

New method of processing heat treatment experiments with numerical simulation support

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Abstract. In this work, benefits of combining modern software for numerical simulations of welding processes with laboratory research was described. Proposed new method of processing heat treatment experiments leading to obtaining relevant input data for numerical simulations of heat treatment of large parts was presented. It is now possible, by using experiments on small tested samples, to simulate cooling conditions comparable with cooling of bigger parts. Results from this method of testing makes current boundary conditions during real cooling process more accurate, but also can be used for improvement of software databases and optimization of a computational models. The point is to precise the computation of temperature fields for large scale hardening parts based on new method of temperature dependence determination of the heat transfer coefficient into hardening media for the particular material, defined maximal thickness of processed part and cooling conditions. In the paper we will also present an example of the comparison standard and modified (according to newly suggested methodology) heat transfer coefficient data's and their influence on the simulation results. It shows how even the small changes influence mainly on distribution of temperature, metallurgical phases, hardness and stresses distribution. By this experiment it is also possible to obtain not only input data and data enabling optimization of computational model but at the same time also verification data. The greatest advantage of described method is independence of used cooling media type.

1. Introduction

Numerical welding and heat treatment processes simulations are very attractive and useful tool for modern engineers. Of course, very important is to deliver them the solution which give the possibilities to provide the calculations as close as it is possible to the reality. Construction and development works are focused now on both the development of new prototype constructions with optimized utility properties and increasing the efficiency and utility of current equipment. In both trends are applied modern and expensive materials. And it is a main reason that more and more often the numerical simulation are the main tools for research of their engineering manufacturability. Especially when the construction parts are big it is usually not possible to test everything on a small pieces at laboratory or results of these tests are not correlated well with real process results [1, 2].

In this area it is possible to find a place for modern numerical simulation software aid. Of course still we have problem, how to obtain relevant input data of numerical simulations. It is needed to assure the sufficient accuracy, to describe not only the dimensions and shape of heat treated part, but also the change of cooling conditions during the movement of processed part in a cooling bath. At this moment there are partial solutions facilitating to obtain the input data needed for the simulations of heat treatment



with more or less accuracy. For these solutions there is a number of limiting conditions lowering the resulting accuracy [3, 4].

Problem of numerical welding simulations is that calculations of temperature fields and other results (as metallurgical phases, heat fluxes distribution and connected with them mechanical changes) are strongly connected with many factors which are describing process and the use a proper methodology. It is caused by the high temperature gradients and non-stationary temperature field. This non-stationary temperature fields are result of moving of mathematically described heat source and the fact that the temperature is a function of coordinates and of time. Also the heat transfer coefficient and mechanisms of heat transfer are complex and different for each stage of process. It is needed to very precisely define them and prepare some experiment to evaluate their changes in different process conditions [3, 4]. In the following paper we will describe a new method of obtaining input data for numerical simulations of heat treatment, simulating a real hardening process, when we set up the same conditions for both small tested part and large scale tested part.

2. Heat transfer modes to the surroundings

Heating and cooling operations are strictly connected with the welding and heat treatment processes. Of course in welding we have a moving heat source and the temperature is both function of the coordinates and time function. Simulations of temperature fields are computed on Furrier's differential formula base. For calculations, it is therefore necessary to acquire the temperature dependence of the heat conductivity coefficient, specifically heat and density [6, 7].

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c \cdot \rho} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \alpha \nabla^2 T \quad (1)$$

where:

- T - temperature [K],
- t - time [s],
- x, y, z - point coordinates [m],
- a - thermal diffusivity coefficient [$\text{m}^2 \cdot \text{s}^{-1}$],
- λ - heat conductivity coefficient [$\text{W} \cdot \text{m}^{-1} \text{K}^{-1}$],
- c - specific heat [$\text{J} \cdot \text{kg}^{-1} \text{K}^{-1}$],
- ρ - mass density [$\text{kg} \cdot \text{m}^{-3}$].

In SYSWELD, thanks to the coupled thermo-metallurgical analysis, modified heat convection equation is used as follow [5]:

$$\left(\sum_i P_i (\rho C)_i \right) \frac{\partial T}{\partial t} - \nabla \cdot \left(\left(\sum_i P_i \lambda_i \right) \nabla T \right) + \sum_{i < j} L_{ij}(T) \cdot A_{ij} = Q \quad (2)$$

where additionally are:

- p - phase proportion,
- i, j - phases index,
- Q - heat sources,
- $L_{ij}(T)$ - latent heat of $i \rightarrow j$ transformation,
- A_{ij} - proportion of phase i transformed to j in time unit.

Nonlinearity of generated non-stationary temperature fields are consequence in using Furriers's differential formula and are given by partial derivations of temperature according individual coordinates, when each partial derivation determinates temperature gradient in the relevant axis direction. But in practice, calculation of temperature fields is based on heat source mathematical definition, represented by thermal flow density into material. After welding or heating in heat treatment, we have a cooling time and it is also need to be described by mathematical equations according to present type of heat

transfer. There are only some differences in heating method and cooling media. But in all of these processes, we can define three main types of heat transfer: conduction, convection and radiation [5, 6].

Conduction is a heat transfer process where is no bulk motion. Energy is transferred by random molecular motion as diffusion of energy. Conduction is the dominating effect for the cooling rates that occur in a welded structure [1, 3, 4, 5].

Another thermal-physical quantity which influences the temperature fields by welding computations is the heat transfer by convection. There is a convection within the weld pool which is extremely difficult to describe. In one way it is dependent on applied welding technology, but it is also responsive to the welding efficiency and welding rate. Heat transfer influence can be expressed by Peclet's number for heat transfer but also it is possible to compensate by the mathematical description of the heat source modification [6].

Same as previous, heat sharing between the solid and the fluid (during welding simulations posed by the surroundings) is very complex and difficult to describe phenomena. During welding heat sharing is partly evident to the surroundings by convection, but also at high temperatures by radiation (although that in a short time). For the temperature dependence detection these both coefficient are important. The advantage is that the heat transfer coefficient does not depend on the welded material type so it depends only on the surface temperature of the welded part and the surrounding temperature. Additionally for the welding simulation, it has no significant influence on the cooling rates. It is mainly needed to cool the part back to surroundings temperature [5, 8, 11, 12].

Of course heat transfer coefficient to the surroundings have the influences on the temperature fields. The temperature dependence determination of this quantity is important not only for the space geometry of welded parts, but also for setting conditions in welding surroundings.

Last heat transfer type is a mentioned radiation. It is different from the other ways because it does not need a mediating substance. This part of transferred energy depends only on the temperature field shape and transit by an electromagnetic waves with a different wavelengths. In welding, radiation dominates the heat transfer to the surroundings at higher temperatures. However, the cooling rates are usually high, thus the time to transfer energy to the surroundings by radiation is low. As a consequence, the net heat transfer to the surroundings by radiation during the - for the welding process - important cooling phase is not very important for the cooling rates [5, 8, 11, 12].

In SYSWELD, model for diffusion controlled transformation based on the Leblond's model for heating and cooling [5, 6]:

$$\frac{dP(T)}{dt} = f\left(\dot{T}\right) \cdot \frac{P_{eq}(T) - P(T)}{\tau(T)} \quad (3)$$

where:

- P - phase proportion,
- t - time,
- T - temperature,
- P_{eq} - proportion at phase equilibrium,
- τ - delay time as a function of the temperature,
- \dot{T} - heating/cooling rate.

For martenisite transformation is used Koistinen-Marburger law [5, 6]:

$$P(T) = 1 - \exp(-b(Ms - T)) \quad (4)$$

where:

- p - phase proportion,

- b - law coefficient,
- M_s - martensite start temperature.

To sum up, as well as for welding, conduction heat transfer have dominant role in surface heat treatment processes that are based on self-cooling by conduction. In heat treatment, the convection heat transfer is dominating the quenching process rather than the conduction heat transfer [5, 8].

3. Experimental procedures of heat transfer coefficient evaluation

Heat transfer coefficient can be also evaluated by experimental measurements. As it was written at the beginning, they have some limiting conditions which can decrease results accuracy.

First solution of determination of cooling rate of hardening is using preheated Inconel probe measuring. In this method we insulate the Inconel's cylinder in colling media (as in the quench test) and by the connected K type thermocouple can be recorded the colling cycle. By using derivation of temperature per time, the cooling rate in tested media can be determined [3, 4]. This method is especially used for testing the change in cooling ability of the media during long-term operation, or it is possible to quantify the differences in cooling intensity among various kinds of media [3, 4]. But there is a one problem with applying this condition to the materials with different thermal conductivity – calculated cooling intensities will be significantly different. Additionally, this method of testing does not take into consideration the dimensions of tested parts [9].

Second possibility is a using classical Jominy test. Main disadvantage of this solution is defining particular test for only one type of cooling media, but also none temperature fields and cooling curves of tested sample are known [3, 4, 9, 10]. In addition this type of testing is suitable only for materials with low hardenability, because hardness in whole controlled length will be almost identical for materials with high hardenability [3, 4].

It is also possible to measure only the thermal cycles with the help of the surface thermocouples on the tested plate and the subsequent determination of the heat transfer with the indirect method of numerical analyses. But this method have also some disadvantages. Main is the measurements in the high temperature. With increasing temperature, increase also measurements mistake, starting with the compensation line and finishing with the radiation of thermocouples.

As it was written, main heat transfer in heat treatment is by convection. It means that a very important parameter during heat treatment is a size and a shape of processed part. Because it is very difficult to include the shape variability, therefore it is more suitable to focus on experiments enabling to include and describe the influence of processed part size. For this kind of research, we propose the testing stand where test specimen is insulated with at least 30 mm of unsodden thermal insulation designed for temperatures up to 1200°C on all sides, except the front as it was presented on figure 1. Therefore the heat dissipation is possible only through frontal side of the tested body and it can be possible to simulate the change in cooling rate towards the thickness of processed part [3, 4]. In this case it does not matter (considering zero losses of the heat through insulating layer) how large the frontal side of tested specimen is because if the frontal side of testing body is enlarged, the amount of accumulated heat in tested body increases proportionally [3].

For realization of suggested experiment a minimal length of the tested body is determined for 50 mm. Maximal length is not limited but it should correspond at least to a half of the maximal thickness of a real heat treated part. Tested body shown in figure 1 is cylinder and on its surface there are at least six temperature sensors for mapping of temperature field in the length direction.

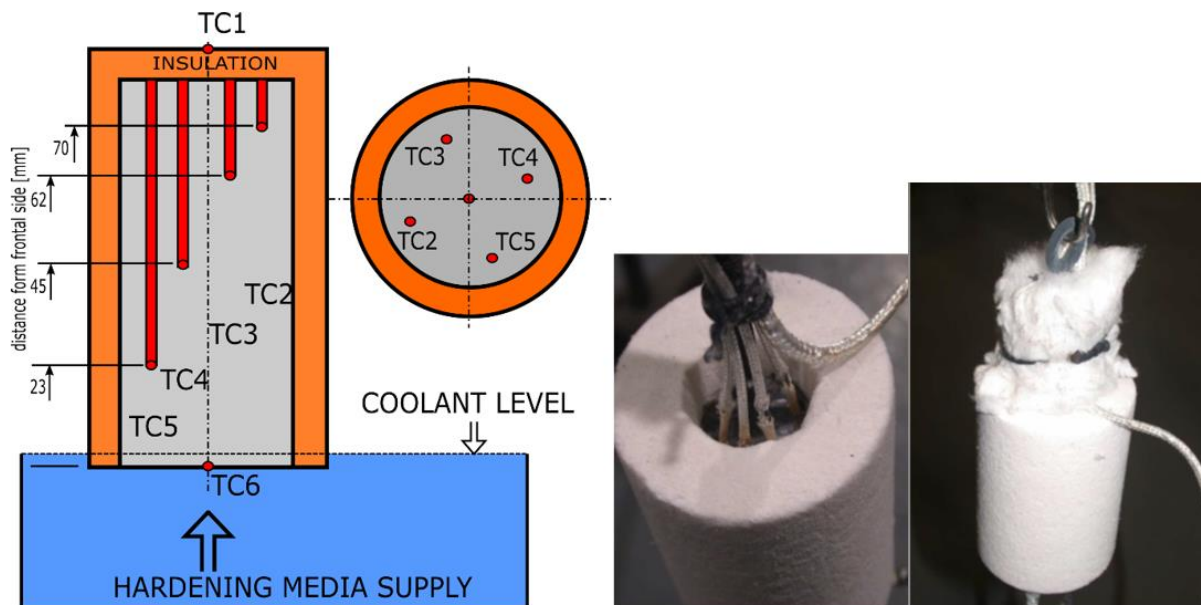


Figure 1. Scheme of test realization and view of insulated specimen with mounted thermocouples.

The testing procedure is heated up specimen in the furnace by technologically defined heating rate up to the field of stable austenite. When the test temperature is reached, testing specimen is taken out of the furnace and placed in the cooling media by immersing the frontal side about three millimetres under the media surface [3, 10]. Boundary condition concerning the constant temperature of cooling media is secured by the cooler and circulation cycle in measurement stand. Thermal cycle is recorded from thermocouples placed in specified parts of specimen.

4. Numerical simulation of heat treatment process

To show how this method can be used in improving the numerical simulation results, some short experiment was prepared. The experimental measurement was carried out on a 30 mm diameter and 75 mm long cylinder from Ck45 steel. It is typical steel for quenching and tempering according to DIN EN 10083. The tested specimens was prepared as cylinder with diameter 30 mm and length 75 mm. Six thermocouples were placed as on figure 1. Insulated specimen was heated in furnace to the temperature about 915°C by 30 minutes and then immersed 3 mm under the water surface from the frontal side.

For the numerical simulation in SYSWELD software 3D model contain 3D solid model with 89055 elements and 81472 nodes was prepared, figure 2. Main advantages of used numerical analyses software are fact, that till now, SYSWELD covers all needed non-linear phenomena as:

- nonlinear heat transfer to any extent,
- nonlinear geometry 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 phase transformations.

Using the Heat Treatment module in SYSWELD, all the parameters of quenching were set as in the real tests. As results were achieved temperature fields and cycles, metallurgical phases distribution, residual stresses and hardness distribution. Numerical simulation of real experiment was run in SYSWELD as typical transient analysis with original and modified cooling media database. This change were a new, measured with our method, values of heat transfer coefficient into the water, figure 2.

The temperature curves clearly show that elimination of heat transfer into surrounding environment by the specimen's wall thanks to the insulation. Heat removal is realised only through frontal side – thermocouples placed more far from the frontal side registered much slower cooling rates. It is because of heat accumulated in the tested specimen is constantly transferred to frontal side. Differences in heat transfer coefficient in range between 20 and 600°C have some influences, not too big, on the thermal cycles (cooling is minimally slower), especially on the thermocouple placed near the cooled surface, figure 3.

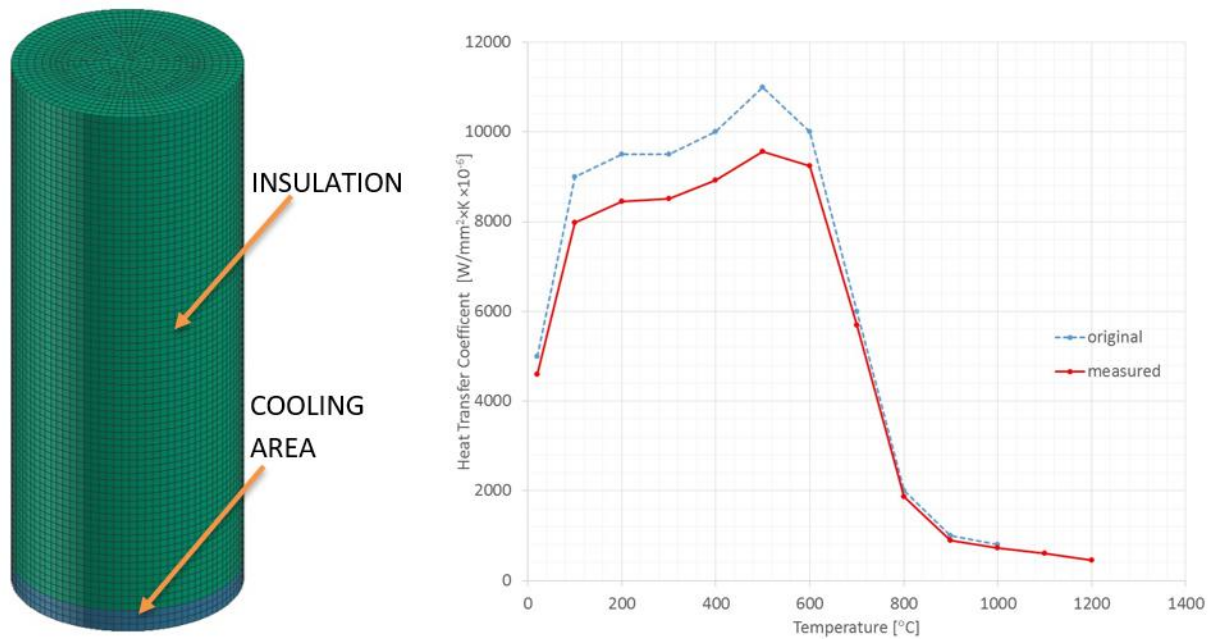


Figure 2. 3D model with visible 3 mm length immersion zone at the bottom (on the left) and used heat transfer coefficient changes in range of temperature for original and modified cooling media database (on the right).

To check this thesis, full numerical simulation (thermometallurgical and mechanical) of two mentioned cases: with original and modified based on the measurement results cooling media database was performed. The main results with visible differences were shown at the figures 5-8. They are not big but signalize importance of the problem. Important is, that distribution of the hardness, metallurgical phases and stresses are also different for two compared cases.

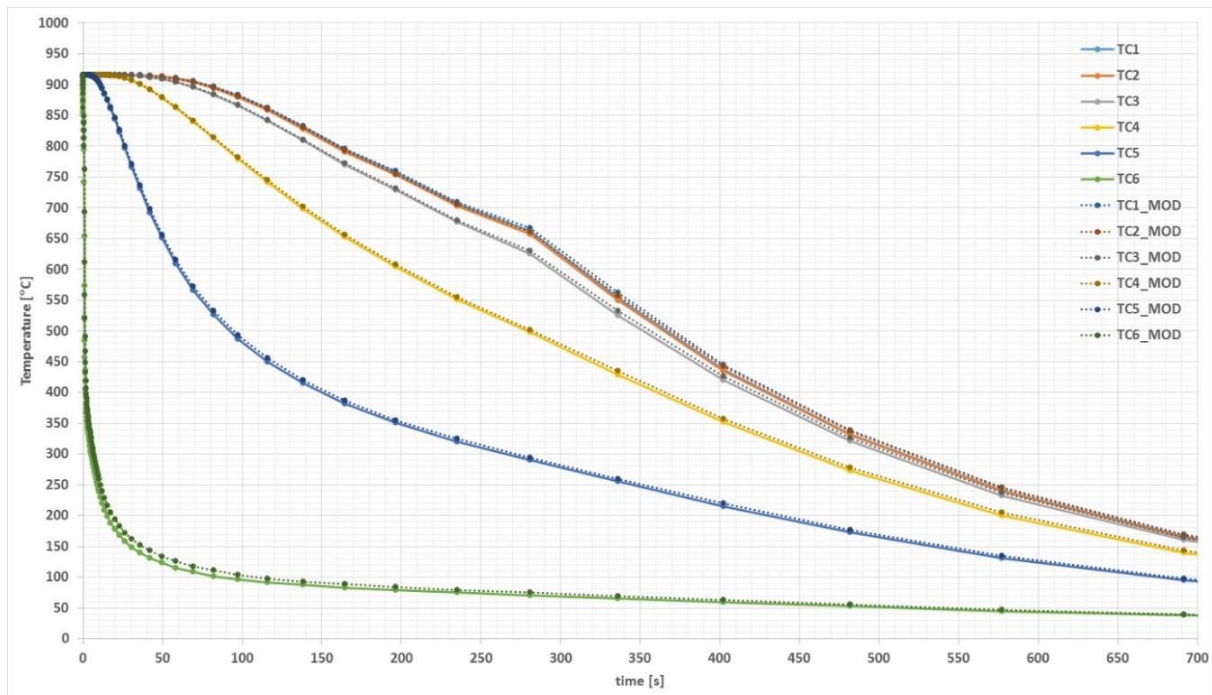


Figure 3. Calculated thermal cycles for TC1-TC6 thermocouples – original (continuous line) and modified (dotted line) cooling media database.

Because of differences in thermal cycles, changed heat transfer coefficient have also influence on cooling rates, figure 4. It is a difference in values but also in time. These changes in the first phase can have significant influences on the metallurgical phases transformation – it is cooling range between the furnace temperature and the temperature at 350°C in first two seconds of the operation. So it can have some influence also on the numerical simulations results as hardness, stresses and metallurgical phases distribution and values, figures 5-8.

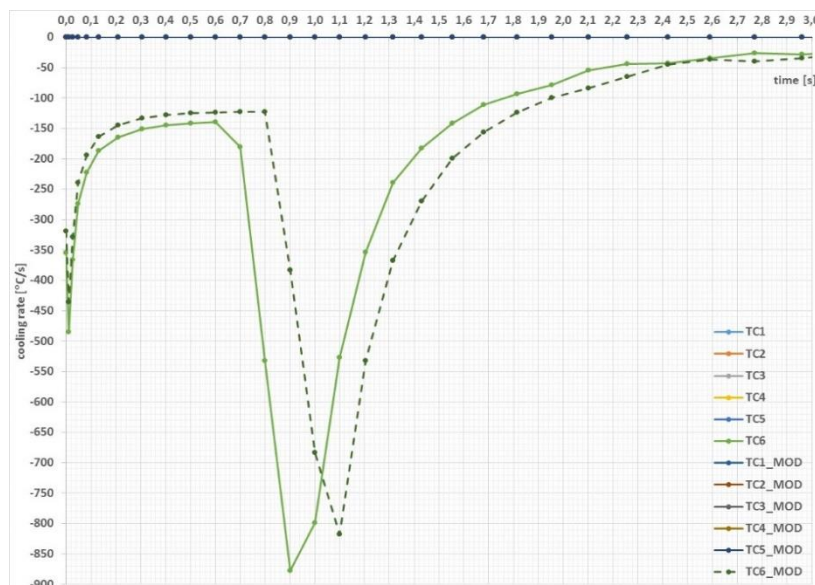


Figure 4. Cooling rates changes in range of temperature at specified measurement points for original (continuous line) and modified (dotted line) cooling media database.

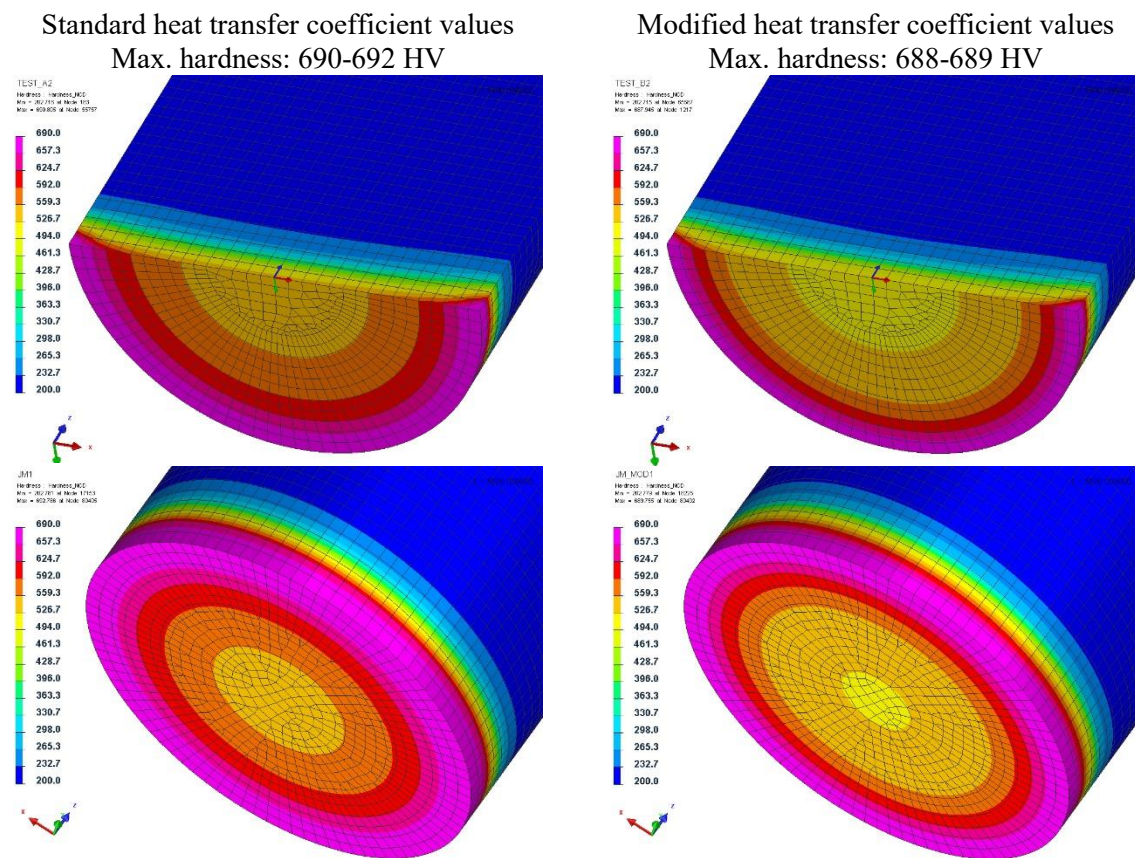
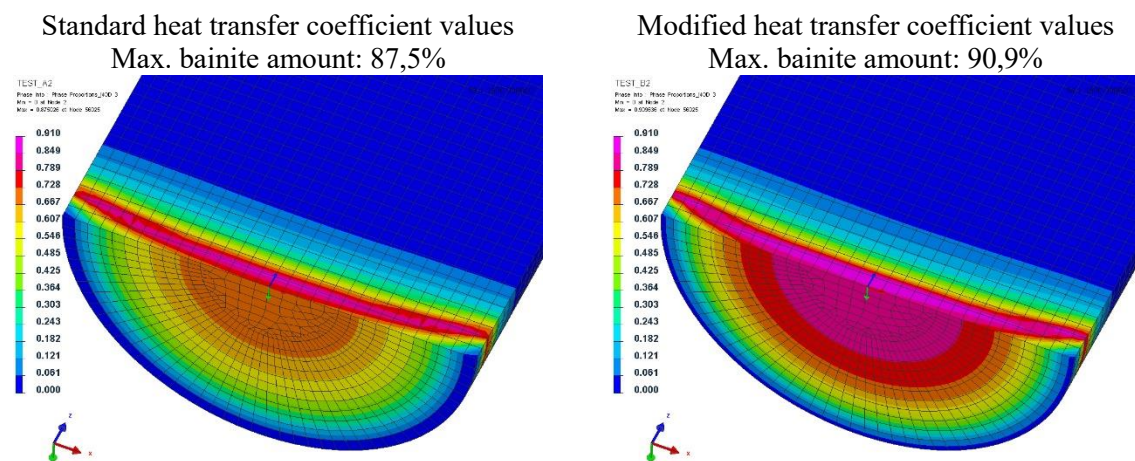


Figure 5. Calculated hardness distribution for original and modified heat transfer coefficient values.



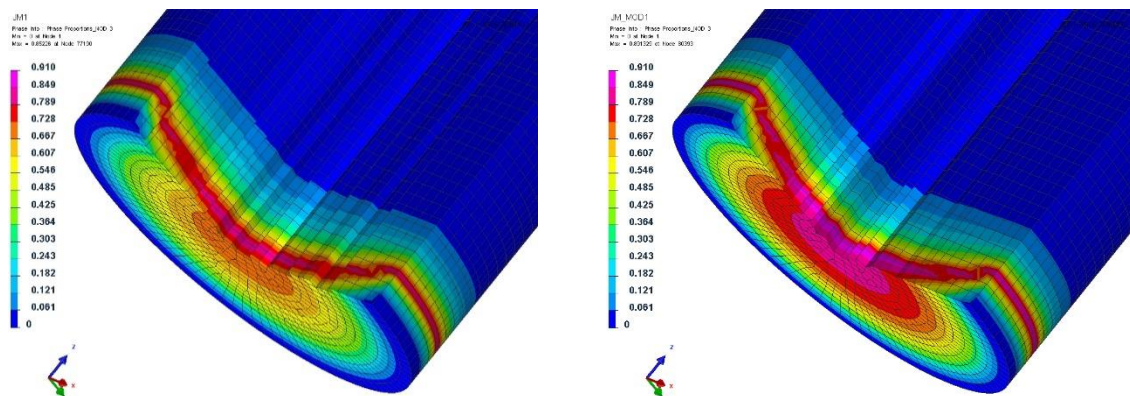


Figure 6. Calculated bainite distribution for original and modified heat transfer coefficient values.

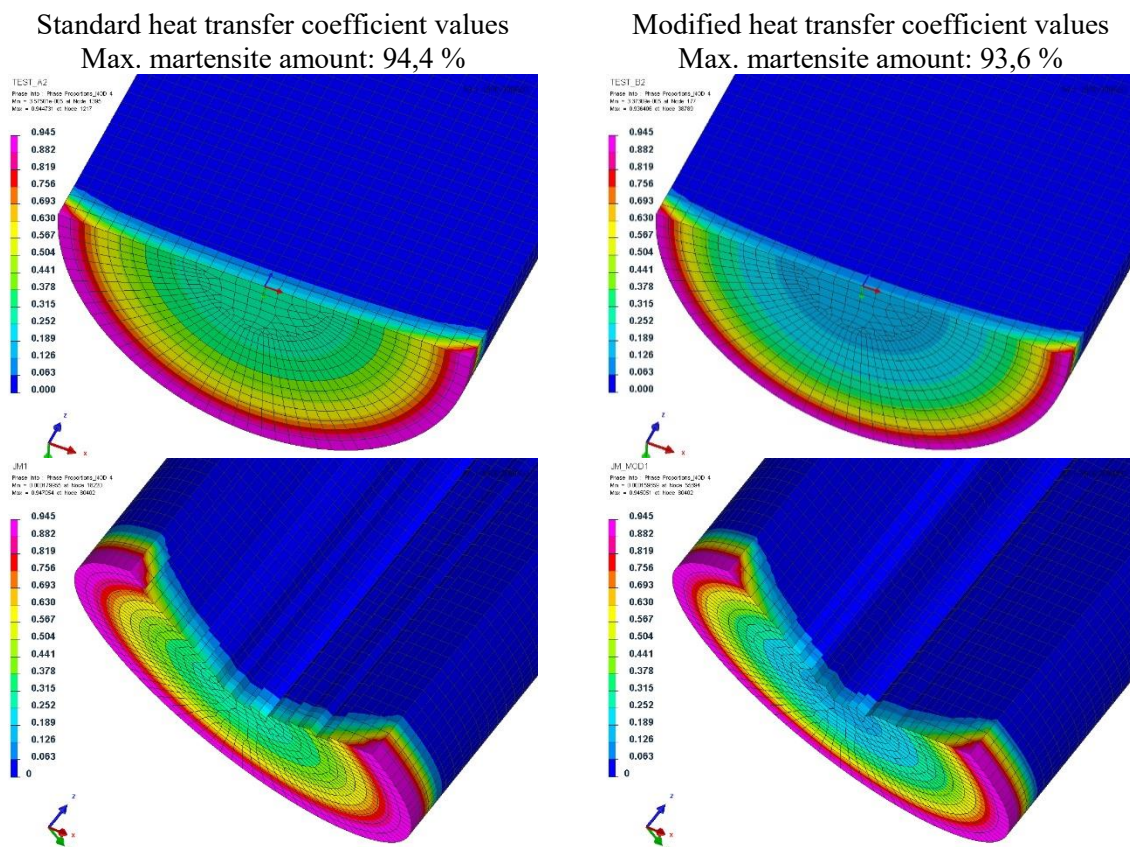


Figure 7. Calculated martensite distribution for original and modified heat transfer coefficient values.

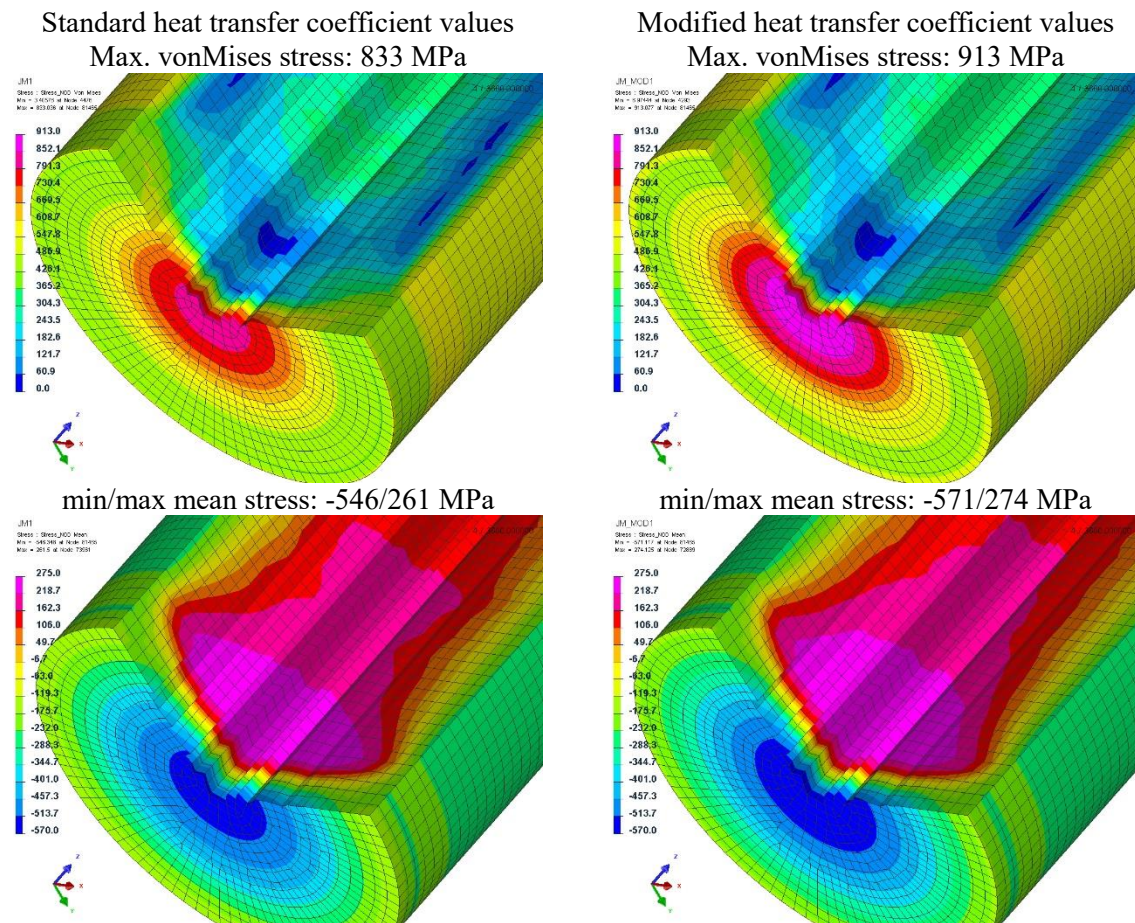


Figure 8. Calculated vonMises and mean stresses distribution for original and modified heat transfer coefficient values.

5. Conclusions

Proposed testing method describe the procedure leading to obtaining relevant input data and data for optimization of computational model during numerical simulations of heat treatment. Thanks to the temperature dependence determination of the heat transfer coefficient into cooling media for the particular material, defined maximal thickness of processed part and cooling conditions, it possible to very precise determine the temperature for large scale hardening parts. By using this experiments it is also possible to obtain verification data for the technology.

Presented analyses results shows how important is to set up very precisely all input data's for numerical simulation. From one side as the material database datas and from the other side as boundary conditions and loads. There is a visible that even that values of numerical simulation of tested element are sometimes not highly different, the distribution of this values is changed what can be significant in simulation of bigger parts with more complex shape. Small differences between some results required more and more precisely tests but also move closer to the reality.

Important is that wide range of required tests and investigations during the material data's preparation and also specialist knowledge of the numerical simulation engineers can results in the high convergence of the results with real world. Real experiments are real money – that's why the numerical simulations give us the big advantage in the present market. Decreasing number of experiment is a faster response on the market demands and saving money. But to achieve this high accuracy is also needed to do a lot of research work in the laboratories with material database and the others factors used at numerical simulations. This knowledge is after it widely used in daily engineering practice.

6. References

- [1] Kik T, Slovacek M, Moravec J and Vanek M 2015 Numerical Simulations of Heat Treatment Processes *Applied Mechanics and Materials* **809-810** 799-804
- [2] Kik T 2014 Numerical analysis of MIG welding of butt joints in aluminium alloy *Biuletyn Instytutu Spawalnictwa* **58(3)** 37-49
- [3] Moravec J, Neumann H and Nováková I 2013 Determination of the temperature dependence of the heat transfer of a hardening media with reference to the type of hardening media, type of basic material and size of hardening sample *Certify methodics* **11** 11
- [4] Moravec J and Nováková I 2014 The way of determination of the cooling ability of a media for individual materials including the simulation of heat treatment of large scale parts *Application form of a device* **PV 2014-185** 10
- [5] Welding simulation user guide 2016 *Sysweld manual ESI Group*
- [6] Moravec J 2010 Influence and choice of heat transfer coefficient by welding simulations of temperature fields *ACC Journal* **XVI** 32-39
- [7] Giętka T, Ciechacki K and Kik T 2016 Numerical Simulation of Duplex Steel Multipass Welding *Archives of Metallurgy and Materials* **61(4)** 1975-1984
- [8] Bergheau J M and Leblond J B 1990 Coupling between heat flow, metallurgy and stress-strain computations in steels - The approach developped in the computer code SYSWELD for welding or quenching, *Proc. of Vth Eng. Found. Conf. on Modeling of casting, welding and Advanced Solidification Processes* (Davos: Switzerland)
- [9] ČSN EN ISO 642 standard, Steel – frontal hardening test (Jominy test)
- [10] Ružbarský J and Žarnovský J 2013 Optimization of parameters in the compression moulding process of thermoset products *Advanced Materials Research* **801** 61-66
- [11] Radaj D 1999 *Schweißprozeß-simulation: Grundlagen und Anwendungen* (Düsseldorf DVS: Verlag)
- [12] Lewis R W, Morgan K, Thomas H R and Seetharamu K N 1996 The Finite Element Method in Heat Transfer Analysis *John Wiley & Sons*