In Process Oven Temperature Monitoring

A Review of Thermocouple Technology....What, Where and How?

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SUMMARY

Oven Temperature profiling is now widely accepted in the paint and powder coating industry as a critical tool in the fight to maintain quality assurance and optimise process efficiency. Despite this fact it is amazing how little or no emphasis is made to the critical role the thermocouple pays in the success of such strategies. The aim of this paper is, therefore, to discuss the basic operation of a thermocouple and in so doing review the options available, and their appropriate use for common cure applications and material types.

Oven Profiling – the principle

To prove that a coated product (powder or other) is experiencing the optimum cure schedule it is essential that a comprehensive temperature history of the component is obtained throughout the entire thermal process. The only means of obtaining such information is to employ in-process temperature profiling as shown in Figure 1.

![Figure 1: Basic Temperature Profiling Principle](image)

(a) Place programmed data logger in thermal barrier.
(b) Attach Thermocouples to parts of product needing measurement.
(c) Send whole system through oven with product to measure product and or oven temperatures at defined intervals (e.g. every 5 s)
(d) Retrieve the datalogger and transfer stored temperature data to PC running profile software.
(e) Review and analyze profile graph data to check that the coating cure criteria are achieved. Provide a comprehensive profile report to validate the whole process.

At the heart of the profile system is the data logger which measures and stores temperature data supplied to it by the thermocouple. This being the case the appropriate choice of thermocouple and placement is essential to the quality of data obtained.
Thermocouple Technology

The thermocouple is a device that consists of a junction of two dissimilar metals that can read temperatures anywhere between -250 to 2000°C. For paint and powder curing the common thermocouple of choice is type K which has one leg comprising of Nickel Chromium “Chromel” and the second leg comprising of Nickel Aluminum “Alumel”. The thermocouple works by creating a voltage difference between the two wires that is proportional to the temperature of the junction. This is called the Seebeck effect in honor of Thomas Seebeck, who first noticed the phenomena in 1821.

Figure 2: Type K thermocouple showing the basic exposed hot junction. The two legs of the thermocouple are welded together to form a bead of metal that is used to create the measurable voltage difference.

The K type thermocouple is popular due to its wide temperature range, rugged operation in an industrial environment and reasonable costing. Although available with different accuracy specifications the recommended is the special limits of error type K thermocouple (ANSIMC96.1 spec) certified to give a measurement accuracy of either ± 1.98 °F or ± 0.4% (of the temperature being measured) , which ever is the largest term, over the temperature range (32 °F to 2282 °F).

Know what you are Measuring

The thermocouple works on a contact temperature measurement principle. This being the case the accuracy of any measurement is governed by three important criteria;

1. Quality of contact between the sensor and item being measured – If contact between the thermocouple is not guaranteed it is very possible that you may be measuring environmental temperature rather than product temperature or some average between Product and Oven temperature.
2. The effect that the thermocouple has on temperature or heating characteristics of the product being measured. Remember that by attaching a thermocouple to an item will change its physical thermal mass by some degree, so change its heating characteristics.
3. Repeatable Placement – Is it possible with repeated testing to be able to reliably place the sensor at the same location on the product being measured? Remember the thermocouple cannot lie it measures what temperature it experiences. Complicated products can have regions in which heating rates will differ significantly due to varying thermal masses.

When selecting and using a thermocouple it is essential therefore that the above issues are carefully considered to ensure that you are definitely measuring what you believe you are measuring.
Select the right Thermocouple for the right Job

Obviously accuracy of reading is important but this has to be considered hand in hand with other issues. These include repeatability of measurement between consecutive tests, ease and speed of probe placement and rugged operation in an industrial environment. There is no benefit to selecting a thermocouple that gives excellent accuracy if the procedure for attaching the thermocouple takes 1 minute and access to the product on a production line (between spray booth and Oven) prior to the oven it limited to 30 seconds. Each paint cure procedure and product type will differ to some degree and some care is required to select the best match of thermocouple type. Although the basic principle of all thermocouples is identical there are many different approaches to attachment. No one attachment technique will be ideal for every situation and often a choice is necessary that requires some compromise regarding accuracy, repeatability or speed and ease of use. This issue is emphasised by comparing two extreme thermocouple choices below.

Figure 3: Comparing the performance of different thermocouple options

Thermocouple 1: Fine gauge patch probe – Fine junction of thermocouple is stuck to the product using a self adhesive patch with additional high temperature tape use to provide some strain relief.

Thermocouple 2: Magnetic Surface Probe – Contact of Thermocouple sensor to a ferrous material employing a magnet and sprung steel locating arm.

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Thermocouple Selection – Review

The following section reviews a range of different probe types and suggests suitable applications and products with which they would be suited.

Standard Magnetic Surface Thermocouple

Automatic location of the sensor on a flat ferrous substrate employing a magnet fixing method. The sprung steel tension arm guarantees that the hot junction of the thermocouple lies flat on the metal surface. To avoid thermal mass errors the magnet is located 3.5” (90 mm) away from the measuring point. Used routinely in the automotive paint industry for the monitoring of painted car body shells. Placement of the thermocouples on the interior of the body shell must be done whilst the car is continuously moving between the paint booth and oven entrance. Up to eight thermocouple need to be located at different points generally in less than 1 minute with care.

MicroMag Surface Thermocouple

Adaptation of the standard magnetic thermocouple in which the thermocouple sensor is embedded into the magnetic. Reducing the footprint the thermocouple can be used in tight recesses and also on curved or uneven surfaces. To avoid thermal masses a small yet very powerful Samarium Cobalt disk magnet is used to provide secure attachment to the product.

When considering the use of magnets as a fixing method it is essential that attention is paid to the effect of temperature on magnetic properties. A strong magnet at room temperature may not perform as well at the cure temperature. A Samarium Cobalt magnet has a Curie temperature of 1508 °F, the temperature at which the magnetic properties are permanently lost. The loss in magnetic strength with temperature is quantified by a Br%°C value of -0.032. This means at 482°F the magnetic strength is only 8% less than at room temperature. This temperature tolerance is significantly superior to many other magnets.

Clip / Clamp Surface Thermocouple

Thermocouple device in which the thermocouple sensor is placed onto the product using a simple spring tensioned clamp. The jaws of the clamp can be opened to accommodate any thickness of product up to 1” of any material. Ideal for aluminum extrusion or similar products comprising of flat narrow sections.

The one limitation of the clamp probe is that it needs an edge to be applied limiting probe location to edges of flat sheet or box section.
Exposed Junction Probes

Figure 7: Exposed Junction Thermocouples
(a) PTFE cable (b) Glass Fibre cable (c) Mineral Insulated Alloy Wire

The exposed junction probe as its names suggests is the simplest form of thermocouple design in which the sensor is simply the connected two legs of the thermocouple wire “hot junction”. These probes are very useful due to their flexibility. Obviously the same probe can be used to monitor either oven environment temperature or product temperature simply by selective positioning of the hot junction. The hot junction has minimal thermal mass therefore its response characteristics are very rapid giving good accurate temperature data of even the lightest gauge metal product.

Cable materials and strategies for attaching this type of probe are heavily influenced by the type of process and temperatures experienced. Such procedures require time to complete and so are often applied to test or scrap items way from the paint line rather than directly on to production pieces.

The PTFE exposed junction thermocouple is the preferred choice for low temperature applications below the working limit of the PTFE material of 265 °C / 509 °F. This provides a flexible easy to handle cable. Working below 509 °F attachment is possible using high temperature Kapton tape as shown right. High temperature tape is very flexible as it can be used on most dry clean substrate surfaces. The attachment method does suffer though if there is a lot of cable movement or tension. Generally a secondary fixing of the cable a few inches from the hot junction is made with either tape or as shown a magnetic probe mount to give strain relief and prevent the probe pulling away from the product.

Working at temperatures above 509 °F requires the use of a glass fibre cable rated up to 1300 °F. High temperature tape can be used up to 600 °F but at higher temperatures a more physical attachment method is recommended as the adhesive loses its tack strength. One Physical attachment method that can be applied to exposed junction thermocouples is spot welding. This technique involves the use of high currents to fuse the metal of the hot junction to that of the substrate being measured. This technique obviously requires sophisticated equipment and skill, but benefits from the fact that the probe becomes part of the product so contact is guaranteed and the attachment is secure.
A less sophisticated attachment method is the use of washers to trap the cable/hot junction onto the surface using either bolts or self tapping screws. Again with this technique it is important to avoid adding significant thermal mass to the substrate with the fixings. For heavy bulky products such as castings the thermal mass of the thermocouple hot junction becomes less significant. Under these circumstances a purpose manufactured washer probe is employed. As shown below the hot junction is formed into the shape of a washer which can be screwed directly onto the substrate.

Increasingly the volume of plastics being coated is growing. Being of low thermal mass it is essential that the thermocouple employed to monitor such materials has minimal thermal mass itself. An ideal choice therefore is the light duty patch probe. Being a single strand thermocouple the exposed junction is easily secured via the adhesive patch. The fine guage thermocouple legs and hot junction lie flat on the substrate responding rapidly to any surface temperature changes. Unfortunately being fine gauge the one draw back of the thermocouple as you would expect is the necessary compromise with regard robust operation. The probe with care can be used for multiple tests but must be viewed as a consumable in normal production rather than laboratory environments.

For extreme temperatures and applications where naked flame or hostile environments are experienced the thermocouple preference will be most generally the mineral insulated thermocouple. The Nicrobel\textsuperscript{TM} sheath of the thermocouple creates a very robust thermocouple which unlike PTFE or glass fibre is resistant to damage from sharp edges. The nature of the construction means that the flexibility of the wire is restricted making placement or fixing a challenge. The hot junction of the thermocouple is located at the tip of the wire. Making contact with a substrate surface must be done with care. The schematic in figure 11 illustrates how best this can be achieved. A solid attachment is provided by the nut and washer and the pilot dimple gives a site of contact for the hot junction.
Aluminium Automotive Probe

Historically the automotive OEMs have favoured steel for production of car bodies. With advancement in techniques the use of aluminum has begun to show more promise due to the mass/strength benefits. Obviously in an oven monitoring arena without the elusive magnet that works on aluminum probe placement is a challenge. To provide a thermocouple that could be attached to the car body whilst travelling along a continuously moving conveyor a spring loaded bobbin attachment device was developed. The bobbin is clipped to any convenient recess or aperture in the inner car body skin. A sprung steel arm assembly is custom adjusted to position the temperature sensor on the outer body skin where the measurement is required.

Profiling IR Cure Processes

Monitoring convection ovens is easy in so much that in general the coating plays no part in the heating characteristics of the product. This being the case testing can be done on non coated products which makes life easy. A dummy test piece or non coated production piece can be used which means that production items are not damaged by the attachment of thermocouples to the painted surface. Removal of thermocouples post run is therefore easy since it is not hindered by cured coating. Employing a dummy test piece “indirect profiling” provides a further benefit in that thermocouples can be left attached to the test rig ensuring repeatability of measurement each and every run.

Profiling IR ovens is possible, but care must be taken to consider the factors affecting the heat transfer mechanism. A desirable feature of IR technology is the very rapid heat transfer possible when the metal substrate absorbs electromagnetic radiation (See Figure 14). The degree of absorption (heating rate) is controlled by the emissivity of the surface. It’s essential that the product being tested is coated with the same powder type and color used in the production run (see Figure 15).
Exposed junction or patch probes will accurately measure the temperature experienced by the coating. They respond very rapidly to temperature change and can be coated easily. For IR profiling the use of a dummy test piece is in almost all situation compulsory due to expected damage to the surface finish by the application of the thermocouple. It is recommended that the exposed junction probe is attached directly to the product surface then covered with high temperature tape and coated with the required coating type and color anticipated during production. For optimisation studies it is recommended that the test piece be profiled in its uncured state to get the best representation of the true production conditions. One important consideration to make with such activity is the probe placement due to the directionality of the IR radiation. Especially with three dimensional products, identify surfaces which may not be perpendicular to the direction of emitted IR. Remember that if a surface is shielded from the IR it will possibly not heat up as quickly and these need to be monitored carefully. See the schematic diagram below which shows that faces of a product not in direct line of site will only experience heat transfer by either conduction or convection, but not from radiation.

For routine IR monitoring it is more practical to use a dummy test piece that is pre-cured. This way it may be necessary to have a series of different test pieces coated in various colors. Repeated heat treatment of a coating will theoretically change the color and emissivity of the surface which could gradually change the level of IR absorption but this will be minimal in the short term. Replacement of test pieces would need to be considered on a case by case basis.

One word of warning: Gas-fired IR emitter temperatures can be very high. If Polytetrafluoroethylene (PTFE) cables get too close or touch the safety cages, they can melt. Fibreglass cables can help eliminate this problem.
CONCLUSION

As part of any oven temperature profiling it is clear that the overall performance of any work is highly influenced by the correct choice and application of thermocouple used. Making the correct choice from the multitude of different options can make all the difference. Selecting the correct thermocouple for the job and applying it with some care and thought provides good reliable data that you can use with confidence to improve your paint cure process.

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