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Precise temperature calibration for laser heat treatment

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Abstract. A new induction-heated fixed-point device was developed for calibration of temperature measurement devices typically used in laser heat treatment for the temperature range 1000–1500 °C. To define the requirements for the calibration method, selected measurement setups were compared as well as process data and results of industrial processes were analyzed. Computer simulation with finite element method (FEM) and finite difference method (FDM) was used to optimize the system components and processing parameters of the induction heating of fixed-point cells. The prototype of the fixed-point device was tested successfully, and the first measuring results are presented here. The new calibration method is expected to improve the quality and reproducibility of industrial heat treatment processes with temperature control.

1 Introduction

The technology of laser surface heat treatment for steel or cast iron parts with high-power diode lasers was developed in the late 1990s and has been established in industrial mass production for more than 10 yr (see, e.g., Bonss et al., 2003, 2005, 2009). Because of the high power density of the laser heat sources and the high processing temperatures often desired to be close to the melting temperature of the materials, precise temperature measurement and control is essential for keeping the process stable and ensuring reproducible quality of the parts. For the successful heat treatment of special high-alloyed steel grades or gray cast iron surfaces, the process temperature needs to be controlled within a band of only a few kelvin. Temperatures too high can cause heavy melting on the surface of the parts and temperatures too low result in lower surface hardness and lower heat penetration depths.

For the measurement of temperature, radiation thermometers and thermal imaging systems are used. One key problem is the nonlinear signal damping by the laser optics in the case of the co-axial view of the measurement device. Very critical is the pollution and wear of optical components during their lifetime, i.e., caused by processing fumes, and the connected drift of the measuring signal damping.

Therefore a fast and precise calibration method is required. Conventional blackbody or fixed-point devices for high temperatures of up to 1500 °C are mostly too large and too slow for this task, not flexible enough and difficult to transport. On-site calibration is needed because the temperature measurement devices are mechanically and electrically integrated into very complex and large machine systems.

To close the gap between existing calibration methods (Hollandt et al., 2003; Anhalt, 2008) and the demands from the industry, a mobile induction-heated fixed-point device for fast calibration in the temperature range 1000–1500 °C was developed within the Euramet EMRP project HiTeMS (EMRP, 2011–2014). As a first step, different variants of temperature measurement configurations, typically used in industrial laser heat treatment, were investigated to define the requirements for the device. The geometry and arrangement of system components and the processing parameters of the induction-heated fixed-point device were optimized by a computer simulation with FEM and FDM.

Based on the results, a prototype of an induction-heated fixed-point device was developed and tested.

2 Temperature measurement in laser heat treatment

The temperature measurement device can be used lateral or co-axial to the laser optics (Fig. 1). When the pyrometer is mounted lateral to the laser optics, it is facing in the direction of the laser interaction zone at the part's surface at an angle to

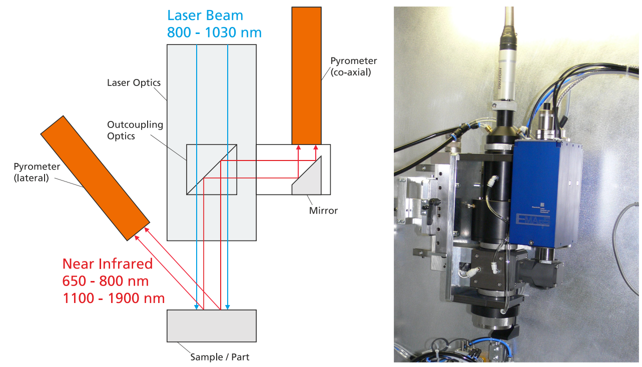

Figure 1. Left: schematic diagram – variants of assembling a temperature measurement device for laser heat treatment. Right: example of the thermal imaging system E-MAqS mounted on special ring optics for co-axial temperature measurement in industrial mass production of valves.

the laser beam axis. The measuring spot of the pyrometer has to be carefully adjusted to the position of maximum temperature. The measuring signal can get lost if edges of the part shadow the pyrometer measuring path, e.g., if heat treating the ground of a groove or a bore hole. In spite of the known disadvantages this variant is used for industrial mass production, the efforts to generate reproducible heat treatment results are high.

One main advantage of direct measurement is the fact that the measurement is not influenced by the laser optics (i.e., by signal damping) and that the calibration values of the manufacturer can be used. Nevertheless, contamination of the pyrometer optics can cause significant measuring errors (cf. Table 1) and calibration and adjustment is needed regularly.

Because of the known problems with a lateral pyrometer setup and measurement, it is preferable today to measure co-axially through the laser optics. For this task special optical components are used that let the laser radiation pass and reflect the near-infrared (NIR) measuring wavelength towards the pyrometer (Fig. 1). If the outcoupling plate is at the position of the collimated laser beam, the pyrometer is focused by the laser lenses and the shape and size of the measuring spot are changed. Using a pyrometer co-axially at the laser optics requires a correction of the characteristic curve of the pyrometer or even a completely new calibration in the mounted state. An example of co-axial temperature measurement in industrial mass production is shown in Fig. 1.

The investigation of typical measurement setups for laser heat treatment has shown that the best wavelength range for temperature measurement between 1000 and 1500 °C is 650 to 2100 nm. The wavelength band of the laser heat sources (800–1070 nm) is not available for a temperature measurement, because the laser radiation overlaps the NIR temperature radiation of the glowing object. To avoid measurement errors, special blocking filters with a high optical density at

Table 1. Influence of contamination of pyrometer optics for temperature measurement with pyrometer MAURER KTR 1075 (manufacturer calibration) at PTB Berlin. The contaminated front lens has been used for several years for laser processing in a laterally assembled pyrometer viewing unprotected at the laser–metal interaction zone.

$T_{\mathrm{blackbody}}$/°C	$T_{\mathrm{clean}} - T_{\mathrm{contaminated}}$/K
1004	18
1113	18
1222	19
1300	26
1409	32

the discrete laser wavelength or wavelength band have to be used.

Towards longer wavelengths the working wavelength of the pyrometer is limited by the optical properties of laser lenses, additional beam-shaping optics, shielding glass and outcoupling optics typically made of fused silica and optimized with special coatings.

Because the interaction time of the laser during a full heat treatment process is within the range of milliseconds to seconds, a short response time of the measuring sensor is required.

If all the preconditions for temperature measurement in laser heat treatment are taken into consideration, thermal radiation detectors based on the widely used silicon or InGaAs photodiodes are suited for laser heat treatment.

3 Requirements for accuracy of the temperature measurement

The requirements for the accuracy of the measurement devices are given by the dependency of the heat treatment result from the temperature. As a result of a typical industrial process, the hardness distribution across the hardening zone was measured; the observed surface hardness and hardening depth are reported below.

As an example, Fig. 2 illustrates the strong dependence of the local hardness on the maximum local temperature during the hardening process. The hardness–temperature curve shows a maximum at a temperature around 1200 °C. The decrease of the hardness towards higher temperatures is caused by stabilization of residual austenite that is not transformed into martensite after cooling down to room temperature. To generate a high hardness level of > 700 HV the absolute surface temperature has to be within a band of several tens of kelvin.

The dependency of the process temperature on the hardening result was analyzed for samples of carbon and tool steel and was investigated for selected industrial applications. Figure 2 shows one example. If the surface temperature exceeds the material-specific austenite start temperature

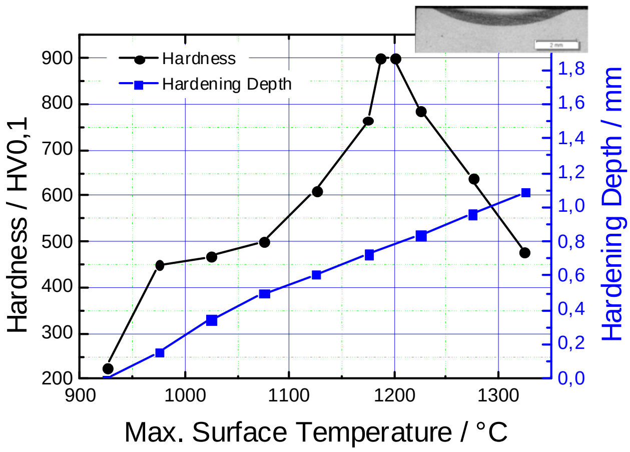

Figure 2. Surface hardness and depth of the hardening zone according to the surface temperature. Flat samples are made of tool steel X155CrMoV12.1, with the depth measured in the etched cross section (example at top of diagram).

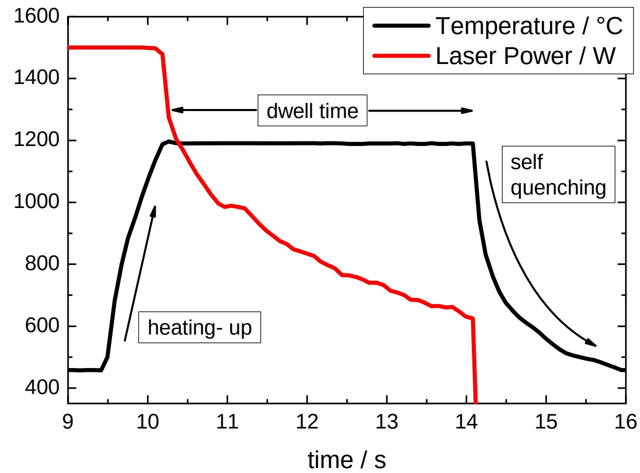

Figure 3. Process data of a temperature-controlled laser heat treatment process for the end face of a screw; temperature measured with pyrometer MAURER KTR 1075.

during the heat treatment process (~ 900 °C in Fig. 2), then the hardening process begins, and once cooled down, a hardening depth is generated. At surface temperatures above this threshold the resulting hardening depth shows a strong dependence on the maximum surface temperature. For typical laser heat treatment parameter sets with a processing speed of 100–500 mm min^{-1}, the hardening depth changes by several thousandths of a millimeter per kelvin.

The generation of a reproducible hardening result is not the only important criterion for reliable industrial production; good process stability is also important.

To ensure the optimum surface temperature during the process, precise temperature controllers are used. Depending on a part's material, geometry and surface quality, temperature fluctuations of ±1 to ±10 K are typical for industrial processes today (Fig. 3).

In particular cases a temperature deviation of +5 to +10 K can cause instable laser processes with oscillating temperature because of localized accelerated growth, delamination and the resulting overheating of oxide layers in combination with overreaction of the temperature controller.

In conclusion, accuracy and reproducibility of temperature measurement in laser heat treatment down to 5 K as well as a calibration method with an uncertainty significantly lower are required.

4 Calibration and inspection of temperature measurement devices

The calibration of radiation thermometers with blackbody or fixed-point radiators is an established method at national metrology institutes for the primary realization of the currently valid international temperature scale ITS-90 (Hollandt et al., 2003). Selected temperature measurement devices that are typically used in laser heat treatment were tested and analyzed at the PTB Berlin using the variable high-temperature blackbody HTBB3200pg (Friedrich and Fischer, 2000). The uncertainty ($k = 2$) of the blackbody device is 2 K. Long-term stability of the temperature by about ±0.3 K can be ensured by temperature control of the graphite heating element.

Different influencing factors on the indicated temperature value were investigated, e.g., contamination of the optical components, variation of the working distance, defocusing of the optics and the influence of different aperture size on the blackbody emitter. From this investigation it follows that the temperature measurement devices typically used in laser heat treatment have the potential to measure temperatures with accuracy down to a few kelvin. However a variety of influencing factors can cause total measurement errors on the order of several tens of kelvin.

Table 1 illustrates the effect of contaminated pyrometer optics, and Fig. 4 depicts the effect of varying the furnace aperture between 6 and 30 mm, the so-called size-of-source effect.

To achieve the aimed accuracy level with temperature measurement devices that are electrically, optically and mechanically fully integrated into complex machines at industrial sites, on-site calibration and inspection with a mobile calibration device is needed. Only the in situ calibration in the final machine setup guarantees a high precision of the temperature measurement. For this reason a portable fixed-point calibration device, based on copper and metal-carbon eutectic high-temperature fixed points, was developed for the use in the temperature range between 1084 and 1492 °C. In order to achieve a compact design and fast operability, the fixed point is inductively heated. The design and operational characteristics of this calibration device were investigated using FEM and FDM simulation.

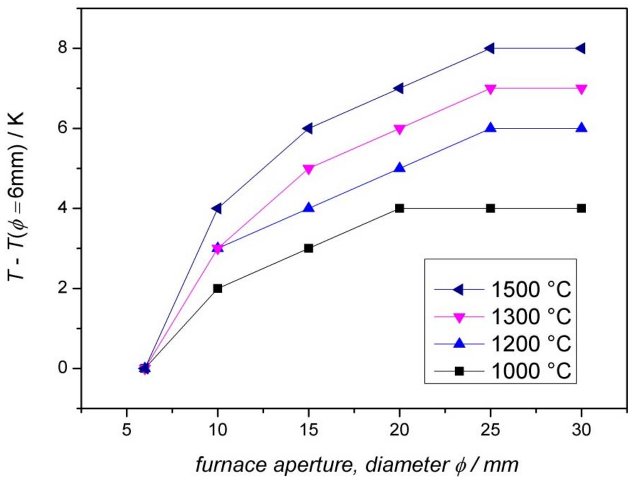

Figure 4. Influence of the size-of-source effect (SSE) on the temperature characteristics of a thermal imaging system based on a CCD camera.

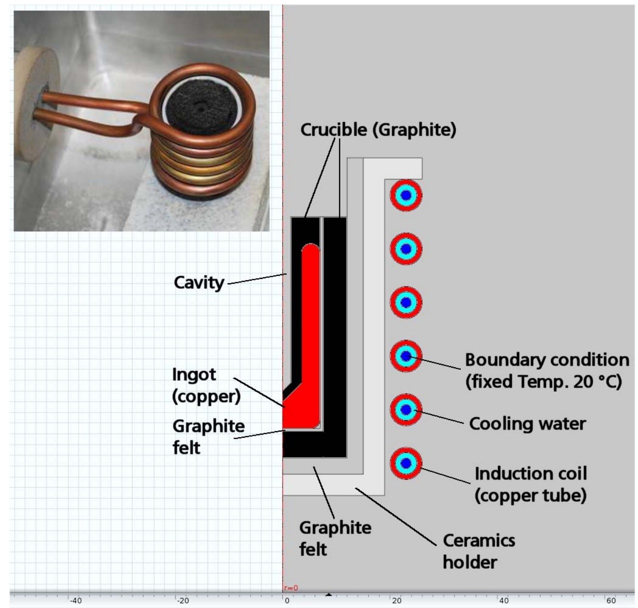

Figure 5. Components of radial symmetrical computer model for induction heating of fixed-point cells. Dimension of the cell: diameter 25 mm × length 45 mm. Photograph shows the technical implementation.

5 Results of FEM and FDM simulation

Induction heating is an established technology for heating up electrically conductive materials to high temperatures, and it is expected to be suited for fixed points.

The fixed-point cells for the high temperature range above 1000 °C are typically heated by a Joule-heated graphite furnace (Friedrich and Fischer, 2000). Following this design, in principle, a theoretical optimization of the induction coil design and the composition and dimension of components are aimed at achieving a good homogeneity of the temperature field across the fixed-point cell. This is essential to achieve a homogeneous melting of the metal alloy and a sharp and precise inflection point in the melt or freeze temperature curves (Figs. 11, 12).

Figure 5 shows the main components of the COMSOL FEM computer model and a photograph of the technical implementation. Graphite felt is used for thermal insulation of the inner components that are heated up to 1500 °C. A fixed-point cell and graphite felt are installed in a special ceramic holder which electrically insulates the graphite components from the induction coil. This setup is expected to provide optimum efficiency and good thermal long-term stability. In the radial, symmetrical FEM model, the physical effects of electromagnetic heating and heat transfer by heat conduction and radiation were taken into consideration. The induction heating was simulated with a constant current flowing through the copper coil. To achieve a steady state, the typical heating time was about 1000 s.

In the FEM simulation a strong influence of the induction frequency on the temperature field was found. The high penetration depth of the electromagnetic fields at low frequencies causes significant direct heating of the metal alloy and high temperature gradients across the fixed-point cell.

A radial symmetrical FDM model was developed to investigate the influence of the distribution of the induction heat sources and the resulting temperature fields on the melting process of the metal alloy. Up to about 8000 single finite elements were used to achieve a good spatial resolution and to minimize errors caused by the size of the finite elements itself. The induction heating was not simulated directly. The absorbed heat portion of each element was defined manually taking the FEM results into account. The physical effects of heat transfer by conduction, heat losses by radiation at the free crucible surfaces and melting of the metal alloy were implemented; all other physical effects neglected. To simulate the effect of melting, the following special variant was chosen: if the temperature of the finite element exceeds the melting temperature, the incoming heat portions during each time step are summed up without increasing the temperature of the element until the melting enthalpy of the material is reached. Then the element is marked as fully molten, the material parameters are changed and the further increase of the temperature is unblocked.

The simulation results show that the cavity temperature is stabilized by the melting metal alloy even in the case of inhomogeneous induction heating. However, the temperature gradient across the cavity wall is strongly influenced by the distribution of the inner heat sources. The inhomogeneous melting of the alloy causes a distortion of the temperature curve around the melting temperature and a shift of the inflection point, depending on the field of view of the pyrometer or thermal imaging system.

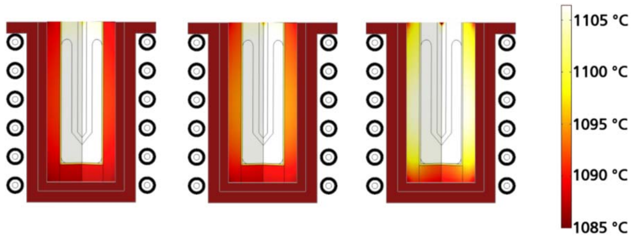

Figure 6. FEM simulation of temperature field across a fixed-point cell after induction heating (variation of induction frequency: left, 125 kHz; middle, 250 kHz; and right, 1000 kHz).

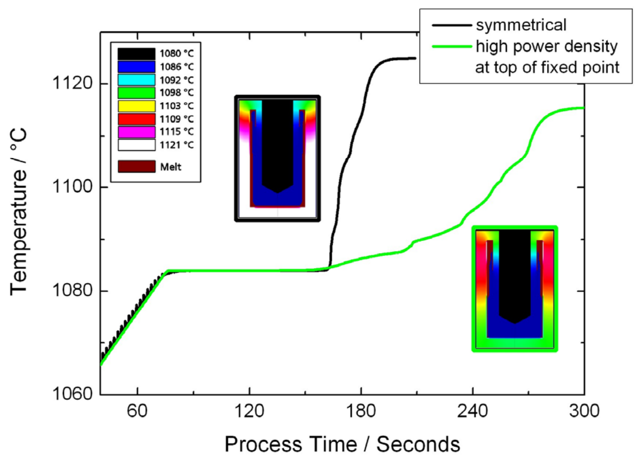

Figure 7. Dependence of cavity temperature of copper fixed-point cell on distribution of the induction heat sources, and the result of FDM simulation. Thermal images show the temperature field during the melting plateau.

If the location of the inner induction heat sources is varied, the run-out of the temperature curve changes drastically after the melting plateau (Fig. 7). The following general relationship was found: if the density of the induction heat sources is higher at the bottom of the cell, then the melting plateau is short and the temperature curve has a steep run-out. In contrast, a high induction power density at the top of the cell causes a long plateau and long and soft run-out of the temperature curve. The knowledge of this behavior can be used for adjustment of the position of the fixed-point cell relative to the induction coil.

6 Design and realization of the fixed-point device

The heat source for fixed-point heating is an induction coil with six loops that works at a frequency up to 420 kHz. The fixed-point cell itself is insulated with graphite felt and placed in a ceramic crucible in order to avoid direct electrical contact with the induction coil (Fig. 5).

The device has a water-cooled and vacuum-sealed housing with ports for connection to a vacuum pump, shielding gas

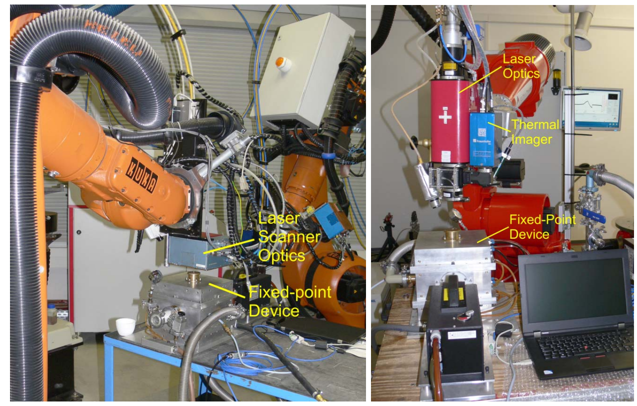

Figure 8. Prototype of the induction-heated fixed-point device, and setups for on-site calibration of laser processing heads mounted on industrial robot systems. Left: calibration of scanner optics with an integrated thermal imaging system at a machine for industrial laser hardening of steam turbine blades (Fraunhofer IWS Dresden, Germany). Right: calibration of zoom optics with variable laser beam width at a machine for job-shop laser hardening (ALOtec Dresden GmbH, Germany).

supply and a special lead-through of the copper tubes of the induction coil. All equipment can be installed in a 19 in. rack for good system mobility. For safety reasons, all important system parameters such as shielding gas flow, water flow and temperature, and residual oxygen content are measured and observed. Figure 8 shows typical test setups used for on-site measurements at industrial laser-hardening machines.

One important result of the computer simulation with FEM and FDM was the high sensitivity of the local temperature field across the fixed-point cell on the induction frequency and the position of the cell relative to the induction coil. It is possible to further improve the homogeneity of the temperature field by installation of an additional metallic or graphite tube between the fixed-point cell and induction coil. Figure 9 schematically shows the cross section of this configuration. To integrate the additional tube, which is used as heating element, the diameter of the induction coil was increased to 54 mm. The lab setup was tested successfully by using Cu fixed-point cells. Because a large percentage of the electromagnetic fields are blocked by the tube element, the fixed-point cell is heated indirectly by the glowing tube and thus the influence of inductor geometry and induction frequency on the temperature gradient across the fixed-point cell is reduced. If a metallic tube is used as the heating element, the lifetime is limited because the chemical reaction with carbon at high temperatures influences the mechanical and thermal properties. An additional aperture is recommended for calibration of temperature measurement devices which are sensitive to the size-of-source effect. In this case it is important to block temperature radiation from the top face of the cell and let only radiation from the cavity pass through. Otherwise, changes in the surrounding furnace temperature,

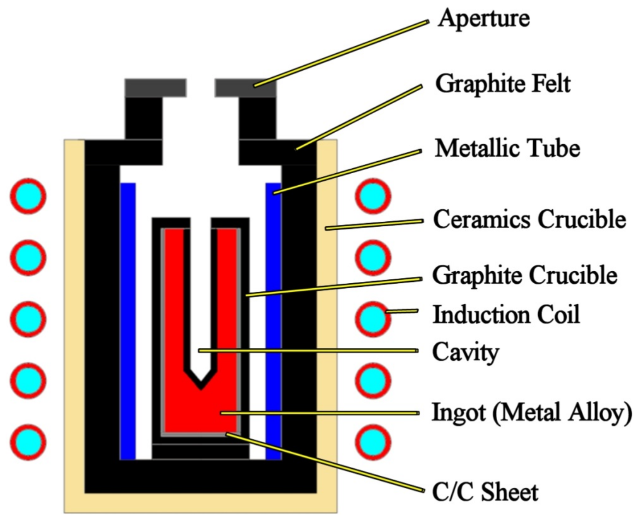

Figure 9. Schematic drawing of the setup for indirect induction heating of a fixed-point cell with a metallic tube as the heating element (outer diameter of ceramic crucible: 50 mm).

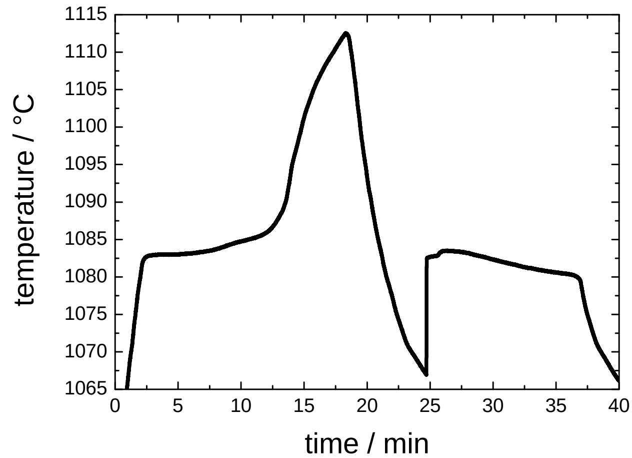

Figure 10. Melt and freeze cycle of a Cu fixed-point cell heated with an induction furnace, wrong inductor position and insufficient thermal insulation at bottom of crucible. Melting temperature: 1084.62 °C. Measured with the thermal imaging system E-MAqS (Fraunhofer IWS Dresden) with a measuring wavelength of 740 nm (compare with typical diagram in Fig. 11).

which occur especially when overheating or undercooling the fixed-point cell, will be sensed by the radiation thermometer during the melt or freeze plateau and a temperature measurement error cannot be excluded; consequently the uncertainty of the temperature measurement after calibration is increased.

7 Experimental results

The induction-heated fixed-point device was tested with Cu, Fe–C and Co–C fixed-point cells. The fixed-point cells cover the temperature range from 1084 to 1323 °C. Different factors influencing the accuracy and reproducibility of the fixed-point plateau temperatures were investigated, i.e., the position of the fixed-point cell relative to the induction coil, the arrangement of the thermal insulation (Fig. 10) and the parameters for overheating and undercooling of the cell in order initiate the melt and freeze of the metal alloy. One melt and freeze cycle in the case of direct induction heating takes about 30 min (±10 min) depending on the thermal properties of the metal alloy and the volume of the filling of the cell.

Figure 10 shows the influence of high temperature gradients across a Cu fixed-point cell on the characteristics of the melt and freeze plateau. The fixed-point cell was positioned in the lower half of the induction coil and the thermal insulation at the bottom of the ceramic crucible was insufficient. The resulting temperature gradient along the axis of the fixed-point cell caused strong distortion of the melt and freeze temperature curves (compare to theoretical curve in Fig. 7).

An inductively heated tube as an additional heating element to improve the homogeneity of the heating was tested with a Cu fixed-point cell in a lab setup within a special

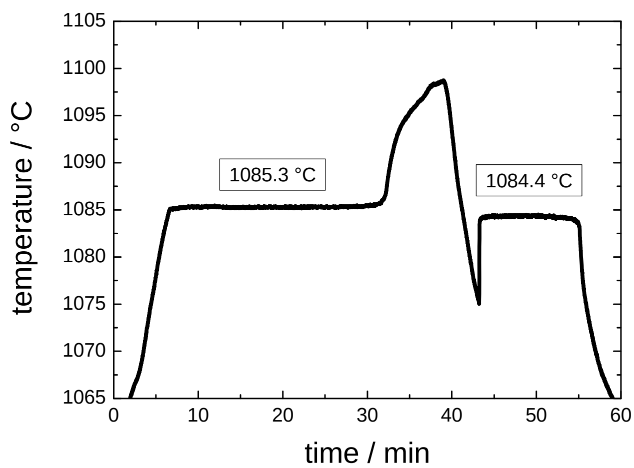

Figure 11. Melt and freeze cycle of a Cu fixed-point cell heated with an induction furnace containing a stainless steel tube as the heating element. Melting temperature: 1084.62 °C. Measured with the thermal imaging system E-MAqS (Fraunhofer IWS Dresden) with a measuring wavelength of 740 nm.

vacuum chamber. The heating element chosen was a tube made of stainless steel. Even if the tube reacts with carbon atoms of the surrounding graphite felt, the heat resistance up to the melting temperature of the material (eutectic temperature of the Fe–C alloy after saturation with carbon atoms) was expected theoretically and was proved in long-term tests. The induction frequency used, about 100 kHz, is normally too low for direct fixed-point heating. Nevertheless, very flat melt and freeze plateaus were measured with a thermal imaging system typically used in industrial laser heat treatment (Fig. 11).

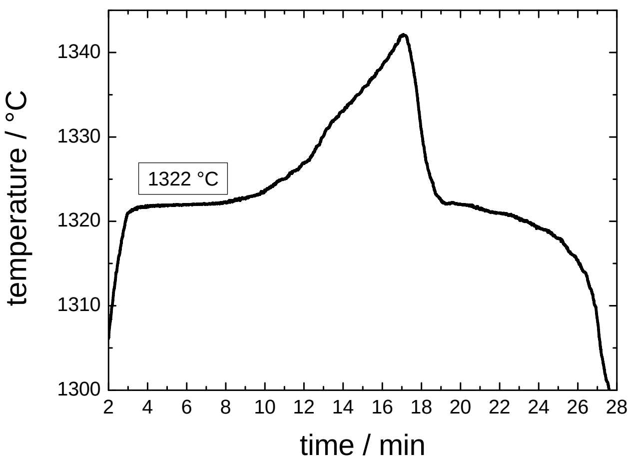

Figure 12. Melt and freeze cycle of an inductively heated Co–C fixed-point cell (cavity diameter 5 mm) after on-site calibration of the laser processing head at an industrial machine for laser hardening of steam turbine blades (Fraunhofer IWS Dresden, Germany). The inflection point of the melt plateau agrees with reference temperature (linear pyrometer LP3 at PTB Berlin) within ±0.5 K.

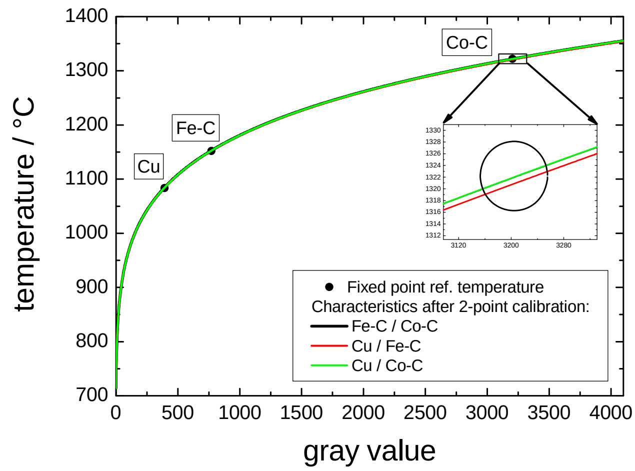

Figure 13. Temperature characteristics of the thermal imaging system after calibration with three inductively heated fixed-point cells. Co-axial temperature measurement was performed through zoom laser optics at an industrial machine for job-shop laser hardening (ALOtec Dresden GmbH, Germany). Maximum temperature deviation over full temperature range: 1.3 K.

The prototype of the mobile fixed-point device was tested on-site for the calibration of industrial laser processing heads currently working in production (compare Fig. 8). The temperature characteristics of three different laser optical systems (scanner optics, zoom optics and 90° mirror optics) with integrated co-axial temperature measurement were inspected and corrected. As a result, temperature deviations up to several tens of kelvin were detected; these were mainly caused by calibration errors, the measurement uncertainty of the radiation thermometer itself, the exchange of optical components after their lifetime and the contamination of optical components by process fumes. As an example, the exchange of the shielding glass of a laser scanning head caused a jump in the temperature measuring value by 10 K. To ensure the best possible accuracy, the glass was exchanged between two melt and freeze cycles of a Co–C fixed point cell (1322 °C) without changing the adjustment and processing parameters. For this case, the reproducibility of the cell temperatures is typically better than 1 K, and the influence of the shielding glass on the temperature signal was measured directly.

After calibration of the industrial laser processing heads, the temperature characteristics, which were generated with inductively heated fixed points, were tested again. All fixed-point temperatures could be reproduced with an accuracy of 1 to 2 K (compare Fig. 12), representing the typical measuring error of the devices under ideal conditions.

Figure 13 shows the typical temperature characteristics of a thermal imaging system that is used industrially for job-shop laser hardening. It was proved that a two-point calibration with two different fixed-point cells is sufficient to achieve an agreement of the temperature characteristics with a third fixed-point temperature within ±1 K.

8 Conclusions

As a first step, the requirements for temperature measurement in laser heat treatment were investigated. Based on the results, a new induction-heated fixed-point device for calibration was developed. The prototype was constructed and manufactured by the PTB Berlin and tested with Cu, Fe–C and Co–C fixed-point cells for the calibration of temperature measurement devices typically used in laser heat treatment. The mobility of the calibration equipment was tested at two industrial sites. Typical temperature deviations in real production and the uncertainty of the calibration procedure were investigated. The pollution and exchange of optical components of laser processing heads and temperature measuring devices were found to be the most critical sources for temperature measuring errors.

By using inductively heated fixed-point cells, industrial laser processing heads were calibrated on-site with a precision that was previously unachievable. The inflection points of the melt and freeze temperature curves agree with the theoretical values within a band of ±1–2 K and are within the measurement uncertainty of the radiation thermometers used.

Further experimental investigations are planned to minimize the uncertainty of the new calibration method. For this task the potential of metallic tubes for indirect induction heating of fixed-point cells could be demonstrated. It is expected that the temperature-controlled processing of this kind of induction furnace will improve the homogeneity of the temperature field during the heating of difficult cell geometries and fillings as well as the reproducibility of the inflection points of the melt and freeze plateaus.

The new possibilities for precise and reproducible temperature measurement in laser heat treatment processes are expected to improve the quality of industrial processes and open the door to new applications for difficult materials whose properties strongly depend on the surface temperature in laser processing.

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