TEMPERATURE MONITORING OF INDUCTION HARDENING USING SPECTRAL PYROMETRY

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Abstract: In this study, a recently developed multispectral temperature measurement method is applied for temperature monitoring of induction hardening of steel. An industry-like induction heating process is used for evaluating the method and an automatic calibration procedure is presented. Thermocouples and a conventional pyrometer are used for comparison, showing that the multispectral method gives more accurate results than the conventional pyrometer. These results confirm that the multispectral method is well suited for accurate, non-contacting temperature measurements for induction hardening processes. Enabling measurements which have previously not been possible. This enables fast selection of process parameters which can improve productivity.

Keywords: induction hardening, pyrometry, spectral pyrometry, ECSP

1. INTRODUCTION

Induction hardening is a common production process for surface hardening of metal components in a fast and energy efficient way (Haimbaugh, 2001). An induction coil through which high currents are passed induces currents in the sample which causes heating in the sample. The coil can either be stationary relative to the sample or moved at a certain progression speed. The rapid heating created by induced currents is usually followed by quenching with quenchant. Material properties are dependent on temporal and spatial temperature distribution. This can be controlled by analyzing the hardened material using destructive testing and adjusting process parameters, such as current or heating time, in an iterative process. Another alternative, which could reduce the number of iterations required, is to measure the temperature of the workpiece during processing. Temperature monitoring is especially useful for progressive hardening of workpieces which are non-uniform with regards to geometry, i.e. if the workpiece cross-section, as seen from the induction coil, changes as the coil or the workpiece is moved. Accurate temperature readings allow the operator to identify when adjustments to process parameters have to be made and serves as an indication to how well the parameters used are working (Haimbaugh, 2001). Precise measurements are a means towards shorter lead-times, in terms of fewer parameter iteration cycles required and more optimal parameters, which could reduce the processing time for each part and lead to improved material properties. Temperature history charts can accompany each produced part, serving as a quality assurance tool.

2. THEORY

In this section, brief introductions to induction hardening and radiative temperature measurements are presented.

2.1. Induction hardening

Thanks to the rapid heating and quenching which can be achieved during induction hardening, and thanks to the skin effect of high frequency induced currents, induction hardening is ideally suited for surface hardening of metallic components. Low-alloyed medium carbon steels which are suitable for induction hardening are most often used in the process. Such induction hardened material can be found in e.g. axles and gears where high surface hardness is a desired property.

Parameters such as current, frequency, coil geometry and progression speed can be varied in order to achieve the desired material properties. Often, the material is analysed after processing to assess the properties and to evaluate the process parameters (Haimbaugh, 2001). This leads to a trial and error procedure employing either destructive or non destructive testing methods, an approach which is time consuming and costly. The determining factor for the hardening process outcome is the temperature history of each volume element. Thus, accurate temperature measurements at relevant points are essential if one wishes to minimize the required amount of destructive testing. For measuring temperature of the component during induction hardening, the use of thermocouples is well established for research applications with stationary samples (Grum, 2002; Haimbaugh, 2001). Also, pyrometers have been used to a limited extent for induction hardening monitoring, for example, Kristoffersen and Vomacka (2001), used a pyrometer for recording the maximum temperature during hardening of AISI 4140 steel. However, the use of pyrometers for this purpose is associated with a number of problems as discussed in the following section.

2.2. Pyrometry

Induction heating is a setting usually not well suited for temperature measurements. If the workpiece is non-stationary, e.g. rotating or progressed through the coil, contact temperature measurement methods such as thermocouples are most difficult to use. The presence of fumes, caused by evaporating quenchant, quenchant droplets and material surface oxidation also complicate the use of non-contact instruments such as pyrometers since they obstruct the field of view or cause the surface properties to change (Hagqvist et al., 2013; Haimbaugh, 2001).

Oxidation is usually a problem for radiometric temperature measurements since it changes the emissivity of the material (Bauer et al., 2009; Zhang et al., 2009). Emissivity is the surface property which decides how well the material radiates. Emissivity is the complement to reflectivity meaning that if emissivity increases, reflectivity decreases. Similarly a shiny, highly reflective material will be a poor emitter and thus have low emissivity. The effects of emissivity increasing with oxidation will make a metal object emit more radiation and thus appear hotter as it oxidises. A common way of performing emissivity compensated temperature measurements is by employing a two-waveband pyrometer which ideally eliminates the emissivity term if the quotient of emissivities at the two wavelengths is constant. Such instruments are also useful when the optical path becomes partially obstructed. However, during oxidation, the assumption of constant emissivity ratios is rarely true and the use of a two-waveband pyrometer might give larger errors than if a single-waveband, non-compensating, pyrometer is used (Zhang et al., 2009).

2.3. Emissivity Compensated Spectral Pyrometry

A method called Emissivity Compensated Spectral Pyrometry (ECSP) developed at University West in Sweden has previously proved to be applicable for situations where material surface composition changes due to e.g. oxidation (Hagqvist et al., 2014a). The ECSP method overcomes the problem of varying emissivity by employing an off-the-shelf USB spectrometer along with intelligent algorithms to act as a pyrometer, which adapts to the varying emissivity of the material (Hagqvist et al., 2014a, 2014b, 2014c). Instead of using one or a few wavelengths for estimating temperature, spectra with over 2000 channels are recorded at each time instance. By exploiting the temporal and spectral characteristics of the recorded signal, noise can be rejected and changes in emissivity can be adjusted for.

The method has been proven to be accurate both in experimental situations (Hagqvist and Christiansson, 2013; Hagqvist et al., 2014a) as well as in simulations (Hagqvist et al., 2014b). Also, an analytical quantification of accuracy has been performed, proving mathematically that the method gives good accuracy and allows for varying emissivity during measurements (Hagqvist et al., 2014c). Because of the recent development of the ECSP method, there are to our knowledge no more references to give.

2.4. Identification of Curie transition

The main drawback of the ECSP method is that it at some point requires a calibration point (Hagqvist et al., 2014a, 2014b). In order to alleviate this drawback, the possibility of using a Curie transition for automatic calibration is investigated in this study. A similar approach has previously been successfully applied to solidifying copper (Hagqvist and Christiansson, 2013). A big difference, when comparing the Curie transition of steel to the solidification of copper is the magnitude of the change in enthalpy. The enthalpy change of the Curie transition in steel is much lower and not as easily detected.

When examining a spectral mean of radiance measurements collected by the spectrometer over time, a slight decrease in heating rate, which corresponds to the Curie transition, can be seen during the heating up of the steel sample in Fig. 1. Note that radiance in Fig. 1 has been converted into pseudo temperature through inversion of Planck's law (Planck, 1906). From the pseudo temperature curve and the described decrease in heating rate, seen on the left flank in Fig. 1, the Curie transition can be identified with respect to time. At this time instant, the temperature is known - the Curie temperature, which is a material dependent constant. The intersection point is automatically found by fitting two third degree polynomials to the left flank of the pseudo temperature curve. The extension in time for the first polynomial is from 0 up to some intersection time, t_{is}. The second polynomial extends from t_{is} to t_{max}, where t_{max} is the time where the pseudo temperature is at its maximum. This intersection point t_{is}, which is found using numerical minimization of the sum of the RMS residuals of the polynomials, corresponds to the Curie transition point. Examples of identified Curie points are shown in Fig. 2a and 2b. This procedure is not possible to use for on-line calibration since it requires post-processing of the entire data set in order to find t_{is}.

The Curie temperature can easily be determined for a certain material/process combination by attaching thermocouples to a single specimen and determining the Curie transition temperature from the thermocouple temperature curve. Note that this only has to be done once for a new material/process combination.

Provided that the Curie temperature for the material is known and that the Curie transition has been identified from the pseudo temperature curve, the temperature is known for the time instance at which the Curie transition has been found to occur. These instances are indicated by dashed vertical lines in Fig. 2a where no quenching is carried out, and in Fig. 2b where quenchant is used. Knowing the temperature at one time instance enables the use of the ECSP algorithm since the calibration point mentioned in the beginning of this section is provided.

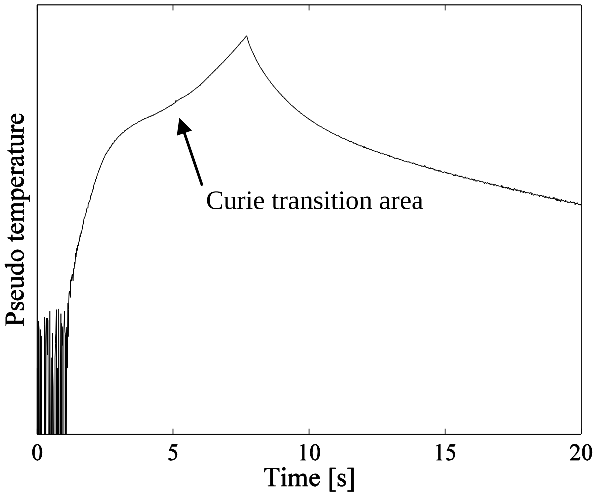
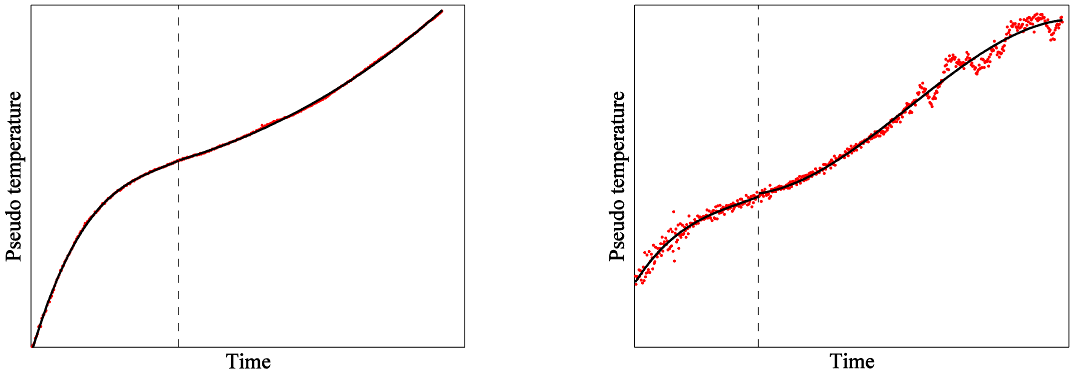


Fig. 1. Pseudo temperature curve created directly from radiance measurements. A slight decrease in heating rate, corresponding to the Curie transition indicated by the arrow, can be seen during heating phase.



a. Without quenchant b. With quenchant

Fig. 2. Red data points fitted with two third-order polynomials shown in solid black. Identified Curie transition indicated with dashed vertical line.

3. EXPERIMENTAL SETUP

Tests have been performed in cooperation between University West and Swerea IVF, simulating an industry like process. Induction hardening of 42CrMo4 steel, which is suitable for induction hardening, was carried out both with and without spraying quenchant. Type K thermocouples were spot welded onto the workpiece to work as references for comparison with the readings from a conventional single-waveband pyrometer (IS9-LO, Impac Electronic GmbH) and the ESCP measurements.

The experimental setup, for the trials with quenchant, is shown in Fig. 3. The sample is moved through the induction coil while current is fed through the coil. This heats the sample progressively, and by controlling progression speed and coil current, the hardening of the sample can be controlled. Quenching is applied through quenchant which is sprayed onto the sample through a nozzle after being heated by the coil, also shown in Fig. 3.

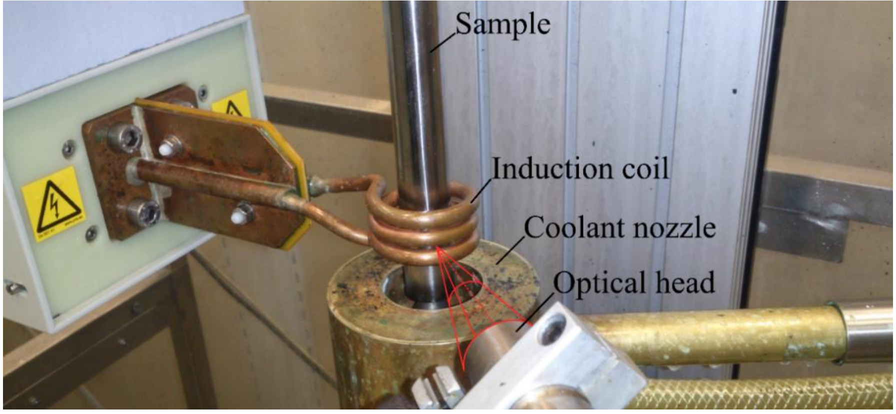


Fig. 3. Overview of experimental setup for trials with quenching. Sample, induction coil, quenchant nozzle, and optical head with optical path (light red) indicated in picture.

Trials, both with and without quenchant were conducted. The trials without quenching were designed to show the applicability of the ECSP method and to compare with the conventional pyrometer and thermocouple. Trials with quenchant simulated the real world scenario, in order to show that ECSP can be applied even for industrial like settings and processes. For the trials conducted without quenching, the thermocouple is spot welded onto the sample and the sample is not rotated nor progressed through the coil during processing. Sample rotation and progression would complicate or prevent the use of thermocouples. For the trials conducted with quenchant spray, no thermocouple was used, and the sample is continuously rotated during processing in order to obtain angularly homogeneous material.

In Fig. 4, a photo sequence of a trial with quenchant is shown. Oxidation of the sample can be seen above the induction coil as a darker segment on the sample. Also, the quenchant droplets which are detrimental to single waveband pyrometry, as discussed above in Section 2.2, are seen flying away from the sample.

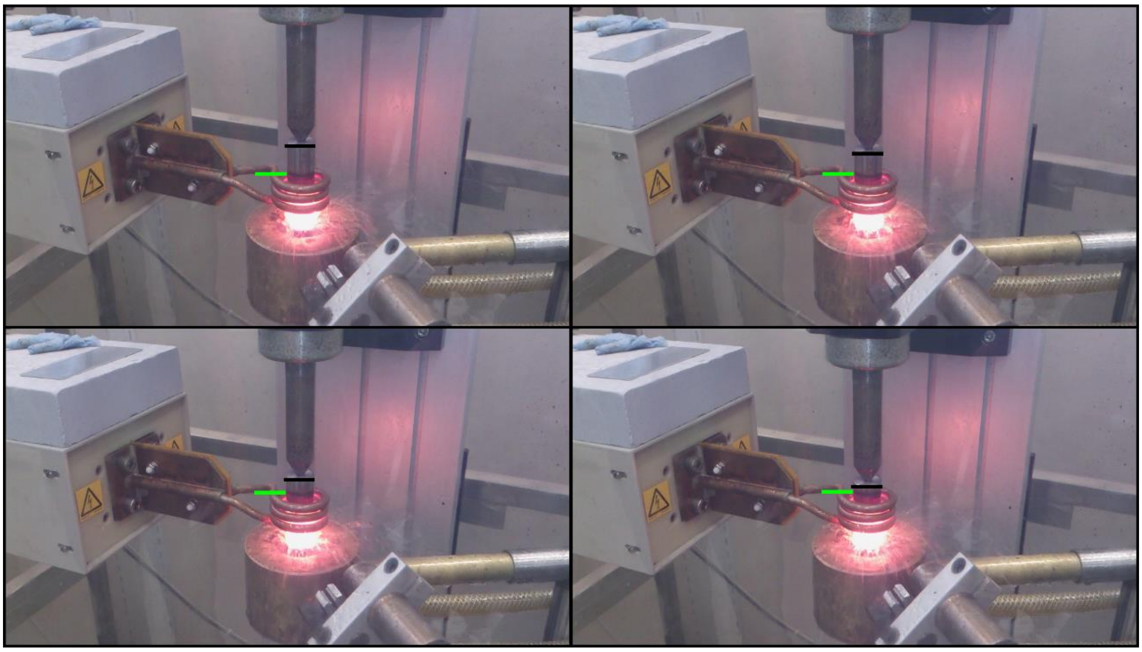


Fig. 4. Photo sequence of induction heating with quenchant. Elapsed time is 1.5s between pictures for a total of 4.5s. Oxidation is visible above induction coil and quenchant droplets can be seen flying away from the sample. Indication of specimen position in black. Indication of oxidation front in green.

4. RESULTS

The results, presented in Fig. 5 and Fig. 6, show that the conventional pyrometer does not give accurate readings as the surface of the workpiece oxidizes. The ECSP method, apart from being resilient with regards to fumes and other disturbances introduced by evaporating quenchant, shows better correspondence with the thermocouple than the conventional single-waveband pyrometer and is thus more accurate. The average error for the ECSP measurements, when compared to the thermocouple, are below 0.5% of absolute temperature while corresponding value for the conventional pyrometer exceeds 19%.

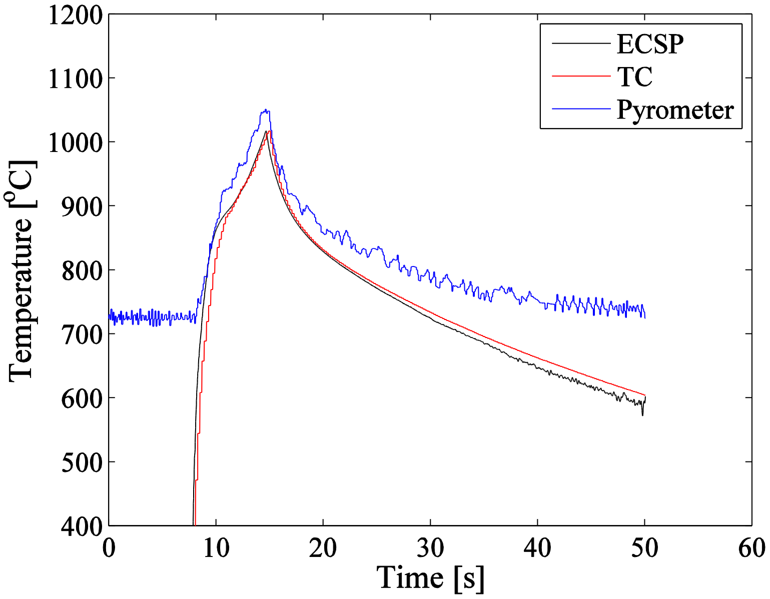


Fig. 5. Temperature curves for trial without quenching. Black line indicates ECSP temperature, red line indicates thermocouple reference and blue line indicates single waveband pyrometer temperature reading.

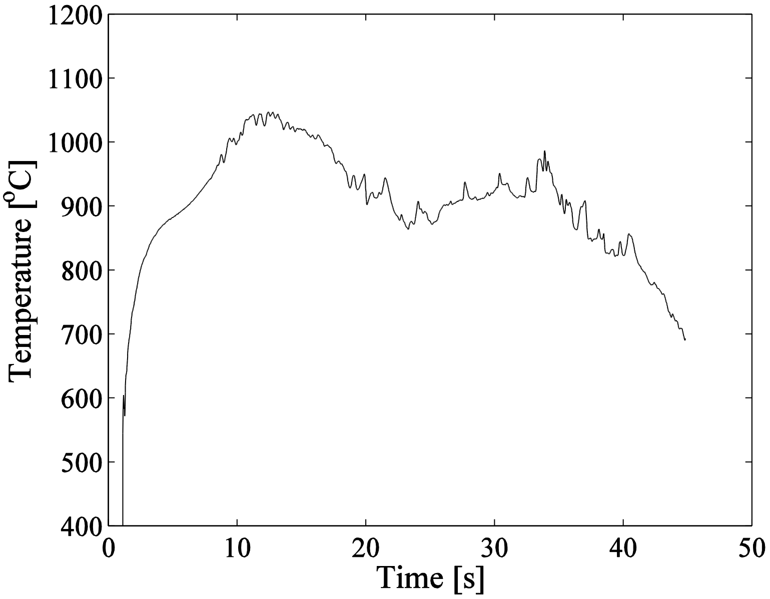


Fig. 6. ECSP temperature curves for trial with quenching.

5. DISCUSSION AND CONCLUSIONS

The systematic differences between the curve for the thermocouples and the ECSP curve is most probably due to that the ECSP measurement spot did not perfectly coincide with the thermocouple. In Fig. 6, significant fluctuations can be seen in the ECSP temperature curve due to disturbance of the optical path by flying quenchant droplets. For a single waveband pyrometer, such disturbances would have given significantly larger fluctuations and, as discussed above in Section 2.2, ratio pyrometers are not well suited for oxidising samples even though they are resilient towards partial obstruction of the optical path.

The automatic detection of the Curie transition has been found to be a successful way of calibrating the ECSP method for induction heating of 42CrMo4 steel as shown in Fig. 2a and Fig. 2b. The combined results of this work suggests that automatic detection of the Curie point is a promising solution to the ECSP calibration problem and that ECSP can be used for accurate temperature measurements within the induction hardening industry. This is true even for cases where the samples visibly oxidize and when there is significant amounts of evaporated and spraying quenchant present.

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REFERENCES

Bauer, W., Moldenhauer, A., Rogge, F., 2009. Influence of a growing oxide layer on band-emissivities used for optical temperature measurements, in: Proceedings of SPIE. Presented at the Thermosense XXXI, Orlando, FL, USA, pp. 1–8.

Grum, J. (2002). Induction hardening. In *Handbook of Residual Stress and Deformation of Steel* . ASM International, Materials Park, OH.

Hagqvist, P., Christiansson, A.-K., 2013. Automatic detection of material phase transitions from spectroscopic data, in: Proceedings of IECON 2013 - 39th Annual Conference on IEEE Industrial Electronics Society.

Presented at the IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, IEEE, Vienna, AUT, pp. 2384–2389.

Hagqvist, P., Sikström, F., Christiansson, A.-K., 2013. Emissivity estimation for high temperature radiation pyrometry on Ti–6Al–4V. *Measurement,* **46**, 871–880.

Hagqvist, P., Sikström, F., Christiansson, A.-K., Lennartson, B., 2014a. Emissivity compensated spectral pyrometry for varying emissivity metallic measurands. *Measurement Science and Technology,* **25**, 025010.

Hagqvist, P., Sikström, F., Christiansson, A.-K., Lennartson, B., 2014b. Emissivity compensated spectral pyrometry—algorithm and sensitivity analysis. *Measurement Science and Technology*, **25**, 025011.

Hagqvist, P., Sikström, F., Christiansson, A.-K., Lennartson, B., 2014c. Measurement error analysis of the emissivity compensated spectral pyrometry method. Submitted to *Metrologia*, 2014.

Haimbaugh, R.E., 2001. *Practical induction heat treating.* ASM International, Materials Park, OH.

Kristoffersen, H., Vomacka, P., 2001. Influence of process parameters for induction hardening on residual stresses. Materials & Design **22**, 637–644.

Planck, M., 1906. *The theory of heat radiation.* P. Blakiston's Son & Co, Philadelphia, PA.

Zhang, Z.M., Tsai, B.K., Machin, G., 2009. *Radiometric Temperature Measurements, Volume 42: I. Fundamentals.* Academic Press, Burlington, MA.