Measurement of temperature in inductive heating systems

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Measurement of material temperature is one of the most important quality assurance provisions in inductive heating. It is normally accomplished using optical systems, so called pyrometers. These are extremely high-cost instruments. Totally precise measurement of temperature is not possible, however, despite measuring instrument accuracies of around 0.3 % and repeatabilities of around 0.1 % of the reading. This article is intended to outline potential influencing factors, in order to enable the user to set the corresponding temperature window correctly.

Induction heating accrues advantages in forging, forming and annealing processes compared to other heating methods. In this way, constant temperature in work pieces can be reached by exact regulation of energy. Constant heating-up duration is often reduced to 1/4 compared to conventional heating techniques with gas or oil. Constant temperature and heating-up allows reproducible conditions and causes low edge decarbonisation and scale.

How induction heating works

Induction distinguishes itself in inducing heat in the work piece from within. Instead of external heat conduction, heating-up is achieved electromagnetically. The work piece is surrounded by an electromagnetic field which induces voltage. This results in a flux that heats-up the work piece caused by ohmic resistance.

Optimizing efficiency using different, and in the majority of cases, higher frequencies are used in inductive heating. The flux is not consistent within the whole work piece because of the so-called "skin effect". On the surface, the current is much higher than in the interior and decreases exponentially towards the core. The work piece's heat is proportional to the square of the flux strength.

Regardless of inner thermal conductions, variations in heat source distribution, causes different temperatures throughout the work piece. In effect, there is permanent thermal conduction between surface and core. Indeed, heat convection and heat radiation will always result in a temperature loss to the surface of the work piece.

The task of inductive heating is to conduct a specific amount of energy into a work piece in a given time in order to change heat content as required. Heat content (enthalpy) is only indirectly ascertainable according to the temperature. In the case of optical temperature measurement, the measurement takes place on the surface of the work piece (**Fig. 1**).

Measuring the temperature alone is not sufficient to deduce to the work piece's enthalpy. Two identical work pieces with equal surface temperatures can have different temperatures in the interior caused by varying frequencies used, heating duration or power density.

Example

In **Fig. 2 and 3** you can see temperature curves for two different heating conditions. They show surface temperature, enthalpy and core temperature. Despite the fact that the surface temperature is similar in both work pieces, core temperature and enthalpy vary.

Today's calculation techniques allow very exact computation. Therefore induction systems can be optimized

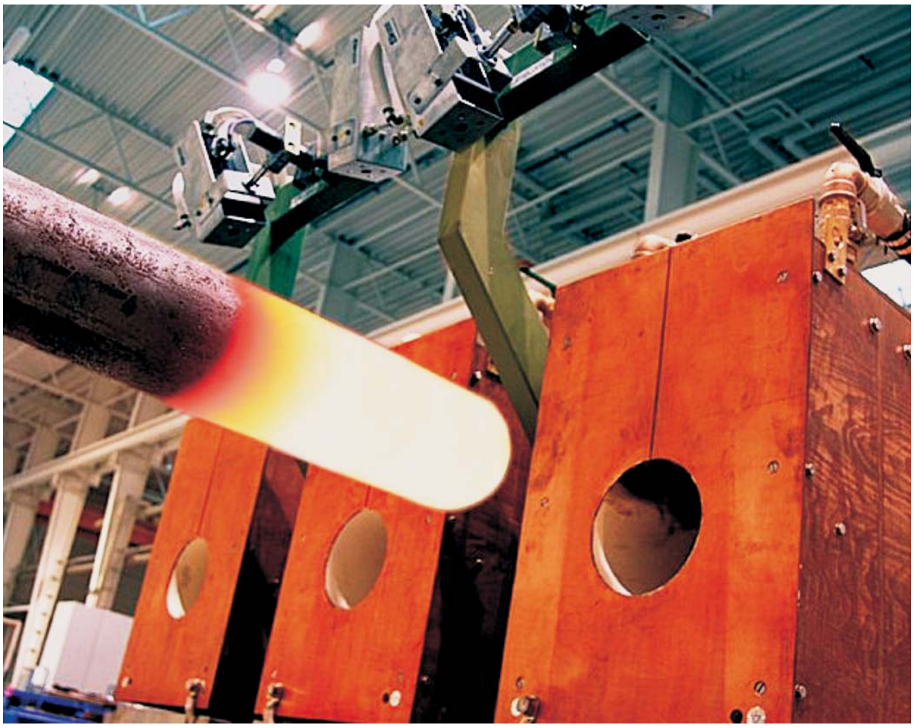

Fig. 1: Detection of the temperature of the inductively heated material

with regard to given parameters such as surface temperature, core temperature, enthalpy etc.

The mentioned temperature and enthalpy differences have certain influences on forming and annealing processes. The manufacturer has to ensure optimal conditions which ensure consistent temperature over the whole work piece.

Optical measurement of surface temperature

Temperature Measurement at the Inductor's exit is a very important part of the heating process. You should concentrate on this measurement method in order to achieve satisfactory results. To this end, an optical temperature meter, a so-called "Pyrometer", is used.

The Thermal Infra-Red Radiation is focused by a lens and aperture system which generates an electric current in a sensor. Increasing temperature produces higher radiation which consequently produces a higher current. In the first instance, the pyrometer is a Radiation Intensity Meter. At his works, the manufacturer calibrates the Pyrometer in front of a "Black Body" under controlled conditions. High-quality instruments reach an accuracy of 0.3 % and a repeatability of 0.1 % in measurement values. In general, such optimal conditions are seldom met elsewhere.

Temperature measurement of steel objects principally concerns surface temperature (**Fig. 4**). The cooler abutting surface temperature in, for example, work pieces to be forged, can only be "seen" if the Pyrometer is aimed to the front face of the work piece. In heavily scaled objects, this is useful since in general, scaling there is only light.

The subject of scale poses a general problem with optical temperature measurement. Scale is a thermal insulator and is always cooler than the hot material. In spite of this, to measure the temperature of the object, the pyrometer has to meet two criteria:

- the Pyrometer's Measuring Area must be very small
- the Instruments' Measuring Time should be in the Region of Microseconds.

It is not sufficient for the Pyrometer to meet only one of the Conditions. The aim of these conditions is for the pyrometer to recognize cracks within the scaled surfaces. This makes very high demands on Pyrometers since long radiation times of the detector enable small measured areas. Short radiation times normally cause large measured areas.

Specially developed peak picker functions achieve extra assurance for measurement recording.

The often praised "Ratio or Two-Colour Pyrometers" are not suitable due to the fact that they are, as a rule, slower, need a larger spot size at the same measuring distance and cannot, as sometimes claimed, measure through Scale in general.

In some measuring tasks, it would be useful to scan the object and be able to analyse the maximum values. The Scanner should have an adjustable frequency and angle possibility.

We always come back to the surface of the measured object. Even when there is no scale on the surface, dark spots which are visible before heating, can cause measurement errors caused by an increased emissivity factor. These spots produce an exaggerated temperature value since the Pyrometer was programmed for a lower emissivity of the scale-free surface. For this reason, objects are mistakenly rejected as too hot or overheated, thus decreasing a production-line's economic efficiency. A close co-operation to the manufacturer's works should be guaranteed in order to accomplish optimal measured values.

Fig. 2: Heating-up time approx. 77 s; surface temperature approx. 1250 °C

Fig. 3: Heating-up time approx. 117 s; surface temperature approx. 1250 °C

Temperature measurement in practice

We proceed on the assumption that feed rate and duration in the electromagnetic field is exactly the same for all work pieces. In addition to this, the power provided during the heating-up is constant. This means that there are no variations in power at the middle of the frequency range. The question is, can we count on the temperatures in the work piece being exactly the same. The answer is clearly "no".

Many parameters have an influence on temperature measurement, e.g. gapped billets in forging process. A diameter's tolerance causes an increase in the square of the weight. If the diameter varies by +1 %, the weight increases by about 2 %.

Under the supposition that energy input is constant, this will effect a change in temperature of about 2 %. As a result a change in diameter will cause a change in temperature. Material processes, e.g. change in alloying, will cause temperature differences as well.

Different geometrically formed work pieces can effect a varying heat source distribution and temperature. Edge overheating and varying inner structures like cracks can also have a strong influence on temperature. Another influencing factor is the temperature of the cold material. There is particularly extreme variation because of the seasons (summer or winter), whether storage is inside or outside or whether the material is in circulation. Varying ingoing temperatures will have influence on the outgoing temperatures in some sort.

There can be additional influences on temperature caused by e.g. vapours, ambient temperature and draughts in the measuring environment.

An absolutely exact energy input is not feasible using induction heating systems. In spite of accuracy in power control and feed rate that regulates errors marginal variations will occur.

Optimal temperature of the material for succeeding forming processes

It is important to consider the previous history of each measurement process. In the forging process for example, each work piece is measured and often logged to ensure high quality standards. There is usually a certain upper and lower temperature set to define quality work pieces. Those above the upper temperature are either recirculated for another heating period or must be eliminated if their temperature exceeds another upper boundary. Work pieces below the lower temperature are too cold for processing and generally can be recirculated.

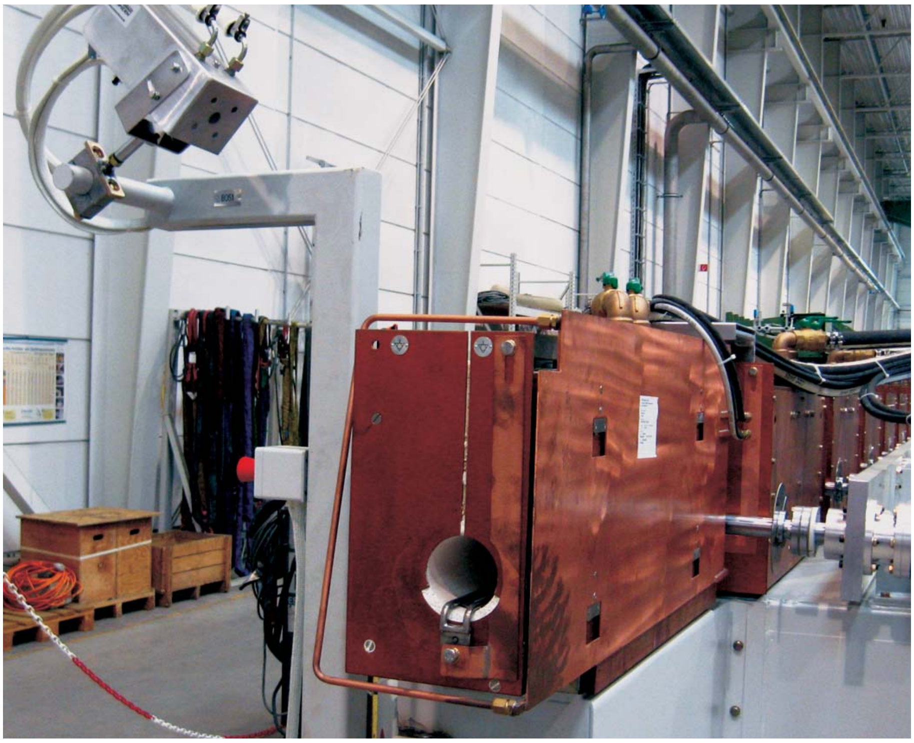

Fig. 4: Examples of pyrometer arrangements

Switches that are indirectly controlled by the pyrometer accomplish sorting of the work pieces.

To set the temperature boundaries, it is important to take into account all factors. Acting arbitrarily in setting too strict boundaries should be avoided due to the fact that the whole production line could decrease in economic efficiency.

All factors are either known so far or can be computed. Thereby the whole process can be optimized concerning temperature boundaries. For quality management reasons, temperature values are often suited to Machine capabilities or Process capabilities. Without in-depth knowledge, serious mistakes are made at this point.

Sometimes the quality upper and lower boundaries are used to limit the Machine Capability Index (cmk)-value. If, for example, all measurement values are optimal, a cmk-value of 1.33 cannot even be reached.

A machine capability measurement concerning temperature is not useful, if each work piece is measured, sorted and logged as it is usual in forging lines.

Conclusion

The control of material's temperature in inductive heating systems essentially influences product quality. This especially determines flow of material. An absolute accuracy of temperature cannot be reached. The influencing factors are either known or can be computed in general. The temperature boundaries can be adapted to specific demand. ■

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