Phoenix Temperature Measurement
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Paper Title: **Challenges and Benefits of 'Thru-process' Temperature Profiling in the Heat Treatment Industry**

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Abstract:

This paper outlines the challenges and benefits of using 'thru-process' temperature profiling and surveying systems in today's heat treatment industry.

An overview will be given to the principles of 'thru-process temperature profiling' where a data logger, thermally protected in a thermal barrier, is passed safely through the heat treatment process. The data logger as it travels measures, via multiple thermocouples inputs, the temperature of the product being heat treated and or ambient conditions in the furnace itself. The resulting temperature profile graph 'thermal finger print' of the process provides all the necessary information to understand, control, improve and validate the heat treat process. The benefits of this approach will be discussed in direct comparison with established techniques such as trailing thermocouples.

We examine how systems are engineered to get safely through such diverse processes as heat treatment of gear parts in Low Pressure carburizing furnaces with high pressure gas quenches, monitoring sealed gas carburizing furnaces with integral oil quenches, homogenising aluminium logs, Controlled Atmosphere Brazing (CAB) processes, and heat treatment of aluminium engine blocks in automated robotic loaded TS rotary furnaces. In all such cases the specific unique designs of the profiling systems will be discussed in detail which allow the collection of accurate product temperature through the entire heat treatment process. Many of these applications have previously not been possible to monitor with existing technology.

We look at how 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. Efficient Temperature Uniformity Survey solutions will be presented to meet the requirements of CQI-9 and AMS2750E. As part of such discussion the application of two-way RF telemetry will be presented allowing remote live real time temperature monitoring of batch and continuous process without the challenges of trailing thermocouples.

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Introduction

'Thru-process' 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 (figure 1) 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 2). 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 industry specific 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. The temperature profile obtained is basically a thermal finger print of the complete heat treat process. This thermal finger print is unique and critical to the understanding, control, improvement and validation of the heat treat process being undertaken.

Fig 1: Typical temperature data logger (up to 20 thermocouple inputs) used in a 'Thru-process' system. Protected by a thermal barrier it travels through the furnace with the product being monitored. Data is stored in memory for download post run or is transmitted live from the furnace using a RF Telemetry option.

Benefits of 'Thru-process' temperature profiling

Prior to the development of these systems 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 'thru-process' 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 'Thru-process' 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 3), 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. A summary of the benefits of 'thru-process' temperature profiling as opposed to trailing thermocouples is provided in Table 1.

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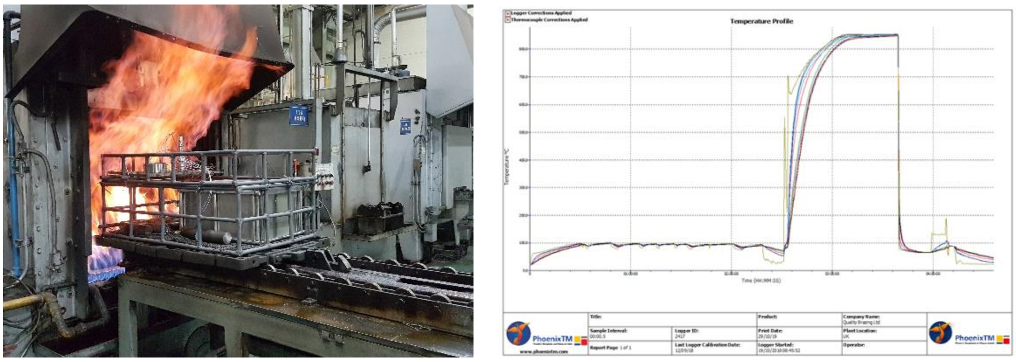

Fig 2: 'Thru-process' temperature monitoring system Loaded in a product basket travelling into and through a continuous sealed gas carburizing furnace and typical resulting thermal profile.

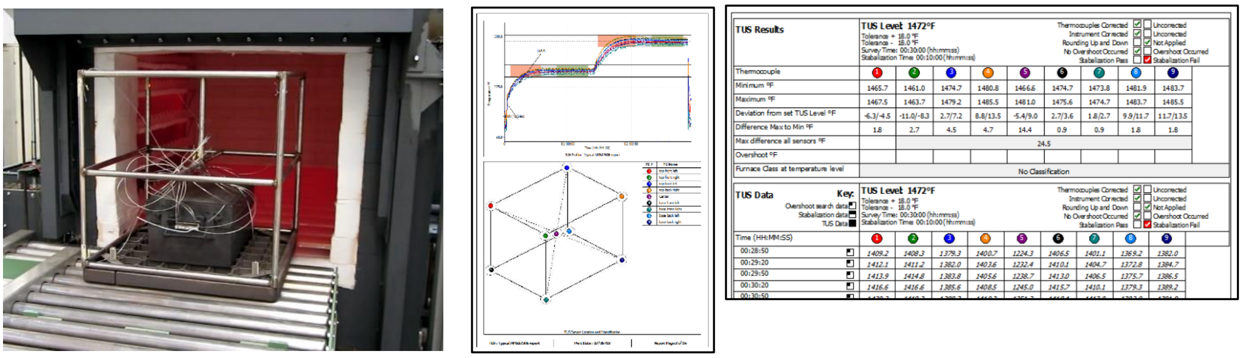

Fig 3: 'Thru-process' temperature monitoring system Loaded into a Batch Furnace with TUS frame to complete a temperature uniformity survey. Resulting fully documented TUS survey report.

	'Trailing Thermocouples'	'Thru-Process System'
Number Measurements	Limited to 1 or 2 Safely	Up to 20
Operator needed during run	Essential to allow safe cable transfer through furnace	Not needed (system travels independently as if product)
Cable Length	Furnace Length Minimum (Cost / risk of damage)	Short (typically few feet)
Cable Snagging / Damage Risk	Potential due to length. Automatic furnace doors may need to be overridden to prevent cable being trapped/damaged.	Minimal
Production Stoppage	Yes - Empty Furnace Needed (Probe retrieval post run!)	No used during production run
Representative of true Production Conditions	No as furnace may need to be empty	Yes, as performed during production run
Robotic Product Loading	Not Feasible	Possible
Multiple Process Steps (Furnace, Quench etc)	Difficult if possible, at all	Possible
Safety	Operators close to furnace to feed thermocouples (H&S)	No issues
Cost	Long thermocouples expensive to replace. Regular replacement risk.	Initial Investment cost of system

Table 1: Benefits of 'thru-process' temperature monitoring over traditional trailing-thermocouples methodology.

Engineering Design – the 'Thru-process' Monitoring Challenges

Although the operating principle of these systems seems relatively straight forward, with the evolution of furnace technology and drive for automated systems the design is often complex as the 'Thru-process' system needs to meet the unique challenges that come with different heat treatment processes. The main process challenge is protecting the measuring system from the heat of the process which in some cases such as slab/billet reheat, is a technical challenge in it's own right, where temperatures of up to 1250°C can be experienced for many hours.

Fig 4: PhoenixTM Profile system post reheat furnace. Thermal barrier (TS07-300-3 3.2 hrs protection at 1300 °C / 2372 °F) loaded on cast steel beam blank reheated prior to rolling into structural metal work for buildings/skyscrapers. The PhoenixTM 1220 data logger at the core of the system stores data measured by the thermocouples inserted into blank at varying depths along its length.

When designing or selecting the most appropriate 'Thru-process' system the following criteria need careful consideration.

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. Product loaded into the furnace in product baskets may restrict the size and shape of the barrier that can be accommodated. With ever increasing automation and multi-camber furnace designs space is becoming increasingly limited requiring a drive to provide the most space efficient barrier solutions.

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 the APT 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 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;

- '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.

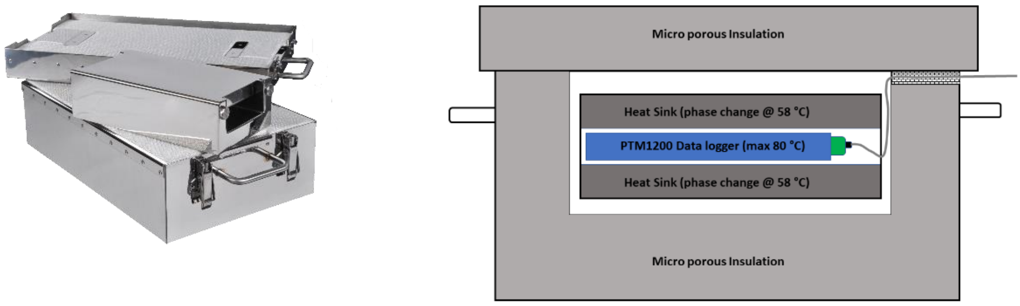

Fig 5: Photo and schematic of a conventional Heat Sink Barrier Technology

- 'Evaporative' technology uses boiling water to keeps the high temperature data logger (max operating temperature 110 °C) 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 is often possible. It is estimated that with a like for like size (volume) and weight an evaporative barrier will provide in the region of twice the thermal protection of a standard thermal barrier with microporous insulation and heat sink.

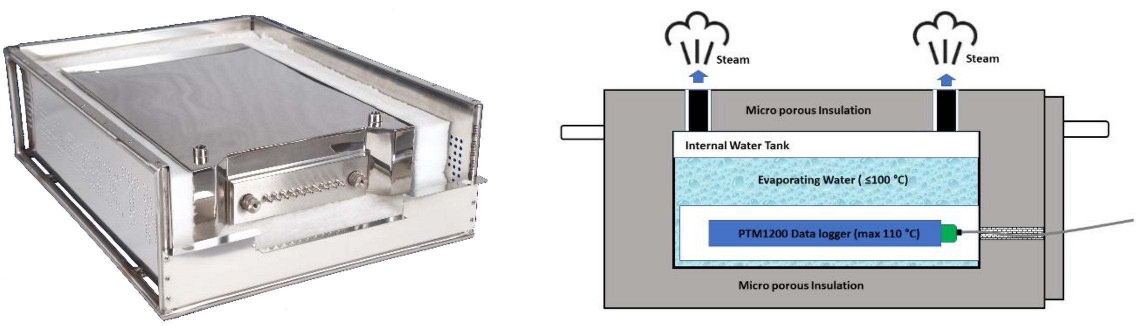

Fig 6: Photo and schematic of an 'evaporative' Barrier Technology

Although offering superior protection, since steam is generated as a by-product of the evaporative barrier technology it is prohibited from use in certain processes where the furnace environment cannot be contaminated. For such processes as Carburizing, Nitriding, Vacuum Heat Treatment and Controlled Atmosphere Brazing (CAB) the heat sink technology is the only viable option.

Quench within the process

If a quench is involved then the type and duration of the quench is important. Historically monitoring the quench was ignored and bypassed due to the technical difficulties of sending a system through. Obviously in many processes knowing the cooling rate of the heat-treated product is as important as knowing the time at temperature of the heating phase (Soak) to achieve the correct metallurgical structure of the metal whilst avoiding distortion and even quench cracks.

- Gas quenches in low pressure carburising processes are common, but the thermal barrier may require a 'Gas deflector' if the pressure of the quench is high (5-20 bar) to prevent distortion of metal work or damage to the thermal insulation.
- 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.
- Oil & Salt quench. The technology for passing a system through either salt or an oil quench has now been developed combining a fully sealed inner barrier and outer robust sacrificial blocks of insulation allowing safe transfer through and monitoring of the full quench. Monitoring the oil quench process is discussed in more detail in Technology Case Story 2 later in this paper.

Innovative 'Thru-process' temperature monitoring Solutions in the Heat Treatment Industry

Case 1: Low Pressure Carburizing (LPC) – Temperature Profiling and TUS

Carburizing has rapidly become one of the most critical heat treatment processes employed in the manufacture of automotive components. Also referred to as Case hardening it provides necessary surface resistance to wear, whilst maintaining toughness and core strength essential for hardworking automotive parts.

The carburizing process is achieved by heat treating the product in a carbon rich environment typically at a temperature of 900 - 1050 °C / 1652 – 1922 °F. The temperature and process time influences significantly the depth of carbon diffusion and associated surface characteristics. Critical to the process is following diffusion a rapid quenching of the product is performed in which the temperature is rapidly decreased to generate the microstructure giving the enhanced surface hardness whilst maintaining a soft and tough product core.

Increasing in popularity in the carburizing market is the use of batch or semi-continuous batch Low Pressure Carburizing furnaces. Following the diffusion, the product is transferred to a high-pressure gas quench chamber where the product is rapidly gas cooled using typically N_2 or Helium at up to 20 bars.

In such process the technical challenge is twofold. The thermal barrier must be capable of protecting against not only heat during the carburizing but very rapid pressure and temperature changes inflicted by the gas quench. From a data collection perspective to efficiently perform temperature uniformity surveys at different temperature levels in the furnace it is important that temperature readings can be reviewed live from the process but without need for trailing thermocouples.

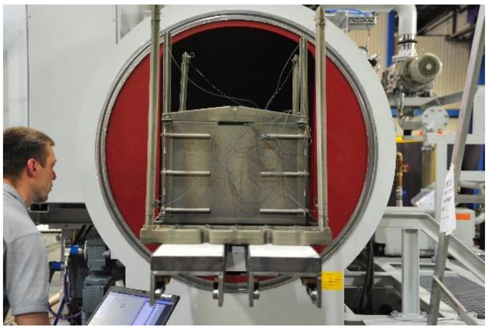

Fig 7: Thermal barrier fitted with Quench Deflector being loaded into LPC batch furnace with TUS frame as part of temperature uniformity survey.

To protect the thermal barrier in the LPC process with gas quench the barrier construction needs to be able to withstand constant temperature cycling and high gas pressures. The design and construction features include;

- **Metal Work** - 310 stainless steel employed to reduce distortion at high temperature combined with internal structural reinforcement.
- **Insulation** - Ultra-high temperature microporous insulation minimizes shrinkage problems.
- **Rivets** - Close pitched copper coated rivets reduce carbon pick up and maintain strength.
- **Lid expansion plate** – Reduces distortion during rapid temperature changes
- **Catches** – Heavy duty catches eliminating thread seizure issues
- **Heat Sink** – Internal heat sink to provide additional thermal protection to data logger

During the gas quench the barrier needs to be protected from Nitrogen N_2(g) or Helium He(g) gas pressures up to 20 bar. Such pressures on the flat top of the barrier would create excessive stress to the metal work and internal insulation / logger. To protect the barrier therefore a separate gas quench deflector is used. The tapered top plate deflects the gas way from the barrier. The unique design means the plate is supported on either four or six support legs. As it is not in contact with the barrier no force is applied directly to the barrier and the force is shared between the support legs. The quench shield in addition to protecting against pressure also acts as an addition reflective IR shield reducing the rate if IR absorption by the barrier in the vacuum heating chamber.

(8.1)

(8.2)

Fig 8. High Performance LPC thermal barrier (8.1) Combined barrier and quench deflector.
(8.2) Separate quench deflector frame (6 legs)

Applying the 'thru-process' monitoring technique there is no hardwired link between the monitoring system within the furnace and the outside world so providing already discussed operational benefits. To achieve real time measurement, as if using trailing thermocouples, the data measurements need to be transferred remotely. This is achieved using a high-performance two-way radio telemetry system. The temperature readings are transmitted as a RF signal from the data logger via external barrier antenna from inside the furnace to a receiver connected to the external monitoring PC (figure 9). The two-way communication protocol allows not only data collection but also direct control of the data logger (reset/download) inside the furnace.

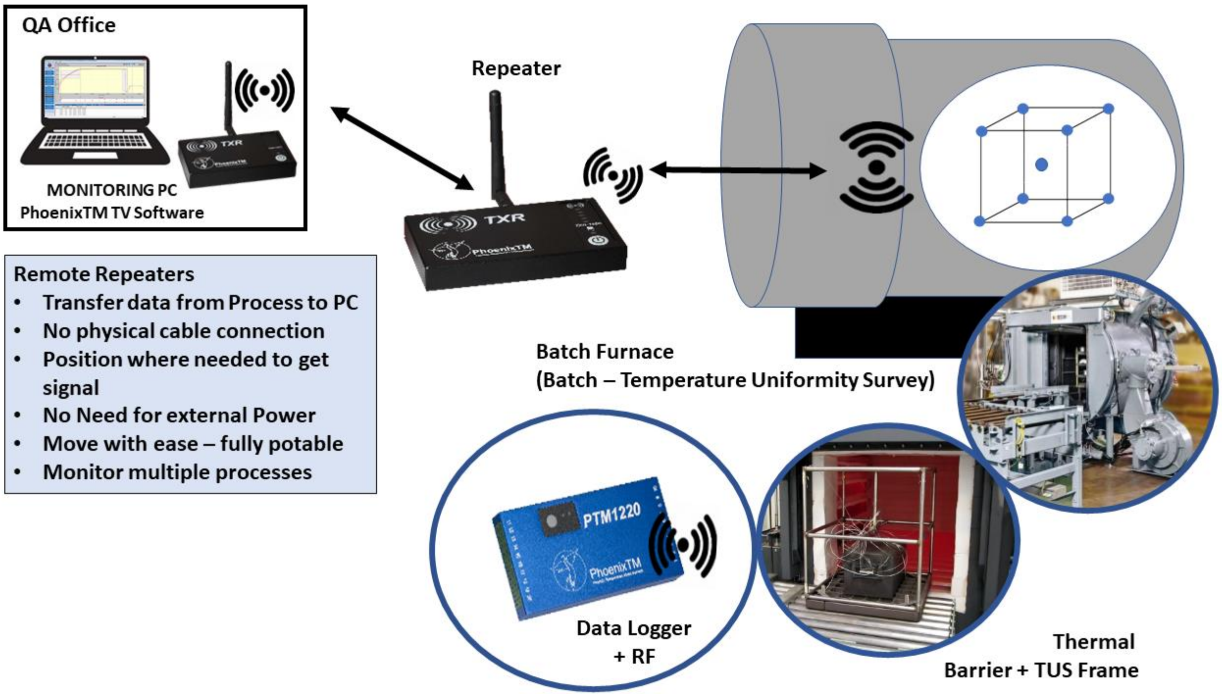

Fig 9: Schematic showing how live TUS data is transferred remotely from the LPC furnace via the two-way RF telemetry system.

Provided with a high performance 'Lwmesh' networking protocol the RF signal can be transmitted through a series of routers linked back to the main coordinator connected to the monitoring PC. The routers are located at convenient points in the process, positioned to maximize signal reception. Being wirelessly connected they eliminate the inconvenience of routing communication cables or providing external power as needed on other commercial RF systems. The routers can be positioned exactly where you need them and be moved with ease when changes are required. Using the repeater network multiple furnaces can be monitored either simultaneously or sequentially. Even in large plants a chain of remote repeaters can transfer the process data direct from the furnace back to the furnace control room or office.

Performing a TUS to comply with AMS2750E /CQI-9 standards require that the survey, analysis of data and reporting is performed in agreement with strict criteria. This can be tedious and lengthy unless using a customised TUS survey software analysis package such as the PhoenixTM Thermal View Survey software.

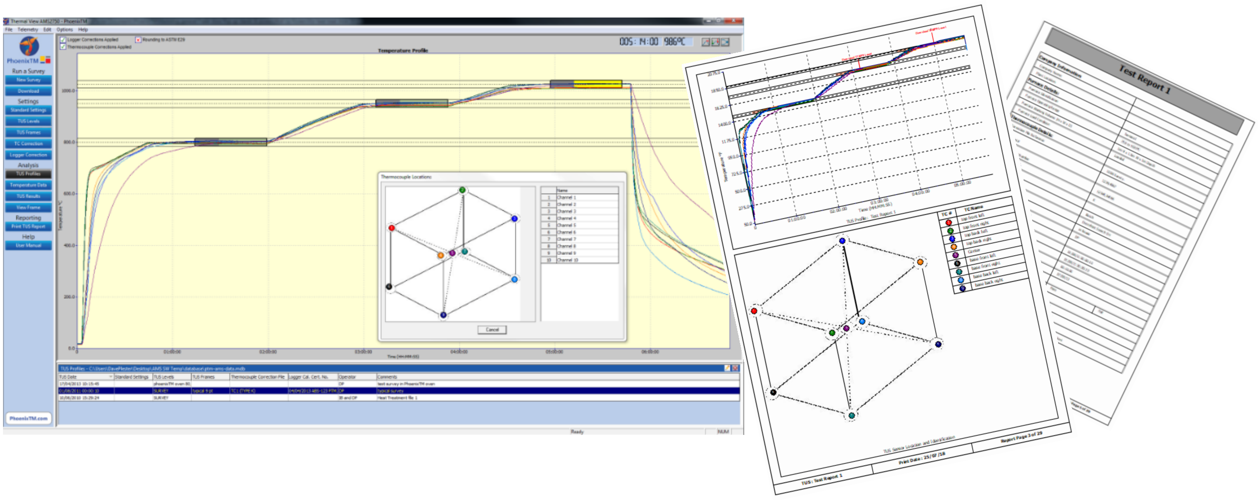

Fig 10: PhoenixTM Thermal View Survey Software showing a TUS Profile at three set survey temperatures. The Probe map shows exactly where each probe is located and easy trace identification. Detailed TUS report generated with efficiency.

Features incorporated into the Thermal View Software to provide full TUS capability include the following;

- **TUS Level Library -** Set-up TUS level templates for quick efficient survey level specification (Survey Temp °F, Tolerance °F, Stabilization and Survey Times)
- **TUS Frames Library -** Show clearly exact TUS Frame construction and probe location using Frame Library Templates – Frame Centre and 8 Vertices.
- **Logger Correction File -** Create a logger correction file to compensate TUS readings automatically from the logger's internal calibration file.
- **Thermocouple Correction File -** Create the thermocouple correction file and use to compensate TUS readings directly.
- **TUS Result Table & Graph View -** For each TUS Temperature level see from the graph or TUS table instantaneous full survey results.
- **Furnace Class Reporting -** Report the specified Furnace Class at each Temperature level.

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Case 2: Sealed Gas Carburizing with Integral Oil Quench – Temperature Profiling

A common process in today's heat treatment industry is the carburizing of lower cost steel products for use in the automotive industry. To achieve this process a popular heat treatment technology used is a sealed gas carburizing furnace with an integral oil quench. For such furnace technology the historic limitation of 'thru-process' temperature profiling has been the need to bypass the oil quench and wash stations. Obviously passing a conventional hot barrier through an oil quench creates potential risk of both system damage from oil ingress, barrier distortion and general process safety.

In such carburizing processes the oil quench rate is critical to both the metallurgical composition of the metal but also elimination of product distortion and quench cracks so the need for a monitoring solution has been significant. Regular monitoring of the quench is important as ageing of the oil results in decomposition, oxidation and contamination of the oil all degrading the heat transfer characteristics and therefore the quench efficiency.

To address the process challenges a unique barrier design has been developed that both protects the data logger in the furnace (typically 3 hours @ 925 °C) but also protects during transfer through the oil quench (typically 15 mins) and final wash station (figure 11).

The key to the barrier design is the encasement of a sealed inner barrier with its own thermal protection with blocks of high-grade sacrificial insulation contained in a robust outer structural frame. Initial attempts to encase the thermal barrier in a sealed enclosure was abandoned due to internal pressure build up in a container softened by holding at the high carburizing temperature.

Fig 11: 'Thru-process' temperature monitoring system for use in sealed carburizing furnace with integral oil quench – (11.1) Barrier Construction (11.2) System in use in Sealed Gas Carburizing Furnace

Case 3: Homogenisation of aluminium logs in a walking beam furnace – Temperature Profiling

After casting, aluminium logs are homogenised before being supplied to the end user, typically extrusion companies. This heat treatment has historically been carried out in batch furnaces but today there is an increasing move to walking beam furnaces for continuous production. The walking beam furnace creates a significant challenge to the temperature monitoring process as the logs rotate as they move through the furnace (12 to 13 hours @ 580 °C). Such rotation would make a trailing thermocouple approach to monitoring impossible but also creates a challenge for a 'thru-process' system which needs to travel though the furnace in the same way as the product.

To address the monitoring challenge a unique cylindrical barrier design is used. As shown in figure 12 the cylindrical barrier is bolted securely (prevent sagging) to the end of a cutdown aluminium log. The diameter of the barrier matches that of the aluminium log so that it can freely rotate with the product through the furnace. Long thermocouples are run along the length of the log running within a cut-out slot to prevent tangling and fixed at locations and depths required.

To provide the thermal protection for the heat treatment duration and space restrictions an evaporative thermal barrier technology is the only viable option. This itself creates challenges as the water tank design needs to prevent loss of water from the tank as the whole system rotates to preserve thermal protection of the data logger.

Fig 12: Cylindrical evaporative thermal barrier technology for use in walking beam aluminium log homogenisation furnace (12.1) Cylindrical barrier design and water tank schematic (12.2) Barrier secured to test aluminium log.

Employing the 'thru-process' temperature monitoring solution major key casting plants have been able to measure the temperature profile of their aluminium log in all three stages of the homogenisation process. With such critical information it has been possible to minimise time in the soak zone to increase productivity and optimise fuel efficiency without compromising product quality.

Case 4: Aluminium Controlled Atmosphere Brazing (CAB)

The aluminium brazing of radiators and condensers is commonly performed using a continuous controlled atmosphere brazing (CAB) process. As part of this brazing process the control of the product temperature is critical to achieve selective melting of the filler alloy (580 – 620 °C) to allow it to flow and fill the joints between the parent metal. As the name of the process suggests the atmosphere in the furnace must be inert and devoid of water or oxygen. If such contaminants are present unwanted oxidation of the aluminium surface can be experienced and formation of highly corrosive HF from flux chemicals can be a risk to thru-process monitoring equipment.

When designing a 'thru-process' temperature profiling system for monitoring a CAB process there are two major technology challenges to address. To allow safe passage through the conveyorized furnace the barrier needs to be low profile, with a safe clearance to allow for deterioration / flux build-up of mesh belts with age reducing furnace height clearance even further. Construction of the barrier and materials used should be made to prevent outgassing of either water or oxygen into the furnace to protect both the controlled atmosphere but also prevent chemical damage of the barrier itself.

Traditional thermal barriers are constructed with unprotected glass cloth covered microporous insulation. Moisture and air trapped in such materials have been shown to severely damage the barrier and reduce its working life due to Hydrofluoric acid formation with flux chemicals.

To overcome such issues a new sealed barrier design has been developed as shown below (figure 13). The front-loaded data logger tray and metal construction limits exposure of insulation materials to potential HF corrosion. The barrier is available with a nitrogen purge facility to remove any risk of outgassing of O_2 (g) into the furnace. Implementing such construction and set-up techniques barriers have been shown to run successfully for in excess of 2500 runs without issue.

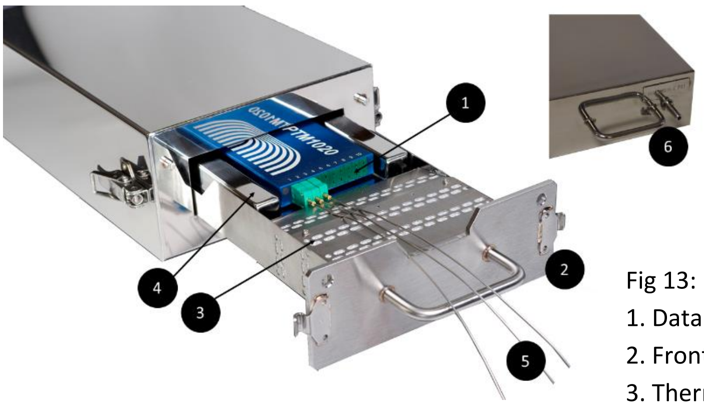

Fig 13: CAB Brazing Thermal Barrier Design
1. Data logger (6 or 10 channels)
2. Front loading logger tray with encapsulated insulation
3. Thermal Breaks reduce conduction to data logger
4. Heat sink provides additional thermal protection
5. Mineral insulated thermocouples attached to radiator fin
6. Optional Nitrogen feed nozzle for insulation purge

Case 5: Aluminium Engine Block T6 Heat Treatment in Rotary Furnace

In modern rotary hearth furnaces such as that shown in figure 14 temperature profiling using trailing thermocouples is impossible as the cables would wind up in the furnace transfer mechanism. Due to the central robot loading and unloading and elimination of charging racks/baskets the use of a conventional thru-process system would also be a challenge.

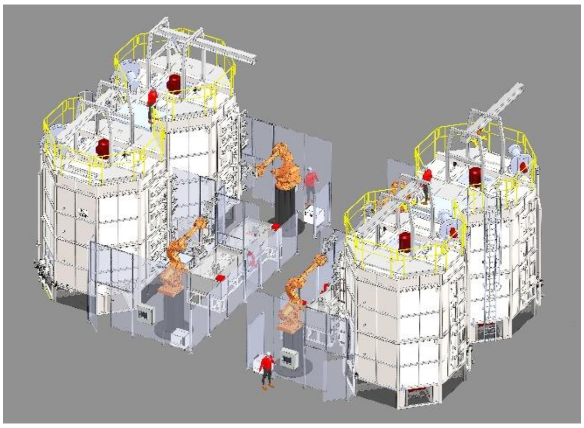

Fig 14: (14.1) Robot loading of combined 'thru-process' system with engine block into BSN rotary T6 furnace. The thermal barrier is designed with a combination of thermal insulation technology capable of fitting in the engine block cavity. With a thermal protection capability of 550 °C for several hours, the system has the ability to monitor the complete T6 process including solution reheat, water quench and aging.

To overcome the loading restrictions a unique thermal barrier small enough to fit inside the cavity of the engine block and allow automated loading of the complete combined monitoring system and product. The system allowed BSN Thermoprozesstechnik GmbH in Germany to commission the furnace accurately and efficiently and thereby optimize settings to not only achieve product quality but ensure energy efficient and cost effective production.

Faced with a similar robotic loading issue the phase evaporative barrier shown in figure 15 was developed. Due to its unique form the barrier has been named the 'Hump Back' barrier. The shape of the barrier was designed to match the shape of the product being processed so that the robot gripper could pick up the barrier and product simultaneously and load them into the rotary furnace.

Fig 15: The 'Hump Back' evaporative thermal barrier with stepped profile to match the product and allow direct loading by robotic gripper Into the furnace with test product.

Summary

Thru-process temperature profiling provides today's heat treater with a safe, efficient means to accurately measure both the furnace and product temperature throughout the whole thermal treatment. With modern innovations and experienced engineering design many systems now offer real time monitoring of processes simply not possible with a trailing thermocouple. With such information, the engineer can understand, control, optimize and validate the process being undertaken with confidence. Not only can the engineer ensure product quality and drive productivity improvements, they can also perform accurate fine-tuning of furnace parameters to achieve potential energy savings.

Author Biography:

Dr Steve Offley (aka "Dr O") is a Product Marketing Manager at PhoenixTM with responsibility for both strategic product management and global marketing of the companies 'thru-process' temperature profiling and surveying systems product range.

Steve joined PhoenixTM in April 2018 after 22 years experience in the industrial temperature profiling market with another well-known company. His role is very varied but a lot of focus has been given to educating the market to the benefits of thru-process temperature profiling through numerous published editorials in various international heat treatment publications.

Steve's academic background includes graduating from Coventry Polytechnic UK with a BSc (Hons) in Applied Chemistry and later PhD from Loughborough University UK in Analytical Chemistry.

Steve (53) lives and works in Cambridgeshire UK, has been married to Beckie for 28 years and has two grown up children Jenny (24) and Christopher (21). His interests include Rugby, Spanish red wine and Photography.
