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Challenges and Benefits of Temperature Profiling in the Heat Treatment Industry

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Abstract: This paper outlines the challenges and benefits of using 'hot box' temperature profiling systems in today's heat treatment industry.

We examine how systems are engineered to get safely through such diverse processes as heat treatment of gear parts in continuous carburising furnaces, homogenising aluminium logs, and monitoring part temperature through a batch carburising furnace with an oil quench, and deliver vital temperature data, which in some cases has not previously been possible to measure.

We look at how the use of this type of system has evolved as Temperature Uniformity Surveying (TUS), has become an ever increasing requirement in aerospace and auto manufacturing industries.

Introduction

'Hot Box' temperature profiling in the heat treatment industry has been around for over twenty years and the principle of operation of these systems is generally well known; i.e. a multi channel data logger is protected by an insulated thermal barrier which allows the system to travel through a furnace together with the product(s) being heat treated (figure 1). Thermocouples feed temperature data back to the data logger and at the end of the process the complete temperature profile can be examined, and critical calculations made using purpose built software supplied by the system manufacturer. Further developments have allowed the data to be sent out of the furnace via RF telemetry allowing examination to be made in real time.

Figure 1 'Hot Box' system in product basket (shown open and with telemetry transmitter fitted)

Benefits of 'Hot Box' temperature profiling

Prior to the development of these system long 'trailing' thermocouples were often used to determine the actual product temperature profile through continuous furnaces. Feeding thermocouples through a continuous furnace had obvious disadvantages, mainly the difficulty of the operation itself, the limited number of thermocouples that could be used, disruption to production, and the accuracy of the data, given that products could not follow the test basket into the furnace (due to the trailing thermocouples), so the furnace loading decreased as the trial progressed.

As the 'Hot Box' method was adopted the monitoring operation simplified, the disruption to production was minimised, and the measurement could always be carried out in a fully loaded furnace reproducing actual product conditions. Data obtained from 'Hot Box' profiling trials gives an accurate assessment of how long a product soaked at a specified temperature, the differences in product temperature around the product basket, quench rates, etc. This data being used to calculate performance against specification, investigate process problems, and optimise the process. An important development has seen these systems used as a primary method to survey furnaces to the AMS2750 specification (figure 2), allowing the survey to be carried out with minimal disruption to production, and saving many hours of furnace downtime while the furnace was cooled and degassed to fit the trailing thermocouples.

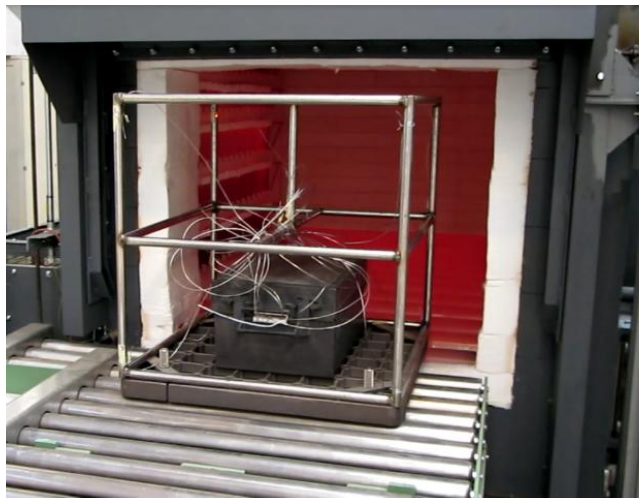

Figure 2 system mounted in a survey frame carrying out a TUS

Engineering Design – the Challenges

Figure 3 monitoring a steel slab being reheated prior to hot rolling.

Although the operating principle of these systems seems relatively straight forward, the design is often complex as the 'Hot Box' system is expected to perform repeatedly in processes as diverse as steel slab reheat, where ambient temperatures will exceed 1250°C (figure 3), to aluminium solution treatment (T6), where after many hours at a temperature of around 550°C the system and products are immersed in quench water, then sent back into the furnace.

When designing the system thought must be given to whether the system itself will have an effect on the process. For example when 'Hot Box' systems are used in the aluminium brazing industry (radiators, condensers, etc. see figure 4), there is a possibility that oxygen may leak into the nitrogen furnace atmosphere during the process, and affect the braze quality. To prevent this, before delivery to the end user, the 'Hot Box' system undergoes a mild heat treatment process where air is extracted from the insulation under vacuum, then back filled with nitrogen.

Figure 4 system entering CAB brazing furnace with product

All components of the system have to be designed with the specific heat treatment process firmly in mind, and manufacturers of these systems generally run through a check list of questions regarding the process to establish the basic design of the insulated 'Hot Box' or thermal barrier. This will in turn govern the type of data logger and thermocouples to be used in the process.

The important criteria are:

- **Space or clearance in the furnace**. Thermal barriers used in these processes will have a certain minimum size to withstand the process temperature and duration. Therefore there needs to be adequate clearance at the furnace entrance and exit to allow the system through. Examination of other 'pinch points' in the furnace, such as baffles, or 'knuckles' to separate heating zones, should also be made (figure 5).

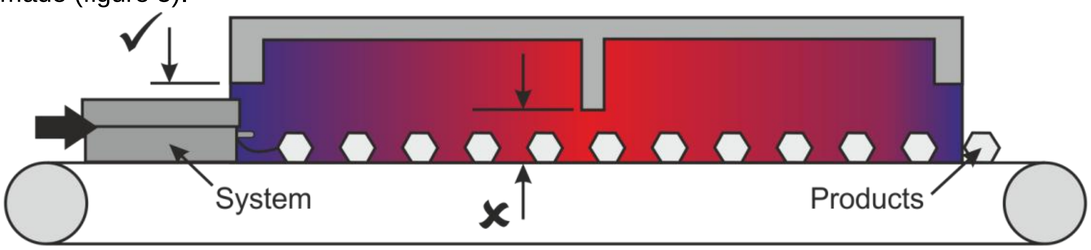

Figure 5 clearances at furnace entrance and exit are OK but is tight at the baffle within the furnace

- **Furnace temperature**. This does not just refer to the maximum process temperature, which is used to determine the type of insulation to be used, and the thermal barrier material, but also a calculation needs to be made to determine the 'Adjusted Process Temperature' (APT). This takes into account rates of heating, cooling, and soaking at the various temperature levels, and is used by the system manufacturer to determine the actual thermal barrier size required to get the system through the process.
- **Process duration**. The full process time within the furnace is used in this calculation. Added to this is the time period after exit from the furnace until the system can be accessed, and the data logger removed. A safety margin is also added to in case of stoppages in the process.

Knowing the full process duration and the APT, the size of the thermal barrier can be determined.

- **Atmosphere in the furnace**. The furnace atmosphere will not only determine the material the thermal barrier will be constructed from, but may also affect the performance of a thermal barrier e.g. a hydrogen atmosphere will lessen the thermal performance, whereas a vacuum will increase the performance. The furnace atmosphere will also determine the thermal barrier 'technology' that can be used. There are two basic technologies that keep the data logger at a safe operating temperature (figure 6);
    - 'Heat sink' technology is a 'dry' technology, where the data logger is housed in a heat sink (a container filled with a eutectic salt) which changes phase at 58°C, keeping the data logger at a stable temperature during the phase change period. A lower operating temperature data logger can be used in this type of barrier.
    - 'Evaporative' technology uses boiling water to keeps the data logger at a stable operating temperature of 100°C as the water changes 'phase' from liquid to steam. The advantage of 'Evaporative' technology is that a physically smaller barrier will have an equal or greater thermal capacity than a 'Heat sink' barrier. A high operating temperature data logger is used with this type of technology.

A furnace atmosphere or environment, for example carburising, vacuum, nitrogen, etc. will prohibit the use of 'evaporative' technology as steam is vented into the furnace. In this situation, only thermal barriers using 'heat sink' technology can be used.

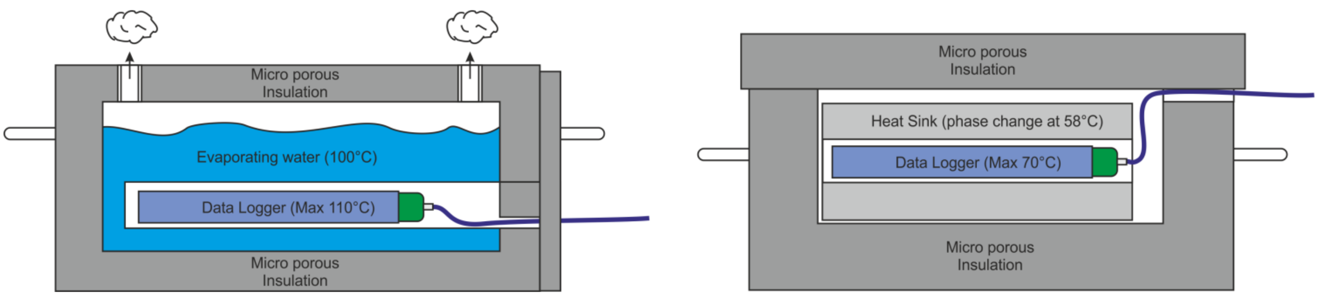

Figure 6 Thermal barriers operate on either 'evaporative' or 'heat sink' technology

- **Quench within the process**. If a quench is involved then the type and duration of the quench is important.
    - Gas quenches in low pressure carburising processes are common, but the thermal barrier may require a 'deflector' if the pressure of the quench is high.
    - Water quenching in T6 processes require the thermal barrier to resist full immersion in water from high temperature, and the technology for this is well established.
    - Salt bath quenches. The technology exists now that allows a thermal barrier to pass through a salt bath quench, but this requires a different thermal barrier technology and a higher cost per trial is required.
    - Oil quench. The technology for passing a 'Hot Box' system through an oil quench has now been developed and this will be discussed in more detail.

- **Specific Examples 1) Surveying in continuous carburising pusher furnaces.** This process is often used for high volume production of transmission parts in the automobile and aerospace industries (figure 7).
    - **Objective**: to survey the furnace to the AMS2750E specification. Big savings in furnace downtime can be achieved if the survey can be carried out as part of the normal production process.
    - **Process conditions**: Furnace type – pusher. Parts are placed in product baskets which are then placed on to trays. These enter the furnace singly through air tight entry and exit doors. Process time generally 6 to 7 hours, with temperatures up to 950°C. Oil quench is common in these processes, but can often be avoided.

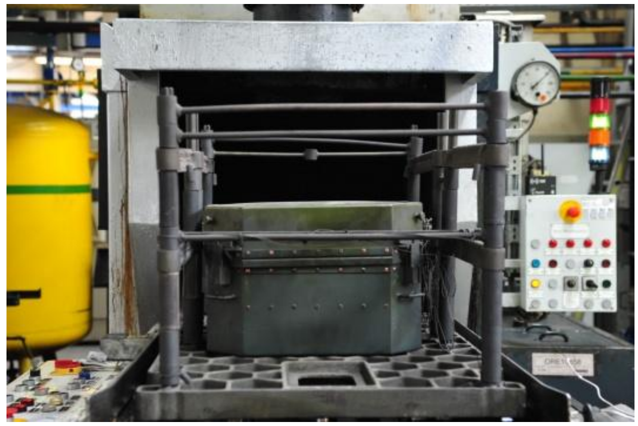

Figure 7 survey basket prepared on tray of pusher furnace

    - **Engineering challenge**: Is for 'Hot Box' manufacturers is to design a system with enough thermal capacity to get through the process, without exceeding the boundaries of the tray, and to keep within the height restrictions in the furnace. It is not possible to extend thermocouples from the system placed on one tray, to the tray preceding, or following the system as the pusher mechanism generally allows only one tray at a time through the furnace doors, and internally trays may turn through 90° to go from one zone to the next.
    - **Engineering solution**. The system must use the 'heat sink' design as an 'evaporative' system cannot be used in a carburising atmosphere. The system can be kept within the boundaries of the tray, and the thermal capacity maximised by using an 'octagonal' thermal barrier design where the catches (which secure the lid to the base) are placed on the 'short corners' (figure 8). Surveying the furnace presents a difficulty as the thermal barrier, of necessity, takes up the whole space on the tray, preventing the positioning of a central surveying thermocouple. However as the process is continuous, then surveying to AMS2750E using the 'plane method' is allowable, and there is generally enough room at the leading edge of the barrier to accommodate the measuring thermocouples.

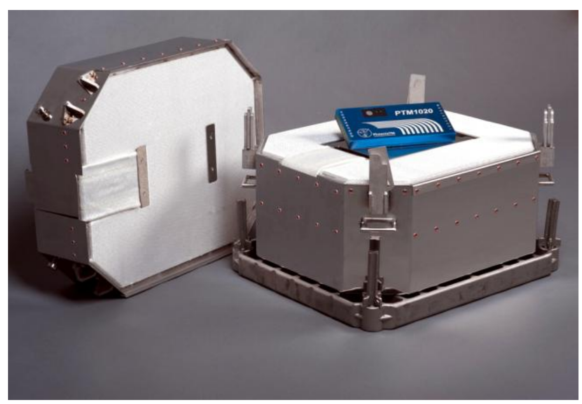

Figure 8 'octagonal' thermal barrier fits within boundaries of tray. Catches are on 'short corners' to maximise thermal performance

- **Specific Examples 2) Monitoring homogenisation of aluminium logs in walking beam furnaces**.

  After casting, aluminium logs are homogenised before supplying to the end user (extrusion companies). This heat treatment process has normally been carried out in batch furnaces but today there is an increasing use of walking beam furnaces for continuous production (figure 9).

  

  Figure 9 aluminium logs exit the furnace. The system is fixed to a shortened log, in which thermocouples are embedded.

  - **Objective**: to monitor the temperature profile of aluminium logs throughout the homogenising process to ensure adherence to the heat treatment specification throughout the product, and to optimise the process.
  - **Process conditions:** Furnace type – walking beam. Although process temperatures (580°C) are not as high as in carburising furnaces, the process durations are long (12 to 13 hours depending on the aluminium log length and diameter).
  - **Engineering challenge:** The system has to be attached to the product as it rotates and travels through the furnace. Therefore a) the thermal barrier cannot exceed the diameter of the log, and b) the interface between the log and the thermal barrier has to be strong enough to prevent the heavy system 'sagging' at the end of the log. Thermocouples by necessity are long (up to 8m) and have to be kept within the boundary of the product.
  - **Engineering solution:** Given the process duration, the temperature, and the diameter restriction on the thermal barrier, an evaporative system is often the best option for this application. As the thermal barrier cannot exceed the diameter of the product it often means that more than one barrier size is required to accommodate the production size range.

    

    Figure 10 rotating evaporative thermal barrier is filled with water from a central position

    The design of an evaporative thermal barrier is complex as it needs to hold the maximum amount of cooling water, and due to the rotation of the barrier it needs to be filled with water from a central position (see figure 10), which means that the water level inside the barrier needs to be higher than the filler spout, without water leakage.

    The interface between the barrier and the product is often the outer shell of the barrier itself and is bolted to the product to maximise strength. A certain amount of machining of the test log is required to allow the thermocouples to stay within the product boundary as it rotates.

- **Specific Examples 3) Monitoring through an oil quench in a batch carburising furnace.**
  Avoiding the oil quench in a batch carburising furnace is not difficult, and is routine where 'Hot Box' systems are used as a surveying tool. However over the years many companies have expressed an interest in monitoring the complete process including the oil quench.
    - **Objective**: to monitor the temperature of parts throughout the carburising process and the oil quench to address any specific problems with part distortion. Or if studies are ongoing into quench oil performance
    - **Process conditions**: Furnace type – batch carburising. Generally two to three hours duration at temperatures of 925°C, followed by a 15 minute oil quench, and finally a wash cycle to clean the parts (figure 11).

Figure 11 'Hot Box' system entering batch carburising furnace with oil quench

    - **Engineering challenges:** The data logger that travels within the 'Hot Box' system needs to be kept at a safe working temperature throughout the process, and then kept dry throughout the oil quench and subsequent washing cycles. Distortion of the system, complexity of operation, and cost per trial, need to be minimised to make the solution a realistic possibility.
    - **Engineering solution:** many attempts, over the years have been made to try to find a solution to this problem. Initial attempts to encase the thermal barrier in a sealed enclosure were abandoned due to internal pressure build up in a container softened by holding at a high temperature, and by the complexity of setting up this type of system. Further attempts to find a solution by encasing a sealed barrier in a low grade, disposable insulation layer were also abandoned due to lack of thermal capacity, and the danger of quench oil surrounding a hot inner insulation layer. The latest development being a system using a high grade, sacrificial insulation layer surrounding a substantial sealed, inner thermal barrier (figure 12). To see in greater detail go to https://goo.gl/ewsCvm

Figure 12 data logger enclosed in quench proof barrier measures part temperature profile

Conclusion

'Hot Box' profiling and survey systems have been part of the heat treatment industry for many years. It is a discipline that requires a good understanding of the process itself, a commitment to accuracy of the data, and development of hardware and software that is innovative, cost effective and reliable. There is no single solution to all heat treatment processes, rather individual solutions that are engineered for a given process and to the customer's requirements. Advances in the technology of insulation materials, electronics, and RF telemetry, have seen major developments in the type of processes that can be monitored now, and further advances may increase the number of processes that can be monitored in the future.