PROCESS OPTIMIZATION FOR AN ENERGY EFFICIENT HEAT TREATMENT OF ADI

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ABSTRACT

Austempered ductile iron (ADI) materials show a good combination of mechanical properties, with high tensile strength levels (800 - 1600 MPa) and an elongation at fracture of up to 10%. Due to its high fracture toughness as well as high fatigue resistance, ADI is a very attractive material group for applications under cyclic loads. However, the material properties are very sensitive to the applied process conditions during heat treatment. The basis for a substantial increase in the application of ADI materials in the industry requires the establishment of a predictable and robust process design.

Here, an integrated process simulation of the heat treatment process coupled to required information about the as-cast quality of the component would aid in understanding process dependencies and defining a robust process window. For the austenitization step, the simulation can be used to determine the needed treatment times and temperatures.

In the process simulation software MAGMA^5, a new fast and efficient algorithm for heat exchange between thermally coupled diffusely radiating interfaces has been implemented and can be used for heat treatment simulation. The accuracy and computational performance of this new radiation model for the heat treatment of ADI is illustrated here for a real industrial suspension part. The steering knuckle is heated in a typical heat treatment box. Surface-to-surface radiation between the parts and with the surrounding furnace results in inhomogeneous temperature distributions.

Integrated capabilities to perform virtual experiments and automatic optimization are used to determine optimal process conditions to meet both the quality requirements and the minimum required treatment time during austenitization.

KEYWORDS

ADI, Numerical Simulation, Austenitization, Quenching, Ausferritization, Radiation, Ray Tracing, Heat Exchange, Robust Designs, Virtual Optimization

INTRODUCTION

ADI is isothermally tempered ductile iron. It is characterized by a very good combination of strength, elongation and high fatigue strength. The microstructure of ADI shows needles of carbide free ferrite and carbon-enriched austenite stabilized without carbides, Fig.1. The retained austenite should be relatively stable (1.8-2.2% C) and should not change to martensite.

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ADI irons obtain their excellent properties in terms of hardness, strength and toughness substantially through a heat treatment process similar to steels. A disadvantage of steels is their high density and the associated weight of conventional designs. In addition, a robust production of steel castings requires special measures due to their feeding demands during solidification and their sensitivity to form cracks during processing. In high carbon cast irons, the material density compared to steels is lower by about 10-15%. In the case of ADI materials, this advantage can be used and coupled with their excellent strength and toughness properties. As the base material for ADI, alloyed ductile iron shows excellent (self-) feeding performance during solidification and a low susceptibility to form cracks or tears. By exploiting the full potential of ADI in terms of its mechanical properties for component design, together with its low density, means that weight reductions of 10% or more are possible. Even compared to lightweight aluminum materials, ADI can prove to have significant weight advantages for a given component.

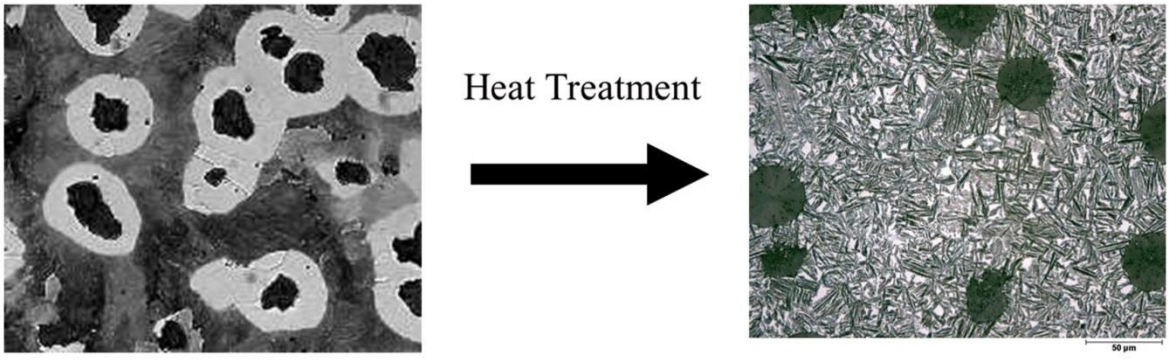

Fig. 1: Microstructure of ductile iron (left) and ADI (right). The ADI structure shows needles of carbide free ferrite and carbon-enriched austenite.

In addition to the static mechanical properties such as the tensile strength, the lightweight potential for the ADI material group is particularly evident when considering their properties under cyclic loading. In comparison to conventional ductile iron materials, ADI can sustain a multitude of load cycles. Especially in light of stochastic operating stresses, significant advantages for cast iron with an ausferritic microstructure arise compared to wrought materials.

Due to the combination of these advantages for ADI materials, wider perspectives for cast iron castings become evident. Nonetheless, the level of application for ADI materials today is still very low, due to their high process sensitivity and the related costs for establishing and maintaining a relatively small process window during heat treatment. Numerical simulation and optimization can be used here to give answers upfront and help to define stable processes.

1. SIMULATION OF THE ADI HEAT TREATMENT PROCESS

For the simulation of the ADI heat treatment process, it is necessary to take the properties and especially the microstructure of the as-cast iron alloy into account. In Fig. 2 the typical process chain is visualized.

The modeling of the casting process starts with mold filling followed by the solidification and further cooling of the casting down to room temperature. The simulation of the as-cast microstructure is state-of-the art and a standard application in casting process simulation. During solidification and casting cooling, the development of the microstructure is simulated

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by considering nucleation and growth kinetics taking the alloy chemistry, melt treatment and inoculation state into account. Local distributions of ferrite and pearlite, alloy segregation profiles and the local size distribution of graphite nodules are typical results of the casting simulation and can be used as input parameters for the following simulation of austenitization as the first step of the ADI heat treatment process.

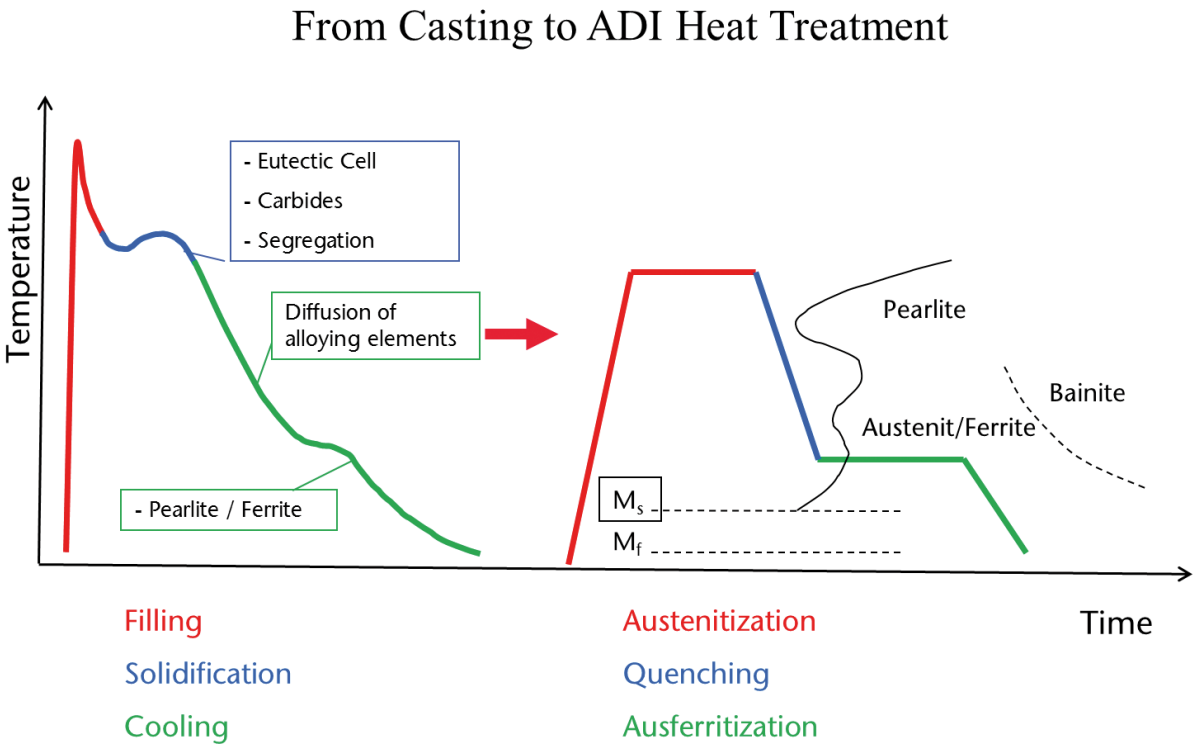

Fig. 2: Different process steps from casting through ADI heat treatment. Information from simulation about the microstructure after casting is taken into account as input for the austenitization step of heat treatment.

1.1. Austenitization

During the heating phase of the austenitization step, the ferrite and pearlite are transformed into austenite and carbon diffuses from the graphite nodules into the austenite regions. The required austenitization temperature and treatment time and the corresponding carbon distribution are dependent on the local chemical composition and the as-cast microstructure. The austenitization temperature controls the amount of carbon which can be dissolved in the austenite matrix. One objective of using simulation is to find the minimum needed time for a complete austenitization and homogenization of the matrix carbon content.

The following assumptions are made to model the austenitization step:

1. Thermodynamic equilibrium is considered at all phase boundaries.
2. Solely diffusion of carbon is taken into account. Diffusion of other alloying elements can be ignored, due to their low mobility.
3. Information about the segregation profiles and the local graphite nodule count from the casting simulation are considered as initial conditions for the austenitization.

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The phase transformation occurs in two steps. In the first step, initially the pearlite transforms into austenite with increasing temperature. Then, the transformation of ferrite to austenite starts. This ferrite/austenite transformation is controlled by carbon diffusion and phase equilibrium. After transformation, the second stage of the austenitization, diffusion and homogenization of the distribution of carbon in the austenite, begins.

1.2. Quenching

The quenching process is the second step of ADI heat treatment. The target is to find the required cooling rate while avoiding any unwanted formation of ferrite and pearlite. The phase transformations during quenching take place under non-equilibrium conditions. Therefore, the simulation model uses accurate CCT diagrams for different chemical compositions, which were measured during the research project LEA [1].

Fig. 3 shows the CCT diagram for an alloy with low nickel content and without molybdenum. For this particular alloy, ferrite and pearlite formation occur for all cooling rates.

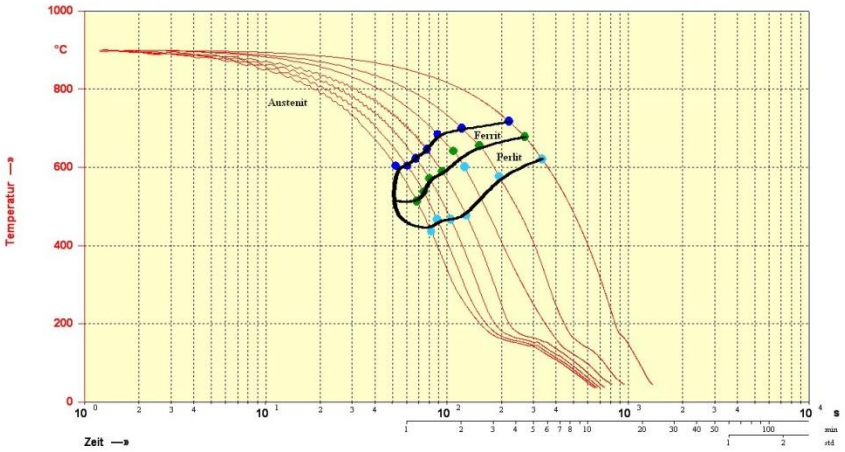

Fig. 3: CCT diagram for an alloy with low content nickel and without molybdenum

Fig. 4 shows the CCT diagram for another alloy with high nickel content and in addition also molybdenum. Ferrite and pearlite formation can be avoided even for low cooling rates.

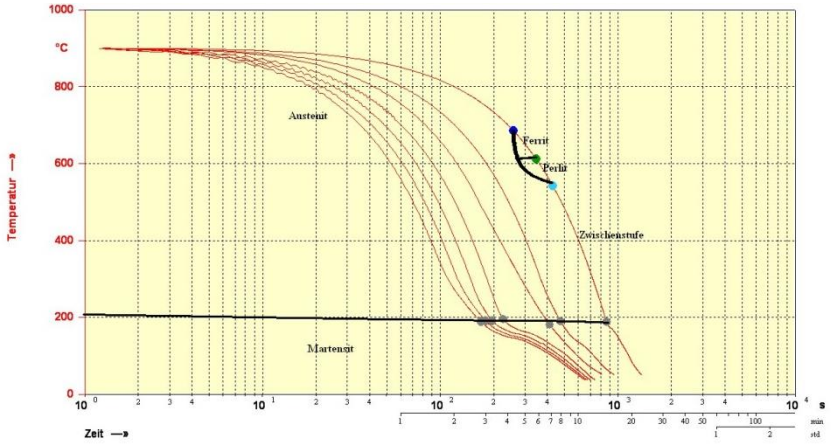

Fig. 4: CCT diagram for an alloy with high nickel content and with molybdenum

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Already with a low cooling rate of 100 K/min the transformation of ferrite and pearlite is avoided. This is what is needed to get ADI.

1.3. Ausferritization

Ausferritization is the last step of the ADI heat treatment process via an isothermal holding of the component in a salt bath with temperatures between 280°C and 400°C. During ausferritization, the typical needle-shaped ADI ferrite is formed. At the same time, the remaining austenite is stabilized through saturation with carbon. The process setup for the ausferritization step requires treatment times which are long enough to ensure a complete ADI transformation. On the other hand, an ausferritization time which is too long promotes the precipitation of carbides and bainite.

The complete heat treatment simulation for the production of ADI was developed and validated in the framework of the research project LEA [1]. The application of the integrated model to an industrial component is shown in this paper.

2. HEAT EXCHANGE BETWEEN RADIATING INTERFACES

Surface-to-surface radiation is an important heat transfer mechanism in many metal casting and heat treatment processes. It needs to be considered in physical process models in order to accurately describe the heat exchange between different surfaces of the mold/casting or between the casting set-up and surrounding equipment. The numerical modelling of the radiative heat transfer in a very complex environment is a computationally expensive task due to the long range effects and the multidimensional nature of radiation. A new fast and computationally efficient algorithm for heat exchange between thermally coupled diffusely radiating interfaces has been developed, which can be applied for closed and half opened transparent radiating cavities. The model has been implemented in the casting process simulation software MAGMA^5 [2].

In the algorithm, interfaces between opaque and transparent materials are automatically detected and subdivided into elementary radiation surfaces named tiles. The radiative heat exchange is considered between tile pairs. Contrary to the classical view factor method, the fixed unit sphere area subdivision oriented along the normal tile direction is projected onto the surrounding radiation mesh and not vice versa.

A hierarchical scheme for the space angle subdivision is selected in order to minimize the total memory and the computational demands during thermal calculations. Direct visibility relations are tested by means of a voxel based ray tracing method. The organization of the ray tracing is critical for the effectiveness of the thermally coupled computational setup. The ray tracing algorithm is fully parallelized using MPI and takes advantage of the balanced distribution of all available tiles among all CPU's. This approach allows tracing each particular ray without any communication.

The new radiation model is used here for the heat treatment simulation of ADI and is shown for an automotive cast part as a first application.

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3. HEAT TREATMENT OF A STEERING KNUCKLE

Within the frame of the research project LEA [1] a steering knuckle was optimized. The goal of the project was to demonstrate the weight saving potential of an ADI design in comparison to a series ductile iron component. Fig. 5 shows the weight optimized version of this casting in comparison to the original design.

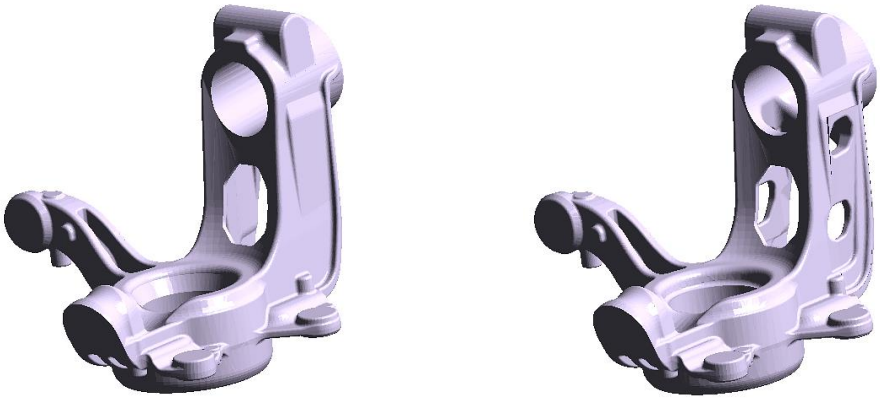

Fig. 5: Design of the steering knuckle in the original (left) and in the weight optimized design (right). A weight savings of 19% could be achieved while still fulfilling the load requirements.

Based on the empirical knowledge of the involved experts, the geometrical changes in the optimized component did not require process changes for the ADI heat treatment. Focusing on an energy efficient heat treatment process, process simulation can be used to analyze the process parameters in terms of austenitization time and temperature. Up to now, austenitization times are typically estimated using empirical rules, resulting in substantial safety factors and unnecessarily long treatment times to ensure a full austenitization. Fig. 6 shows a typical configuration in which parts are positioned side by side in heat treatment boxes. In the example, three boxes are stacked resulting in a total of 27 castings which were put into the furnace.

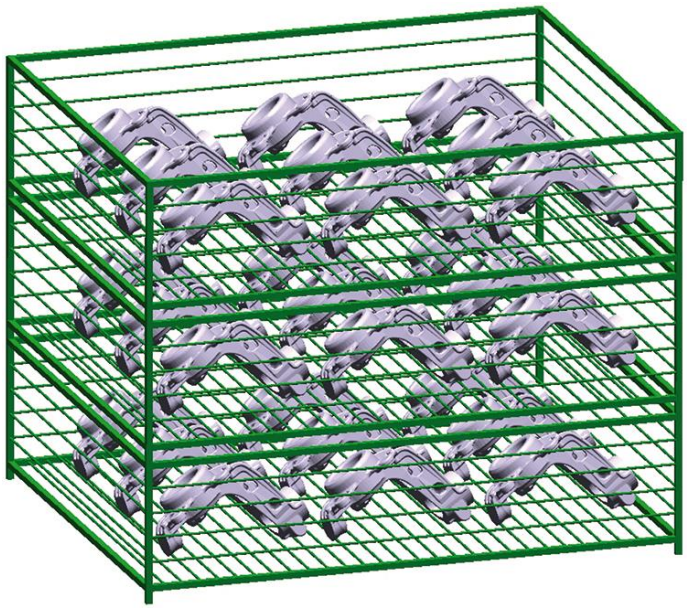

Fig. 6: Configuration of three heat treatment boxes stacked on top of each other, with 27 castings in total

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For the following simulation results, the previously described radiation model was used. The austenitization temperature was defined to be 880°C. The salt bath temperature for the quenching and ausferritization step was specified to be at 360 °C. The required boundary conditions and radiation properties to consider heating in the furnace as well as heat transfer coefficients for the quenching step were taken from an existing database in the process simulation software.

Fig. 7 shows the treatment time the components required to reach full austenitization (austenitization time equivalent to 99% of the maximum carbon saturation in the austenite matrix). After 45 minutes, all castings were fully austenitized. Due to shadowing effects and secondary heat exchange between the components in the boxes, the local heating behavior and resulting austenitization time is different for each component. Figure 7 shows a half section of the configuration of Fig. 6 (9 sectioned parts in the front and 9 complete parts in the back).

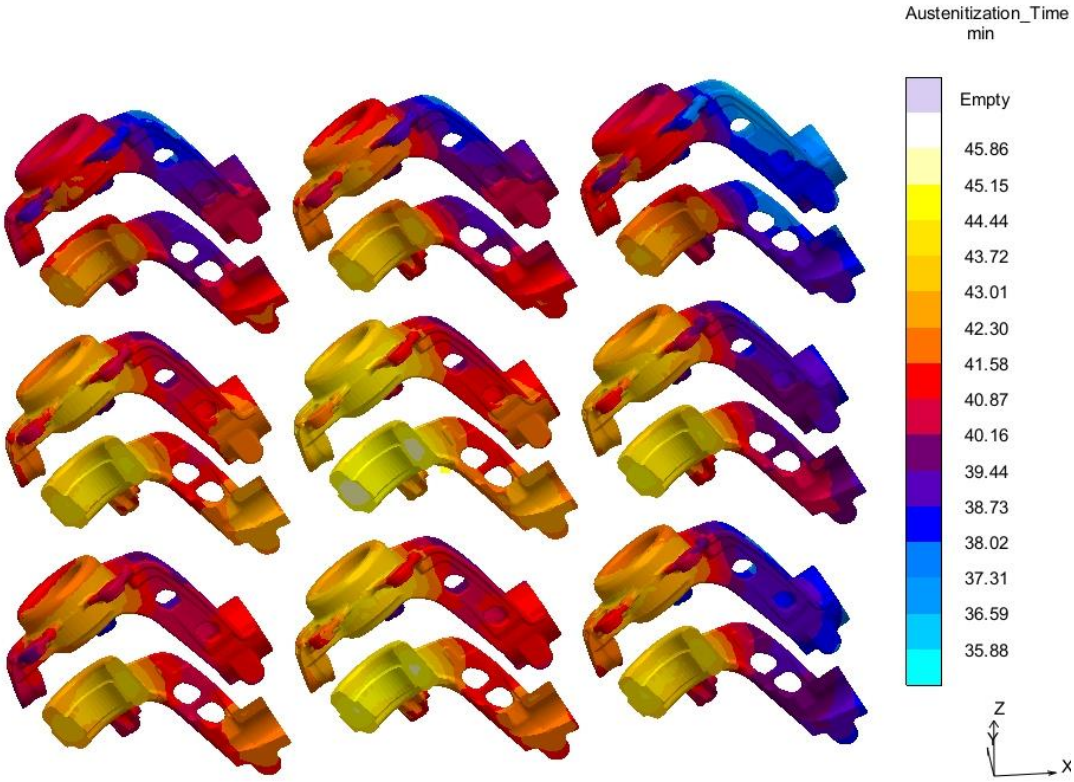

Fig. 7: The maximum austenitization time of the steering knuckles (with 880°C austenitization temperature) is 46 minutes.

To get a better impression of how the different parts heat up in the furnace, Fig. 8 shows a sequence of pictures illustrating the temperature evolution in the different components. For better comparison, the temperature scale has been fixed between 852°C and 880°C.

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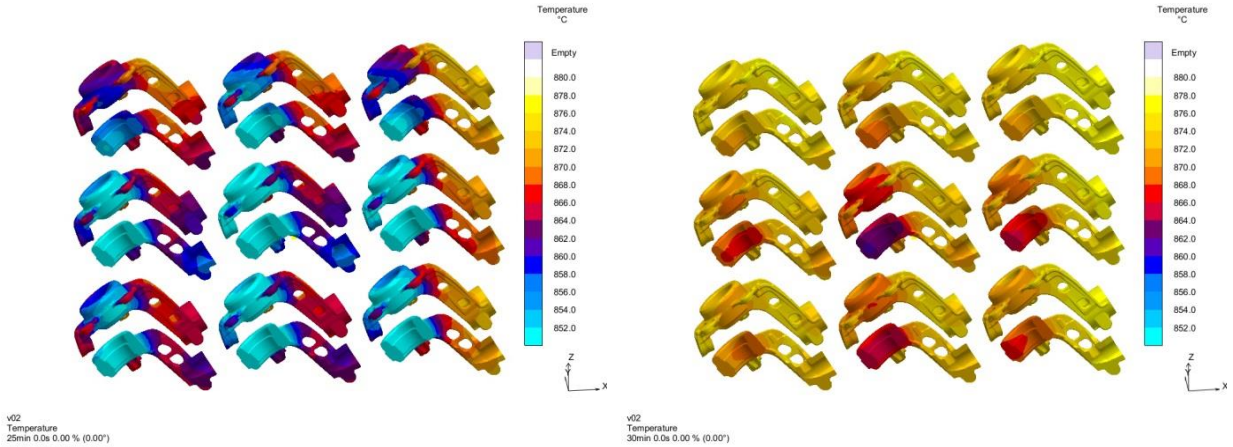
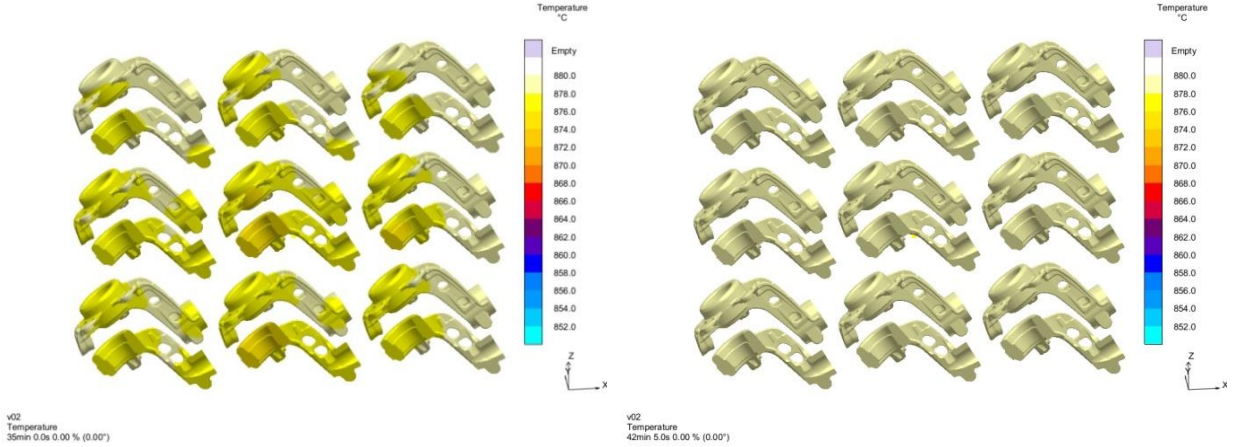


a) Temperature distribution after 25 min

b) Temperature distribution after 30 min



c) Temperature distribution after 35 min

d) Final homogeneous temperatures after 42 min

Fig. 8: Temperature development during austenitization from 25 min to 42 min (a-d)

After 25 minutes, the outer parts of most of the components exceed 852 °C, showing a temperature difference of 40 °C. After 30 minutes, the temperature in all components is clearly above 852 °C, but still temperature differences can be identified. A nearly homogenous temperature of 880 °C, leading to a maximum carbon saturation for all parts, is only reached after 42 minutes.

A helpful criterion to assess the austenitization step is the predicted carbon concentration in the austenite. During the austenitization step, diffusion as a function of the local temperature and the grain size (diffusion lengths between the graphite nodules and austenite) is the key transport mechanism to reach the required carbon concentration. Consequently, the model predicts local differences in carbon concentration, especially during the early stages of heating, Fig. 9a. At the end of the austenitization treatment, carbon has nearly reached the maximum possible concentration within all parts, Fig 9b. Again, the simulation results clearly show that the carbon concentration develops different in all the parts, caused by the differing temperature histories shown in Fig.8.

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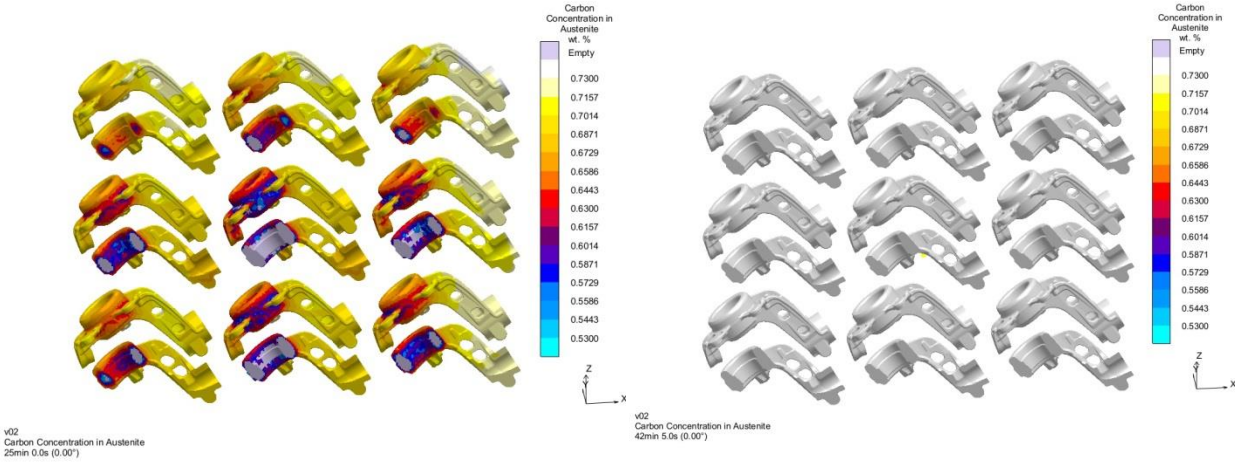
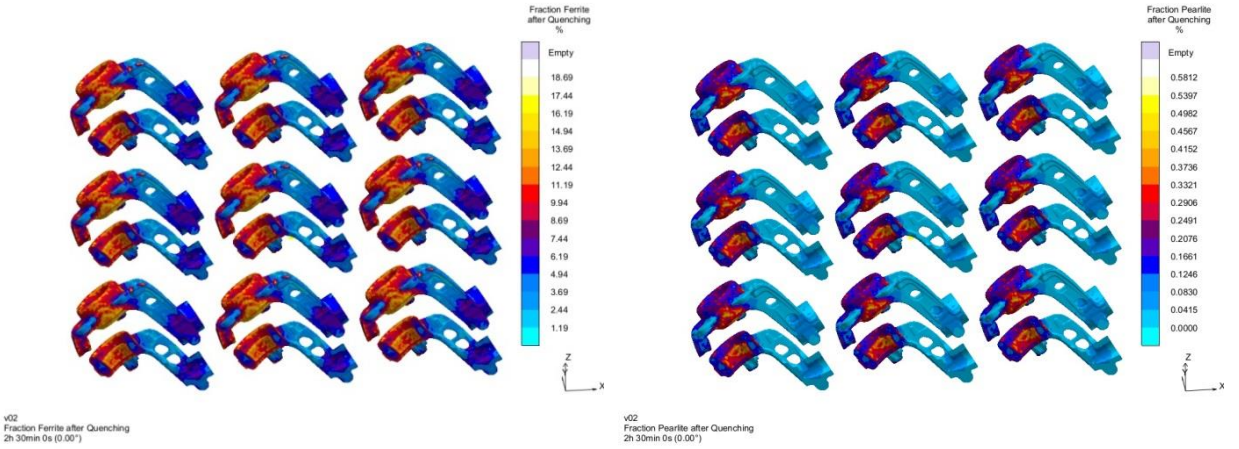


a) Carbon Concentration after 25 minutes; gray areas indicates zones which have not reached austenite transformation yet

b) Carbon Concentration after 42 minutes

Fig. 9: Criterion for the austenitization step: carbon concentration in austenite. At the local austenitization time, a homogeneous carbon concentration is achieved (b).

After austenitization, the components are quenched in a salt bath with a specified temperature of 360°C. The local cooling rates should be high enough to avoid perlite/ferrite formation during cooling. Fig. 10 shows the fraction of ferrite (a) and pearlite (b) after quenching. The amount of pearlite is below 0.6% for all parts.



a) Fraction Ferrite after Quenching

b) Fraction Pearlite after Quenching

Fig. 10: Fraction of ferrite (a) and pearlite (b) after quenching in a salt bath at 360°C

The microstructure after quenching is the basis for the final ausferritization step. The ausferritization is realized by isothermal holding of the components in the 360 °C salt bath. During ausferritization, the needle shaped ADI ferrite will be formed. For the given configuration with 27 parts, more than 80% fraction ausferrite can be reached, Fig. 11a. In practice, a treatment time of 1 h was applied. The simulation results confirm that the predefined time of 1 hour was an over estimation, as in the simulation the ausferrite transformation is complete after approximately 33 minutes in all parts, Fig. 11b.

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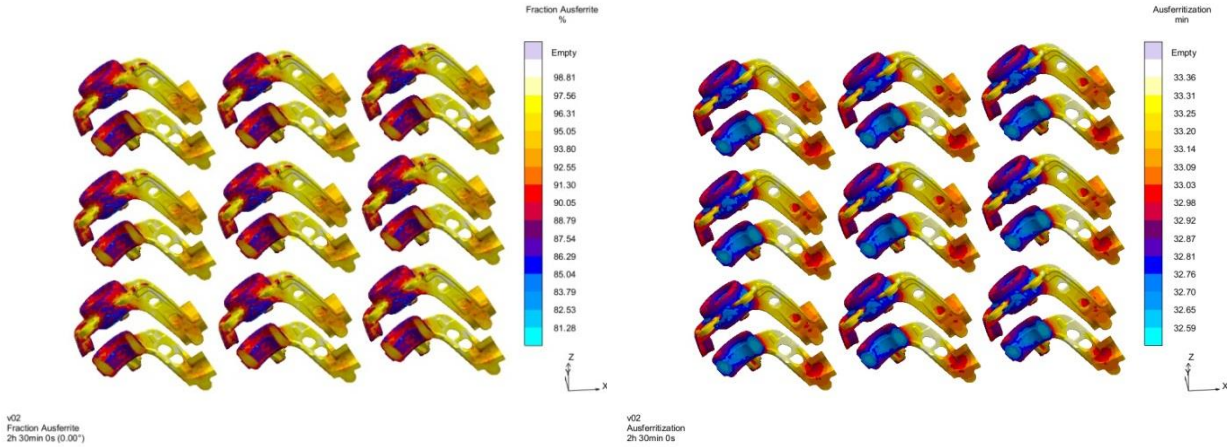

a) Fraction ausferrite after 1 hour b) Required ausferritization time (min)

Fig. 11: Fraction ausferrite (a) and the required local maximal ausferritization time (b)

The simulation of the ADI heat treatment process for a configuration with 3 boxes and 27 parts shows that an austenitization time of 42 minutes would be sufficient to reach a homogeneous austenitization temperature and the related carbon saturation in all parts. The estimated time used in the heat treatment shop of 1.5 hours could therefore be significantly reduced. The quenching and ausferritization steps could also be reduced from 1 hour to 33 minutes. After these initial findings, automatic virtual experimentation was applied to identify key controlling process parameters and establish a robust process

4. OPTIMIZATION OF THE AUSTENITIZATION STEP

Increasing energy and resource efficiency of heat treatment processes requires in-depth understanding of the controlling parameters on the required treatment conditions for a given part quality To find such stable process conditions, the integrated casting and heat treatment process simulation can be coupled with statistical methods from Design of Experiments (DoE) to determine the influence of selected process parameters [3].

In this example, a set of virtual experiments were performed to assess the ADI heat treatment process. The expert has the freedom to define any relevant process parameter as a so-called design variable to be varied. In this example, the inoculation method used during casting and the treatment time during austenitization were chosen as the design variables. As a main criterion to assess the treatment quality, the carbon concentration was chosen. The main goal of this Design of Experiments was to minimize the austenitization time under the given process conditions. Therefore, a minimization of the difference between the maximum and minimum carbon concentration in the parts after austenitization was defined as the objective for this optimization.

MAGMA[5] allows an easy assessment and analysis of the main effects of the design variables with respect to the selected objectives. Fig. 12a shows the effect of different inoculation methods applied during casting (and hence on the resulting nodule counts in the as-cast component, leading to different diffusion conditions during heat treatment) on the differences in the carbon concentration. In Fig. 12b the dependency between treatment time and carbon concentration differences is shown. The first point at the left of the main effect diagram shows that with a treatment time of 30 minutes a significant difference in the local carbon concentration in the parts exists. This means that the chosen treatment time is too short for a

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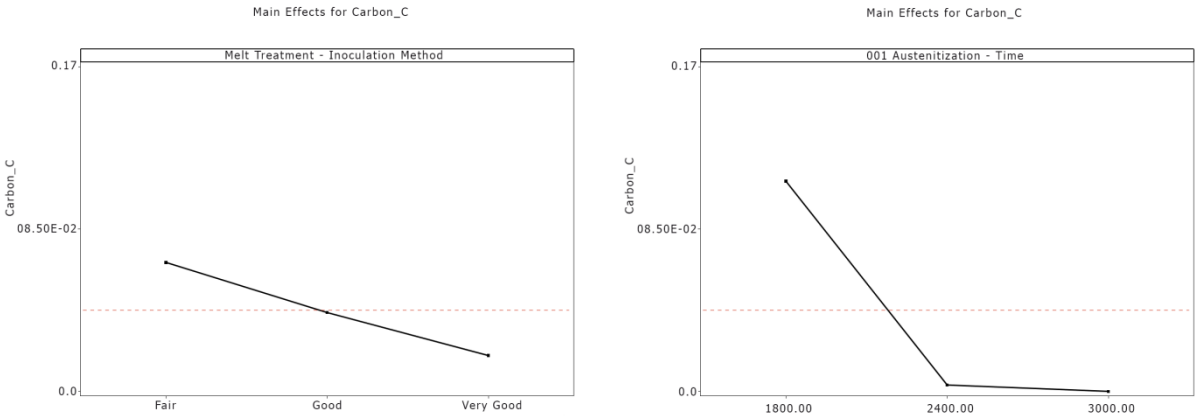
complete austenitization and carbon homogenization in all parts. After 40 minutes (middle point), the calculated value for the objective ‘carbon concentration difference’ is almost zero. This means that this treatment time is sufficient to realize the required objective. The flat line segment between the second and third points indicates that a treatment time beyond 40 minutes does not lead to any further improvement of the objective of a homogeneous carbon distribution.



a) Effect of inoculation method on carbon concentration difference after austenitization

b) Effect of austenitization time on carbon concentration difference after austenitization

Fig. 12: Main effect diagrams as a result of an automatic virtual optimization

In addition to color plots and main effect diagrams, the optimization results can also be displayed in so-called parallel coordinate charts, Fig. 13. In this example, the process variables treatment time during austenitization and inoculation method are shown together and are linked to the resulting objective ‘carbon concentration difference’, which has to be minimized. The lines in this diagram represents the input and output values of a possible design.

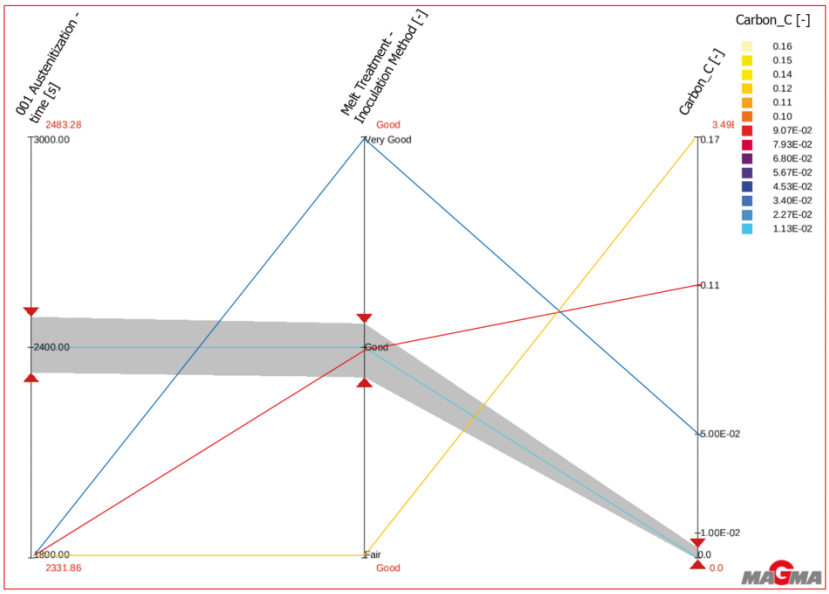


Fig. 13: The best process conditions of 40 minutes treatment time during austenitization and a medium quality inoculation method (level good) result in a homogeneous carbon concentration

The parallel coordinate chart can interactively be used to find an optimum, by limiting the accepted quality criterion to the required values. Using this filter, the chart directly shows the

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process conditions which will fulfil the chosen objective. If the expert applies a medium inoculation treatment (level good) and a treatment time of 40 minutes, derived from this chart, he can expect a robust quality level for all parts in the box.

5. SUMMARY

ADI (austempered ductile iron) is a very attractive material group offering high fracture toughness as well as high fatigue resistance and is especially suited for applications under cyclic loading conditions. To reach the required properties, a special heat treatment process is necessary. Integrated process simulation predicting the as-cast structures and the following heat treatment process allows the establishment of the best conditions for a robust process, aimed at high quality parts and minimized energy consumption.

The simulation of the ADI heat treatment process can be significantly improved by using a model taking into account the radiation exchange in the furnace and between the parts. This model allows consideration of the heat exchange for real treatment conditions of multiple parts in a box. To realize the best compromise between quality requirements and energy efficiency during heat treatment, a virtual design of experiments approach integrated in the software MAGMA[5] was used to determine the minimum required austenitization time for all parts.

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