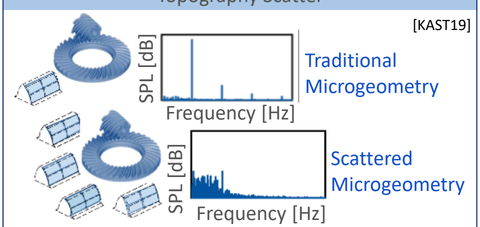


Source: [HARR58, AKER01]

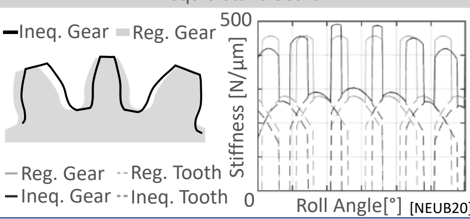
Quieter Designs: *Noise Excitation*

Tonality Reduction Approaches

Topography Scatter



Inequidistant Gears



Controlled Stiffness Design

Powder Metallurgy	How different design affect the stiffness ?
↓	↓
Complex Gear Body Geometry	How varying stiffness impact on NVH ?
↓	↓
Varied Stiffness Pattern	Which design favors improved noise behavior ?
↓	

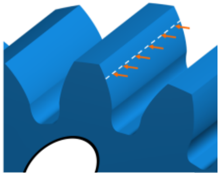
Could a **controlled stiffness pattern** reduce whining ?

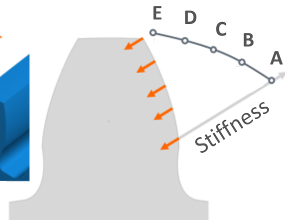
Source: [KAST19, NEUB20]

The Impact of Gear Body Modification

Model Input

Material: PM alloy
Load: 180 Nm
Support: Fixed
App. Diam.:
Contact A to E



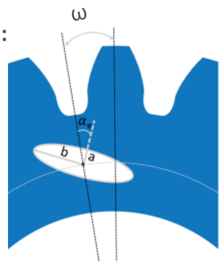


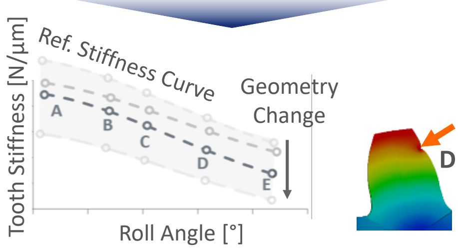
Model Output

Deflection Profile for different gear Body Geometries

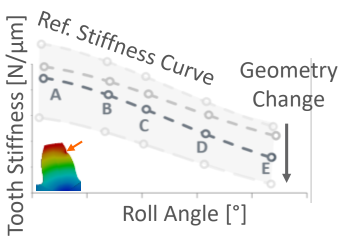
Ellipse Parameters:

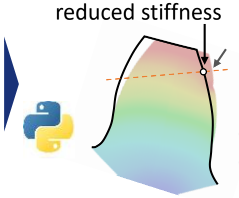
- Major Axis (a)
- Minor Axis (b)
- Ellipse Angle (α)
- Angular position (ω)



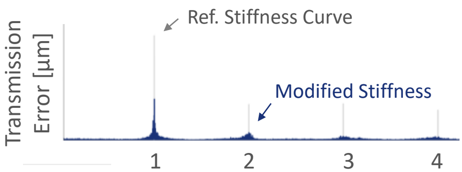


The relationship between Varied Stiffness and NVH

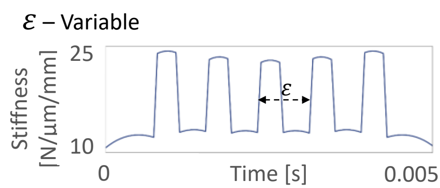




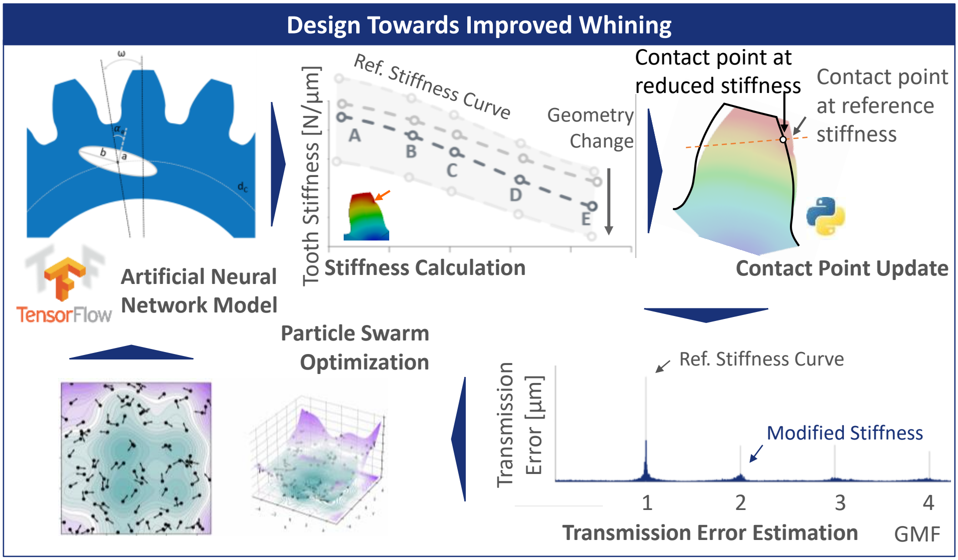
Contact Point Calculation



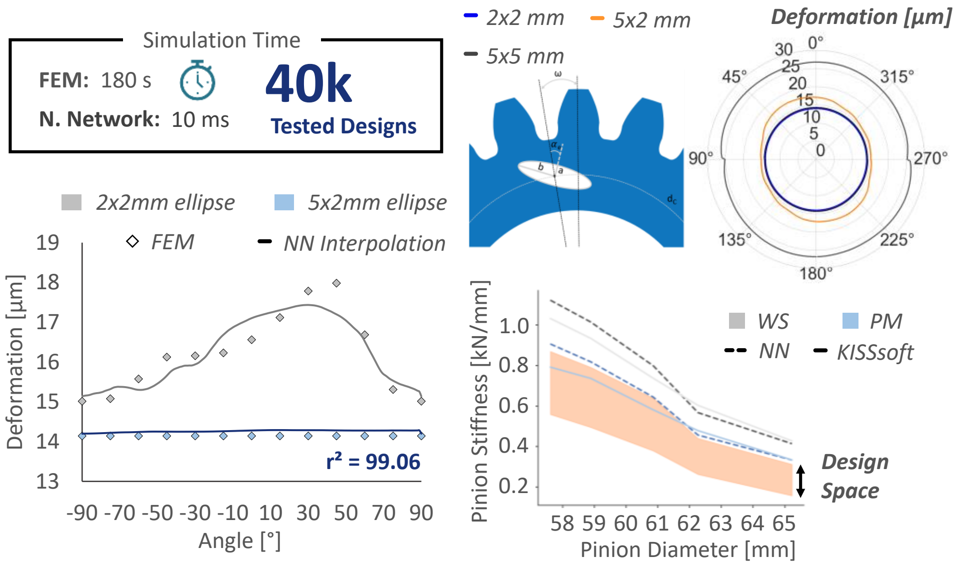
Transmission Error Estimation



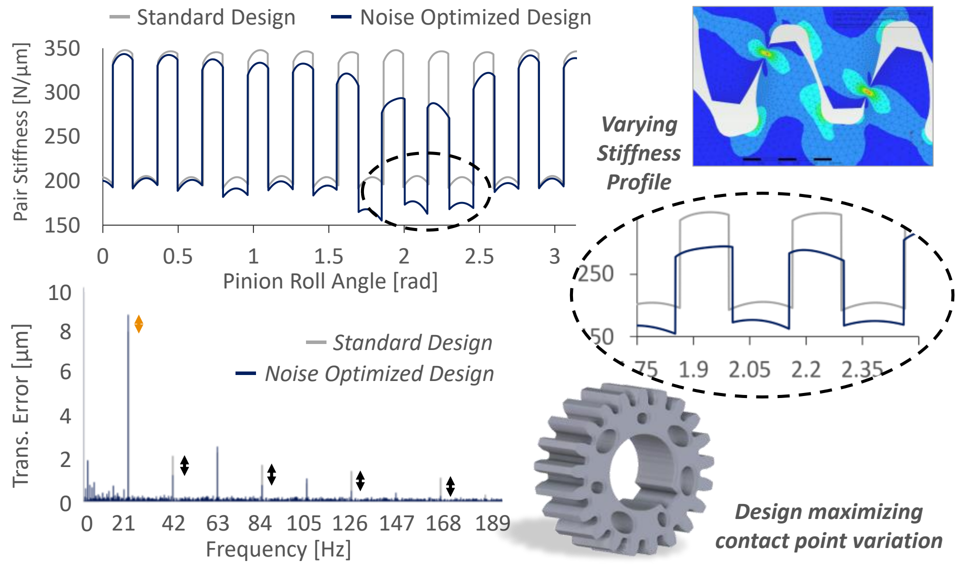
Quieter Designs: *Noise Excitation*



Quieter Designs: *Design Towards Improved Whining*



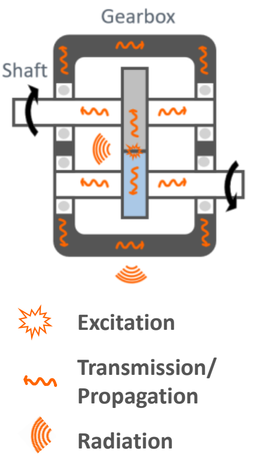
Quieter Designs: *Design Towards Improved Whining*

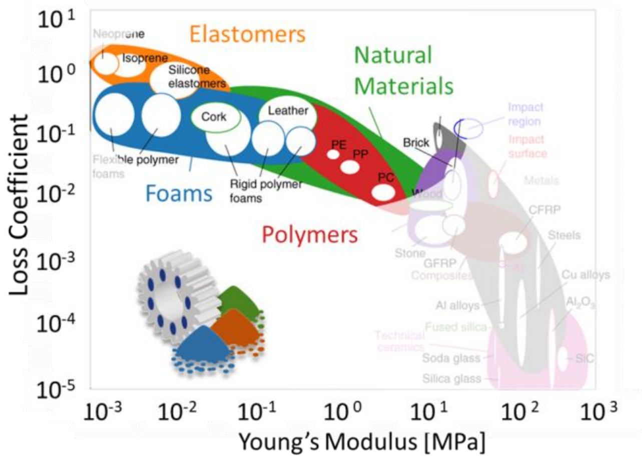


Agenda

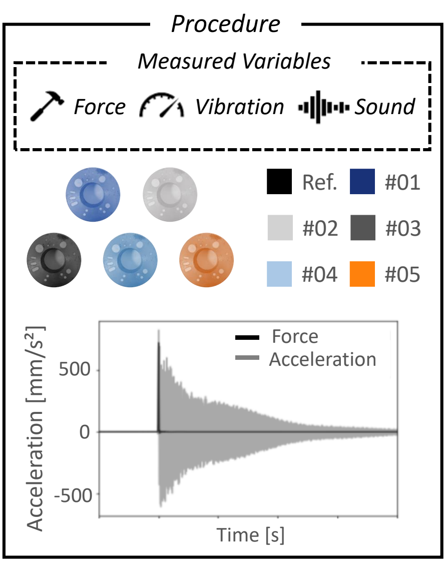
1. Why Quieter is the Way to Go
2. Quieter Designs: Noise Excitation
3. **Quieter Designs: Noise Propagation**
4. Summary and Outlook

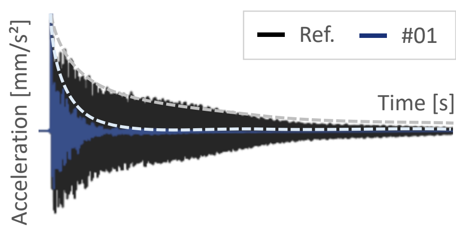
Material Damping





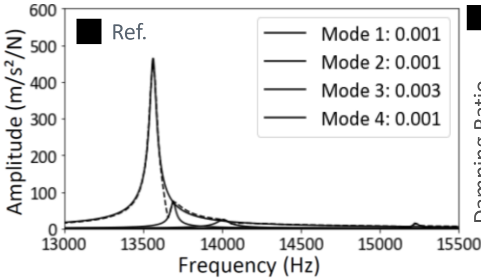
Source: [ASHB11]



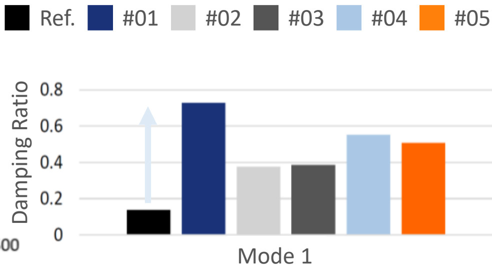


Quieter Designs: *Design Towards Low Propagation*

Frequency Response Function



Samples



Increase in damping [Ref.]

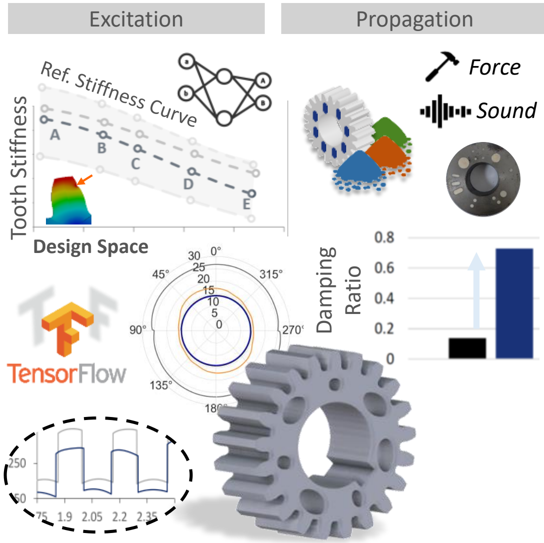
	#01	#02	#03	#04	#05
Mode 1	427%	171%	179%	300%	268%
Mode 2	275%	20%	113%	167%	139%
Mode 3	164%	71%	171%	92%	85%
Mode 4	531%	421%	752%	346%	394%

Agenda

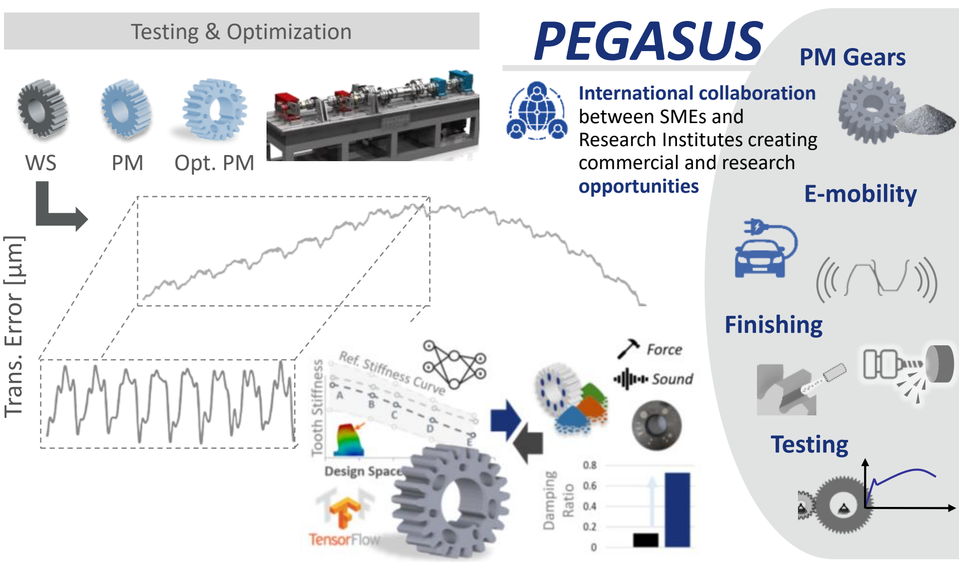
Summary

Takeaways

- Deep learning was successfully applied to modeled gear teeth displacement with acceptable accuracy.
- Closed-looped design space search enabled to test out more than 40k design choices.
- Gear body optimization modelling resulted in varying contact meshing points with potential for improving NVH behavior.
- Polymer have been successfully infiltrated to gear body showing significant reduction in vibration propagation



Outlook



BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

WZL | RWTH AACHEN UNIVERSITY

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

II. Gears for Electromobility: How Finishing Routes Impact on the Surface Integrity Evolution? –

Caio Gomes, M.Sc. (ITA) / Juarez Tenório, Eng. (CIP)

Mobility electrification has affected vehicle systems' design requirements, so a global debate is started regarding the necessity of continuously tightening manufacturing tolerances for proper operation behavior. As the finishing steps are decisive for geometrical accuracy, the finishing routes must be revisited to assess their capability to meet the gear surface requirements of the e-mobility gears. This investigation's objective is the comprehension of how surface integrity heterogeneities induced by distinct gear finishing routes affect their capability to meet the electromobility requirements. Analyses on surface integrity along the grinding and shaving finishing chains evidenced how different residual stress profiles and heterogeneities were generated. The grinding chain led to a more compressive residual stress state and high homogeneity, which tends to improve gear fatigue lifetime and is a good alternative to deal with the increased power densities of electric vehicles. The shaving route gears presented a highly stable profile, thus leading to lower tendencies for relaxation during operation. Dimensional analysis of the samples revealed that both chains generated similar profile and helix slope deviations, while profile and helix form deviations presented higher differences. As the finishing routes influence the surface integrity of the gears, the conclusion is that the finishing process must be selected to meet the electromobility requirements demanded by the application, by stating surface integrity aspects as residual stresses as a target.

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CENTRO DE COMPETÊNCIA EM MANUFATURA

The Brazilian Gear Conference ITA-WZL 2023

Gears for Electromobility: How Finishing Routes Impact on the Surface Integrity Evolution?

Caio Gomes, M.Sc. *(ITA)*

Juarez Tenório, Eng. *(CIP)*

São José dos Campos, October 18th & 19th, 2023

Agenda

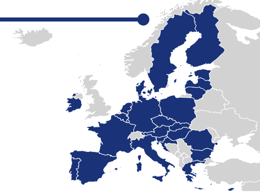
1. E-Mobility in Emerging Economies Context
2. Dimensional Evolution Along the Finishing Routes
3. Residual Stress Induced by the Finishing Routes
4. Summary and Outlook

Electromobility: *Distinct Trends Around the Globe*

EU countries approve ban on sale of petrol, diesel cars from 2035

29 de mar. de 2023

[EURACTIV]



One in Four Cars Sold in China in 2022 Was an EV With BYD Powering Country's Outperformance

MARCH 15, 2023

[COUNTERPOINT]

- **Government investment**.

Brazil seen to have massive EV potential

November 15, 2022

[BNAMERICAS]

Where Do Emerging Markets Stand in the Electric Vehicle Transition?

Mar 29, 2023

Emerging Markets Provide Key Materials for Electric Vehicles

[GLOBAL X]

- **55%** of the world's **lithium reserves** lie in Chile, Argentina and Bolivia.
- Emerging markets constitute over **70%** of global **copper supply**.

- Private sector is driving environmental **efficiency improvements** in the transportation sector.

Introduction: *E-Mobility Quality Requirements for Gears*

ANSI AGMA 6011:

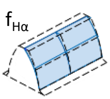
Specification for High Speed Helical Gears Units

Pitch Line Velocity [m/s]	ANSI/AGMA ISO 1328-1-B14 Flank Tolerance Class
35 - 100	5
100 - 150	4
Over 150	3

Accuracy grade (A): 1 to 11

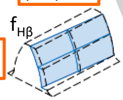
← Accuracy

ITA Geometry at **15,000 rpm** → **v ≈ 47 m/s**



$$f_{H\alpha} = (0.4m_n + 0.001d + 4)\left(\sqrt{2}\right)^{A-5}$$

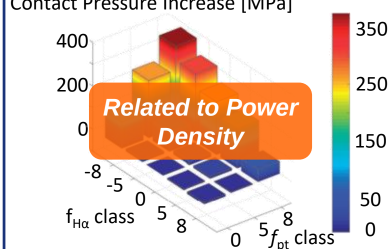
$$f_{H\beta} = \left(0.05\sqrt{d} + 0.35\sqrt{b} + 4\right)\left(\sqrt{2}\right)^{A-5}$$

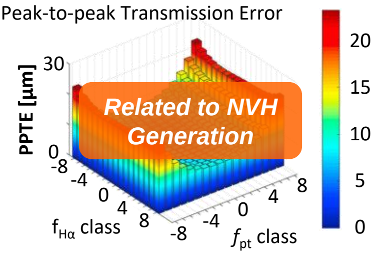


The current specifications in the **automotive industry are classes 8, 7 and rarely 6**!

Source: [CARV20, HJEL21]

Taking a look at the deviations influence

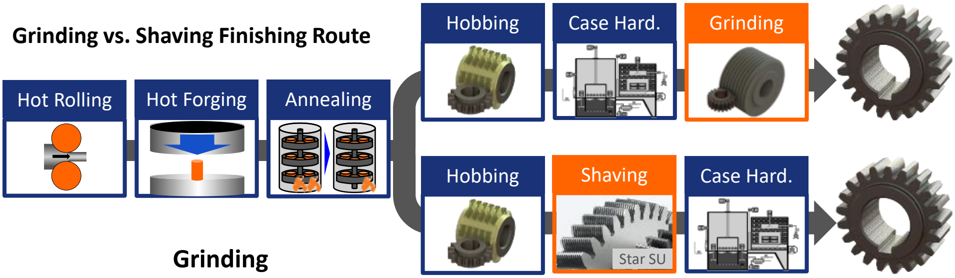


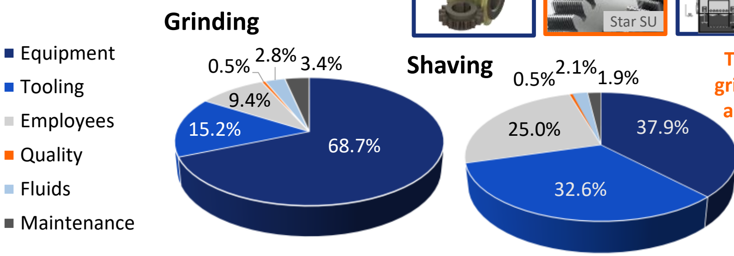


Introduction: *Gear Finishing Routes*

- Gear finishing typically contributes **15-25%** toward the total mfg. cost

Grinding vs. Shaving Finishing Route





The cost reduction from grinding to shaving can be approximately 26-46%*.

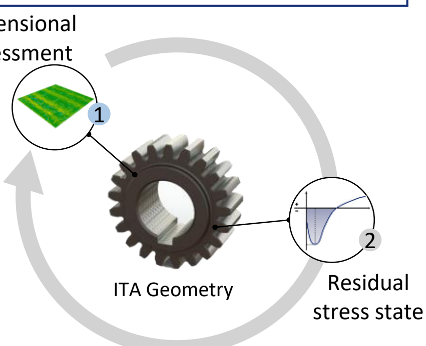
*Based on the Production Performance Cost

Source: [ANDE14, GUPT17]

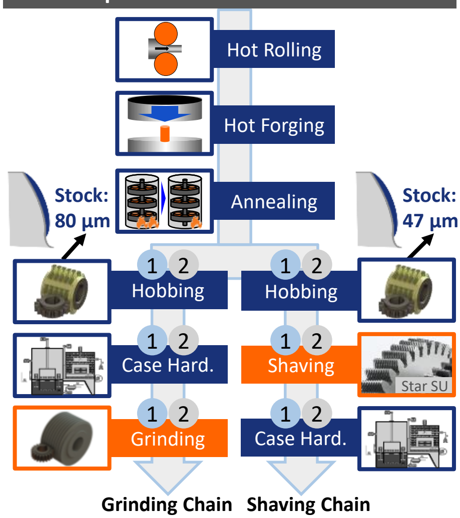
Objective and Approach

Objective

Comprehension of how **surface integrity heterogeneities** induced by distinct gear **finishing routes** affect their capability to meet the **electromobility requirements**.



Specimens: SAE 4320 based

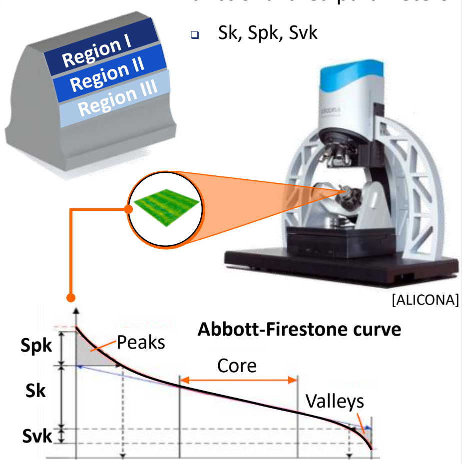


Agenda

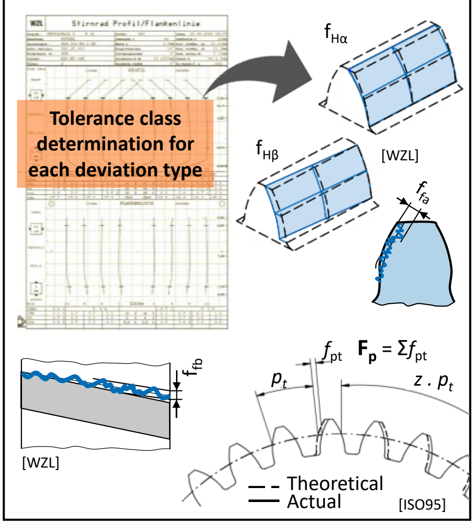
Method of Investigation: *Surface Integrity Assessment*

Topography Analysis

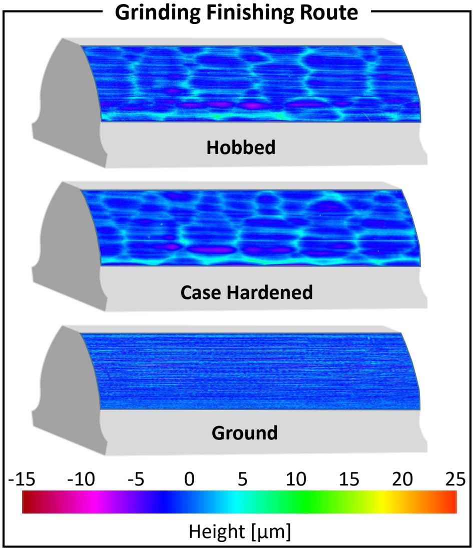
- Functional area parameters
  - Sk, Spk, Svk

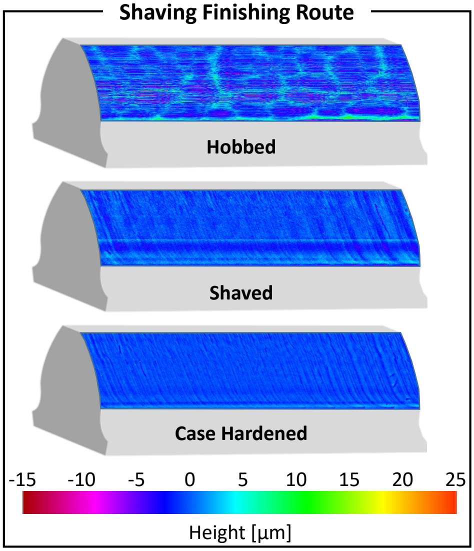


Manufacturing Deviations Evolution

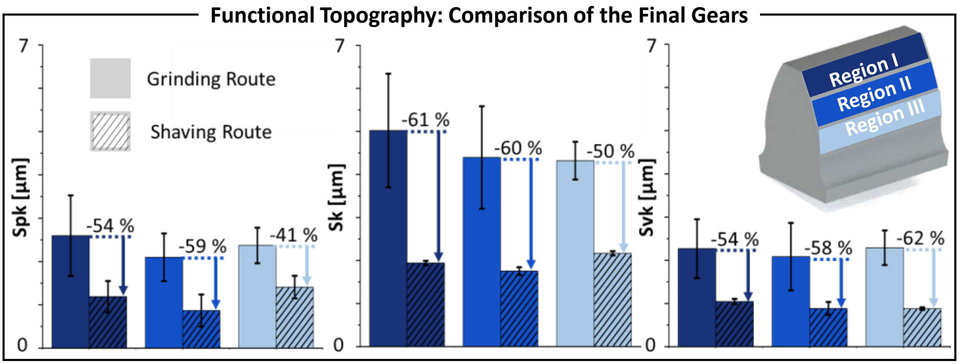


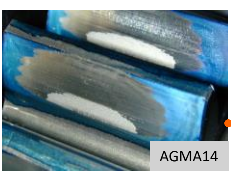
Surface Integrity Evolution: *Plastification Pattern*



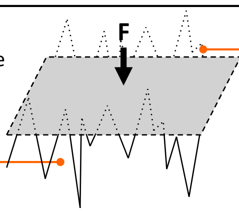


Surface Integrity Evolution: *Topography*

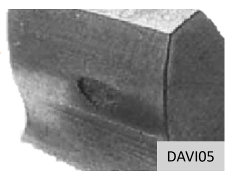




Svk may influence the micropitting occurrence

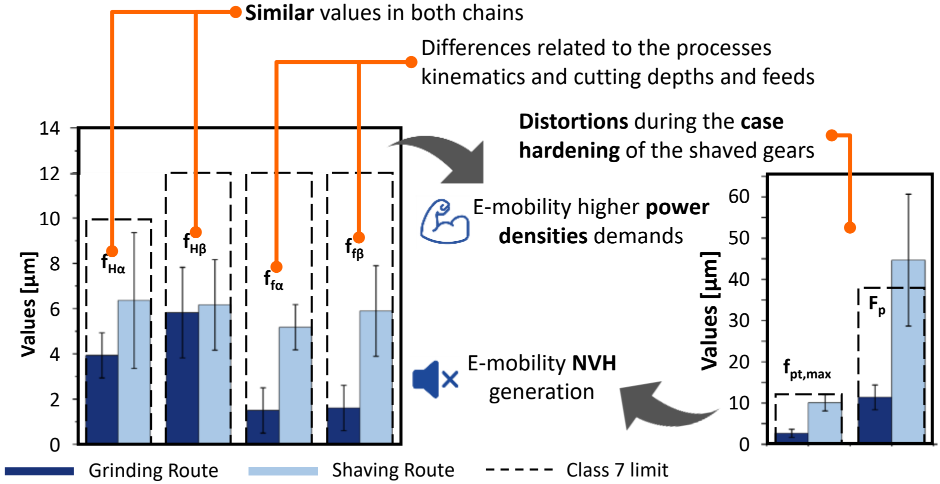


Sk and Spk are associated with contact stress level



Surface Integrity Evolution: *Manufacturing Deviations*

- Determination of the tolerance classes obtained by each finishing route



Surface Integrity Evolution: *Manufacturing Deviations*

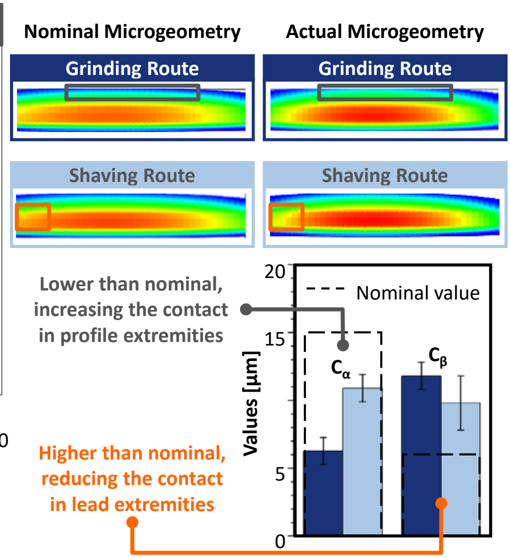
Loaded Tooth Contact Analysis (LTCA)

- *ITA Geometry*;
- Grinding and shaving actual deviations;
- T = 240 Nm

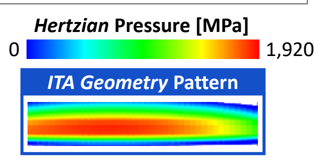
KISSsoft A Gleason Company

Condition	Microgeometry	Input Speed
1	nominal	15,000 rpm
2	actual	15,000 rpm

Hertzian pressure flank distribution

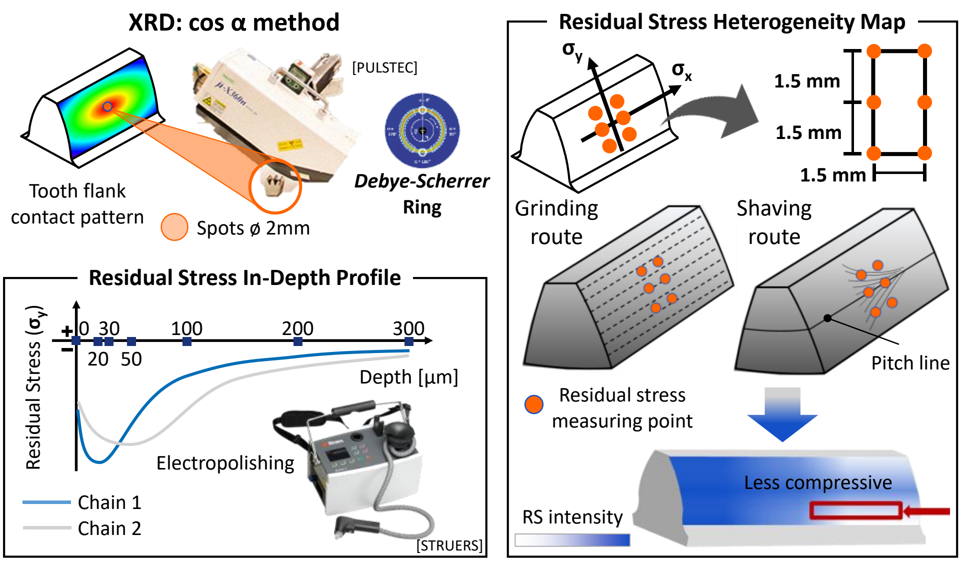


Permissible Deviations as Designed

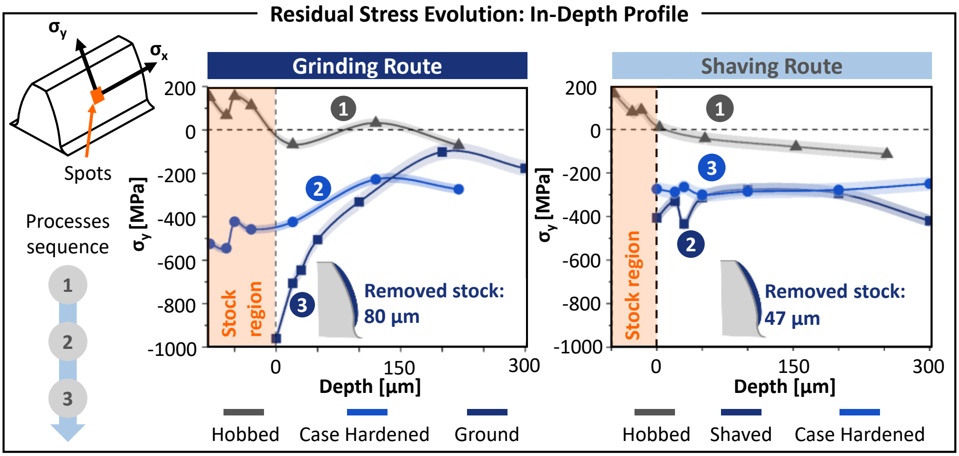


Agenda

Method of Investigation: *Residual Stress Assessment*



Surface Integrity Evolution: *Residual Stress Profile*

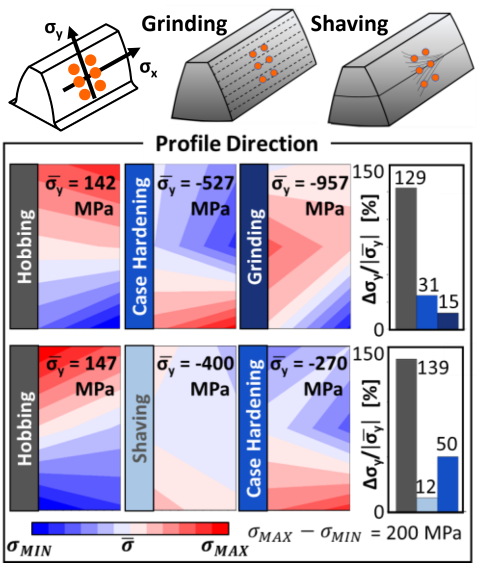


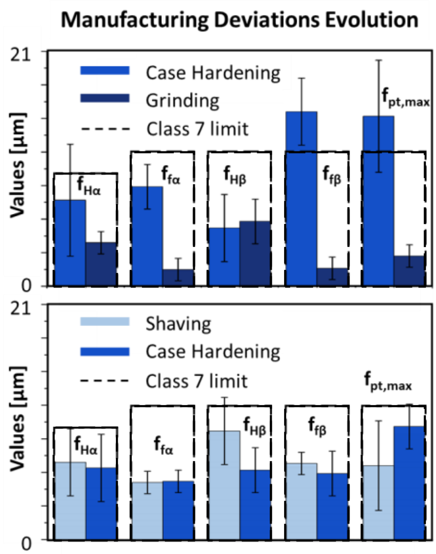
Higher compressive RS at the surface for the ground samples

Steep compressibility reduction in the subsurface of the ground gears

Highly stabilized RS profile at the end of the shaving route

Surface Integrity Evolution: *Residual Stress Heterogeneity*





Agenda

Summary

- **Finishing routes influence the final surface integrity state of the gears**
  - The finishing process must be selected to meet the electromobility requirements demanded by the application.

- **The electromobility requirements**
  - Higher power densities
  - Minimized distortions
  - Torque efficient systems
  - Reduced NVH solutions

Finishing Routes Improvements on the Final Gears

Route	Contact Press.	Distortion	Topography	Compressive RS	RS heterog.	RS Stability
Grinding	↗	↑	↗	↑	↑	↘
Shaving	↗	↗	↑	↗	↓	↑

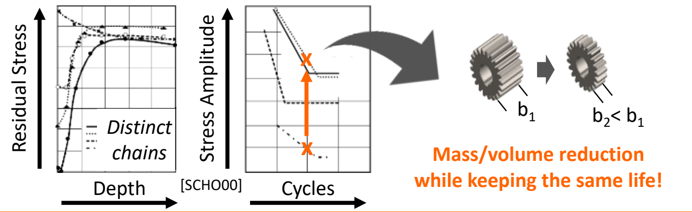
↑ High Positive Impact ↗ Positive Impact ↘ Negative Impact ↓ High Negative Impact

- Design for Residual Stress (DRS)
  - Design and production chain can be defined with stating **Residual Stress as a target**
  - Challenge: Residual Stresses' benefits **are <u>still not captured</u> by gear design standards**

DRS Program

Ph1: **Structuring** → Ph2: **Developing** → Ph3: **Standardizing**

Development of a technical and economical demonstrator of residual stresses!



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IX. Influence of the System Tolerance Chain on the Operational Behavior Using the Example of a High-Speed Transmission for Electric Vehicles –

Laurenz Roth, M.Sc. (WZL)

In addition to the quality of the gears, deviations in surrounding components are also relevant for the operational behavior of a gear unit, as these can influence the characteristics of the gear mesh. The correlations between the characteristics of the operational behavior and deviations in housing elements, bearings, shaft functional shoulders and gear bodies are often not clear in detail, so that empirical tolerance specifications are used for the tolerancing of geometric features in the overall system. Since the definition of manufacturing tolerances is decisive for the manufacturing processes to be selected and thus for the costs, the tolerance required to achieve a function should be specifically defined depending on the requirements. In this presentation, the influences of component deviations on the transmission error under load, the flank pressure and the gear efficiency are investigated for the use case of the WZL-High-Speed Demonstrator Gearbox. For this purpose, a substitute model is used to relate the deviations of surrounding components to the axes alignment of the gears and to analyze their effects on the operational behavior. It was found that component deviations affect the operating behavior of the gears in various ways and to various intensities. The deviation scatter defined as a starting point is then optimized in a function-oriented manner.

Influence of the System Tolerance Chain on the Operational Behavior Using the Example of a High-Speed Transmission for Electric Vehicles

Author and speaker: Laurenz Roth M.Sc.

WZL of RWTH Aachen
Prof. Dr.-Ing. Christian Brecher
Prof. Dr.-Ing. Thomas Bergs
Dr.-Ing. Jens Brimmers

Funding:
Seit 1956
Since 1956
WZL Getriebekreis
Gear Research Circle

The Brazilian Gear Conference ITA-WZL 2023, October 18th / 19th 2023

Fraunhofer IPT

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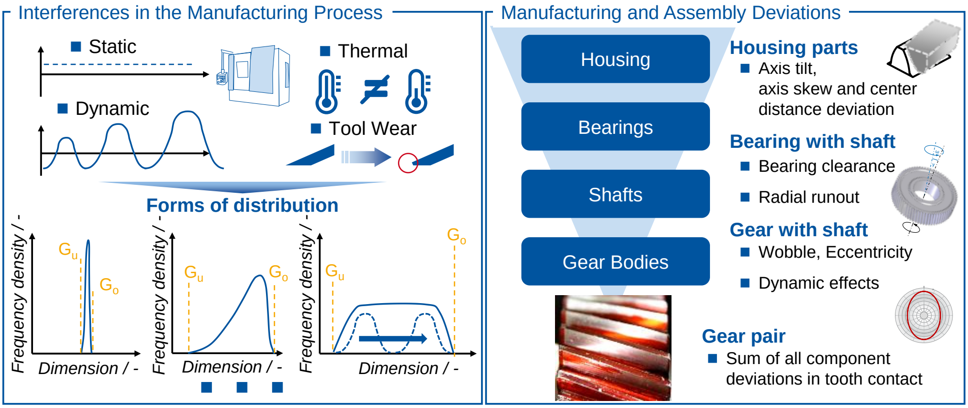
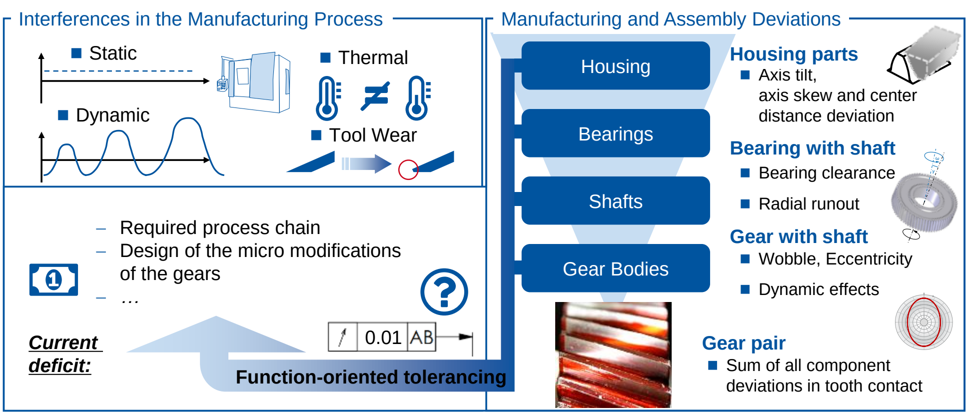
Agenda

1	Motivation and Objective
2	Method for Investigating the Influence of the System Tolerance Chain on the Operational Behavior
3	Application of the Method to the WZL High-Speed Demonstrator Gearbox
4	Modification of Tolerances under Consideration of the Operational Behavior
5	Summary and Outlook

Motivation and Objective
Influence of Component Deviations on the Gear Meshing Conditions



Motivation and Objective
Influence of Component Deviations on the Gear Meshing Conditions



Objective and Approach

Objective

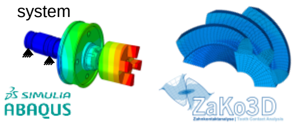
Method of determining the **influence** and **design** of **component tolerances** under consideration of the **operational behavior** of the gearing using the example of the high-speed demonstrator gearbox

Method

- Model design ZaKo3D
- Mapping of production scatter

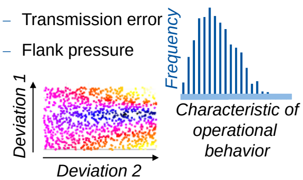
- Geometry-based substitute model

- Load-dependent deformations of the system



Impact Analysis

- Estimation of basic tolerance
- Variant calculations (*DoE*)
- Sensitivity / interaction analysis for:
  - Transmission error
  - Flank pressure



Optimized Design

- Specific modification of the component tolerances

Product quality

Rejection rate

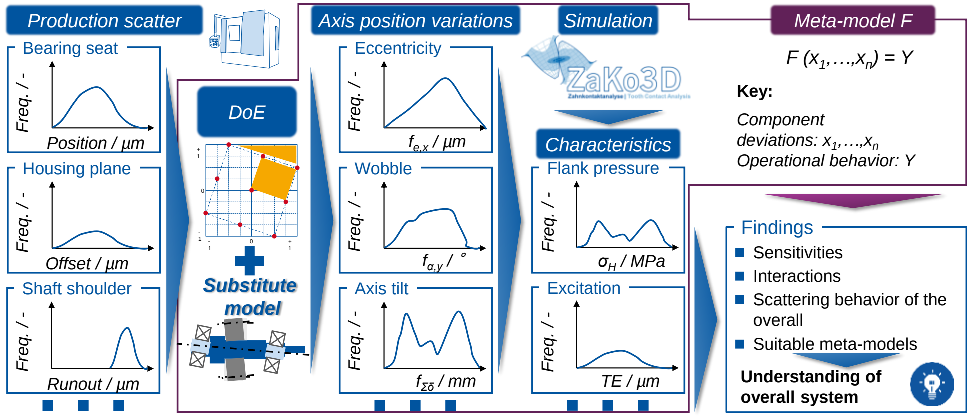
Production costs

Picture Source: Dassault Systèmes

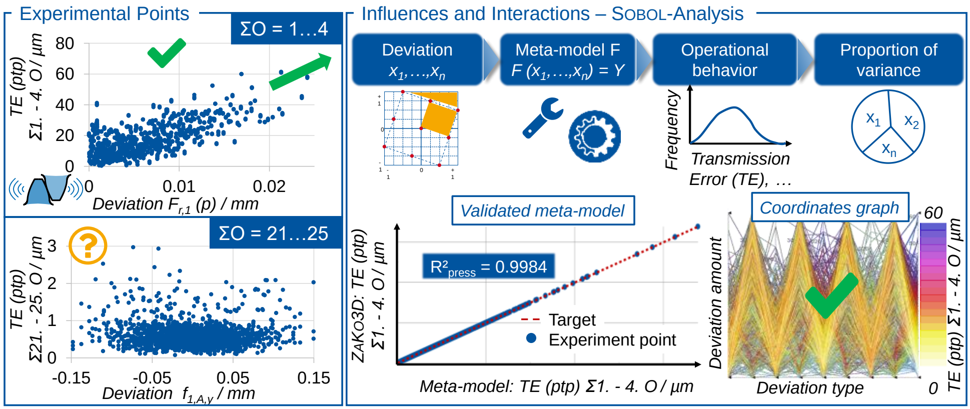
Agenda

1	Motivation and Objective
2	Method for Investigating the Influence of the System Tolerance Chain on the Operational Behavior
3	Application of the Method to the WZL High-Speed Demonstrator Gearbox
4	Modification of Tolerances under Consideration of the Operational Behavior
5	Summary and Outlook

Method for Investigating the Influence of the System Tolerance Chain on Operational Behavior
Functionality and Application

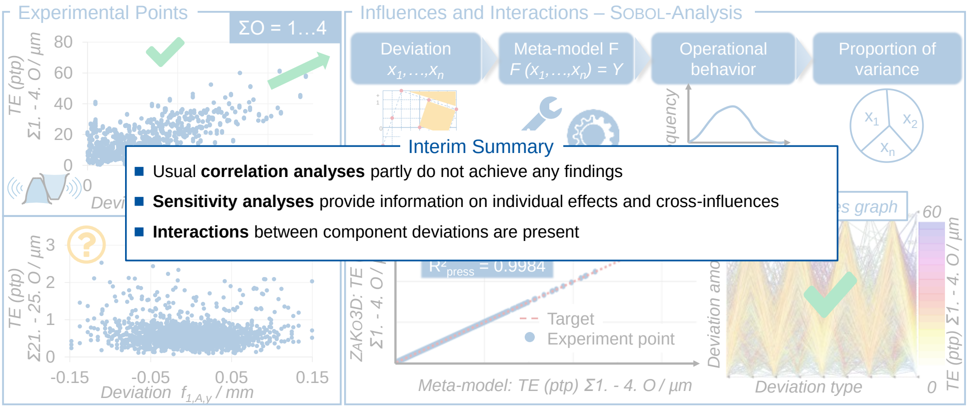


Method for Investigating the Influence of the System Tolerance Chain on Operational Behavior
Limited Validity of the Common Correlation Analyses



Method for Investigating the Influence of the System Tolerance Chain on Operational Behavior

Limited Validity of the Common Correlation Analyses



Interim Summary

- Usual **correlation analyses** partly do not achieve any findings
- **Sensitivity analyses** provide information on individual effects and cross-influences
- **Interactions** between component deviations are present

Agenda

1	Motivation and Objective
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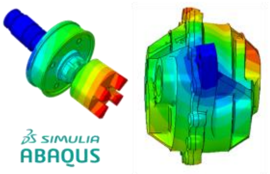
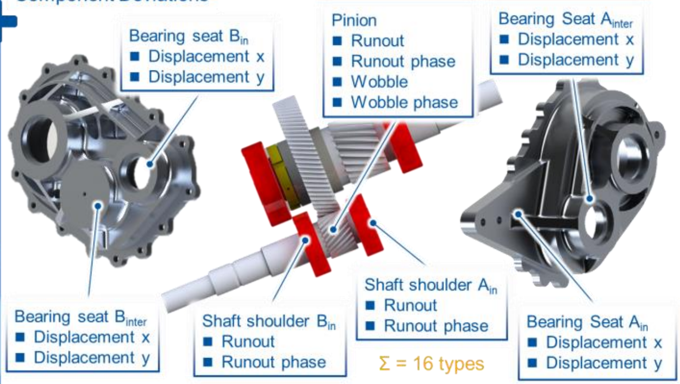
Application of the Method to the WZL High-Speed Demonstrator Gearbox
Simulation Range and Component Deviations

Displacement Behavior
- Drive flank of first gear stage
- Min = 40, 80, 120 Nm



TCA Model
- Reference microgeometry from variant calculation

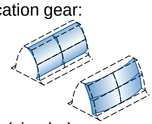
Component Deviations



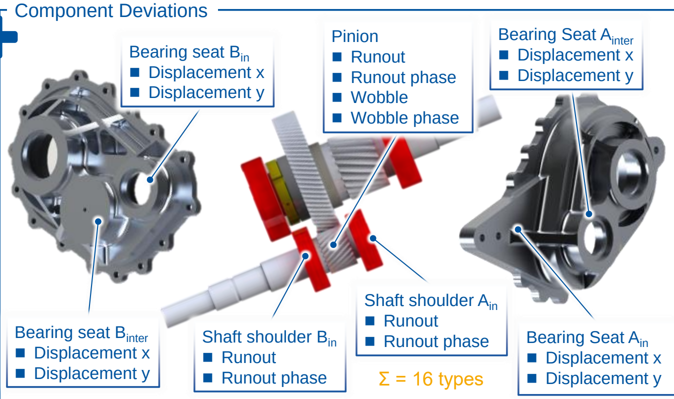
Picture Source: Dassault Systèmes

Application of the Method to the WZL High-Speed Demonstrator Gearbox
Simulation Range and Component Deviations

Gear Data
- z_1 / z_2 = 23 / 87
- m_n = 1.421 mm
- α_n = 20°
- β = -/+ 24.2°
- b_1 / b_2 = 27 / 23 mm
- a = 85.6 mm
- Micro modification pinion:
  - $C_{a,1}$ = 9 µm (circular)
  - $d_{Ca,1}$ = 38.56 mm
- Micro modification gear:
  - $C_{H\alpha,2}$ = 4 µm
  - $C_{\alpha,2}$ = 4 µm
  - $C_{H\beta,2}$ = 4 µm
  - $C_{\beta,2}$ = 4 µm
  - $C_{a,2}$ = 10 µm (circular)
  - $d_{Ca,2}$ = 136.25 mm



Component Deviations

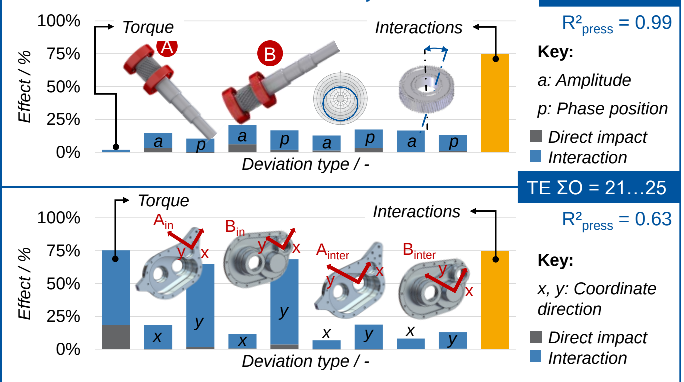


Application of the Method to the WZL High-Speed Demonstrator Gearbox
Influence of Component Deviations on the Transmission Error (TE)

Simulation Parameters

- z_1 / z_2 = 23 / 87
- m_n = 1.421 mm
- α_n = 20°
- β = -/+ 24.2°
- b_1 / b_2 = 27 / 23 mm
- Integration of load-dependent shaft deformations / clearances of bearings
- Reference microgeometry for pinion and gear
- M_{in} = 40, 80, 120 Nm
- 1,500 simulated variants
- 30 rolling positions per pitch
- 23 simulated pitches
- Meta-model: KRIGING
- 10,000 integration points

Influences and Interactions – SOBOL-Analysis

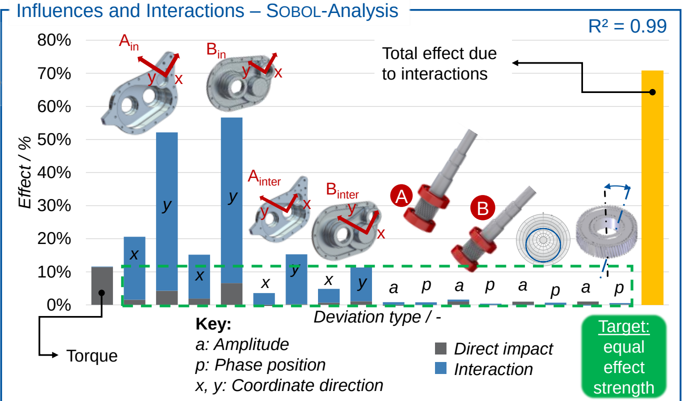


Application of the Method to the WZL High-Speed Demonstrator Gearbox
Effects on the Maximum Flank Pressure

Simulation Parameters

- z_1 / z_2 = 23 / 87
- m_n = 1.421 mm
- α_n = 20°
- β = -/+ 24.2°
- b_1 / b_2 = 27 / 23 mm
- Integration of load-dependent shaft deformations / clearances of bearings
- Reference microgeometry for pinion and gear
- M_{in} = 40, 80, 120 Nm
- 1,500 simulated variants
- 30 rolling positions per pitch
- 23 simulated pitches
- Meta-model: NEURAL NETWORK
- 1,000 integration points

Influences and Interactions – SOBOL-Analysis

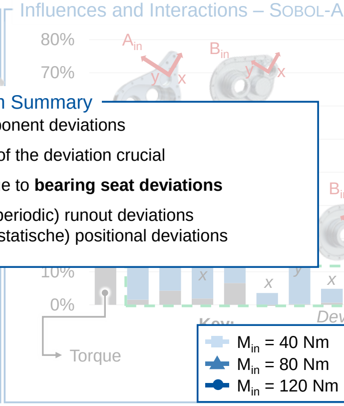


Application of the Method to the WZL High-Speed Demonstrator Gearbox

Effects on the Maximum Flank Pressure

Simulation Parameters

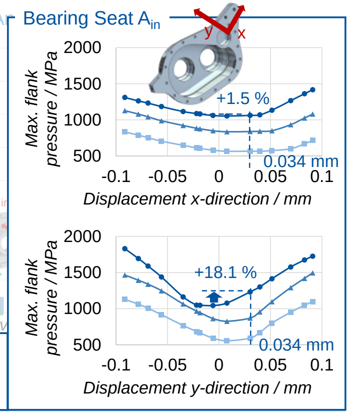
- z_1 / z_2 = 23 / 87
- m_n = 1.421 mm
- α_n = 20°



Interim Summary

- **Cross influences** between component deviations
- **Distance to gear** and **direction** of the deviation crucial
- Main effect on **flank pressure** due to **bearing seat deviations**
- **Long-wave** transmission error: (periodic) runout deviations
  Short-wave transmission error: (statische) positional deviations

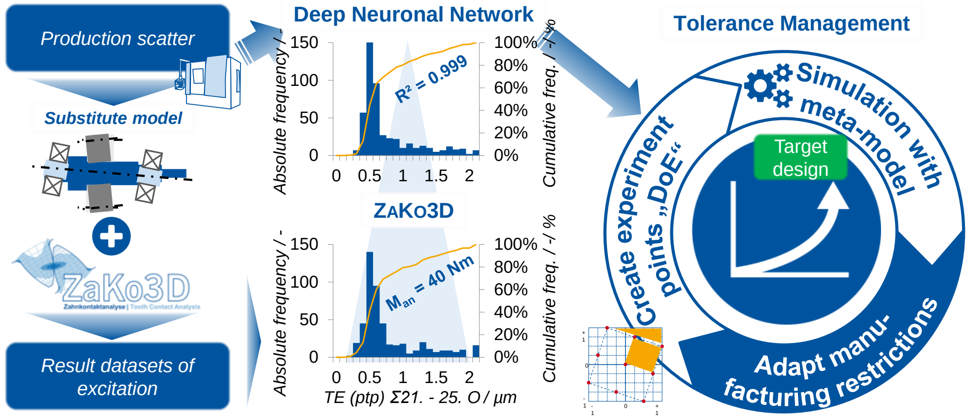
- 1,500 simulated variants
- 30 rolling positions per pitch
- 23 simulated pitches
- Meta-model: NEURAL NETWORK
- 1,000 integration points



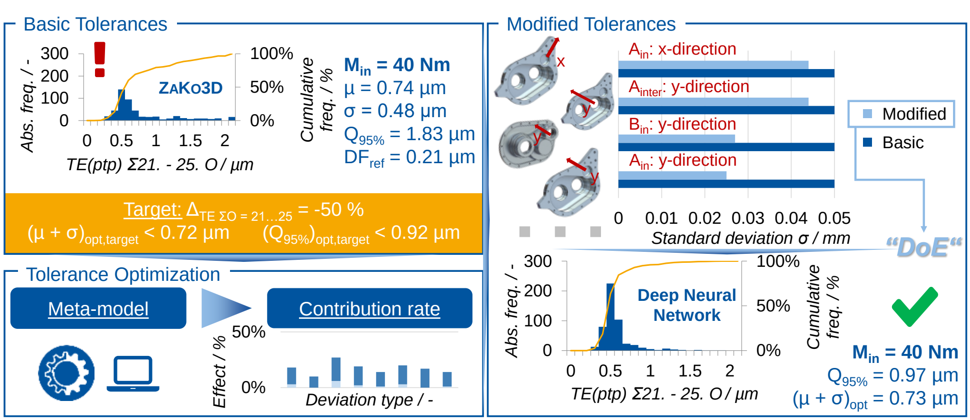
Agenda

1	Motivation and Objective
2	Method for Investigating the Influence of the System Tolerance Chain on the Operational Behavior
3	Application of the Method to the WZL High-Speed Demonstrator Gearbox
4	**Modification of Tolerances under Consideration of the Operational Behavior**
5	Summary and Outlook

Modification of Tolerances under Consideration of the Operational Behavior
Method for Time-Efficient Tolerance Design



Modification of Tolerances under Consideration of the Operational Behavior
Identification of New Target Tolerances Based on their Contribution Performance



Agenda

Conclusion
Summary and Outlook

Summary

- Influence of component deviations on the application behavior depending on geometric conditions and orientation
- Interactions between deviations determine the resulting application behavior
- Tolerance design process using meta-modeling based on contribution performance

Outlook

- Extension of the substitution model for further gearbox variants
- Development of a design method for robust micro-corrections depending on the distribution forms of component deviations
- Investigate the suitability and comparison of meta-models to increase simulation efficiency

BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

WZL | RWTH AACHEN UNIVERSITY

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

X. Investigation of MoS_2-Based Coatings to Improve Gear Efficiency and Durability –

Angelo Carvalho, M.Sc. (ITA) / Izabel Machado, Prof. Dr. (USP)

The introduction of the electric motor in automotive sector brings a set of new challenging requirements for the gear transmission system. Coatings is a promising technology for addressing the challenges posed by electrification, providing gears with higher efficiency, contact fatigue lifetime, wear resistance, and even NVH emission reduction. Despite the potential benefits of coatings, there remains a significant knowledge gap regarding how substrate surface integrity influences the overall performance of the coated surface. The objective of this study is the comprehension of the interaction between MoS2-based coating and substrate surface integrity for electric mobility gear systems. Given its economic advantage at a national scale, the use of Nb as a dopant in MoS2 was investigated and results demonstrated that this strategic metal improves the coating properties. Substrates with different manufacturing-induced surface integrity states was characterized and subjected to coating deposition with the same parameters. Coatings deposited on substrates with different residual stresses and topographies are compared and showed alteration in terms of tribological behavior, enhancing the motivation for deeper investigations to maximize their benefits. Additionally, the development of a High-Speed Twin Disc Test Rig, on which the coatings will be tested under high-speed condition, is presented.

Investigation of MoS_2-Based Coatings to Improve Gear Efficiency and Durability

Angelo Carvalho, M.Sc. *(ITA)*
Izabel Machado, Prof. Dr. *(USP)*

São José dos Campos, October 18th & 19th, 2023

Agenda

1. Introduction & Approach
2. Preliminary Results
3. Summary & Outlook

Introduction & Approach

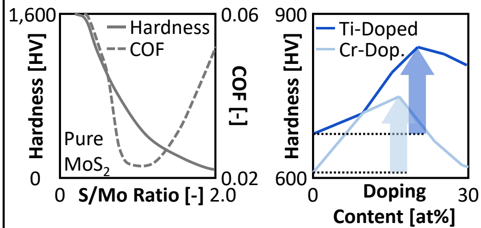
E-Mobility Trends

- Fewer Gears/Vehicle
- Higher Motor Speed
- Higher Mileage/Vehicle
- Silent Motors

MoS_2 Coatings

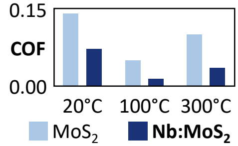
- Excellent low-friction material
- Commonly applied in aerospace industry
- Usually doped to improve mechancial properties and chemical stability

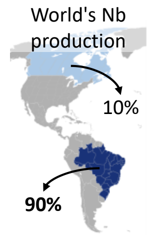
Doping Effect



$Nb:MoS_2$ - Innovation Opportunity

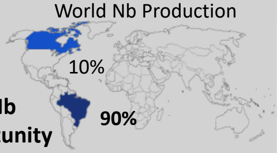
- Similar Performance
- Economical Advantage
- Few Researches





Source: [NABO90, DING10, ARS10, PERE14]

Introduction & Approach



+

Higher Speed

Higher Efficiency

Less NVH Emission

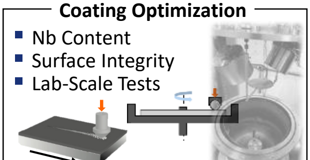
Higher Durability

Latent Demands for Gears

Objective	Assessment of the benefits of the **innovative $Nb:MoS_2$-based coatings** on gear fatigue strength and efficiency

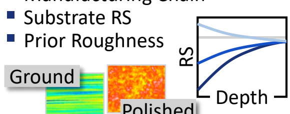
Coating Optimization

- Nb Content
- Surface Integrity
- Lab-Scale Tests



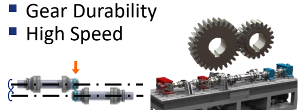
PVD-Oriented Chain

- Manufacturing Chain
- Substrate RS
- Prior Roughness



Testing for E-Mobility

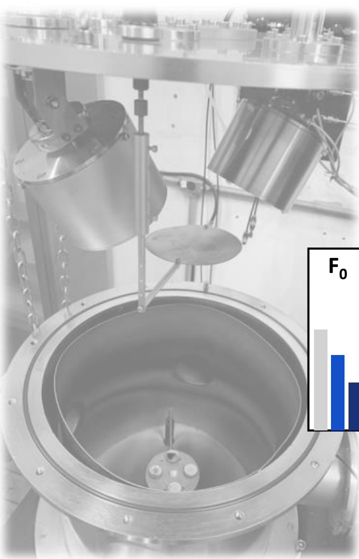
- Efficiency Performance
- Gear Durability
- High Speed



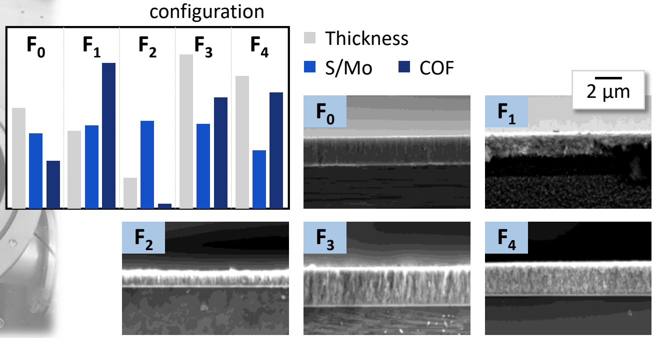
Source: [PERE14]

Agenda

Nb:MoS_2 Coating Evaluation

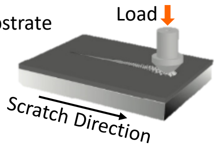


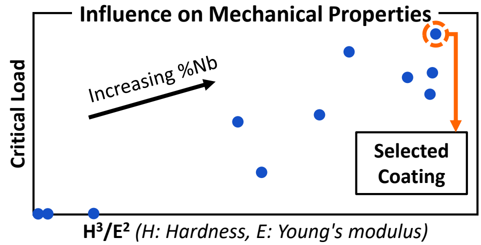
- Hybrid Reactor
  - Physical Vapor Deposition System
  - Versatility from test bench to industrial scale
  - Quick and easy synthesis of multiple configuration
  - Up-to three different materials sources
  - Reactive deposition enabled
  - Low temperature deposition

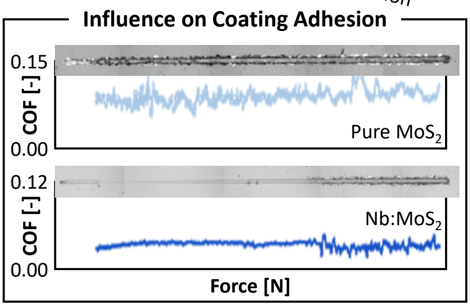


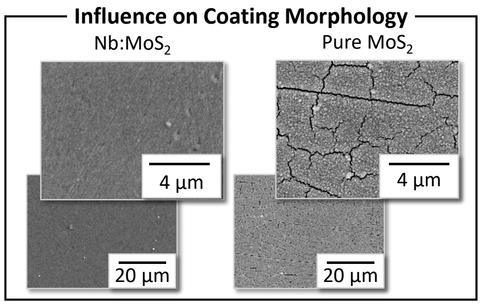
Nb:MoS_2 Coating Evaluation

- Nb doping MoS_2 allows tunning
  - Structure and morphology
  - Mechanical properties
  - Adhesion to the substrate



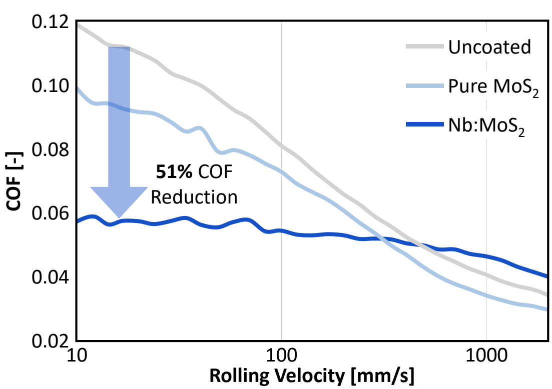






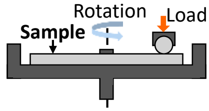
Nb:MoS_2 Coating Evaluation

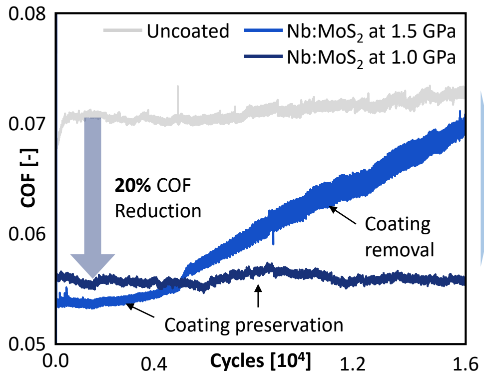
- Mini-Traction Machine
  - **Ball** on **disc** configuration
  - Variable Sliding to Rolling Ratio (**100%**)
  - Lubricated contact (**PAO ISO VG 8 base oil**)

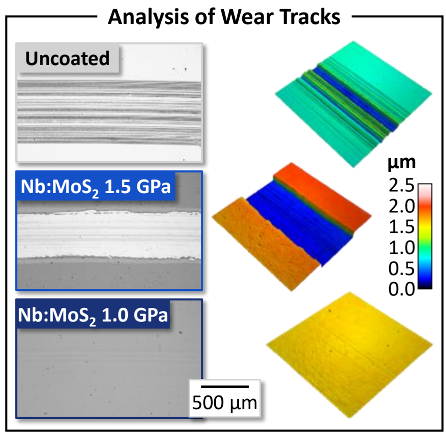


Nb:MoS_2 Coating Evaluation

- Ball-on-Disc Test
  - P_H: 1.5 GPa and 1.0 GPa, v_t: 1 m/s
  - Polished SAE 8620 substrate
  - PAO ISO VG 8 base oil

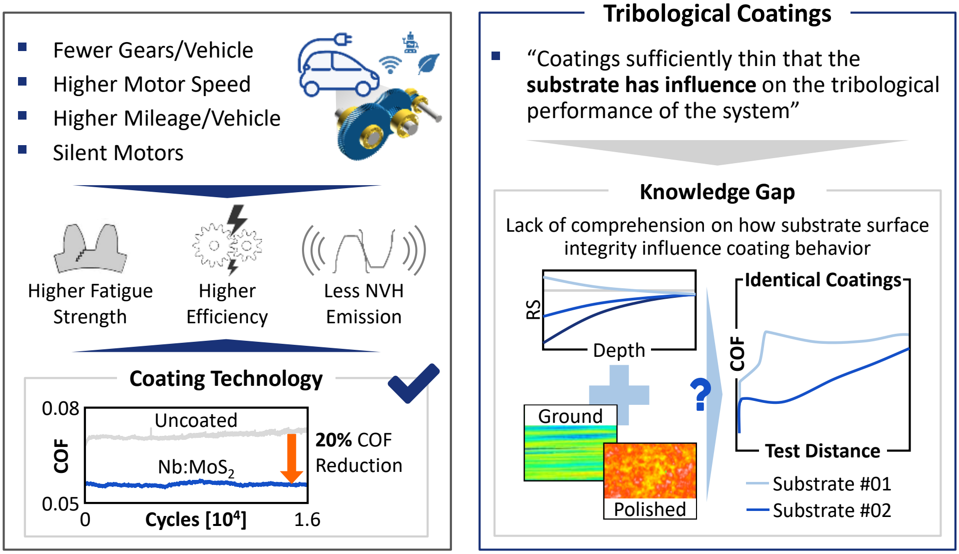




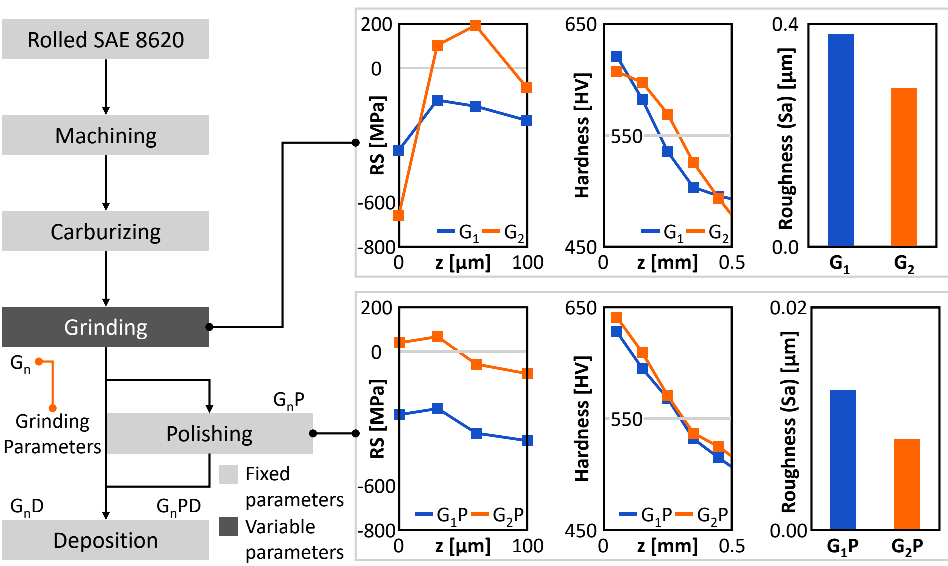


Agenda

Influence of Substrate Surface Integrity on Coating Behavior



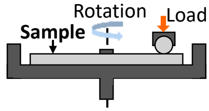
Influence of Substrate Surface Integrity on Coating Behavior

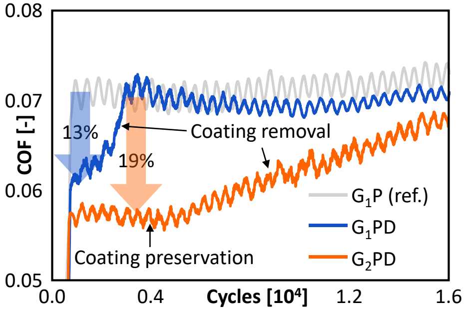


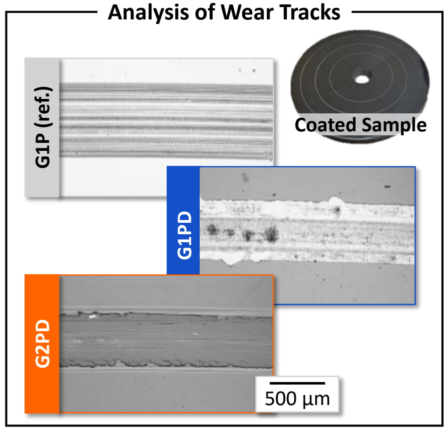
G_1: Ground with Al_2O_3 grinding wheel; G_2: Ground with SiC grinding wheel; P: Polished; D: Deposited

Influence of Substrate Surface Integrity on Coating Behavior

- Ball-on-Disc Test
  - P_H: 1.5 GPa, v_t: 1 m/s, and PAO ISO VG 8 base oil



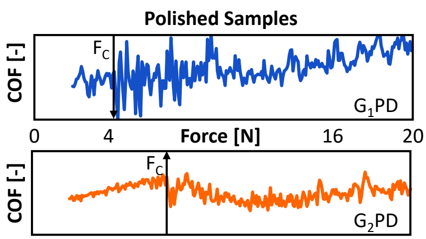


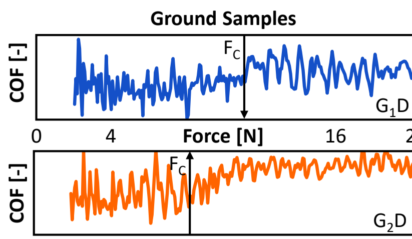


- **Controlling substrate RS:**
  - Higher COF reduction: 13 to 19% in G_2PD
  - Higher adhesion: coating preservation and smooth removal in G_2PD

G_1: Ground with Al_2O_3 grinding wheel; G_2: Ground with SiC grinding wheel; P: Polished; D: Deposited

Influence of Substrate Surface Integrity on Coating Behavior

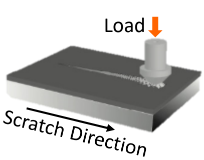




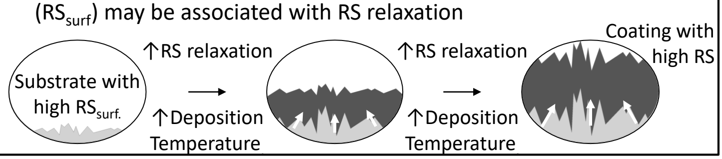
	Sa	$RS_{surf.}$	F_C
G_1PD	↑	↓	↓
G_2PD	↓	↑	↑

Critical Force ↕ Coating Removal

	Sa	$RS_{surf.}$	F_C
G_1D	↑	↓	↑
G_2D	↓	↓↓	↓



- The higher adhesion obtained with less compressive surface RS (RS_{surf}) may be associated with RS relaxation

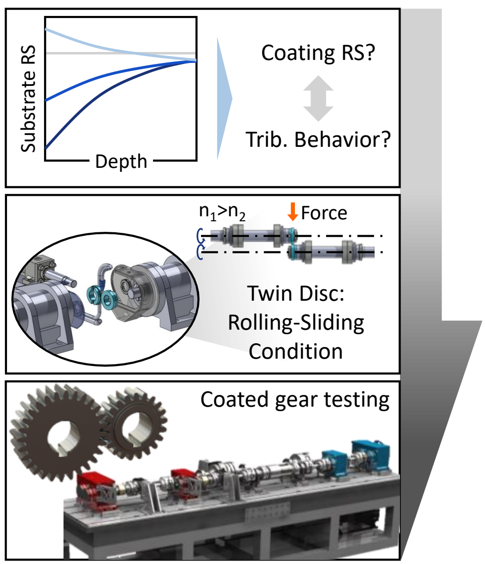


G_1: Ground with Al_2O_3 grinding wheel; G_2: Ground with SiC grinding wheel; P: Polished; D: Deposited

Agenda

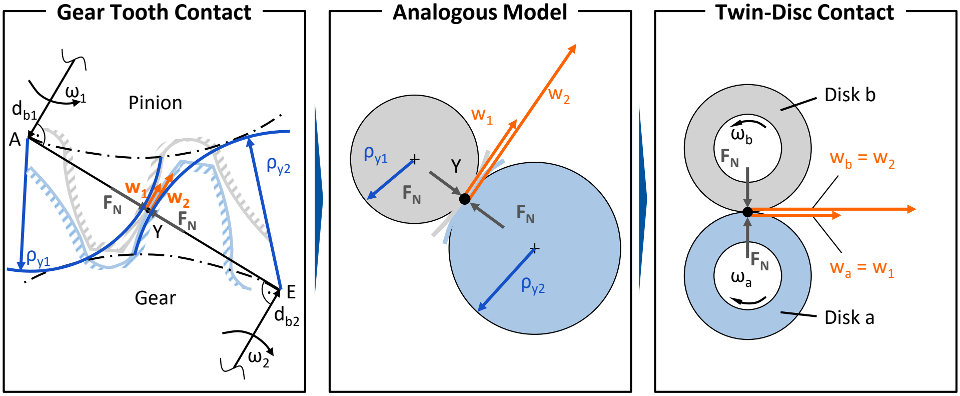
Summary & Outlook

- Nb doping can improve mechanical and tribological properties of MoS_2 coatings
- Substrate RS state influences the tribological behavior of the coating
  - This may be related to the relaxation of the RS during deposition
- Twin Disc will enable fatigue tests in rolling-sliding condition
- Next Steps:
  - The comprehension on how substrate surface integrity influence coating behavior can guide the design of a **PVD-oriented gear manufacturing chain**
  - Nb:MoS_2 coating will be evaluated in terms of **fatigue tests in rolling-sliding condition** and **gear contact fatigue**



High-Speed Twin Disc Development

- **Twin Disc** Concept



d_b: Base Diameter

ρ_y: Radius of Curvature at Point Y

w: Tangential Speed

F_N: Normal Force

ω: Angular Speed

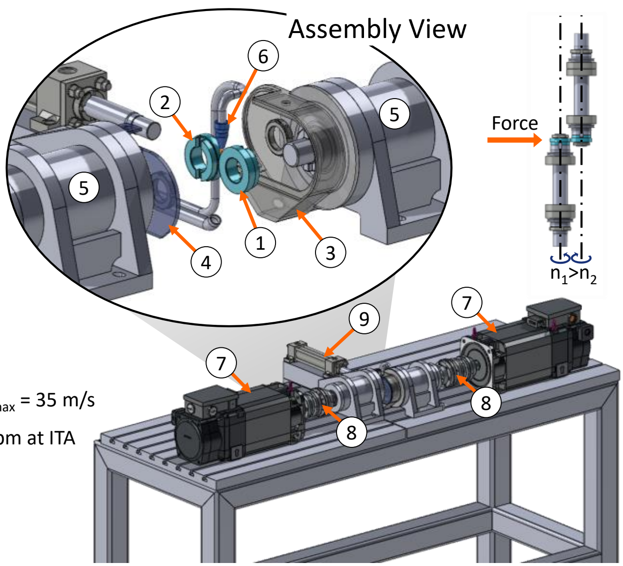
A/E: Start/End of Path of Contact

Source: [GOER20]

High-Speed Twin Disc Development

- Conceptual Project

1. **Test Disc (Cylindrical)**
2. **Counter Disc (Crowned)**
3. Housing
4. Housing Cover
5. Spindle
6. Oil-jet
7. High Speed Motor
8. Torque Transducer
9. Hydraulic Actuator



- Operating Conditions
  - n_1 up to 12,000 rpm ↔ $v_{R,max}$ = 35 m/s
    - Equivalent to 35,000 rpm at ITA Geometry
  - P_H up to 3 GPa
  - SRR: -200%/200%

BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

WZL | RWTH AACHEN UNIVERSITY

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

V. Laser Sintered Gears: Surface Densified for Higher Performance

– *Izabel Lima, Eng. (ITA) / Arthur Mascheroni, M.Sc. (Alkimat)*

Indirect Selective Laser Sintering (iSLS) has demonstrated disruptive potential to meet the requirements of drivetrain components, such as gears, in terms of materials and product design for electromobility application. Higher torque efficiency, lower levels of noise, vibration and harshness are expected for the gears. iSLS manufacturing enables solutions in this regard, mainly due to the faster print speed when compared to other Additive Manufacturing (AM) techniques. This speed is linked due to the combination of reduced laser power, high scanning speeds, larger layers, and lower melt temperatures of the polymeric matrix for the generation of the "green part". However, challenges still exist regarding to the low densities arising from the intrinsic characteristics of the coated metal powder and the need for sintering. The Shot Peening (SP) process has the potential to densify surfaces, since during blasting at high speeds, the kinetic energy causes plastic deformation in the material, but its implications are still little addressed in the literature. The objective of the present study was to explore the impacts of Shot Peening with parameter variations on the properties of iSLS surfaces produced with carburized 20MnCr5 steel. The decision of the peening parameters for explaining the densification phenomena were based on a numerical approach. Sample density and surface integrity characteristics induced from printing to peening and residual stress, were evaluated. From the perspective of automotive applications, the results provide information about the density of iSLS processing on cemented steel, as well as the depth of the densified layer on cemented steels obtained by shot peening.

The Brazilian Gear Conference ITA-WZL 2023

Laser Sintered Gears: Surface Densified for Higher Performance

Izabel Lima Criscuolo, Eng. *(ITA)*

Arthur Mascheroni, M.Sc. *(Alkimat)*

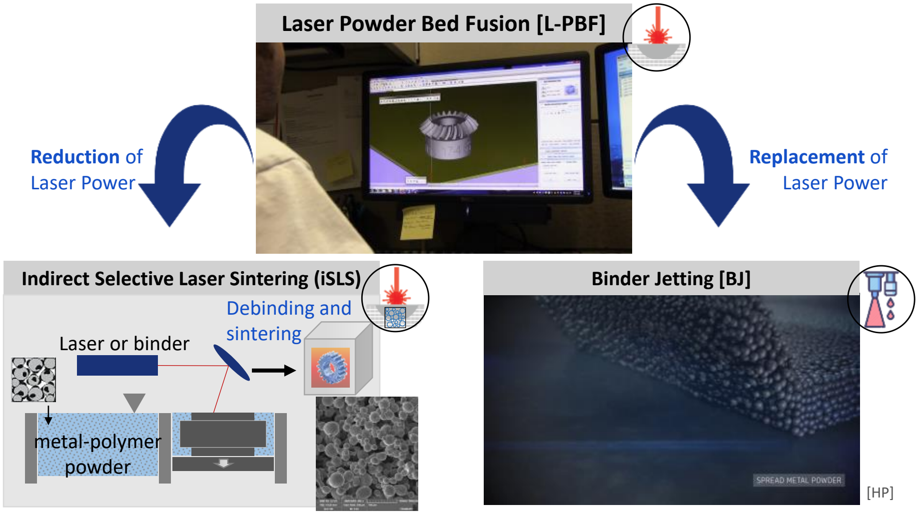
São José dos Campos, October 18th & 19th, 2023

Agenda

1. Additive Manufacturing Alternatives for Gear Production
2. Potential of Densified iSLS Gears with Shot Peening
3. iSLS Surface Densification with Shot Peening
4. Summary and Outlook

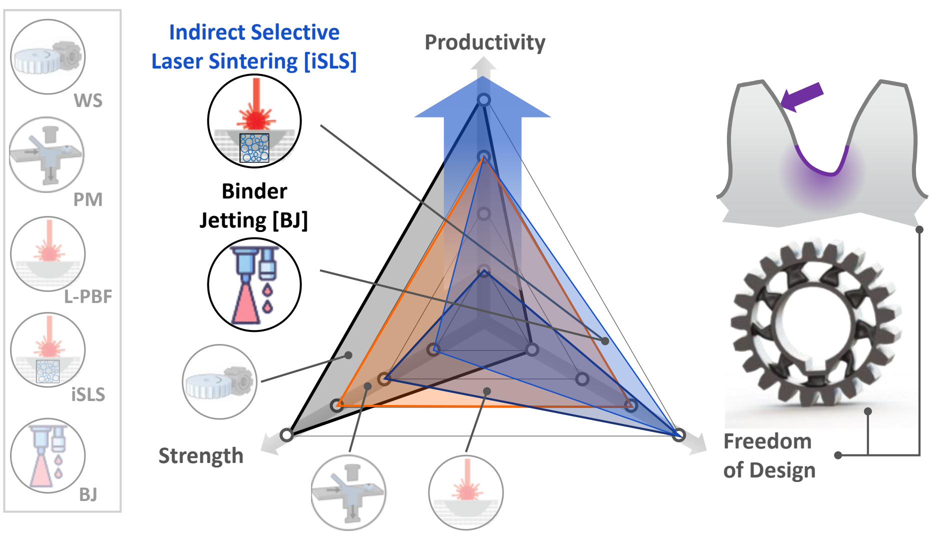
Introduction: *Additive Manufacturing Alternatives for Gear Production*

Two Additive Manufacturing trends for gear manufacturing: DIRECT and INDIRECT processes



Introduction: *Gear Requirements for E-Mobility*

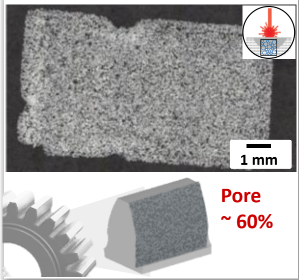
- Disruptive **geometries** required, but with **durable** and **productive** solutions

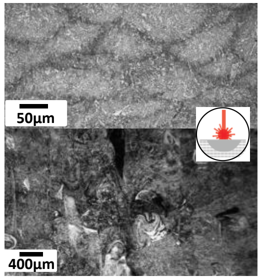


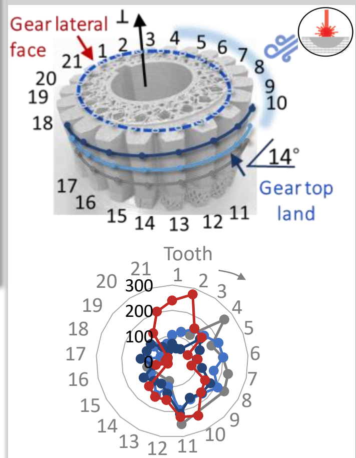
Introduction: *Deepening the Need for Freedom of Design*

Challenges of Additive Manufacturing processes

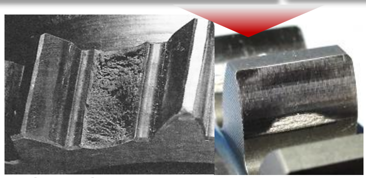
High Porosity [iSLS]	Microstructural Stress Concentrators	Heterogeneous Residual Stresses







[LECH99]



Source: [ROBA22]

Agenda

1. Additive Manufacturing Alternatives for Gear Production
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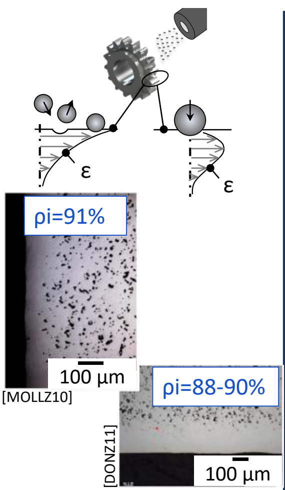
Shot Peening for iSLS Surface Densification



Densification is limited to a **low depth magnitude (<170 µm)**

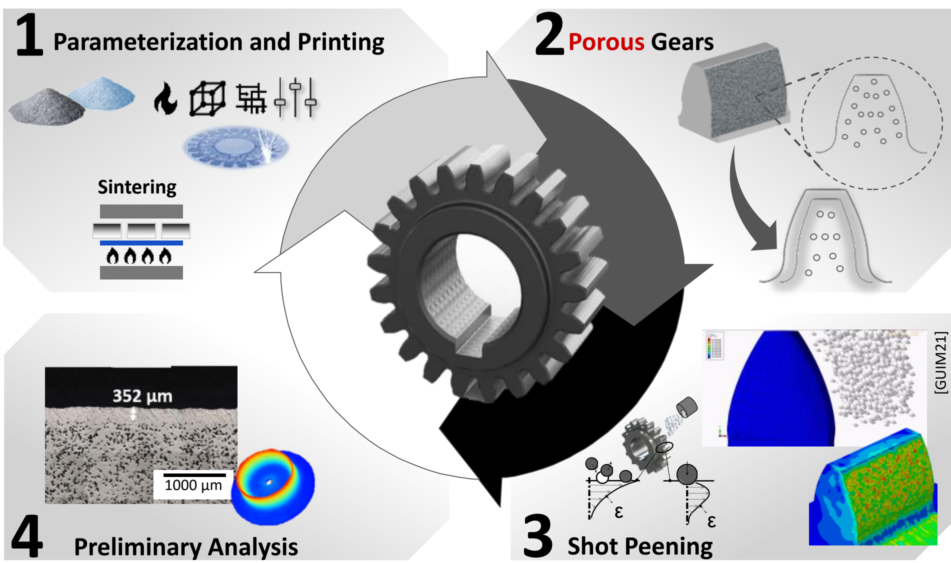
Potential for densifying iSLS surface layers with Shot Peening

- Surface plastic deformation
- Induction of compressive RS
- Mechanical impact of small round hard particles ("media")
  - Kinetic energy converted in plastic deformation energy
- Noise damping

Challenges of SP for densification of ISLS gear surface layers

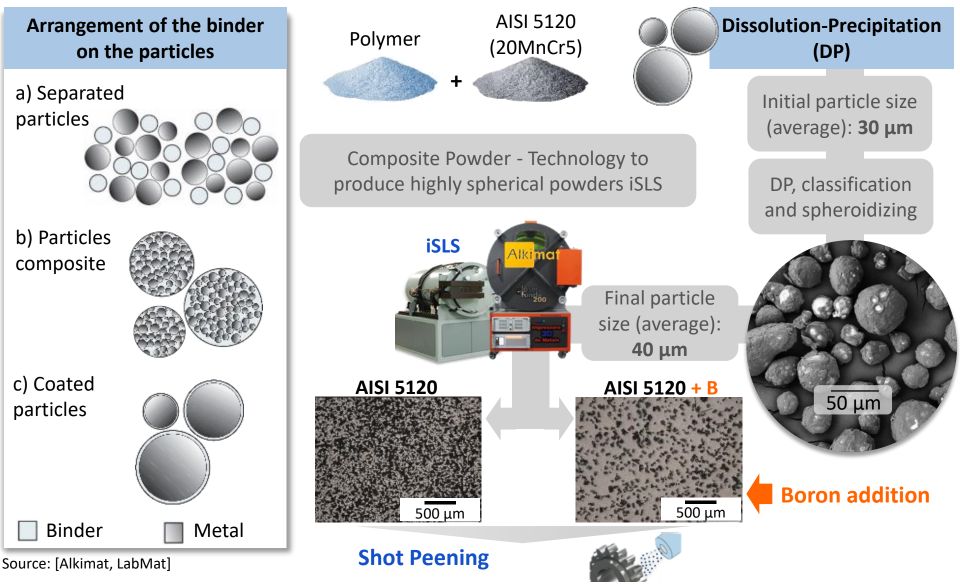
- Material Porosity iSLS
- Tooth Root Geometry
- Shot Peening Machine Configuration
  - Peening speed
  - Peening angle
  - Coverage
  - Exposure time
- Media Properties
  - Shape
  - Material
  - Diameter/Size
  - Hardness

Deepening the Need for Freedom of Design: *Selective Densification*



Agenda

Material Development for iSLS

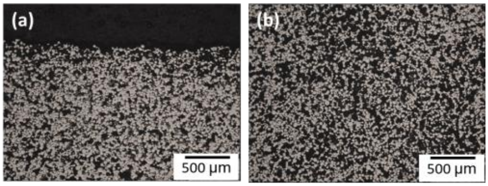


Source: [Alkimat, LabMat]

iSLS Sample Density

AISI 5120 (20MnCr5) - Dissolution-Precipitation (DP)

AISI 5120 (20MnCr5)

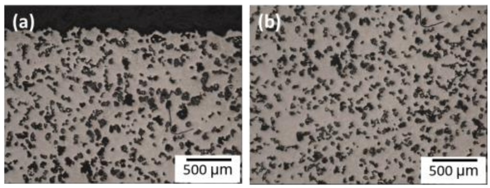


(a) Surface (b) Core

DENSITY ~50%

AISI 5120 + B - Dissolution-Precipitation (DP)

AISI 5120 + B



(a) Surface (b) Core

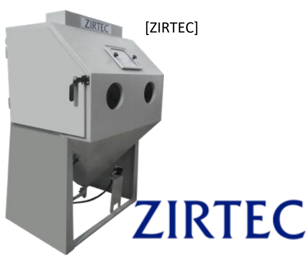
DENSITY ~75%

iSLS Sample Density

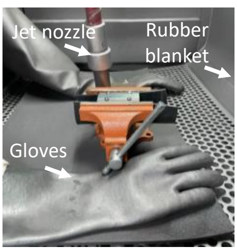
AISI 5120 (20MnCr5)

AISI 5120 + B

[ZIRTEC]



Shot peening machine GP-9075

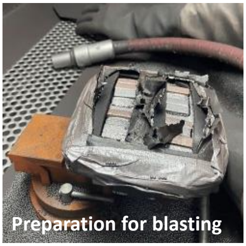


Interior of the shot peening machine cabinet

Possibilities of variables

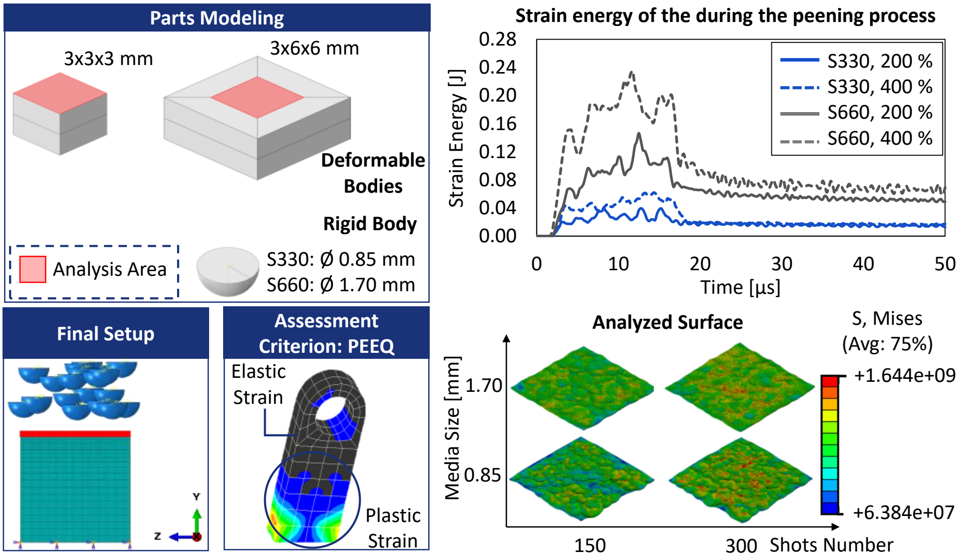
- Shot Peening Machine Configuration
- Media Properties

Selected Variables:
- Temperature: 23°
- Coating:
200 and 400%
- Coverage:
S330 (Ø 0.85 mm) and S660 (Ø 1.70 mm)

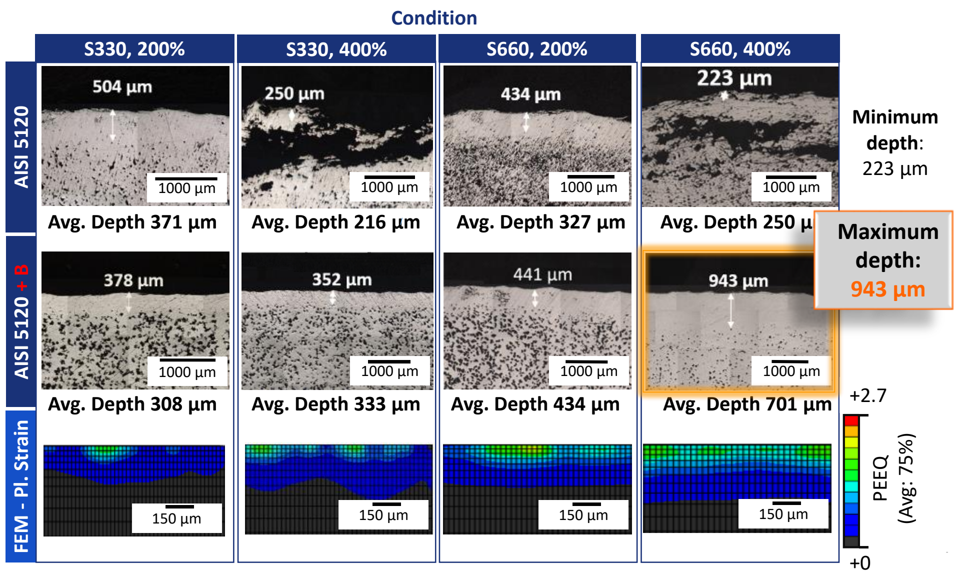


Simulation, execution and analysis

Simulation of iSLS Surface Densification: *Shot Peening*

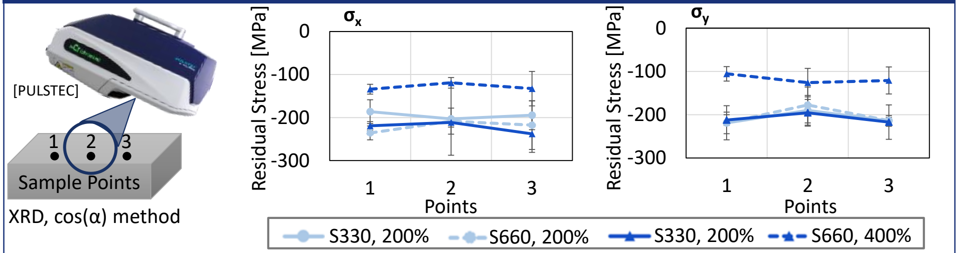


Densified Surface Layer: *Shot Peening*

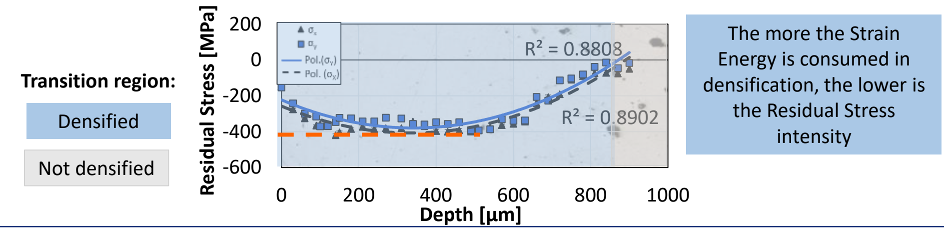


Surface Integrity: *Residual Stress Analysis on AISI 5120 + B*

Residual Stress Assessment



In-Depth Residual Stress Assessment - S660, 400%



Agenda

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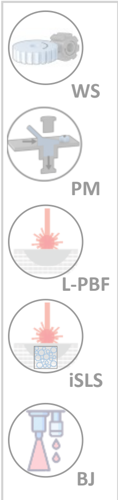
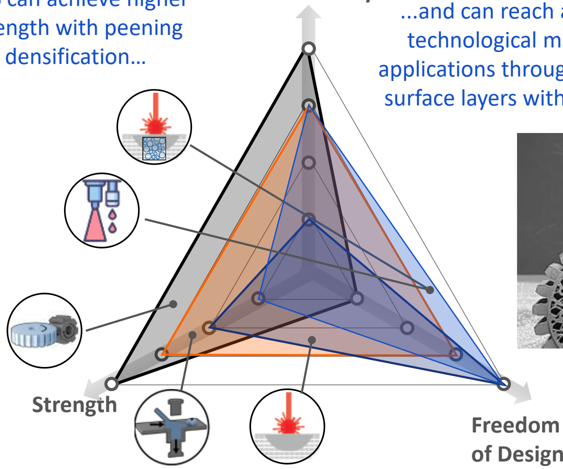
Summary

- Disruptive **geometries** required, but with **durable** and **productive** solutions



iSLS can achieve higher strength with peening densification…



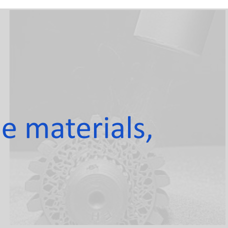
...and can reach a higher level of technological maturity for **gear** applications through **densification** of surface layers with **Shot Peening**.....

Summary

- Disruptive **geometries** required, but with **durable** and **productive** solutions

iSLS can achieve higher strength with peening densification…

...and can reach a higher level of technological maturity for **gear** applications through **densification** of surface layers with **Shot Peening**.....



… E-mobility brings one certain:

Gears won't be produced anymore with the same materials, design and manufacturing processes

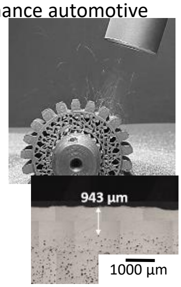
This is the chance for iSLS.

Outlook

Proof-of-concept validations presented the potential of iSLS for high performance automotive transmission gears.

Further steps should focus on:

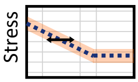
- New alloys and metal-polymer composites.
- Understanding the complexity of other shot peening parameters to improve contact fatigue resistance.
- Warm peening concepts to realize the increase of plastic deformation with increasing sample temperature.
- Load-carrying capacity testing: **Project "AGILE"**



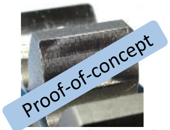
Densified iSLS knowledge must be better disclosed!

Flexibility
(customized alloys)

Reliable results
"Stable" behavior



Reasonable fatigue strength



[LECHNER]

Efficiency improvement

NVH reduction

Production costs

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III. New Surface Requirements for Electrical Mobility: Interaction Between Isotropic Superfinishing and Grinding –

Gilberto Martins, M.Sc. (ITA) / Antonio Gallinucci, M.Sc. (Engrecon)

The future of mobility is tied to increased efficiency and energy utilization, where downsizing components becomes a key-task. In the perspective of gearboxes, the need for increased load-carrying capacity is highlighted. The gearing optimization itself can be achieved through surface improvement, as a consequence of further developments in manufacturing processes. In this scenario, the isotropic superfinishing appears as a great potential candidate of achieving the new requirements of surface integrity. Superfinishing stands as the final finishing process for gears, usually proceeded by a grinding process. However, the interaction of isotropic superfinishing with previous manufacturing steps and their corresponding characteristics is not explored by the state-of-the-art. In this way, the evaluation of the influence of the manufacturing chain and how surface integrity is affected is unknown for the superfinishing process. In the grinding process, fluidic flow, feed rate, and wheel grit were varied, resulting in different residual stress states. It was possible to verify the influence of the grinding process; this influence was tied to hardness, microstructural, fatigue life, and residual stress factors, which preserved the heterogeneity and residual stress intensity previously defined in the grinding. This variation is understood by the Design for Residual Stress (DRS) concepts, demonstrating the need to observe the entire manufacturing chain to understand the state of surface integrity. Understanding the interaction between isotropic superfinishing is essential to electric mobility applications assisting in implementing other manufacturing processes to optimize other surface parameters as needed for the application, highlighting airplanes, tractors, and cars.

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CENTRO DE COMPETÊNCIA EM MANUFATURA

New Surface Requirements for Electrical Mobility: Interaction Between Isotropic Superfinishing and Grinding

Gilberto Martins, M.Sc. *(ITA)*

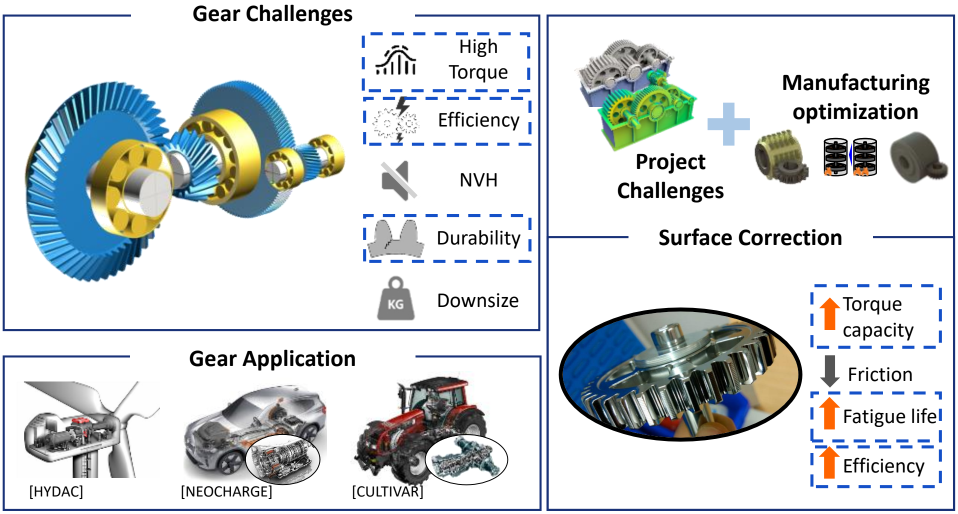
Antonio Gallinucci, M.Sc. *(Engrecon)*

São José dos Campos, October 18th & 19th, 2023

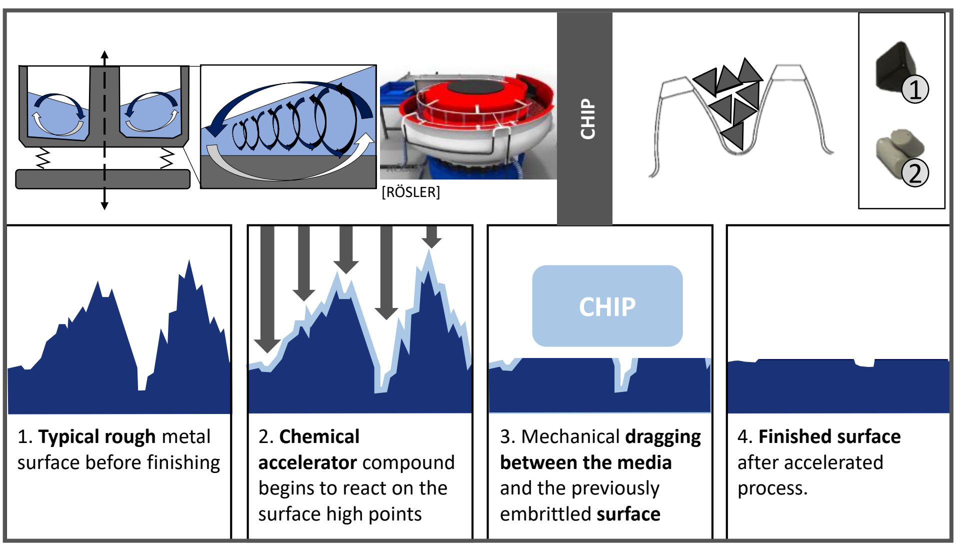
Agenda

1. Superfinishing in Gear Manufacturing Chain
2. Processing Difficulties of Isotropic Superfinishing
3. The Impact of Grinding on the Isotropic Superfinishing
4. Summary and Outlook

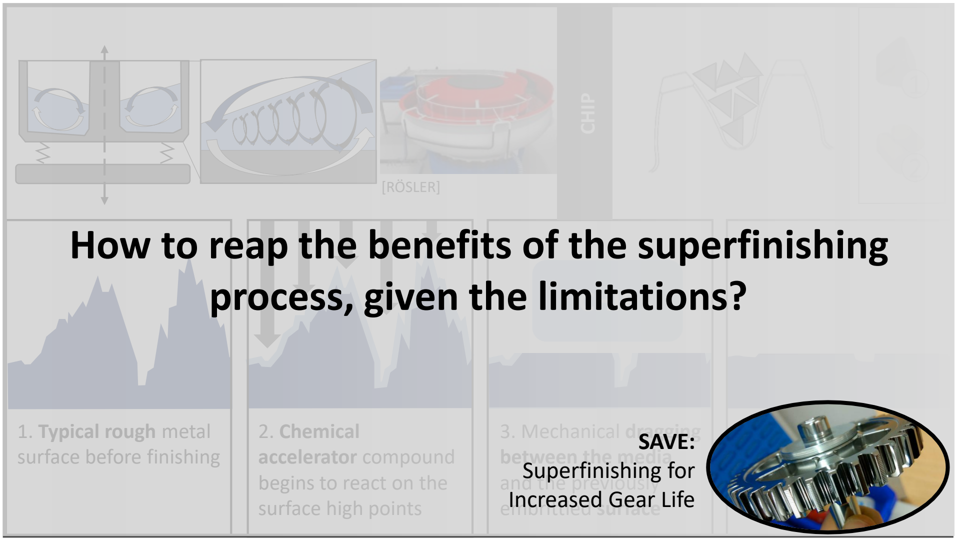
Superfinishing in Gear Manufacturing Chain



Superfinishing in Gear Manufacturing Chain: *Isotropic Superfinishing*



Source: [MITT97, BIGE08]



How to reap the benefits of the superfinishing process, given the limitations?

Source: [MITT97, BIGE08]

Agenda

1. Superfinishing in Gear Manufacturing Chain
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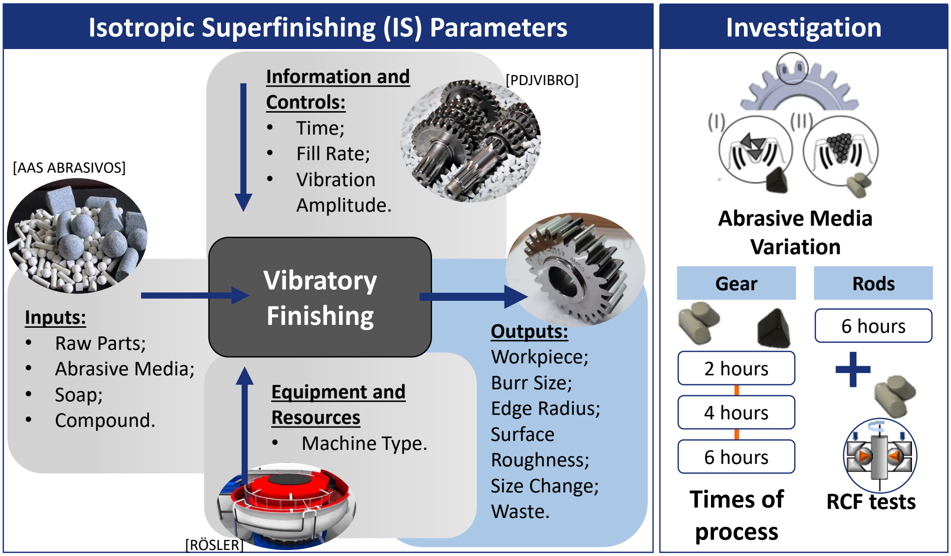
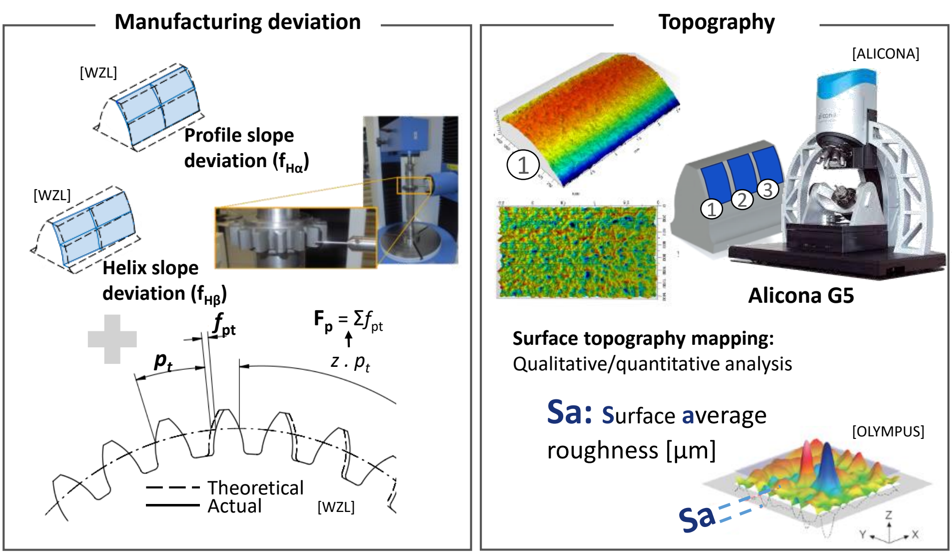
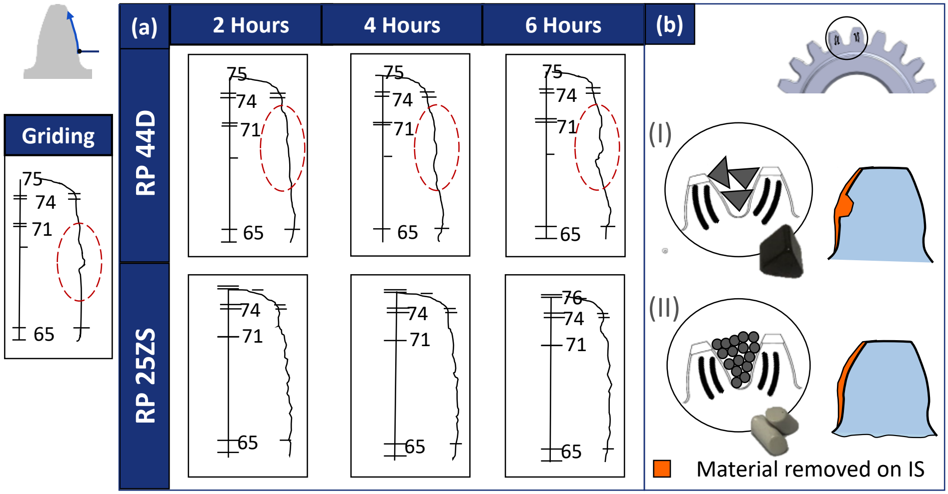
Processing Difficulties of Isotropic Superfinishing



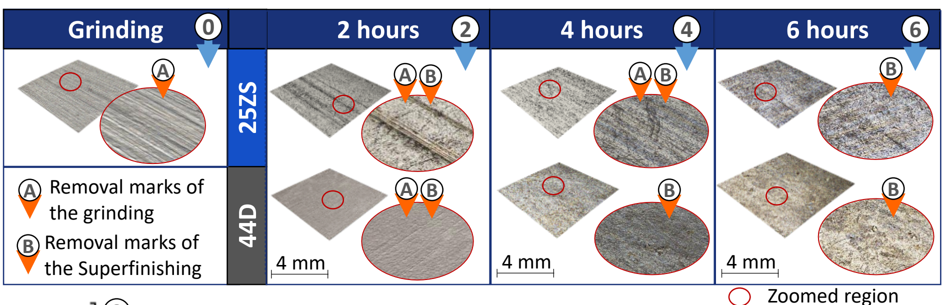
Materials and Methods: *Surface Integrity Analysis*

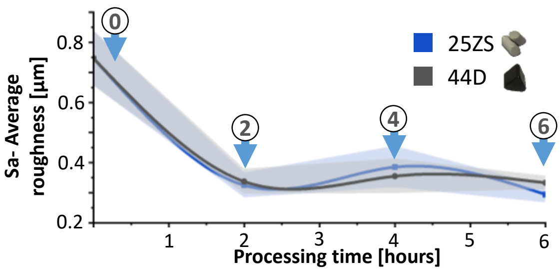


Manufacturing Deviation in the Superfinishing Process



Surface Integrity Analysis: *Roughness Reduction*





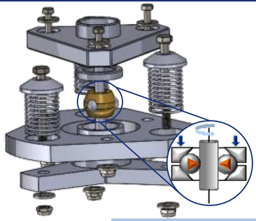
Tukey test (95 % Confidence level)

	GRIN	44D 2	44D 4	44D 6
GRIN	-	≠	≠	≠
25ZS 2	≠	=	=	≠
25ZS 4	≠	=	=	≠
25ZS 6	≠	=	≠	≠

= Statistically different

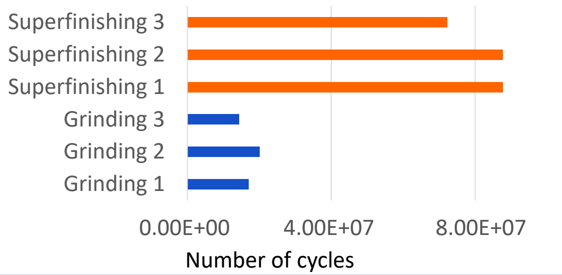
Rolling Contact Fatigue Tests: *Grinding Compared to IS*

Ball-Rod Test Rig

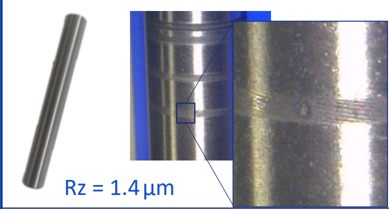


F = 252 N

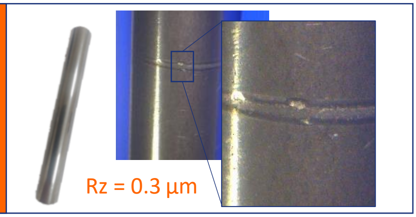
Rolling Contact Fatigue Tests



Grinding



Superfinishing



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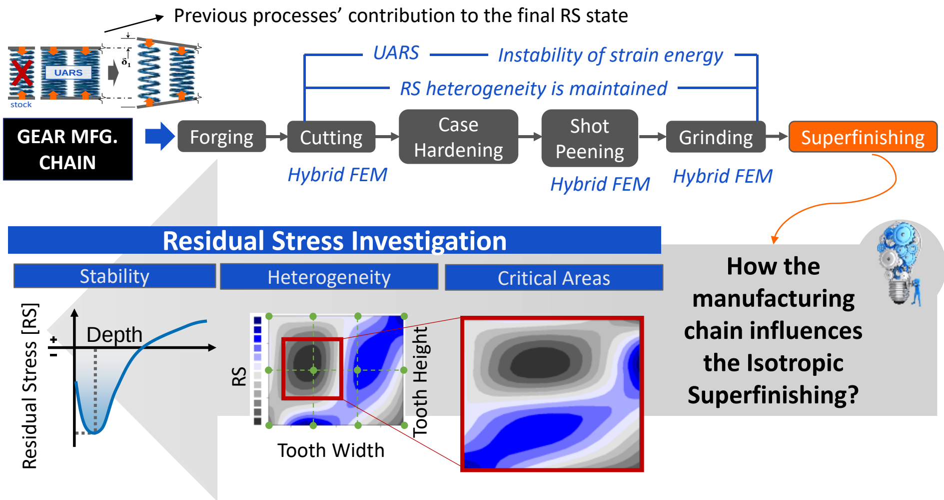
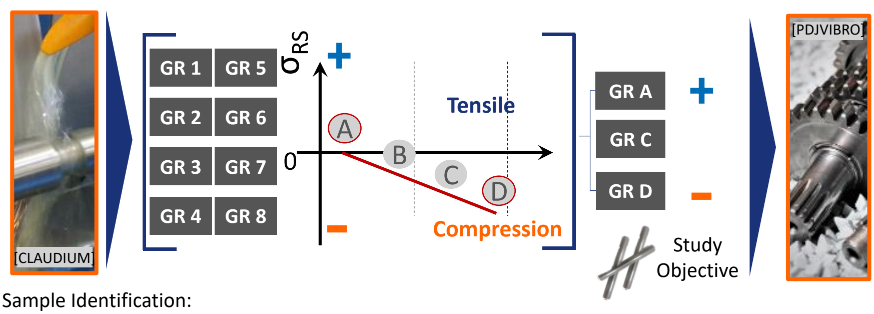
The Impact of Grinding on the Isotropic Superfinishing

Design for Residual Stress (DRS) Developments



Source: [REGO16, DOLI16, DOLI21, GUIM21]

Materials and Methods: *Grinding Parameters*



Sample Identification:

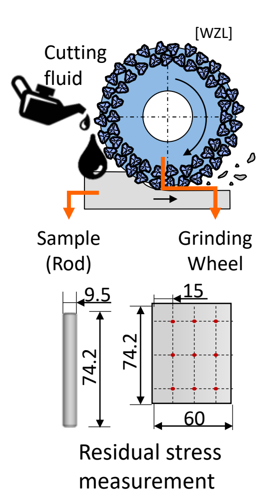
GR Grinding

IS Isotropic Superfinishing

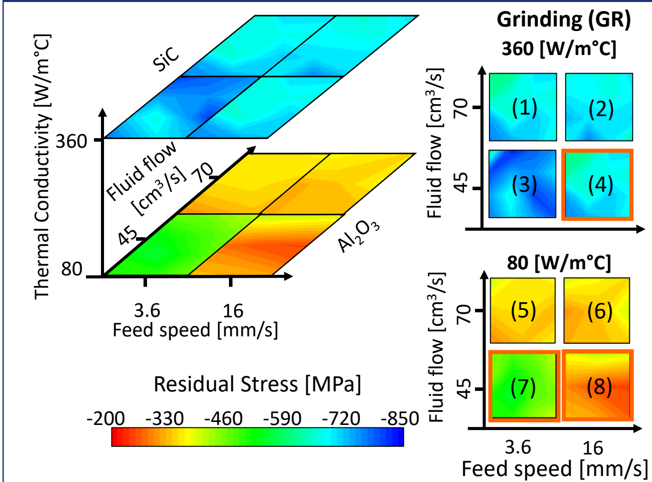
Parameter	GR 1	GR 2	GR 3	GR 4	GR 5	GR 6	GR 7	GR 8
Thermal conductivity [W/m° C]	360 (SiC)				80 (Al_2O_3)			
Feed speed [mm/s]	3.6	3.6	16	16	3.6	3.6	16	16
Fluid flow [cm^3/s]	45	70	45	70	45	70	45	70

Residual Stress Distribution on Ground Samples

Experiment Config.



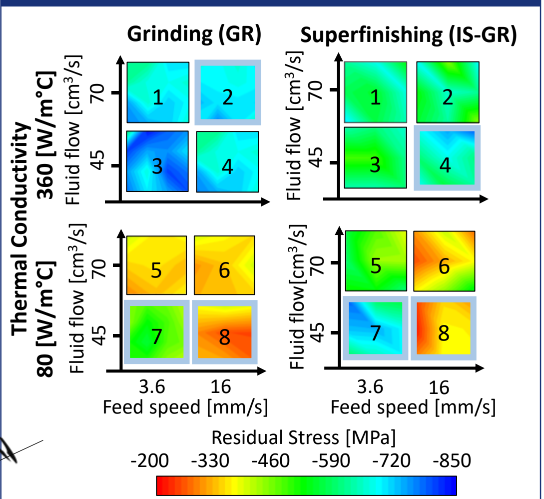
Residual Stress Variation on Grinding



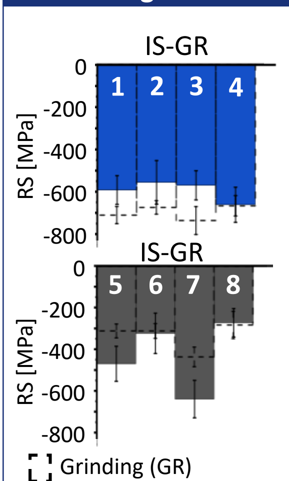
OBS: Measures in millimeters [mm]

Residual Stress Heterogeneity

Residual Stress Interaction

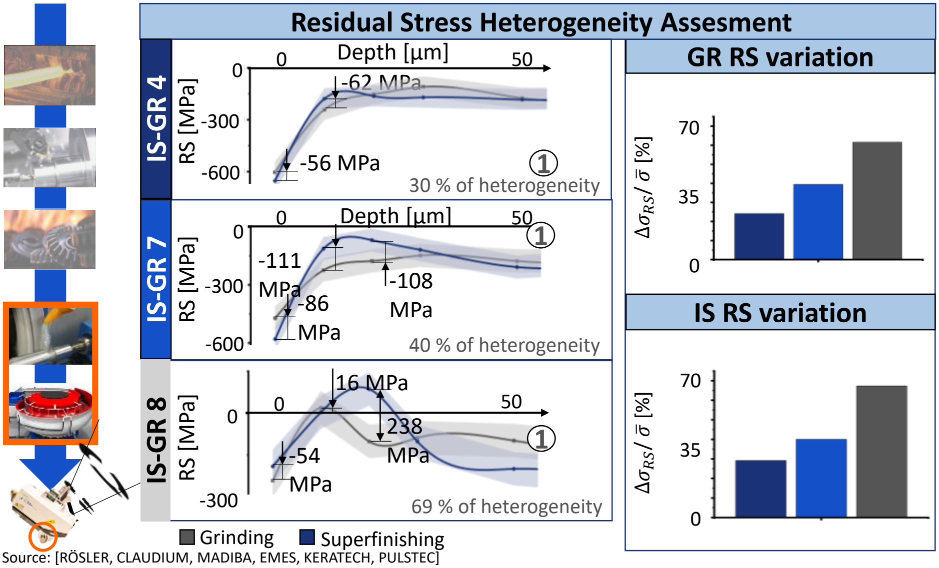


Average of RS



Source: [RÖSLER, CLAUDIUM, MADIBA, EMES, KERATECH, PULSTEC]

Residual Stresses Heterogeneity



Source: [RÖSLER, CLAUDIUM, MADIBA, EMES, KERATECH, PULSTEC]

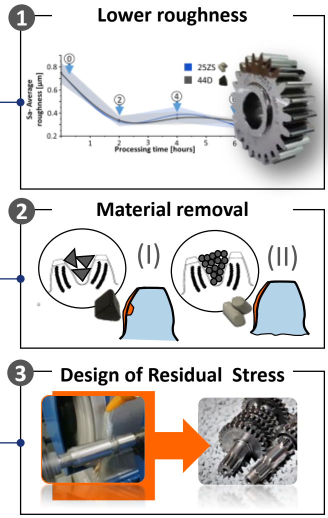
Agenda

Summary and Outlook

New Surface Requirements for Electrical Mobility:
Interaction Between Isotropic Superfinishing and Grinding

Conclusions

- The isotropic superfinishing induces a **lower roughness and a more homogeneous surface**;
- **Different media** can change the amount and shape of **material removal during superfinishing**;
- This study **confirms** the preposition of the effect of residual stress along the **manufacturing chain -DRS**.



Summary and Outlook

SAVE: Superfinishing para Aumento da Vida útil de engrenagens

Engrena ITA

\+

Design a custom gearbox for **agricultural vehicles** with new requirements

[Valtra]

Safety **NVH** **Emission** **Efficiency**

Objective	Upgrading of Agricultural Gearboxes with New Requirements through Isotropic Superfinishing

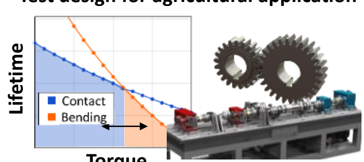
Transmission System Design

[Valtra]

Load Carrying Capacity

Torque Efficiency

Test design for agricultural application



BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

VI. Overcoming E-Mobility Challenges Through Additive Manufacturing

– *Guilherme Guimarães, M.Sc. (ITA) / Lukas Klee, M.Eng. (WZL)*

Market movement toward sustainability and electromobility impose new demands on the Gear Industry in terms of materials, design and manufacturing. In this context, additive manufacturing has been under the spotlight for being one of the most promising Industry 4.0 technologies. On the other hand, anisotropic properties, distortions, and heterogeneous residual stresses bring up new challenges, especially for parts subjected to complex load conditions such as gears. Therefore, this study approached the potential and challenges of additive manufacturing for gear applications, highlighting the application of laser powder bed fusion and binder jetting. Since the surface integrity state induced by the additive manufacturing chain is hardly found on literature, the study began approaching the processability of 20MnCr5 for L-PBF and 17-4Ph for Binder Jetting. The study also approached the surface integrity mapping along the manufacturing chain, including finishing processes. Topography, distortion, residual stresses and microstructure was mapped from printing to grinding, highlighting the challenges and differences from wrought steel to additive manufactured. Furthermore, the study showed great potential for applying additive manufacturing to gears while also mapping the major challenges in using these components successfully in industrial applications .

The Brazilian Gear Conference ITA-WZL 2023

Overcoming E-Mobility Challenges Through Additive Manufacturing

Guilherme Guimarães, M.Sc. *(ITA)*

Lukas Klee, M.Eng. *(WZL)*

São José dos Campos, October 18th & 19th, 2023

Agenda

Future of Mobility Translated to Gear Requirements

Ford Opens Cologne EV Center, Home Of Europe's Electric Explorer SUV

Production of the electric Explorer starts this year, followed in mid-2024 by a second MEB-based EV dubbed a "sports crossover."

[InsideEVs, 2023]

One shared car 'replaces ten private cars' in Flanders

[The Brussels Times, 2023]

Transportation

Uber is taking its car-sharing service to North America

Kirsten Korosec

[Techcrunch, 2023]

Electric cars demand in Europe grows as over 1 million passenger EVs registered in Q1, 2023

[InsideEVs, 2023]

San Francisco is a postcard from a driverless car future. Here's what it's like.

[Washington Post, 2023]

Chinese EV maker Xpeng expands self-driving capability to streets of Beijing as it bids for autonomous car leadership

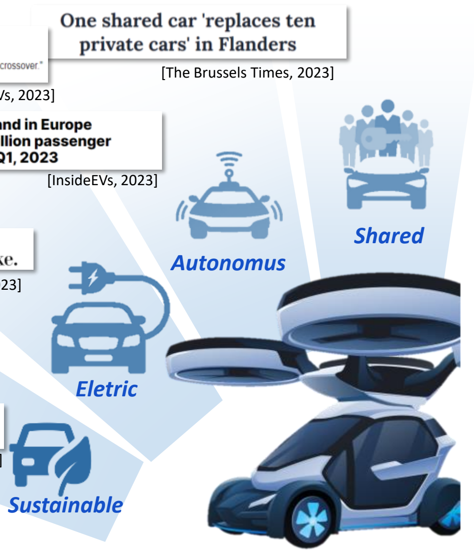
[South China Morning Post, 2023]

EU Climate Policy Reforms Set Conditions for Large Global Manufacturers to Decarbonize

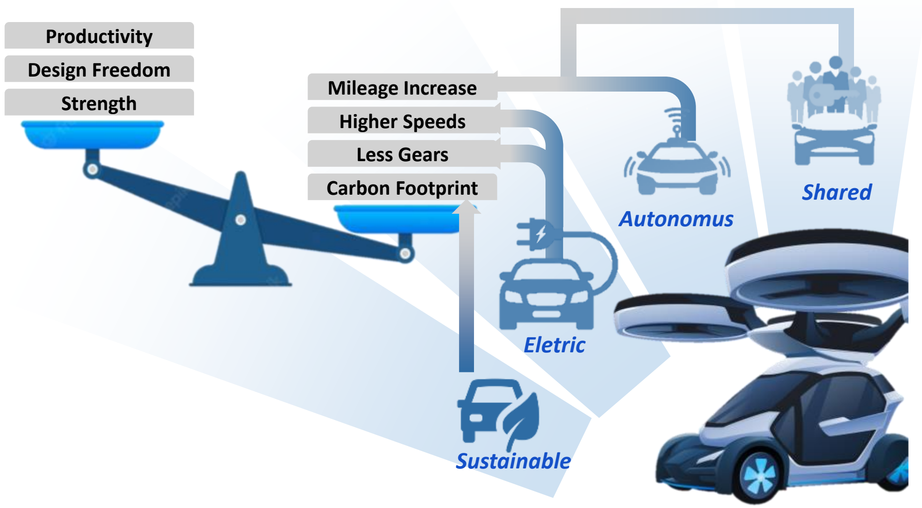
[EnvironmentLeader, 2023]

SKF announces five-year, $278m decarbonisation investment

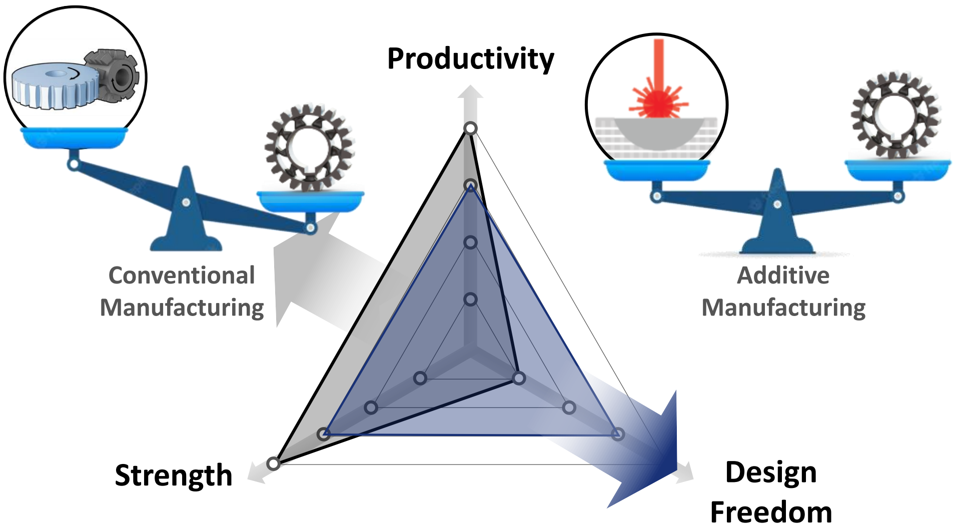
[Power Technology, 2023]



Future of Mobility Translated to Gear Requirements

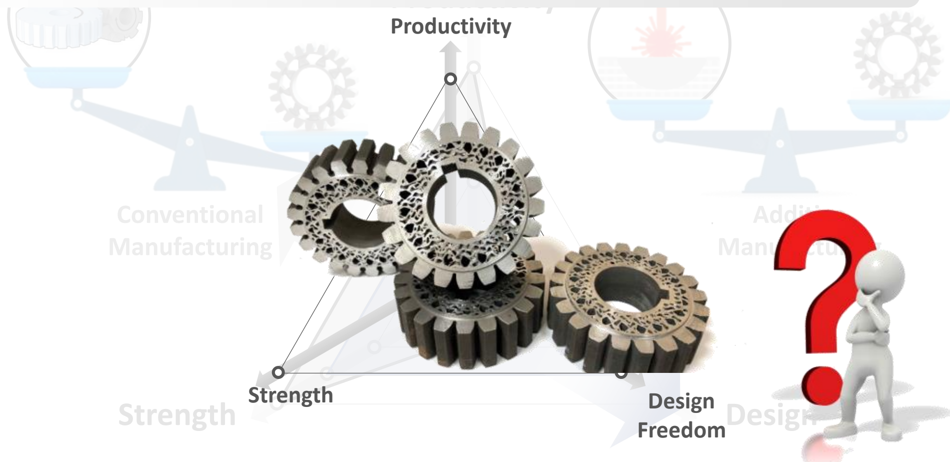


Future of Mobility



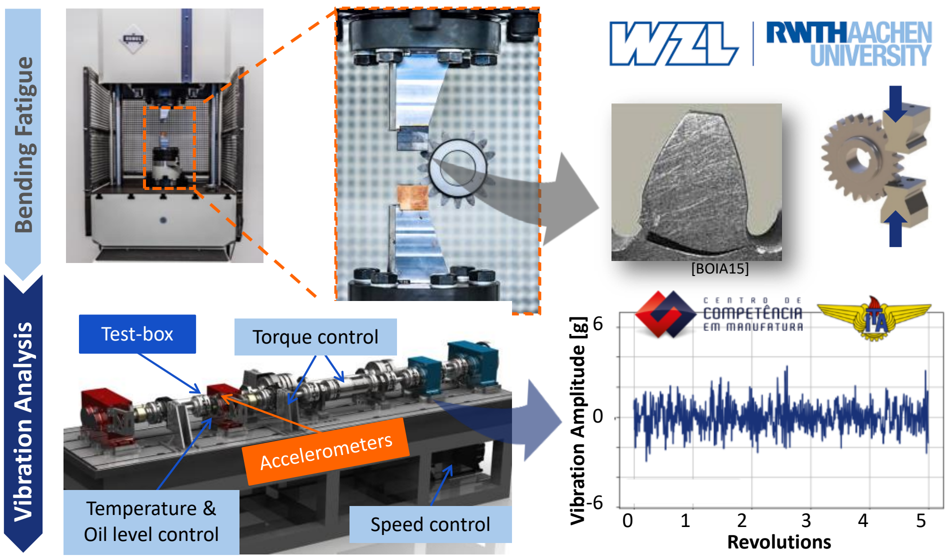
Future of Mobility

What about Performance?



Agenda

Testing Facilities

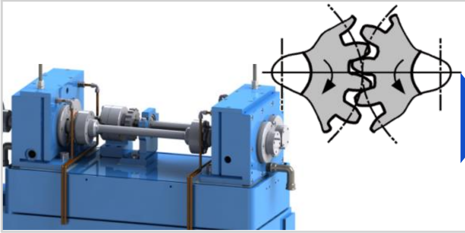


Tooth Root Load Capacity

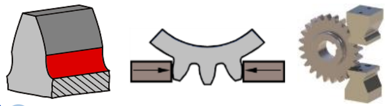
Bending Fatigue

Vibration Analysis

Running Test



Analogy Test – Tooth Root



- Reduced Number of Test Samples
- Reduction of Test Duration
- Good Transferability

Gear Geometries

Binder Jetting (17-4PH)

Number of Teeth z_2	= 20
Module $m_{n,2}$	= 3.175 mm
Tip Diameter $d_{a,2}$	= 71.698 mm
Root Diameter $d_{f,2}$	= 56.093 mm
Pressure Angle $\alpha_{n,2}$	= 20°
Helix Angle β	= 0°
Profile Mod. Factor x_2	= 0.205
Tooth Width b_2	= 18 mm

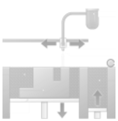
L-PBF (16MnCr5)

Number of Teeth z_2	= 16
Module $m_{n,2}$	= 4.5 mm
Tip Diameter $d_{a,2}$	= 82.450 mm
Root Diameter $d_{f,2}$	= 61.594 mm
Pressure Angle $\alpha_{n,2}$	= 20°
Helix Angle β	= 0°
Profile Mod. Factor x_2	= 0.1818
Tooth Width b_2	= 14 mm

Tooth Bending Strength: *Endurance Stair Step*

Bending Fatigue

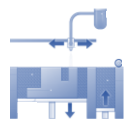
Vibration Analysis



316L: $2 \cdot F_{A,mean}$ = 6.26 kN; $\sigma_{F0,Pulsator,mean}$ = 351 N/mm²

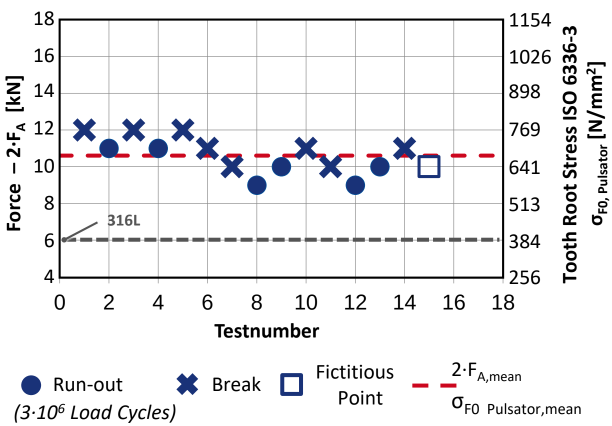
VS

17-4PH: $2 \cdot F_{A,mean}$ = 10.60 kN; $\sigma_{F0,Pulsator,mean}$ = 688 N/mm²



Process Parameters	
F_0	- 0.5 kN
F_u	Variable
F_A	Variable
f_{P4}	143 Hz
$Z_{Clamped}$	4
P_a	50 %
T_a	21 °C

Electromagnetic Resonance Pulsator
RUMUL TESTRONIC 150

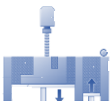


Source: [KLEE22]

Tooth Bending Strength: *Endurance Stair Step*

Bending Fatigue

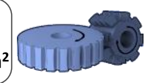
Vibration Analysis



16MnCr5
$2 \cdot F_{A,mean}$ = 17.58 kN
$\sigma_{F0,Pulsator,mean}$ = 1037 N/mm²

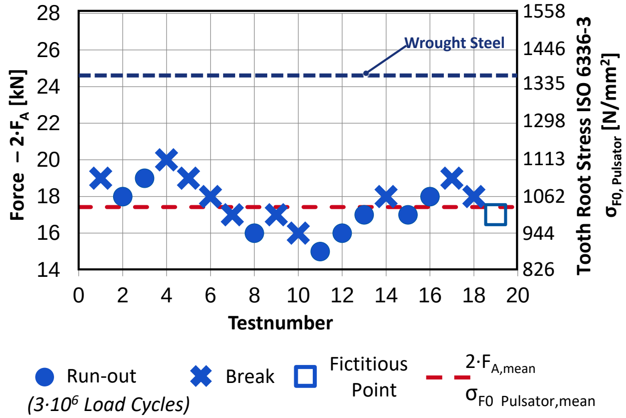
VS

16MnCr5
$2 \cdot F_{A,mean}$ = 24.31 kN
$\sigma_{F0,Pulsator,mean}$ = 1353 N/mm²



Process Parameters	
F_0	- 1 kN
F_u	Variable
F_A	Variable
f_{P4}	30 Hz
$Z_{Clamped}$	3
P_a	50 %
T_a	21 °C

Unbalanced resonance pulsator SCHENCK PHT 010N

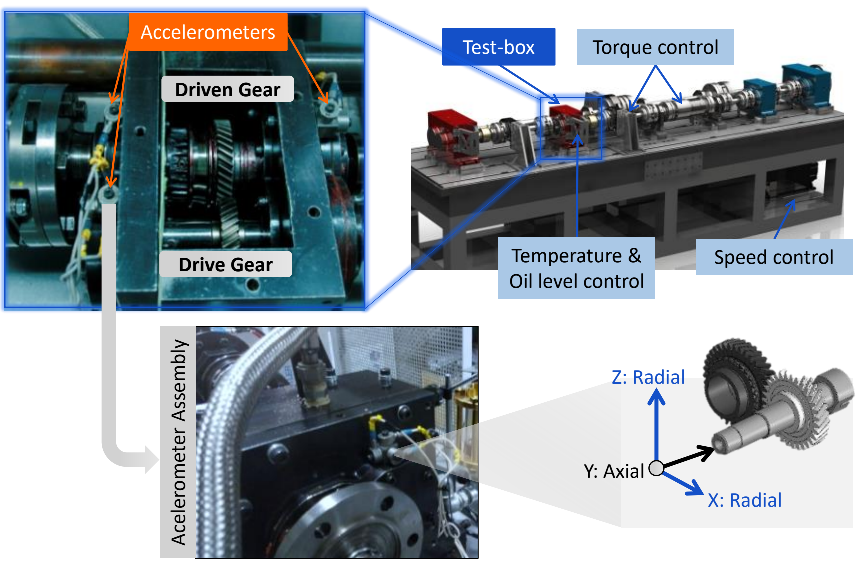


Source: [KLEE22]

ITA Test Rig: *Vibration Analysis*

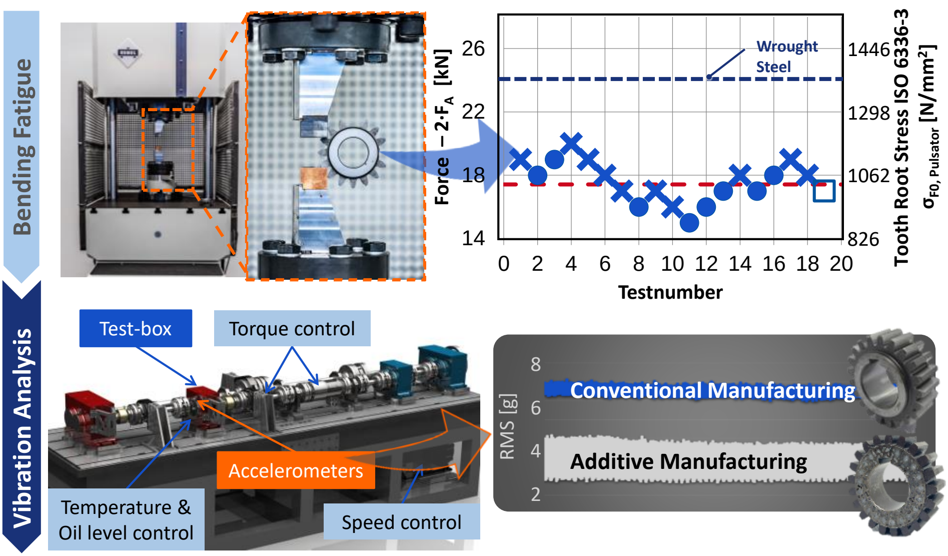
Bending Fatigue

Vibration Analysis



Running Behavior: *Gear Vibration*

ITA Test Rig: *Vibration Analysis*



Agenda

Gear Measurement After Hard Finishing

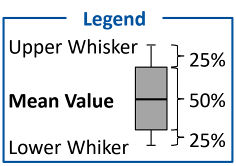
Quality within ISO 1328 IT5 Standard

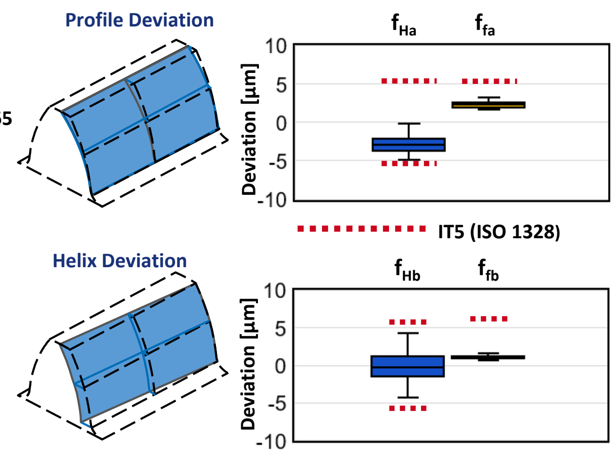
Material
17-4PH Binder Jetting

Gear Measurement KLINGELNBERG P65
100 % 3-Tooth Measurem.

Grinding Machine
KAPP KX 500 FLEX

Grinding Tool
3M Cubitron
Ceramic Grit

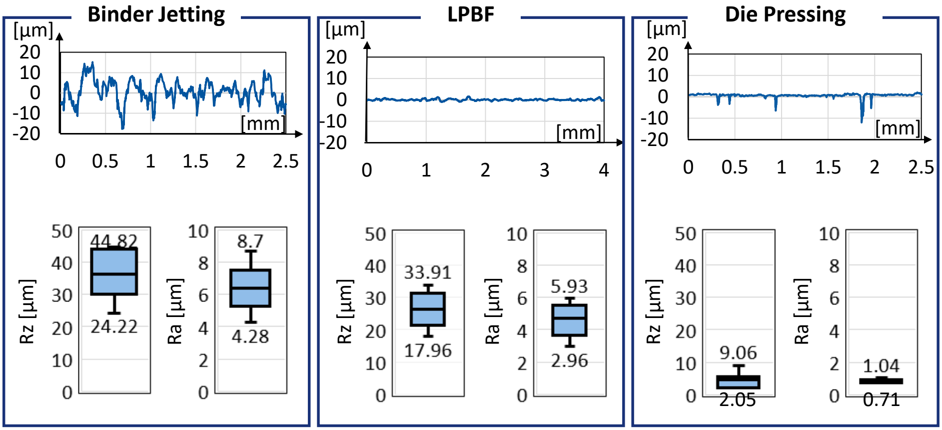




Source: [KLEE22]

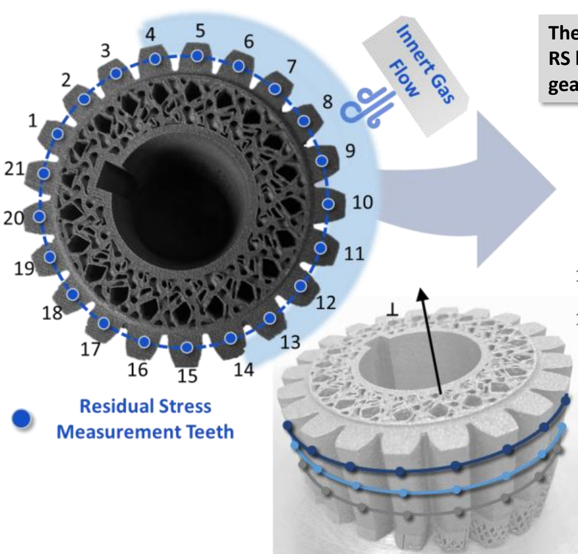
Roughness Profiles Before Hard Machining

Still Requires improvement

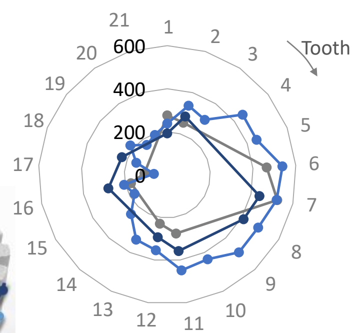


Source: [KLEE22]

Residual Stresses on Additive Manufacturing



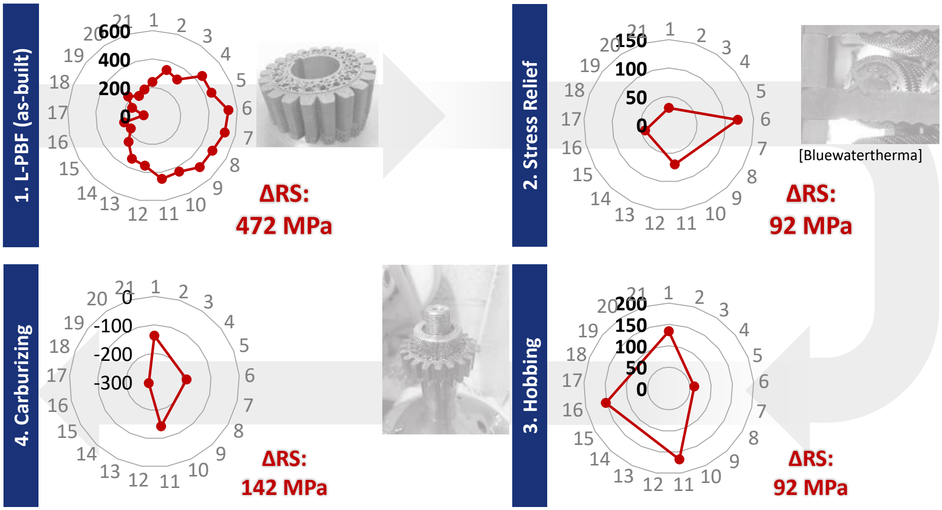
The complex combination of effects ⇒ RS heterogeneity at the gear lateral face



Higher teeth ⇒ Higher RS
Higher support structure
Lower heat transfer rate

Source: [ROBA22]

Residual Stresses Through Manufacturing Chain



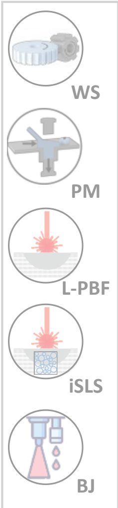
Source: [ROBA22]

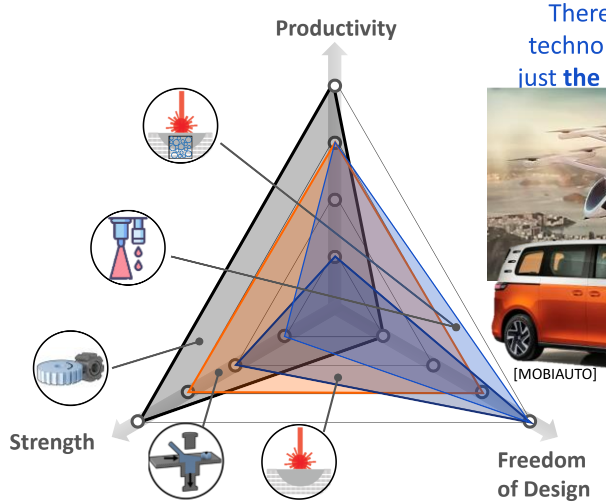
Agenda

1. Future Mobility versus Gear Requirements
2. What about Performance?
3. Challenges & Limitations
4. **Conclusion & Outlook**

Conclusions and Outlook

- Disruptive **geometries** required, but with **durable** and **productive** solutions





There is no right technology. There is just **the most suitable**

Conclusions and Outlook

There is no right technology.
There is just **the most suitable** for each application…

… but E-mobility brings one certain:

Gears won't be produced anymore with the same materials, design and manufacturing processes.

This is the chance for Powder!

BGC 23

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WZL | RWTH AACHEN UNIVERSITY

RWTH Aachen University (Germany),
Laboratory for Machine Tools and
Production Engineering

HEXAGON SMT Bruker alicona That's metrology! RÖSLER finding a better way ... OTEC

KAPP NILES KISSsoft A Gleason Company ESTUDIO PIÑA Mitutoyo Sul Americana ZANINI RENK

VAS TECNOLOGIA INDUSTRIAL Member IMC Group Iscar Ingersoll Cutting Tools LIEBHERR Gleason DWIH São Paulo Land of Ideas

I. Simulative Study of the Manufacturability of Topological Modifications for Gear Skiving –

Lukas Klee, M.Eng. (WZL)

Deviations from the involute of gears that are specifically addressed can positively influence the acoustic excitation behavior and the load carrying capacity of the gear. These standard modifications can be described by linear and quadratic functions. Modifications that can be described by functions of higher order are called topological modifications. Gears featuring topological modifications exhibit an improved excitation behavior compared to gears with standard modifications, they also exhibit an improved load carrying capacity. Among the processes that can produce these modifications are generating and profile grinding. A process that has received little attention in this regard is gear skiving. Gear skiving enables soft and hard finishing of both internal and external gears. The machining can also be carried out on a single machine. When applied as hard finishing process, this method is responsible for the last quality-assuring step in the manufacturing chain. This brings the process to the forefront for the manufacturing of modifications. The aim of this report is therefore the simulative investigation of the extent to which topological modifications can be produced by gear skiving. The results of this report indicate a manufacturability of modifications in principle, especially by kinematics.

Simulative Study of the Manufacturability of Topological Modifications for Gear Skiving

Speaker: Lukas Klee M.Eng.
Author: Christopher Janßen M.Sc.

WZL of RWTH Aachen
Prof. Dr.-Ing. Christian Brecher
Prof. Dr.-Ing. Thomas Bergs
Dr.-Ing. Jens Brimmers

Funding:
Seit 1956 Since 1956 WZL Getriebekreis Gear Research Circle

The Brazilian Gear Conference ITA-WZL 2023, October 18th / 19th 2023

Fraunhofer IPT | WZL | RWTH AACHEN UNIVERSITY

Agenda

Introduction and Motivation
Fields of Application of Skiving and Technical Necessity

Soft and Hard Fine Machining

- Both **soft machining** and **hard finishing** of gears can be performed by skiving
- Gear manufacturing can be done on **one machine**

Internal and External gears

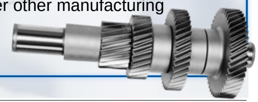
- Manufacturing of both **internal** and **external** gears
- The manufacturing can also be done on one machine

Technical Necessity

- Increasing **industrial relevance** of skiving
- Used in hard fine machining. As a **quality-determining** process step, responsible for the application of modifications

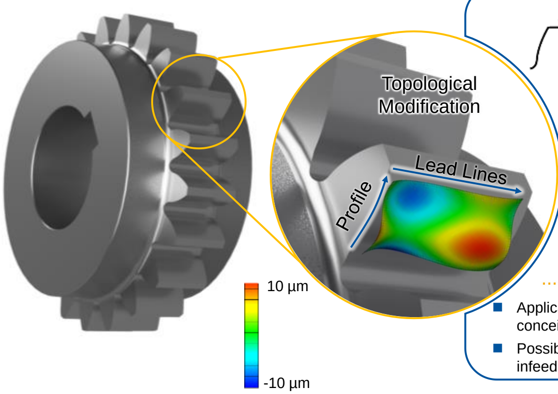
Insensitive to interfering contours

- A short **run-in** and **run-out** path enable the production of gears with interfering contours
- This is an advantage over other manufacturing processes

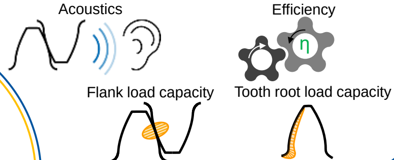


Quelle: Pratt & Whitney, EMAG

Introduction and Motivation
Application Areas of Topological Modifications and Aapplication



... the Operating Behavior of Gears — Influence

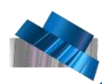


… e.g. by grinding process — Are applied

- Adjustment of the path curves
- Dressing of profile wheel or dressing of grinding worm

... through the skiving process ?

- Application of flank modifications for skiving conceivable
- Possible adjustment of axis cross angle, infeed, tool profile



Agenda

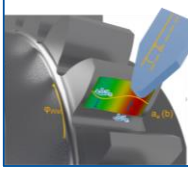
1	Introduction and Motivation
2	**Objective and Approach**
3	Lead Line Modifications
4	Profile Modifications
5	Combination
6	Summary and Outlook

Objective and Approach
Objective and Definition of Subtarget

Simulative investigation of the manufacturability of topological modifications in Gear Skiving

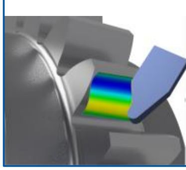
Lead Modifications

Investigation of the influence of the kinematic parameters on the topography.



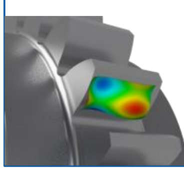
Profile Modifications

Application of profile modifications by means of adapted tool profile



Combination

Investigation of the extent to which profile and lead modifications can be overlapped



Objective and Approach
Gear and Tool Data and Methodology

Gear and Tool Data

Gear Data

z_2	= 36	
m_{n2}	= 3.5	mm
β_2	= 19.3	°
d_{a2}	= 140	mm
b_2	= 44	mm

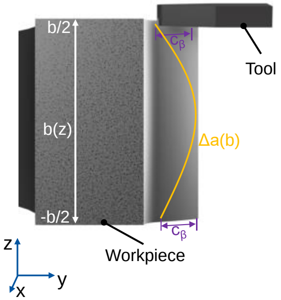
Tool

m_{n0}	= 3.5	mm
α_{n0}	= 20	°
β_0	= 0	°
z_0	= 32	
d_{a0}	= 121.3	mm

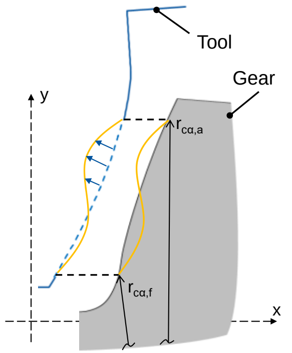
Process

Σ	=-19.3	°
a	= 120.6	mm
f_a	= 0.5	mm

Kinematical Adjustments

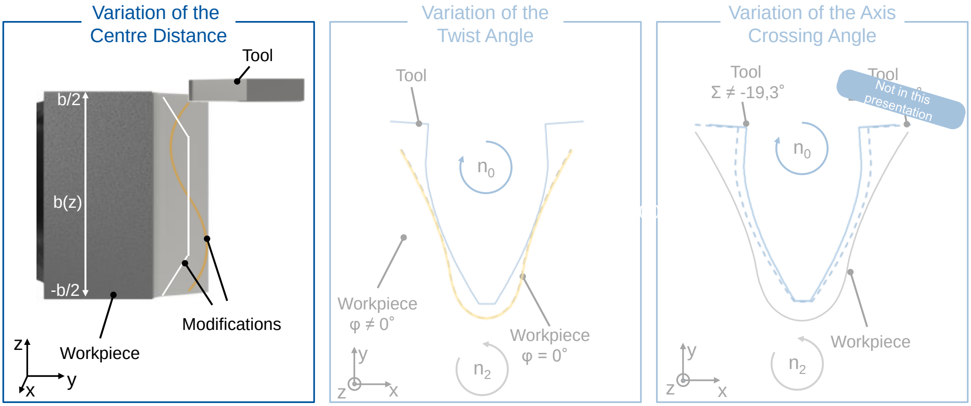


Modification of the Tool Profile



Agenda

Lead Line Modifications
Procedure of Kinematic Modifications



Lead Line Modifications
Quadratic Modifications

Gear

z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool

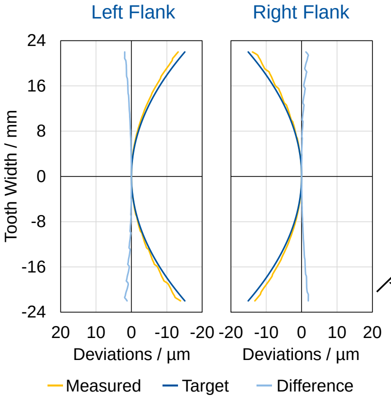
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

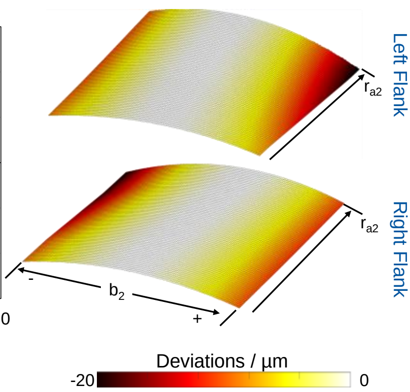
Process

f_a = 0.5 mm
Σ = -19.3 °

Modification

Polynomial degree 2
r_{meas} = 67 mm





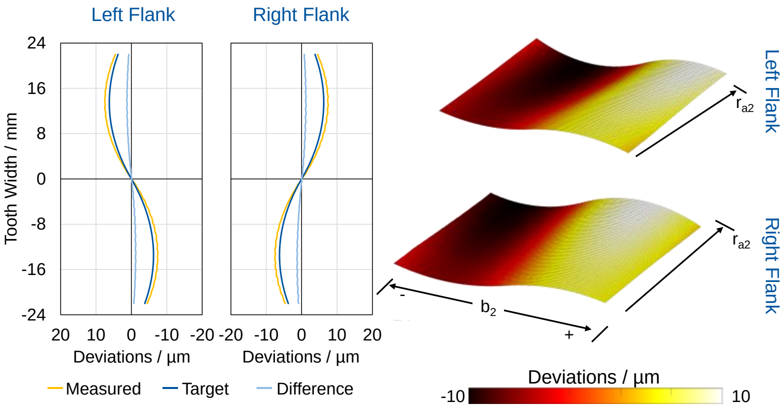
Lead Line Modifications
Topological Modifications of Degree 4

Gear
z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process
f_a = 0.5 mm
Σ =-19.3 °

Modification
Polynomial degree 4
r_{meas} = 67 mm



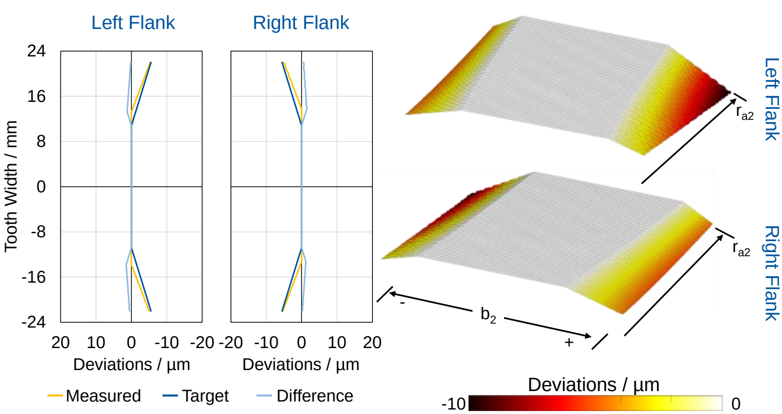
Lead Line Modifications
End Relief

Gear
z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

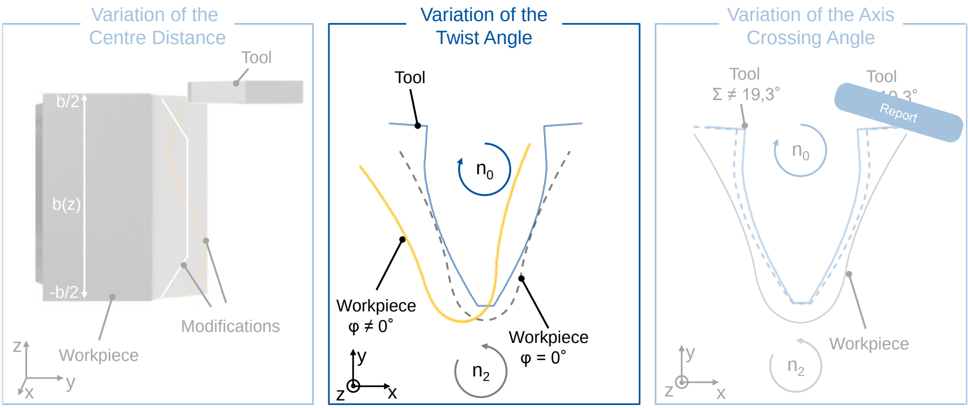
Tool
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process
f_a = 0.5 mm
Σ =-19.3 °

Modification
End relief
r_{meas} = 67 mm



Lead Line Modifications
Procedure of Kinematic Modifications



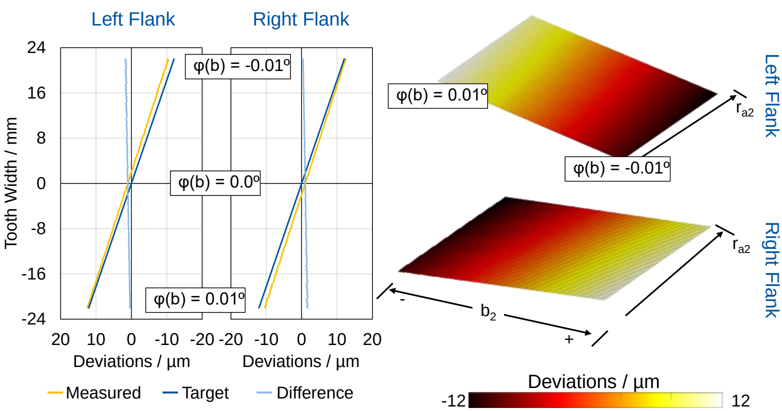
Lead Line Modifications
Linear Variation of the Twist Angle

Gear
z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process
f_a = 0.5 mm
Σ =-19.3 °

Modification
Polynomial degree 1
-0.01° ≤ φ ≤ 0.01°



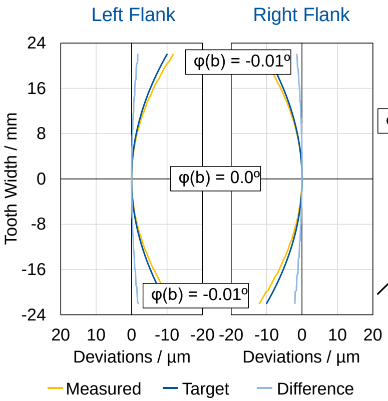
Lead Line Modifications
Quadratic Variation of the Twist Angle

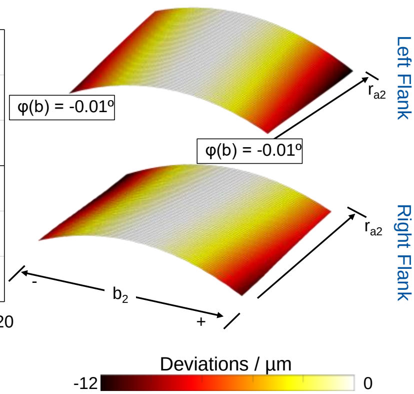
Gear
z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process
f_a = 0.5 mm
Σ =-19.3 °

Modification
Polynomial degree 2
-0.01° ≤ φ ≤ 0°





Agenda

Objective and Approach
Gear and Tool Data and Methodology

Gear and Tool Data

Gear Data

z_2	= 36	
m_{n2}	= 3.5	mm
β_2	= 19.3	°
d_{a2}	= 140	mm
b_2	= 44	mm

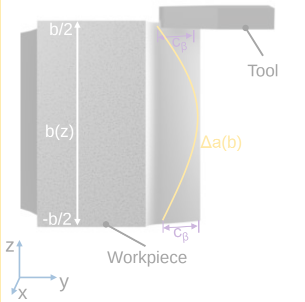
Tool

m_{n0}	= 3.5	mm
α_{n0}	= 20	°
β_0	= 0	°
z_0	= 32	
d_{a0}	= 121.3	mm

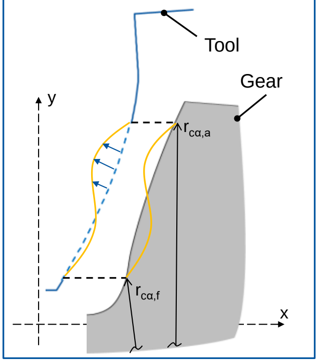
Process

Σ	=-19.3	°
a	= 120.6	mm
f_a	= 0.5	mm

Kinematical Adjustments



Modification of the Tool Profile



Profile Modifications
Linear Profile Modifications

Gear

z_2	= 36	
m_{n2}	= 3.5	mm
β_2	= 19.3	°
d_{a2}	= 140	mm
b_2	= 44	mm

Tool

m_{n0}	= 3.5	mm
α_{n0}	= 20	°
β_0	= 0	°
z_0	= 32	
d_{a0}	= 121.3	mm

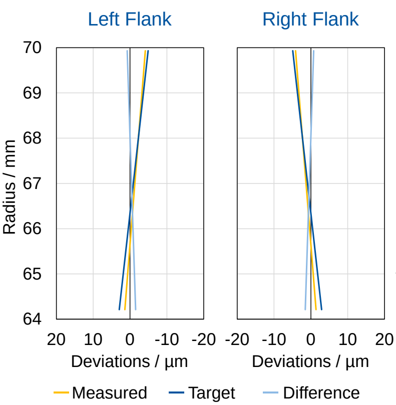
Process

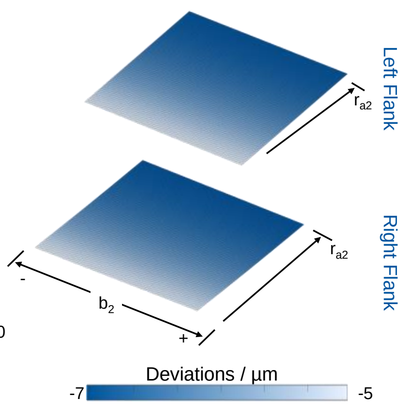
f_a	= 0.5	mm
Σ	=-19.3	°

Modification

Polynomial degree 1

z_{meas} = 0 mm





Profile Modifications
Quadratic Profile Modifications

Gear

z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool

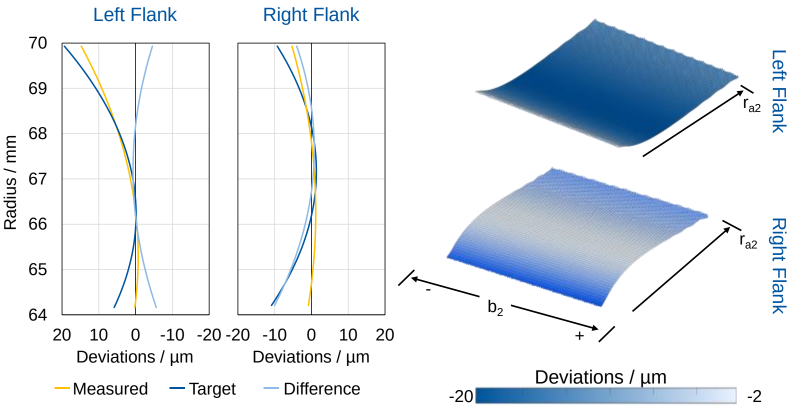
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process

f_a = 0.5 mm
Σ =-19.3 °

Modification

Polynomial degree 2
z_{meas} = 0 mm



Profile Modifications
Topological Profile Modification

Gear

z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool

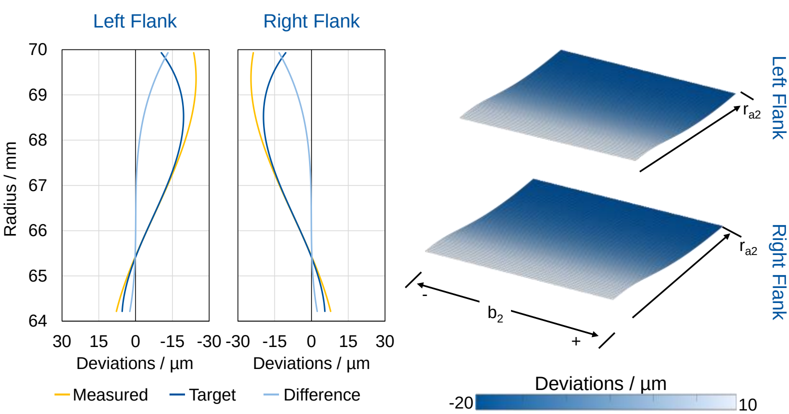
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process

f_a = 0.5 mm
Σ =-19.3 °

Modification

Polynomial degree 3
z_{meas} = 0 mm



Agenda

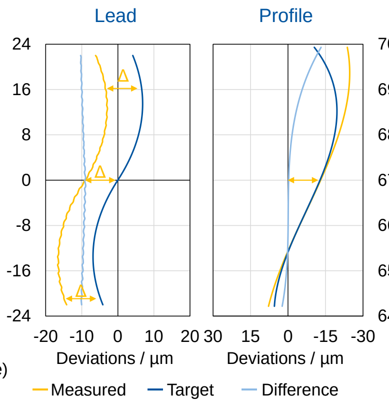
Combination
Superimposition of Center Distance Change and Adapted Tool Profile

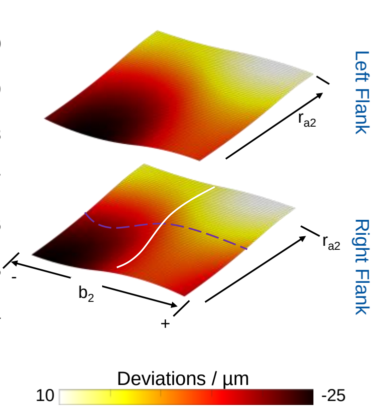
Gear
z_2 = 36
m_{n2} = 3.5 mm
β_2 = 19.3 °
d_{a2} = 140 mm
b_2 = 44 mm

Tool
m_{n0} = 3.5 mm
α_{n0} = 20 °
β_0 = 0 °
z_0 = 32
d_{a0} = 121.3 mm

Process
f_a = 0.5 mm
Σ =-19.3 °

Modification
Polynomial deg. 3 (Profile)
Polynomial deg. 4 (Lead)





Agenda

Conclusion
Summary and Outlook

Summary

- Good agreements between kinematic specifications and results
- Potential for profile modifications exists
- Combination of profile and lead line modifications possible

Outlook

- Adjustment of the kinematic realization of the modifications
- Adjustment of the tool profile design
- Transfer of the results to the manufacturing process also for internal gears

BGC 23

THE BRAZILIAN GEAR CONFERENCE

ITA-WZL

Oct 18th & Oct 19th, 2023 – São José dos Campos, Brazil

Aeronautics Institute of Technology, Competence Center in Manufacturing

RWTH Aachen University (Germany), Laboratory for Machine Tools and Production Engineering

VIII. The Future of Gear Cutting: A New Approach for Tools Design –

Bruno Oliveira, M.Sc. (ITA) / Pedro Toresin, Eng. (Star SU)

The industry of gear cutting tools is, in general, characterized by small batches, long manufacturing times and high costs, dealing with tailor-made and high value-added tools. In this context, additive manufacturing finds a vast potential of bringing disruptiveness and efficiency increase. This study presents developments regarding the application of the technology for manufacturing gear cutting tools. The design for additive manufacturing (DfAM) and the manufacture of HSS steel prototypes through Laser Powder Bed Fusion (L-PBF) are the highlighted topics, along with the corresponding potentials and challenges. The geometric complexity of a hobbing tool and use of HSS steels leads to challenges related to the emergence of cracks along the deposition. An integrated product development approach is applied to evaluate the design possibilities considering the manufacturing constraints. The constraints led to the decision to work with a shaper tool due to less complexity, but the concept could be evolved into a skiving tool. A lighter design with a better optimization of the thermal exchange was obtained through the creation of regions for the circulation of the cutting fluid. The challenges and alternatives for the processing of the new design are discussed. Geometry opportunities such different construction material for body and tool are approached for productivity and economical gains. Issues are also raised for the implementation of such solutions. In conclusion, additive manufacturing can be a key-technology for gear cutting tools in the future, bringing a disruptive path of new opportunities.

The Brazilian Gear Conference ITA-WZL 2023

The Future of Gear Cutting: A New Approach for Tools Design

Bruno Oliveira, M.Sc. *(ITA)*

Pedro Toresin, Eng. *(Star SU)*

São José dos Campos, October 18th & 19th, 2023

Agenda

1. Motivation
2. Gear Cutting Tools
3. Summary and Outlook

Motivation

Gear Machining

Source: [OTTO02, CLAUD09, GUPT15]

Gear Machining

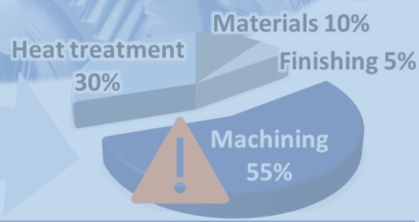
"Profit is determined at the cutting tool tip"

Prof. Schlesinger, TH Berlin 1907

How to disrupt tool manufacturing and design?

The majority of gears are produced by machining[1]

> 900 million gears/year are produced by hobbing[2]



Typical gear manufacturing costs[3]

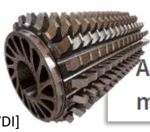
Source: [OTTO02, CLAUD09, GUPT15]

Additive Manufacturing: *World Cutting Tools Development*

Kennametal Revs Up Metal Cutting Innovation with 3D Printed Tool for Automotive Supplier Voith

[KOMET GROUP]

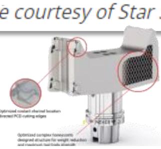
[Kennametal]



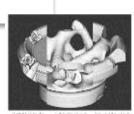
[VDI]

Additive manufacturing of high strength wear resistant materials -3D-printed metals gives new possibilities

Star Cutter distributes Neher 3D-printed cutting tools through the sister company Star SU. Image courtesy of Star SU.



Improving Machining With 3D Printed Tools



[nTopology Inc]

The Case for 3D Printing Downhole Tools

AM of Hobbing Tools: *Geometry Challenges and Opportunities*

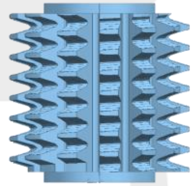
OPPORTUNITIES

- AM geometry freedom may bring new **design opportunities** for hobbing tools:
  - **Conformal cooling channels:** efficient lubrication and cooling, allowing **higher cutting speeds** and **productivity**
- **Lightweight design** and the **near net shape** AM characteristic:
  - **Material** and **manufacturing time savings**
  - **Significant stock reduction**

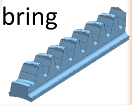

[VDI]

CHALLENGES

- High inclination angles and thin teeth: may require **reinforced supports** to avoid distortion and defects.



AM customized Indexable inserts (teeth row): may eliminate supports necessity and bring **productivity benefits**



National AM Cooperation for Tooling Development: *FERA*

Engrena ITA

2018 Additive Manufacturing prioritized

2019 Feasibility study

FERA
Ferramentas e Engrenagens Reparadas Aditivamente
Höganäs ZANINI RENK

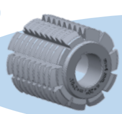
Prospection of AM for gear hobbing tool repair

2020 Project proposal to Rota2030

+20 companies and 3 Science and Technology Institutions

Development of Additive Manufacturing (AM) for the repair and manufacture of Tools for the Brazilian Automotive Industry

2021-2024

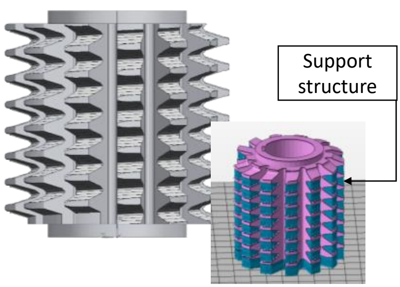


Prospection of AM for gear hobbing tool manufacturing

Agenda

New Technology / Old Mindset

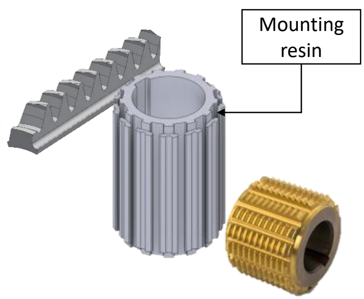
Monolitic



Printing Challenges

Reinforced supports is needed to avoid distortion and defects.

Indexable inserts

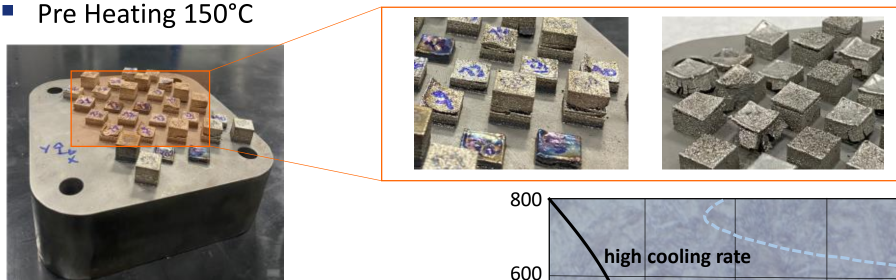


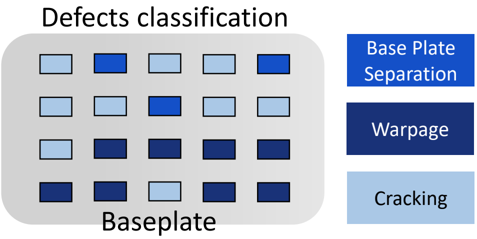
PVD Chellenges

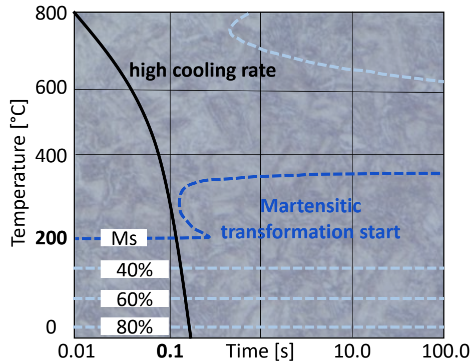
Mounting Resin is not allowed in the PVD process

Manufacture

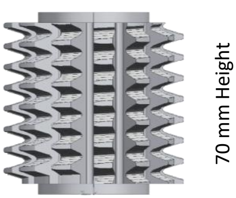
- Pre Heating 150°C

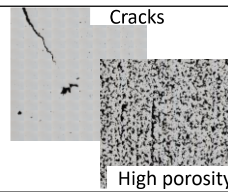




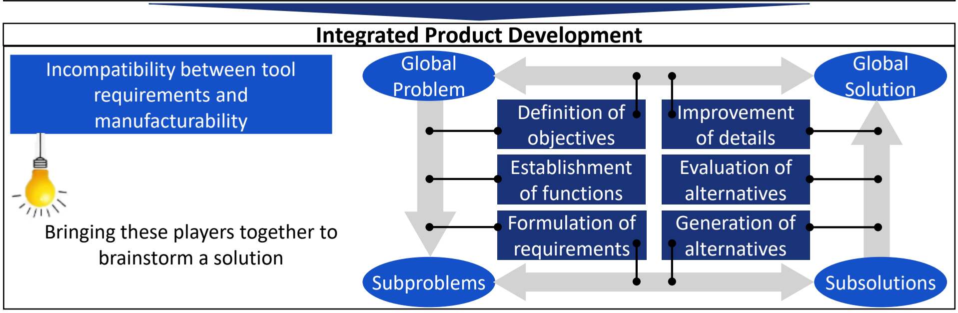


Requirements x Manufacturability





Distortion levels and residual stress heterogeneity are more expressive in components with higher heights



Agenda

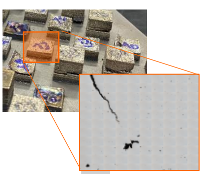
1. Motivation
2. Gear Cutting Tools
   - 2.1 New Technology and Old Mindset
   - **2.2 New Technology and New Mindset**
3. Summary and Outlook

Integrated Product Development (IPD) Approach

Informational Stage

State of the art review

Stakeholders needs

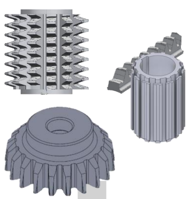


- Design Recommendations
- Manufacturing Constraints
- Harmonization of Needs

System Requirements

Concept Design

System Requirements

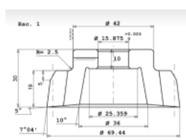


- Functional Analysis
- Morphological Charts
- System Simulations
- Structured Decision-Making

Solution Selection

Detailed Design

Selected Solution

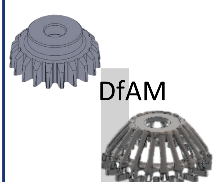


- Microgeometry
- Component Detailed Design
- Manufacturing Plan Review

Parts Drawings

Manufacturing

Parts Design



- Pilot Production
- Process Validation
- Component Validation
- System Validation

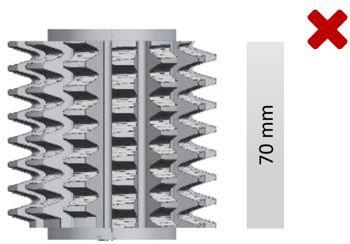
Testing

Integrated Product Development (IPD) Approach

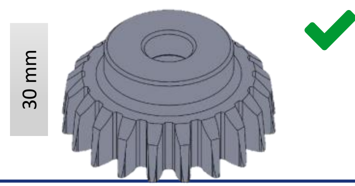
Requirement and Restrictions

- cutting stability
- Thermal exchange
- cutting performance
- Shorter manufacturing chain
- Smallest possible height
- lead time reduction
- Improve lubrication
- Reduce tooling inventories
- Reduced use of noble material

Possible Designs

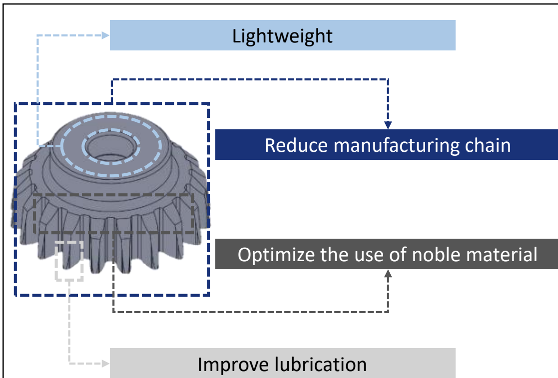


Alternative

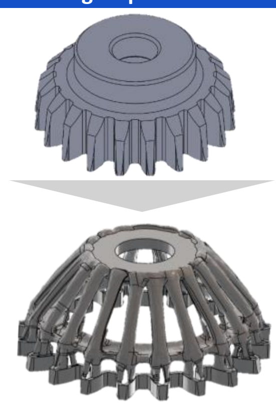


New Technology / New Mindset

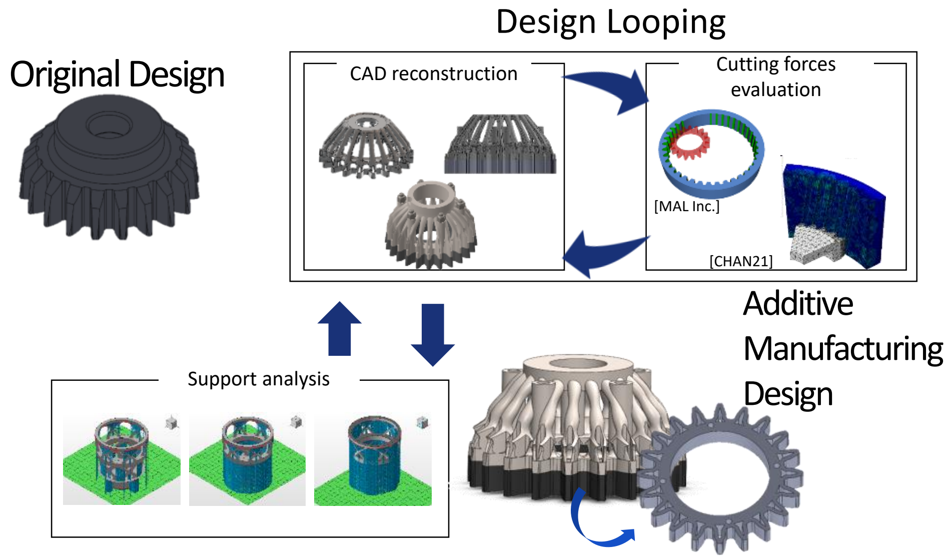
- DfAM
  - How to improve the design to improve the performance?



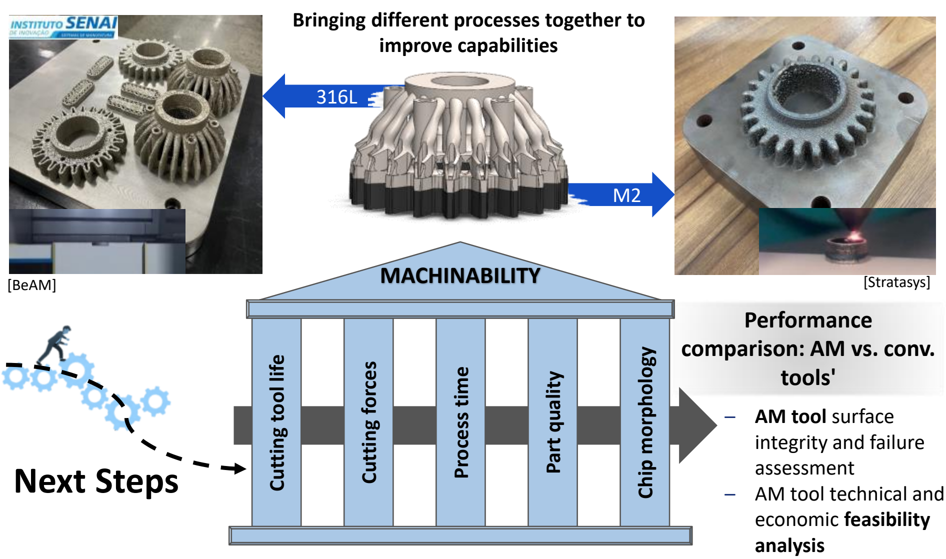
Rough Optimization



Design Evolution



Requirements x Manufacturability



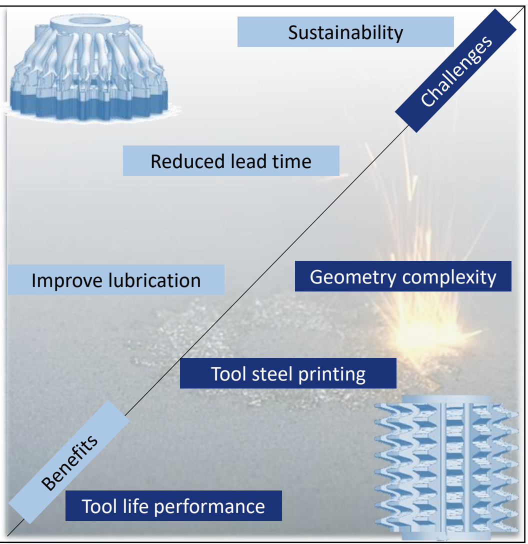
Agenda

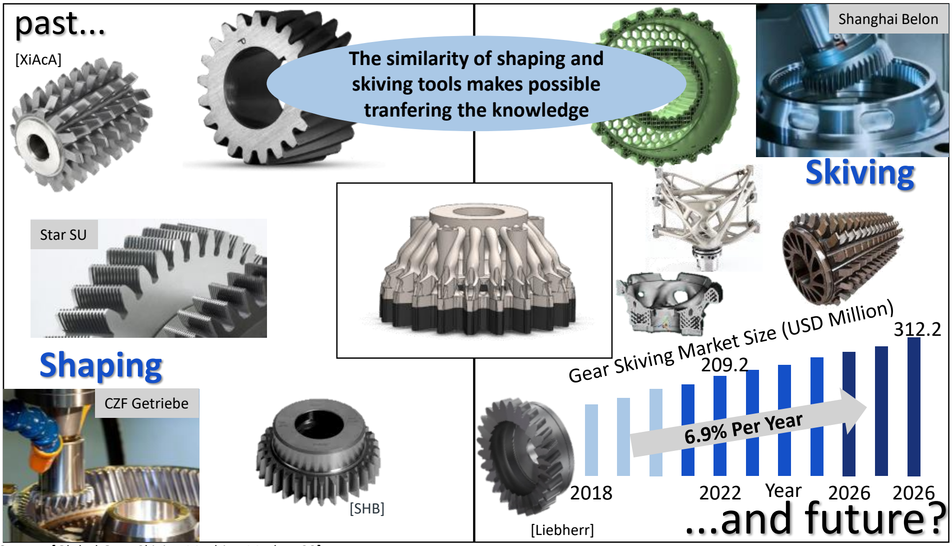
1. Motivation
2. Gear Cutting Tools
3. **Summary and Outlook**

Summary and Conclusion

- Design freedom makes it possible to add functions to the tool;
- Near net shaping manufacturing enable to reduce the production lead time;

- Geometrical challenges due to design complexity;
- Tool steel printing is still a challenge in metallurgical terms;





Source: [Global Gear Skiving Machine Market, 23]