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Modeling and Experimental Validation of Specimen Geometry Effects on Temperature Homogeneity of Advanced High-Strength Steels by Direct Electrical Heating

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Abstract

All kinds of matter are built up from elements in different compositions under physical laws. Thermal processes produce complex compositions, such as metal alloys. The quality of these processes heavily affects precise thermal conditions. Therefore, a homogeneity study of the temperature field on the surface of metal sheets under Direct Electrical Heating (DEH) was performed. The study was focused on measurements by infrared cameras and temperature field analyses. The most frequent steel, 22MnB (Svoboda et al. 2019), was used to prove the simulations. Suggestions for actions to optimize and enlarge homogeneous heating areas are raised up. The steel 22MnB5 is often used in the automotive industry for hot-stamping processes that require high strength, toughness, and durability, such as in structural components. The homogeneity of direct heating temperature depends on the type of heating (AC or DC), the shapes, positions, and dimensions of the electrodes. The relationships and balance among these parameters, as well as the optimum homogeneity, depend on cost, complexity, and technical capabilities. Using simulations, we optimized trench parameters in the samples and compared the results with real measurements.

Keywords Direct Electrical Heating, Skin Effect, Homogeneity, Trenches, 22MnB, 42SiCr

1 Introduction

In the automotive industry, press hardening is widely employed in the production of inner body components, as it enables high strength, toughness, and durability. Conventionally, 22MnB steel has been used for such applications; however, new generations of advanced steels are currently under development, offering substantially improved performance, particularly with respect to the strength–ductility balance. These enhanced mechanical properties are critical for effective energy absorption during vehicle impacts. Additionally, the use of such steels contributes to overall weight reduction in vehicles. Among these materials, the 42SiCr steel developed by the authors has demonstrated remarkable potential. When processed via the

quenching and partitioning (Q–P) route, this steel can absorb up to three times as much deformation energy as conventional brands. To investigate and optimize these characteristics, a dedicated thermomechanical process modeling tool was developed to accurately replicate real processing conditions, including the integrated Q–P treatment.

The objective of this development was not only to refine and calibrate the time–temperature response curve, but also to achieve a uniform temperature distribution within the test specimens while simultaneously increasing their dimensions. The resulting methodology and findings are applicable not only to sheet steels and tubular blanks but also to other metallic semi-finished products subjected to thermomechanical processing. The study of the homogeneity of the temperature field on the surface of metal sheets under Direct Electrical Heating (DEH) was performed. The study focused on simulation and measurements using infrared cameras, temperature field analysis, and comparisons. Furthermore, suggestions for actions to optimize and enlarge the homogeneous heating area. For the demonstration, the most frequent 22MnB steel and the experimental 42SiCr steel were used. The mathematical model for heating steel (22MnB5) is well presented in the referenced papers (Livatyalı 2024; Chen et al. 2017; Hart-Rawung et al. 2023).

The temperature homogeneity of the direct heating depends on the shapes, positions, and dimensions of the electrodes. The relationships between these parameters and optimal homogeneity depend on cost, complexity, and technical capabilities. We compare and simulate one electrode composition (related to our hardware) and the metal sheet dimensions against real measurements.

2 Modeling and simulations

The simulation was performed using COMSOL Multiphysics software, which includes modules for coupling the electromagnetic field and heat transfer. The general partial differential equations for both fields were supplemented by boundary conditions. Boundary conditions for heat transfer include convection and radiation as well. The magnetic field can be described by the parabolic PDE for magnetic vector potential A in the form

$$curl\left(\frac{1}{\mu}curlA\right)+\gamma\frac{\partial A}{\partial t}=J_{ext}, \tag{1}$$

where μ is the magnetic permeability, γ denotes the temperature-dependent electric conductivity, J_{ext} is the vector of the external harmonic density in the inductor. The solution of (1) is, however, not expedient because of a deep disproportion between the frequency of the field current and the time constant of heating. However, as in the case of heating of nonferromagnetic material, the field can be considered linear; it can be described by the Helmholtz equation as follows:

$$curl\ curl\left(\underline{A}\right)+j\cdot\omega\gamma\mu\underline{A}=\mu\underline{J}_{ext}, \tag{2}$$

where ω denotes the angular frequency.
The process of heat transfer in the specimens is described by

$$div(\lambda gradT)=\rho\cdot c_p\left(\frac{\partial T}{\partial t}+v\cdot gradT\right)-w. \tag{3}$$

Here, λ denotes the thermal conductivity, c_p represents the specific heat at a constant pressure, and ρ is the mass density (all these parameters are also temperature-dependent functions). This equation is supplemented by the boundary condition respecting both ways of heat transfer – convection and radiation

$$-\lambda \cdot \frac{\partial T_S}{\partial n} = \alpha \cdot (T_S - T_0) + \sigma \cdot C(T_S^4 - T_r^4). \quad (4)$$

The COMSOL also allows optimization of trench parameters. We parametrize three dimensions of the trench, as you can see on (Fig. 1). The criteria for optimization are maximum temperature homogeneity in the area indicated with a rectangle.
Three optimization methods were used :

- The Nelder–Mead Method
  The BOBYQA Method (Boundary Optimization BY Quadratic Approximation)
  The EGO Method (Efficient Global Optimization)

All three solvers are derivative-free and therefore do not require gradient information. They are well suited to optimization problems where derivatives are unavailable or expensive to compute. Nelder–Mead is generally tolerant of no smooth objectives, whereas BOBYQA and EGO typically perform best on reasonably smooth objective functions.

The simulation was performed to reach temperatures of 750 °C, 800 °C, 850 °C, 900 °C, and 950 °C at the centers of the specimens.
The analyses of simulation results are shown in figures (Fig. 2, Fig. 3, and Fig. 4). (Fig. 5) compares all three optimization methods. The BOBYQA optimization method was used for the comparison with the real measurement.

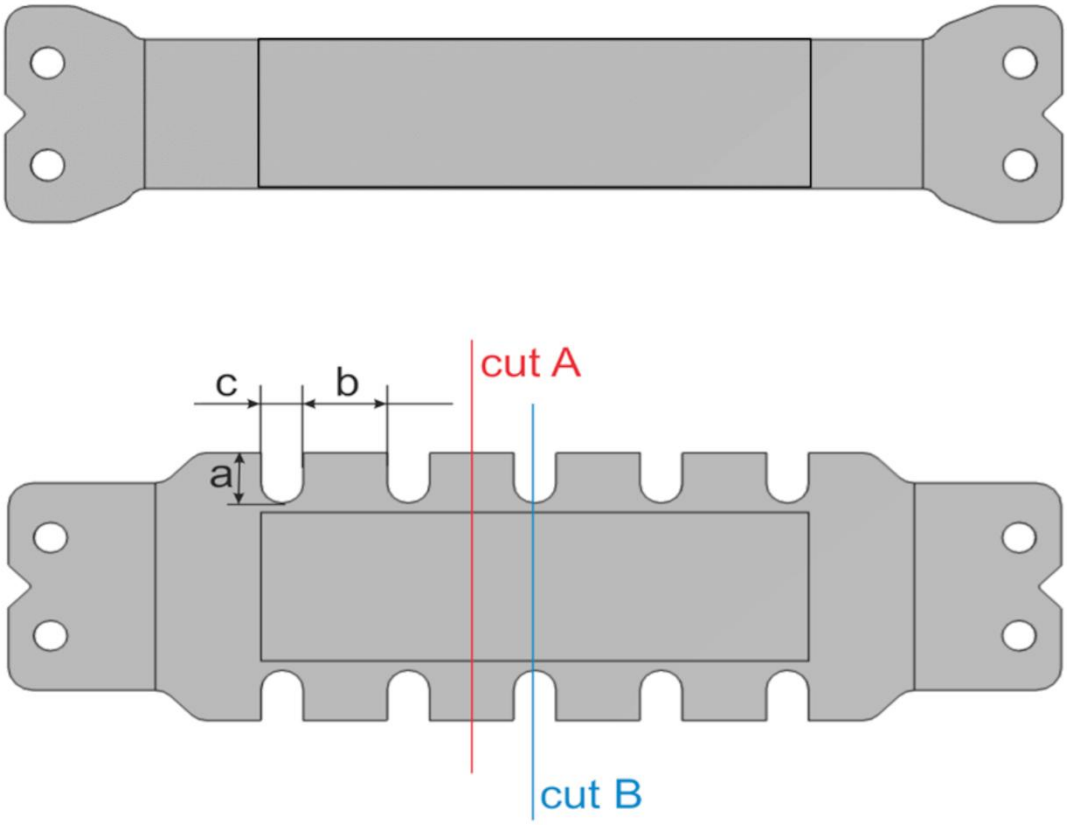


Fig. 1 Dimensions of the specimen with and without trenches, optimized parameters are a, b, c.

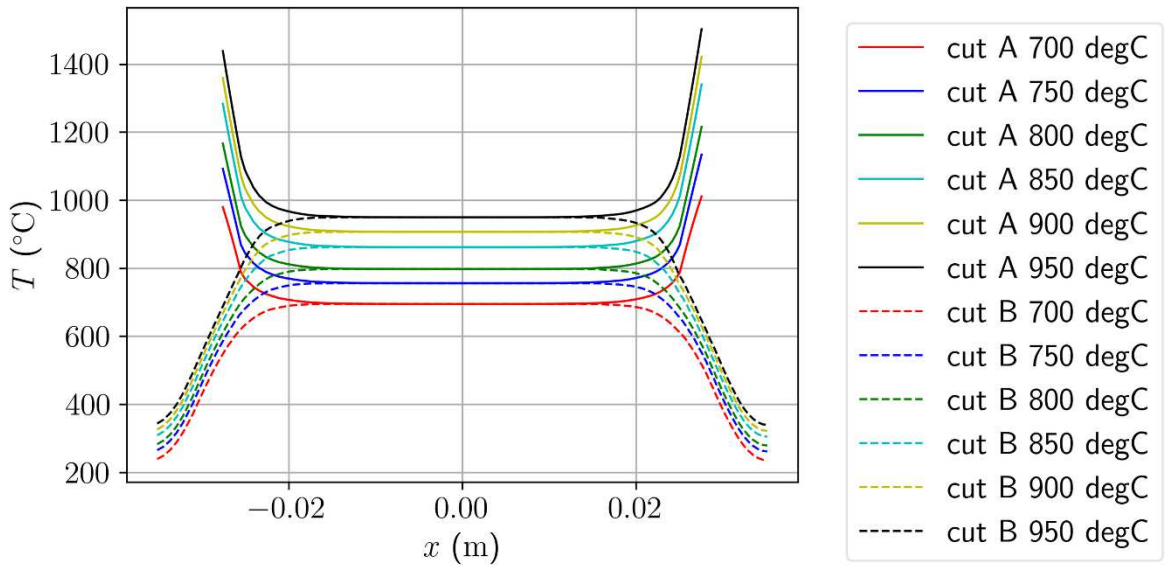


Fig. 2 Simulation results EGO solver

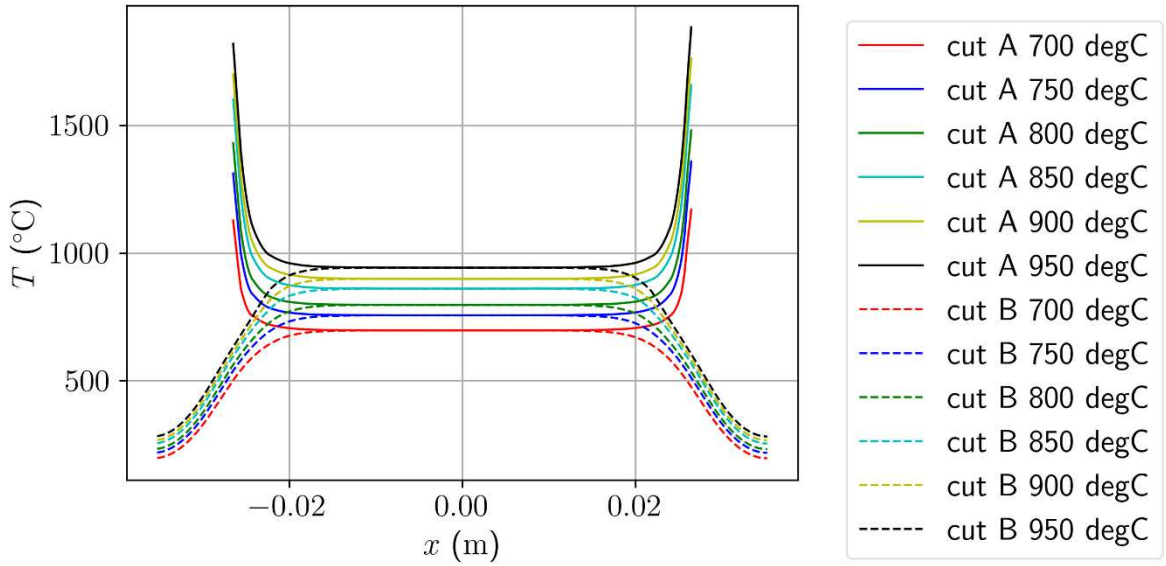


Fig. 3 Simulation results BOBYQA solver

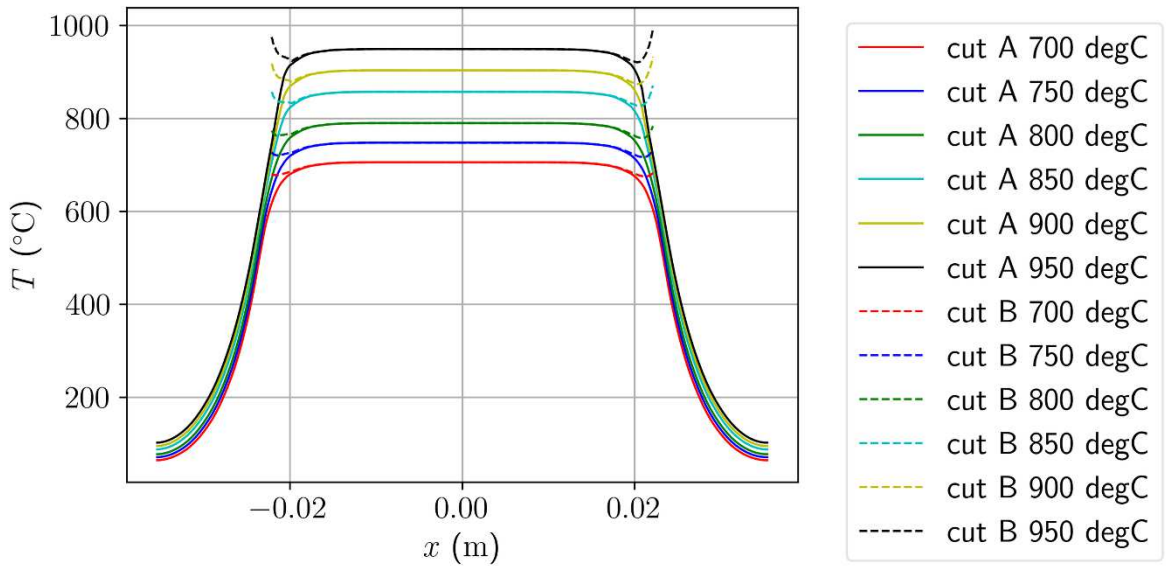


Fig. 4 Simulation results Nelder-Mead solver

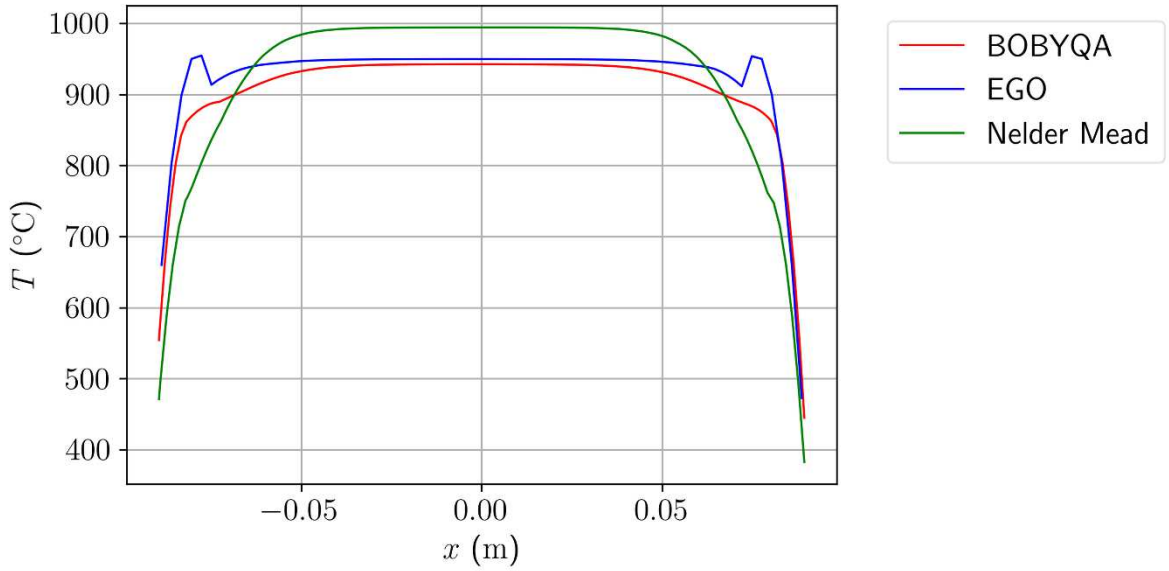


Fig. 5 The results of three optimization solvers - comparison

The basic specimen without edge modifications (Fig. 6) confirmed a significantly inhomogeneous temperature field. The edges of the specimens were modified using special trenches to homogenize the temperature field. (Fig. 7) shows simulation results with special treatment of long edges by trenches. The intervention assures the homogeneity of the temperature field across the whole surface. For the experiment, the shape of the trenches was enhanced with a circular hole at the inner end of each trench. Two dimensions of the holes are used to observe the scale of temperature homogenization.

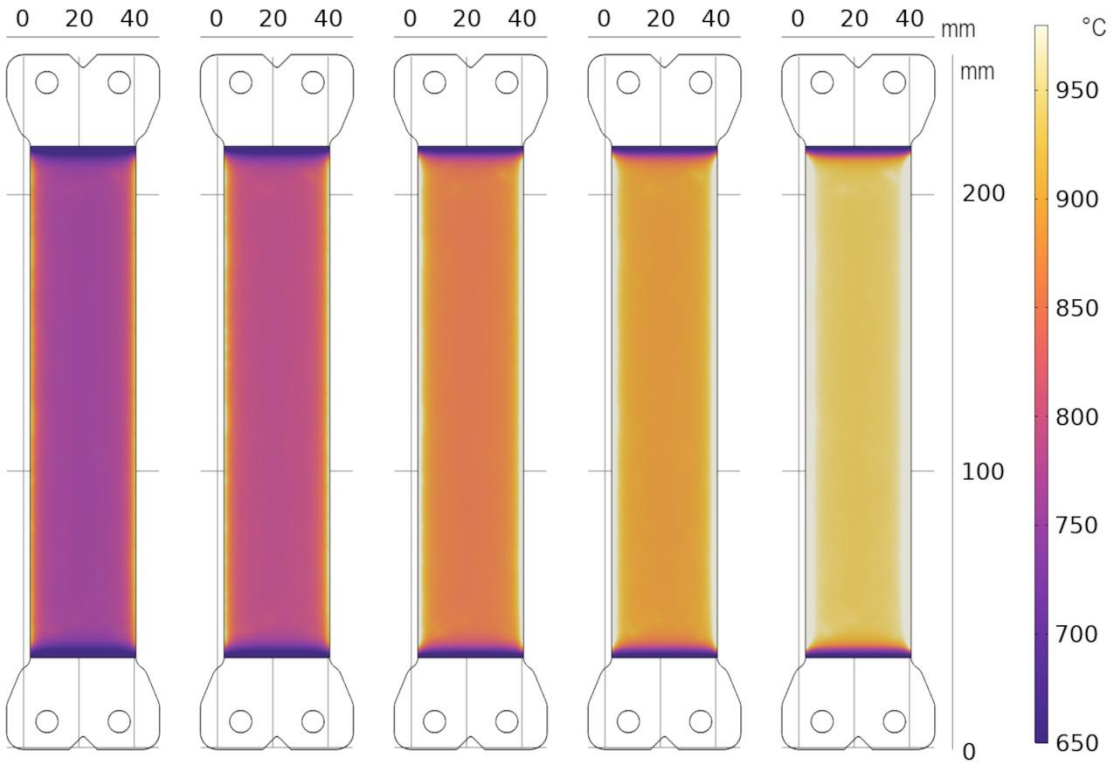


Fig. 6 Simulation results of heated specimens without homogeneity means.

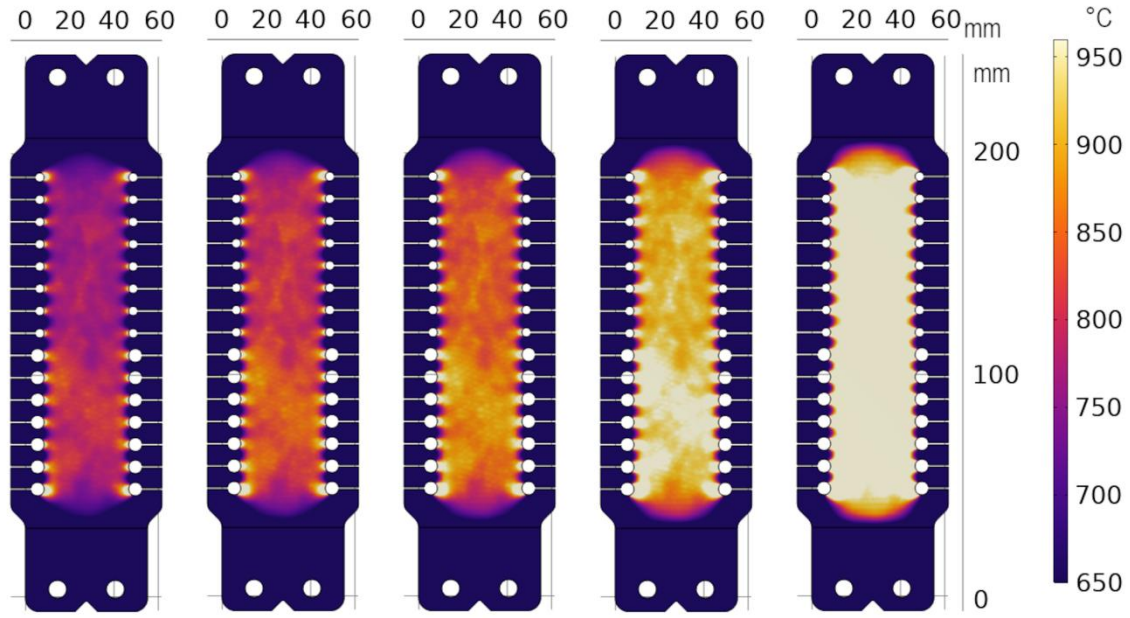


Fig. 7 Simulation results of heated specimens with homogeneity means.

3 Direct Heating

Direct electrical heating (DEH) is a progressive temperature-treatment method for metals. The exact dynamic temperature control is possible. The dynamic parameters of heating, such as speed, power, efficiency, and dimensions, are superior to those of all indirect heating types.

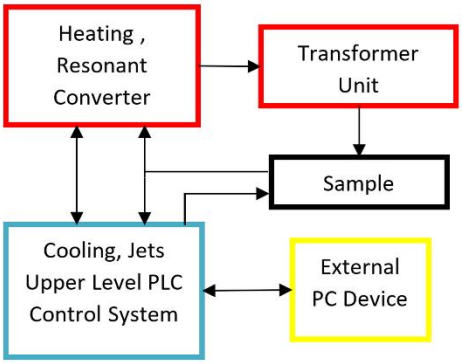
The technical approach to DEH depends on the demands and parameters of the heated material. Two fundamental approaches are possible. The DC or AC used for heating is the main difference. Both approaches have advantages and disadvantages. Both methods require converting a power distribution network into an appropriate form of electrical energy suitable for heating. Low voltages and high currents are required due to the very low ohmic resistance of the heated metal. The power of these converters must be proportional to the dimensions and shape of the heated metal part. Of course, the power net should be able to deliver that amount of power. To save electrical energy, the resonant converter is the best choice. On the other hand, the skin effect is a limiting phenomenon for the heated metal. The dimensions and shape of such metal sheet specimens are also important. The metal sheet used in a car's structural parts requires a homogeneous temperature field during forming. The skin effect depth depends on the frequency, metal type, resistivity, temperature, and permeability.

The DC approach has advantages in no skin effect and simpler control circuitry, unlike the AC approach. The disadvantage of the DC approach is slightly higher energy needed and worse homogeneity. We expect the specimens to be a flat metal sheet of the specified shape (see Chapter Homogeneity of Temperature Field).

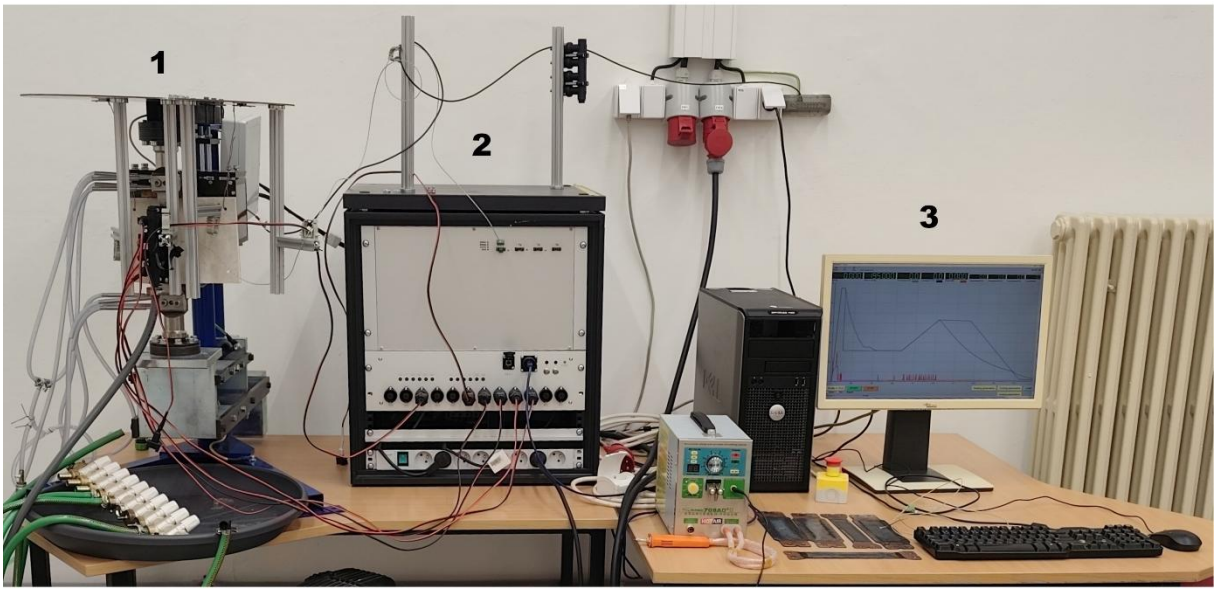
4 Resonant Converter

(Fig. 8a) shows the block diagram of the thermomechanical treatment simulator and the actual appearance of the measuring station (Fig. 8b). The heart of the simulator is the Resonant Converter (RC). The specimen itself is threatened by direct resistive heating from the resonant frequency converter, which operates at a maximum power of 9 kW at 16 kHz. The maximum control capability of the heating process is 100 °C/s. Tensile strain can be realized by the 20 kg payload at the bottom of this simulator. The operator designs a temperature profile (see Fig. 9) using a spreadsheet or a graphical interface. A PLC regulator equipped with a Kalman-filter-based control precisely follows the predesigned temperature profile.

The Kalman filter approach enables the automatic adjustment of control algorithm parameters when the parameters of the heated-cooled specimen change.



(a)



(b)

Fig. 8 Thermomechanical treatment simulator block diagram (a) and thermomechanical treatment simulator (1. Stand for specimen affix, 2. 16 kHz resonant converter and cooling regulator, 3. Control PC) (b).

5 Quenching

The methods of controlled heating and cooling (Xiao et al. 2022; Aziz and Aqida 2013) enable the achievement of the required composition of the crystalline structure through specified temperature treatment. The Thermomechanical Treatment Simulator (TTS), designed to perform the features mentioned above, was manufactured for tests (Fig. 8b). In addition to the Resonant Converter for heating, the TTS is equipped with air and water moisture jets, which enable precise control of the cooling treatment profile using a dedicated PLC. The temperature probe is bonded to the specimen, ensuring accurate temperature control. The cooling also needs homogeneity measures based on a special arrangement of jets.

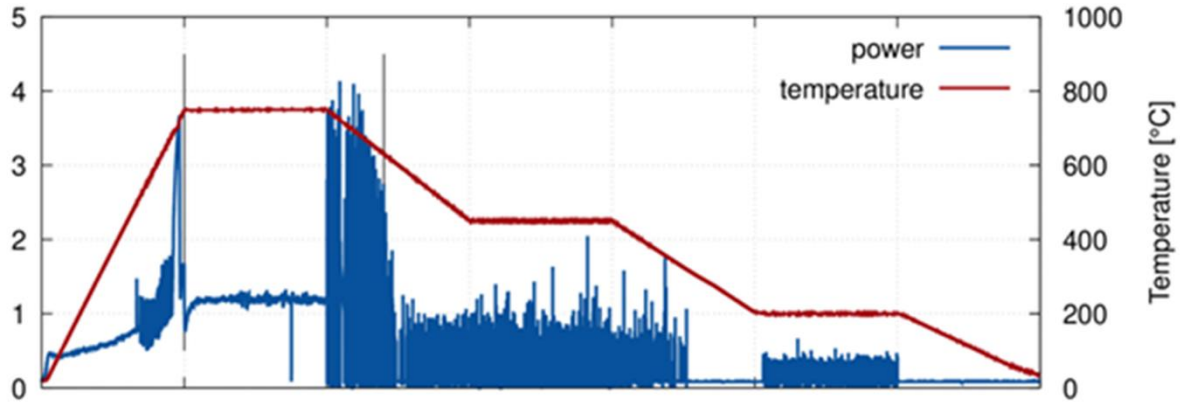


Fig. 9 Example of the used temperature profile.

6 Research related to Homogeneity of Direct Electrical Heating Studies

The heating studies presented in our research are part of a more comprehensive investigation into dynamic changes in the composition of a steel lattice using the Quenching and Partitioning (Q&P) steel treatment method. Especially the Phase Transitions are under our focus. These states of steel are already under research using various imaging methods, including electron microscopy, synchrotron imaging, and X-ray imaging. The last method is still in development and has advantages and disadvantages (Vavrik et al. 2025; Urban et al. 2025). We use the X-ray tube with a pencil-beam collimator and pixel detectors for the diffraction measurements. The Q&P method requires precise temperature control of the specimen, which the TTS regulator ensures. Two cooperating digital regulators perform the heating and cooling regulation. One regulator is dedicated to heating. The heating PID regulator is based on a Digital Signal Processor (DSP) from Texas Instruments. The cooling regulator is based on a microcontroller from STMicroelectronics. The cooling process respects accuracy requirements, and the PID regulator is equipped with a Kalman filter. The cooling process depends on the specimen's shape, material, and TTS features. The Kalman approach to regulation involves dynamic adjustments of PID parameters in response to changes in specimen shape and size. The general specimen model reflects the changes and self-updates to perform optimal regulation. All these special features enable the temperature to be maintained within 1% of the actual value, even when the temperature sensor is not in place, but one or more sensors cannot cover the entire surface of the specimen. That is why the temperature homogeneity across the specimen should be maintained throughout the heating and, of course, the cooling. There are two approaches to maintaining a homogeneous temperature in the area of interest. The first step is to select an appropriate heating method, and the second is to obtain accurate sensor data. (Pan et al. 2022)

7 Homogeneity of Temperature Field

The material quality area treated by Quenching also depends on the homogeneity of the temperature field. The homogeneity of the temperature field created by DEH during heating depends on the current field (Západočeská univerzita v Plzni 2024). The simulation shows the current and temperature distribution.

One of the goals of this work was to design and verify the change in the shape of sheet metal specimens to achieve a more homogeneous temperature distribution during material processing. The actual experiment consisted of heating the sheet metal specimen using the designed resonant converter operating at 16 kHz to temperatures of 750°C, 800°C, 850°C, 900°C, and 950°C at the center of the specimen. The temperature was measured using a

thermocouple, which was also used for camera calibrations. Two thermal cameras were used to measure the temperature distribution and its homogeneity: the Optris PI400 (Optris GmbH 2019) and the Microepsilon TIM M-1 (Micro-epsilon 2022). These two cameras use scanning in different spectral bands. The Optris PI400 camera features a detector based on microbolometers and operates within a spectral band of 7.5-13 μm. This camera was used in a temperature range of 150°C to 900°C. The TIM M-1 camera operates in the spectral range of 0.85-1.1 μm, allowing the capture of temperatures ranging from 450°C to 1800°C. This camera is based on a CMOS sensor, which exhibits lower error rates with varying surface emissivity. The surface emissivity of sheet metal specimens and its dependence on material temperature cause a specific error in absolute measurement values. In our measurement, we minimized the error using a special thermographic paint, LabIRPaint HERP-HT (LabIRPaints, 2025), with high emissivity and resistance up to 1000°C. Furthermore, for our own evaluation of homogeneity, we primarily used data from the TIM M-1 camera, which is less dependent on measurement accuracy due to the material's emissivity (Optris GmbH 2024). The obtained thermoimages are shown in (Fig. 10) and (Fig. 11). In (Fig. 10) are the thermoimages of specimens without trenches at temperatures of 750°C, 800°C, 850°C, 900°C, and 950°C. (Fig. 11) shows the same for specimens with trenches.

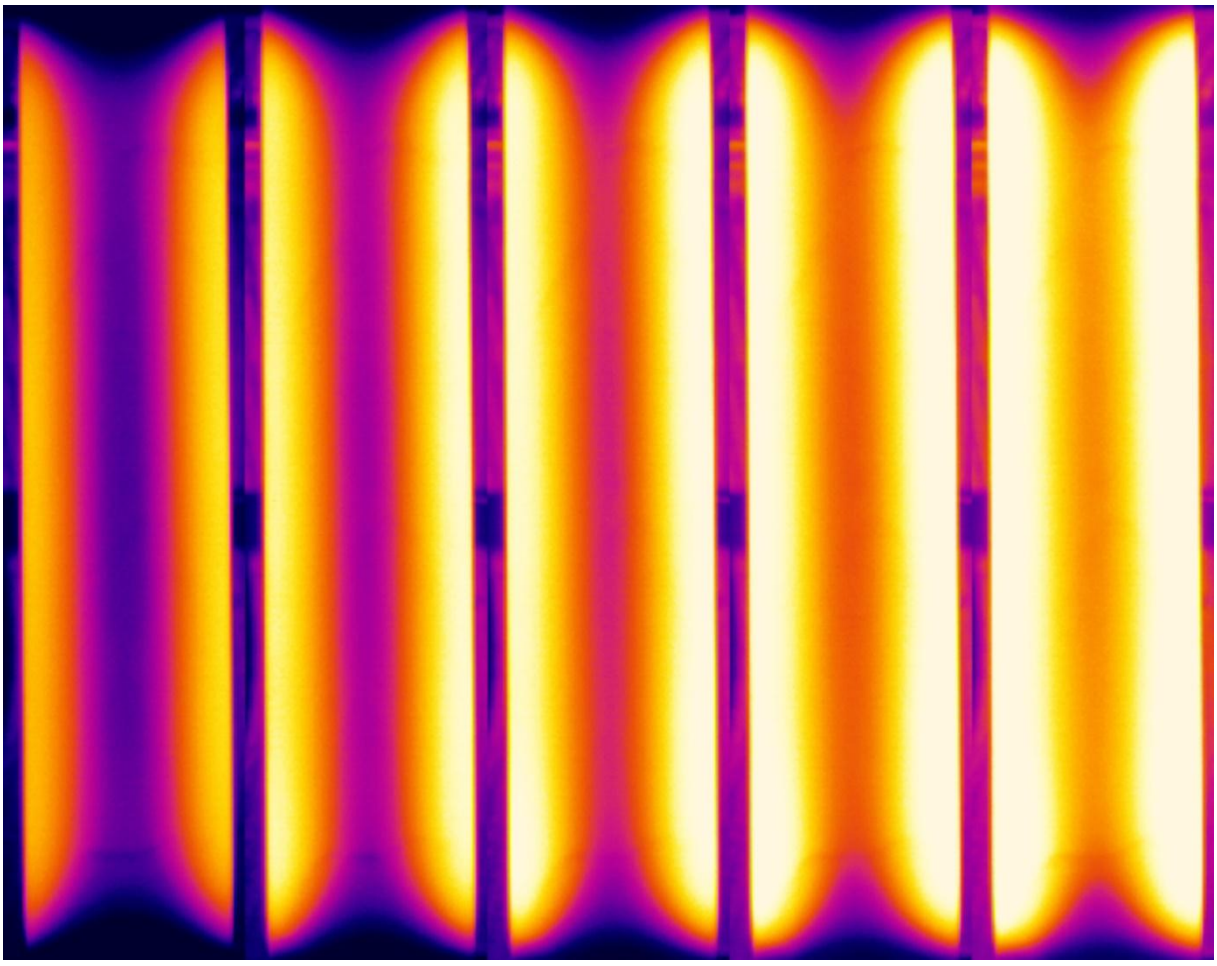


Fig. 10 Thermoimages of metal specimens without trenches.

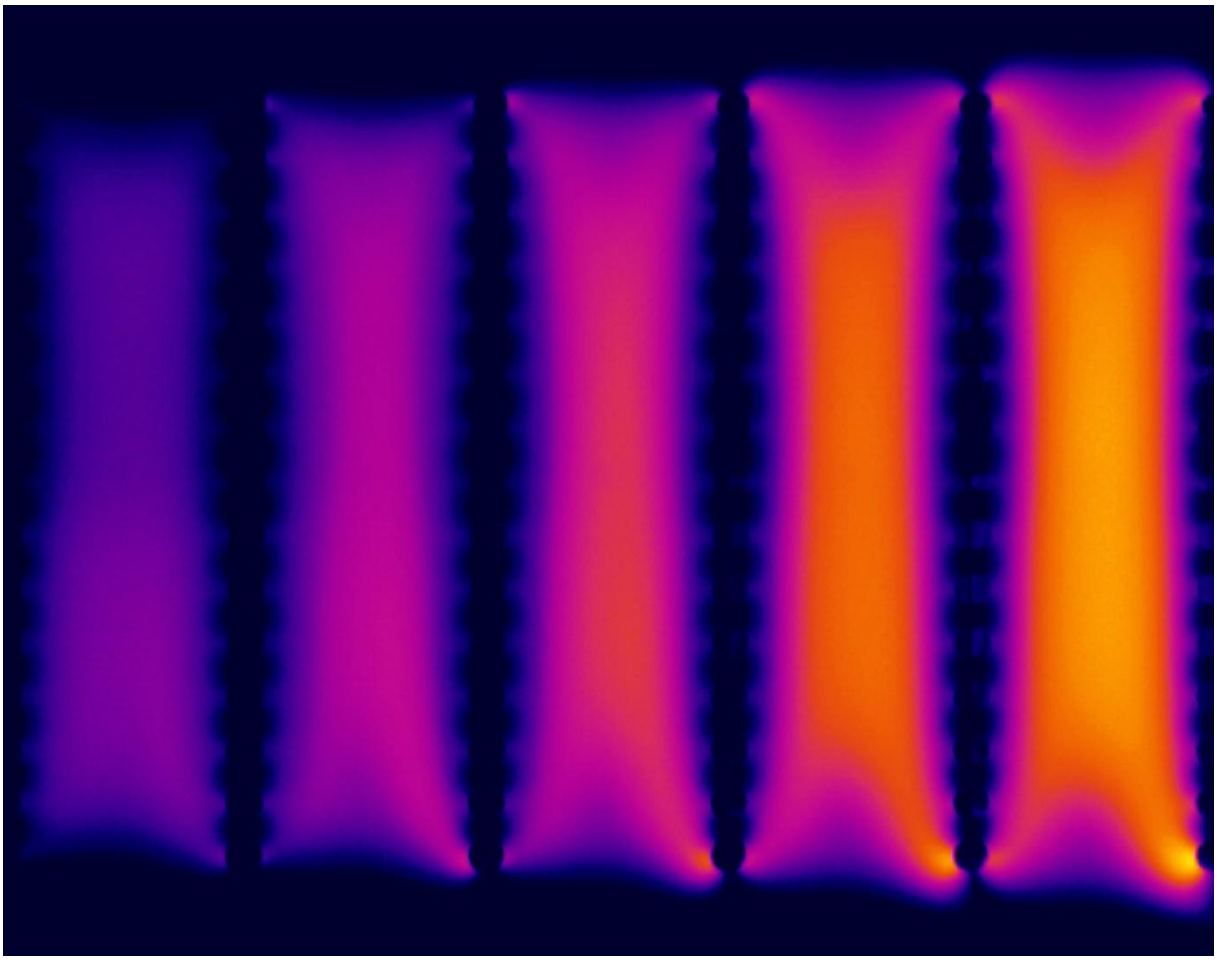


Fig. 11 Thermoimages of metal specimens with trenches.

To evaluate the homogeneity of the temperature distribution, the temperature profile was monitored across the specimen's width in the central region. The measured temperature values for specimens without/with modified edges using trenches and end temperatures in the range of 750°C - 950°C are shown in (Fig. 11). In the case of measuring specimens without trenches, the significant temperature increase from the center to the edges of the specimen is evident, caused by the skin effect. In the modified specimens, by contrast, a decrease in temperature is observed at the edges of the specimen due to the trenches, which effectively create cooling ribs. However, this temperature decrease is only very close to the edges, and higher homogeneity was achieved in the central part of the specimen. The magnitude of the influence of trenches depends on their shape, density, and length. You can see it on graphs, and it will be the subject of further experiments. (Fig. 12) shows the temperature differences compared to the center spot of the specimen, where gradual temperature changes in the central part of the modified specimens are more evident.

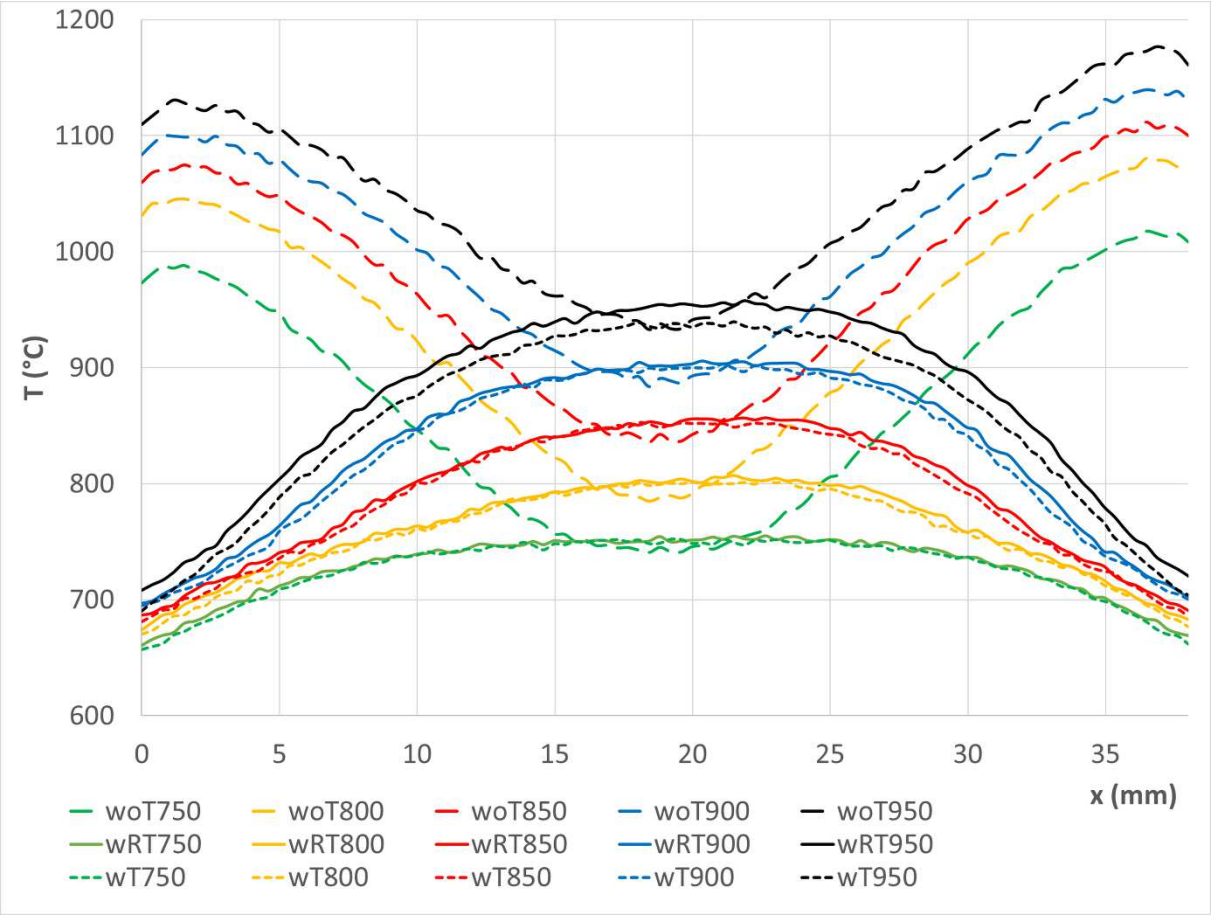


Fig. 12 Surface temperature distribution graph for specific temperature in the center - real measurement results (woT - without trenches, wRT – with rounded ends of trenches, wT – with straight trenches).

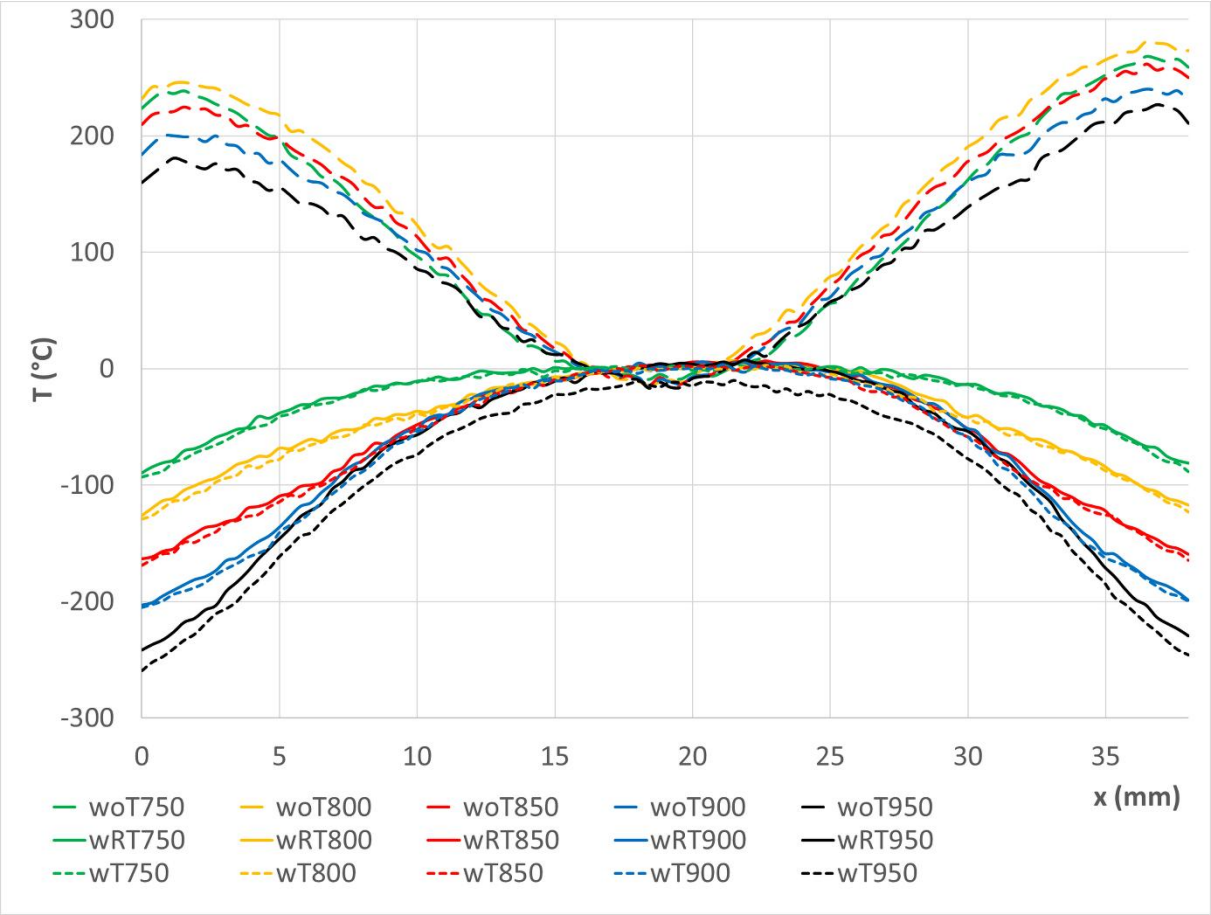


Fig. 13 Temperature differences compared to the center spot - real measurement results (woT - without trenches, wRT – with rounded ends of trenches, wT – with straight trenches).

The trenches used serve as a proof of concept, and we observe the opposite phenomenon of the skin effect. The higher temperature on the long edges of the specimen, caused by the skin effect, was even lower than the average temperature across the specimen surface using the trenches, as shown in (Fig. 11). To reach the same average temperature as the entire surface, the trenches' shape should be optimized.

8 Discussion

The modification of specimen geometry—particularly along its longitudinal edges—was found to have a markedly positive effect on the homogeneity of the temperature field, which is otherwise strongly influenced by the skin effect. Tailored alterations to the specimen shape, incorporating various types of notches, can be used to balance the current density and edge cooling rate, thereby maintaining a uniform temperature field throughout the specimen. The outcomes of this study are of considerable significance not only for the detailed analysis of complex and dynamic thermomechanical processing phenomena but also as a potential pathway toward future industrial applications. Specifically, the presented principle could serve as an alternative to indirect heating for processing smaller semi-finished flat and tubular components, enabling lower processing temperatures, reduced energy consumption, and decreased CO_2 emissions. This innovative approach has been patented (University of West Bohemia in Pilsen,

2024), and a significant increase in the performance of both the conventional 22MnB steel and the experimental 42SiCr steel is expected upon its application.

In addition, alternating current (AC) heating is a promising technique that offers lower power consumption due to the converter circuit's resonant characteristics. The reduced ohmic component of the electrical system under resonant conditions directly improves energy efficiency. The field of simulation-based process design, combined with experimental validation, provides a broad platform for further exploration of which the present study represents only a partial contribution. Future work will therefore focus on investigating various power sources, including direct current (DC) simulations and corresponding experiments, to compare the AC and DC heating approaches. Further studies will also address the influence of electrode positioning and geometry, as well as specimen configuration, on the resulting temperature homogeneity. Moreover, advanced power control strategies will be developed to enhance the uniformity of the temperature field further.

Finally, the implications of these homogeneity simulations and experiments extend directly to related studies of material characterization. By enlarging the surface area that exhibits a stable temperature field over time, it becomes possible to obtain a larger region suitable for preparing specimens used in microstructural or mechanical characterization.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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