Employing ‘thru-process’ temperature profiling to Understand, Control and Maximize the efficiency of your Porcelain Enamel Coating process.

……Getting to the heat of it!

Author: ***Dr Steve Offley “Dr O”***
Product Marketing Manager PhoenixTM

Introduction – The need for accurate product temperature measurement

For anyone involved in porcelain enamel (Vitreous enamel) a critical need of any firing process is the ability to measure and control both process and product temperature. The temperature control of the firing application, typically between 1,380 and 1,560 °F (750 and 850 °C) is critical to ensure that the powdered glass “Vitreum” fuses correctly to the substrate. Aesthetic and functional properties of the porcelain enamel surface coating are very temperature dependent. Temperature and rate of temperature change of the product will influence the melt, flow and fusing characteristics of the final coating and its performance.

Despite the fact that modern furnaces/ovens now are supplied with sophisticated control systems they are still not capable of truly giving an accurate picture of the firing 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. As with air sensors, being fixed, typically IR sensors only give information at that specific furnace location which prevents accurate calculation of firing times at critical temperatures. Without additional information firing times and temperatures may need to be extended well beyond the target to guarantee that the firing process is completed with confidence but with an obvious compromise to throughput and energy consumption.

Product Temperature Profiling

To fully understand the operational characteristics of the firing process it is necessary to measure both the environment and product temperature continuously as it travels through the process. This 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, optimization and validation of the porcelain enamel firing process as summarized in Table 1.

Value Statement	Benefit
Product Quality	Confirm accurately that the porcelain enamel firing specifications (Time @ Temp) to give physical and cosmetic properties has been met. Prevent costly rejects or rework.
Problem Solving	Identify the cause of furnace problems quickly. Suggest and prove corrective action with process data. Reduce production downtime to a minimum.
Process Optimization	Maximize the productivity and efficiency of your process with confidence. Optimize settings to improve throughput, fuel economy with no risk to firing quality. Optimize new product processes with ease and efficiency eliminating delays to production.
Regulatory Compliance	Generate the process validation certification necessary to prove process control for quality standards.

Table 1: Top level Benefits and Value of Temperature Profiling

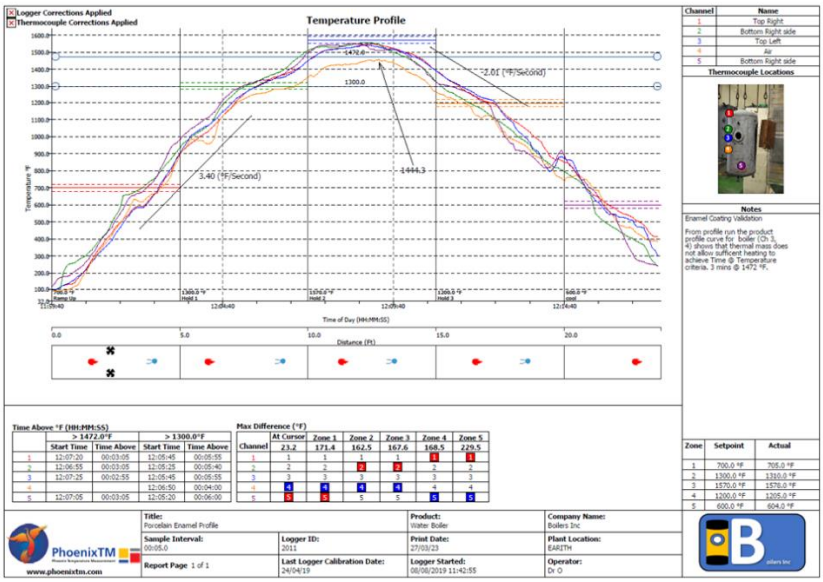
Historically the measurement of the product temperature profile has been performed by one of two methods. The more traditional basic approach has been to apply the principle referred to as 'Trailing Thermocouples'. A very long thermocouple is attached to the product which is manually fed through the furnace as the product travels through. The data logger measuring the live temperature readings is kept external to the furnace. Although possible this technique is limited in the information it provides and comes with many practical hurdles as detailed in Table 2. 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 logger at a safe operating temperature (See Figure 1). Temperature readings recorded by the data logger (See Figure 3), 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 (See Figure 2) provides a comprehensive picture of the thermal process.

	'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 a 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 (true furnace loading conditions)
Safety	Operators close to furnace to feed thermocouples (H&S)	No issues
Live Data Review	Yes if data logger connected to PC	Yes if RF Telemetry option used
Cost	Long thermocouples expensive to replace. Regular replacement risk.	Initial Investment cost of system

Table 2: Table showing the numerous benefits of 'Thru-process' temperature monitoring over traditional 'trailing thermocouples' methodology.

Figure 1: 'Thru-process' temperature profiling system entering a continuous porcelain enamel firing furnace. The thermal barrier protecting the operational data logger travels along with product test piece (boiler tank) being monitored, hung from the overhead conveyor. Short thermocouples attached, to key parts of the product, record temperature during the journey at specified intervals recording the accurate temperature of the product/ enamel surface interface.

Figure 2: Typical Temperature Profile obtained from the 'Thru-process' system. The temperature vs time graph shows an accurate record of the critical boiler tank temperature at each point through the porcelain enamel furnace process.



Monitoring critical factors effecting the product firing conditions

When focusing on the porcelain enamel firing process there are many factors that can influence the product firing conditions and resulting temperature profile. It is helpful to break the factors down into three specific groups of Product, Furnace and Process. Table 3 shows how the big three play a critical role in the behaviour of the firing characteristics.

Factors influencing the porcelain firing conditions shown in the temperature profile	
PRODUCT	
Product Material	Thermal Conductivity & Product Starting Temperature
Product Thermal Mass	Thickness (Thin Panel vs Heavy Structural Members) & Heat up rate
Product Location	Heating Uniformity @ Different locations (Top to bottom / Left to Right / Line of sight of IR)
FURNACE	
Furnace Type	Box / Conveyorized
Heating Technology	IR (Indirect Heated Radiant Tubes) IR (Resistively heated Coils/Wire)
Settings	Heating Ramp Up and Set-points (Zone to Zone)
Line Speed	Product Throughput
PROCESS	
Process damage	Hot & Cold Spots - ineffective furnace insulation (Ceramic Block/Brick/Matting) - Faulty IR emitter coils / tubes
Loading Patterns	Furnace loading (product mass causing furnace temperature drops)
Heat Stability	Furnace Stabilization times from startup & seasonal variations

Table 3: Table showing the factors influencing porcelain firing conditions.

Temperature Profiling Technology

Data logger Design and Operation

At the heart of profiling system is the temperature data logger designed specifically for use in a hostile industrial process. A variety of designs are available with choice of channel configurations 6, 10 or 20 and thermocouple types (K, N etc). To guarantee the maximum measurement accuracy the data logger offers a high performance cold junction compensation (CJC) feature. During transfer through the process in the thermal barrier any change in the internal temperature of the data logger, which will normally create a thermocouple reading error, will be compensated for automatically. The accuracy of the data logger over an operating temperature of 32 to 175 °F (internal data logger temperature) is therefore maintained at ±0.5 °F (Type K).

Figure 3: Multi-channel data logger designed for thru-process use.

To maximize the detail / resolution of the temperature profile the data logger memory is maximized (3.8 M data points) allowing fast sampling down to 0.2 s across all thermocouples (up to 20 channels). Supplied with customer replaceable, commercially available, alkaline batteries the data logger can be used efficiently for many weeks and runs before replacement is necessary.

Conventionally the data logger stores the profile data during the test run which is downloaded post run to the computer where it can be reviewed and analyzed. If real time monitoring is required the system can be supplied with an optional 2way RF Telemetry capability. A radio transmitter within the data logger allows remote logger communication, providing direct logger control and live data review. A RF antenna exits the thermal barrier allowing the RF signal to be transmitted direct from the internal furnace. Remote battery operated repeater units pick up the RF signal and relay the signal back to the master coordinator receiver connected to the monitoring PC. Free positioning of the repeaters allows manual optimization to maximize signal strength over the production floor.

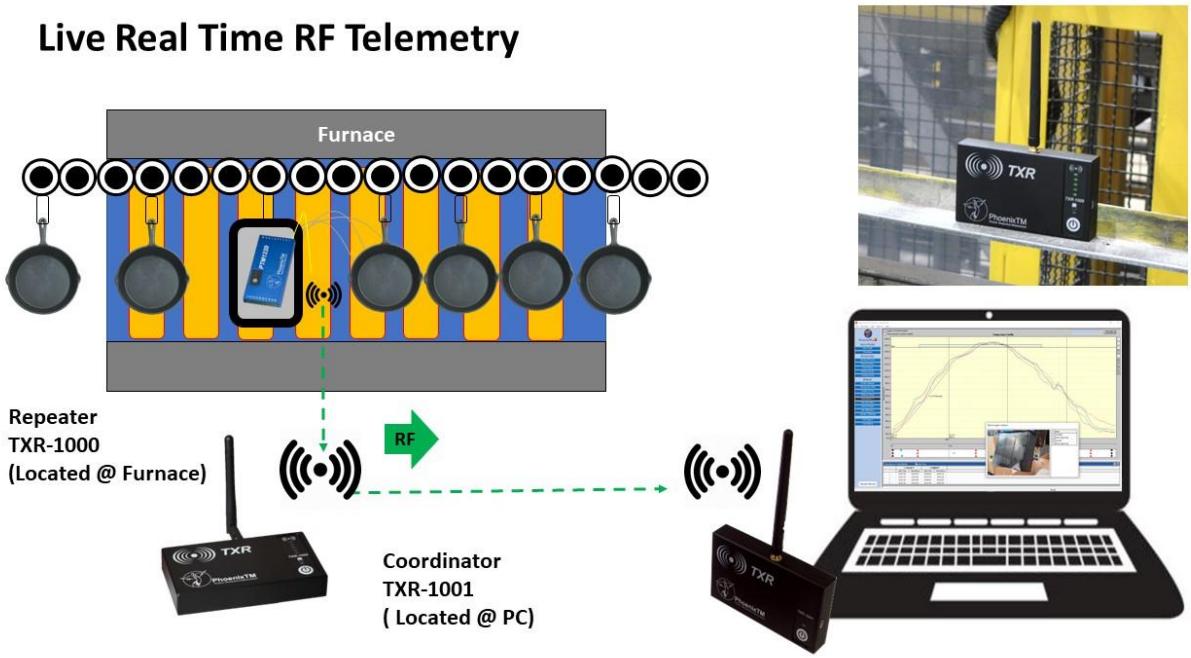


Figure 4: Schematic showing the RF Telemetry set-up for live real time monitoring of the porcelain enamel firing process.

Thermal Barrier Protection

Protecting the logger as it travels through the firing furnace, a thermal barrier maintains the logger temperature at < 176 °F to guarantee measurement accuracy and prevent thermal damage (See Figure 5). Offering a dual protection approach the barriers provide high levels of protection without becoming too large or heavy. Combining high performance microporous insulation and heat sink technology, data logger protection is maximized even in the event of line stoppages. The heat sink onto which the data logger sits optimizes the thermal protection using the principle of phase change. The material will change from a solid to a liquid at 136 °F. The phase change chemical reaction occurs over a period of time, during which the temperature is maintained at that temperature, which is below the safe upper operating temperature of the data logger .

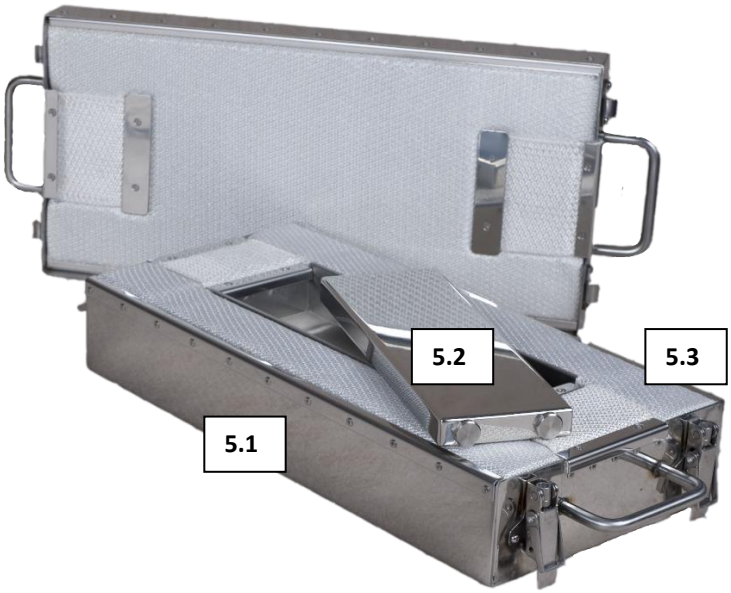


Figure 5: Thermal barrier designed for high temperature thermal protection.
TS01-125 Thermal Protection 1 hour @ 1500 °F 4.9 x 9.5 x 23.2 inches (H x W x L) 27 lbs
5.1 Microporous insulated stainless steel thermal barrier
5.2 Heat Sink (phase change thermal protection)
5.3 Glass fibre cloth with replaceable thermocouple wear strip

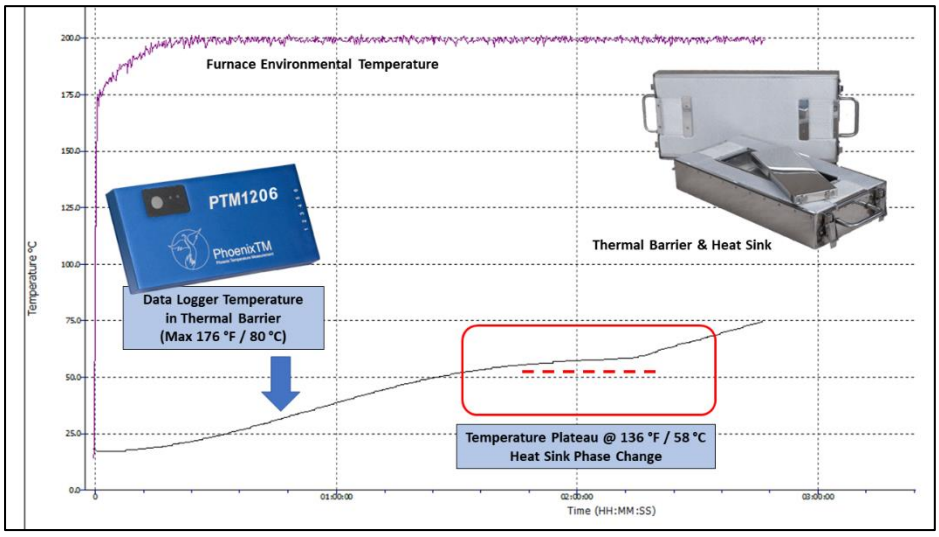


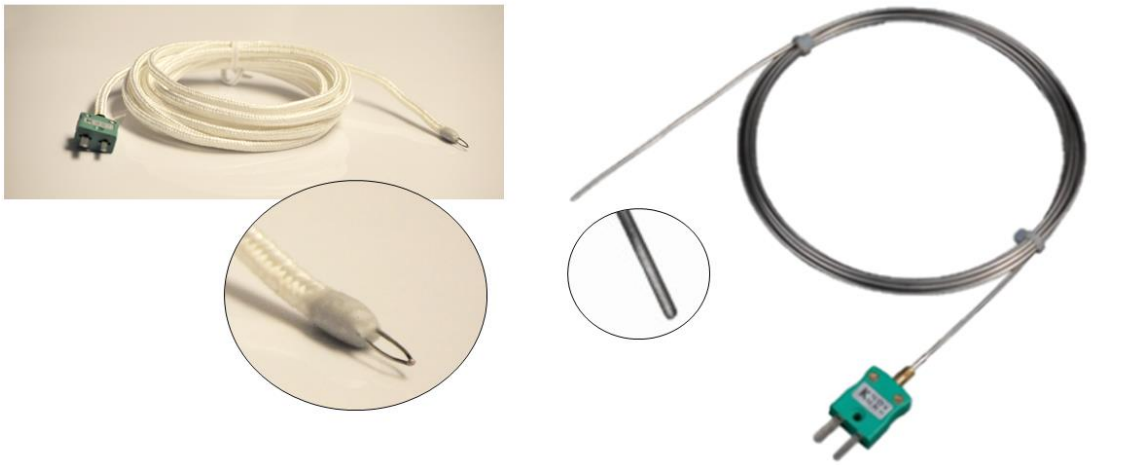
Figure 6: Thermal barrier heat sink performance showing how the data logger internal temperature is maintained at a safe temperature during the phase change process (136 °F) extending the total thermal barrier protection.

Thermocouples

Although often overlooked a critical part of the temperature profiling task is making sure you are measuring what you want run to run. It is important that thermocouples are placed accurately and repeatably so that comparisons can be made over time. At the temperatures experienced for enamel firing the regular thermocouples used for paint and powder coating motoring, which employ a flexible PTFE cable (Max 509 °F), are unfortunately not an option. The use of magnets to attach thermocouples to steel products are also prohibited, for the same reason, as the power of the magnet is lost at elevated temperatures.

The thermocouple of choice for enamel firing is an exposed junction thermocouple. The thermocouple is insulated either by a high temperature Nextel or Mineral insulated sheath protecting the core thermocouple wires as shown in Figure 7. Complying to ANSI-96.1 the thermocouple accuracy is certified to +/-0.4% of the temperature measured or +/- 2.0 °F (whichever is greater). For a porcelain enamel firing temperature of 1500 °F the measurement accuracy of the system, which is the sum of data logger accuracy and thermocouple accuracy, is therefore ±6.5 °F (Data logger ±0.5 °F + Thermocouple ±6.0 °F).

For an exposed junction thermocouple, the measurement of temperature is performed at the hot junction where the two core thermocouple wires are joined. For a braided cable thermocouple this is the bead at the thermocouple tip and for the MI thermocouple the very end of the wire (See Figure 7).



Flexible braided thermocouple
Type K, Nextel insulated exposed junction thermocouple Maximum Temperature 1830 °F ANSI MC96.1 Special Limits (±2.0 °F or ± 0.4%)

1/16 " mineral insulated thermocouple.
Type K UHT Alloy sheathed Insulated hot junction, terminating in miniature plug. Maximum Temperature 2190 °F ANSI MC96.1 Special Limits (±2.0 °F or ± 0.4%)

Figure 7: Exposed junction Thermocouple options for porcelain enamel temperature monitoring.

To measure accurate temperature the hot junction of the thermocouple needs to be in good contact with the product/substrate being measured. Thermocouples can be welded, mechanically held (screw & washer), or retained in drilled pilot holes to record temperatures at critical points. It is recommended that a test piece is set-up specifically for monitoring purposes. An old scrap product is perfect for this, providing a permanent test sample, ready for use with thermocouples left permanently attached. Each and every profile run therefore will be measured in exactly the same way allowing confident identification of whether the furnace operation has changed over time.

Analysis Software ……. the power of process understanding, optimization and validation

A critical component of the porcelain enamel profiling system is the profile analysis software such as Thermal View Finishing software shown in Figure 8. Designed specifically for the needs of the coating market it allows not only the set-up/download of the data logger but the raw process data to be converted into meaningful information. Such information can be used to understand exactly how the process is operating, allow informed changes and provide certified evidence to prove to others the quality you are providing. (Refer to Figure 8 below)

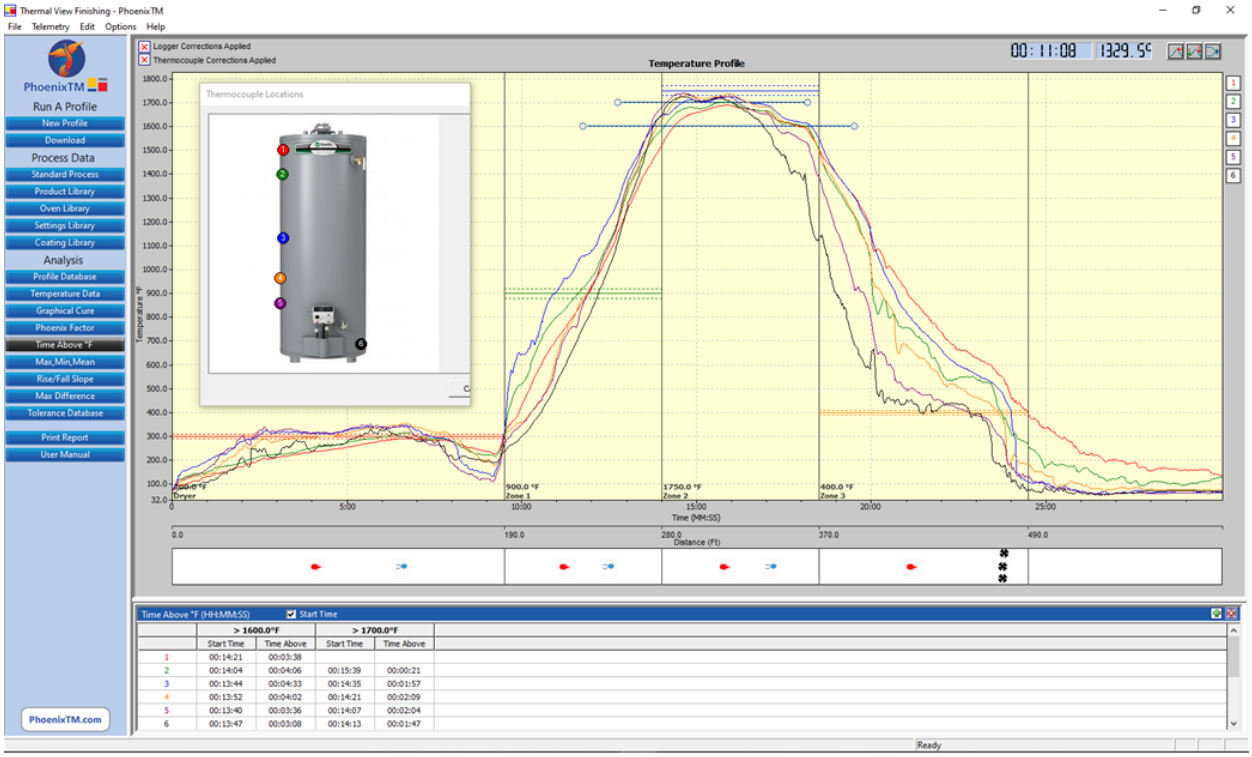


Figure 8: PhoenixTM Thermal View Finishing Software

Main Features of the Finishing Software:

8.1 Configurable Data logger Settings (Start Method, Sample Interval, Number & location of Thermocouples).
8.2 Clear Full Colour Graph with zoom capability on screen Notes.
8.3 Detailed Analysis Calculations – Customize to your specific process requirements.
8.4 Process Files to describe fully the Process Conditions – Furnace Settings (Zones & Features) Product/Firing criteria.
8.5 Firing/Cure Analysis – Graphical Analysis showing Time @ Temperature & Peak Temperature against Pass Fail Criteria.

From the thermal profile trace a full understanding of the firing conditions experienced by the product can be reviewed and analysed in a clear and accurate fashion. Such information can help significantly overcome some of the inherent problems experienced by the application and identify the potential root cause(s) (Table 3). After corrective action the profile can be rerun to check that firing anomalies are resolved.

Table 4 gives a summary of some of the QA issues associated with getting the firing process wrong and where obtaining the product temperature profile is invaluable to optimize your process and eliminate the risk of costly product rejects or lengthy process down time.

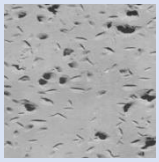
Porcelain Defects	Characterization of Defect	Defect Cause
Fish Scaling 	Small enamel particles chipping off the surface coating (half-moon shaped cracks). Occurs directly after firing, after cooling or after further delay. Caused by release of H_2(g) from the steel substrate creating pressure at the substrate / coating interface. Repair / correction difficult if not impossible.	Cause – incorrect firing conditions in conjunction with other issues. **Over firing** – increased H_2(g) degassing from substrate **Under firing** – poor adhesion of porcelain to substrate
Poor adhesion	Metallic bond between base metal via an oxide adherence layer to the ionic bond of the enamel layer too weak.	Cause – incorrect firing conditions **Under or Over Firing**
Blisters	Circular holes & bubbles in a cooled enamelled surface due to gas evolution.	Cause – **Under Firing**.
Colour variation	No uniform colour either within or batch to batch. Non uniform firing conditions over furnace causing variation in pigment thermal treatment.	Cause – imbalance in furnace temperature or different thermal masses of products.

Table 4: Table showing the range of porcelain enamel defects caused by incorrect firing conditions being applied.

Summary

The correct and reliable firing of porcelain enamel is critical to the performance and cosmetic appearance of the coated product. A valuable tool in the Understanding, Control and Optimization of the firing cycle is the use of 'Thru-process' temperature profiling. Obtaining the thermal profile "Thermal fingerprint" of the product/process gives the production management and or quality team invaluable insight into how the process is performing against specifications to guarantee product quality and efficient furnace operation.

PhoenixTM your furnace to Find, Fix and Forget your firing problems!

Author

Dr Steve Offley
Product Marketing Manager
PhoenixTM Ltd UK
www.phoenixtm.com
steve.offley@phoenixtm.com

Presented at the 85th PEI Technical Forum Wednesday April 26th, 2023 by Mr Mike Handscombe (PhoenixTM Sales Manager)

For more information Contact:

PhoenixTM LLC
www.phoenixtm.com/en_US/
Tel: +1 727 608 4314
Email: info@phoenixtm.com