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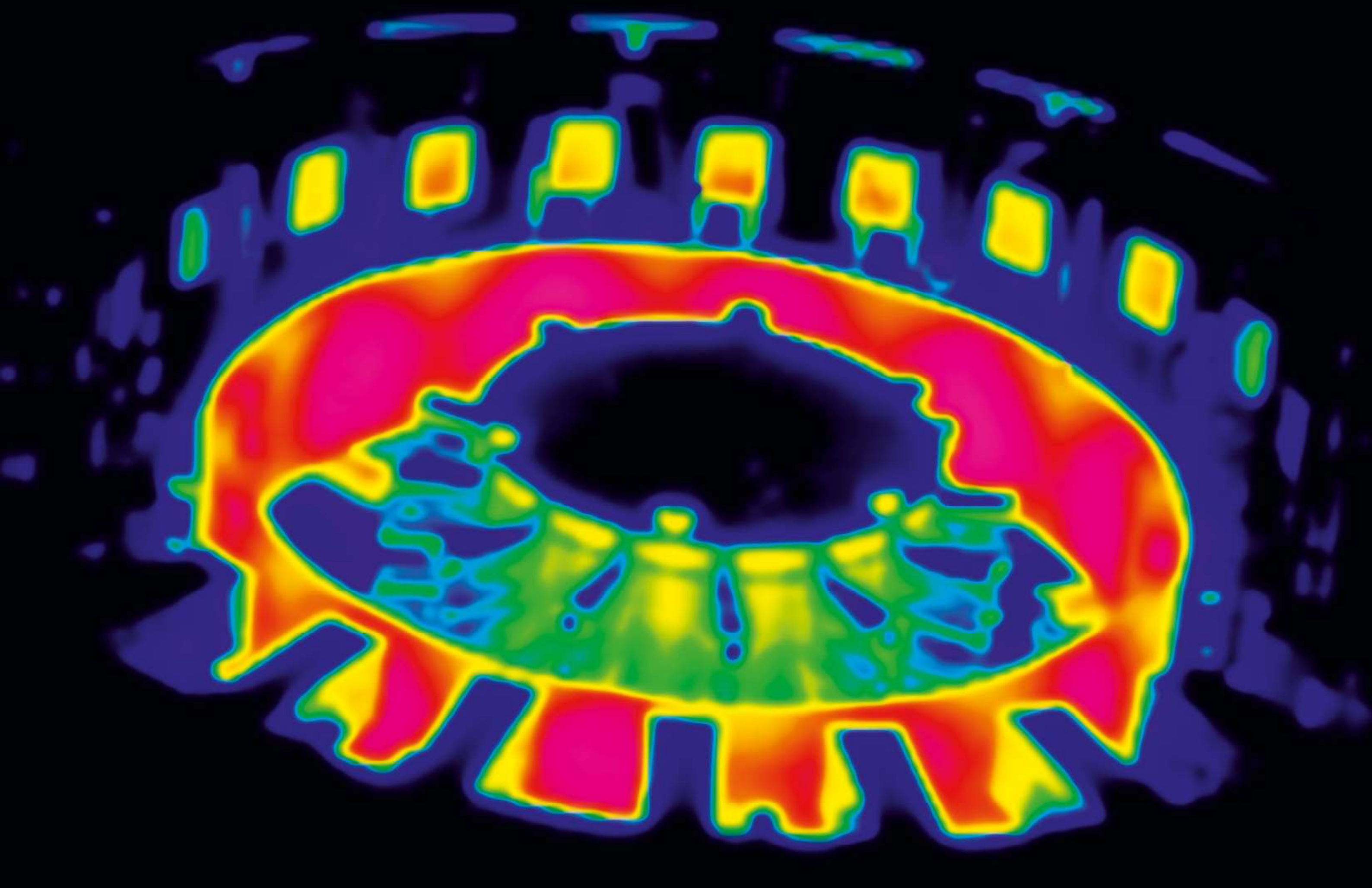

## Conference Proceedings

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*Conference Proceedings*

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# Monitoring product temperature in a combined carburising furnace and oil quench bath

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**Abstract**

The following paper describes a through process temperature monitoring technique that can be used to monitor the combined heat treatment and oil quenching of parts such as automotive gears. The temperature profile traces obtained can be insightful to understand the different heat transfer behaviour, at the product level, both during the heat treatment and quenching steps. Variations in heat transfer efficiency can be identified for both different locations on an individual gear part or different sizes of gear part (domestic & commercial gear parts).

The thermal barrier design developed for use in combined heat treatment and oil quench applications will be discussed. Combining different thermal protection concepts will be shown to safely protect the encapsulated data logger not only from the high temperature of the carburising furnace but the rapid temperature change and oil ingress when plunged into the oil quench.

**Keywords**

Temperature Measurement, Thru-process, Quench Monitoring

## 1 Gas Carburisation

Carburising 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 carburising process is achieved by heat treating the product in a carbon rich environment (Figure 1) 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 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.

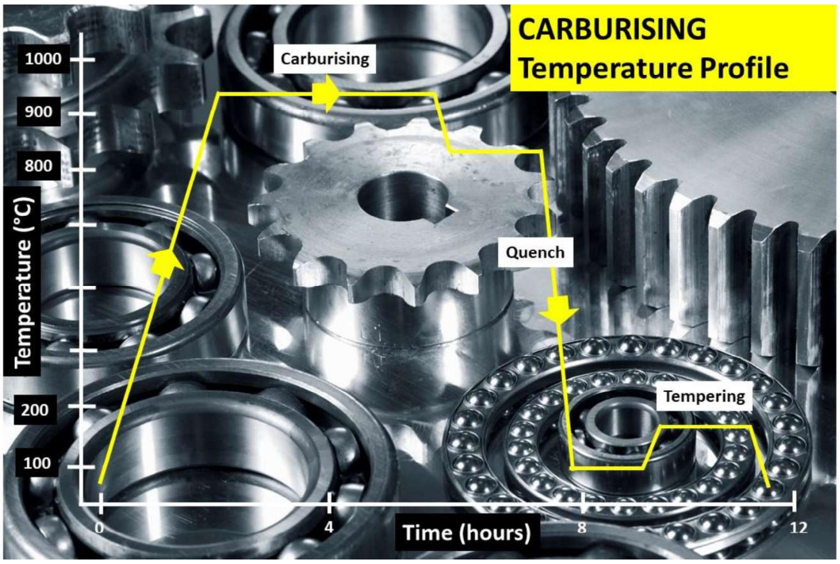


Figure 1: Typical carburising heat treat temperature profile showing the critical temperature/time steps (i) Carburisation (ii) Quench (iii) Temper

## 2 Critical Process Temperature Control

As discussed, the success of carburisation is dependent on accurate, repeatable control of the product temperature and time at temperature, through the complete heat treatment process. Important to the whole operation is the quench, in which the rate of cooling (product temperature change) is critical, to achieve the desired microstructural changes to give the surface hardness. It is interesting that the success of the whole heat treat process, can rest on a process step which is so short (minutes), in terms of the complete heat teat process (hours). Getting the quench correct, is not only essential to achieve the desired metal microstructure, but also to ensure that the physical dimensions and shape of the product are maintained (no distortion/warping) and issues such as quench cracking are eliminated.

To achieve the desired carburised product, it is necessary to control and hence monitor the product temperature through the three phases of the heat treat process. Conventionally product temperature monitoring would be attempted using the traditional 'trailing thermocouple method'.

As detailed previously [Offley 2019] for many modern heat treat processes including Carburisation the 'trailing thermocouple method' is difficult and often practically impossible. The movement of product/product basket from stage to stage, often from one independent sealed chamber to another, makes the monitoring of the complete process a significant challenge.

Thru-process temperature monitoring as a technique overcomes such technical restrictions [Offley 2019]. The data logger is protected by a specially designed thermal barrier, therefore, can travel with the product through each stage of the process measuring the product/process temperature, with short, localised thermocouples that will not hinder travel. The careful design and construction of the monitoring system is important to address the specific challenges the different heat treat technology brings.

Presently, the most common traditional method of gas carburising for automotive steels is often referred to as sealed gas carburising. In sealed gas carburising automotive parts are surrounded by an endothermic gas atmosphere. Carbon is generated by the redox Boudouard reaction during the carburisation process typical at 850–1000 °C. Despite the dramatic appearance of a sealed gas carburising furnace, with its characteristic belching flames, (Figure 2) 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.

# 3 Experimental set-up

## 3.1 Experimental set-up – oil quench temperature monitoring technology

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 (Figure 2). The key to the barrier design is the employment of three phase thermal protection. The data logger is encased in an inner IP67 thermal barrier protecting from oil ingress. This inner thermal barrier has its own unique microporous insulation and heat sink (phase change @ 58 °C) designed to keep the data logger below 85 °C. The sealed inner barrier is further insulated with blocks of high-grade sacrificial insulation contained in a robust outer structural frame giving structural rigidity and strength (Figure 3). The outer insulation blocks are contaminated by oil during the quench step so are replaced between runs.


Figure 2: 'Thru-process' temperature monitoring system for use in a sealed carburising furnace with integral oil quench – (2.1) Monitoring system entering furnace with thermocouple fixed to automotive gears, product test pieces. (2.2) System exiting oil quench tank. (2.3) System inserted into wash tank with product basket

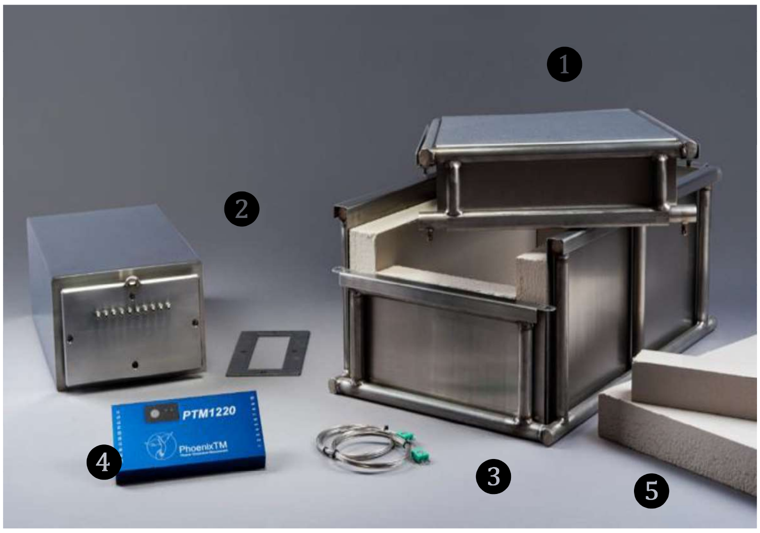


Figure 3: 'Thru-process' temperature monitoring system oil quench compatible thermal barrier design

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 fittings; 4. Multi-channel high temperature data logger; 5. Sacrificial insulation blocks replaced after each run

For all experimental temperature profile runs the data logger recorded from 10 thermocouples, every 0.5 s during the entire temperature-time cycle. The sample interval of 0.5 s was chosen to give the best profile resolution, particularly during the quench step, to accurately capture the rapid temperature changes experienced by the product. The profile run was downloaded to the PC after the profile test was completed. It is possible to also monitor the profile in real time using RF telemetry. The temperature data (min sample rate 1 s) is transmitted from the datalogger, via a sealed external antenna, to a receiver unit connected directly to the monitoring PC. Although live RF data transmission through the oil in the quench is not physically possible the systems innovative ‘catch up’ feature allows transfer of this data once reception is re-established post quench.

### 3.2 Experimental set-up – furnace and product

This experimental work was carried out on gear main bodies made of 20MnCr5 case hardening steel. The test pieces employed were used without formed gear teeth. The two size classes used have a mass of approx. 1 kg (size category passenger cars) or 8 kg (size class commercial vehicles) respectively, as shown in Figure 4.

The tests were carried out in a multi-purpose Aichelin type furnace with oil quenching and a batch volume of 1,100 × 600 × 650 $mm^3$ (max 650 kg). The processes were driven without a carburising atmosphere. The temperature-time profiles were, however, based on real carburising processes.

Figure 5 shows a photograph of the profile system set-up in which the thermal barrier was placed on the batch grate at a maximum distance from the load. Thermocouple pilot holes were drilled into the gear bodies with a diameter of 1.1 mm at various positions. Thermocouples (1.0 mm type K mineral insulated) were inserted into the corresponding holes to the required depth. The thermocouples were secured to the gear against movement by means of physical bolt strain relief. All holes were made from one side of the disc, so that the heat transfer on the side of the disc to be measured was not disturbed by the thermocouple exit.

| Measure | Passenger Car (mm) | Commercial Vehicle (mm) |
|---|---|---|
| Outside radius $r_a$ | 57,5 | 115 |
| Inside radius $r_i$ | 20 | 40 |
| Height h | 30 | 60 |
| Hub thickness c | 7,5 | 15 |
| Web thickness b | 7,5 | 15 |
| Gear rim thickness b | 7 | 14 |
| Web location d | 15 | 30 |
| Radius $r_c$ | 4 | 8 |
| Radius $r_c$ | 4 | 8 |

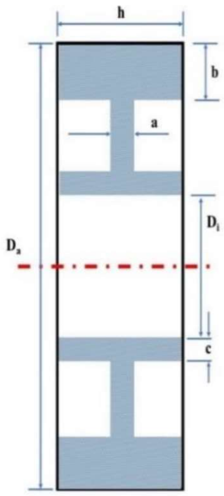


Figure 4: Dimensions of gear main bodies tested during investigation. The two size classes used have a mass of approx. 1 kg (size category – passenger cars) or 8 kg (size category – commercial vehicles)

Figure 5: 'Thru-process' temperature monitoring system configured with test gear main bodies with thermocouples located at different locations on the gear body

| Description | Set Point Temperature (°C) | Duration (min) |
|---|---|---|
| Oven entry | 850 | 64 |
| Hold | 850 | 30 |
| Preheating | ≥ 945 | 45 |
| Cooling | ≤ 865 | 27 |
| Hold | 860 | 50 |
| Quench | 60 | 40 |

Table 1: Carburisation process temperature profile characteristics with temperatures and corresponding times in each phase of the furnace program. Longest process tested – Commercial vehicle (256 min). The passenger car process was shorter at 120 min; (90 min @ 860 °C Oven entry and hold, 30 min @ 60 °C Quench)

# 4 Experimental results

## 4.1 Experimental results – thermal barrier performance

The custom thermal barrier successfully passed through the complete carburising process without damage from either the heat of the furnace, rapid temperature change within the quench or from the physical oil itself. As shown in Figure 6 at the end of the process, the maximum temperature within the wear insulation was < 360 °C (profile line trace 2). Inside the data logger a maximum value of < 40 °C was reached (profile line trace 3). The data logger temperature is still well below the allowable safe maximum operating temperature of 85 °C and the phase change material used in the heat sink, with a melting temperature of 58 °C, remained un-melted at the end of the cycle time. It is therefore proposed that longer residence times or higher furnace temperatures would be also possible. For more demanding processes larger thermal barriers with a larger internal encapsulated barrier and increased quantities of sacrificial thermal insulation block would offer even more thermal protection.

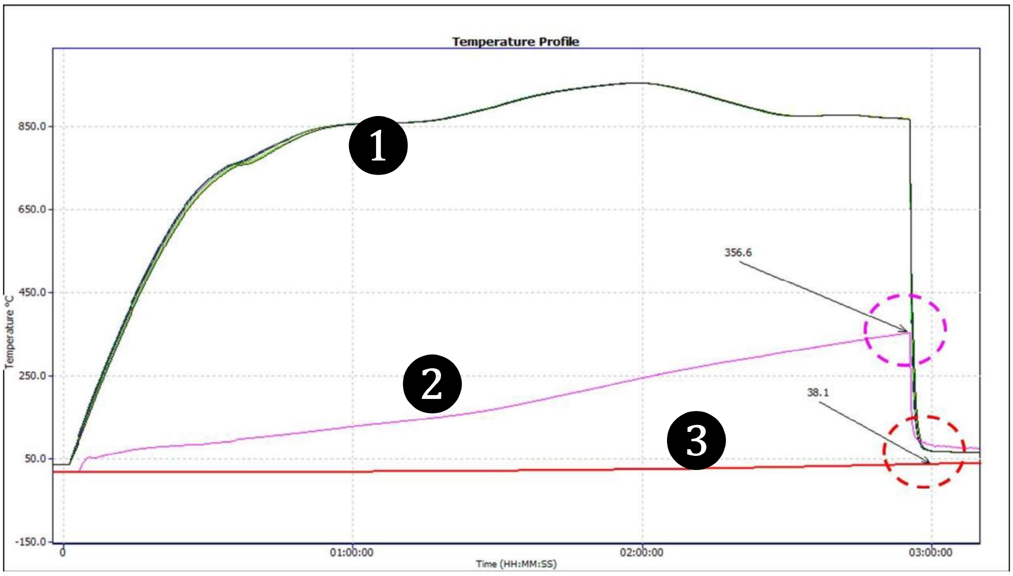


Figure 6: Carburisation process temperature profile characteristics with temperatures and corresponding times in each phase of the furnace program. Longest process tested Commercial vehicle (256 min) (1) Gear temperature profile (2) Sacrificial insulation temperature (3) Data logger temperature

## 4.2 Experimental results – gear cool curve in quench

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 optimization. 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 (Figure 7) taken from a complete carburising profile run the three unique heat transfer phases making up the oil quench cool curve can be clearly identified.

1. Film Boiling “Vapor blanket”: The oil quenchant creates a layer of vapor (Leidenfrost phenomenon) covering the metal surface. Cooling in this stage is a function of conduction through the vapour envelope. Slow cool rate since the vapour blanket acts as an insulator.

2. Nucleate Boiling: As the part cools the vapour blanket collapses and nucleate boiling results. Heat transfer is fastest during this phase typically two orders of magnitude higher than in film boiling.

3. Convective Heat Transfer: When the part temperature drops below the oil boiling point the cooling rate slows significantly. The cooling rate is exponentially dependent on the oils viscosity.

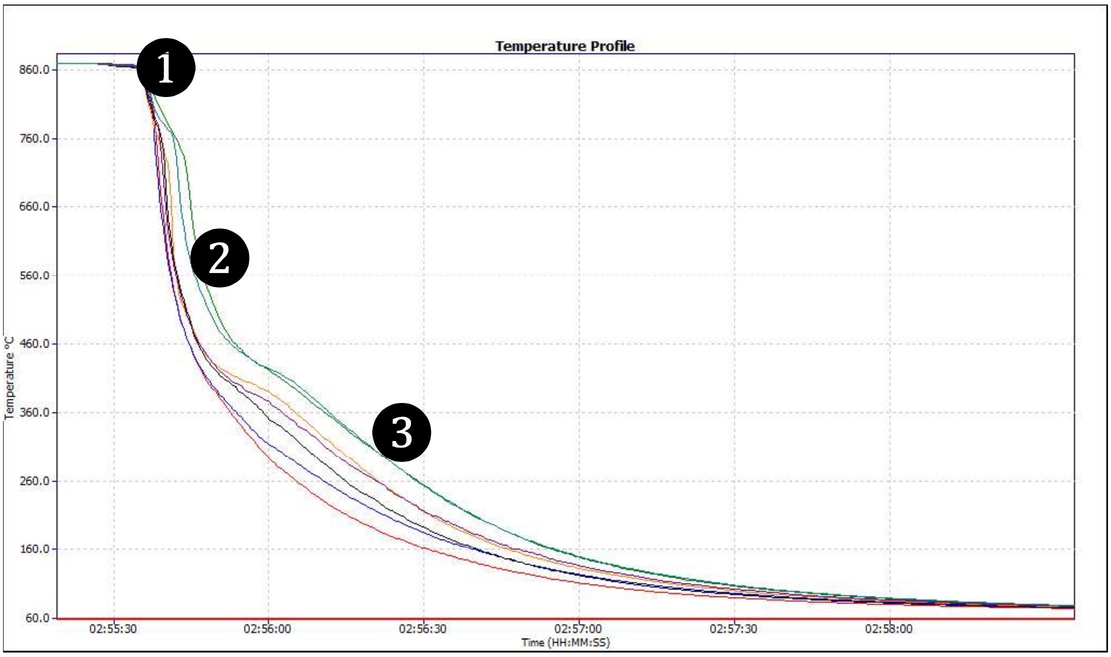


Figure 7: Oil quench temperature profile for different locations on an automotive gear test piece showing the three distinct heat transfer phases (1) Film boiling "Vapor blanket" (2) Nucleate boiling (3) Convective heat transfer

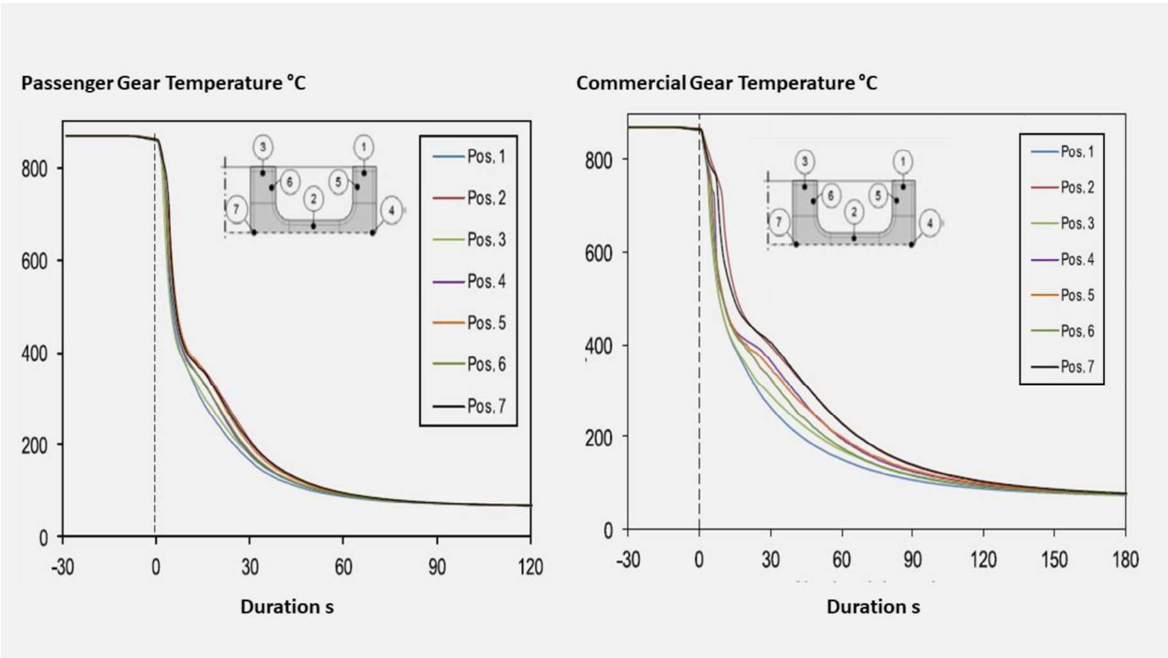


Figure 8: Oil quench temperature profile for different locations on an automotive gear test pieces for two size classes (left) passenger and (right) commercial

The results of the temperature profile quench cool curves for the two gear size classes, passenger car and commercial vehicle, using the carburisation heat treat furnace programs (Table 1) are shown in Figure 8. As expected, the cooling curves are unique to the product and significantly influenced by the thermal mass of the product. The cool curve for the commercial vehicle gear is significantly slower than the passenger car being eight times heavier. For both gear sizes it can be seen that in the nucleate boiling phase and particularly convective cooling phase that there is clear separation of the individual temperature traces. This indicates that different positions on the gears are cooling at different rates governed by variation in heat transfer characteristics. The profile trace separation is clearly more pronounced for the larger commercial gear than the passenger gear. Interestingly for both tests it can be seen that the fastest cooling rate is observed at the end faces of the sprocket (position 1) and hub (position 3).

# 5 Summary

As discussed in this article one of the key process performance factors associated with gas carburisation is the control and monitoring of the product quench step. Employing an oil quench, the measurement of such operation is now very feasible as part of heat treat temperature monitoring. Innovations in thru-process temperature profiling technology offer specific system designs to meet the respective application challenges of measuring the product cooling curve in the oil quench as part of the production flow.

Monitoring the quench process allows a full understanding of how an individual product or products within a product basket are quenched. The influence on product size, thermal mass and design construction on the cool curve can be accurately determined, to confirm that the carburisation process has been achieved to specification whilst avoiding possible distortion and worse quench cracking risks.

Routine 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. Quench monitoring therefore further allows economic oil replacement schedules to be set, without risk to process performance and product quality.

**Acknowledgement**

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**References**

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