Capturing the Influence of Jet Fluctuations on Particles in Plasma Spraying

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Abstract

Instabilities and fluctuations of the plasma jet can have a significant influence on the particle in-flight temperatures and velocities, thus affect the properties of plasma sprayed coatings. Presented in this paper is a novel method for capturing the effects particles are exposed to in the plasma spraying process. High-speed camera images of a plasma jet generated by a cascaded three cathode plasma generator (TriplexPro-210) are recorded for varying operating conditions. The images are processed using the inverse Abel transform. This transformation accounts for the fact that the images represent a 2-D projection and generates correct intensity values of the plasma jet images. These images are then combined with particle tracks resulting from CFD simulations of the plasma jet to match the particles path with the recorded plasma jet. This new method allows a precise description of the plasma intensity experienced by individual particles with a high temporal resolution. The results show a high sensitivity of the method, it can even detect the influence of the plasma jet originating from the cascaded triple arc plasma generator, which is considered as rather stable, on the particles.

Introduction

First developed in the 1910s and 1920s, thermal spraying is a coating process where particles are deposited onto a substrate in molten, semi-molten or solid state. With this technique, coatings ranging in thickness from microns to millimetres can be applied over a large area and at a fast deposition rate compared to other similar methods. The choice of coating material is also wide, including metals, plastics and ceramics. This allows thermal spray coatings to find application in several areas in industry, including transport, energy and manufacturing.

Plasma spraying is a thermal spray technique that makes use of a plasma jet to heat and simultaneously accelerate the feedstock (generally a powder) [1]. The process exhibits very high temperatures, with plasma jet temperatures reaching as high as 20,000 K, allowing the processing of the wide range materials mentioned above. The primary limit to this technique is that the melting temperature of the coating material must be somewhat 300 K below the vaporization (or decomposition) temperature in order to avoid low deposition efficiencies.

A major issue in describing this process is the large number of technical parameters that are required to capture each step in this process: the electron-gas interactions that create the plasma, the plasma-particle interactions when the feedstock is introduced to the plasma jet and finally the particle-substrate interactions when the coating material impacts on the substrate [2]. It must also be noted that several of these parameters are time dependent, such as variation in the electrical power due to continuous modification of the arc length, as well as turbulence in the flow. These fluctuations in the plasma jet cause different residence times and uneven heating of the feedstock can have significant implications on the properties of the resulting coatings [3].

One approach used to improve the stability of the jet has been the introduction of multiple arcs and the cascaded anode design. The cascaded design of the anode increases the distance between the electrodes thus raising the arc voltage rather than the arc current in order to achieve the necessary power. At the same time, the movement of the arc is restricted, which also reduces the fluctuation of the power output. By combining this measure with the division into three arcs, the stability of the power output can be further increased, resulting in a very stable plasma jet [4], [5].

However, even this stable free jet is affected by turbulence and thus continues to exhibit fluctuations. These varying jet size and movements affect the temperatures experienced by the individual particles as they pass through the plasma. An approach to generally describe the instability of plasma jets, including observations of fluctuations in the electric arc and the effect this has on the plasma jet and resulting coatings, has already been performed in literature [6], [7]. However, until now they did not concentrate on the instabilities in the jet of the cascaded three cathode plasma generator.

Advances in camera hardware have allowed for new optical approaches to describe the plasma spraying process. Many of these focus on the particles in flight after they have passed through the plasma jet [8], [9]. It is likely that optical approaches will continue to improve in the future with the abilities of cameras constantly improving [10]. State-of-the-art cameras are now able to precisely capture the highly dynamic processes of turbulence in the plasma free jet.

The approach of this paper was to apply a high-speed camera to capture the plasma jet fluctuations and its variance in intensity on the particles in plasma spraying. This was carried out on the assumed stable cascaded multi cathode plasma generator to prove that this type of plasma generator leads to varying particle properties. Due to the extreme brightness of the plasma, the...
path of the particles as they pass through the plasma cannot be observed without additional laser illumination. At the same time a laser illumination would outshine the plasma jet. For this reason, a CFD simulation was performed to calculate the particle trajectories within the plasma jet. These trajectories were then mapped onto the high-speed recordings of the jet. By combining the recordings and the particle tracks the effect of the plasma jet fluctuations on individual particles were assessed.

**Experimental Procedure**

**High-Speed Imaging of Plasma Jet**

The used cascaded triple arc plasma generator in this study is the TriplexPro-210 Plasma Spray Gun by Oerlikon Metco. The torch was equipped with a 9 mm diameter nozzle. As mentioned earlier, this plasma gun exhibits an increased plasma stability compared to commonly used models like the F4 or SG-100. Pure argon was used as the plasma gas. The electric current was varied at the levels I = 200 A, 350 A and 500 A, while the plasma gas flow rate took the following steps \( V_{\text{gas}} = 50 \, \text{slpm}, 70 \, \text{slpm}, 120 \, \text{slpm} \). The combinations of these leads to the process parameters outlined in Table 1.

| Trial | Arc Current [A] | Gas Flow Rate [SLPM] |
|-------|----------------|---------------------|
| 1     | 200            | 50                  |
| 2     | 200            | 70                  |
| 3     | 200            | 120                 |
| 4     | 350            | 50                  |
| 5     | 350            | 70                  |
| 6     | 350            | 120                 |
| 7     | 500            | 50                  |
| 8     | 500            | 70                  |
| 9     | 500            | 120                 |

High-speed videos of the plasma jet emerging from the plasma generator were recorded perpendicular to the torch axis. The camera used is a Fastcam model SA-Z by Photron, which was mounted with an Irix 150 mm f/2.8 macro lens. Higher frame rates can only be achieved with the Photron Fastcam by reducing the maximum image size and thus the field of view. For this investigation a frame rate of 210,000 fps was used, along with an exposure time of 1.25 \( \mu \text{s} \). This allowed for a field of view large enough to capture the entire length of the plasma jet while maximising the frame rate. A neutral density filter (ND64) was used to decrease the intensity of the recorded imaging to 1.5 \% of the original, preventing overexposure. An ultraviolet filter was also used to protect the lens.

**Calculation of the particle trajectories**

The particle trajectories were calculated using an existing CFD simulation in Ansys CFX. The simulations are composed of two different models. The first model solves the magnetohydrodynamic equations within the plasma generator. This approach is capable of calculating the velocity and temperature profile of the outlet of the TriplexPro-210 torch for the given process parameters. The model was developed in 2011 [11] and has been consequently expanded [12]–[14]. The second model calculates the propagation of the plasma jet into the atmosphere as well as the acceleration and melting behaviour of injected particles. The basics and details of this model are described in [15], as these would also go beyond the scope of this paper. The model has been validated by experimental measurements of the plasma jet fluctuations on individual particles were assessed.

A current of I = 500 A and a plasma gas flow rate of \( V_{\text{gas}} = 50 \, \text{slpm} \) were used for the calculations in the plasma generator model. In the model of the plasma jet a powder feed rate of \( \dot{m}_p = 24 \, \text{g/min} \) and an injector gas flow rate of \( V_{\text{inj}} = 5 \, \text{slpm} \) were applied as process parameters. The outcome of the model is individual 1,000 particle trajectories, each containing the \( x \), \( y \) and \( z \) components for the location and the respective time. Since the camera images only have two dimensions, the particles were projected onto a plane that lies along the axis of the injector and the plasma torch, thus reducing the dimensions as well. Fig. 1 shows the calculated and particle trajectories projected onto the mentioned plane and displayed in field of view of the recorded images.

![Figure 1: Calculated particle trajectories plotted into the later used field of view.](http://example.com/figure1.png)
Image Processing (Python/Matlab)

An inverse Abel transformation, as shown in the equation below, was carried out on the high-speed camera images in order to correct for the fact that they are a 2D projection of the plasma jet.

\[ f(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{dF}{dy} \frac{dy}{\sqrt{y^2 - r^2}} \]

It is necessary to apply this transformation to the plasma jet images before the mapping can be done. This is because the camera captures a 2D projection of an originally 3D plasma jet. The inverse Abel transform restores the 3D object from its 2D projection. If this transformation would not be applied the captured intensities of the plasma jet would not correctly represent the reality. The transformation was done in python, using a package called PyAbel [18]. This package provides efficient implementation of several Abel transform algorithms, allowing for quick trial of different algorithms in order to determine optimal results in reasonable time.

The instability of the plasma jet makes carrying out the transform difficult, as a prerequisite to carry it out is cylindrical symmetry. In order to minimise this issue each image loaded into python is split into pixel columns, which are individually centred by their intensity (scipy center_of_mass function) before being re-joined into a single image. The idea is to minimise the impact flickering of the jet has on one transform. This shift of the images must then be reversed after the transform has been carried out, as the particles would experience this flickering should the flight paths intersect.

Due to the extremely high frame rate used in this study, the number of files is in the thousands, and so an efficient algorithm is advantageous. A thorough investigation of the different transform algorithms is already available [19], both for sensitivity and speed, and it was found that the iterative Hansen Law method provides optimal results. [20]

Mapping of the particle trajectories onto the high-speed images

The calculated particle trajectories and high-speed imaging can then be combined in order to determine the potential plasma intensities profile single particles would experience. A full illustration of the complete image processing method carried out can be seen in Fig. 2. This process was done in Matlab. As the plasma jet is time dependent it is not possible to simply overlay the flight path over one image. The time steps from the CFD simulation were converted to equivalent image frames and for each step the intensity at each particle point could then be read. This was then combined to describe the intensity profile experienced by each particle.

It must be noted that the CFD simulation has a longer flight path than the trajectory presented in Fig. 2 c). This is due to the reason, that the simulation includes a representation of the powder hose and the powder injector. The path and consequently the needed time of a single particle to propagate through this section is very large in relation to the length of the recordings. If one were to take the uncorrected simulation time as a basis, the particles would only arrive in the interesting section after the end of the video. For this reason, the frame numbers were normalised after assessing the intensity profile such that each particle enters frame on frame 1 (but globally this is a different frame for each particle). This was done to simplify a comparison of the times the particles take to reach the plasma jet, residence times, etc.

Fig. 2: a) Original plasma jet image for an Argon plasma gas flow rate of \( V_{gas} = 50 \) slpm and an electrical current of \( I = 500 \) A. b) Inverse Abel transformation of the plasma jet image. c) Calculated particle trajectory mapped on plasma image.
Results and Discussion

A sample of the plasma jet imaging for each of the arc current and gas flow parameters is shown in Fig. 3. The plasma jet shown in the top left has the smallest arc current and plasma gas flow, at \( I = 200 \) A and \( V_{gas} = 50 \) slpm respectively, while the plasma jet in the bottom right has the highest at \( I = 500 \) A and \( V_{gas} = 120 \) slpm. Comparing the images from left to right, higher arc currents in the creation of the plasma flame result in a greater emission intensity. This was to be expected, since higher currents also lead to higher power levels. At the same time the emission intensity decreases with increasing plasma gas flow rate. This influence was again predictable and can be explained by the fact that with higher gas flow rates a greater mass has to be heated and thus the plasma jet reaches lower temperatures. Due to the deliberately consistent parameters chosen when the recordings were made, the images taken of the parameters with a current of \( I = 200 \) A barely show a plasma jet at all. This is especially true for the higher gas flow rate. Therefore, the results of these parameters are omitted in the following.

Fig. 4 shows the development of the plasma jet over the course of 14 ms. Two parameters, both with a current of \( I = 500 \) A and two different gas flow rates \( V_{gas} = 50 \) slpm and \( V_{gas} = 120 \) slpm are displayed. The videos, which unfortunately cannot be shown here, indicate a difference between the parameters. However, it is difficult to evaluate this difference. Purely visually it is not possible to tell which one of the parameters exhibits a higher stability. The same applies to the photographs shown here; the sequence of images alone does not reveal any significant difference between the parameters. This highlights the need for a methodical approach towards a quantitative assessment. The results of such an approach are presented onwards.

1,000 particles were included in the CFD simulation. The intensity profiles for each of these was recorded for different plasma gas flows and arc currents. A typical example of the intensity profile of a single particle of trial 9 (\( I = 500 \) A, \( V_{gas} = 120 \) slpm) is shown in Fig. 5. For the first approximately 0.6 ms the particle does not come in contact with the plasma jet. At this point it was moving slowly and was not exposed to significantly increased temperatures of the plasma jet. At the 0.6 ms mark the intensity begins to increase, however some
smaller fluctuations can be observed. These could be caused by the inherent fluctuations in the plasma jet, primarily caused by instability in the electric arc supplying the power to heat up the plasma. These fluctuations become greater as the particle continues its flight, as turbulence impacts the jet more and more. Eventually the particle exits the jet completely and continues out of frame. It must be remembered that the Triplex plasma gun used is considered to be a stable plasma jet and only stayed in the apparent plasma jet for about $t = 0.4$ ms. However as made clear in Fig. 4 even during this short period of time the intensity fluctuations experienced by a single particle can be extreme, which can drastically alter the in-flight properties of the particles like its temperature.

Fig. 5: Plasma jet intensities based on high-speed camera imaging and CFD particle flight simulation ($I = 500$ A, $V_{\text{gas}} = 120$ slpm).

The key concern in this case is the fact that not all particles experience the same intensity profile, as the plasma jet fluctuates both in position and intensity, and small differences in particle trajectory (see CFD simulation flight paths in Fig. 1) can result in significantly different residence times and different penetration depth in the plasma jet. The intensity profiles shown in Fig. 6 result from five different particles and were separated out by 1 ms for clarity. Even visually it is apparent that there are significant differences in the intensities that these particles would experience travelling through the plasma jet. Consequently, the temperatures of the particles could vary likewise.

Fig. 6: Plasma jet intensity profiles of 5 consecutive particles based on particle CFD simulation flight coordinates and plasma flame imaging ($I = 500$ A, $V_{\text{gas}} = 120$ slpm)

However, the fluctuation of intensities within the particle trajectories is again not relevant. The particles are influenced over the entire path, therefore only the total energy absorbed from the plasma jet plays is important. This can be approximated by the integral of the intensity of a particle over its flight. In Fig. 7 it is possible to compare the integrated intensities of 50 particles experienced for the different plasma jet conditions with an electric current of $I = 500$ A. It is obvious that there are strong variations between the integrated intensities of the individual particles. However, in this display no statement can be made about the differences between the process parameters.

Fig. 7: Integrated intensity profile for the first 50 particles in the CFD simulation. ($I = 500$ A, varying plasma gas flow rates $V_{\text{gas}}$).

To investigate this further the particle CFD simulation flight paths for all 1,000 particles were applied to the plasma jet images with various parameters, as described previously. By analysing the large number of particles, it is possible to carry out a statistical evaluation in order to assess the parameters quantitatively. Fig. 7 showed that there is a large variance in the intensities experienced by different particles. While there are some trends through parameters, mentioned above, individual
particles can receive twice as much intensity as others under identical conditions. The values of these integrated intensities can be statistically analysed by calculating the standard deviation $\sigma$ of the integrated intensities. This standard deviation is shown in Fig. 8 for the analysed parameters. These were confined to parameter specific groups in order to determine if certain parameters could impact the standard deviation then this would reflect on which parameters improved the instability of the plasma jet and which worsened it.

The most important result of this investigation is certainly that fluctuations can still be observed in the plasma jet of the cascaded triple arc plasma generator, which is assumed to be stable, and that these fluctuations in intensity have the potential to affect the particle in-flight properties. The presented method has also shown that it will be able to detect differences between varying parameters in the future. With the help of further simulations such investigations can be carried out in a next step. In addition, the results presented here still need to be further substantiated by investigations, such as measurements of particle properties in flight.

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Fig. 8: Variance in integrated total of intensity profiles for 1000 particles according to plasma jet parameters.

Conclusions

High-speed imaging proves to be a useful approach to analyse the plasma spraying process in detail. The fluctuations in the plasma jet are reduced by adjustments such as the implementation of staggered electrode systems, however the particles still experience significant sudden plasma jet intensity fluctuation, in particular as they move in the jet towards the substrate and turbulence that cannot be avoided. This fluctuation is not taken into account when a plasma jet is assumed to heat homogeneously and not time dependently, which is often the case. By combining particle flight paths from a CFD simulation and high speed imaging of a plasma jet under several operating conditions, the effect of such fluctuations was identified.
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