A New Approach to Online Thickness Measurement of Thermal Spray Coatings

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A New Approach to Online Thickness Measurement of Thermal Spray Coatings

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Abstract

In the past ten years, significant progress has been made in the field of advanced sensors for particle and spray plume characterization. However, there are very few commercially available technologies for online characterization of the as-deposited coatings. In particular, coating thickness is one of the most important parameter to monitor and control. Current methods such as destructive tests or direct mechanical measurements can cause significant production downtime. This paper presents a novel approach that enables online, real-time and non-contact measurement of individual spray pass thickness during deposition. Micron-level resolution was achieved on various coatings and substrate materials. The precision has been shown to be independent from surface roughness or thermal expansion. Results obtained on typical HVOF and plasma sprayed coatings are presented. Finally, current fields of application, technical limitations and future developments are discussed.

Introduction

Thermally sprayed coatings are used for many industrial applications in various sectors: aerospace, automotive, energy, biomedical, pulp and paper, etc. Their main roles include protection from corrosion, erosion, abrasion or high temperature[1-5]. Coatings can also be used to promote the biocompatibility of medical implant surfaces, to create functional surfaces, to build new parts or to repair worn ones [1,2,6-9]. For most of these applications, the coating thickness is an important, if not critical parameter.

On the production floor, precise control of the coating thickness is often a challenge because small deviations in spraying conditions may result in considerable variation in the deposit efficiency (DE). For example, changes in powder injection profile due to variations in powder granulometry or shape, carrier gas pressure or simple clogging of the injection nozzle will influence the trajectory of the particles in the spray plume, thus influencing particle temperature and velocity, coating structure, and (DE) [10-13]. Another well known example is the degradation over time of coating structure and DE in DC plasma spraying processes because electrode wear caused by the high torch currents increasingly affects the plasma, and therefore the particle properties [14,15].

The effect of DE on coating thickness is a major concern of the industry. Significant progress has been achieved over the last ten years in the development of advanced sensors for online monitoring of critical spray plume parameters such as velocity, diameter, temperature and trajectory of the sprayed particles [10,16-19]. One of the benefits of these sensors is a reduction in DE variations due to tighter control of spraying conditions.

However, plume sensing technology has not eliminated the need to verify the final coating thickness which is still often done by comparing the dimensions of the part before and after coating. The measurements are carried out using mechanical gauges such as micrometers, vernier calipers, etc. Other methods such as Eddy current or magnetic induction are also used when the magnetic properties of the coating and/or substrate materials make such measurements possible [20]. These approaches are time consuming as they require the part to be cooled down to room temperature before the measurement is carried out manually by the operator. If the coating thickness is below the target thickness, the part has to be returned in the spray room, reheated and coated again to reach the desired thickness. On the other hand, if the coating is too thick, the part has to be stripped and recoated.

Several other non-contact thickness gauging methods, such as photothermal techniques and laser-ultrasonics, have been investigated [20,21]. However, complexity, precision and implementation costs significantly limit their applicability in actual production environments. Furthermore, ultrasonic techniques require an *a priori* knowledge of the sound velocity to obtain physical dimensions from echo time intervals. Factors such as porosity, density, etc. affect the elastic properties of several types of coatings, such as TBC's, and therefore present an additional challenge for ultrasonics. Conventional ptical triangulation methods have also been investigated. The thickness is obtained by comparing the size of the part before and after coating. This approach is severely limited by other factors affecting the part geometry such as thermal expansion, often larger that the coating thickness itself. As for interferometric techniques, they tend to be difficult to implement in the harsh environment intrinsic to thermal spray production floors [22,23].

In this paper, a novel approach for online monitoring of the coating thickness in thermal spray processes is presented. Using optical triangulation and differential profilometry, the device measures the coating thickness deposited per pass as it is sprayed. The basic concepts of this new approach are first described, followed by results obtained off-line and on-line. Current fields of applications and technical limitations are also discussed.

Basic Concepts

At the heart of this approach is the idea of measuring the thickness of single spray passes which can then be added up in order to obtain the total coating thickness. A single pass produces a smooth step profile over the immediately adjacent, uncoated (or previously coated) surface. The idea is to use simple optical triangulation methods to detect this profile referenced to the adjacent surface, therefore producing a per-pass thickness measurement independent of part motion, thermal expansion, etc. The chosen strategy is to record the profile of the coating at the frontier between the new layer and the previous one using a laser line projected across the pass side and captured with a digital CCD camera.

Theoretically, on a flat substrate, the coating profile along a direction perpendicular to the torch-substrate movement would look like two offset flat lines joined by a smooth, gradual step. This ideal case is illustrated schematically in Figure 1. The thickness is calculated from the height difference of the two flat lines that represent the previous layer and the new one.

Of course, the profile of a completely coated surface is never perfectly flat. At best, it is mostly flat with some surface

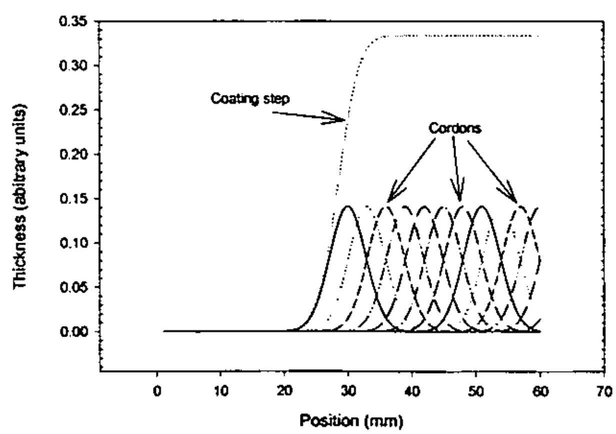

Figure 1: Formation of the step in the coating profile by the addition of overlapped bell-shaped cordons.

roughness that can vary from 1 to 20 microns and can clearly become a limiting factor for this approach. However, the measurement is done in real time and the profile is always established on a surface in motion. In other words, this technique implies an intrinsic and crucial surface averaging that diminishes the influence of the roughness while keeping the integrity of the layer step.

The compliant geometries for this concept are relatively flat surfaces in the direction of the profile. Although special algorithms have been developed to compensate for moderately curved surfaces, any curvature higher than the second order within the field of view of the profilometer may limit the precision of the measurement. This effect can be attenuated by the fact that the real step is at a known position in the profile. Initially, applications on flat surfaces, rollers and cylinders are targeted for the first industrial implementations of this technology.

This method can be utilized in two different manners. The simplest one uses a sensor in a fixed position and the profile of the surface is constantly monitored at a specific point in space. As the cordons are sprayed, the layer step will appear and travel trough the field of view of the sensor. The thickness can then be measured either by calculating the height of the step or by subtracting two consecutive profiles separated by a short time interval. This last calculation translates into measuring the amount of added matter that was deposited during the time interval. The main advantages of this setup are that the sensor can be mounted far away from the gun trajectory and that the measurement does not depend on a precise a priori knowledge of the substrate shape. It is the simplest way to integrate an online, per pass, thickness measurement than can be used to control the overall thickness of the coating.

The other configuration offers the advantage of continuous real time measurement with the sensor attached to the gun. In this case, the technical issues of mounting the sensor close to the gun and on the same displacement unit can become complex. Nevertheless, because this configuration offers possibilities for complete spatial mapping of the coating's final thickness and real-time monitoring of the DE, most of the work up to now, including online tests, has been steered in that direction.

Experimental Setup

To reveal the layer step's profile, an 80-mm long laser line (660 nm visible wavelength) is projected on the surface at a fairly low angle (30 degrees above tangent). The image of the laser line on the part surface is recorded with a 10 bit monochrome 1280X1024 digital camera aimed perpendicular to the observed surface. Anamorphic optics is used to image a rectangular region of 80 mm per 10 mm on the 6.4 mm per 5 mm CCD array. Like shadows growing longer at sunset, deflection of the laser line by the layer profile is amplified

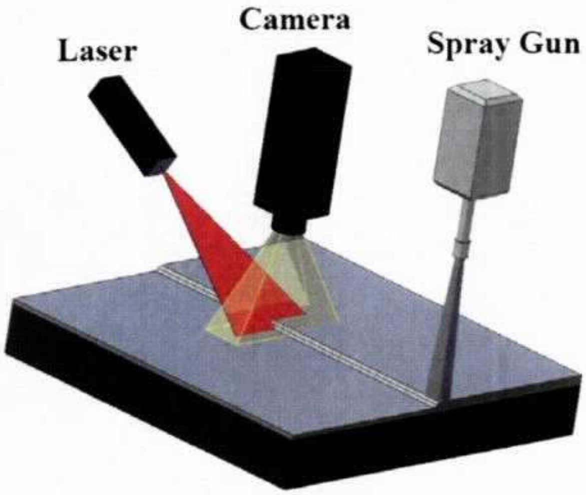

Figure 2: The laser line is aimed at the new layer frontier and its deflection is imaged by a digital camera. The height of the deflection, which corresponds to the layer thickness, is obtained through image analysis.

when the projection angle approaches the surface's tangent. However, the depth of field reduces accordingly. At 30 degrees, the profile is "amplified" by a factor of two. The depth of field is therefore equal to 5 mm, half of the camera's field of view in the deflection direction (perpendicular to the laser line). The experimental setup is schematized in Figure 2. The total weight of the profilometer head is 1.6 Kg.

The anamorphic configuration increases the spatial resolution along the deflection direction. Because of the high anamorphic ratio, optical aberrations are present in the other direction (perpendicular to the line) but they do not affect the analysis of the layer step. Furthermore, special algorithms are applied to the raw image to compensate for the geometrical deformations caused by large aperture optics with short focal lengths.

Results and Discussion

Offline Results

The very first validation tests of the concept were made offline using pre-coated flat samples with pre-calibrated steps. Those experiments confirmed that the measurement of a 5-micron step was possible with the surface averaging effect of a moving sample. They also helped in establishing optimal operating parameters such as line projection angle, anamorphic ratio of the camera lens and its digital resolution.

Figure 3 shows raw profiles of four different HVOF coating steps varying form 12 to 45 microns. The smooth profile was recorded on a surface moving at a typical spray gun speed. As mentioned earlier, the intrinsic surface averaging of this technique greatly diminishes the profile ripple caused by surface roughness.

The first task of the image analysis algorithm is to find the position of the line within the CCD array. This position calculation must have a micron level precision to be able to measure a single pass of a few microns with a reasonable accuracy. For example, with the CCD's 1024 pixel lines capturing a 10 mm field of view and using a 30 degree angle for the line projector, a 10 micron layer step will induce a deflection of about 2 pixels. Therefore, the required precision corresponds to sub pixel resolution of the line position.

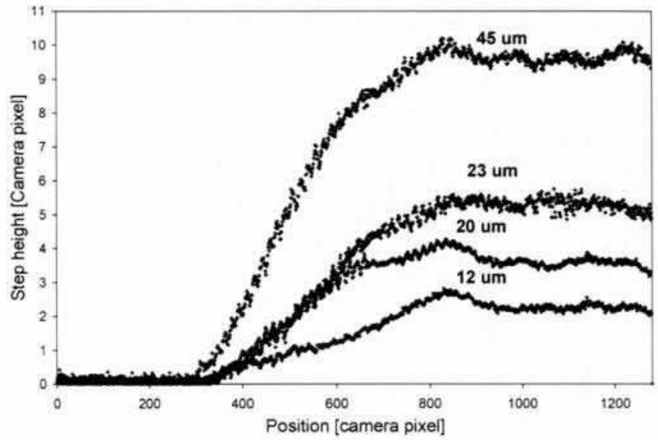

Figure 3: Raw profiles of four different step heights from 12 to 45 microns. Those results were recorded on a previously coated, moving surface.

The offline development was then shifted to axis symmetric geometries like cylinders. Four inch diameter aluminum cylinders were produced and coated with WC-12%Co by HVOF and YSZ by plasma spray. Each sample was divided in four sections coated with an increasing number of layers in order to obtain three well defined steps per cylinder. The steps were mechanically measured with a micrometer and some samples were cut and measured with a scanning electron microscope. The results of those measurements are presented in Table 1.

Table 1: Height of the three coating steps between the four sections of the four cylinders used in the offline tests.

Cylinder	Step #1(μm)	Step #2(μm)	Step #3(μm)
HVOF #1	45 ± 3	20 ± 3	9 ± 3
HVOF #2	23 ± 3	12 ± 3	4.5 ± 3
Plasma #1	50± 3	25± 3	12± 3
Plasma #2	25± 3	12± 3	6± 3

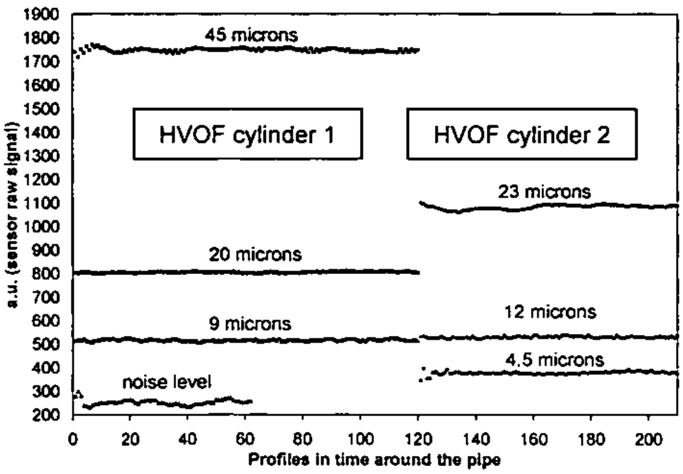

Figure 4: Continuous recording of coating step profiles on two rotating, WC-12%Co pre-coated, 4-inch diameter aluminum cylinders. The step heights vary from 5 to 45 microns.

A continuous measurement of the step was recorded to verify the stability of the reading. The results are displayed in Figure 4. The results show, on average, a very good stability. However, individual profiles sometimes were observed to differ significantly from the step model presented in Figure 1. These isolated cases represented less than 5% of the profiles. A numerical averaging of 10 to 20 profiles was sufficient to diminish the effect of bad profiles and reach a precision of a few microns. With the current sampling rate of 10 profiles per second, this translates into a reaction time between one and two seconds. The algorithm was also adjusted to reject profiles with unusual steps. The rejection criterion was based on the position of the step in the screen as well as on its height. The minimum and maximum height limits were dynamically set in accordance with the standard deviation and the average value of the last fifty profiles.

The results obtained offline on the pre-coated cylinders demonstrated the achievement of the targeted resolution with the measurement of a 5 micron single pass step of WC-Co coating with a signal to noise ratio above ten. This ratio is calculated by dividing the difference of amplitude between the 5 micron level and the noise level by the noise's standard deviation. Figure 5 presents the linear relation between the optical measurement and the physically measured step height.

Once calibrated from the HVOF data points of Figure 5, the system was tested with the plasma sprayed cylinders. The thickness measured by the sensor was in very good agreement with the real values of the steps and therefore confirmed that the measurement is independent of the coating material.

<u>Online results</u>

With the offline tests, key issues like minimum resolution, calibration and material independent measurements were confirmed. Online tests were essential to develop the real-time configuration of the sensor. Mechanical vibrations, hot gas birefringence and thermal expansion are some of the factors that could affect the sensor in a production environment.

A total of five cylinders where sprayed with multiple layers of WC-12%Co. Spray parameters like the gun speed, the cylinder rotation velocity and the powder feed rate were adjusted to deposit various layers with thicknesses ranging from 8 to 40 microns. The sensor was mounted with the gun directly on the robot using a special bracket able to handle both. In order to protect the sensor from the spray plume, additional metallic shielding and air blowing was added to the online installation.

A first series of online results was obtained on a seven inches, diameter, 20-inch long steel cylinder coated with a total of nine layers. Each layer was monitored by the sensor. The same spraying parameters were applied to the first six layers and the approximated thickness deposited per pass was about 13 microns. For the three other layers, the powder feed rate was doubled. Figure 6 shows the real-time thickness measurement of all nine passes. It also shows the noise level recorded with a live gun without powder feed. The online noise levels were observed to be significantly higher. Most of this increase is attributed to deformations in the profile due to refraction effects created by random circulation of hot gasses in the sensor's field of view. Similar variations could be induced offline simply by blowing hot air in front of the device.

However, noise levels were low enough not to compromise correlation between the measured thickness signal and the powder feed rate. In fact, the sensitivity of the sensor is still excellent and comparable to the offline sensitivity. The source of the observed fluctuations of the measurement is still not fully understood. Of course, its effect can be further reduced by increasing averaging.

The general tendency of the 200 thickness measurements per

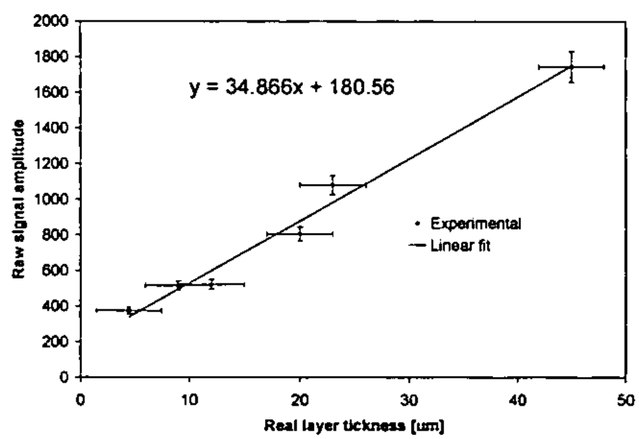

Figure 5: The profilometer raw amplitude as a function of the coating step thickness. The linear fit is used for the calibration of the system.

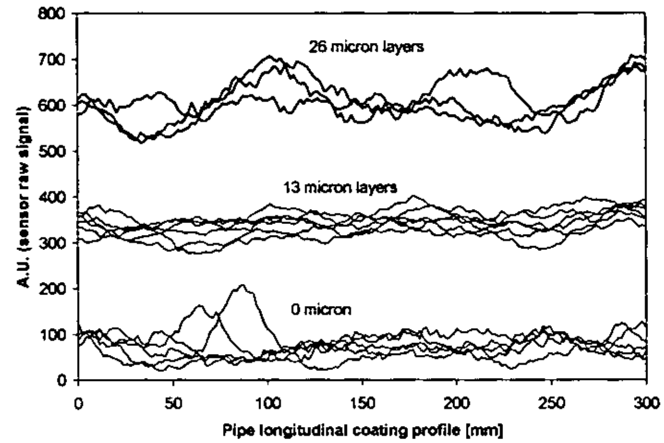

Figure 6: real-time online measurements of the layer thickness during deposition. The six lower curves indicate the measurement output with a zero powder feed rate. The six middle curves indicate the measurement of approximately 13-micron layers. The three upper curves are the measurements with the powder feed rate doubled.

pass shown in Figure 6 is linear and stable. An averaging of 200 profiles may be a good starting point for further online experiments. This, of course, will increase the reaction time of the sensor to around 20 seconds, which is still more than sufficient for the intended purpose.

The final coating thickness is given by adding every layer. Figure 7 shows the profile of the total coating thickness given by the sensor and by a destructive, scanning electron microscopy measurement. On the same figure are the separate

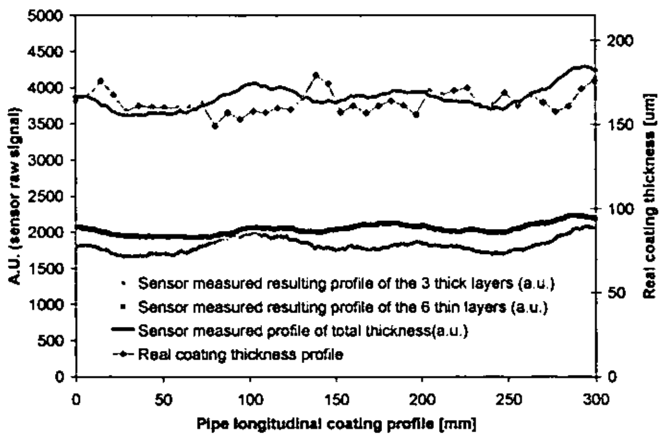

Figure 7: In the lower part of the graph, the thick black line is the sum of all three thick layers and the thick grey line is the sum of all six thin layers. The calculated sum of these two lines is plotted as the continuous thin black line at the top of the graph. It exhibits a variance comparable to the destructive measurements of the final coating displayed as gray diamonds.

totals of the first six thin passes and the last three thick passes.

The second online measurements were performed on four aluminum cylinders measuring six inches in diameter and 20 inches in length. Each one of them received six layers of HVOF sprayed WC-12%Co. The main goal was to compare the relation between the thickness and the measurement with online results. To do so, the spraying conditions were modified from one sample to the other in order to get four different total coating thicknesses. Destructive measurements were performed on the cylinders at various locations in order to determine their actual thickness profiles.

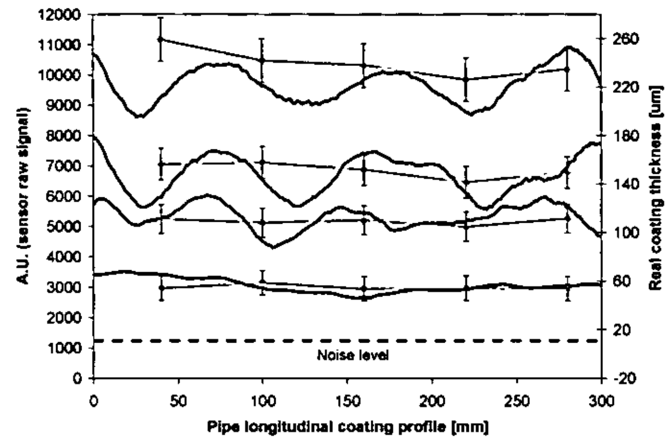

Figure 8: The black lines show the four different coating profiles measured by the sensor. The black dotted line shows the noise level of the sensor which offsets the linear calibration equation. The grey data points plot the real thickness profiles of the coating (measured by optical microscopy) for each sample. The error bars represent the standard deviation of the local thickness around each measurement point.

The results, shown in Figure 8, confirm the linear relationship between the sensor measurements and the coating thickness. However, some measurements presented variations that were not correlated with the actual thickness profile. With further analysis, a few surface regions were found where the coating profile strongly differed from the ideal step function. Those exceptions seem related to the spraying conditions and are more significant with smaller cylinder diameters. They could also be attributed to the surface condition of the cylinders as well.

Figure 8 also shows that the oscillations are important and synchronized in the two thicker samples. The cylinder rotation speed and the gun speed were the same in the two conditions. Only the powder feed rate was increased. Fortunately, for usual spraying speeds used in HVOF, those variations are much less apparent. Once again, the results are in favor of the longer averaging approach for real time monitoring. Nevertheless, experiments are underway to understand the causes of those variations and establish a more robust algorithm for the detection/rejection of bad profiles that could bias the thickness measurement.

Conclusion

A novel approach based on optical triangulation to achieve non-contact online thickness measurement of thermal spray coatings was presented. The sensor monitors the layer thickness as it is deposited. The required micron level resolution was easier to achieve for offline measurements on pre-coated cylinders than for live, online tests where it was limited to approximately 5 microns. The online tests have confirmed the functionality of the sensor in a production environment. The measurement was found to be independent of the coating/substrate nature, the surface roughness or the thermal expansion of the coated part. Further work will be oriented toward increasing the resolution and the depth of field of the instrument. Beta-test sites will also play a key role in evolving this technology towards full industrial applicability.

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