Spray pattern analysis in TWAS using photogrammetry and digital image correlation

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Abstract. In terms of arc spraying processes, the spray plume characteristic is mainly affected by the flow characteristic of the atomization gas at the nozzle inlet and intersection point of the wire tips, which in turn affect the particle distribution at the moment of impact when molten spray particles splash onto the substrate. With respect to the route of manufacturing of near net-shaped coatings on complex geometries, the acquisition of the spray patterns is pressingly necessary to determine the produced coating thickness. Within the scope of this study, computer fluid dynamics (CFD) simulations were carried out to determine the distribution of spray particles for different spray parameter settings. The results were evaluated by three-dimensional spray spot analyses using an optical measurement based on photogrammetry and digital image correlation. The optical measurement represents a promising and much faster candidate to measure spray patterns compared to the tactile measurement system but with an equal accuracy. For given nozzle configurations and spray parameter settings, numerous spray patterns were examined to their shape factors, demonstrating the potential of an online analysis, which encompasses a "fast sample loop" and a data processing system to generate a three-dimensional surface of the spray spot profile.

1. Introduction
In terms of twin wire arc spraying (TWAS), the in-flight particle conditions and gas flow characteristics across the expanded spray plume get mainly determined by the flow characteristics of the atomization gas at the nozzle inlet and intersection point of the electrode tips, as well as the electrode phenomena during atomization [1-6]. Thus, in addition to electrodynamic aspects, the presence of the electrodes (wires) and contact-tubs in the gas flow has an enormous impact on the resulting flow regimes. Moreover, the configuration of the nozzle design (i.e. nozzle inlet, or air cap) affect both, the resulting flow regimes at the electrode tips, and the gas flow characteristics across the expanded spray plume. In order to optimize the nozzle design in a TWAS process, numerous studies have focused on the flow regimes by means of computational fluid dynamic (CFD) simulations using different nozzle configurations [6-13]. According to these studies, the major objective was focused on the gas flow characteristics inside and outside the spray gun, as well as gas-particles interactions. Although many numerical studies have been conducted to investigate the flow characteristics, there have been only few examinations on the spray plume divergence and spray pattern. Studying different nozzle concepts, Hussary et al [11] evaluated different designs with respect to the trajectories of spray particles, velocity distributions and the deposit distribution. It was found that the spray plume divergence decreases significantly with an increasing atomization gas pressure. The authors also reported that the incident angle of the secondary gas, since it used for the setup, affect the spray plume divergence significantly. Same results were found in [12, 13]. According to Gedzevicius et al. [12], the supply of a secondary gas, depending on the local injection, has not only a focusing effect, but also
leads to a further disintegration (secondary atomization) of the molten spray particles. However, the authors [13] previously demonstrated that the spray plume divergence get distinctly influenced by the nozzle design used for spraying.

With respect to complex geometries, there is a great need to apply near net-shape coatings in order to minimize costs for post-processing. Nowadays, complex geometries obtain component features such as various radii. In this respect, the spray pattern plays an important role as a focused spray plume can lead to a controlled coating deposition. Previous studies [14, 15] already emphasized the relevance of the acquisition of three-dimensional spray patterns (footprints) in order to assess the particle distribution at the moment of impact onto the substrate. The footprints can be described by a mono-modal spherical-shaped or irregular-shaped distribution. Moreover, the footprints can be characterized by the spray pattern area, diameter, eccentricity or circularity. It is therefore necessary to determine these characteristics in order to evaluate suitable spray process parameters, and nozzle designs, respectively. Horner et al. [15] studied the spatial characteristics of deposited spray patterns such as spray area, eccentricity, flatness, and deposition rate for various spray parameters. It was experimentally shown that the spray area get mainly influenced by the atomization gas pressure. Thus, a large-scaled spray area results from low atomization gas pressure and low secondary gas pressure. In contrast, the spray pattern eccentricity was most dependent on secondary gas pressure, whereas the spray pattern flatness was most dependent on atomization gas pressure and arc current used during spraying. To conclude, the study demonstrated that an amendment on the operating conditions in TWAS leads to a great change of the resulting footprint.

With respect to the aforementioned studies [14, 15], the footprints were produced on large-scaled metal plates. A high resolution surface profiling system was used to measure the three-dimensional footprints in order to characterize the particle concentration at the moment of impact onto the substrate. As a result, a great experimental expenditure is necessary to scrutinize the footprints experimentally.

Within the scope of this study, CFD simulations were conducted to determine the distribution of spray particles for different spray parameter settings. The results were evaluated by three-dimensional footprint analyses using an optical measurement based on photogrammetry and digital image correlation. The footprints were analysed for various spray operating conditions examining the potential of an online analysis, which encompasses a “fast sample loop” and a data processing system to generate a three-dimensional surface of the spray spot profile.

2. Computer-Fluid-Dynamics (CFD) Simulation

The 3D-CFD analysis is performed inside the spray gun and for 110 mm standoff distance along the spraying axis. An inlet port is assigned for the entrance of the atomization gas into the spray gun as shown in figure 1. The function of the two connecting tubs, which are connected to the electrode ports is to charge the wires electrically to different poles (anode and cathode). The wires are intersecting at the back of the spray gun, as the connecting tubs are inserted in two intersecting channels. The atomization gas is directed towards the arc zone.
Figure 1. Section views of a 3D-CFD model of the twin-wire arc spraying (TWAS) process showing the output gas velocity

The internal gas flow is shaped according to the outer solid surfaces of the assemblies inside the spray gun, and the external flow analysis is only bounded by the defined computational domain boundaries. For shorter computation time, the brick cells were used for gridding the computational domain. But for achieving higher simulation accuracy [6], finer grid size is used for the narrow channels inside the spray gun and along the centre core of the spray flow.

A TWAS was completely modelled by using the Flow Simulation Analysis tool in SolidWorks® software according to the following computational domain parameters, the input fluid pressures are 4, 6, 8, 10 and 12 bar air pressures and the solid surfaces of the models are assumed to be ideally adiabatic. The ambient initial conditions were assumed, and the standard k-ε turbulence model is used in the analysis. The used mesh settings are based on a prior mesh sensitivity convergence analysis to obtain the proper mesh setting, which ensures a compromise between the simulation accuracy and the required computational time.

The numerical simulation study is required for time and cost saving measures to estimate the particle concentration in the moment of impact on the substrate.

3. Experimental Setup

Rectangular (150 mm x 150 mm x 16 mm) C45 steel specimens were employed as the substrate material in order to produce spray pattern profiles. For the preparation of the coating deposition a 15 mm wide frame of the substrate was shielded from grit blasting and spraying during the manufacturing of the samples. This polished area has been used within the scanned profile as a reference height and to compensate the small rigid body rotations due to an imperfect placement of the specimen. After that, the surfaces were grit-blasted and cleaned in an ultrasonic ethanol bath.

The spray torch of the Durspray 450 arc spraying system (Durum Verschleißschutz, Germany; OEM: T-Spray) was carried by a robot type IRB 4600 (ABB, Sweden) to achieve a perpendicular alignment at the centre of the surface at the desired distance of 110mm. With regard to the feedstock material, an iron-based solid wire 316L Si (T-Spray, Germany) was used. The PGP was varied in a range as seen above. No SG was used during the study as interactions (flow characteristics, secondary atomization behaviour) would become more complex. For the experimental setup, the voltage and current were kept on a constant level (voltage = 34 V, current = 110 A, spray-time 3s).
After applying the coating for 3 seconds the contour of the specimens was measured with a coordinate measuring machine type Prismo Vast (Zeiss, Germany). The measuring accuracy of this machine is about 2μm and a maximum of 200 measuring points per second can be recorded. In the present case, approximately 1.7s were required per measurement point due to larger probing distances. One hour was needed to measure one footprint with 2120 points. Also, the transport and mounting of the specimens and configuration of the machine were time consuming.

The shielded field was used to define a plane as the zero level for reference. Through the grit-blasting, the start level for the coating is about 0.075mm to 0.15mm below the zero level. The spatial resolution is essentially not only limited by the equidistant measuring grid, but also by the 0.5 mm sapphire ball-tip. The measurements used two different measuring grids. In a range of 18x18mm around the centre of the specimen, on which the TCP of the coating robot was aligned, a grid of 0.5mm x 0.5mm was used. For the remaining area (100mm x 100mm) a grid of 4mm x 4mm was used. As an alternative, an optical measuring system was used. The optical measuring method is based on the principle of photogrammetry. The footprint is synchronously photographed by two Nikon D800E SLR cameras, which were mounted on a rail. For calibration, a special checkerboard pattern was used. The purpose is to determine the properties of the camera lenses, as well as the alignment of the cameras to each other and thus enable a true-to-scale measurement. The digital image correlation (DIC) is used to assign an area of the footprint in the two camera images. For this method, the surface must have a high-contrast random pattern. This is given by the coating itself in good approximation.

The software used for this measurement is Istra4D (Dantec Dynamics, Denmark). The calculated surface contour can be exported as measuring coordinates comparable to a coordinate measuring machine. But these values refer to the camera coordinate system. To make them comparable a best plane fit transformation must be performed. There is a source of error in this case, because this step is not only applied on the protected edge, but also on the entire considered sample.

4. Results
To analyse the measuring data the software OriginLab 2017 (OriginLab Corp., USA) and for comparison of the two different measurement systems the software GOMinspect (GOM, Germany) was used.

The simulation does not give direct information about the footprint but a distribution of the spray plume velocity. This is equated to a footprint shape. Figure 2 shows a comparison of the simulated data and the tactile measurement of a coated footprint with the same parameters. The top view looks similar, but the side view shows a significant dip. Accordingly, the differences between simulation and measurement become clear. The simulation can give a hint to choose appropriate parameters but a measurement is always necessary if the actual footprint shape is necessary. The circularity is a property which can be extracted from this data. Figure 3 shows the comparison of the circularity values of the simulation data and the tactile measurement. Varying the PGP between 4 and 12 bar directly influences the circularity of the footprint. The tendency is equal with both datasets.

The main disadvantage of the tactile measurement systems is the long measurement time, and that the result accuracy depends on the stylus geometry and the measurement procedure. The values between the measuring points are interpolated. Therefore especial high gradients as they occur with the crater-like structure of the footprints produced by the TWAS process lead to big deviations. In order to reduce this influence, the measuring grid has to be reduced, which would increase the measuring time considerably. To reduce this disadvantage a new approach is used. A camera based measurement system can capture the whole footprint at once. Also the measurement point density is clearly larger, as shown in figure 4. Both footprints are comparable, but there is a little difference in the absolute value. This deviation is a result of the previously mentioned error of the calculated reference plane and by the deviation due to the interpolation between the coarse densities of the measuring points of the tactile measuring system. Figure 5 shows an error map calculated with the software GOMinspect. The influence of gradients and an offset-error due the reference plane is recognizable.
Figure 2. Comparison between a simulation footprint and a digitalized footprint profile by using a 3 D tactile measurement system

Figure 3. Comparison of the circularity of the simulated and the tactile measured footprints
Figure 4. Comparison between a digitalized footprint profile by the camera system and a digitalized Footprint profile by a 3 D tactile measurement system

Figure 5. Measurement deviation between the tactile and the optical system

Footprints with smoother contour produced, for example, by the HVOF process, are having a much lower error in the same measuring setup. But for the circularity criteria, the absolute values are not important. A direct comparison of the simulation, tactile and optical measurement shows this in figure 6.
5. Conclusion and Outlook
In this paper a CFD-simulation is shown as a possibility to evaluate the influence of a pressure variation to the spray plume with a given setup. The resulting footprints were verified using tactile measurements by comparing the circularity value. A big disadvantage of the tactile measurement is the time-factor. For a better detection of small edge areas, a finer grid would be desirable. But this would require a significantly longer measuring time. A new and innovative measurement system is introduced in order to overcome these disadvantages. The new camera-based system is significantly faster than the tactile measurement system, and the system can obtain very close results to the tactile measurement. Further works shall deal with the improvement of the optical measurement method and an optimization of the simulation.

6. References
[1] Wilden J and Wank A and Schreiber F 2000 Wires for Arc- and High Velocity Flame Spraying - Wire Design, Materials and Coatings Properties (Thermal Spray: Surface Engineering via Applied Research) pp. 609-617
[2] Pourmousa A and Abedini A and Mostaghimi J and Chandra S 2004 Particle Diagnostics in Wire-Arc Spraying System (Thermal Spray: Advances in Technology and Application) pp. 962-968
[3] Planche M P and Liao H and Coddet C 2004 Relationships between In-flight Particle Characteristics and Coating Microstructure with a Twin Wire Arc Spray Process and Different Working Conditions (Surf. Coat. Technol. 182) pp. 215-226
[4] Jandin H and Liao H and Feng Z Q and Coddet C 2003 Correlations between Operating Conditions, Microstructure and Mechanical Properties of Twin Wire Arc Sprayed Steel Coatings Mater. Sci. Eng. 349 pp. 298-305
[5] Wang X and Zhuang D and Pfender E and Heberlein J and Gerberich W 1994 Effect of Atomizing Gas Pressure on Coating Properties in Wire Arc Spray Thermal Spray Industrial Applications pp. 587-592

[6] Tillmann W and Abdulgader M and Anjami N and Hagen L 2015 Studying the Effect of the Air-Cap Configuration in Twin-Wire Arc-Spraying Process on the Obtained Flow Characteristics Using Design of Experiment Oriented Fluid Simulation J. Therm. Spray Technol. (vol 24) pp. 1-2, 46-54, DOI: 10.1007/s11666-014-0183-1

[7] Chen Y and Liang X and Liu Y and Xu B 2009 Numerical Analysis of the Effect of Arc Spray Gun Configuration Parameters on the External Gas Flow J. Mater. Process. Technol. 209(18-19), pp. 5924-5931

[8] Chen Y and Liang X and Wei S and Chen X and Xu B 2011 Numerical Simulation of the Twin-Wire Arc Spraying Process: Modeling the High Velocity Gas Flow Field Distribution and Droplets Transport J. Therm. Spray Technol. (vol 21(2)) pp. 263-274

[9] Toma S L and Bejinariu C and Baciu R and Radu S 2013 The Effect of Frontal Nozzle Geometry and Gas Pressure on the Steel Coating Properties Obtained by Wire Arc Spraying Surf. Coat. Technol. (vol 220) pp. 266-270

[10] Bolot R and Planche M P and Liao H and Coddet C 2008 A three-dimensional model of the wire-arc spray process and its experimental validation Journal of materials processing technology (vol 200(1)) pp. 94-105

[11] Hussary N and Schein J and Heberlein J 1999 Control of jet convergence in wire arc spray systems Tagungsband Conference Proceedings ed E Lugscheider and RA Kammer pp. 17-19

[12] Gedzevicius I and Valiulis A V 2006 Analysis of Wire Arc Spraying Process variables on coatings properties Journal of Materials Processing Technology (vol 175) pp. 206-211

[13] Gedzevicius I and Bolot R and Liao H 2003 Application of CFD Wire-Arc Nozzle Geometry Improvement Proceedings of the International Thermal Spraying Conference (ITSC, Orlando/USA) pp. 977-980

[14] Tillmann W and Hagen L and Abdulgader M and Rademacher H G and Schmidt A and Müller H and Wiederkehr T 2014 Investigations of Technological Developments in Nozzle Design for Twin Wire Arc Spraying by Means of Spray Plume Characteristics Proceedings of the International Thermal Spraying Conference (ITSC, Barcelona / Spain) pp. 455–46

[15] Horner A L and Hall A C and McCloskey J F 2015 The Effect of Process Parameters on Twin Wire Arc Spray Pattern Shape Coatings (vol 5) pp. 115-123.

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