UNIVERSITÀ DEGLI STUDI DI PADOVA

Modelli multiphysics per lo studio della tempra a induzione di materiali usati nell’industria aeronautica

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Outline

<u>Gear hardening simulation</u>

- Motivation for the project
- Geometrical model
- Material choice and modeling
- Presentation of results
  - Simulation activity
  - Impact of relative permeability
  - Impact of quenching phase
  - Investigation of different recipes
  - Experimental activity
- Conclusion and perspectives

source: precisiongears.com

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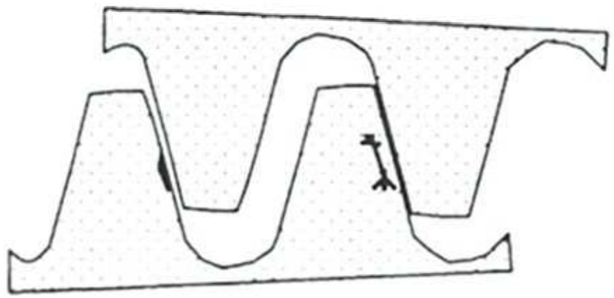
Damaging of aerospace gears

- Rotation speed of gears: 40-60 krpm
- Possible modes of failure:

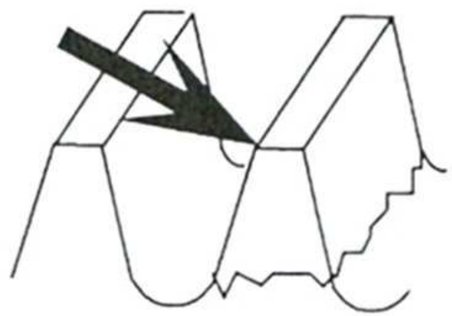
Contact fatigue



Solution:

High superficial hardness

Bending fatigue



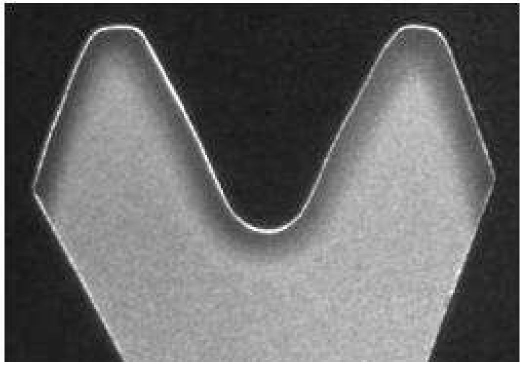
Solution:

Compressive residual stresses in the tooth root

Surface hardening treatment enhances fatigue performances!

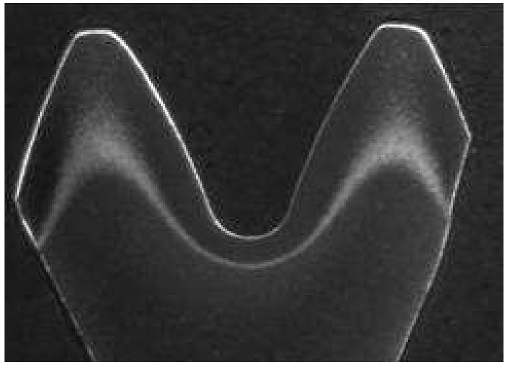
Case- vs. Induction-hardening

Case-hardening



- Mastered process
- Toxic and polluting cements
- Time-consuming (several hours)
- Very high maximal hardness
- Residual stresses very sensitive to %C and cooling kinetics
- High distortions
- No over-tempering zone

Induction hardening



- Non suitable for treating complex geometries
- "Green" process
- Fast and reliable process (1 sec)
- High maximal hardness
- Residual stresses easily achievable
- Low distortions
- Presence of a ductile zone due to over-tempering

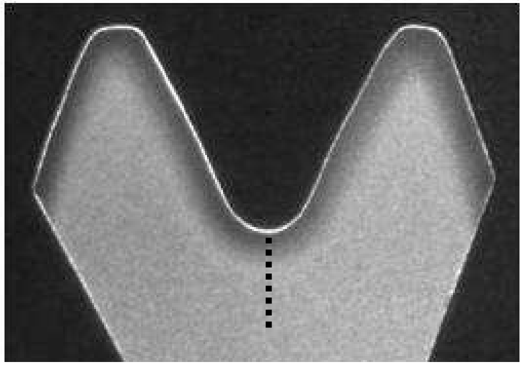
Over-tempering zone 1/2

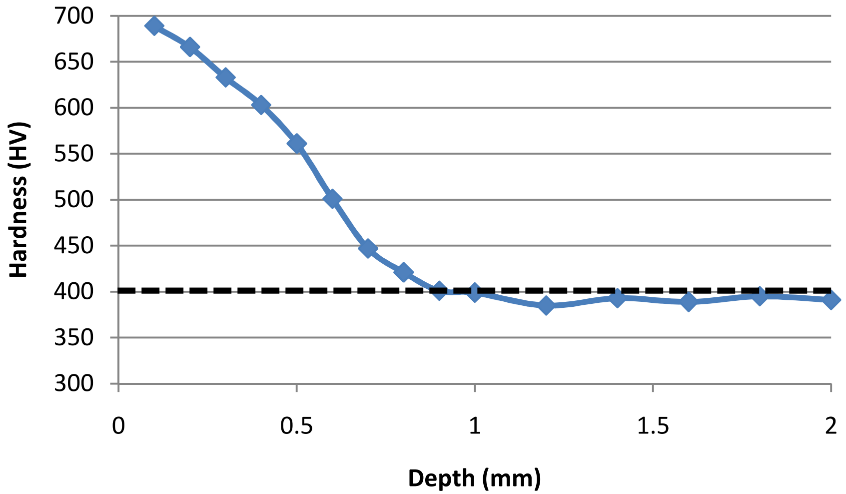
- Experienced in Q&T microstructures only
- Core martensite → tempered martensite
- Softer transition zone between the hardened layer and core material
- Lower hardness than reference bulk material
- Hardness loss/drop

Need to develop a tool able to predict the hardness loss due to induction surface heat treatment!

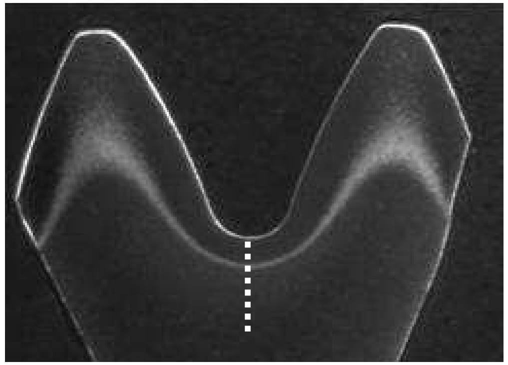
Over-tempering zone 2/2

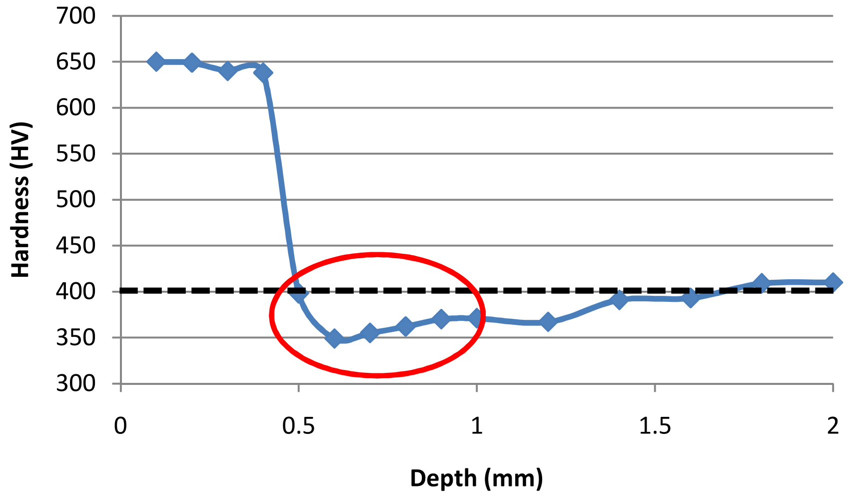
Case-hardening





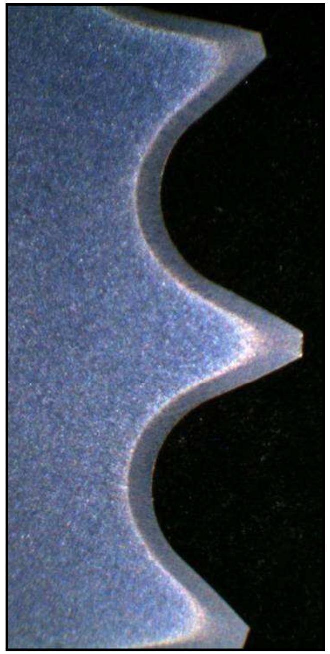
Induction hardening





Quality of the hardness pattern

- System coupling (coil-to-load)
- Coil type and geometry
- Distribution of heating sources
  - Frequency, magnetic yokes
- Imposed heating/cooling rate
  - Power, dwell time, soak time
- Starting metallurgical structure



Need for accurate modeling of the hardening process!

Project goal

- Develop an affordable tool able to simplify gear induction hardening simulation
  - Eddy current heating → Temperature
  - Metallurgical structure → Phase transitions
  - Mechanical properties → Deformations and RS
- Support experimental activity, optimizing labor and costs

Project strategy

- Exploitation of current state-of-the-art in commercial simulation software
- Development of ad-hoc coupling software, routines, and user interfaces
- Benchmarking and optimization of computer modeling in order to address experimental issues at best (time-accuracy tradeoff)

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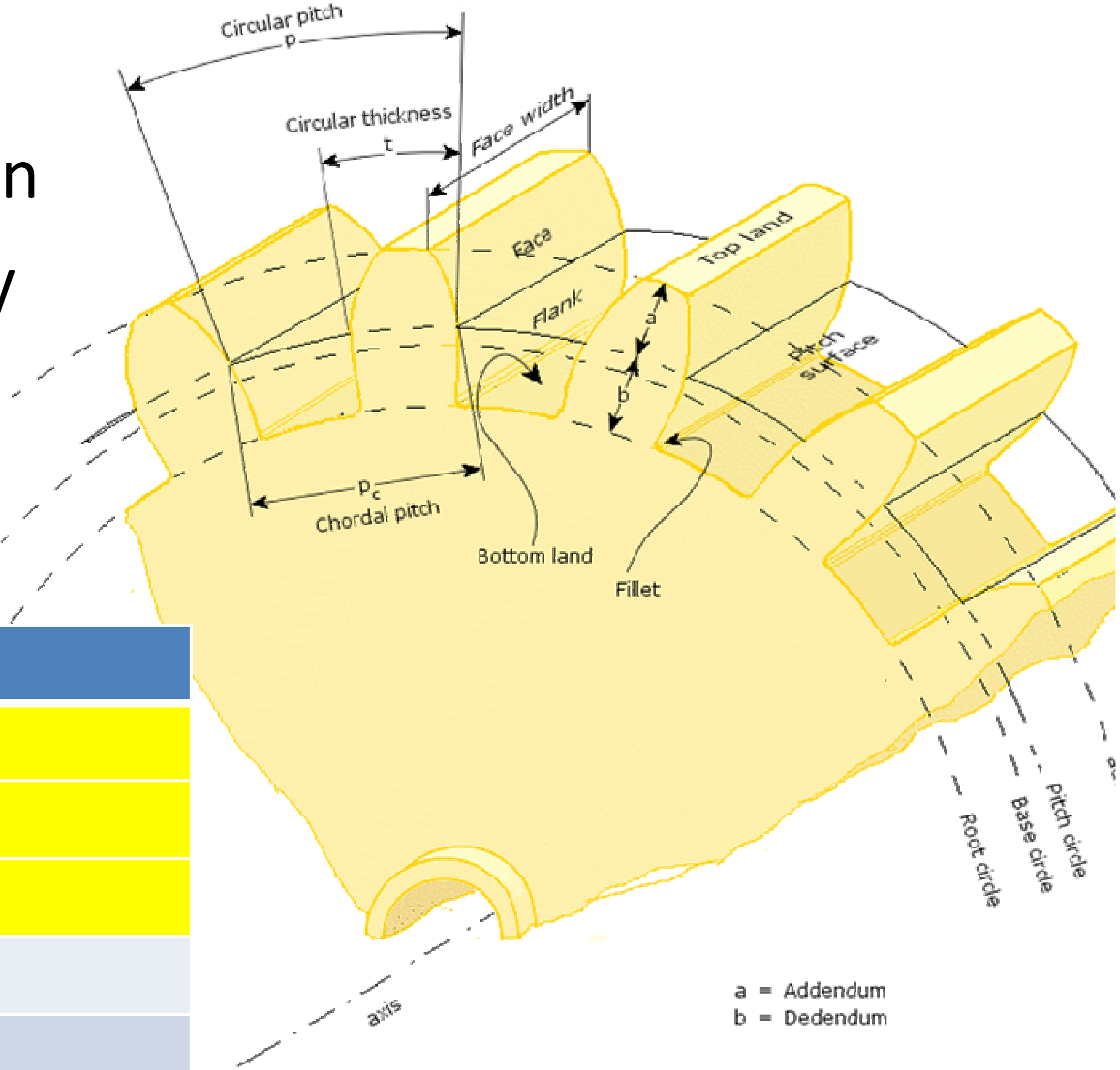
Gear test case

<u>Spur gears</u>

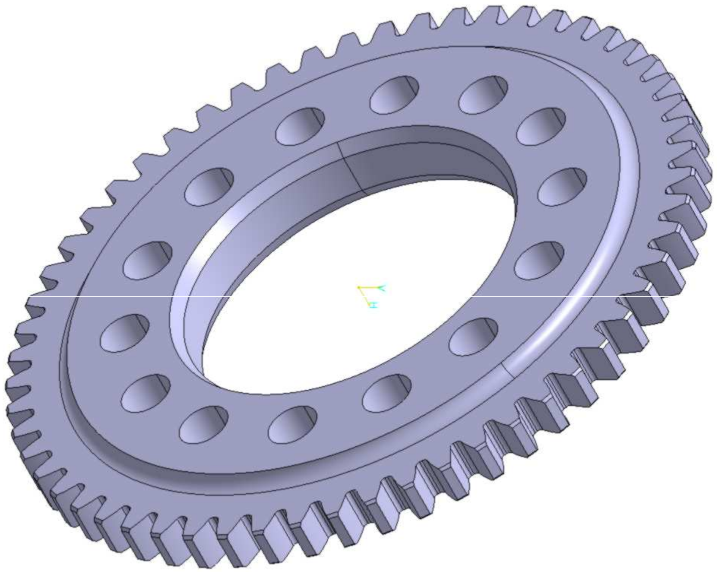
- Relatively easy design
- Symmetric geometry
- Simple to heat-treat



Parameter	Test case
Pitch diameter (mm)	140
No. teeth	57
Module (mm)	2.54
Tooth thickness (mm)	5.715
Face width (mm)	9

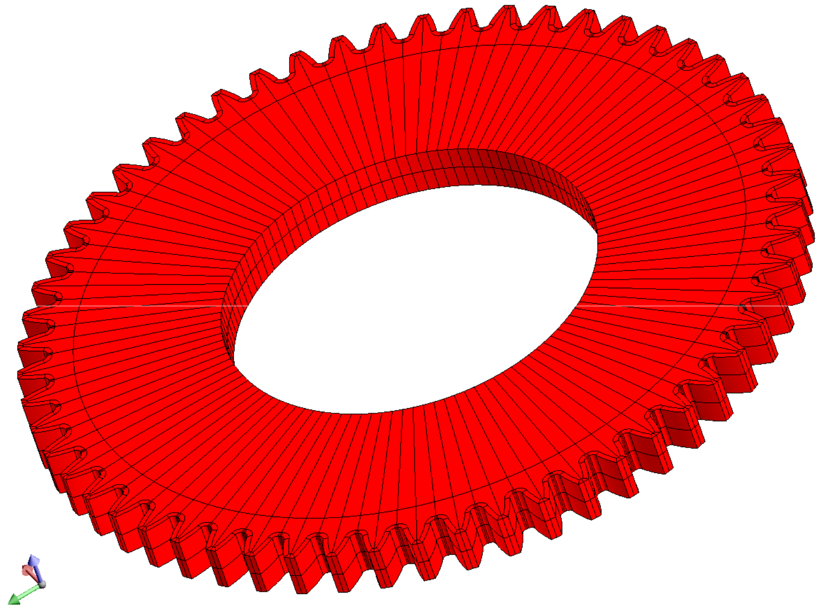
Gear geometry

CAD tool



- 🟢 Parametrized model
- 🟢 Accurate tooth profile (spline)
- 🔴 Requires CAD software and FEA importation modules

FEM tool



- 🟢 Parametrized geometry
- 🟢 Directly built in the simulation environment
- 🔴 Approx tooth profile (root fillet)

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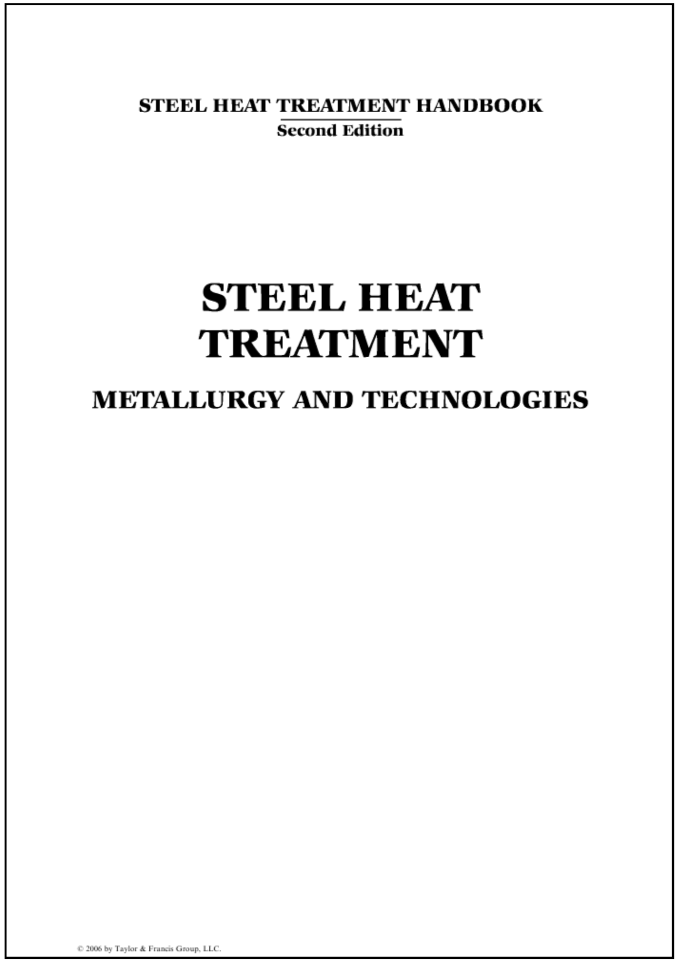
Material choice

- Required properties
  - Low-alloy, mid-carbon steel
  - Aeronautical grade
  - Good hardenability
  - High hardness
- Steel options
  - AISI 6150 (50CrV4)
  - AISI 4340


STEEL HEAT TREATMENT HANDBOOK
Second Edition

STEEL HEAT TREATMENT

METALLURGY AND TECHNOLOGIES

© 2006 by Taylor & Francis Group, LLC.

Material modeling

- Non-linear magnetic properties
  - B-field saturation → $\mu(H)$
  - Curie temperature transition → $\mu(T)$
- T-dependent electric and thermal properties

Symbol	Quantity	Initial value
ρ	Electrical resistivity	$21 \times 10^{-8}\ \Omega \cdot m$
α_ρ	Temperature coefficient ρ	$2.5 \times 10^{-3}\ K^{-1}$
k	Thermal conductivity	$46.7\ W/m \cdot K^{-1}$
α_k	Temperature coefficient k	$-2.5 \times 10^{-3}\ K^{-1}$

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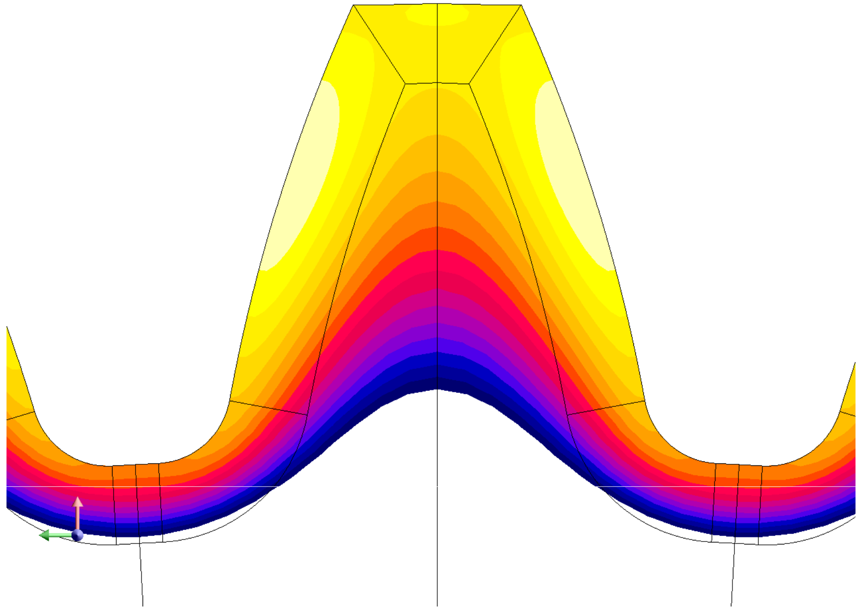
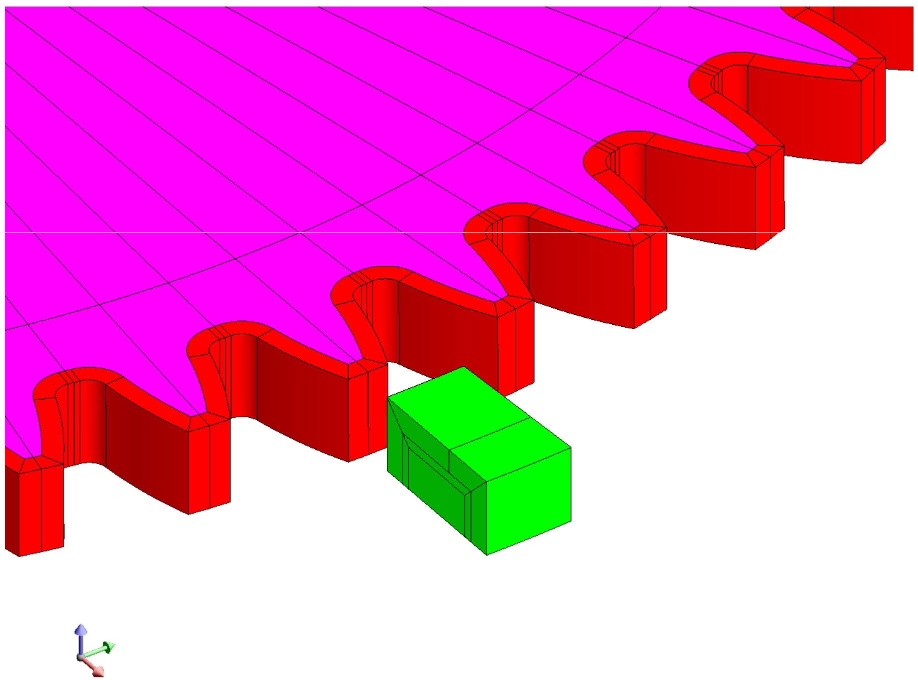
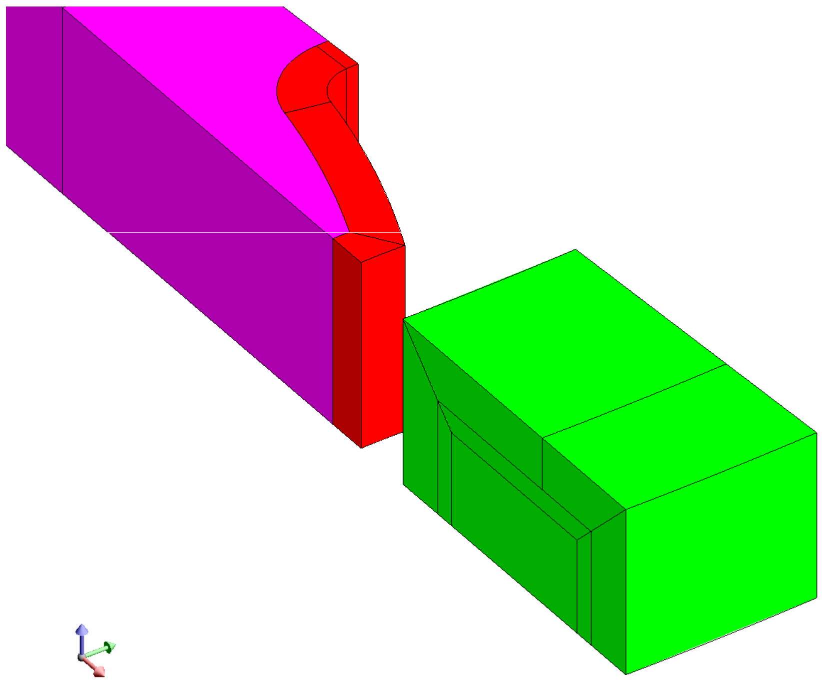


Heat treatment development tool

SIMULATION ACTIVITY

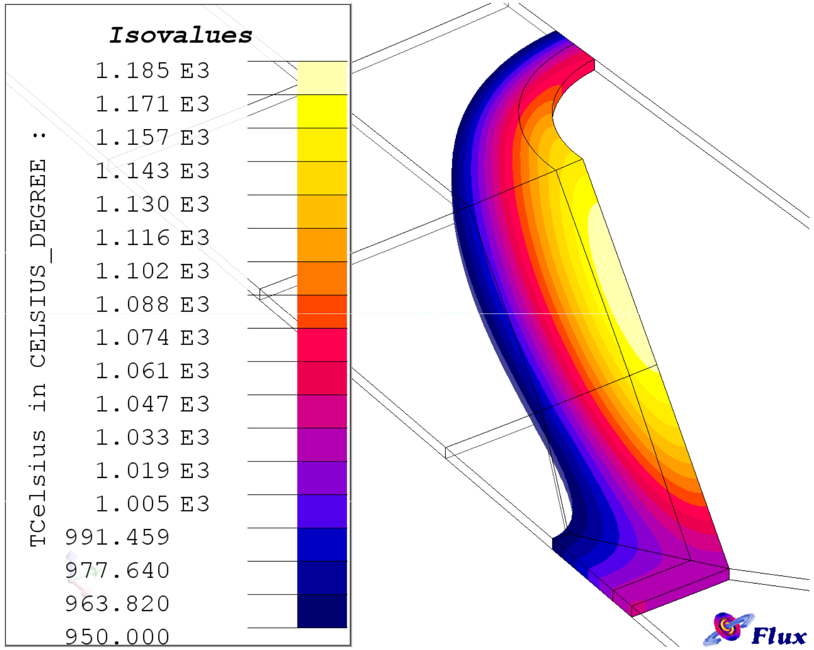
Geometrical model





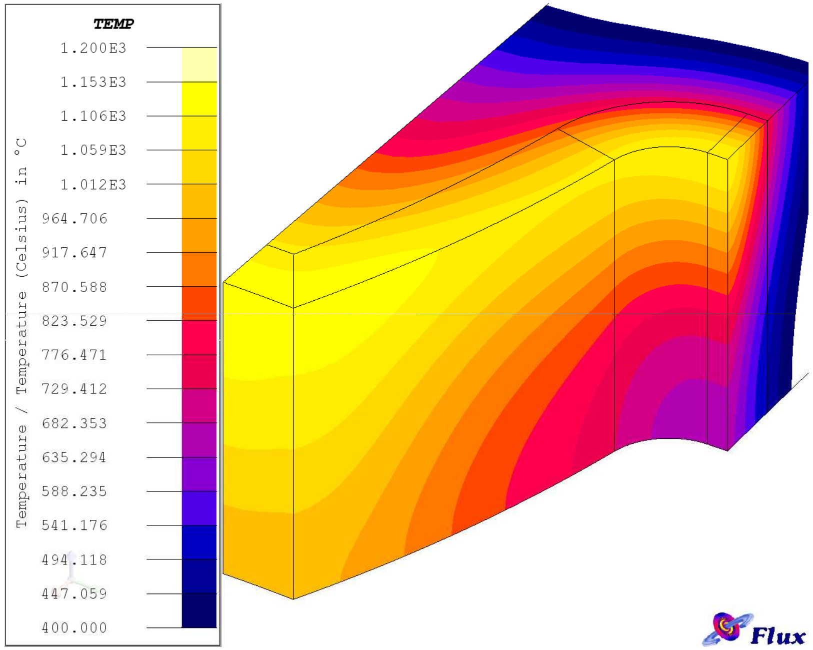
Geometrical model

Reduced model (slice)



- Normal magnetic field on section
- No edge effects
(due to geometry simplifications)
- No electromagnetic proximity effect
(due to coil modeling)

Full model



- Real magnetic field distribution
- Edge effects and proximity effects
both taken into account
- Computation time

Hardness and over-tempering prediction

- Evaluation of the hardened layer
  - Martensite phase proportion; displacive transformation → f(T) (Koistinen-Marburger, 1959)

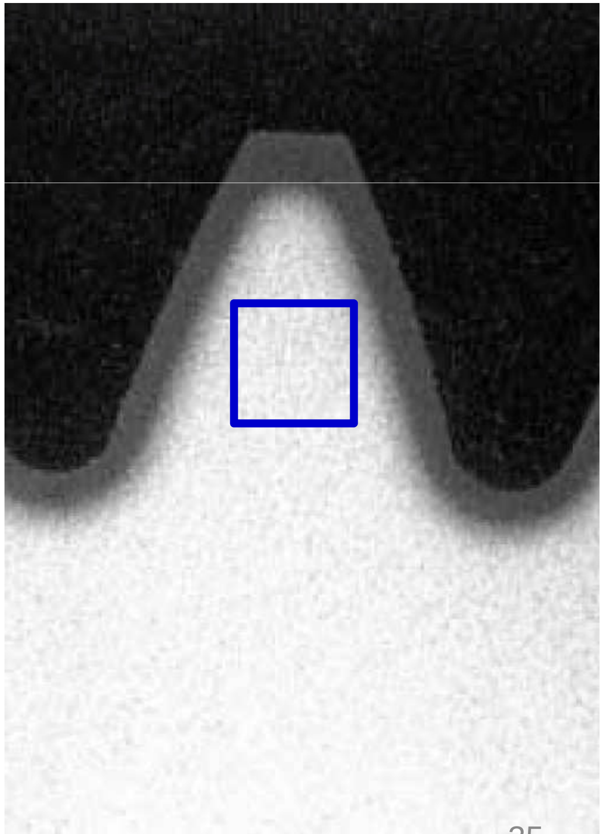
$$P(T) = 1 - \exp\left[-b(M_S - T)\right]$$

  - Residual austenite after the heat treatment based on cooling rate (Meyzaud, 1994)

$$\gamma_r = \exp\left(-0.011(M_S - 20)\left(1 - f(\Delta t_{300}^{700})\right)\right)$$
$$f(\Delta t_{300}^{700}) = 0.41\left(1 - \exp\left(-0.03(\Delta t_{300}^{700})^{0.6}\right)\right)$$

- Over-tempering region estimation
  - Analytical relation (Ducassy, 2010)
  - Hardness loss based on experiment

$$HV(t,T) = d\ln(t) + e(T)$$



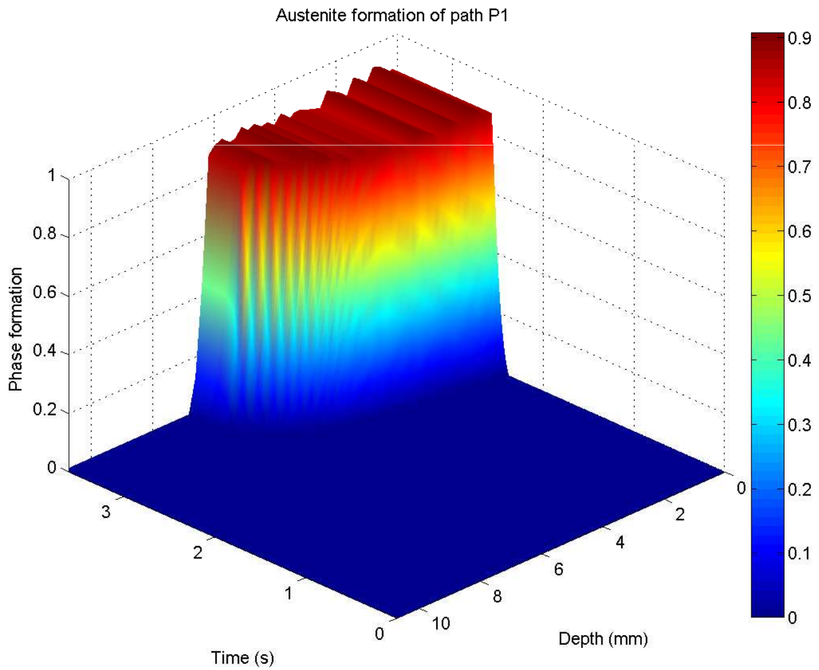
Microstructure prediction

- Diffusive transformations → f(t,T) (Avrami, 1939 → JMAK)
  - Based on CCT/TTT diagrams
  - Thermal history taken into account
  - Short-time austenitization on heating
  - Phase transitions on cooling

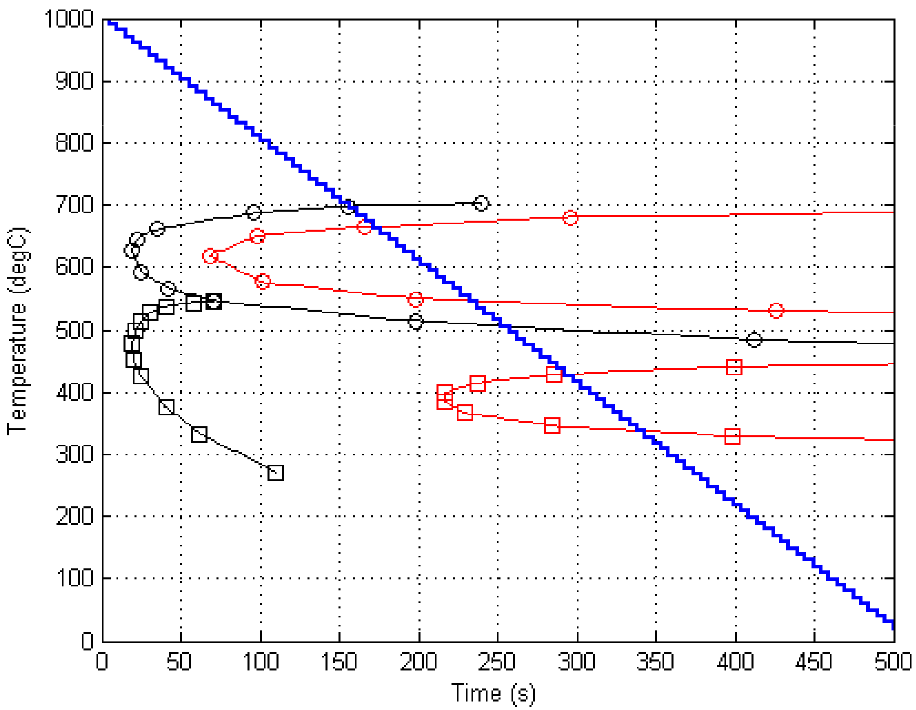
$$P(t,T)=1-\exp\left(-a(T)\cdot t(T)^{n(T)}\right)$$

Microstructure prediction

Austenitization

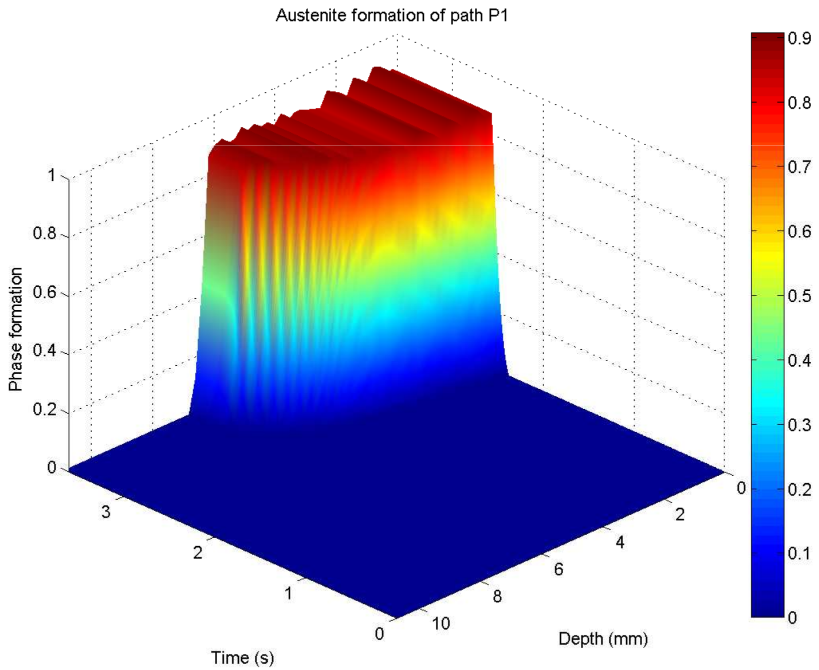


Phase transitions

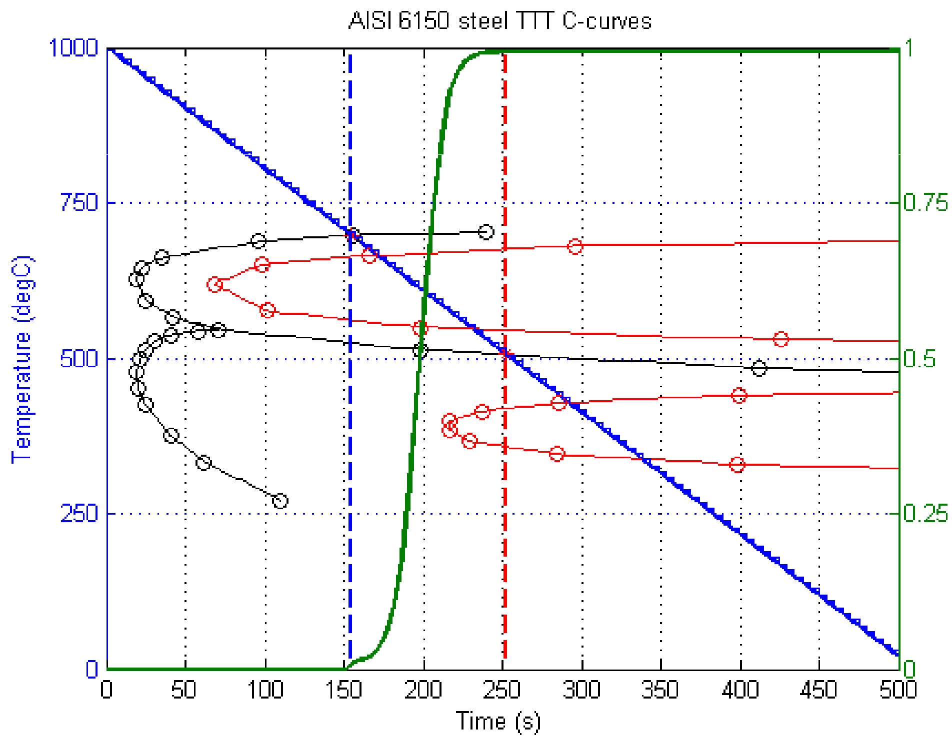


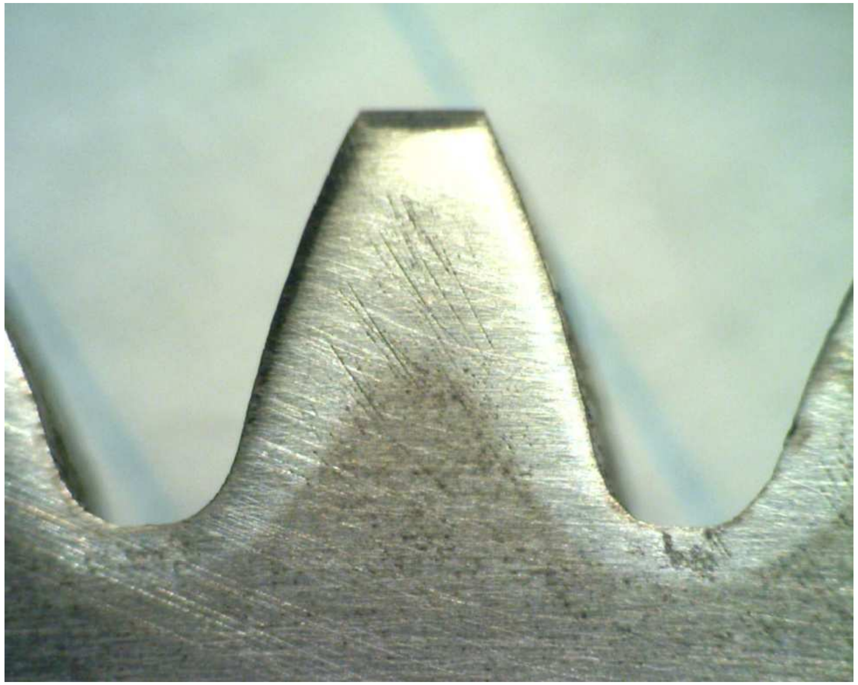
Microstructure prediction

Austenitization



Phase transitions

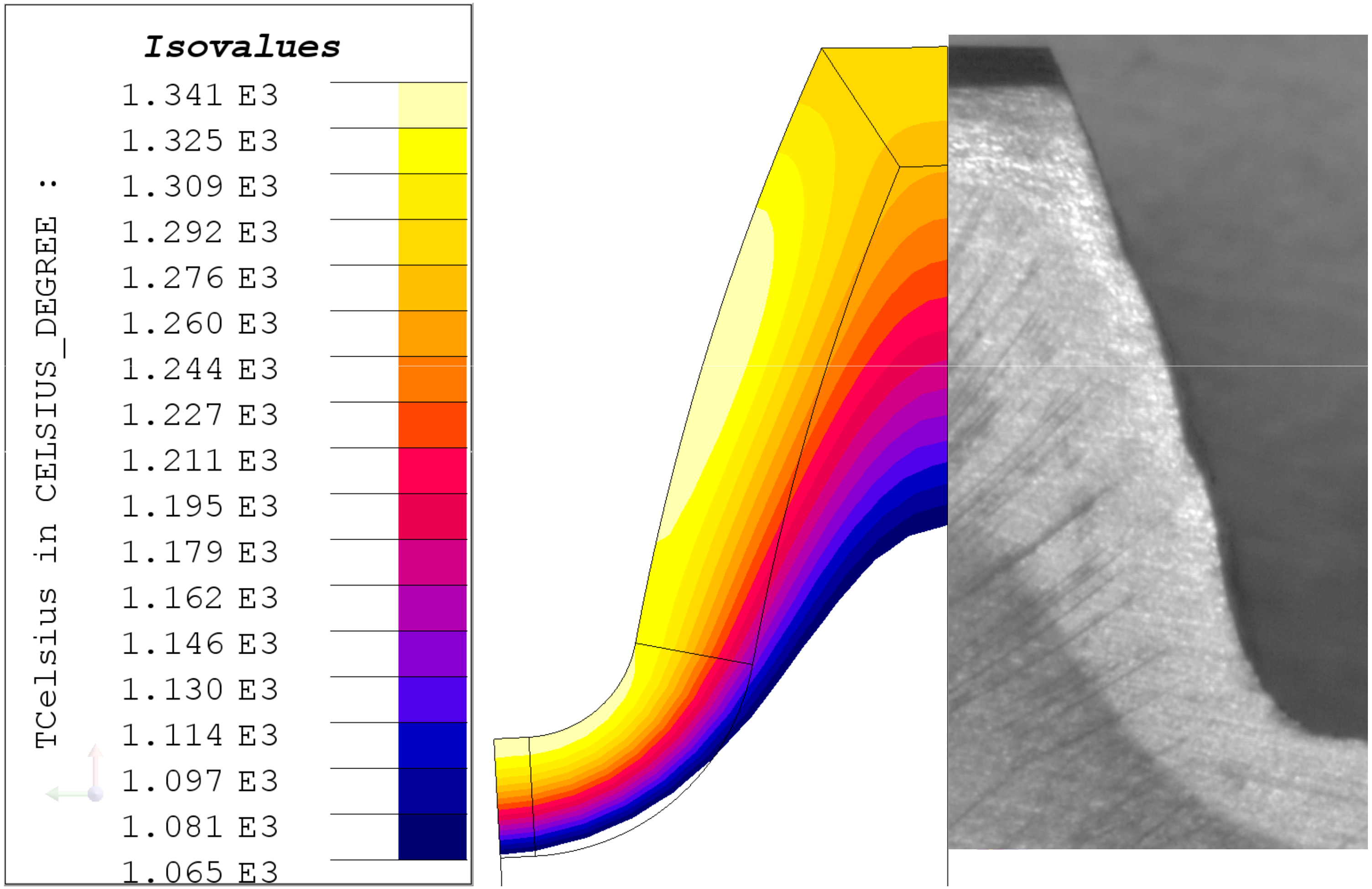




Validation of simulation results

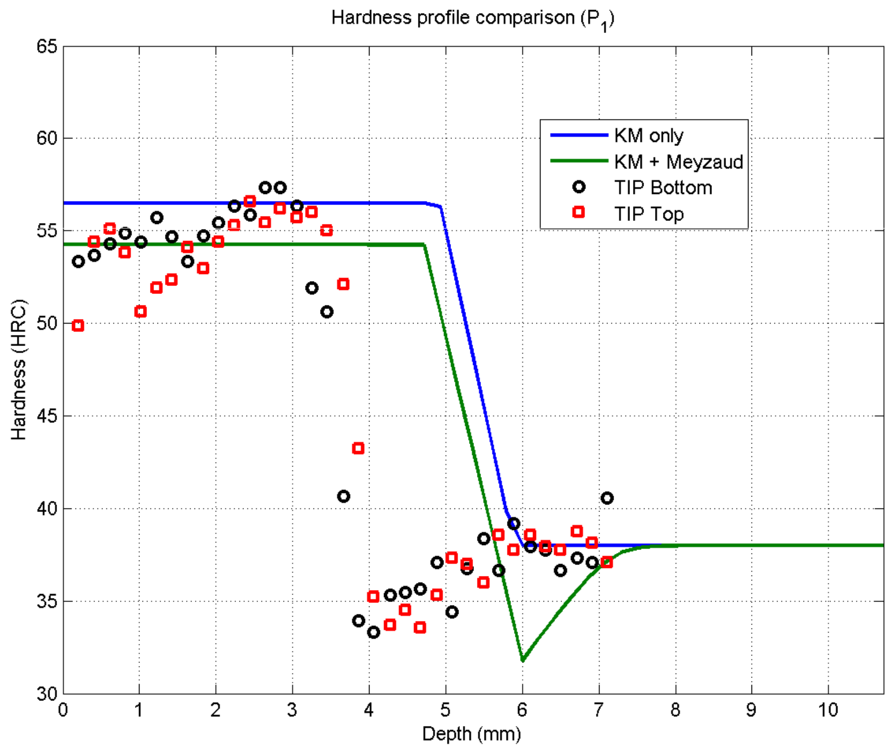
EXPERIMENTAL ACTIVITY

Thermal comparison

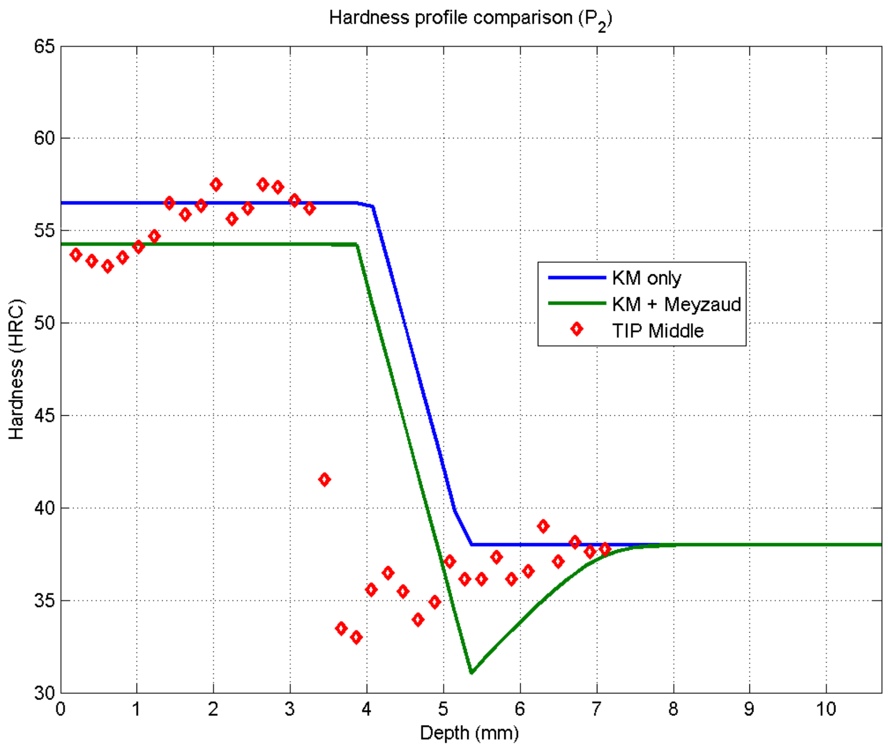


Hardness comparison – TIP

Top + Bottom section

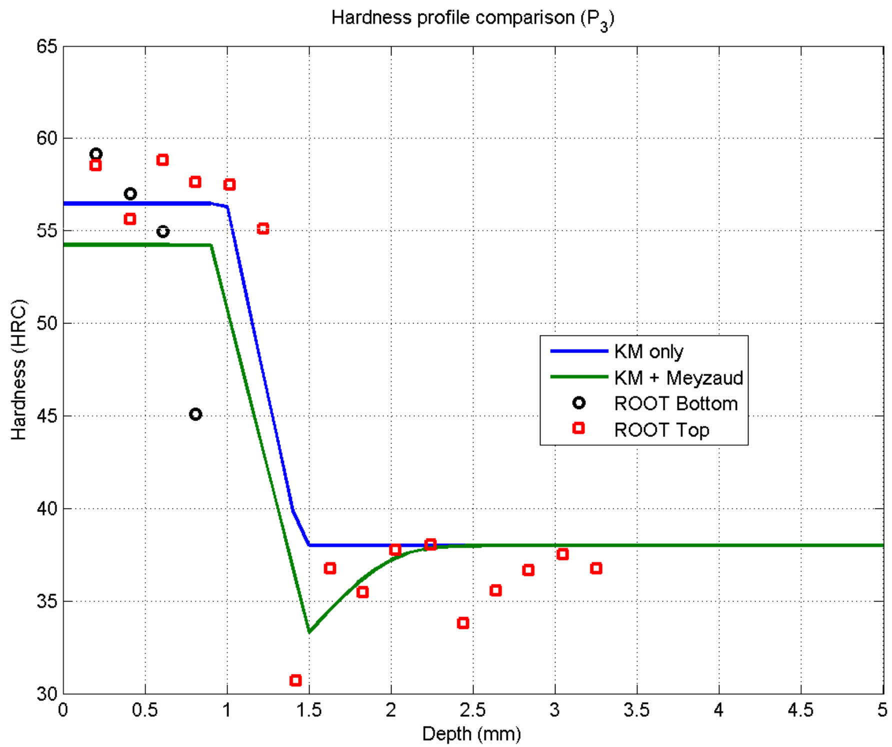


Middle section

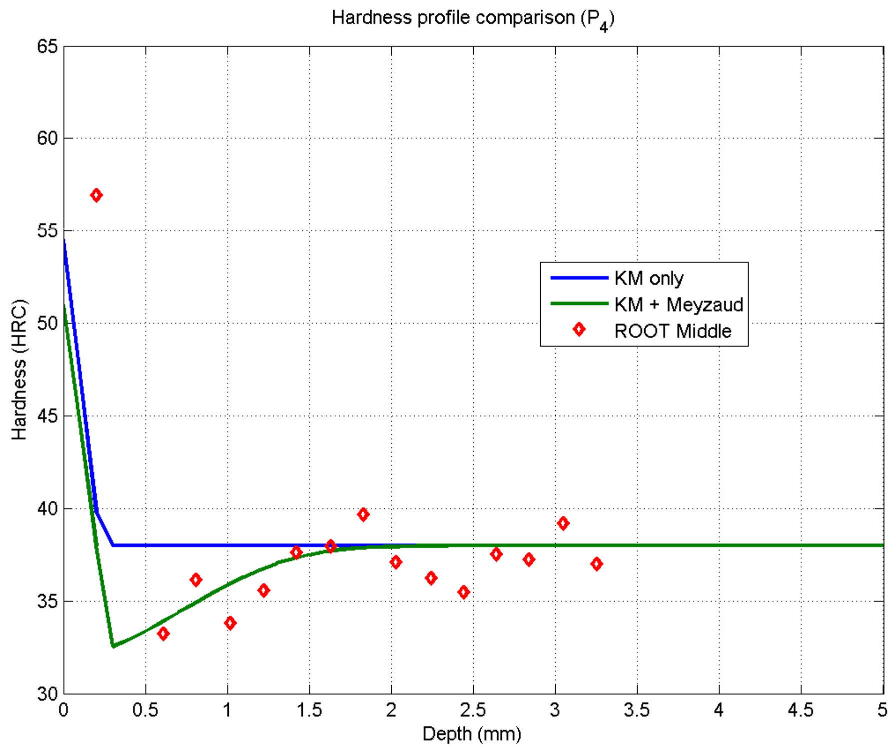


Hardness comparison – ROOT

Top + Bottom section



Middle section



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Conclusions

- Numerical simulation allows to assess the impact of several aspects on final hardness
  - Modeling of relative permeability
  - Influence of quenching rate and dwell-time
  - Heating by different recipes
- Experimental activity is mandatory to validate the obtained results
- What's next?

Ongoing and future work

- Comparison of simulation results with experimental tests
  - Heat treatment process on dedicated equipment
  - Temperature measurements by thermal paints
  - Hardness and residual stress measurement, microstructure analysis
- Implementation of phase transitions during the magneto-thermal solution
  - Adding multiple phase transition (Perlite, Bainite, Martensite)
  - Hardness prediction based on structure
  - Model refinements
    - Austenite grain growth above Ac3
    - Change of thermal properties on cooling
- Prediction of resulting residual stresses and main mechanical properties

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THANK YOU FOR YOUR ATTENTION! (ANY QUESTIONS?)

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