The success or failure of heat treatment affects not only manufacturing costs, but it also determines product quality and reliability. Heat treatment must therefore be taken into account during development and design, and it has to be controlled in the manufacturing process.

Heat treatment is an indispensable step in the manufacture of steel products, as mechanical properties such as hardness, static, and dynamic strength and toughness are selectively controlled by deliberate manipulation of the chemical and metallurgical structure of a component. However, apart from the desired effects, the heat treatment process can be accompanied by unwanted effects such as component distortion, high material hardness, low material strength, a lack of toughness—which can lead to crack formation—and inadequate hardness depth, which can lead to fatigue failure. Therefore, success or failure of heat treatment not only affects manufacturing costs but also determines product quality and reliability. Heat treatment must therefore be taken into account during development and design, and it has to be controlled in the manufacturing process.

**Simulation-Based Design**

In simulation-based design and manufacturing it is desirable to calculate the effects of heat treatment in advance and to optimize them by varying materials and workpiece shape. Once the part shape is designed it is of utmost importance to make sure that the heat treatment process is correct and that the process window is safe against process parameter variation. With the aid of the finite element analysis software SYSWELD, such calculations can be carried out for all generally applied heat treatment processes, taking all significant physical effects into account. Thus, the part designer/heat treatment practitioner can have a deliberate influence on minimizing manufacturing costs and optimizing product reliability and quality.

SYSWELD is a powerful tool that can be used to judge the heat treatment process on an actual part and efficiently provide answers to these basic questions:

- Is the selected heat treatment process feasible?
- Is the selected steel feasible?
- Is the selected quenching media suitable?
• Is the process window safe against process tolerances?
• Is the part hard where it should be hard?
• Is there any crack risk occurring during the process?
• Are the obtained distortions acceptable?
• Are the residual compressive stresses high enough and well positioned?

Heat treatment is a complex process involving heat transfer, and mechanics, including phase transformation. With the help of the heat treatment advisor, the set-up of a numerical computation is extremely fast. This does not mean that the simulation engineering is simple. The use of a user-friendly, intuitively driven graphical interface does not change the fact that the physics behind a heat treatment simulation is complex. Heeding the adage from Albert Einstein that “One should never do too much, but never less than necessary” to avoid obtaining incorrect results from an incorrect model, SYSWELD provides detailed training for heat treatment simulation that covers real-life situations.

Software and Applications
Dedicated solutions for both heat treaters and part designers can be obtained. Heat treaters focus on the feasibility of the heat treatment process and need answers to their questions instantly. Dedicated solutions are available that fit the needs of a heat treatment job shop. Part designers focus on trying to determine the optimum balance of cost, part shape, material, and heat treatment process. In this case, dedicated solutions are available that provide meshing and computation capabilities.

CAD Data Import and Export
Visual mesh for heat treatment provides graphical modeling capabilities for manipulating finite element meshes. Native CAD data is imported, automatically cleaned, and meshed by a batch-meshing algorithm dedicated to heat treatment applications (Fig. 1). Simulations are performed on the real
Fig. 6: Results of the martensite-transformation fitting; retained proportion of martensite depending on the temperature.

Fig. 7: Continuous cooling transformation (CCT) diagram of a 100Cr6 steel [12].

Fig. 8: The Heat Treatment Wizard offers an intuitive set-up of a heat treatment simulation.

Fig. 9: It is only necessary to load a project name to launch a computation.

Fig. 10: Case hardening of a splined shaft.

Fig. 11: Simulation of a gear component simulated in the C.A.S.H. project made from 483,103 nodes and 1,889,096 elements on a single processor computer. Courtesy DaimlerChrysler AG.
geometry. It is not necessary to work with simplified objects.

Specific technical capabilities are provided for the finite element modeling of the heat-treated structure. The demand for high quality in computed results requires a refined layered mesh from the surface through a few millimeters of thickness of the part. A guided layered mesh generator is available for two-dimensional (2D) and three-dimensional (3D) structures (Figs. 2-3), which drastically reduces the time to mesh parts while offering high quality finite element models. The group concept allows simple, complete interfacing to any existing meshing tool and, therefore, the definition phase of the numerical problem is extremely short and simple.

In cases where information for a specific quenching medium is not yet accessible in the SYSWELD database, it is necessary to adjust the convective heat transfer coefficient of the quenching medium as a function of the temperature (Fig. 4). Measurements of cooling rate and temperature over time performed using ISO or JIS probes are usually available through the vendor of the quenching media. However, the quality-assured European and Japanese measurement specifications have been included in the database. By performing a few simple recursive computations, the convective heat transfer coefficient of the quenching media can be easily evaluated for the defined specimen (Fig. 5). The values obtained provide a good starting point to compute good behavior tendencies on the real parts. The higher the BIOT numbers typical for the real part, the more precise the computations using the evaluated heat transfer coefficient will be. The lower the BIOT numbers, the higher the sensitivity of the computed results against variations in the convective heat transfer coefficient depending not only on temperature, but also on space coordinates. The adjustment has to be done only once for each quenching media, and the results stored in a database for future use.

**Fitting the Martensite Transformation**

In cases where information is not yet accessible in the database it is necessary to adjust—especially for case hardening simulations—the martensite transformation depending on the carbon content, the martensite start temperature depending on the carbon content, and the retained austenite proportion at room temperature depending on the carbon content (Fig. 6). Martensite start temperatures and the retained proportions of austenite usually are known. Based on this data, fine-tuning of the parameters relationship to the Koistinen-Marburger Law—which describes the martensite transformation by mathematical means—can be performed using the SYSWELD PHASE module. The adjustment has to be done only once for each steel. The results can be stored in a database and are then accessible for further computations.

**Fitting the Continuous Cooling Diagram**

It is necessary to adjust the continuous cooling transformation diagram of the steel if specific information is not available in the database, extracting basic parameters from an ITT (isothermal temperature transformation) diagram and parameters for the fine-tuning from the CCT (continuous cooling transformation) diagram. For numerical reasons, it is preferable...
to describe the cooling behavior of steel by differential equations rather than by pairs of temperature-proportion values. Those differential equations have been defined, for example, by Johnson-Mehl-Avrami and Leblond and contain phenomenological parameters that have to be adjusted individually for each CCT diagram. Using the PHASE module and the ITT/CCT display tool, the adjustment of a CCT diagram is straightforward and simple (Fig. 7). The adjustment has to be done only once for each steel and the results stored in a database for future use. The major steels used in heat treatment are already available in the database.

Material Thermal and Mechanical Properties

The thermal, metallurgical, and mechanical material properties of a heat-treated steel depend on temperature, phases, and carbon content. A comprehensive material database includes the major steels that are used for case hardening, surface hardening, and through hardening. The values in the database are average values extracted from experiments and literature; missing values have been completed by best simulation engineering practice. In addition, steel properties depend on the manufacturer, the year, and the country, etc. Therefore, the material properties represent an average material that will give good tendencies; the data, in any case, do not fit precisely to an individual steel.

Simulation Setup and Solution

A graphical user interface (heat treatment advisor) allows an intuitive and process-driven methodology to set up simulations (Fig. 8). Once a dedicated project is defined and stored then parts, process, and material parameters can be exchanged within the project and a computation of a variant can be started in less than one minute.

With the help of the advisor, case hardening and through hardening processes can be fully defined. In case of surface hardening, a few additional simple operations with the standard capabilities of the software are needed to adjust the energy input through the surface.

Heat treatment problems are solved automatically, covering all related complex mathematics and material physics. Depending on temperature, phase proportions, and proportion of chemical elements,
Fig. 12: Computed hardness of a through-hardened train wheel.

Fig. 13: Distortions after quenching.

Fig. 14: Computed final yield stress (the yield stress depends on the composition of phases) displayed on cross sections through the structure.
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Fig. 15: Cooling rates displayed over the CCT diagram; examination of critical points where the hardness is too low or missing.

Fig. 16: Temperature field at the beginning of the quenching. Courtesy VSTC.

Fig. 17: Distortion of a large gear after quenching. Courtesy VSTC.

Fig. 18: Comparison of computed and measured hardness of a Jominy test of 16MnCr5 material.
thermal and mechanical properties are computed, including large strains. Isotropic and kinematic hardening (including phase transformations), transformation plasticity, nonlinear mixture rules for the yield stress of phases, phase-dependent strain hardening, restoring of strain hardening during diffusion-controlled phase transformations, melting and solidification of material, material properties depending on temperature, phases and proportion of chemical elements, and all features dedicated to the methodology of finite elements are taken into account. The user need not be familiar with the mathematics involved to perform heat treatment computations, but only needs to load the project and to start the solver (Fig. 9).

Multi-physics processing capabilities provide instantaneous process information for the evolution of:

- Temperature field
- Heating and cooling rates
- Metallurgical structure of the material
- Distortions
- Stresses
- Yield stress of the modified material
- Plastic strains

A variety of techniques for reviewing process results include:

- Contour plots
- Iso-lines and iso-surfaces
- Vector-Display
- X-Y diagrams
- Symbol plots
- Numerical presentation
- Cutting planes
- Animations

Examples of some of these capabilities are shown in Figs. 10-17. The system also provides the capability to review movies of the step by step evolution of results on the surface or through the structure. The simultaneous display of the evolution of results gives a deep understanding of process and computed results.

**Jominy Test**
The Jominy test is implemented as a predefined, ready-to-run simulation project in SYSWELD. The user defines the chemical composition of the steel, and the computation of the Jominy test is done automatically. The most important results—e.g., hardness profile—are displayed at the end of the computation (Fig. 18). The Jominy test is key to a precise heat treatment simulation. When the computed hardness coincides well with the measured hardness it ensures that the CCT-diagram of the steel being examined is numerically well implemented for a full range of possible cooling rates. In case of discrepancies the CCT diagram can be modified to precisely meet the measured hardness profile. Because the formulas used for the hardness computation are empirically approved, existing CCT diagrams can be tuned following hardness measurements. Based on the optimized CCT diagram the core hardness of complex parts can be precisely predicted, which is of utmost importance for the lifetime of parts and components under dynamic loads.
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