Online Quality Control of Thermally Sprayed Coatings

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Abstract

An industrial and cost-effective online quality control method for thermally sprayed coatings will be presented. A new concept in pulse-thermography allows online, during the spraying process, the non-destructive evaluation of coated surfaces. This technique employs a heat source that produces a heat impulse. The impulse is directed toward the examined surface and the from the surface reflected and/or emitted signal is collected by an infrared-camera and subsequently treated in a computer. It will be demonstrated that the spraying process itself can be used as a heat source.

In principle, the fading behavior of the signal captured by a high speed infrared camera is observed, or else the progression of the induced heat wave within the coating. Differences in coating thickness, coating and adhesion defects, microstructural changes, an aggregation of pores as well as oxide or metallic inclusions provoke a significant change in the signal intensity and are therefore detected.

Pulse-thermography enables the non-destructive assessment of the quality of thermally sprayed coatings. A coated part can be examined to check if the desired coating structure has been successfully attained or if and where there are any areas with critical deviations in respect to coating thickness or coating microstructure. The simple set-up allows the integration of the technique in the production line.

Pulse-Thermography

The successful development of functional surface coatings such as ceramic coatings for structured printing rolls or hard metal coatings for wear protection is costly and requires intensive studies before it can be applied on a real part. For safe and reproducible manufacturing of these coating systems, complex system controls of the production lines and well trained personnel remain indispensable.

This expenditure is in no relation to the limited means available today for the non-destructive evaluation of quality attributes, respectively for the preventive failure inspection of functional surfaces. This holds especially true for parts with large coated areas. They can only be assessed point by point and the investigation is usually limited to one quality attribute.

Other methods either do not possess the necessary resolution to detect small but critical defects (in thermal spray coatings, these may be as small as 20 to 100 μm), or they can not be employed on-site or then the required measurement times are uneconomically long. On the opposite, a new concept in thermography allows the non-destructive and fast evaluation of large areas of coated surfaces.

The recent development of a new generation of infrared sensors and ultra-fast electronic devices provides the means today for an industrial application of the so-called "active" or "pulse-thermography". This technique employs a heat source that produces a well defined heat impulse – be it a single impulse or a continuously modulated, e.g. sinusoidal signal. The impulse is directed toward the examined surface and the reflected signal is collected by an infrared-camera and subsequently treated in a computer. The set-up and the technical devices needed are shown in figure 1. The simplicity of the set-up allows measurements on-site or the integration of a system into a production line.

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Although, one infrared system for the solution of all problem definitions does not exist. A measuring system is to be aligned regarding the requested thermal resolution, time resolution and spectral sensitivity and to the spectral behavior of the object surface which can be examined. For successful problem solution the correct measurement procedure has to be selected also, meaning how and when to apply the heat pulse and how and when to pick up the data. If the complete system and measurement procedure is defined correctly, the measurement itself is easy.

Determining factors for the construction of a measuring system are the chemical composition of the object to be evaluated, its geometry, as well as the operational surrounding field at the measuring point. During the problem-related design of a testing facility the dependency of the material properties of the measurement object and the minimum failure size to be detected is to be determined. This succeeds in good approximation with simple analytic procedures. Thus an estimation of the sample rate is possible and the requests to the pulse source are determined. The behavior of the variable temperature field in dependency of the minimum defect size is calculated in advance. The results supporting the technical designer for the selection of the needed hardware components in the measurement chain (pulse source, infrared scanning device, etc.) [1].

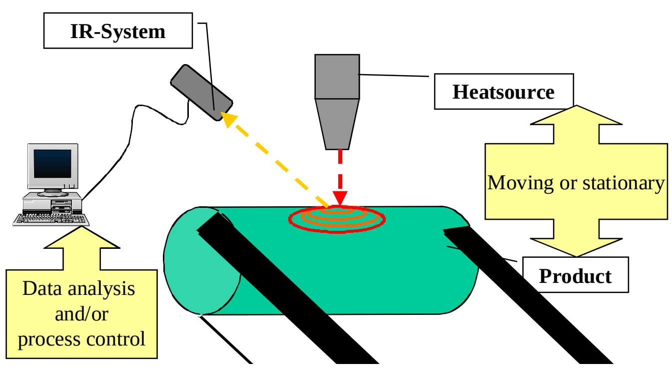

Figure 1: Measurement set-up used for pulse-thermography

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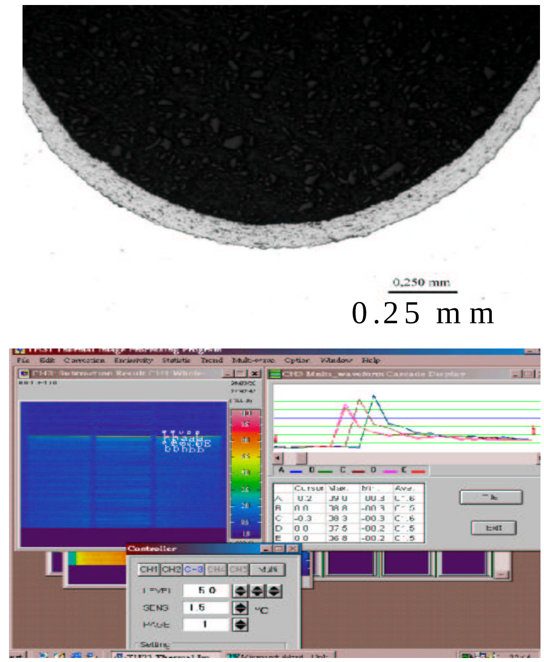
Application Areas

Measurement of Coating Thickness

For the determination of coating thickness (over small or large surface areas), pulse-thermography has an edge over conventional methods because it delivers fast results and no restrictions apply with respect to the investigated materials. It can be used for large surfaces – several square meters if necessary – or also very accurately at precise locations (actual smallest measurement spot size = 0,2 x 0,2 mm^2), see fig. 2. The coating thickness is a function of the time decay and the maximum amplitude of the captured infrared signal after heat pulse. Typical infrared signals as function of time one can see in the two infrared images given in fig. 2. Due to an analytical model the coating thickness can be calculated directly. Therefore, the user finally sees only the requested thickness values and not the infrared images. Thus, it is easily possible to determine the thickness of a magnetic coating on top of a magnetic substrate (e.g. a ferritic steel coating on a ferritic steel part) [2].



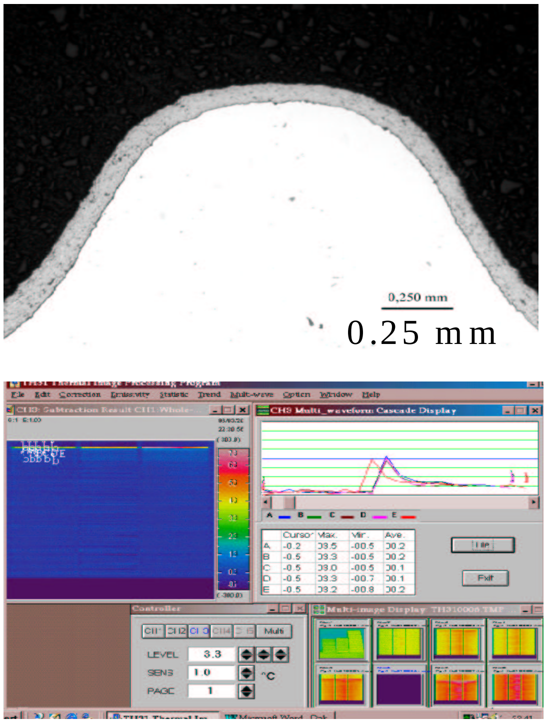


Figure 2: Cross-sections and images taken by pulse-thermography (2 dimension, gray scale and line-scan) of a valley between two tooth (top) and the peak of a single tooth of a toothed wheel (bottom). Coating material: WC-Co-Cr. Substrate: mild steel. Coating thickness 84 µm (top) and 52 µm (bottom). Precision of measurement +/- 3 µm

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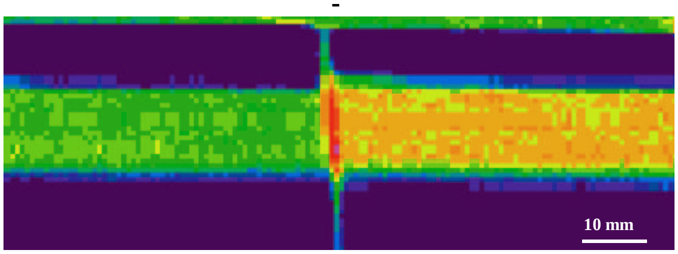

Figure 3: Pulse-thermography image of two WC-Co coatings (bright grey areas in the middle of the picture). Both coatings are identical with respect to thickness and porosity. The left coating , however, contains 5 vol.-% more brittle phases. Time of measurement: 10 ms

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Quality Surveillance

Figure 3 shows pulse-thermography images of two WC-Co coatings. Both coatings are identical with respect to thickness and porosity. The left coating, however, contains 5 vol.-% more brittle phases. This increase of brittle phase is related to a more drastic decrease of the erosion resistance of this coating and reducing the service-lifetime of the coated part. Pulse-thermography offers the potential for a non-destructive assessment of the quality of functional coatings, as it is demonstrated in fig. 3, where even this small change in coating composition could be easily visualized (here change of gray level). Therefore, a coated part, such as a large roll used for paper production, can be examined to check if the desired coating structure has been successfully attained or if and where there are any areas with critical deviations in respect to coating microstructure or porosity levels.

Detection of Defects

Pulse-thermography allows a fast and reliable search for hidden coating defects, such as oxide or metallic inclusions, aggregation of pores, adhesion defects, interface corrosion or cracks.

Figure 4 shows the pulse-thermography image of a steel plate with built-in defects, thermally sprayed with a 0.3 mm thick steel coating. The purposely built-in defects – optically not visible – are unmistakably identified and visualized by the pulse-thermography method. The defects are caused by a sprayed, 10 to 20 µm thick interlayer of partially stabilized zirconia in the shape of a wedge and several circles of varying size. The detection limit is around 0.5 mm in terms of defect diameter, according to the measurement parameters used in this example. The geometrical resolution can however be increased to allow for detection limits in the micrometer range if required.

For coated parts, the presence of interface corrosion and the loss of coating adhesion can be examined fast, non-destructively and without mechanical contact. To examine the surface area shown in fig. 4, a measurement time of only a few milliseconds was necessary.

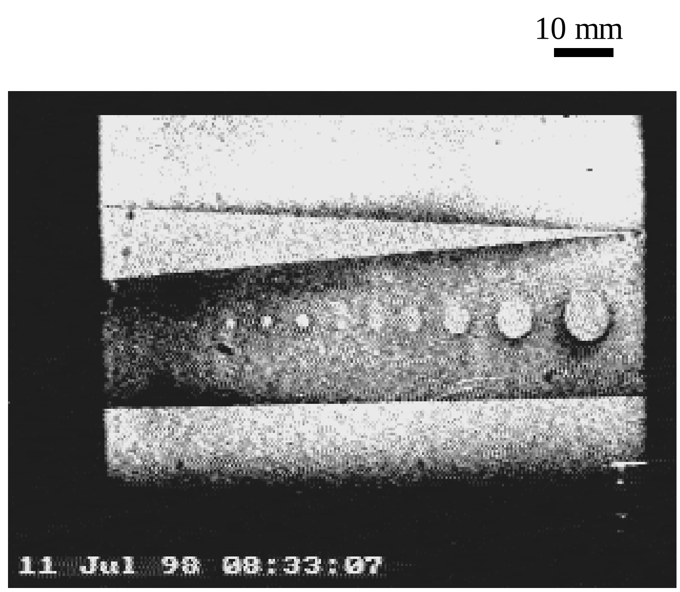

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Figure 4: Visualization of bonding defects by pulse-thermography. IR-Image of hidden bonding defects in the interface. Looking through a steel coating with 300 µm thickness

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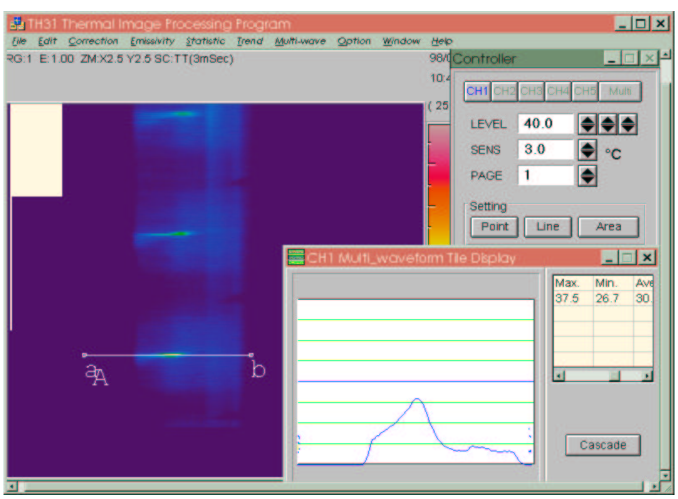
On-Line Measurements

Thermal production processes as welding or thermal spraying offering the great opportunity to do all the measurements mentioned above on-line, directly during the process. In that case the process itself is the heat pulse. The heat pulse must not be necessarily a short impulse it could be also a heat source moving on the object to be observed as it is the case for thermal spraying. The big advantage of that kind of on-line measurements is the simplified experimental set-up. There is no more a need for an additional heat source and furthermore, due to the high energy density of the process itself, environmental perturbations of the signal can be neglected.

Several properties of a coating during spraying process can be measured with the same set-up at the same time, specially the coating thickness or coating growth as well as bonding defects. Bonding defects creating an infrared signal that relates exponential to the applied heat pulse in opposite to an approximately linear signal for differences in coating thickness. Also the general signal decay as function of time and maximum signal intensity for both measurement problems differing strongly as demonstrated in the fig. 5 and fig. 6. Therefore both measurement tasks can be measured clearly in one step.



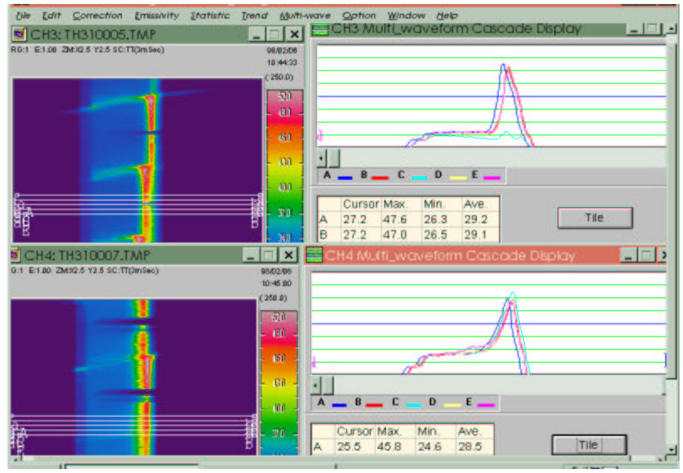


Figure 5: On-line infrared signal (2 dimension, gray scale and line-scan) of a coating with and without bonding defect during plasma spraying. Top: no defect; bottom: bonding defect

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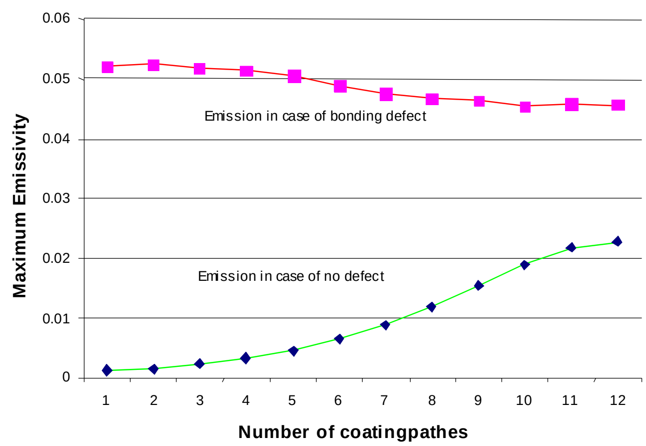

Figure 6: Peak value of infrared signals as function of coating paths and bonding defect during plasma spraying

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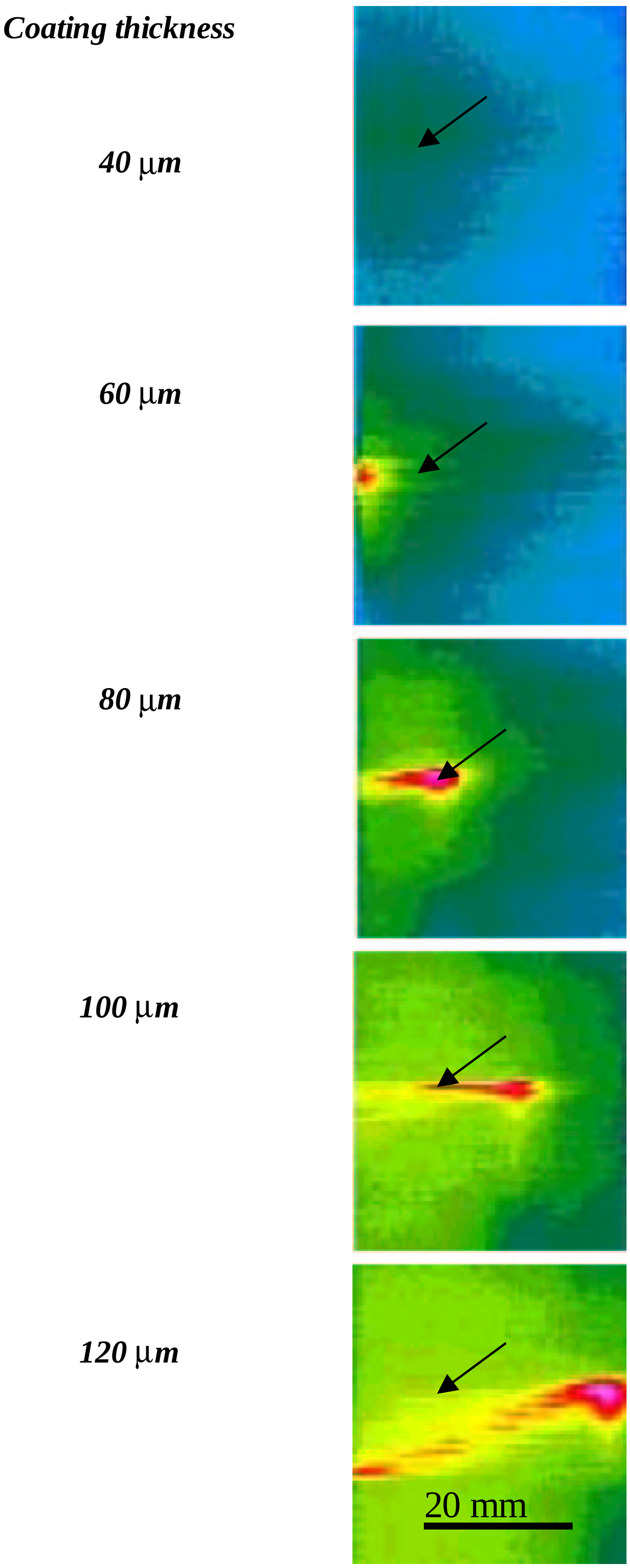

Figure 7: two-dimensional on-line infrared images (gray scale) of a surface during plasma spraying. Arrow indicates area of bonding defect -

The measurement results given in the fig. 5 and fig. 6 were taking during atmospheric plasma spraying of an iron base wear protection layer on the inner surface of an aluminum cylinder, 100 mm inner diameter. The pulse-source was the plasma itself. An infrared sensor line with 330 single sensor elements was taken for the measurement. The applied sensors were sensitive in the wavelength range between 8 to 14 µm. All 330 elements were read out together at 207 Hz. The sensor was placed in 200 mm distance from the surface to be coated under an observation angle of 30°. The optical lenses of the camera was protected by a gas shield.

The following fig. 7 shows a series of infrared images (wrong color) of an area of 40 x 40 mm^2 of the inner surface of the previous mentioned cylinder during coating process at different realized coating thickness. The coating parameters were kept constant. Before spraying the grid blasted surface was marked with a pencil in the center of the given images. The line has had a thickness of 0.5 mm and a length of 20 mm, starting from the left side. First of all one can see, taken the pictures from the top to the bottom, that the overall color changed from dark gray to bright gray. This general change in color corresponds in the first magnitude of order to the change of the infrared signal as a function of coating thickness. Furthermore, the pencil line causes a bonding defect that becomes strongly visible from the beginning of the measurement (black arrow in the pictures shows point of gravity of the pencil line).

Summary and Conclusions

Using pulse-thermography, large areas of thermal spray coatings can be tested and evaluated within economical time limits and with excellent geometrical resolution, even on-line.

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The application of pulse-thermography allows early detection of growing defects – before expensive damage occurs.

The method is non-destructive and the simple set-up allows the integration of the technique in the production line.

In short, pulse-thermography offers the following advantages as compared to other testing methods:

- Independent of substrate or coating material.
- Independent of the chemical composition of the part.
- Fast testing method.
- Non-contact testing method.
- Easy to apply.
- Large surface coverage.
- Resolution down to the micrometer range.

Literature

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