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Integrated Heat-Treatment Simulation with Virtual Inspection of Distorted Gears

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Abstract

Heat-treatment simulation is a powerful tool for gear design and process troubleshooting, but many times the predicted gear distortion is difficult to compare to physical gear measurements and to required specification charts or measurements. To help ease this burden, two software programs are utilized to provide powerful gear analyses to heat-treatment simulation results. This paper briefly describes the software used, DANTE and Integrated Gear Design (IGD), and presents a simple case study. The stress and deformation from the heat treatment of a small gear made of SAE 10B22 are predicted using DANTE. The distorted gear geometry is then imported into IGD and the predicted distortion is compared to the actual measurements of the gear.

Introduction

Gear design is a complex process, involving dozens of parameters, tolerances, and relationships to mating components. Generally, professional standards guide the gear designer to the appropriate gear dimensions, given mating and loading requirements. [1 – 2] After heat-treatment, gears are inspected using a slew of methods, depending on the particular gear geometry and critical locations of interest. [3 – 5] Heat treatment simulation provides a cheaper and faster alternative to physical testing but is lacking capabilities to relate the predicted distortion back to gear measurements made on the shop floor or in the metallurgical lab. In general, predictions to the diameter changes are easily understood and correlated back to actual measurements, but simulated predictions on parameters such as tooth thickness, tooth profile, and runout can be more challenging to evaluate and are often ignored in published analyses involving heat-treatment simulation. [6 – 8]

To help ensure simulation results can be understood in terms of common gear measurements, and therefore made more accessible and useful to a wider community of professionals, two software programs, DANTE and Integrated Gear Design (IGD) are used to construct the gear geometry, create the finite-element model, simulate the heat treatment process, analyze the simulation results, and compare the predicted results to actual gear measurements. This publication will briefly introduce both software programs and then provide a case study to highlight the capabilities of using IGD and DANTE together to evaluate gear distortion in the virtual environment.

Software Description

DANTE (Distortion Analysis for Thermal Engineers)
DANTE is a state-of-the-art multi-phase material model used, in conjunction with the finite element solvers ABAQUS or ANSYS, to simulate heat treatment processes of metals; including steel, aluminum, and nickel-based alloys. Rate-based phase transformation models, combined with an internal state variable mechanical model, provide accurate predictions for in-process and final microstructure (including precipitates, if applicable), stress, and distortion for the entire component being modeled. The final hardness is also predicted. Carburization processes, including carbide formation and dissociation, and nitriding processes, including nitride formation and dissociation, can also be simulated with DANTE.

DANTE comes standard with a sizable steel alloy material database, which includes many low and medium alloy steels and several high alloy steels. The database includes material properties for the individual steel phases: austenite, ferrite, pearlite, bainite (upper and lower), martensite, and tempered martensite. Included are thermal properties as a function of phase, carbon content, and temperature; mechanical properties as a function of phase, carbon content, temperature, strain, and strain rate; diffusive properties, including carbide or nitride formation and dissolution, for carbon and nitrogen as a function of species concentration and temperature; phase transformation properties as a function of carbon content, alloy content, and temperature; precipitation properties as a function of temperature; and hardness as a function of phase, carbon content, and formation temperature.

DANTE has been successfully used in industry to: 1) Improve current processes with respect to residual stress, final distortion, microstructural control, and quench cracking [9 – 11]; 2) Perform heat treatment process design optimization concurrently with geometry design during product development [12 – 14]; 3) Troubleshoot current process problems, allowing for root causes to be easily identified and solutions to be defined and tested on the virtual twin before physical testing [15 – 16];

and 4) Perform process parameter sensitivity studies, gaining an in-depth understanding of how the component being heat treated may respond to the allowed variations in process parameters. [17 – 20]

To aid in model pre- and post-processing activities, the DANTE interface, shown in Fig. 1, provides straightforward model definitions, including sections to define the material, process steps, initial conditions, and boundary conditions.

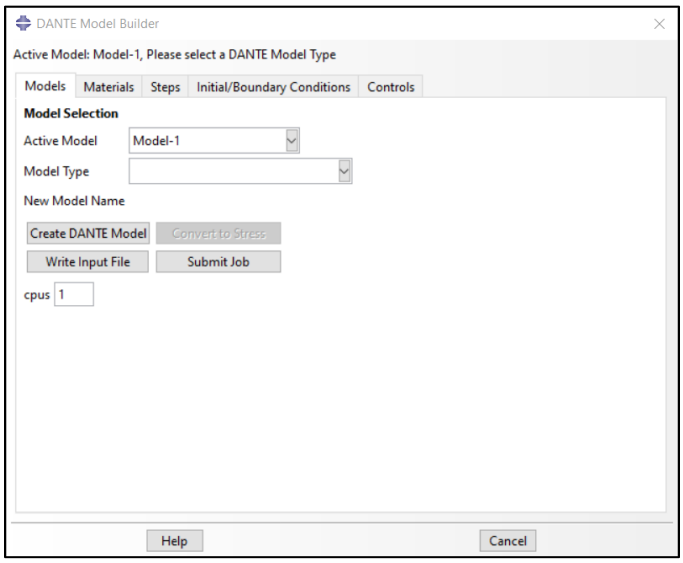

Figure 1: DANTE Plug-In used for DANTE model setup in ABAQUS.

IGD (Integrated Gear Design)

IGD is a computer program that enables advanced design and simulation of gear drives. It is currently being developed through a collaborative effort between the Rochester Institute of Technology and the Polytechnic University of Cartagena. The software is built upon modern gear theory, allowing the generation of virtual gear geometries based on the chosen manufacturing process. To facilitate the analysis and simulation of gear drives, IGD provides a set of computational tools such as tooth contact analysis (TCA), finite element modeling (FEM), and gear geometry comparison. Surface micro-geometry modifications can be applied directly to the tooth surfaces or through corrections to the cutting blade of the generating tool and the parameters that describe the cutting action. One of the standout features of IGD is the automatic generation of finite element models for ABAQUS or ANSYS computer programs, eliminating the need for tedious finite element modeling setup and making it accessible to users with varying degrees of expertise.

Historically, predicting distortions caused by heat treatment has been a challenging task, often deemed nearly impossible through accurate numerical simulation. This lack of predictability has led to limited opportunities for gear inspection post-heat-treatment because baseline values could not be reliably established. This study presents a method for virtual inspection of heat-treated gears using DANTE to model the heat treatment distortion and IGD to reconstruct post-heat treatment geometry. By controlling distortions of heat-treated surfaces through the use of simulation, gear drives benefit from improved quality and lifespan, while the lifespan of grinding tools is also extended.

Recently, IGD has been developed to provide the finite element models needed by DANTE to create and run gear heat-treatment simulations. Gear geometry and finite element models can be easily obtained from IGD to continue the heat-treatment simulation process with DANTE. After the simulation, the distorted geometry can be reconstructed in IGD for further analysis or virtual inspection. The comparison of geometries is an important feature of IGD, as it allows for the computation of deviations of any primary selected geometry with respect to any secondary selected geometry. Therefore, it allows the comparison of the heat-treated geometry with respect to the pre-heat-treated geometry to study the distortion caused by the heat treatment or the comparison between the heat-treated geometry and the finished geometry to assess the stock that needs to be removed during the finishing process.

Case Study

The following case study is provided to highlight the capabilities for virtual inspection of heat-treated gears using IGD and DANTE. The slope profile deviation change after quench hardening is the main focus of this study, though many more avenues of investigation exist with IGD. The pinion gear of the study is made of SAE 10B22 steel, with the chemical composition shown in Table 1. A description of the process is outlined in Table 2.

Table 1: Chemical composition of SAE 10B22

Element	C	Mn	P	S	B
Percent	0.18 – 0.22	0.70 – 1.10	0.030 Max	0.050 Max	0.0005 – 0.0030

Table 2: Description of simulated process.

Process Step	Time	Ambient Temperature	Notes
Gas Carburization	2 hrs.	920° C for 1.5 hrs.; 880° C for 0.5 hrs.	1.0% C_P at 920°C; 0.8% C_P at 880°C
Austenitize	40 min.	860° C	1.5 hr. preheat to 400° C
Transfer to quench tank	30 sec.	400° C	
Oil Quench	15 min.	60° C	
Cool to room temperature	2 hrs.	20° C	
Temper	2 hrs.	180° C	
Cool to room temperature	2 hrs.	20° C	

Model Setup

The advanced gear geometry design in IGD allows for the precise definition of geometry according to commonly used industry parameters. Table 3 outlines the geometric parameters from the part drawing used to construct the geometry of the gear in IGD and that will be used for the DANTE simulations. These parameters include tip and root diameters, form diameters, circular tooth thickness, and ball/pin diameter and distance over ball/pins. Utilizing these geometric parameters, the software calculates the gear geometry and generates a 3D model. Figure 2 shows the IGD definition window with the pre-heat treatment gear geometry settings.

Table 3: Geometric parameters used to construct the geometry of the gear in IGD.

PINION DATA

NUMBER OF TEETH	13
DIAMETERAL PITCH	12/14
PRESSURE ANGLE	12°
PITCH DIAMETER	(27.516)
BASE DIAMETER	(26.915)
OUTSIDE DIAMETER	34.37-34.50
FORM DIAMETER	27.1 MAX
ROOT DIAMETER	25.8-26.0
CIRCULAR TOOTH THICKNESS	3.973-4.027

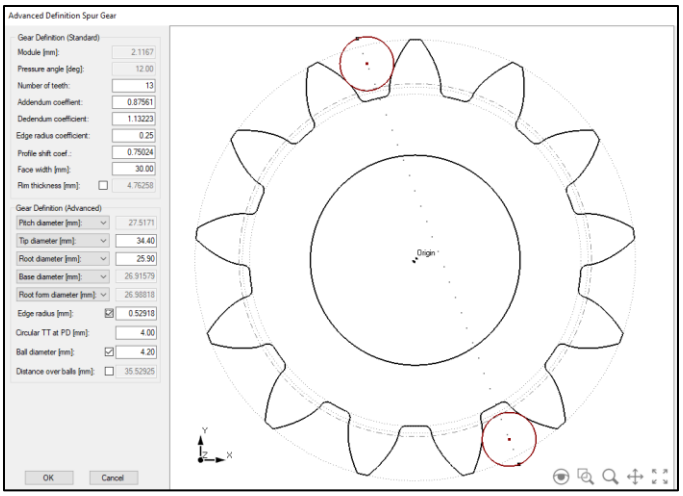

Figure 2: Definition of the pre-heat-treated geometry of the gear in IGD.

The initial slope profile deviation measurements (fHA) for both tooth flanks after gear manufacturing, but prior to hardening, are shown in Figure 3 for 4 of the 13 teeth. The average slope profile deviation for the right flank of the 4 teeth is 17.7 µm and 12.9 µm for the left flank teeth, with a range of approximately 5 µm for both sides. Including the original deviations in the virtual twin is critical for accurate quench hardening predictions. The averages for each side reported above are used for the initial slope profile deviation in this study.

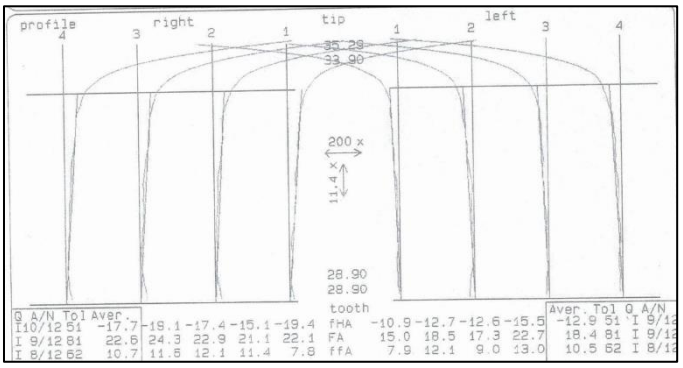

Figure 3: Initial slope profile deviation measurements.

Incorporating variations to the nominal geometry using common CAD software programs can be a daunting challenge, depending on the geometry modification that is required. Changing the slope profile deviation is no easy task for many software programs, so IGD allows a direct definition of the slope profile deviations over a given position. Figure 4 shows the definition in IGD for the initial left flank slope profile deviation, based on the diametrical position. Note that the Y-Scale in Figure 4 is linear with respect to the corresponding roll angle for the represented diameters but not for the diameters shown. Figure 5 shows the initial slope profile deviations for both flanks using IGD's "Involute Profile Measurement" tool. Here, the scale was represented linearly with respect to the diameter, showing the actual deviation pattern achieved in the gear tooth surface along the profile of the gear. Subtracting the

deviation values, the initial slope deviations match the average measurements.

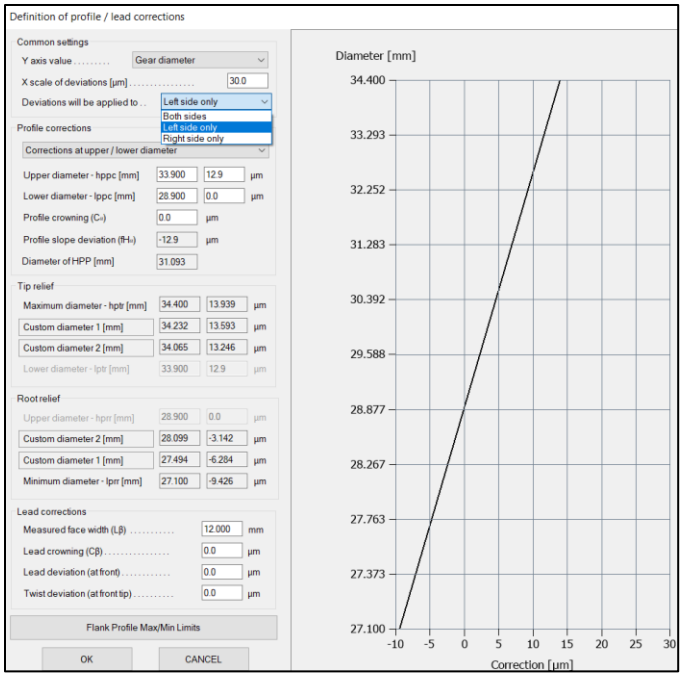

Figure 4: Initial left flank slope profile deviation definition in IGD.

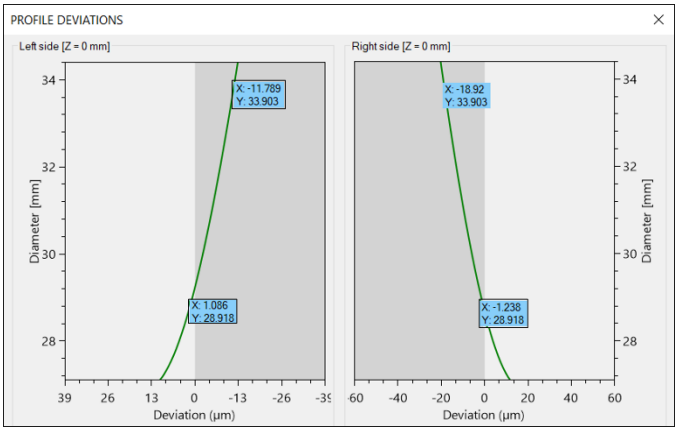

Figure 5: Initial slope profile deviations for both flanks using IGD's "Involute Profile Measurement" tool.

After the gear is created in IGD with all relevant initial deviations, the next step is to create the finite element model for the DANTE simulation. This task can be carried out automatically in IGD, providing the finite-element mesh and many of the definitions that DANTE needs to set up the heat-treatment simulation. Figure 6 shows the window for defining the finite element model mesh in IGD. The number of elements in the longitudinal direction sets the number of elements along the face width, including the number of elements on the layer of elements under the exposed surfaces at the front and back of the gear. The number of elements in the profile direction sets the number of elements in the active profile of the gear.

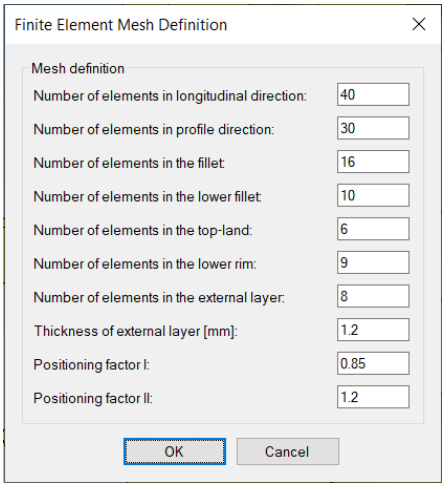

Figure 6: Mesh definition window in IGD.

Figure 7 shows the finite element mesh and surface definitions of the pre-heat-treatment geometry of the gear, generated using the meshing parameters shown in Figure 6.

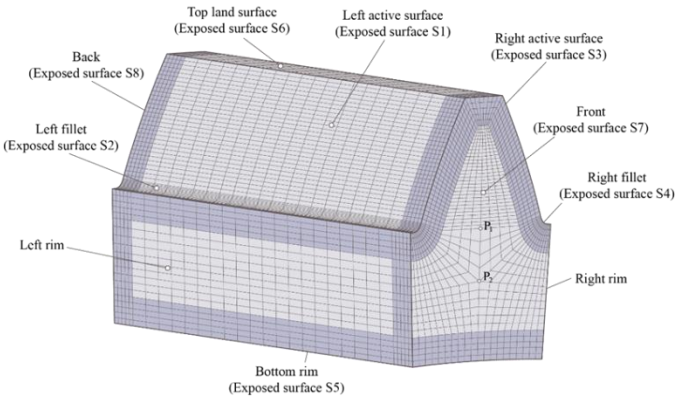

Figure 7: Mesh and exposed surfaces of the finite element model.

The positioning factors I and II establish the position of points P1 and P2 on each transverse section of the gear. The radius of point P1 is the tip diameter of the gear minus the positioning factor times the whole depth of the gear tooth. If the positioning factor were equal to 1.0, the radius of point P1 would be the root radius of the gear. If the positioning factor were 1.2, the corresponding point will be under the root radius. By controlling the position of points P1 and P2, the maximum distortion of the finite elements of the model can be reduced.

After defining the mesh information in IGD, an ABAQUS input file containing the mesh information is generated and imported into ABAQUS for DANTE preprocessing. DANTE preprocessing consists mainly of assigning a material from the DANTE database, assigning the initial conditions, and assigning the carburizing, thermal, and mechanical boundary conditions.

Results

The results obtained from the heat-treatment simulation can be useful in many ways and easily compared to many common measurements. One of the most common quality assurance measurements to ensure microstructural requirements are being met is hardness. Figure 8(A) shows the predicted hardness contour plot in ABAQUS at the mid-length of the tooth, with a line plot of the hardness profile perpendicular to the tooth flank. Measurement data can then be plotted with and compared to the prediction. The same is true of carbon, though not as common a measurement, which is shown in Figure 8(B).

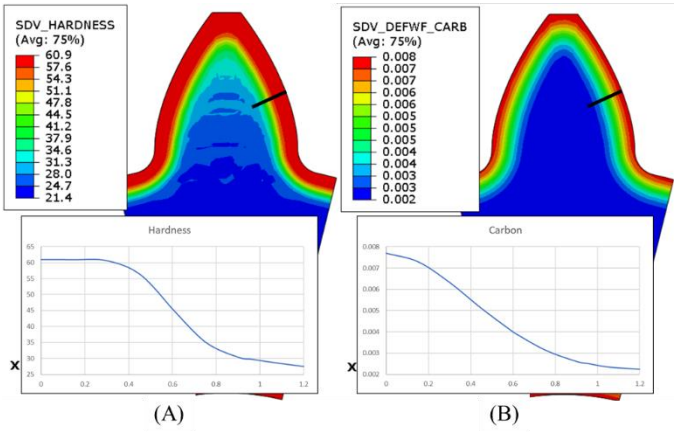

Figure 8: (A) Hardness and (B) Carbon predictions shown as contour and line plots at tooth mid-length at the end of the process.

Accurate representations of the microstructural evolution during heat-treatment processes for steel are crucial for accurate stress and distortion predictions. DANTE predicts microstructural evolution using rate-based equations, which is helpful when determining root causes related to quench cracking, distortion, unfavorable residual stress profiles, and many more common issues. The changes in microstructure are the cause of most hardening related issues and being able to interrogate the simulation throughout the entire process to ascertain when the problem occurred, and why it happened, is invaluable. Figure 9 shows, clockwise from top left, the predicted tempered martensite, lower bainite, pearlite, and upper bainite phase fractions at the end of the process; retained austenite and ferrite are negligible.

Predicting the evolution of stress allows the process to be evaluated for its potential to cause quench cracks, as well as allowing for residual stress optimization; optimization is simplified and expedited by knowing how the residual stresses are generated. The residual stress tensor can also be utilized in subsequent in-service loading or fatigue-based models to evaluate part performance in-service. Figure 10 shows the predicted maximum and minimum principal residual stress at the mid-length of the tooth; the entire stress tensor, and all its many forms, are available for postprocessing and exporting to downstream models. The stress and phase predictions can also be plotted along paths, just like the hardness and carbon, to compare to measurements made on actual components.

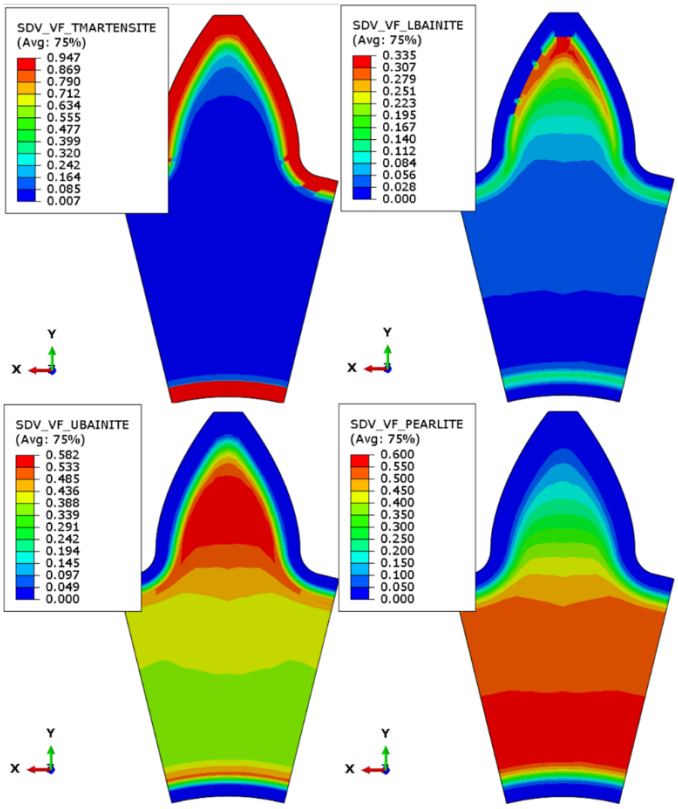

Figure 9: Phase predictions at tooth mid-length at the end of the process for, clockwise from top-left, tempered martensite, lower bainite, pearlite, and upper bainite.

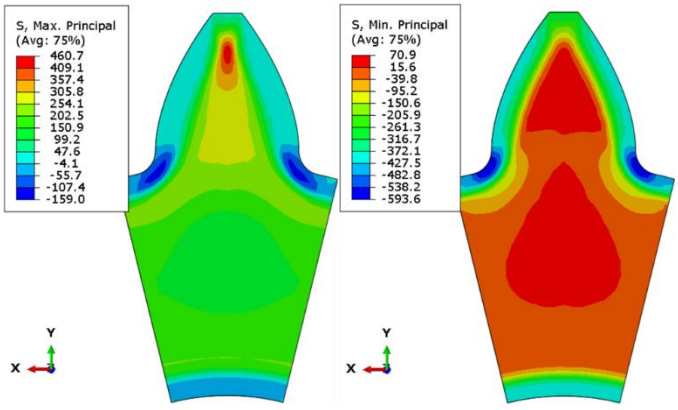

Figure 10: Predicted maximum and minimum principal residual stress prediction at the mid-length of the tooth.

While the relationship between actual measurements and DANTE model results, as viewed in ABAQUS or ANSYS, is straightforward for hardness, carbon (and nitrogen), microstructural phases, and stress, the same cannot be said of distortion. Evaluating general trends in distortion is possible and can be useful in determining how a given heat treatment, and any subsequent processing parameter changes, will affect

the final distortion. The radial displacement can generally be evaluated accurately, but that is usually where the ease of comparison to simple measurements ends. Figure 11(A – C) shows the DANTE prediction for displacement along the X-, Y-, and Z-axes, respectively. The Y-axis can represent the radial displacement of the tooth tip in this instance, but all other surfaces lie in multiple planes. Coordinate measurement machines (CMM) can make measurements and generate the data necessary for comparison to prediction results shown in Figure 11, but those measurements and data analysis can be costly and time-consuming, putting them out of reach for many quality assurance measurements used on a daily basis. Figure 11(D) is the radial displacement of the flank using cylindrical coordinates defined with respect to the flank radius. Nodes on the flank surface can be plotted to evaluate the flank profile, but without automating the process with unique algorithms, it can be time-consuming. In this regard, IGD provides algorithms and a graphical user interface to postprocess simulated gear geometries like they are measured in industry.

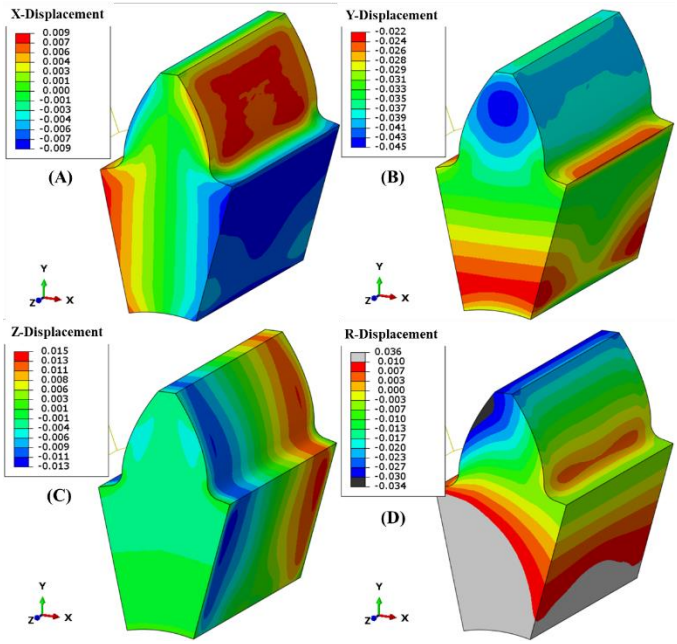

Figure 11: Displacement prediction along the (A) X-axis, (B) Y-axis, (C) Z-axis, and (D) radial direction of the flank using cylindrical coordinates defined with respect to the flank radius.

The slope profile deviation is one measurement of how well a gear will perform in service because it is a root cause of transmission errors and therefore a source of noise and vibration. Figure 12 shows the measurements for the after heat-treatment slope profile deviations of the four teeth shown in Figure 3. The average slope profile deviation for the right flank of the 4 teeth after heat treatment is 36.7 µm, with a range of approximately 15 µm. The average for the left side is 28.3 µm, with a range of approximately 3 µm. Figure 13 shows the predicted final slope profile deviations for both flanks using IGD's "Involute Profile Measurement" tool. Subtracting the deviation values, the right side has a slope profile deviation after hardening of 33.9 µm and the left side has a deviation of 28.9 µm. Thus, the predicted deviation values fall within the range of values measured.

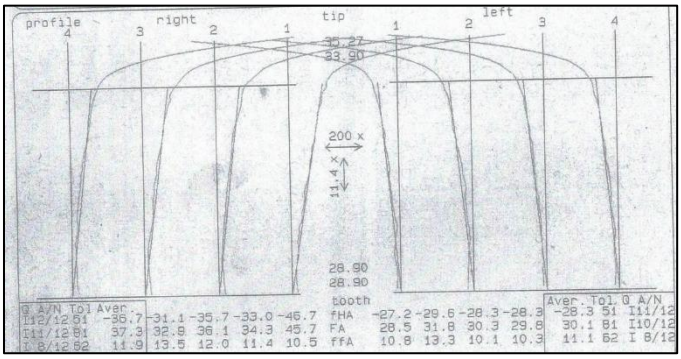

Figure 12: Measurements for the after heat-treatment slope profile deviations.

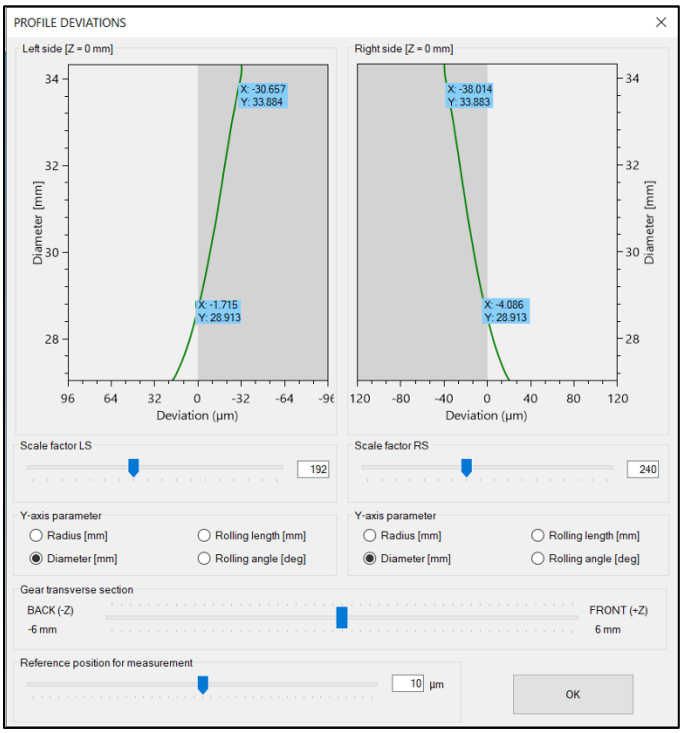

Figure 13: After heat-treatment slope profile deviation prediction for both flanks using IGD's "Involute Profile Measurement" tool.

The data generated by IGD's postprocessing tools can also be exported as a comma-separated data file that can be opened in spreadsheet software to manipulate and compare the effects from various process parameter changes. Figure 14 shows the simulated initial and predicted final slope profile deviations of the tooth flank plotted in Excel.

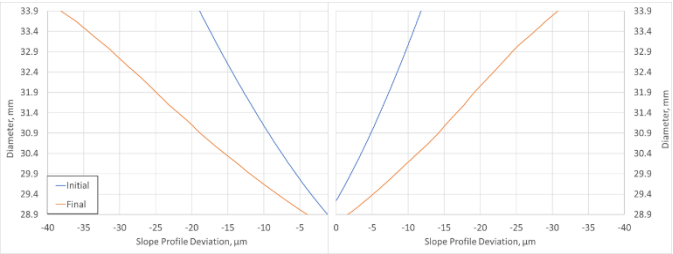

Figure 14: Simulated initial and final slope profile deviations of the tooth flank plotted in Excel.

Additional virtual inspection capabilities

Virtual gear inspection capabilities in IGD also include measuring the distance over balls and pins, as well as the measurement of the base tangent length for heat-treated distorted geometries. To measure the distance over balls, a numerical algorithm is utilized to find the tangent points of the balls over the gear tooth surfaces and measure the distance over the balls. Since constitutive equations fail to provide accurate measurements for distorted geometries due to their inability to accurately capture the accumulation of strain during stress reversals, only the virtual measurement of the gear based on a numerical approach can be relied upon for inspection purposes of the distorted geometries.

In addition to the distance over balls, the distance over pins can also be computed. In the case of spur gears, the measurement over pins will yield the same value as the measurement over balls. However, when it comes to helical gears with an odd number of teeth, the distance over pins will provide a distinct value from that obtained from the measurement of the distance over balls.

Another important measurement is the base tangent length. This measurement depends on the span number of teeth. Figure 15 shows the measurement of the distance over balls, distance over pins, and base tangent length over the span of three teeth for the distorted geometry. These measurement values provide valuable information for post-heat treatment inspection of the gears, enabling manufacturers to make informed decisions about gear design and production to ensure optimal gear production and performance.

Conclusions

In conclusion, IGD and DANTE were briefly introduced, and a simple case study was provided to highlight the capabilities of using IGD and DANTE in conjunction. It was shown that IGD simplifies FE model setup, including adjusting the original gear geometry to account for manufacturing variation. The improved geometric accuracy used for the DANTE heat-treatment simulation results in a more accurate prediction, which was then verified using IGD's postprocessing tools.

By combining DANTE's state-of-the-art heat-treatment simulation capabilities and IGD's powerful virtual gear inspection capabilities, common gear measurements and metallurgical lab results can be directly compared to heat-treatment simulation results of gears. This allows heat treatments to be designed and optimized on the virtual twin and verified experimentally much more simply than what was previously possible.

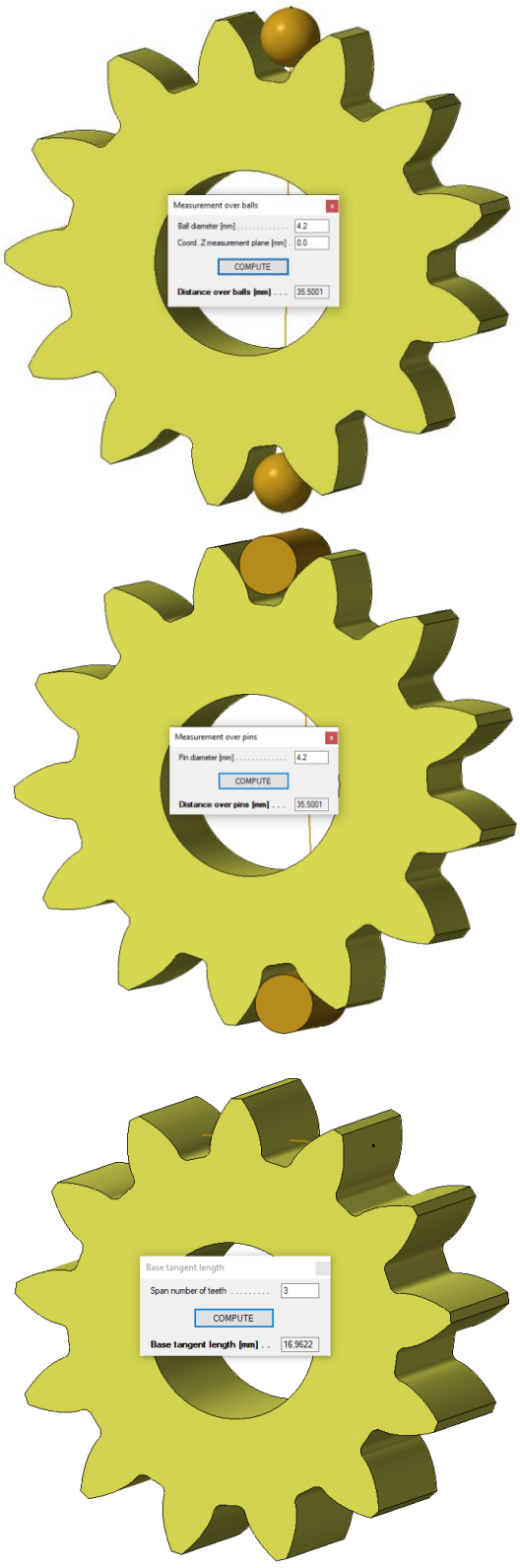

Figure 15: Virtual measurement of the distance over balls, distance over pins, and base tangent length for the distorted heat-treated geometry.

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