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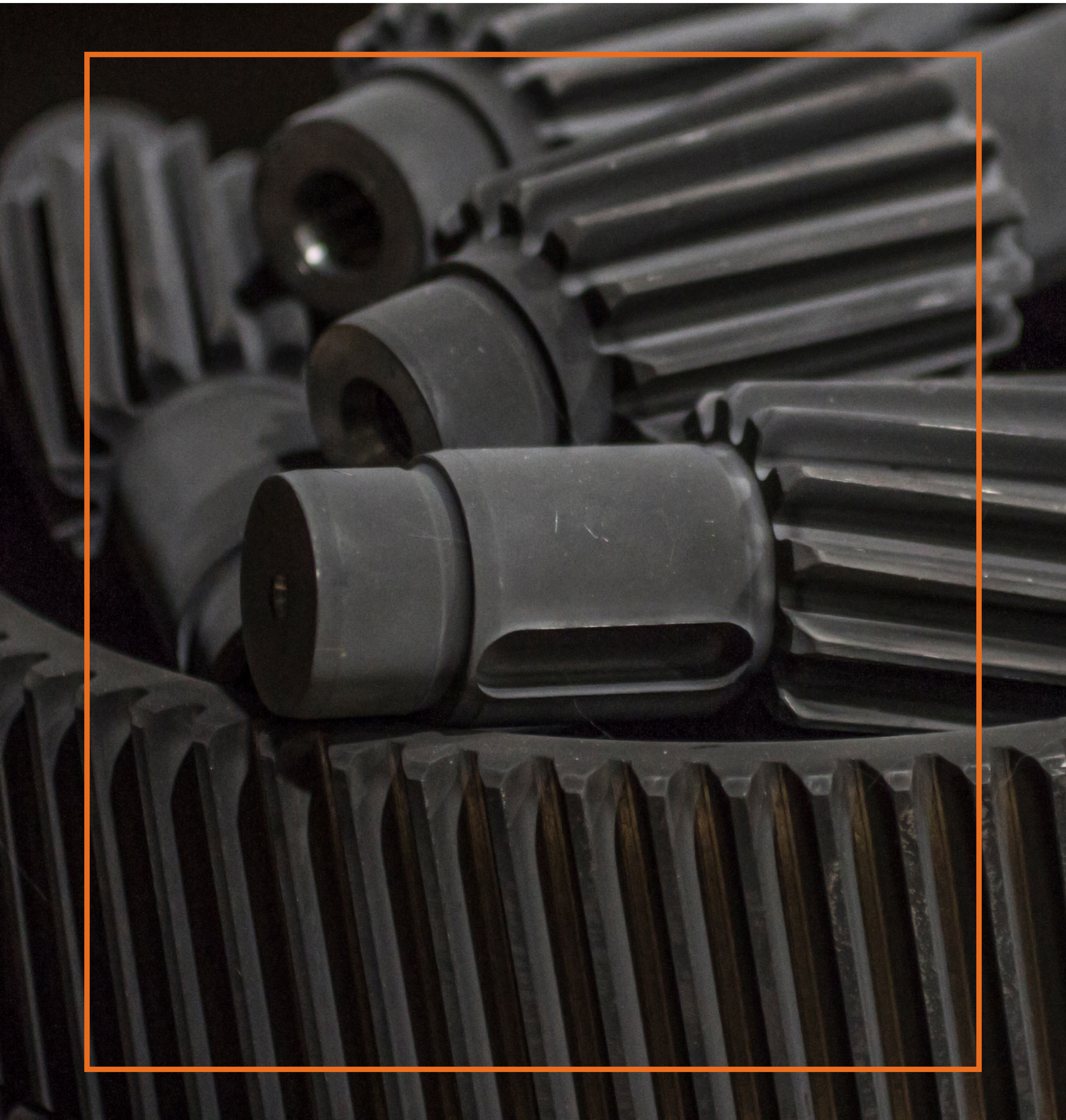

Simulation of heat treatment of jominy specimen to improve quality of automotive gear components

E. Morgano, C. Viscardi, L. Valente

Microstructure and mechanical performance play a key role for gear box reliability. According standard quality assurance procedure steel grade analysis is a fundamental base to identify correct mechanical properties achievable after heat treatment cycle. With the aim to make more robust production cycle of gear box components, samples are cut from parts and Jominy test is performed on this specimen. In case of small components like gears, specimen for Jominy test cannot be obtained and the only approach to validate process is supplier certificate obtained on steel before heat treatment.

Quenchability of component can be different from data reported on nominal supplier datasheet with the risk to have failure during testing or exercise of gear box; tests on failed parts demonstrated that chemical composition variation, notwithstanding inside allowed range, drove to lower mechanical performance according microstructure not properly quenched.

In order to validate heat treatment cycle, microstructure and mechanical properties, Jominy test has been virtualized into heat treatment simulation software. Real Jominy tests have been transferred inside simulation software for different steel grades used for automotive gear box application. A model to forecast microstructure and mechanical properties for Jominy specimen is built and benchmarked with experimental data. Alignment between simulation results and reality allows to transfer model definition from Jominy samples to complete real components, improving quality assurance capability for real process thanks to usage of heat treatment cycle virtualization for gear box realized with different steel grades.

KEYWORDS: HEAT TREATMENT SIMULATION - QUENCHING - MICROSTRUCTURE HARDNESS - RESIDUAL STRESS - DISTORSION - DEFORM HT

Introduction

Gear box performances are based on mechanical properties that each part can achieve after manufacturing cycle and in particular after final heat treatment. Reliability of gear box assembly requests to validate each component of the assembly and respect of specification. Gears for automotive transmission are in general realized using hardening steel and quality of heat treatment is defined by several standards that are mandatory for automotive applications [1,2,3,4].

Enrico Morgano
FCA CRF Metal Bulk, Italy

Cristian Viscardi, Lorenzo Valente
Ecotre Valente Srl, Italy

Steel composition of component is defined by standards and drawings; small variations in chemical composition are allowed. These fluctuations of composition impact on quenchability of the part and so on its final mechanical performance.
To keep under control these variations, a simple but efficient test to validate mechanical performance of a quenched and tempered gear in hardening steel is Jominy Test. This methodology requests a specimen with an exact geometry (Fig. 1) and water quenching condition. Quenched specimen is tested to get a hardness profile across thickness which is a curve with hardness value versus distance from quenched end.

Standard size of specimen represents a problem in case of small parts because it's not possible to get exact sample accordingly technical specification.
Moreover, Jominy test is a water quench exam [5] while gear components are in general quenched with different media and in this way it's difficult to compare Jominy curve provided by steel mill certificate with hardness profile obtained on real component.

A new approach is necessary to allow proper usage of Jominy Test results for components hardened with different methods and with geometry not allowing extraction of standardized sample.

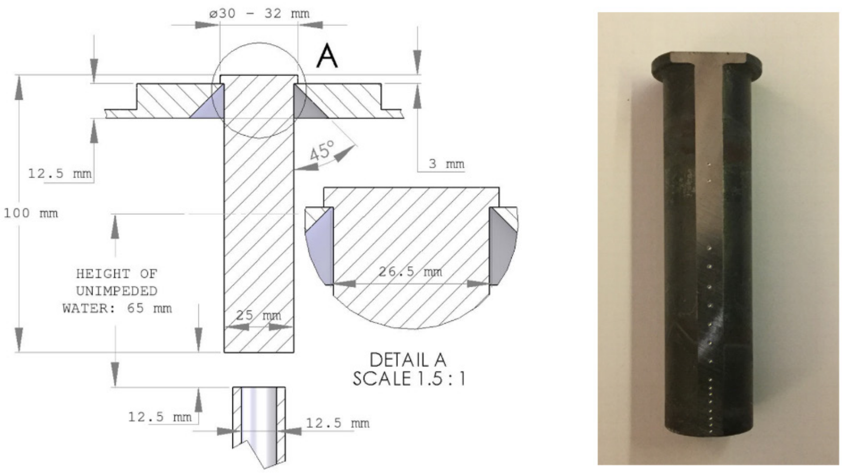

Fig.1 - Jominy Test geometry and slice of a real specimen showing hardness test indentation

Jominy test

Jominy test virtualization

In order to get a reliable model to forecast performance of hardened steel gear, FEM software DEFORM-HT has been used to simulate Jominy test [6].

Jominy specimen is in steel 17 NiCrMo7 and chemical composition in reported in table 1.

Tab.1 - 17 NiCrMo7 analysis

17 NiCrMo7 composition														
C	Ni	Cr	Mn	Si	Mo	V	Cu	Al	P	S	Nb	Ti	B	Fe
0.17	1.91	0.53	0.58	0.34	0.26	0.0027	0.16	0.015	0.01	0.03	0.002	0.001	0.0005	Rem.

Initial temperature of sample is 865 °C with full austenite microstructure; applied heat transfer coefficients for test is shown in figure 2 [7,8,9].

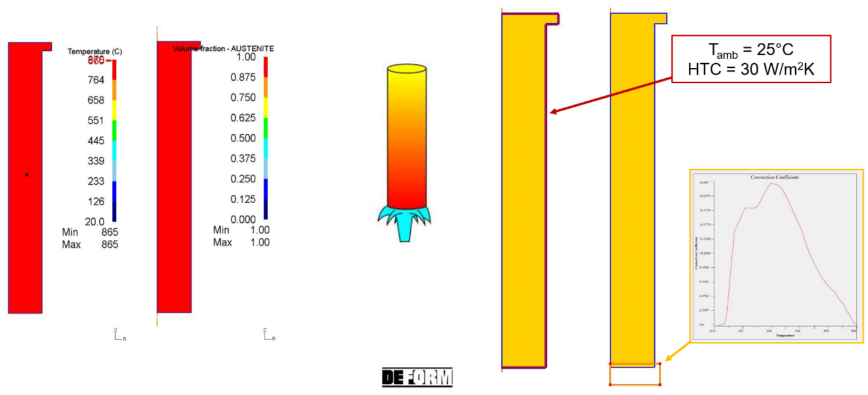

Fig.2 - Initial condition and boundary condition applied to DEFORM-HT simulation for Jominy Test

Due to standardization, effects of specimen geometry and quenching can be neglected, which is an advantage of this test. In DEFORM-HT determination of hardness profile can be approached with 2 different methods: Jominy Curve from Jominy Distance or Jominy Curve from Phase Fraction. Jominy Curve from Jominy Distance is an approach valid only for Jominy Test; given specimen geometry and water quenching condition from standard; hardness profile result is affected only by sample chemical composition and grain size, inclusion and oxides. Cooling rate achieved across thickness is driven only by conductivity and specific heat of steel. This kind of test is very easy to carry out but it's not flexible in case of application to different quenchant media or geometry. Jominy Curve from Phase Fraction propose to a more refined approach because it provides hardness profile result as a function of transformed phase fraction and its hardness. This approach is independent by geometry or quenching system because resulting hardness is coming from transformation from austenite "mother phase" into different "children phases" like martensite or bainite; HRC hardness is the result of the percentage of each phase at the end of heat treatment. DEFORM-HT uses the TTT curves in a dynamic way for microstructural calculation; this means that, despite the use of TTT is always taken into account, the kinetics of phase transformations and hence the cooling rate have a fundamental role for predicting microstructure. Microstructural transformation, like Austenite → Pearlite or Austenite → Bainite, is described based on a TTT Diagram, like shown in Figure 3.

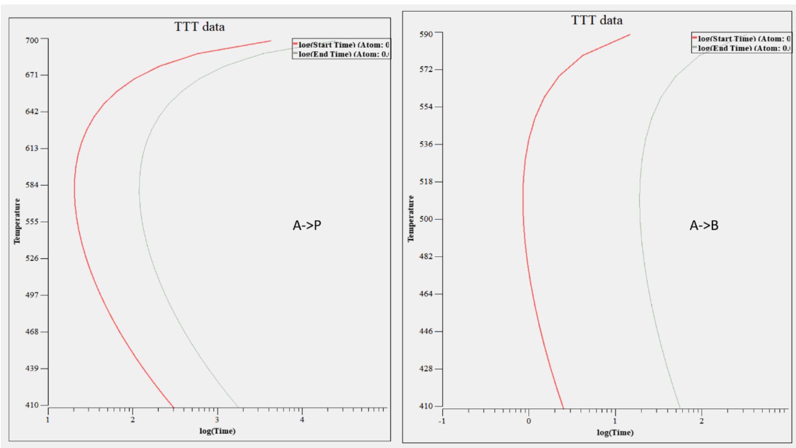

Fig.3 - Kinetics of microstructural transformation defined for DEFORM-HT: Austenite to Pearlite and Austenite to Bainite

Jominy test experimental results

Jominy test results on sample in steel 17NiCroMo7 are reported in table 2

Tab.2 - 17NiCrMo7 Hardness profile

17 NiCrMo7 Hardness Profile [HRC] as a function of distance from surface [mm]										
Distance [mm]	1.5	3.0	5.0	7.0	9.0	11.0	13.0	15.0	20.0	25.0
Hardness [HRC]	44.5	44.0	41.5	37.0	33.0	30.0	29.0	27.0	24.0	23.0

Jominy test simulation results

In order to validate reliability of simulation compared to reality, in particular for Fraction of Phase approach, HRC hardness profiles have been plotted in the same graph, shown in figure 4.

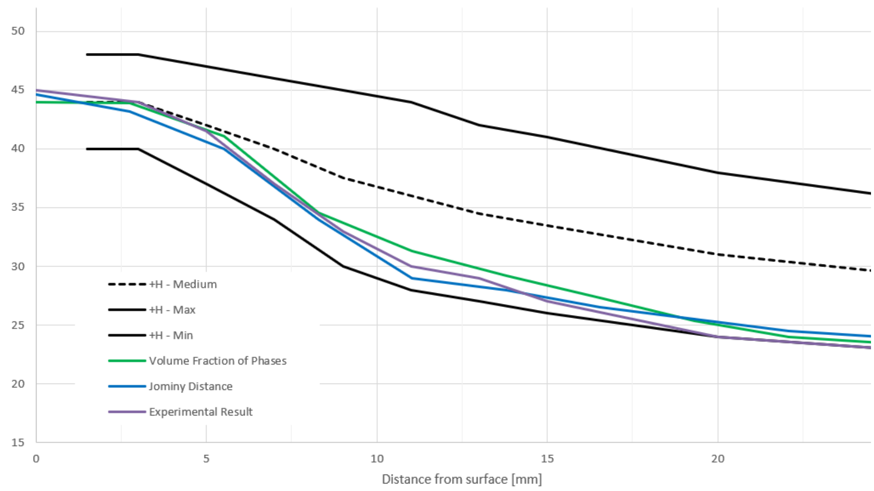

Fig.4 - Hardness profile of experimental results, DEFORM-HT simulation results and scatter band for H+ from Standard

Experimental results are inside H+ scatter band imposed by EN Standard. Both Jominy Distance and Volume Fraction of phases are well aligned to experimental results. Jominy Distance result aligned to experimental result is a confirmation of correct input and correct calculation of DEFORM-HT simulation.

Regarding Volume Fraction of Phases, this result confirms that approaching hardness estimation based on transformation of single phases can allow to reach correct results; a representation of phases distribution at 90 seconds after quench beginning is shown in Figure 5.

In every step "Mother" phase coexists with the other "Children" Phases.

Other information that can be used to monitor heat treatment stage are Time between 800 °C and 500 °C that is called also μ and it's an index of cooling rate of material [7].

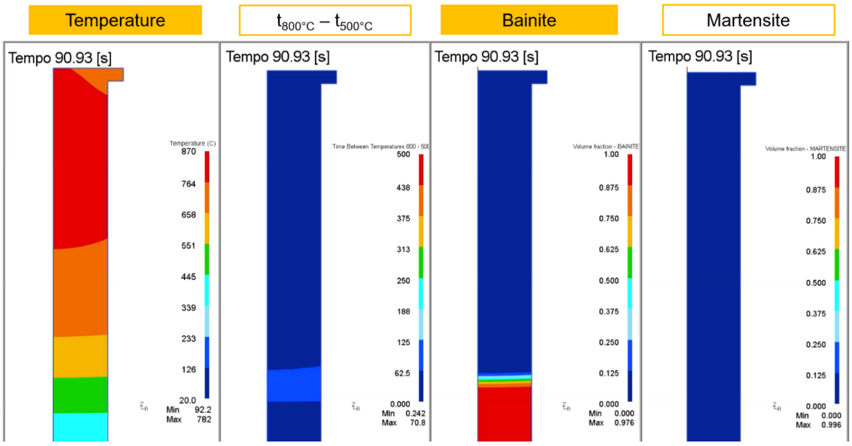

Fig.5 - DEFORM-HT distribution of temperature, Time 8/5, Bainite and Martensite after 90 s from water quench beginning

This method, as it's not based on fixed geometry and fixed quenching conditions as defined in standards, allows to use simulation with different geometries and in particular for small components that are hardened and quenched with different technology.

Application to pinion gear

Heat treatment cycle for gear

Results obtained from validation of Jominy test has been transferred on a pinion gear in hardening steel 17NiCroMo7, shown in Figure 6.

Fig.6 - Pinion gear simulated with DEFORM-HT.Hardening Heat treatment cycle in DEFORM-HT simulation software is described in table 3

Tab.3 - Hardening heat treatment cycle

17 NiCrMo7 Pinion – Hardening Heat Treatment Cycle			
Duration [s]	Operation	Temperature [°C]	Carbon concentration [%]
1800	Heating Furnace	550	0
3600	Carburization Furnace	850	0.8
1200	Oil Quench	100	0
1800	Heating Furnace	225	0
3600	Air Cooling	30	0

Results obtained on pinion gear

In this simulation, carburization stage introduces an additional variable.

Carbon content is modified across gear thickness during a heating in carburization furnace and this means that it's necessary to introduce in TTT curves in DEFORM-HT also dependence from Carbon content. In this way it will be possible to consider different TTT curve location in Temperature-Time diagram and different Martensite temperatures.

According this modification in material input data, simulation has been run on shown pinion gear.

In Figure 7 some results of simulation are shown; it is visible how Carbon content is various across thickness and at different slice locations as well as Hardness distribution. Both pictures are captured at the end of Oil Quench operation.

This simulation has been run coupling together Thermal calculation, Microstructural calculation, Stress calculation; as in Jominy Test, for all "Children" phases Thermal, Microstructural and Elastic-Plastic properties are defined as a function of temperature and carbon content to obtain an accurate solution.

Deformed gear can be exported from simulation in order to be compared with 3D scanning of experimental component.

Simulation results are in alignment with experimental data measured on pinion gear in a range of ± 5%.

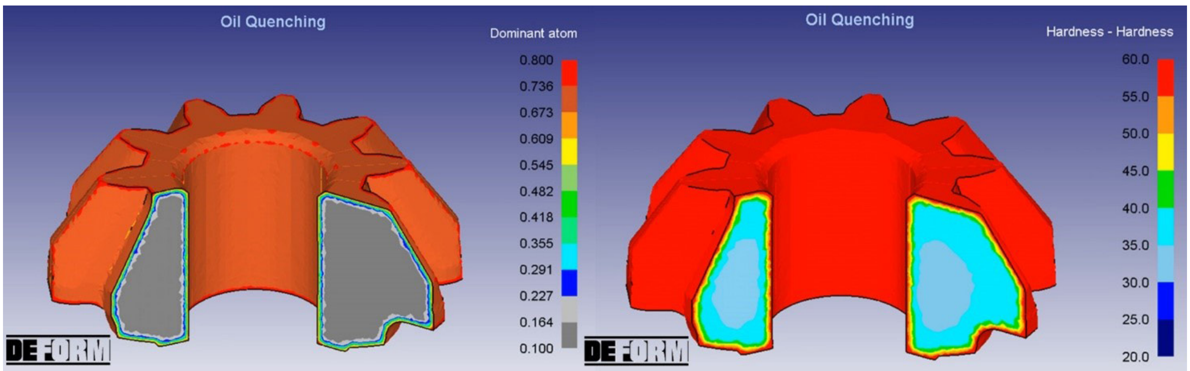

Fig.7 - Pinion gear simulation with DEFORM-HT: Carbon content and HRC Hardness on two different slices

Conclusion

DEFORM-HT simulation results are aligned with experimental Jominy Test results.
Simulation results of approach based on Volume Fraction of Phases, valid for every type of heat treatment, are aligned with simulation results of Jominy Distance approach, valid only for Jominy Test.
According this alignment, DEFORM-HT Volume Fraction of Phases approach has been transferred on a pinion gear and comparison between experimental and simulation data is in a range of ± 5%.

Finally, DEFORM-HT predicts microstructure, residual austenite, mechanical properties, hardness, residual stress and deformations of gear.

Acknowledgements

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