# Technical challenges and solutions to the complete thru-process temperature monitoring of key heat treatment applications combining heating and quench phases.

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## ABSTRACT

This paper outlines the challenges and benefits of using 'thru-process' temperature profiling and survey systems in today's heat treatment industry. Specific focus will be given to heat treat applications where a quench operation is a key component to the heat treat performance from a metallurgical and product performance perspective yet is often bypassed, during monitoring operations, due to technical challenges experienced. 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 product temperature being heat treated and or ambient conditions in the furnace itself. The resulting temperature profile graph 'thermal fingerprint' 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 address the environmental challenges of heat treatment applications employing quenching technologies including water, salt, oil, and high pressure gases. In each specific heat treat application the design of thru-process technology will be reviewed to address the unique challenges that each quenching method brings to reliable, robust, and accurate temperature monitoring operation. Technology designed specifically for real time monitoring of such processes will be further discussed, and how RF technology is adapted to meet the added challenges of the quench step. An overview of the benefits of monitoring the heating and the quench step will be made with specific reference to heat treat applications such as T6 aluminium solution reheat, austempering of medium to high carbon steels and sealed gas carburising (integral oil quench) or low pressure carburising (high pressure gas quench) of steel products.

**Keywords:** thru-process temperature profiling, heat treat monitoring, quench monitoring, real time monitoring

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## 1. INTRODUCTION

For anyone involved in industrial heating a critical need of any heat treatment process is the ability to measure and control both process and product temperature. The temperature control of the heat treatment application is critical to the metallurgical and physical characteristics of the final product, and hence its ability to perform its intended function. Achieving the correct maximum product temperature, time @ temperature (soak) can be essential to, not only product quality, but the efficiency (energy use and productivity) of the process.

Despite the fact that modern furnaces now are supplied with sophisticated control systems they are still not capable of truly giving an accurate picture of the heat treatment process from a product perspective. Temperature sensors positioned along the furnace give only a snapshot of what the environmental temperature is at that specific point in the furnace. Furnace controllers, as the name suggests, can give confidence that the process heating is performed in a controlled manner but will never give an accurate view of what the actual product temperature is. IR pyrometers and thermal imagers can provide surface temperature measurements but require, line of site, so limit the areas of the product that can be measured. Products loaded at the bottom of a product basket for example may be impossible to measure accurately. Without sophisticated mathematical modelling the surface temperature, although helpful, will not give core temperature information which in most situations is the more critical. As with air sensors, being fixed, typically IR sensors only give information at that specific furnace location which prevents accurate calculation of soak times at critical temperatures. Without additional information, soak times and temperatures may need to be extended well beyond the target to guarantee that the heat treat process is completed with confidence, but with an obvious compromise to throughput and energy conservation.

To fully understand the operational characteristics of the heat-treat process, it is necessary to measure both the environment and product temperature continuously as it travels through the process. Such technique provides what is referred to as a 'temperature profile' which is basically a thermal fingerprint for that product in that particular furnace process. This thermal fingerprint will be unique but will allow understanding, control, optimisation, and validation of the heat treat process. Historically the measurement of the product temperature profile has been performed by one of two methods. The more traditional basic approach has been to apply the principle referred to as ‘Trailing Thermocouples’. A very long thermocouple is attached to the product which is manually fed through the furnace as the product travels through. The data logger measuring the live temperature reading is kept external to the furnace. Although possible this technique is limited in the information it provides and comes with many practical hurdles[1]. An alternative approach to ‘Trailing Thermocouples’ is the application of ‘Thru-process temperature profiling’. In contrast to ‘Trailing thermocouples’ the data logger travels with the product, through the furnace. The data logger is protected by an enclosure, referred to as a thermal barrier, which keeps the data logger at a safe operating temperature (Fig 1).

Fig. 1 - Thru-process temperature profiling system shown entering a gas carburising furnace, heat treating automotive gears. The data logger travels through the Furnace, protected by a thermal barrier, with the product being monitored collecting a thermal profile of the heat treatment process.

Temperature readings recorded by the data logger from multiple short length thermocouples can be retrieved post run. Alternatively, if feasible, the data can be read in real time as the system passes through the furnace, using a two-way RF telemetry communication option. The resulting temperature profile graph provides a comprehensive picture of the thermal process. The self-contained design of the monitoring system allows use in continuous and semi-continuous multi-stage processes, which may be separated by distance or physical barriers such as automated doors. This further permits the potential monitoring of the often overlooked critical quench stage of the heat treat process. As discussed in this paper, the design of unique thermal barriers allows not only the monitoring of the heating phase of many applications but also different quench media including water, oil, salt and high pressure gas. Such information is invaluable to fully understand different heat treat processes to guarantee correct metallurgical transitions are achieved, without physical quench distortion or material damage (cracking).

## 2. T6 ALUMINIUM SOLUTION REHEAT MONITORING

To meet the challenges of the T6 process, the conventional thermal barrier design employing microporous insulation is replaced with a water tank design, with thermal protection using an evaporative phase change temperature control principle. Evaporative technology uses boiling water to keep 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. Passing through the water quench, the water tank re-fills allowing continued protection through the final ageing furnace.

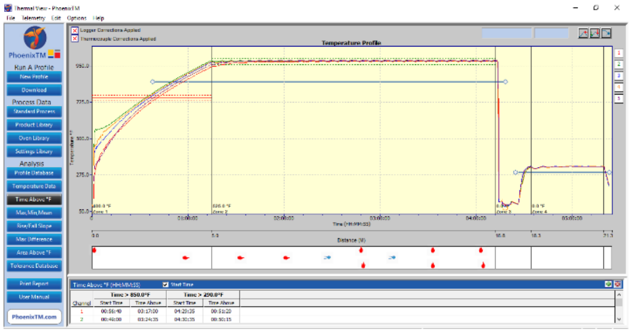
The TS06 thermal barrier design (Fig 2) incorporates a further level of protection with an outer layer of insulation blanket contained within a structural outer metal cage. The key role of this material is to act as an insulative layer around the water tank to reduce the risk of structural distortion from rapid temperature changes, both positive and negative in the T6 process.

Fig. 2 - T6 Aluminium heat treat monitoring of engine blocks. Phased evaporative thermal barrier design allowing safe transition through furnace and quench.

Fig. 3 – (3.1) TS06 Thermal barrier innovative IP67 bi-directional rubber gasket seal. (3.2) Quick easy installation of Mineral Insulated (MI) thermocouples and RF antenna aerial.

Passing through the T6 water quench, the data logger needs to be protected from water damage. This is achieved in the system design by combining a fully IP67 sealed data logger case and thermal barrier water tank front face plate through which the thermocouples exit. Traditionally in heat treatment applications, mineral insulated thermocouples are sealed using robust metal compression fittings. Although reliable, the compression seals are difficult to use requiring long set-up times. To overcome the frustrations of compression fittings, an alternative innovative thermocouple sealing mechanism has been designed by PhoenixTM for use on the T6 thermal barrier (Fig 3).

For a process time as long as the T6, real time monitoring capability is a significant benefit. The unique 2-way RF telemetry system used on the PhoenixTM system helps address the technical challenges of the three separate stages of the process. The RF signal can be transmitted from the data logger through a series of routers linked back to the main coordinator connected to the monitoring PC. The routers being wirelessly connected are located at convenient points in the process (solutionizsing furnace, quench tank, ageing furnace) to capture all live data without any inconvenience of routing communication cables. A major challenge in the T6 process is the quench step from a RF telemetry perspective. A RF signal cannot escape from water in the quench tank. To overcome this limitation, an innovative 'catch up' feature is implemented. Once the system exits the quench and RF signal is re-established, any previously missing data is retransmitted, guaranteeing full process coverage.



| Channel | Time > 850.0°F Start Time | Time > 850.0°F Time Above | Time > 290.0°F Start Time | Time > 290.0°F Time Above |
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| 1 | 00:56:40 | 03:17:00 | 04:29:35 | 00:51:20 |
| 2 | 00:46:00 | 03:24:35 | 04:30:35 | 00:50:15 |

Fig. 4 - Complete temperature profile of the aluminium T6 process (solutionising, water quench & ageing) allowing understanding of part heat treat behaviour and application of control and optimisation strategies to guarantee product quality.

Collecting the complete product temperature profile (Fig 4) through the entire T6 process is invaluable to understanding the heat treat process and allowing control and optimisation. Obtaining the quench curve the rate of cooling of the aluminium parts at different locations in the product basket can be calculated. Such information is vital to ensure all parts of the product meet the desired cooling specification to allow alloy elements to precipitate out of solution and form the required "super saturated solid solution" necessary to give the required metallurgical properties of the aluminium alloy. At the same time, differential cooling rates for different thermal masses or excessive cooling rates can be identified – either could result in part distortion/ warpage or at worse quench cracking.

## 3. GAS CARBURISING WITH OIL QUENCH

The carburising process is achieved by heat treating the product in a carbon rich environment typically at a temperature of 850 – 1050 °C. The temperature and process time significantly influences the depth of carbon diffusion and associated surface characteristics. Critical to the process is following diffusion, a rapid oil 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.

Despite the dramatic appearance of a sealed gas carburising furnace, with its characteristic belching flames, (Fig 1) from a monitoring perspective the most challenging aspect of the process is not the heating but the oil quench cooling. For such furnace technology, the historic limitation of 'thru-process' temperature profiling has been the need to bypass the oil quench and wash stations missing a critical process step from the monitoring operation. 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.

Fig. 5 - 'Thru-process' temperature monitoring system oil quench compatible thermal barrier design.
1. Robust outer structural frame keeping insulation and inner barrier secure.
2. Internal thermal barrier - completely sealed with integral microporous insulation protecting data logger. 3. Mineral insulated thermocouples sealed in internal thermal barrier with oil tight compression fitting. 4. Multi-channel high temperature data logger. 5. Sacrificial insulation blocks replaced after each run.

Monitoring of the quench is important as ageing of the oil results in decomposition (thermal cracking), oxidation and contamination (e.g. water) of the oil, all degrading the viscosity, heat transfer characteristics and quench efficiency. Control of physical oil temperature and agitation rates is also key to oil quench performance. Quench monitoring allows economic oil replacement schedules to be set, without risk to process performance and product quality.

To address the process challenges, a unique thermal 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 [2]. 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 (Fig 5). Monitoring the oil quench in carburisation gives the operator a unique insight into the products specific cooling characteristics which can be critical to allow optimal product loading, and process understanding and optimisation. Monitoring the cooling curves for different locations on complex parts allows not only validation that the carburisation has been successful over the whole surface, but also control and reduction of distortion risks. From a scientific perspective the quench temperature profile trace, although only a few minutes in duration, is complex and unique. From a zoomed quench trace (Fig 6) taken from a complete carburising profile run, the three unique heat transfer phases making up the oil quench cool curve can be clearly identified.

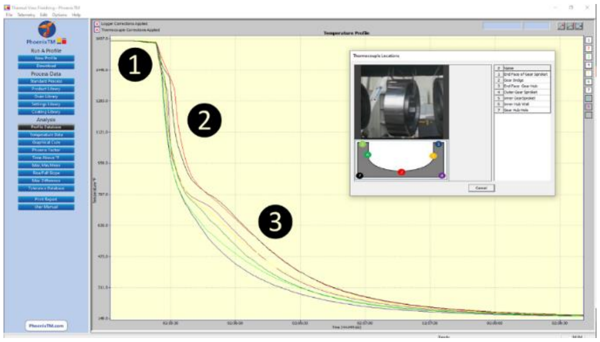

Fig. 6 - Oil quench temperature profile for different locations on an automotive gear test piece showing the three distinct heat transfer phases (1) Film Boiling “Vapor blanket” (2) Nucleate Boiling (3) Convective Heat Transfer.

## 4. AUSTEMPERING WITH SALT QUENCH

In some heat treat applications, often due to temperature requirements, salt is used as an alternative to oil as a quench media. Salts have excellent thermal stability and with temperature ranges up to typically 700 °C, significantly higher than possible with oil, slower cooling can be achieved reducing distortion issues. A classic heat treat application where salt quenching is ideal is that of austempering of medium and high carbon steels. The process is applied in the heat treatment of typical products such as lawnmower blades to give increased ductility, toughness and strength. The part is heat treated to above 800 °C and soaked to austenitise before then being quenched in salt. The molten salt cools the part to just above the martensite phase transition temperature typically 200 °C, and isothermally holds it in the bainite region before a final air cool. Monitoring such processes uses the same principle and thermal barrier technology as that discussed for oil quenching (Fig 5). Monitoring challenges faced with salt revolve around the specific gravity and higher quench temperatures. The thermal barrier needs to be larger than used for an oil quench equivalent and it needs to be securely fixed to the product basket and weighed down to allow safe smooth submersion. Salt build-up needs to be cleaned post process and the single-use sacrificial insulation replaced.

## 5. LOW PRESSURE CARBURISATION (LPC) – GAS QUENCH

Increasing in popularity in the carburising market is the use of batch or semi-continuous batch low pressure carburising furnaces. Carburising in a vacuum with acetylene, as the hydrocarbon source, at 980 °C provides a typical case depth of 0.8-1.0 mm. Following the diffusion phase, the product is transferred to a high-pressure gas quench chamber where the product is rapidly gas cooled/quenched using typically $N_2$ or helium at up to 20 bars. In such process the monitoring technical challenge is twofold. The thermal barrier must be capable of protecting against not only heat during the carburising, but very rapid pressure and temperature changes inflicted by the gas quench.

Fig. 7 - Thermal barrier designed for protecting the data logger against severe temperature and pressure changes in the LPC $N_2$ / Helium Gas quench at 20 bar pressure. Quench deflector shown fitted to barrier.

It is obviously important to protect the data logger from thermal damage, but the thermal barrier protecting the data logger needs to be robust enough to protect against physical damage in both metal work (distortion/warpage) and thermal insulation (compaction/shrinkage). The life expectancy of the system (regular use) requires the correct specification of materials and construction design. A key part of the design is the tapered lid quench deflector protecting it from potential damage from both top and bottom pressure. The lid is supported either on 4 or 6 legs with no contact to the barrier ensuring that no force is directed through the barrier lid. The force is shared equally between the support legs.

## References

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