Virfac® | The Virtual Factory
Virtual Manufacturing Made Real

Simulations of the Surface Heat Treatment of a forged crankshaft using High Performance Computing

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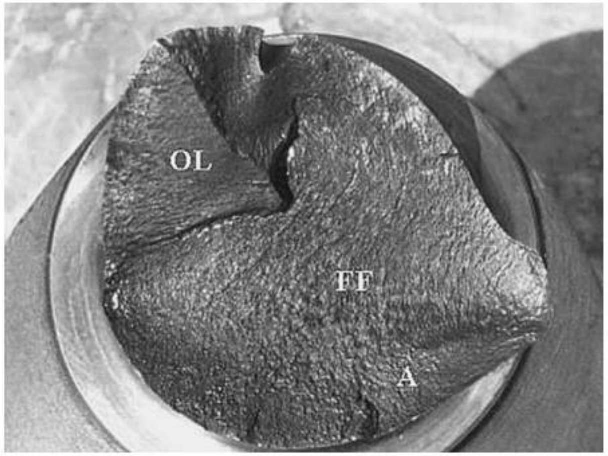
PROBLEM STATEMENT

- Stringent demands on fuel efficiency have driven improvements in performance of several automotive parts including those belonging to the powertrain
- Failure in crankshaft is commonly due to fatigue failure

Crack location in a failed crankshaft [1]

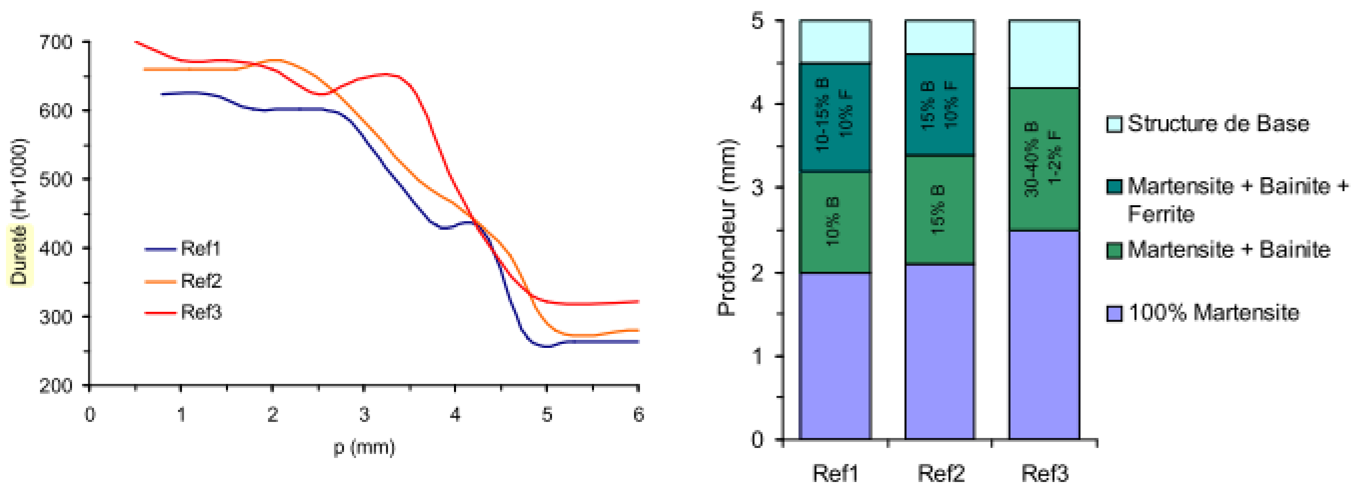


Fracture surface showing crack-initiation (A), fatigue failure (FF) and overloaded (OL) regions [1]

[1] Asi, O. (2006). Failure analysis of a crankshaft made from ductile cast iron. *Engineering Failure Analysis*, *13*, 1260–1267.

PROBLEM STATEMENT

- Remedy – hardening the surface of the crankshaft in order to improve fatigue resistance
- Methods – Nitriding, Surface hardening heat treatment

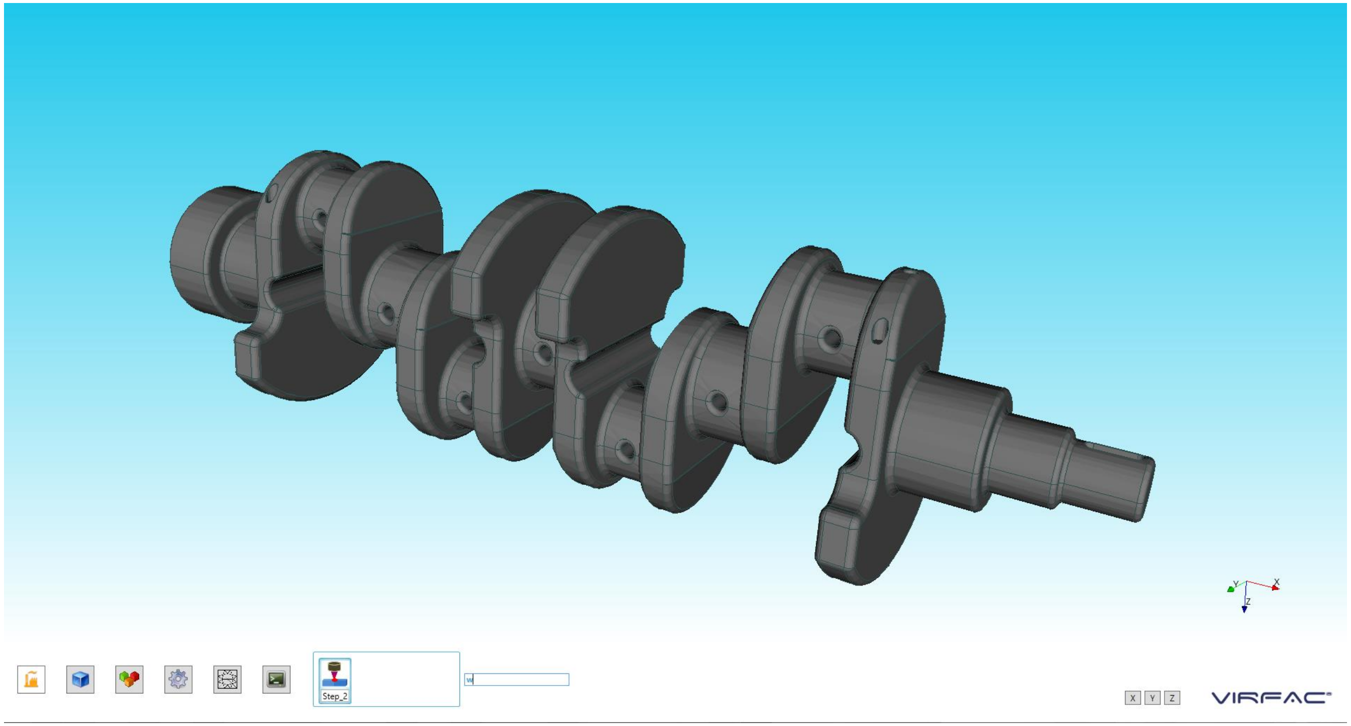


Surface hardening by induction heating and quenching [1]

[1] Bristiel, P. (2001). *Modélisation magnetothermique, métallurgique et mécanique de la trempe superficielle après chauffage par induction appliquée aux vilebrequins*. Ecole Nationale Supérieure d'Arts et Métiers, Centre de Bordeaux.

PROBLEM STATEMENT

- The present work models the induction heating and quenching of a journal in the crankshaft – taking into account the physics of the thermal, mechanical and metallurgical phenomena.



OUTLINE OF THE PRESENTATION

- Process description
- Material
- Simulation setup
- Results
- Computational performance
- Conclusions

PROCESS CHAIN DESCRIPTION

Stage 1: Surface heating by induction

- Very high heat flux at the surface : 5 – 50 $MW.m^{-2}$[1]
- Heating rates of 1000°C/s or more
- Highly localized austenitization in the zone near the surface

Stage 2: Hold

Stage 3: Water quenching

- Austenite converted to Martensite
- Accompanying distortions and residual stresses are developed

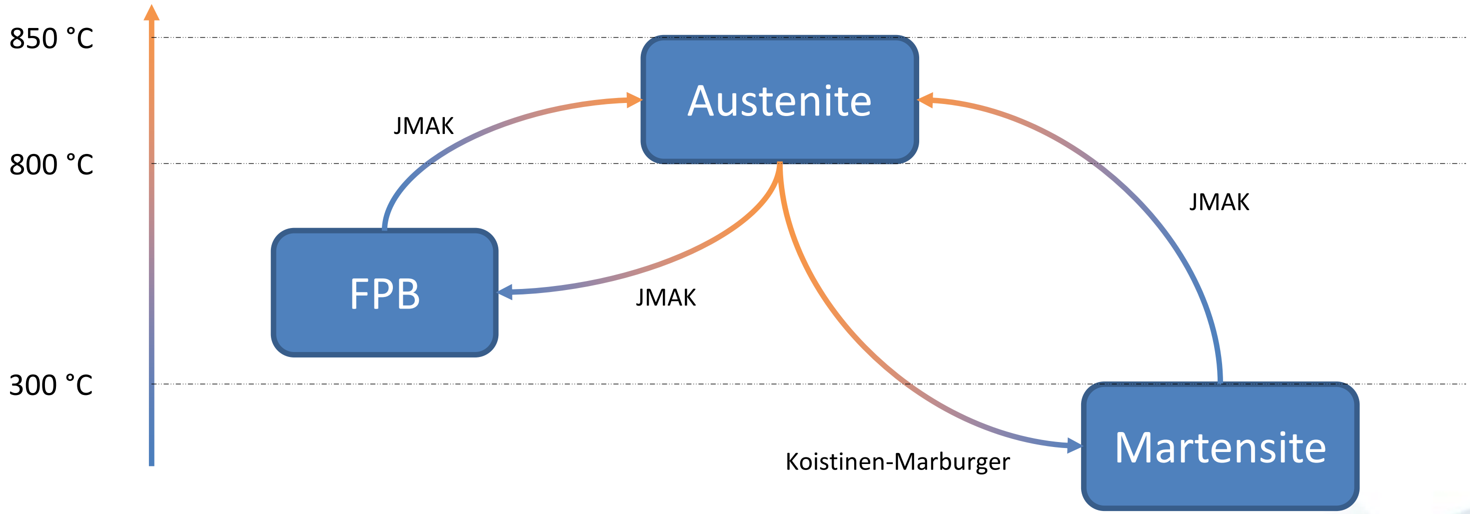
[1] Wanser, S. (1995). Simulation des phénomènes de chauffage par induction - Application à la trempe superficielle, 126.

MATERIAL

- 38MnSiV6 steel with the following composition

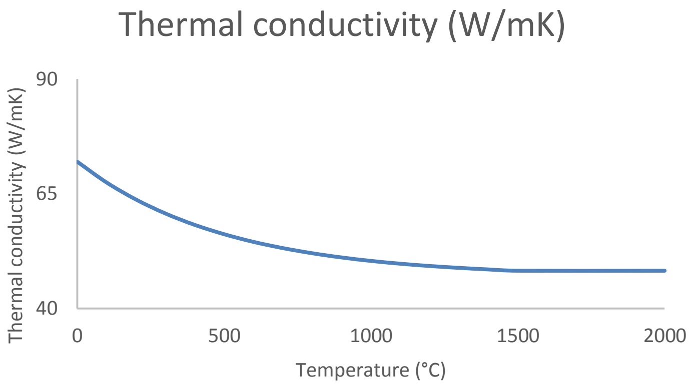
C	Si	Mn	P	S	V
0.35-0.4	0.5-0.8	1.2-1.5	0.035 max	0.03-0.065	0.08-0.13

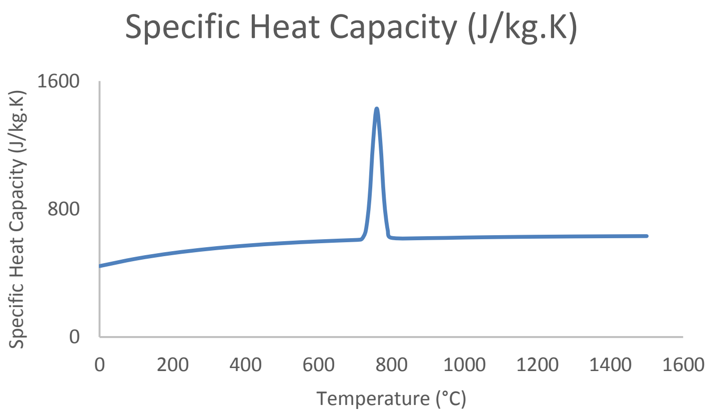
- Phases present: Ferrite-Pearlite-Bainite (FPB) (initial phase), Austenite, Martensite
- Phase transformations



MATERIAL PROPERTIES

- Temperature-dependent material properties are provided
- Mechanical properties are described using an elasto-plastic power law of the type $\sigma = \sigma_Y + H\varepsilon_p^N$
- The specific heat capacity includes the latent heat of transformation from the low-temperature phases to Austenite

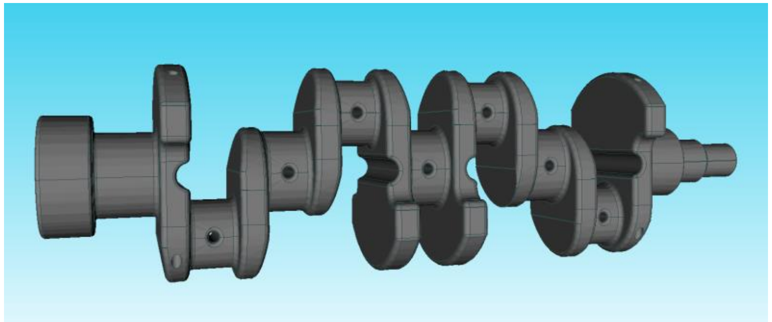


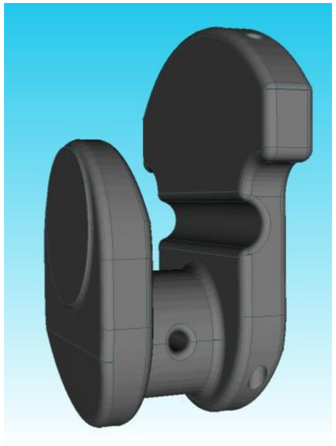


Simulation Set Up

Two different simulations are carried out:

- Full model – with the entire crankshaft geometry
- Reduced model – containing a single journal





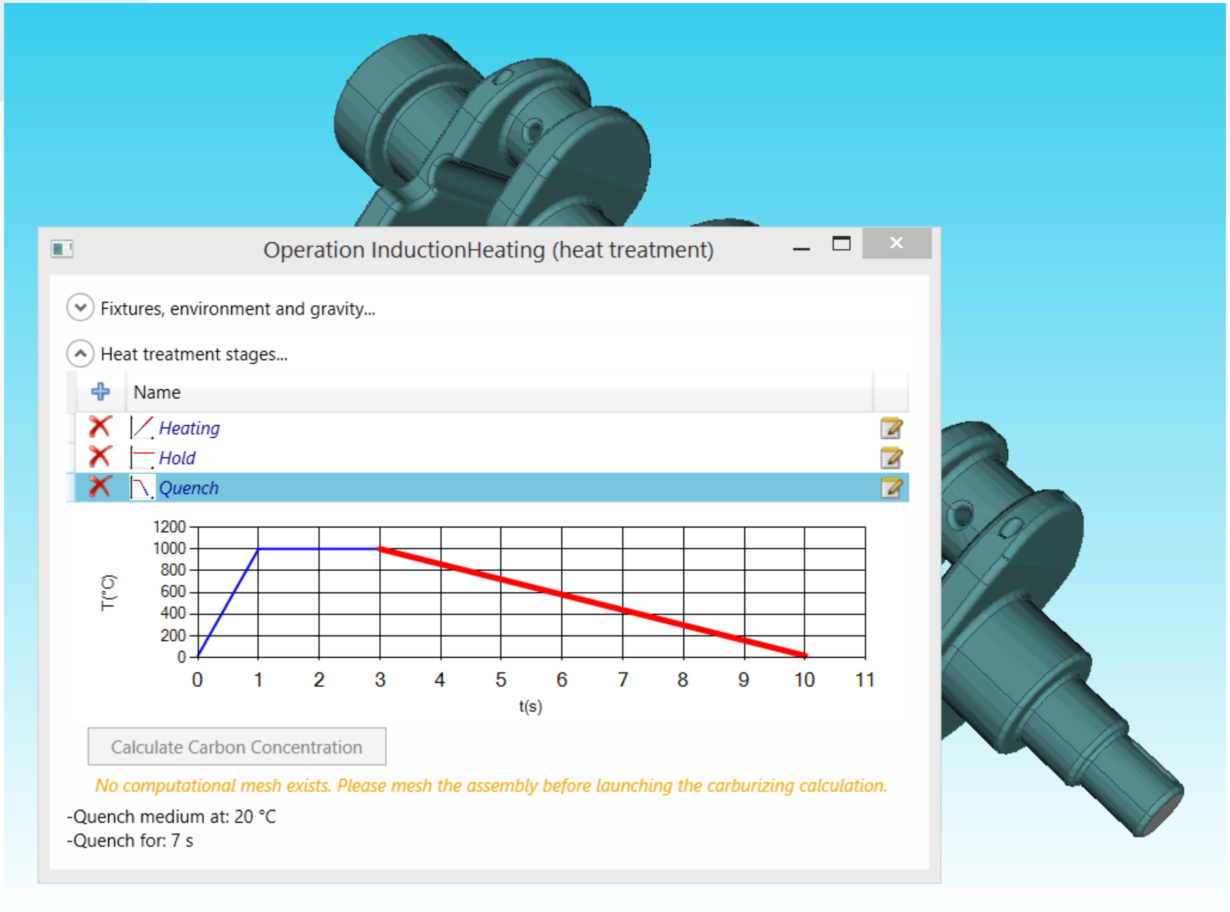
Full model:
Nodes: 900’035
Elements: 4’705’964
Analysis: Thermal-Mechanical

Reduced model:
Nodes: 185’589
Elements: 960’244
Analysis: Thermal-metallurgical-mechanical

SIMULATION SET UP

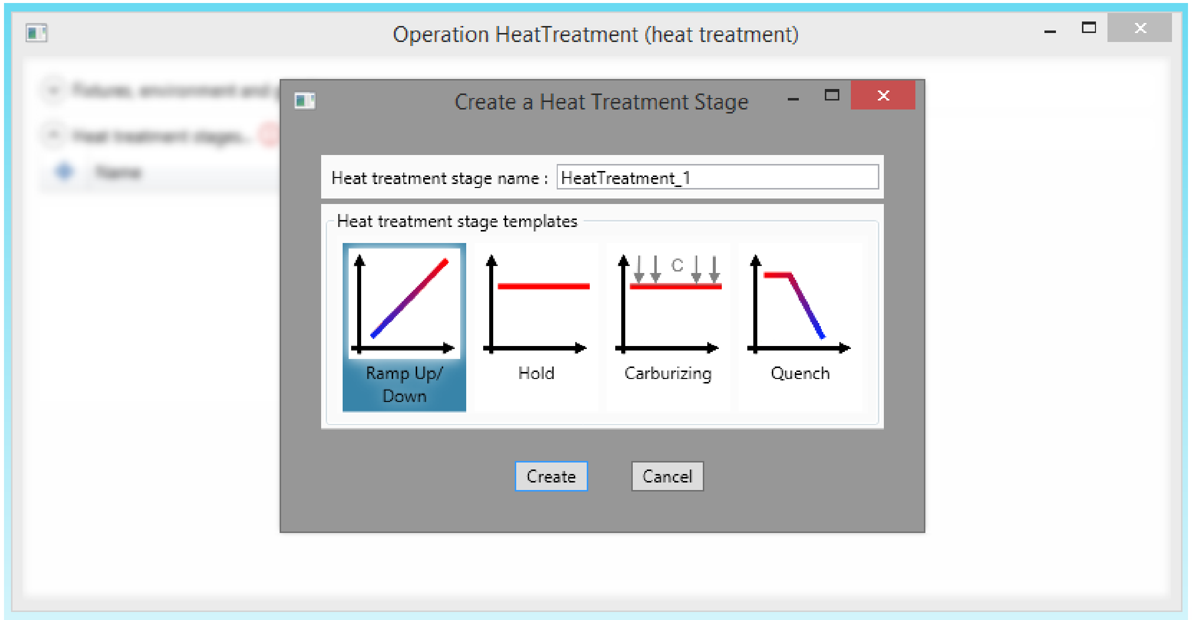
Thermal cycle:

- Induction Heating
- Hold
- Quench



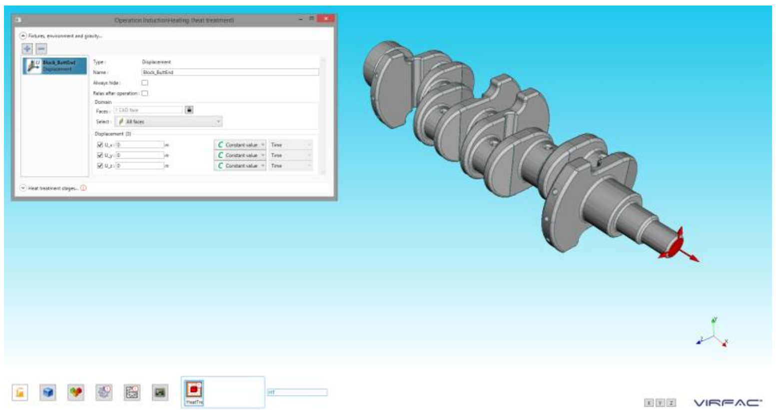
SIMULATION SET UP - FIXATION

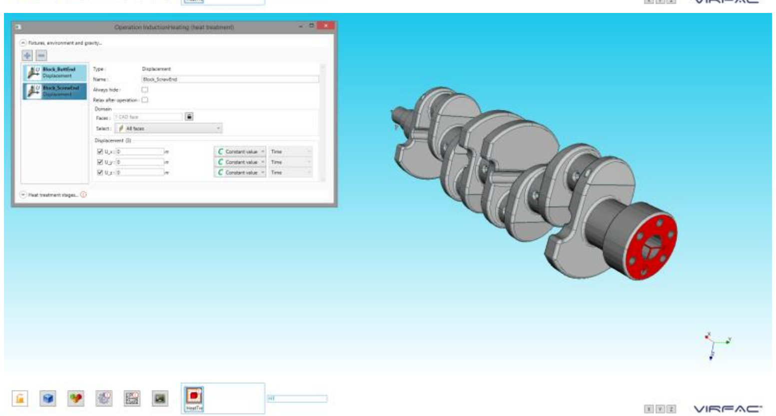
- The simulations are set up using the Heat Treatment analysis in Virfac® - Virtual Factory developed by GeonX
- Types of heat treatment stages available in Virfac Heat Treatment:
  - Ramp Up/Down
  - Hold
  - Carburizing*
  - Quench

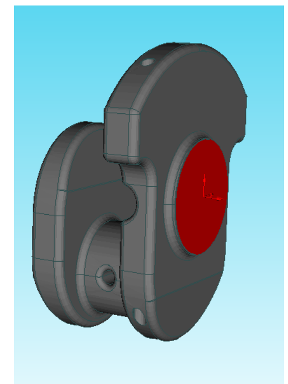


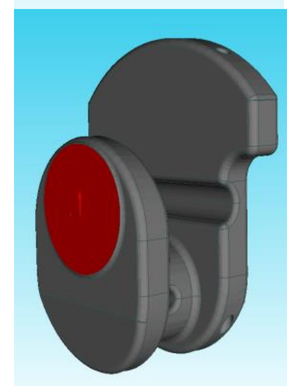
SIMULATION SET UP - FIXATION

- The simulations are set up using the Heat Treatment analysis in Virfac® - Virtual Factory developed by GeonX
- The ends of the geometry are blocked



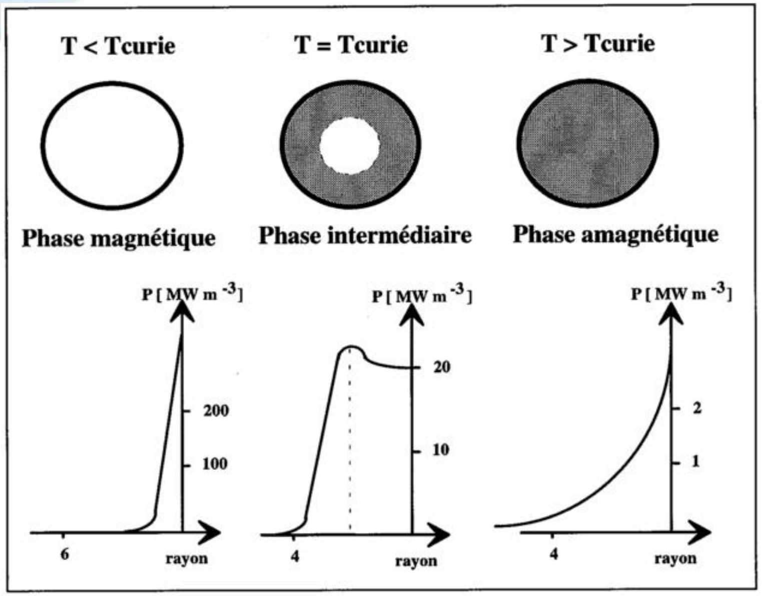






Simulation Set Up – Thermal Loads

- Volume flux due to induction heating



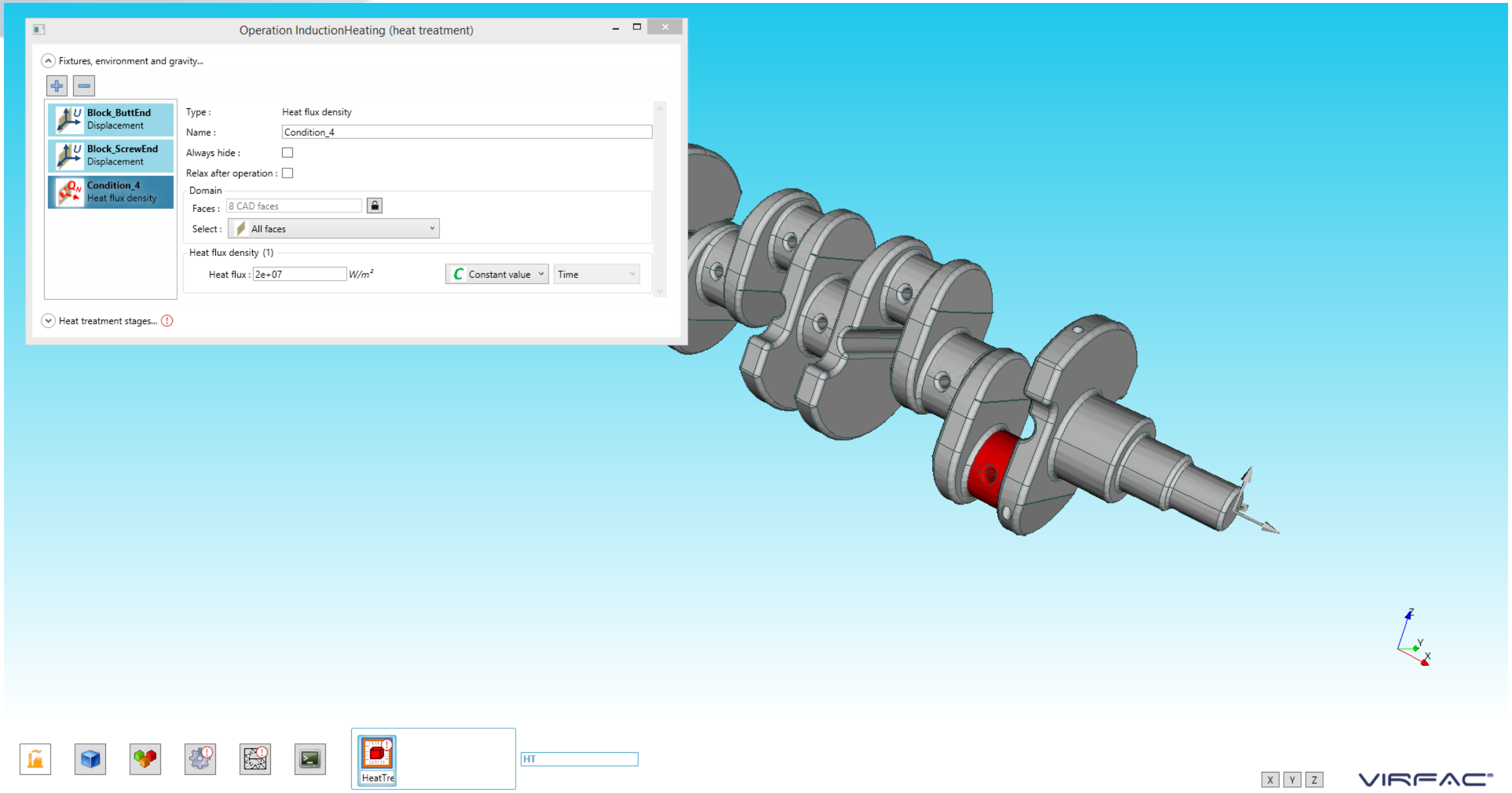
Heat flux in the volume due to induction [1]

- Industrial processes have surface flux in the range of 5–50 $MW.m^{-2}$ [1]
- Heating rate of 1000 °C/s in the skin

[1] Wanser, S. (1995). Simulation des phénomènes de chauffage par induction - Application à la trempe superficielle, 126.

SIMULATION SET UP – THERMAL LOAD HYPOTHESIS

- Constant surface flux of 20 $MW.m^{-2}$ on one journal surface



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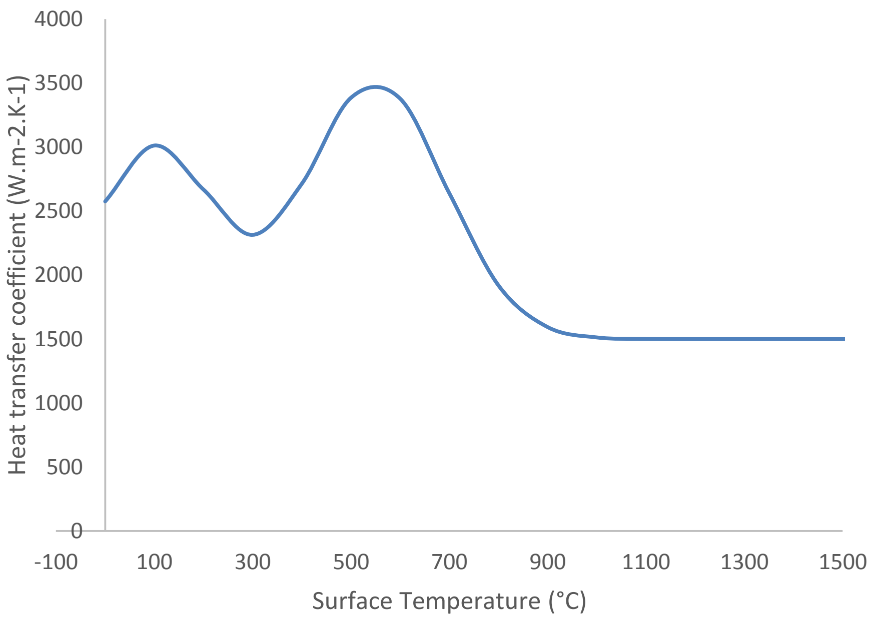
Simulation set up – thermal boundary conditions

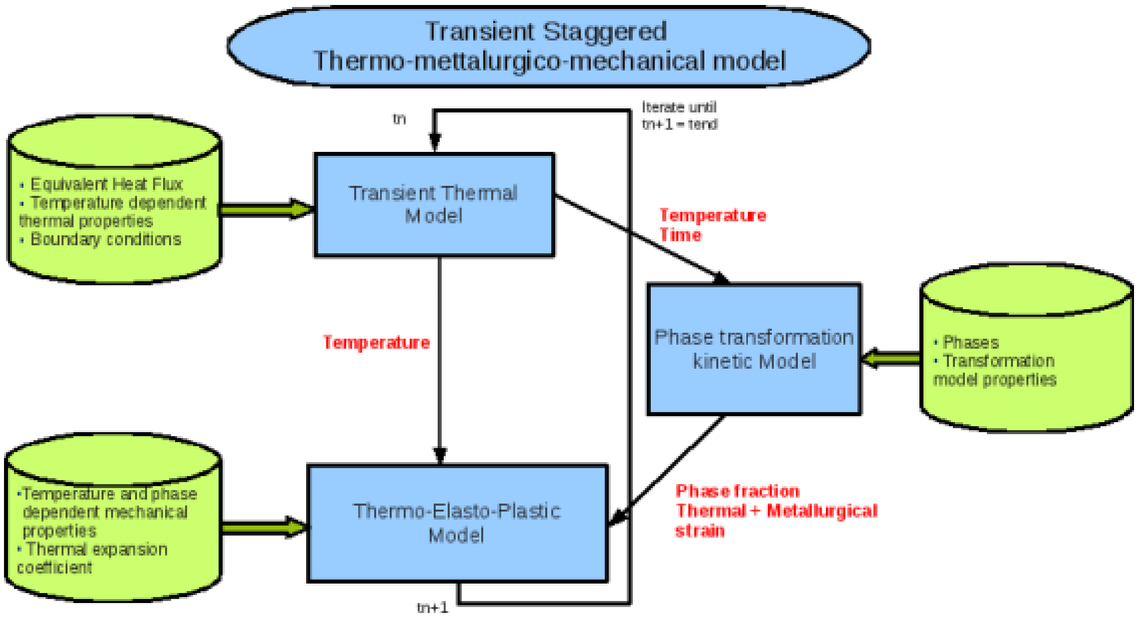
- Convection is applied on the entire surface
  - Heating + Hold: Constant convection coefficient 20 $W.m^{-2}.K^{-1}$
  - Quenching phase: Variable convection coefficient [1]



[1] Bristiel, P. (2001). *Modélisation magnétothermique, métallurgique et mécanique de la trempe superficielle après chauffage par induction appliquée aux vilebrequins*. Ecole Nationale Supérieure d'Arts et Métiers, Centre de Bordeaux.

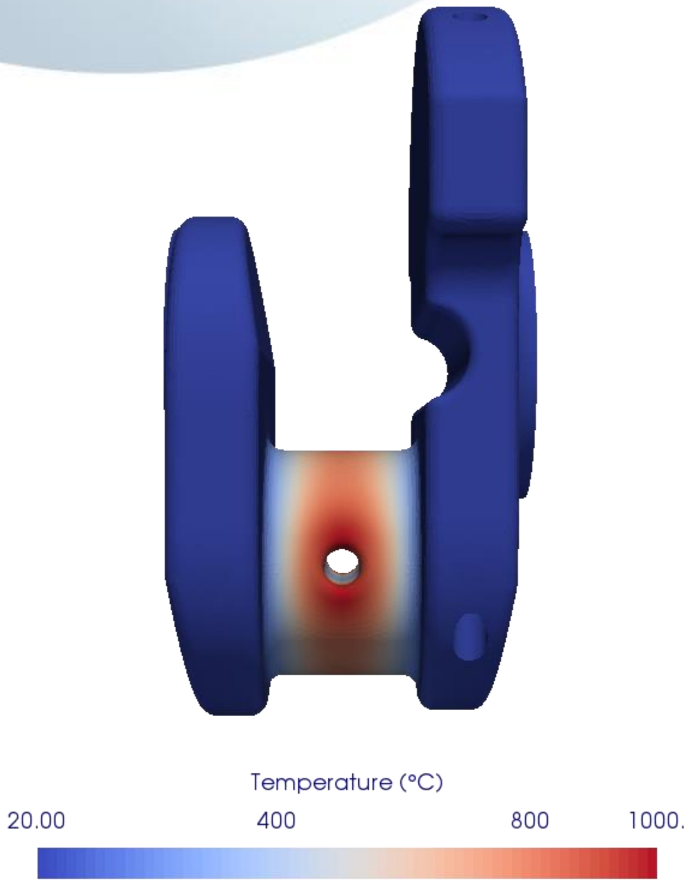
Simulation strategy in Morfeo

- The Finite Element Solver Morfeo is used for the simulations
- Staggered coupling between thermal-metallurgical-mechanical calculations
- Massively distributed parallel computation



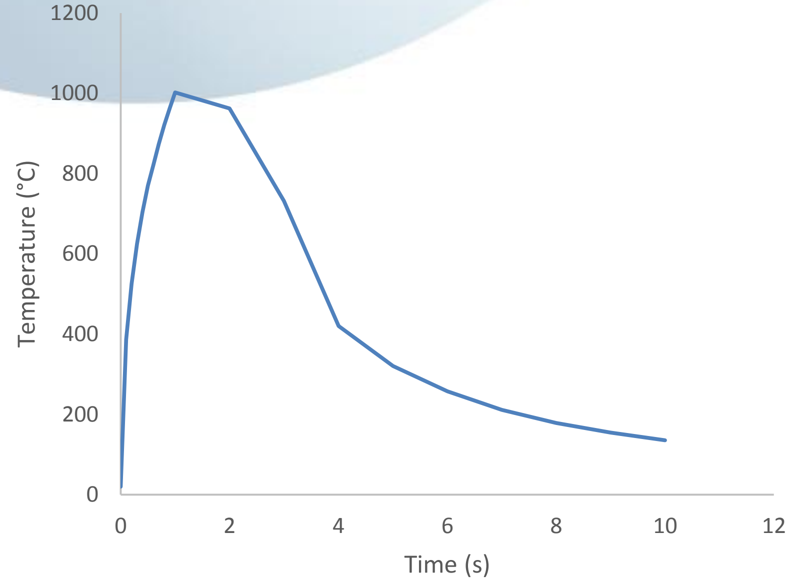
RESULTS

- Temperature field at the beginning of the hold stage

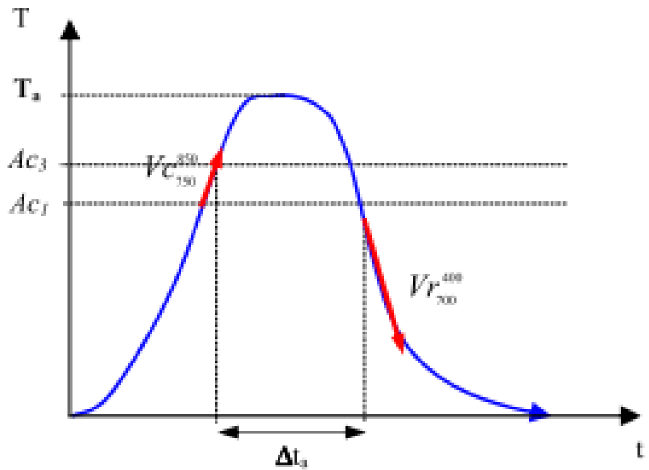


RESULTS

- Thermal cycle



Temperature history for a point on the surface in the simulation



Schematic representation of a real heating cycle [1]

- Heating curve is not identical because of constant flux approximation
- Slopes are maintained in the austenitization and cooling stages

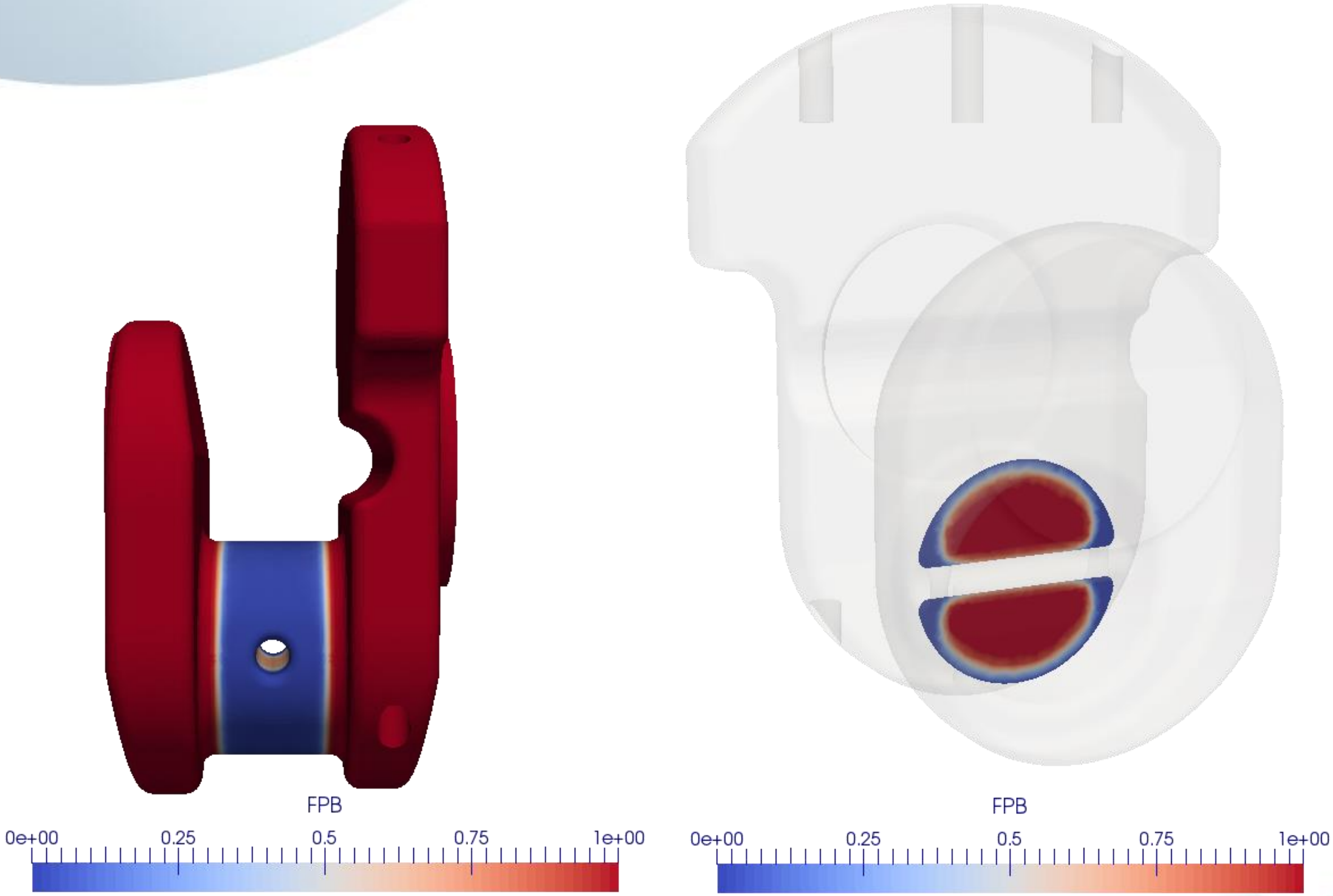
[1] Bristiel, P. (2001). *Modélisation magnétothermique, métallurgique et mécanique de la trempe superficielle après chauffage par induction appliquée aux vilebrequins*. Ecole Nationale Supérieure d'Arts et Métiers, Centre de Bordeaux.

RESULTS

- Phases present at the beginning of the hold stage – Austenite

Results

- Phases present at the beginning of the hold stage – FPB



RESULTS

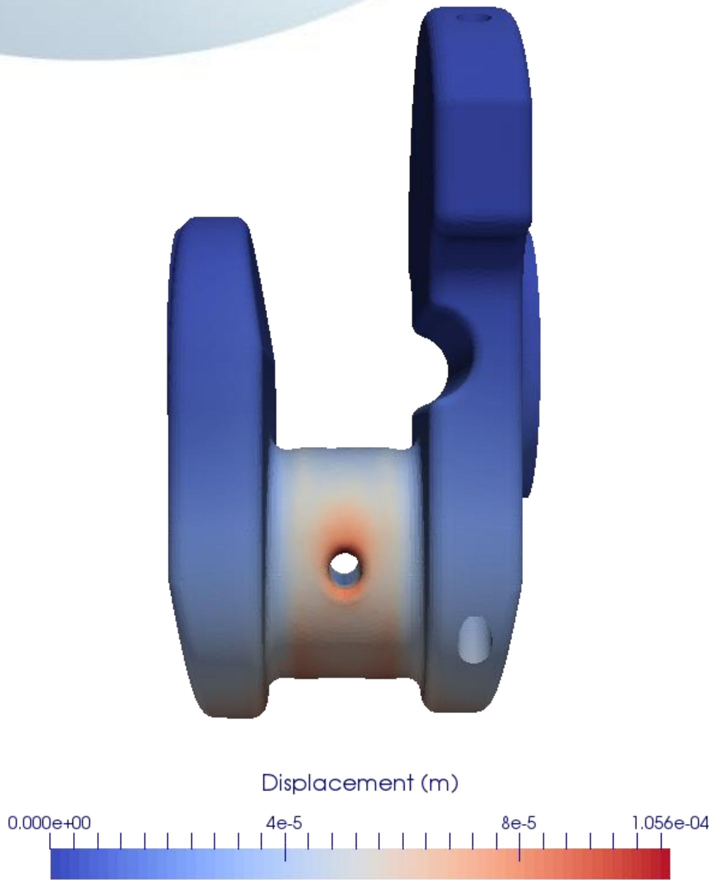
- Phases present at the end of the quench stage - Martensite

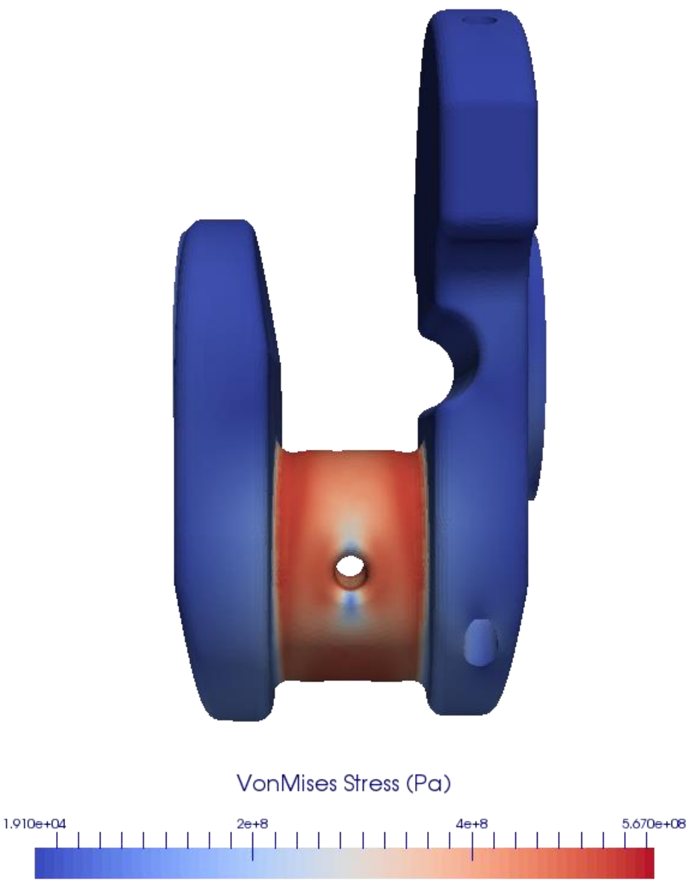
RESULTS

- Phases present at the end of the quench stage - FPB

Results

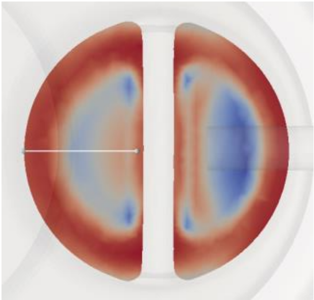
- Residual stresses and distortions at the end of the quenching phase

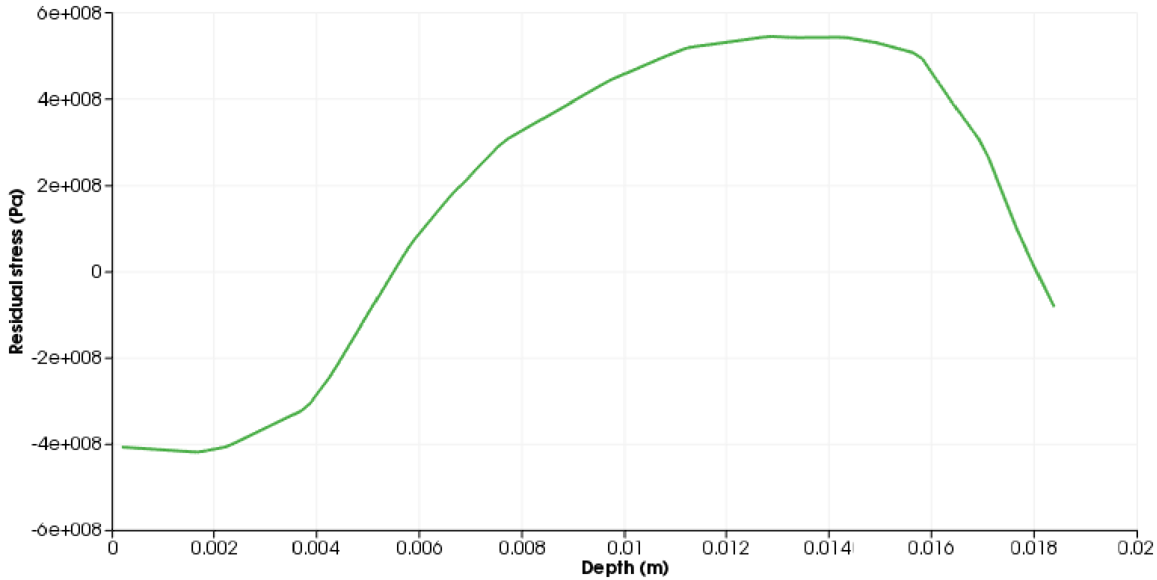


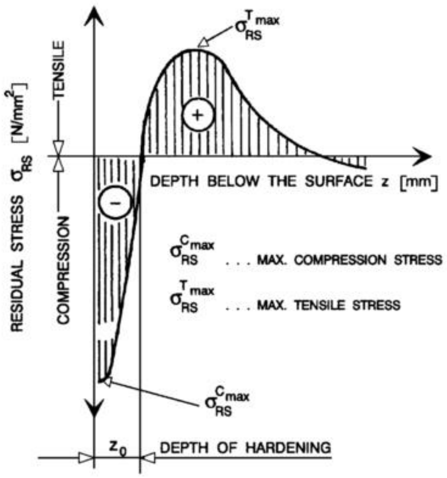


RESULTS

Residual stresses profile





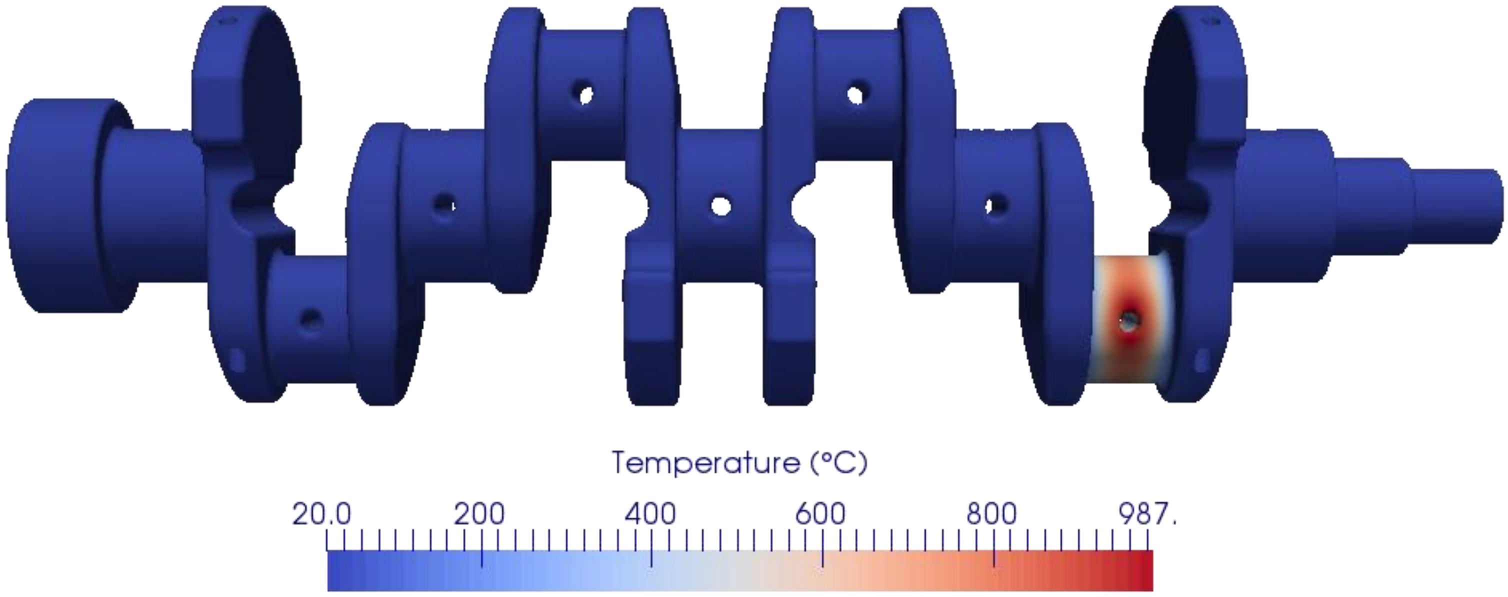


Typical residual stress profile after induction hardening [1]

[1] Grum, J. (2001). A review of the influence of grinding conditions on resulting residual stresses after induction surface hardening and grinding. *Journal of Materials Processing Technology*, *114*, 212–226.

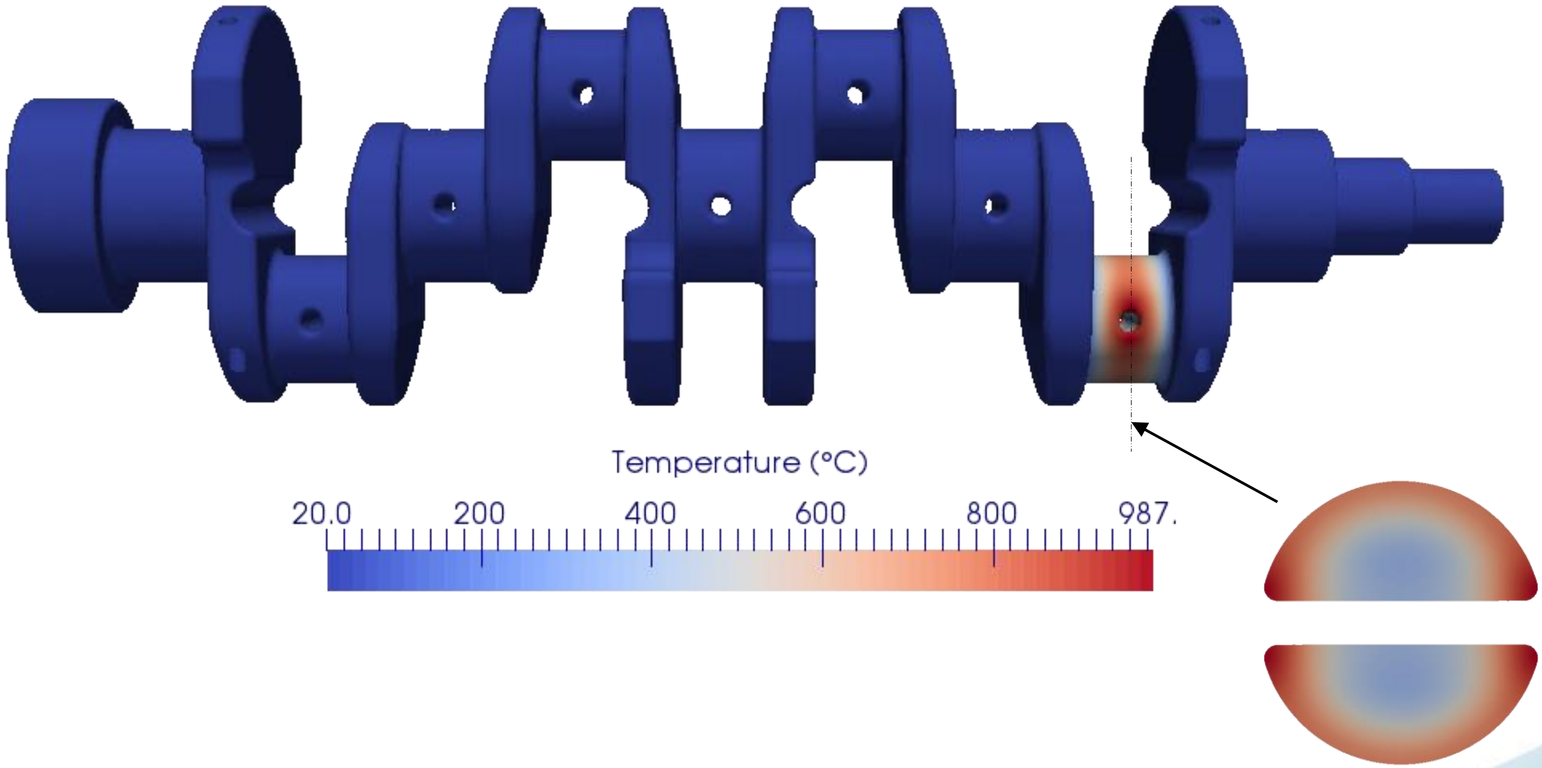
Results – Complete model

- Temperature at the beginning of the hold stage



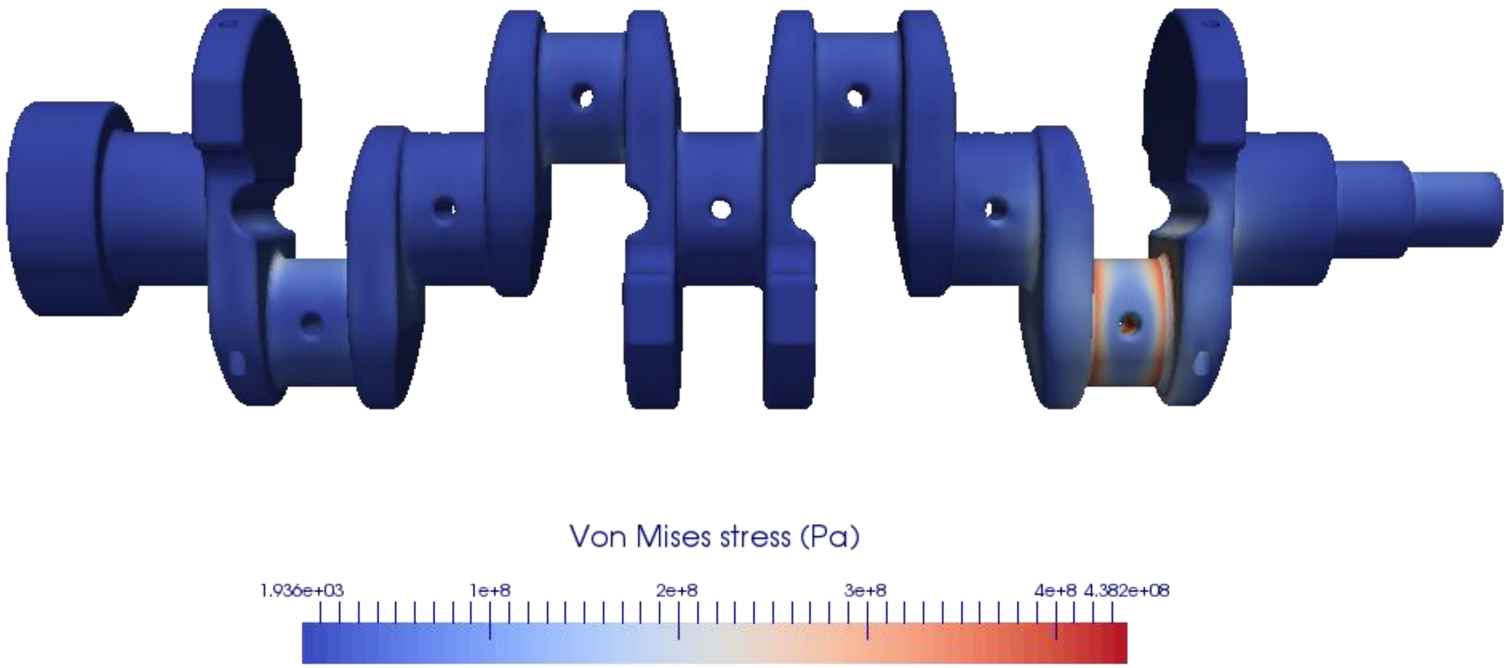
RESULTS – COMPLETE MODEL

- Temperature at the beginning of the hold stage – identical to the reduced model

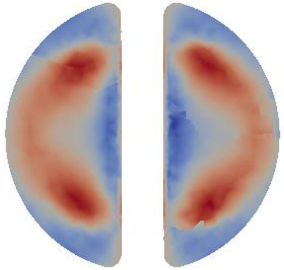


RESULTS – COMPLETE MODEL

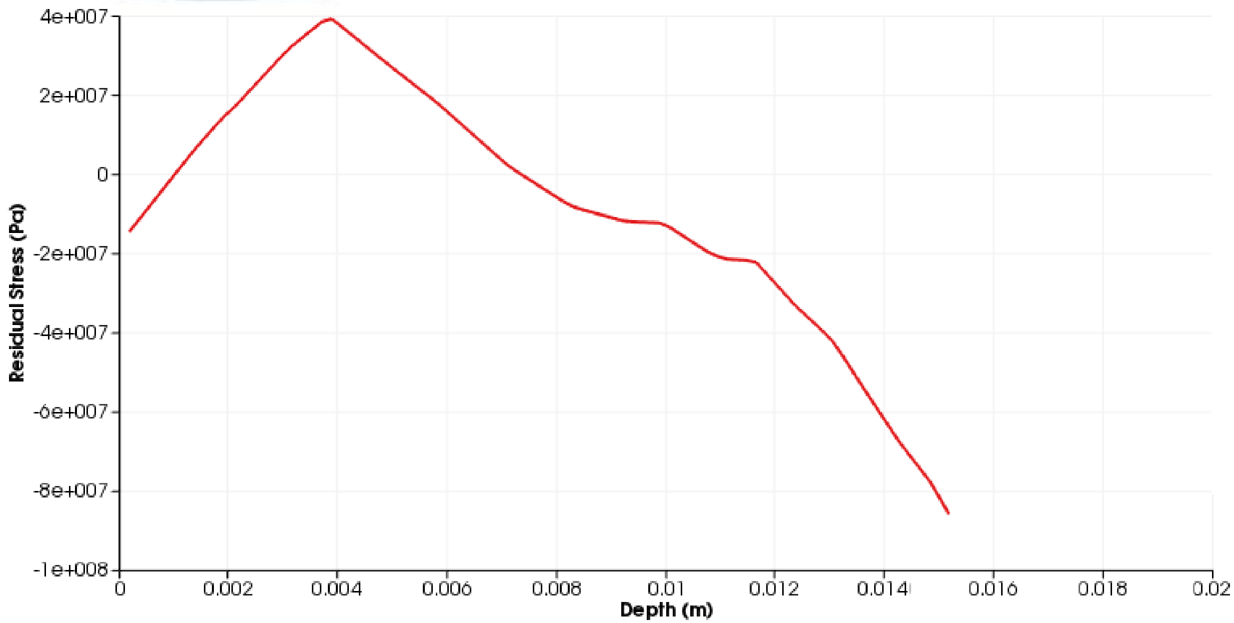
- Residual stresses at the end of the quenching stage

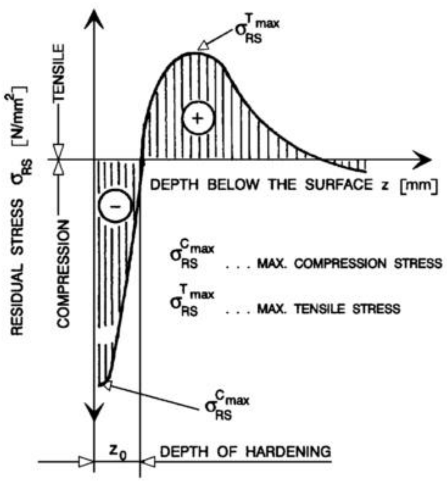


Results – Complete model



- Residual stresses at the end of the quenching stage





Typical residual stress profile after induction hardening [1]

- As expected, residual stresses are underestimated due to missing metallurgy

[1] Grum, J. (2001). A review of the influence of grinding conditions on resulting residual stresses after induction surface hardening and grinding. *Journal of Materials Processing Technology*, *114*, 212–226.

RESULTS

- Thermal cycle is approximated using constant heat flux during heating, and variable heat transfer coefficient during quenching
- Martensite is obtained in the skin of the workpiece and the FPB phase is retained in the core
- The formation of Martensite in the skin creates compressive stresses in this region, characteristic of surface hardening treatments

- The analysis without metallurgy ignores the effects of transformation plasticity and hardening and thus predicts lower residual stresses and distortions

RESULTS – COMPUTING PERFORMANCE

- Reduced model – Nodes: 185’589; Elements: 960’244
  - Thermal-metallurgical-mechanical coupling
  - Shared memory processing: 1 node, 12 processors
  - Computational time: 18:14 hours or 5:54 minutes per increment
- Complete model – Nodes: 900’035; Elements: 4’705’964
  - Thermal-mechanical coupling
  - Distributed memory processing using Virfac Cloud on Bull supercomputing facility

Number of processors	Total time (hours)	Number of time steps	Time per increment* (minutes)
72	21:32	190	6:48
96	11:05	190	3:31

*Includes overheads such as communications and input/output processing

CONCLUSIONS

- A heat treatment simulation of the surface hardening of a crankshaft part was set up using Virfac® and carried out using Morfeo
- Simulation set up time using Virfac® Heat Treatment: 15 minutes
- A thermal-metallurgical-mechanical coupling simulation was carried out on a reduced model, and a thermal-mechanical coupling simulation on the entire crankshaft geometry
- Thanks to distributed parallel computation, results on a full component are obtained in less than 24 hours
- Access to a supercomputer was possible due to Virfac® Cloud on Bull infrastructure within a web interface

Future work

- Modelling induction heating with magneto-thermal coupling
- Simulation of crankshaft surface hardening by carburizing/nitriding
- Extending the heat treatment to tempering post-induction hardening

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