Core temperature measurement in slab reheat

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The article describes the correct use of data loggers for profiling slab reheat processes. It examines the necessary thermal protection measures and ways to avoid measurement errors. Costs and benefits are discussed, for instance regarding the number of thermocouples, the insulation material, and the investment in radio technology. The author furthermore gives practical advice on handling and installation.

Prior to rolling, steel slabs need to be reheated to target temperatures of 1,100 to 1,300 °C all through the compact steel body. Too low a temperature can accelerate wear on the rolls, and too high a temperature will cause high scale levels which lead to reductions in yield and depleted quality. Unerring process monitoring and control are therefore imperative.

The temperature settings in reheat furnaces are based on mathematical models which must be verified on a regular basis by measuring the actual slab temperatures. These measurements are typically carried out by means of a data logger system which passes through the entire, approximately three to five hour long process with the slab (Fig. 1). The electronics device records detailed temperature profiles via thermocouples placed at critical points within a test slab. A thermal barrier isolates the data logger from the high process temperatures.

At the end of the measurement run, the data from the logger memory is downloaded to a computer for visualization, analysis, and comparison with the mathematical model’s data. These directly measured, precise values can be used to adjust the furnace parameters (zone temperatures, line speed) and specify the virtual furnace model. Such verification trials can also provide useful information that may not be immediately available from the mathematical model, such as the temperature at the base of the slab in the “shadow” of the beam in walking beam furnaces.

Data logger systems significantly facilitate measurements in this kind of heat treatment process irrespective of the type of furnace. Without trailing sensor cables, there is no longer a risk of severed lines in walking beam furnaces. For the same reason, data logger systems are the first feasible monitoring solutions for roller hearth furnaces, where trailing sensor cables can hardly be used and the air temperatures measured by the fixed furnace sensors do not provide sufficient insight into the process. Only the introduction of highly advanced thermal insulation technologies has enabled reliable measurements inside the furnace by protecting sensitive electronics for hours on end.

Data logger trials should be painstakingly prepared and carried through. On the one hand, very good protection measures are necessary in order to ensure data quality and prevent data loss. The sensitive data logger electronics must be handled correctly, and it requires effective insulation in order to survive several hours at ambient temperatures of approximately 1,300 °C without a loss of function. On the other hand, a lot of material and valuable time goes into these measurements. The preparation of a slab and sensor placement and protection take a lot of effort. Thermocouples and insulation can only be used once. These costs must be justified by a successful measurement.

Fig. 1: Attached to a test slab, the data logger system can pass with it through the furnace, in this case a walking beam furnace.
**SELECTION CRITERIA FOR DATA LOGGER SYSTEMS**

The following crucial aspects must be considered for the selection of a data logger system:

- Will the thermal barrier clear all the low points in the furnace?
- Does the thermal barrier have sufficient thermal capacity to get through the process, as well as enough reserve capacity to deal with any unexpected delays, such as roll changes?
- How many thermocouple measuring points are required?

The usual response to the question about the number of thermocouples is “as many as possible.” The benefits of the additional data produced should be balanced with the cost of extra thermocouples and the difficulty of manoeuvring them into a thermal barrier. 10 to 20 thermocouples, placed at various depths and across the length of the slab, will generally provide sufficient data for comparison to a mathematical model. There is a range of 10- and 20-channel loggers for this kind of application available in the market today.

The time a logging system can spend within a furnace without suffering damage is directly related to the amount of material used. The bigger the thermal barrier, the bigger its thermal capacity and the longer the maximum time the data logger can spend in the furnace. However, furnace specifications restrict the permissible barrier size. Furnace entrances and exits are built with limited clearance to improve energy efficiency. Consequently, measurement systems need to be compact. Today, low-height systems with the capacity to withstand six-to-seven hour processes are commonly used.

**FUNCTIONAL MULTI-COMPONENT INSULATION**

Most thermal barriers work by combining multiple layers of high-grade insulation around a water-filled barrier housing the actual data logger. The underlying principle is that the data logger is able to operate at 100 °C, the boiling point of water. As long as there is sufficient water, the data logger is within specification. The insulation layers delay the water from reaching the boiling point quickly, enabling the system to pass through the reheat furnace before the water has evaporated (Fig. 2).

High-grade insulation layers may be supplemented by high-temperature protective blankets as the outer insulation layer, in order to achieve good insulation even in furnaces with very low clearance. In the past, ceramic fibre blankets were used as the outer insulation layer in the system, but they have now been classified as a possible carcinogen in many countries. Less expensive, safe ceramic blanket insulating materials are unsuitable for this application due to an upper operating limit of 1,250 °C. At process temperatures around 1,300 °C, they may shrink and not give the protection needed in a reheat furnace. The minimum specification for the outer insulating layer for this type of application should be: maximum operating temperature > 1,400 °C, thermal conductivity 0.3 W/mK (at 1,200 °C) or better, and a density of 100 kg/m³ or more. Mullite fibre blankets, not harmful to health, though admittedly costly, are a suitable material (Fig. 3 and 4).

**MINIMIZING DATA COLLECTION ERRORS**

There are several potential sources of error in the process of data collection in slab reheat trials; some can be avoided, others cannot, but can be reduced. Water cooling can cause condensation within the thermal barrier. If, subsequently, water trickles onto the legs of the thermocouple plugs, it can cause inaccurate or bizarre readings on the logger. This can be avoided by wrapping high-temperature tape around the thermocouple plugs and placing the logger in a small barrier, where materials on the inside surfaces will prevent humid air from condensing and dripping down onto the data logger. By far the biggest source of errors concerns the thermocouples used to collect the data. The material (type), size (diameter), protection (thermal insulation and protection from mechanical damage), and positioning of the thermocouples need to be considered carefully.

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**Fig. 2**: Cross section of a data logger system with a trial setup: various insulation measures combined keep the logger temperature within specification.

**Fig. 3 and 4**:
Thermocouple types
The type of thermocouple used for these trials is influenced by the conditions in the furnace, including:

- temperatures: 1,300 to 1,350 °C,
- duration: three to four hours (or more),
- slab dropout temperature: approximately 1,250 °C,
- atmosphere that may be carbon-rich, if there is a requirement for “neutral” atmosphere for higher-carbon steel products.

Noble metal thermocouples such as Type S or R are generally not considered for this application, as they are expensive and fragile, and the metallic environment in which they are required to operate without protection may affect their accuracy. The best options are base metal Type K or N thermocouples. If the operating temperature is up to 1,300 °C, then Type N are preferred, as they are considered to be more stable and less prone to oxidation. However, if the temperature is likely to exceed 1,300 °C at some stage in the process, then Type K is normally used, as it has a higher cut-off point (Fig. 5).

Thermocouple insulation:
There are two options for thermocouple insulation: ceramic beading and mineral insulation metal sheath (MIMS). The former are difficult to handle on the slab and very susceptible to damage. Therefore, MIMS thermocouples are by far the most popular. Once again, there are several additional decisions to make in selection. They include:

- Type (K or N): The choice must be based on the process temperature maximum as discussed before. There is very little difference between the cost of Type K and N thermocouples today.
- Accuracy: The accuracy of a thermocouple is affected by many factors. A major consideration is the purity of the alloy that makes up the thermocouple wires. This is reflected in the class of thermocouple. For example, the ANSI specification MC96.1 for Type K thermocouples comprises two classes: ANSI Special Limits of Error (+/-1.1 °C or 0.4 %) and ANSI Standard Limits of Error (+/-2.2 °C or 0.75 %). Although the higher class is more expensive, it may be worth balancing the extra cost against the better quality of the data obtained. It is also possible today to have thermocouples calibrated even at higher temperature ranges. Thereby, the error at specified levels is known and can be corrected, using specialized software.
- Sheath material: There is a huge choice of metallic sheath materials from low-grade, inexpensive stainless steels to high-grade alloys. Although a thermocouple is likely to be used only once (they are normally cut through at the end of the run to extract the data logger from the system), it is worth spending extra on high-
temperature alloys, such as Hastelloy X or Nicrobell D to ensure the thermocouples stay intact and provide the best quality data.

- Thermocouple diameter: The thicker the thermocouple wire, the better the data accuracy, however, the greater also the heat transfer back into the thermal barrier – via the wires and through the wider gap in the barrier. In contrast, thinner wires are easier to handle due to smaller bending radii. The diameter of a MIMS thermocouple is generally understood to be the diameter over the protective sheath. Standard sizes are 1.5 mm, 3 mm, 4.5 mm, and 6 mm. Medium-size thermocouples are a good compromise. For instance, a 3 mm thermocouple is relatively easy to manoeuvre from the measuring point (generally deep in the slab), along the slab, and into the thermal barrier while also providing an acceptable accuracy of 4 to 7 °C.

**Thermocouple positioning:**
The measuring depth within the slab may be 10 or 20 cm. It is difficult, if not impossible, to drill a 3.5 mm wide hole in a steel slab 20 cm deep to house a 3 mm diameter thermocouple. The solution is to drill a much wider hole and fill in around the thermocouple. A variety of materials have been used as filler, ranging from ceramic blanket insulation to ceramic cement. Perhaps the best solution is to drill the hole the same size as standard steel bar stock and cut pieces of bar 40 to 50 mm long. These pieces can be fitted with 3.5 mm wide holes more easily, allowing for the thermocouple to be sunk into the slab at the required depth very comfortably and well protected.

**Thermocouple protection:**
Thermocouples have to run from the measuring point to the thermal barrier, which is normally situated at the end of the slab. The wires, exposed on the surface of the slab over a distance of up to 7 m, need to be protected, mainly against mechanical damage from the curtain-type seals on the furnace entrance doors, but also against any direct impingement from the burners. The normal method of protecting the thermocouples is to bunch them together along the length of the slab and cover them with an inverted steel angle, which is then tack-welded to the slab. Care should be taken not to accidently weld the thermocouple to the slab, as well as the angle.

Instead of drilling a number of holes, the slab may be fitted with a slot to accommodate all the thermocouples, with steel blocks welded over the top. While milling a long deep slot is a costly effort, it takes care of the problem of safely guiding the thermocouples to the barrier and thereby contributes to high data quality.

**ATTACHING A PROFILING SYSTEM TO A SLAB**
The data logger system must be securely attached to the slab so it passes through and out of the furnace with it. Should it get stuck at any point in the furnace, it would be damaged through over-heating, the data would be lost, and all preparations would have been in vain. Since clearance within the furnace is often restricted, it is customary to remove part of the slab, so that the thermal barrier will sit partially within the profile of the slab. The cut-out should not be positioned towards the centre of the slab as that might cause an area of weakness. Positioning the cut-out at either end of the slab allows for easy removal of the data logger after the trial.

There are two ways to manufacture a support to hold the system in place throughout the process:

- A plate can be welded into position to carry the profiling system through the furnace. This is the easiest method, but is also the riskiest. If the welds are made incorrectly, the slab and the thermal barrier can part company, leaving the system in the furnace. The support plate should always be welded on the top and bottom using good fillet welds. A central slot should always be cut into the support plate to allow for expansion. If this is not done, the support plate can buckle, forcing the barrier upwards and possibly causing it to get stuck or be damaged.

- The preferred method of supporting the thermal barrier is to use forged hanger bars. In contrast to welds, forged
angles will not fracture at high temperatures. The bars also need to be securely welded to the top of the slab.

REMOVING EQUIPMENT AFTER A TRIAL
Removing the data logger from the thermal barrier is often seen as the trickiest part of the operation. After the slab exits the furnace at 1,100 to 1,300 °C, it needs to be transported to a location where it can be placed in a safe position and the data logger can be extracted quickly. There must be no flammable materials close-by, since the slab will retain extreme heat for many hours. The retained heat will continue to heat the barrier, still risking damage to the electronics. Handlers must wear full protective clothing and visor, high-temperature gloves and footwear. The following tools should be placed at the ready beforehand: tongs to remove any hot insulation blankets and bolt cutters to sever the thermocouples. As soon as the data logger is removed from the thermal barrier, it must be relocated to a safe area where data can be downloaded to a computer. The barrier can remain on the hot slab and cool down slowly.

DATA TRANSMISSION VIA RADIO: COST AND BENEFITS
The development of radio frequency (RF) transmitters and antennas that can operate at high temperatures has enabled real-time data transmission (Fig. 6). A transmitter placed inside the thermal barrier can send data to a connected computer even from the centre of a roller hearth furnace. The data is stored immediately and is accessible at any time even in case of data loss from the logger memory. Additional advantages claimed include easier, more precise process control, more immediate reaction to problems, and real-time data input to a mathematical model.

While data backup is a valid argument, operators should weigh the cost versus the benefits. There is considerable wear and tear on the transmitting antennas, which greatly

Fig. 7: Application-tailored software functions quickly show whether the specifications have been met and enable documentation of sensor placement (bottom right)
reduces their lifetimes and raises replacement costs. At the same time, recent data logger and thermal barrier generations are very robust and, if handled correctly, ensure high data availability. The value of real-time access to process data is also questionable. During transmission through the massive furnace walls, there may be up to 5% signal loss. Therefore it is unadvisable to use the RF data for analysis or process control. These had better be based on the comprehensive temperature profiles that are available virtually immediately after the measurement run (Fig. 7).

ADDITIONAL APPLICATIONS
The same data logger system is also suitable for monitoring the temperatures of high-performance alloy billets before forging as well as reheat and quench of formed and forged parts. By means of thermocouples placed at various depths all through the billet, the exact point in time when the billet reaches the target temperature can be determined. In one such trial, the temperature profiles revealed a potential for productivity increases of 15%. Based on data from a Datapaq Furnace Tracker system, the dwelling time within the rotary hearth furnace was significantly decreased. Due to its remarkably wide measured temperature range, the system is also employed in quench applications. For railway wheels to achieve correct hardening, the correct quench rate must be observed. The thermocouples are placed at various depths in the forged wheel. The measurement system is able to compile a complete profile of the three-hour reheat treatment in the rotary hearth furnace and the subsequent quench phase. Thereby it constitutes a crucial quality assurance tool.

CONCLUSION
Carrying out a trial to verify the mathematical model in a reheat furnace is simplified by using a data logging system. The cost of the consumables, the system, and the time involved in setting up and running the trial require that the greatest care is taken in specifying the correct type of materials, and all the necessary steps are followed in setting up the equipment. In this way, costly errors can be minimized and the user is assured the data obtained is as accurate as possible.

Radio frequency technology can now be used in reheat applications, but a cost/benefit assessment is necessary before specifying this additional equipment. Data can be transmitted in real time from inside the furnace to a computer. There will, however, be some data loss, and after the trial run the temperature profiles will be available in full.

Lastly, data profiling systems find various uses. In one and the same operation, they can be used for production monitoring, quality control, and documentation in multiple applications. Process optimizations based on exact temperature profiles help reduce operating costs, save resources, and improve yield.

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