Process Control of Thermal Spraying

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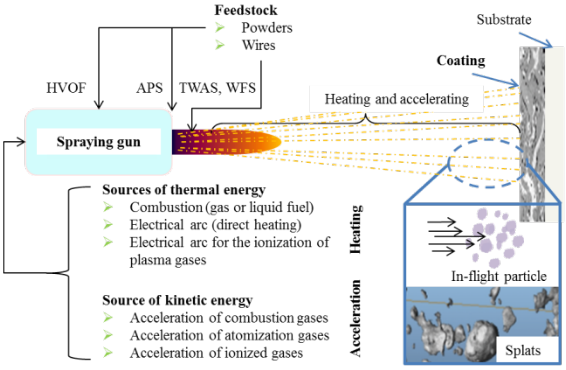
Abstract. Online process control of the thermal spraying process is a relevant factor for the continuous production of high quality coatings. Therefore different systems for process monitoring like optical systems are used. Another method for the process control is the analysis of the acoustic emission during the spraying process and the cooling-off time of the component. On this way a monitoring of the process parameters, an estimation of the coating thickness and the detection and localization of cooling-off cracks are possible.

In this work the experimental setup for the process monitoring by acoustic emission analysis is shown. So the sensors were mounted on the component and on the spraying nozzle in order to get more information about the process. Measurements on different spraying systems with defined process parameters were done and analyses in order to correlate the acoustic emission signals with spraying parameters. By analyses of the emission signals the coating thickness can be also measurement. After the spraying process cracks during the cooling-off time were detected. So this system shows an interesting alternative for the process control of the thermal spraying process.

Introduction

Protective coatings with a desired quality are produced by thermal spraying processes which simultaneously using of thermal and kinetic energy. The molten or semi-molten material is propelled toward a prepared substrate surface by expansion of the process and atomization gases. The coating process comprises the heating / melting, acceleration, impact, rapid solidification and incremental build-up of a large number of individual particles [1-8]. Therefore, the main properties of the obtained deposition are driven by the parameters which directly or indirectly influence the particle formation, particle inflight characteristics and the flattening behaviour of droplets on the substrate surface [2, 3]. The obtained coating quality is directly dependent on the characteristics of spraying plume and thus on those of the inflight particles as illustrated in Pic. 1.

The particles in the twin wire arc spraying (TWAS) spraying plume are initiated and formed through the atomization of a molten feedstock. The atomization occurs by the impingement of a fast and continuously flowing atomization gas jet (mostly compressed air) upon the melting wire tips of consumable electrodes. The wires as shown in Pic. 1 (one connected as anode (+) and the other one as cathode (-)) are fed together to ignite an arc at the shortest distance between the electrically conductive part in the wire tips. Beside the mass flow and velocity of the atomization gas, the type of gas used plays a dominant role on metal atomization. Therefore, a high gas velocity is required for the production of smaller inflight particles, and a tight particle size distribution in the spraying plume. The gas outlet velocity is related directly to the shape and size of both straight bore nozzle and air-cap throat diameter as shown in Pic. 2. The noise of exit flow increases by the size of the atomization straight bore nozzle and decreases by the diameter of the air-cap throat. Both, the alternating arc ignition as well as the streaming gas are very important parameter in determining the noise level at the gun outlet [9]. The acoustic signal recorded at the spray gun side is important for the reliable prediction about the accuracy of the adjusted parameters. At the substrate side, the recorded acoustic signal could give an indication regarding coating thickness and delamination.



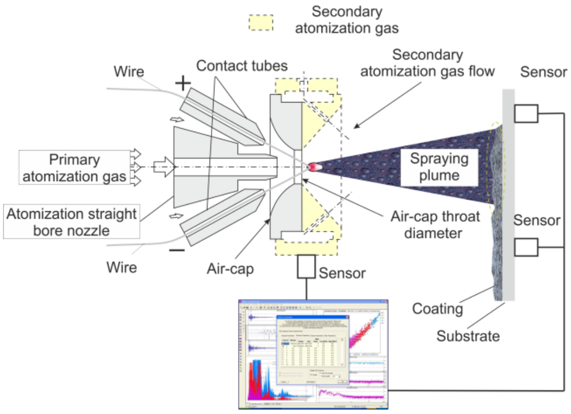
Pic. 1. Sources of acoustic signals in thermal spraying technique

Even though, TWAS technology has become an important part of modern industry for the provision of coatings which offer customized surface properties for a variety of industrial applications. It is still facing a challenging objective regarding reliability and reproducibility of the sprayed coatings. Therefore, the control over the spraying process is a very important issue as it is the key to meet the industrial demands regarding the predictability and reproducibility of the desired coating quality. This work aims to investigate the possibilities of utilizing acoustic techniques to monitor the TWAS process. The acoustic signals were recorded for iron solid wire. Correlations between emitted acoustic signals and adjustable process parameters are clarified. The main task is to enhance the understanding of the TWAS process and to enable the use of acoustic emission analysis for the process monitoring. An attempt is also made to establish a correlation of the adjusted process parameters, the wires used, and the emitted acoustic signal at the gun side as well as the substrate side. The obtained results are the basis for further investigations regarding the correlation between the recorded acoustic signals and the obtained coating quality. The findings can lead to an accurate prediction of the obtained coating quality and an improved process control of the TWAS process could be achieved.

1. Experimental Setup

1.1 Measurement of acoustic signals

A Smart Arc 350 PPG (Co. Sulzer Metco, Switzerland), as an advanced electrical wire arc spraying system, is utilized to investigate the acoustic signals emitted by the twin wire arc spraying (TWAS) process Pic. 2. A high definition acoustic recording system PCI-2 (Co. Physical Acoustics B.V.) was used to record the emitted acoustic signals of the spraying process. The system consists of two transient recorder channels, two pre-amplifiers, and two broadband microphones sensors (100 kHz - 1,000 kHz). One of the system sensors (microphones) was attached at the nozzle and the other one at the substrate as illustrated in Pic. 2.



Pic. 2. Acoustic monitoring in twin-wire arc-spraying process

In this way, the acoustic signals at the nozzle and at the substrate were recorded simultaneously. Additionally, a noise filter was activated in the transient recorder to eliminate the effect interference. The analysis was carried out on solid wires (Sprasteel 11, Co. Sulzer Metco) with the following composition in wt.-% (Fe Bal., C 0.07%, Si 0.96%, Mn 1.63%). Table 1 shows the regions of the adjustable parameters analyzed.

Table 1. Recommended Font Size

Parameter	**Range**
Current (U) [A]	180-260
Voltage (I) [V]	28-32
Primary gas pressure (PG) [bar]	2-6
Secondary gas pressure (SG) [bar]	2-6

1.2 Data processing and validation

The emitted acoustic signals were recorded and processed with a special signal processing software (Noesis Professional, Co. Physical Acoustics Corporation PAC, USA). A Fast Fourier Transformation (FFT) was applied to transform the recorded data from time domain to frequency domain. The frequencies of the emitted acoustic signals were plotted against the amplitude in all diagrams. The in-flight particle velocity and temperature were measured at a stand–off distance of 130 mm, using AccuraSpray-g3 (Co. Tecnar, Canada). The measurements were used to explain the different behavior of emitted acoustic signals.

2. Results

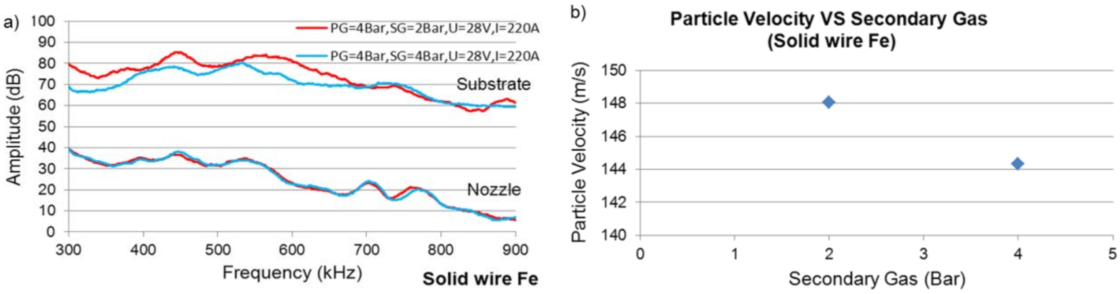
Two kinds of forces simultaneously impact the wire tips in the TWAS process. Firstly, the continuously operating aero dynamic force, applied by the primary atomization gas pressure which causes a steady acoustic signal. Its magnitude depends on the nozzle configuration and the adjusted gas pressure. The second force is the alternating arc ignition. The fluctuation in the electrical arc is caused by a widening and narrowing between the two wire tips caused by the removal of molten material by the atomization gas. In order to ensure a steady spraying process the wires are continuously fed together. The results of these experiments are later used to underline the effect of the arc ignition, by analyzing the recorded acoustic signals of the spraying process. The applied analyses for the emitted acoustic signal are characterized regarding the adjusted process parameters.

2.1 Effect of the Gas Pressure

The emitted acoustic signals were recorded simultaneously at the nozzle and at the back side of the substrate. At the nozzle side a higher signal was observed at a higher primary atomization gas pressure (PG) setting. At the substrate side, the signals recorded were in general much higher than those recorded at the nozzle side. This is due to the effect of the impacting particles at the substrate surface. The number of particles per time unit is depending on the adjusted deposition rate. Some similarities in peaks, with a slight time delay, are obviously. The acoustic signals are simultaneously recorded at both sides. The signals recorded show a dependency with respect to the changing PG setting. At a lower PG, a higher signal was recorded at substrate. These can be ascribed to the larger particles at lower PG settings.

Changing the secondary atomization gas pressure SG shows almost no effect on the emitted acoustic signals at the spraying gun side as shown in Pic. 3 a). At the substrate side, the effect is higher.

One reason for this behavior is related to the atomization intensity of the inflight particles. The inflight particles become smaller particles at higher SG settings due to the intersection between the PG stream and the SG stream, which enhances the secondary atomization of the inflight particles. Therefore the lower amplitude of acoustic signal recorded at the substrate is observed at a higher SG setting.

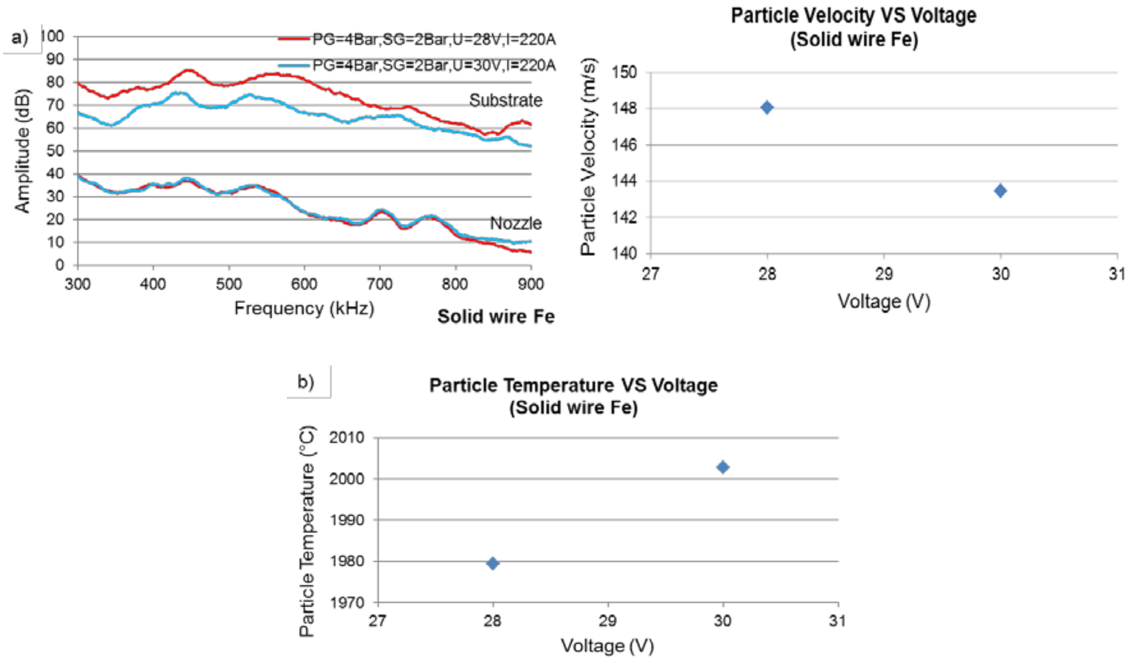


Pic. 3. a) Effect of the adjusted gas pressure on the emitted acoustic signals
b) Particle velocity at different SG settings

Another reason for the lower amplitude is the instability in TWAS process which is directly related to fluctuations in the arc ignition. The wires intersection point, the point where arc ignites, is located outside the gun. Therefore, a precise relation between arc fluctuations and emitted acoustic signals is very challenging task. The measured inflight particle velocity could help in understanding the emitted acoustic signals at different SG settings Pic. 3 b). Even though a higher SG at the setting PG=4 Bar and SG=4 Bar compared to PG=4 Bar and SG=2 Bar, a lower signal was recorded for the higher setting. By comparing the inflight particle velocity for both settings, a slight decrease in the inflight particle velocity was recorded at higher SG setting. This can be explained by the fact that, the secondary gas causes a reduction in velocity of the primary gas flow at their interference point. Downstream this point, both flows are combined and the secondary gas flow may lead (depending on the ratio between adjusted SG and PG) to an increase in the total gas velocity for solid wire Fe.

2.2 Effect of Voltage Adjustment

While increasing the voltage causes to a decreased acoustic signal at the substrate side, no changes were detected at the spray gun side as shown in Pic 4 a). A higher voltage increases the induced heat, which decreases the surface tension of the molten material at the wire tips and thereby larger particles can be disintegrated from the parent wires.



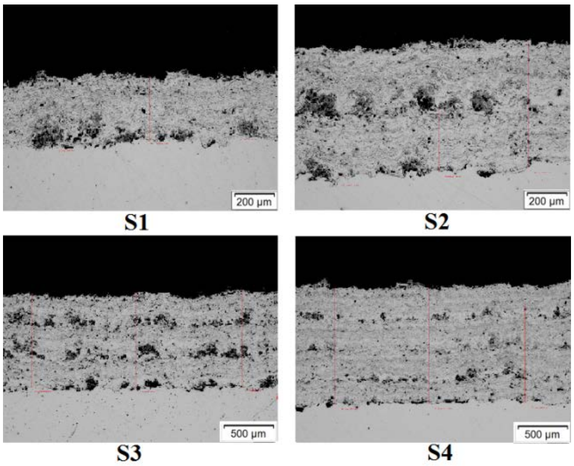
Pic. 4. a) Effect of the adjusted arc voltage on the emitted acoustic signals
b) Particle velocity at different SG settings for solid wire Fe
c) Particle temperature at different SG settings for solid wire Fe

The variation of the in-flight particle size for different voltage settings could be explained with the different particle velocities recorded. Although the gas pressure was the same in both voltage settings, a higher particle velocity was obtained when applying U=28V. The minor difference in the particle velocity (150m/s by 28V setting and 143,3m/s by 30V) is an indication for a variation in the particle size between both voltage settings in Pic. 4 b). Not only is the generated heat at higher voltage settings larger, but also the heat effect zone in the wire feedstock. The temperature distribution is also wider as can be seen by the increased particle temperature (Pic. 4 c)). The reason for larger particles could be explained due to the heat propagation in solid wires. As the arc ignites it causes a melting of the faced area of both wires. The areas of the feed wires directly underneath the molten zone are heated, due to the heat propagation in metals, to a semi-molten state. Therefore, the particle size distribution and the amount of bigger particles in the case of elevated voltage settings are higher than at lower voltage settings. At a voltage setting of 30 V the initiated particles are larger in diameter, hotter, and are slower than those initiated by a voltage setting of 28 V.

2.3 Effect of the numbers of overruns

In order to produce a given coating thickness, the component will be sprayed several times. The already sprayed coating will dampen the signal of the newly sprayed particles. The coating thickness can be measured online during the spraying process by evaluating the damping behavior. During the spraying process, the acoustic signals were recorded. In the previous experiments, it is already found that the acoustic signal was damped by the sprayed coating and the amplitude of acoustic signal decreased with increasing coating thickness. In order to investigate this relationship exactly, more experiments were carried out in which four samples with 1, 2, 3, and 4 spraying overruns were produced.

All samples were analyzed by metallographic methods. The corresponding results are shown in Pic. 5.

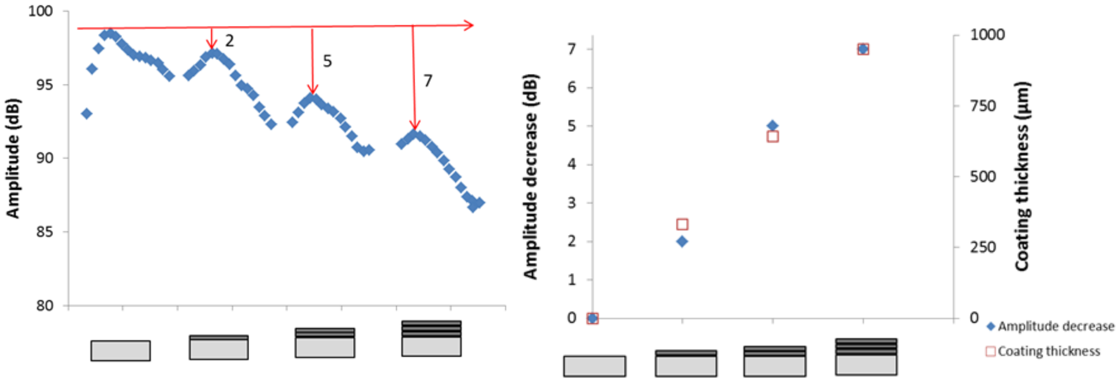


Pic. 5. Metallographic measurement of coating thickness of samples S1, S2, S3, S4

Table 2. Recommended Font Size

	S1	S2	S3	S4
MP 1 [µm]	358.4	651.7	933.7	1172.5
MP 2 [µm]	323.1	643.0	951.1	1161.7
MP 3 [µm]	309.6	631.1	968.4	1183.4
Average [µm]	330.4	641.9	951.1	1172.5

Next step is to evaluate the correlation between the amplitude decrease and the determined coating thickness through metallographic analysis, and then to check if both match. Pic. 6 a) shows the decreased amplitude with increased coating thickness after four overruns. The symbols in the diagram indicate the specimen before the overrun. Correlation between amplitude decrease and coating thickness was constructed as shown in Pic. 6 b).

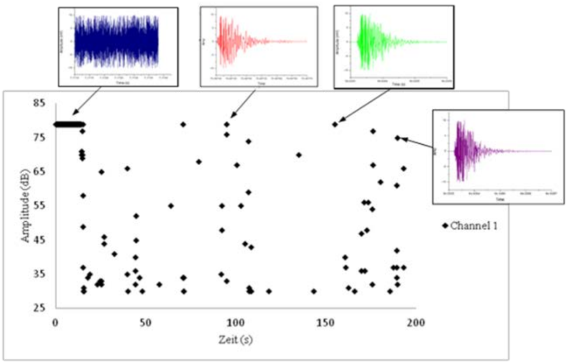


Pic. 6. a) Decreased amplitude with increased coating thickness with 4 overruns
b) Correlation between amplitude decrease and coating thickness

The measurements during the spraying process documented that the coating thickness can be estimated online by evaluation of the amplitude of acoustic signals during the spraying process.

2.4 Detection of cooling-off cracks

For this investigation the signals from the sensor which is fixed on the backside of the substrate was recorded during and after the spraying. Pic. 7 shows the amplitude of the signal against the measurement time.



Pic. 7. Acoustic measurement data of cooling process after spaying

For the first about 10 seconds the spaying is active and a continuous signal is detected. Then during the cooling process after spraying acoustic signals with different strengths were recorded. It was found that the signals with high amplitude show a typical burst signal for the crack formation, shown in Pic. 7 for three typical signals. These signals show a similar behavior as the signals which were recorded during tensile tests before. Thus, the crack during cooling process after spraying can be detected with the aid of acoustic emission analysis.

3. Conclusion

Detailed knowledge of the emitted acoustic signals and the adjusted process parameters are crucial to use the acoustic signal analyses monitor the TWAS process. The emitted acoustic signals of twin wire arc spraying processes using solid wires were recorded simultaneously at the nozzle and at the backside of the substrate. The signals detected at the nozzle depend mainly on primary atomization gas pressure of the spraying system. The signals recorded at the substrate shows in general much higher amplitude than those recorded at the nozzle. At the substrate side, the emitted acoustic signals are dependent on the feedstock materials and adjusted process parameters. In this way a process control with respect to the spray parameters and the spray material is possible.

The online measurement of coating thickness during spraying process using acoustic emission analysis has been successfully achieved in this work. The correlation between the amplitude decrease and coating thickness could be verified. The increasing coating thickness is interpreted by the amplitude decrease accordingly.

In the detection of cracks during cooling process after spraying with the help of acoustic emission analysis, the typical burst signal for the cracks was found and proved in the pre-experiments with tension test.

Our future works will cover the adaptation of the emitted acoustic signals to the substrate in order to predict the coating quality as well as the online measurement of the coating thickness in thermal spraying processes.

Acknowledgement

The authors gratefully acknowledge the financial support of the DFG (Deutsche Forschungsgemeinschaft) within the collaborative research Centre SFB708/TP-B3.

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