IV. Tracking the Economical Benefits of Residual Stresses –

Caio Gomes, M.Sc. (ITA) / Guilherme Guimarães, M.Sc. (Eigendauer)

The residual stress state can be used to enhance the gear load-carrying capacity, without increasing the component's dimensions. This qualitative concept is widely accepted, but the lack of objective data to evidence the advantages for production hinders further exploration in the Industry. This investigation's objective is the quantification of the economical benefits of residual stresses in the design and manufacturing of a gear. In contrast with the classical approach of considering residual stresses as an additional safety factor for the gear design, the present approach uses them as a proper design tool. A case study is presented, where the joint effect of residual and actuating stresses were considered to downsize a gear while keeping its tooth bending fatigue lifetime. Gear samples with different tooth widths were designed to have the same durability, by compensating distinct residual stress states. They were manufactured in a high cleanness steel, using a conventional manufacturing chain of machining, case hardening and shot peening. The induction of the optimized residual stress to the gear tooth root was performed by distinct shot peening configurations among the gears of distinct tooth widths. The results highlight the economical benefits of this proposed approach to the residual stress influence, as reductions in the manufacturing time and cost, in the energy consumption and in the CO2 footprint, besides mass/volume reduction.

Tracking the Economical Benefits of Residual Stresses

Caio Gomes, M.Sc. *(ITA)*
Guilherme Guimarães, M.Sc. *(Eigendauer)*

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

Agenda

1. Residual Stresses in Future Gear Design
2. DRS: Coupling Internal and External Stresses in the Tooth Root
3. Estimating the Impact on Production Costs
4. Summary and Outlook

Electromobility Demands on Fatigue Strength of Gears

E-Mobility Trends

- MOVER: Green Mobility and Innovative Programme (Brazil)
- Net Zero Industry Act (European Union)

Gear Requirements

Higher **Power Density**

High **Torque Efficiency**

Silent: NVH Protagonist

How can gear design solve the existing trade-offs and meet the requirements?

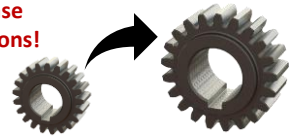
Source: [AGMA21]

Gear Design Method

Actuating Stress ≤ **Permissible Stress**

1. To reduce actuating stresses...

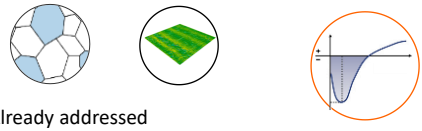
... **increase dimensions!**



2. To increase permissible stresses...

... **improve surface integrity!**

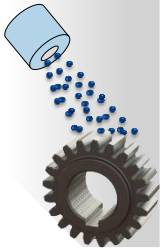
Material* Topography* **Residual Stresses**



*Already addressed by the gear standards

The Influence of Residual Stresses on Fatigue Behavior: *The Gap*

Survey on the lifetime benefits of shot peening gears





ROOT BENDING

Source	Fatigue Improvement	
DALY77 M.I.C.	29%	MAX / MIN
KÖCH94 WZL	31%	33%
	40%	45%
BENE02 Trento	20%	50%
SHAW03 Newcastle	56%	76%
STEN07 TUM-FZG	42%	66%
	31%	66%
	57%	
	38%	50%

Widely known benefits of compressive RS ...

... but are these benefits effectively captured by design standards?

The benefit values attributed to shot peening are

a) ML — 0 %

b) MQ — 10 %

c) ME — 5 %

ISO 6336-5:2006

The shot peening benefits shall be applied to bending stresses on carburized case hardened gears only.

The maximum compressive stress remains relatively unchanged regardless of peening parameters, as it is primarily a function of the material's surface hardness and strength;

AGMA 938-A05

Objective and Approach

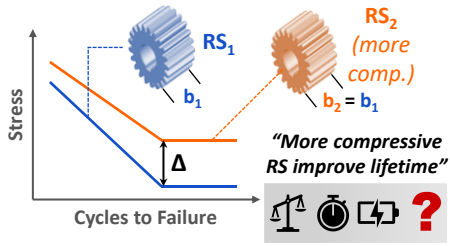
Challenge

The residual stress benefits are hidden and must be disclosed to stimulate their inclusion in the designing process of mechanical components.

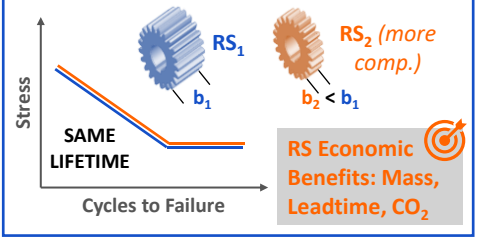
Objective

Quantification of the economical benefits of residual stresses in the design and manufacturing of a gear.

Classic Approach



Proposal: Inverted Approach

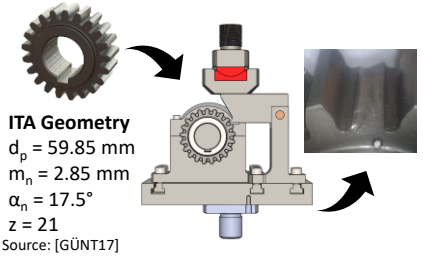


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Methods: *Isolating the Residual Stress Effects in Fatigue Life*

- To isolate the residual stress influence in fatigue life, other surface integrity aspects must be carefully considered:
  - Reduction of metallurgical stress concentrators
    - DIN 25CrMo4-based **clean steel**
  - Reduction of topographical variability
    - **Finishing step** (Manual Polishing)
- Failure mode: Bending Fatigue

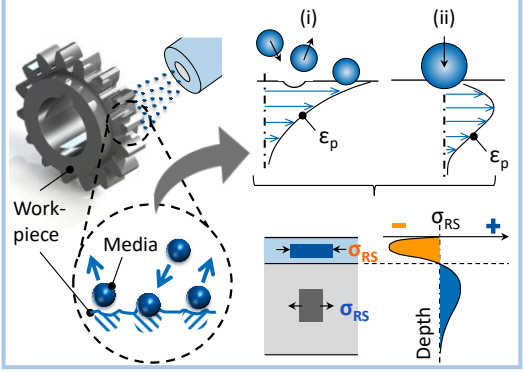


ITA Geometry
d_p = 59.85 mm
m_n = 2.85 mm
α_n = 17.5°
z = 21
Source: [GÜNT17]

Control Process for Residual Stress Induction

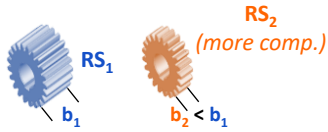
- **Surface Cold Working Process:** *Shot Peening*

Nearly pure mechanical compressive excitation:
Stretching stresses (i) + *Hertzian* **contact** pressure (ii)



Coupling Internal and External Stresses in the Tooth Root: *Methods*

- **Dang Van fatigue criterion**

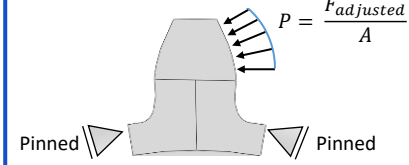


$$\tau_W = \tau_{max}(t) + a_{DV}[\sigma_H(t) + \sigma_{H,res}]$$

τ_W	fatigue limit in reversed torsion
σ_W	fatigue limit under reversed bending
$\tau_{max}(t)$	instant. value of the Tresca shear stress
$\sigma_H(t)$	instant. hydrostatic component of the stress tensor
$\sigma_{H,res}$	hydrostatic component of the residual stress tensor
a_{DV}	constant calculated from τ_W and σ_W

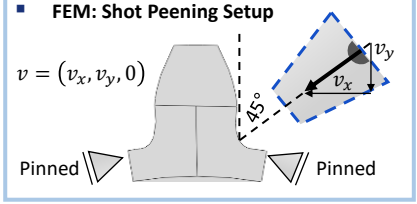
Actuating Stress Contribution

- **FEM: Bending Setup**



Residual Stress Contribution

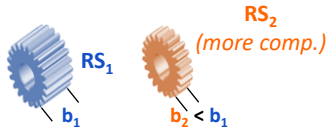
- **FEM: Shot Peening Setup**



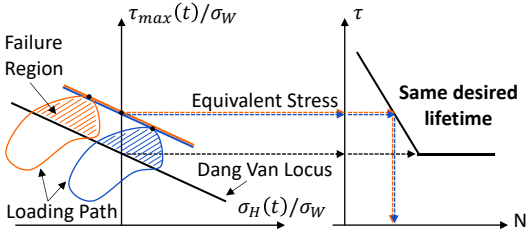
Source: [DESI06]

Coupling Internal and External Stresses in the Tooth Root: *Methods*

- **Dang Van fatigue criterion**

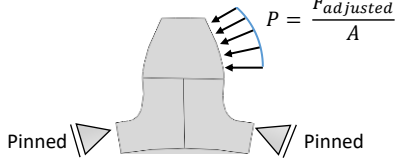


$$\tau_W = \tau_{max}(t) + a_{DV}[\sigma_H(t) + \sigma_{H,res}]$$



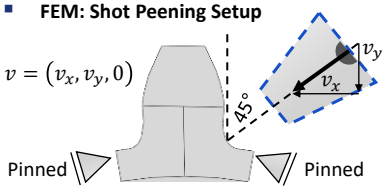
Actuating Stress Contribution

- **FEM: Bending Setup**



Residual Stress Contribution

- **FEM: Shot Peening Setup**

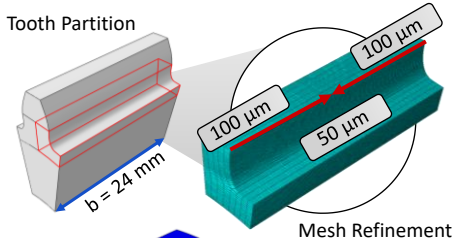


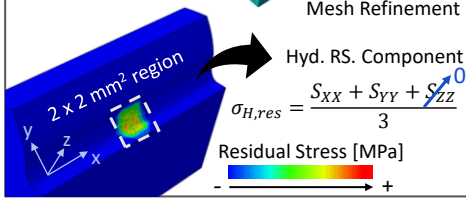
Source: [DESI06]

Modelling Tooth Root Bending and Residual Stresses: *FEM Approach*

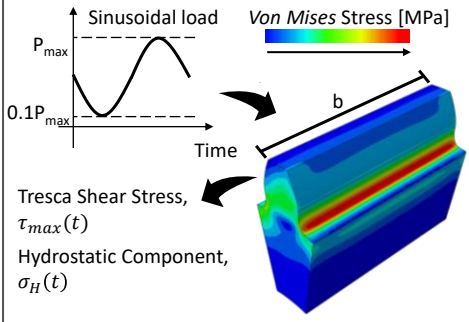
Shot Peening Process

- Media classes: S170 and S230
- Shot velocities: 10 - 30 m/s





Tooth Root Bending

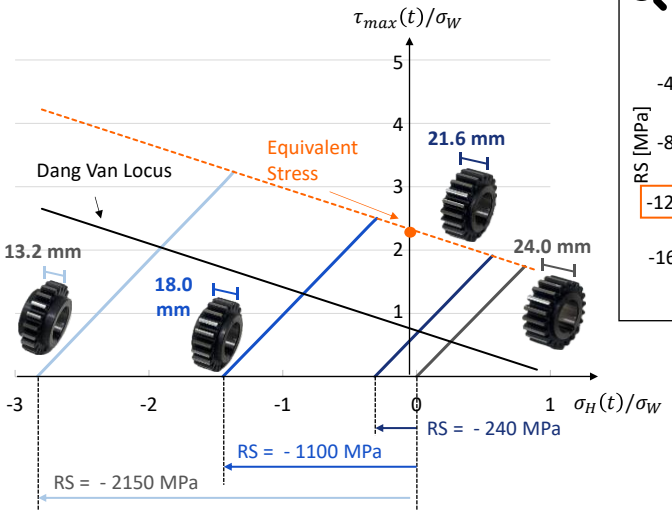


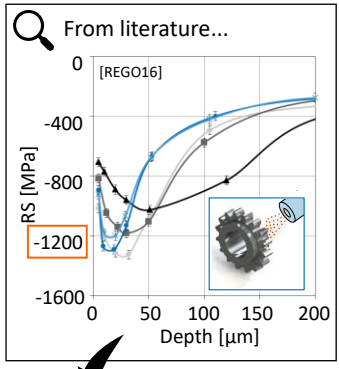
- Gear tooth widths (b):



Bending Fatigue Life Verification

- Required Residual Stress from Shot Peening





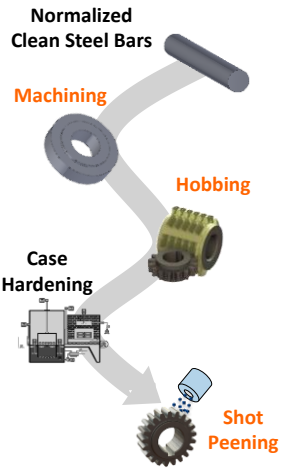
The RS values required for b = 18.0 mm are achievable by shot peening!

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Estimating the Economical Benefits of Residual Stresses

Manufacturing Chain



- Adopted metrics for the assessment of the economical benefits of residual stresses:
  - Mass Reduction
  - Energy Consumption
  - CO_2 Emissions
  - Manufacturing Time
  - Production Costs
- **Mass reduction benefits obtained:**

b [mm]	Δb [%]	Mass [kg]	ΔMass [%]
24.0	-	0.421	-
21.6	10	0.397	6
18.0	**25**	**0.365**	**13**
13.2	45	0.318	24



ITA Geometry

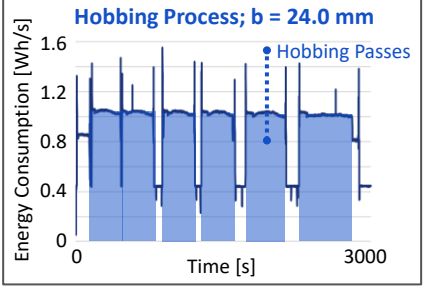
13% of mass reduction!

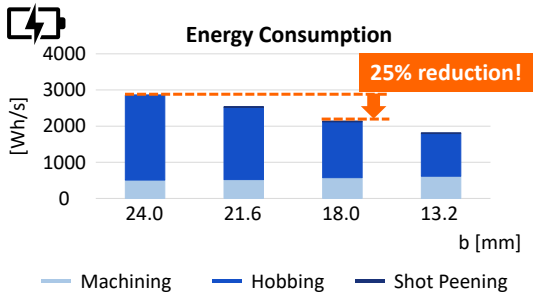
Processes which metrics were analyzed

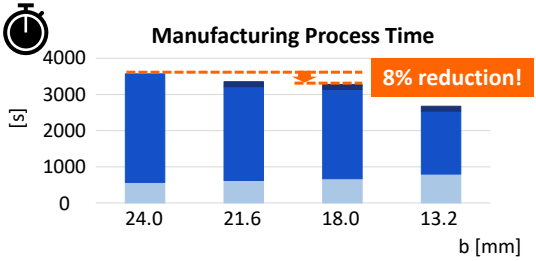
Manufacturing Time and Energy Consumption Impacts

Energy Consumption Assessment

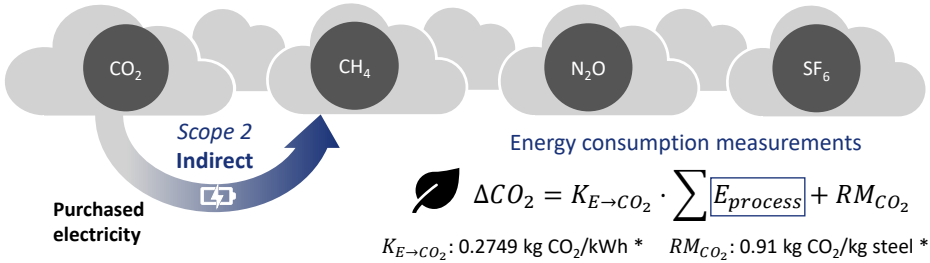








Estimating the Impact on CO_2 Emissions per Part



Energy consumption measurements

$$\Delta CO_2 = K_{E \to CO_2} \cdot \sum E_{process} + RM_{CO_2}$$

$K_{E \to CO_2}$: 0.2749 kg CO_2/kWh * RM_{CO_2}: 0.91 kg CO_2/kg steel **

Tooth Width [mm]	Material*** [kg CO_2]	Machining [kg CO_2]	Hobbing [kg CO_2]	Shot Peening [kg CO_2]	TOTAL [kg CO_2]
24	1.070	0.140	0.648	-	1.858
21.6	0.963	0.143	0.549	0.006	1.661
18	**0.803**	**0.158**	**0.425**	**0.006**	**1.392**
13.2	0.589	0.170	0.315	0.012	1.086

* CO_2 average emission factor in Brazil in the year of 2024
** emissions due to raw material (Brazilian steel manufacturer)
*** considering tooth width dimensions

Total reduction of 25%!

Estimating the Impact on Production Costs

Direct Costs of Production

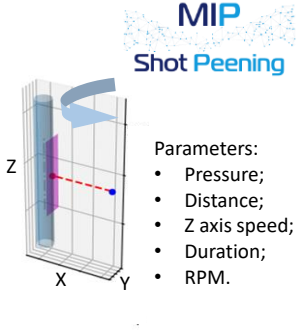
- *Raw material*
- *Direct labor*
- *Production equipment*
- *Packaging*
- *Transportation*

Indirect Costs of Production

- *Electricity*
- Maintenance and repairs
- Depreciation
- Indirect labor
- Computer and software

Manufacturing Parameterization Softwares

- Manufacturing simulation softwares can assist in parameterizing processes to achieve a residual stress target.
  - Reduction of trial-and-error parameterization.



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Summary

- **Economical benefits** can be obtained by the consideration of residual stresses in the design phase of gears.
  - Residual stresses need to be seen as a **potential designing tool**, not only a manufacturing consequence.



ITA Geometry

b_1= 24 mm

RS Target Definition

Revisiting Fatigue Models

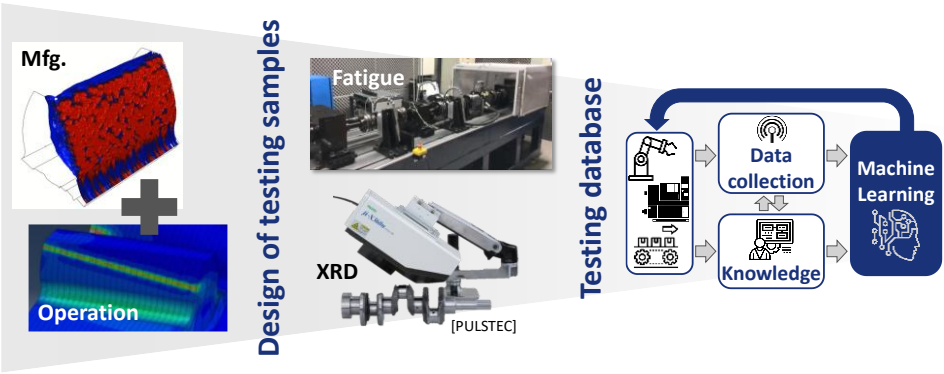
b_2= 18 mm

Residual Stress Economical Benefits

- **13%** reduction in mass
- **8%** reduction in total manufacturing time
- **25%** reduction of energy consumption
- **25%** reduction of total equivalent CO_2 emissions

Outlook: *International Collective Effort*

- Integrated approach: **FEM ↔ Experimental ↔ Artificial Intelligence**



Robust comprehension to draw an algorithm (analytical protocol) that could feed gear design standards