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Journal Article

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Publication date:
2023-03

Permanent link:
https://doi.org/10.3929/ethz-b-000584655

Originally published in:
Journal of Thermal Spray Technology 32(2), https://doi.org/10.1007/s11666-022-01495-w

J Therm Spray Tech (2023) 32:548–558
https://doi.org/10.1007/s11666-022-01495-w

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Importance of Measurement and Evaluation Procedure of Particle State in Atmospheric Plasma Spraying

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Submitted: 18 August 2022 / in revised form: 19 October 2022 / Accepted: 28 October 2022 / Published online: 23 November 2022

Abstract In-flight particle state parameters (PSPs) have been shown to play a crucial role in determining the properties of atmospheric plasma-sprayed coatings. Therefore, PSPs are frequently measured before starting a coating run as part of process control. This paper shows the importance of the measurement procedure used and subsequent data processing applied for the evaluation of PSPs, with the focus on process control applications. The paper demonstrates this on the example of coating of yttria-stabilized zirconia, using a commercially available sensor system Accuraspray-G3C for measuring the ensemble particle temperatures and velocities as descriptors of the PSPs. Experimental results show a longer stabilization time of the particle jet than what is practically considered, revealing the need for an appropriate choice of the measurement procedure. Furthermore, it is demonstrated that information about PSPs can be acquired also during the coating run by periodically moving the coating gun to a stationary sensor system only for a short measurement duration. Lastly, it is shown how different data processing methods affect the evaluation of the acquired PSPs.

Keywords atmospheric plasma spraying · data processing · in-flight particle diagnostics · particle state parameters · process monitoring · process control

Introduction

Atmospheric plasma spraying (APS) is a highly complex coating process where a plethora of interdependent variables affect the resulting coating characteristics. Fauchais (Ref 1) estimates there to be 50-60 different influencing parameters, while Brunet and Dallaire (Ref 2) estimate the number to be even greater, up to 150. Deviations in these parameters can result in significant process variations, reducing process repeatability and reproducibility.

The coating characteristics are determined by flattening and bonding of particles when impinging on the substrate. This process is strongly influenced by the in-flight particle state before the impact, as remarked by Fauchais (Ref 1). The particle state is commonly characterized by the velocities and temperatures of the particles. Hence, a great deal of research has been dedicated to monitoring these particle state parameters (PSPs) in order to detect process deviations and use them for process control.

A study on the long-term stability of the APS process, conducted by Leblanc and Moreau (Ref 3), demonstrated that the PSPs change significantly over time even if the (known) process input parameters are kept constant. The total spraying time of the study was 55 h. Significant

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This article is an invited paper selected from presentations at the 2022 International Thermal Spray Conference, held May 4-6, 2022 in Vienna, Austria, and has been expanded from the original presentation. The issue was organized by André McDonald, University of Alberta (Lead Editor); Yuk-Chiu Lau, General Electric Power; Fardad Azarmi, North Dakota State University; Filofteia-Laura Toma, Fraunhofer Institute for Material and Beam Technology; Heli Koivuluoto, Tampere University; Jan Cizek, Institute of Plasma Physics, Czech Academy of Sciences; Emine Bakan, Forschungszentrum Jülich GmbH; Šárka Houdková, University of West Bohemia; and Hua Li, Ningbo Institute of Materials Technology and Engineering, CAS.

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changes were also observed in the case when the gun power was kept at a constant level. The changes in PSPs were correlated to the variations observed in the coating characteristics. A similar study by Mauer et al. (Ref 4) also showed that monitoring of PSPs can be useful in detecting process deviations. However, it was remarked that due to the limited coverage and sensitivity of the PSPs, the detection of process deviations might not necessarily be possible in all cases. During both of these studies, the guns have been subjected to multiple ignitions. Re-igniting the gun can influence the PSPs. Dwivedi et al. (Ref 5) confirmed that the variation in the PSPs is smaller during a single run (of 3 h) at constant input process parameters than between multiple runs, i.e. after multiple gun re-ignitions. However, they noted that the variations in the PSPs between the runs were reduced in their case due to performing injection optimization procedure before each run. This procedure was suggested by Srinivasan et al. in (Ref 6) and later described in more detail in (Ref 7, 8). In the same work (Ref 6), Srinivasan et al. also demonstrated an iterative procedure for tuning of PSPs by adjusting the process input parameters after gun ignition to decrease the variability in PSPs between multiple runs, which was also reported to reduce the variability of coating properties. Despite the demonstrated benefits of both suggested improvements, the authors noted that the two procedures require an additional preparation time before starting a coating run, which would necessitate a cost–benefit analysis for the use in industrial applications.

Indeed, up to now these approaches have not yet been widely implemented in industry. Nevertheless, it has become quite common to measure the PSPs prior to coating a part, especially in high-end applications, and make go/no-go decisions based on whether the measured PSPs are inside a predefined process window. The research by Colmenares-Angulo et al. (Ref 9) showed that different commercially available sensor systems can be used for such purposes as well as for tuning the PSPs. In production environments, the observed procedure for the go/no-go decision is typically as follows: the gun is ignited and the jet forms; before proceeding, it is waited for a certain period for the plasma jet to stabilize (e.g. 60 s); afterward the particle stream is started; followed by another waiting period for the particle jet to stabilize (e.g. 30 s); thereafter, the PSPs are measured for a certain period (e.g. 30 s) based on which the go/no-go decision is taken. It is understandable that the measurement and waiting times are kept short because they negatively affect the productivity. However, as it will be shown by the findings presented in this paper, the stabilization time of the particle jet could be longer than what is commonly considered. Hence, it might be necessary to make a longer measurement in order to make an informed go/no-go decision, especially under tight process window constraints. Moreover, it is imperative to apply appropriate data processing techniques to the acquired data to extract the relevant information for the targeted application.

Furthermore, if PSPs are measured at all in industrial applications, they are predominantly measured only prior to coating and no information about the PSPs is collected during the actual run. The main reasons for this are the following. Firstly, it is most informative to measure PSPs at the spraying distance since those can be directly related to the coating properties. However, measurements cannot be conducted at the spraying distance when a sample is physically placed there for coating. To still get some information about the particle jet during the coating, which could be used for process control, a compromise can be made by moving the measurement position closer to the gun exit. Nonetheless, integration of a PSP sensor system on a position that could monitor the particle jet continuously during operation is cumbersome. As an alternative, the PSPs can be monitored during a coating run by periodically moving the coating gun to a separate, stationary PSP sensor system. However, in this case the coating has to be interrupted to conduct the measurement. The longer the interruption, the larger the influence it could have on the ensuing coating. Moreover, the influence of the gun movement on the validity of PSP measurements needs to be considered.

The paper shows the importance of the measurement and subsequent evaluation procedure of the PSPs by: (1) analyzing the stabilization time of the particle jet to reach a (quasi) steady state of PSPs at the start of a run; (2) investigating the approach of monitoring PSPs during a coating run by periodically moving the gun to a stationary sensor system; and by (3) highlighting the role of different data processing used for the evaluation of the acquired PSPs.

Methods and Materials

Monitoring of PSPs in Industrial Applications

There are different commercialized sensor systems available for monitoring of the PSPs. A review of those is provided, among others, by Fauchais et al. (Ref 10). While these commercial systems differ in terms of their implementations, they are all based on the same physical principles. The particle velocity is measured using the *time-of-flight method*, while the particle temperature is measured based on the *two-color pyrometry*.

There are two approaches to evaluate the PSPs. The first one is to measure properties of individual particles. A small measurement volume is used in this case. An implementation of this approach is the DPV 2000 sensor system (Tecnar Automation, Quebec, Canada), which was developed based on the work of Moreau et al. (Ref 11). By measuring the properties of a sufficiently large number of particles, it is possible to acquire a distribution of the PSPs. In order to gather information about the PSPs of the whole jet, the measurement needs to be repeated at multiple positions of the jet's cross section. The second approach is based on measuring the properties of an ensemble of particles, where a sufficiently large measurement volume is used to capture the whole jet width. In this case, all the particles in the measurement volume jointly contribute to the velocity and temperature estimates. An implementation of this approach is the Accuraspray sensor system (Tecnar Automation, Quebec, Canada), which was initially described by Bisson et al. (Ref 12). Despite the differences between the two approaches, it has been confirmed by Mauer et al. (Ref 13) that they are in good agreement when taking into account their operating principles.

Nevertheless, both approaches have their pros and cons. The single-particle measurement approach provides more detailed information about the particle jet, especially when scanned across the jet's cross section, while the ensemble measurement rather provides just a characteristic descriptor of the PSPs conditions than a value that can be directly linked to the ensuing coating properties, as remarked by Sampath et al. (Ref 14). Therefore, the single-particle measurement approach is preferred for research applications. But, as noted by Fincke et al. (Ref 15), it is less suitable for control applications because it takes a while to record a statistically significant amount of particles, is sensitive to spatial movements of the jet, and usually requires reduced powder feed rates for correct detection of individual particles. In the latter case, it is then assumed that the same results are obtained under actual spray conditions with higher powder feed rates. However, as it was demonstrated by Shinoda et al. (Ref 16), changes in the powder feed rate result in changes in the PSPs. Moreover, the sensor system based on the ensemble technique requires simpler components, resulting in lower system costs, as remarked by Bourque et al. (Ref 17). For these reasons, systems based on the ensemble technique, like the commercially available sensor system Accuraspray, are favored in control applications in industrial environments. Therefore, the Accuraspray (version G3C) was also used in this study.

Measurement Procedures

In order to investigate the stabilization time required for the particle jet to reach a (quasi) steady state at the start of a run, the PSPs were recorded using the Accuraspray-G3C. Three measurement procedures were used. In the first variation, the measurement procedure followed the one typically applied in industry, i.e. to start measuring the PSPs 30 s after the start of the particle stream. The PSPs were measured for 120 s before the coating was commenced. The second variation differed slightly—by starting to measure the PSPs simultaneously with the start of the particle stream. In this case, the measurement of PSPs was taken for 180 s before proceeding with the coating.

Furthermore, to investigate the approach of monitoring the PSPs during a coating run without having to install the sensor system on the robot arm, the PSPs were also measured after coating of each two layers by moving the gun in front of the sensor system. The measurement was conducted for 120 s before the coating was resumed. Such a long measurement duration is impractical in industrial applications because the production time of a part would be vastly increased. Moreover, the coating characteristics could possibly be modified due to the different part cooling. However, within this study, the long PSPs monitoring time of 120 s served a twofold purpose. Firstly, to reliably evaluate how the PSPs are changing during a single run, and based on that provide a representative descriptor of the PSPs during the run. Secondly, to investigate how the gun movement toward the sensor system affects the acquired data. It should be noted though that the measurement of PSPs during the coating was conducted just for the first two sets of gun passes, in order to shorten the duration of the experiments.

Lastly, a third measurement procedure was used to validate different signal processing options on a continuously recorded signal. The procedure consisted of simply measuring the PSPs for 10 min since the start of powder injection, without coating any samples.

Experimental Setup

The setup used in this study is schematically shown in Fig. 1. An F4MB-XL gun (Oerlikon Metco, Wohlen, Switzerland) was used with two powder injectors placed on opposite sides along the vertical axis. The injectors were offset 7 mm from the spray axis and 2 mm from the nozzle

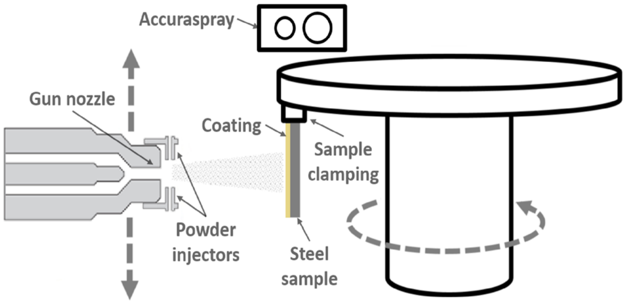

Fig. 1 Schematics of the coating setup

exit. The nozzle had a diameter of 8 mm. The powder used was yttria-stabilized zirconia (YSZ) 204NS-G (Oerlikon Metco, Wohlen, Switzerland). As indicated in Fig. 1, the Accuraspray was placed just above the sample in a way that allowed measuring of PSPs at the coating distance and also prevented the sample from interfering with the measurement, while simultaneously minimizing the required robot travel distance.

The PSPs were recorded for five sets of process input parameters, which are listed in Table 1. They were selected based on previous experience from the industry to produce a wide range of possible PSP combinations. This was to investigate whether there are any inherent differences influencing the evaluation of different PSPs. Each parameter set was repeated twice with the first measurement procedure and once with the second one. In order to validate the investigated signal processing options, the third measurement procedure was performed three times for each set of process input parameters. This way, a total of 30 runs was conducted.

Evaluation of Accuraspray-G3C Data

In order to avoid ambiguity regarding sensor data analysis, it is necessary to understand the details about the sensor's implementation. The Accuraspray-G3C internally samples the particle jet at 16 Hz. Besides the PSPs, it also records the intensity profile of the plasma jet using a CCD camera. All measured values are then stored in a buffer. The acquisition software logs the mean and the standard deviation of the buffered values at 1 Hz. The user can specify the size of the buffer through the so-called reaction time setting in the acquisition software. It is generally recommended to use a value between 5 and 15 s. However, setting the value to 1 s allows for logging of the signals in their rawest form available (Ref 18). Increasing the reaction time essentially applies a larger simple moving average (SMA) filter to the data before downsampling the signal to 1 Hz. Since custom processing of the PSP data has been investigated in this research, the data were acquired in its rawest form available.

Table 1 Process input parameters used in experiments

Process parameter set	A	B	C	D	E
Powder feed rate (per injector) [g/min]	30	30	49	30	40
Spray distance [mm]	140	160	124	120	160
Hydrogen [NLPM]	6.0	5.3	7.2	7.5	7.5
Argon [NLPM]	30	35	28	30	25
Carrier gas [NLPM]	1.5	2.0	1.6	1.8	1.5
Current [A]	500	560	503	546	449

In the acquired data, it has been observed that individual data points are occasionally missing, i.e. the logging frequency was inconsistent. Therefore, the missing values were filled based on the nearest-neighbor interpolation method to get a uniformly sampled signal to simplify further processing.

The recorded data points are inherently subjected to multiple sources of uncertainties, which can be evaluated as per the GUM recommendations (Ref 19). While it is difficult to estimate all of the possible different contributions, their combined uncertainty can be estimated by taking into account the inherent uncertainty of the measurement device (estimated as Type B uncertainty u_B) and the variation between multiple observations, i.e. the experimental standard deviation (Type A uncertainty u_A). Based on the uncertainty evaluation provided in the calibration reports (Ref 20) of the Accuraspray-G3C, the relative expanded uncertainties (at a 95% level of confidence) in the used measurement range are estimated to be on average: 1% for particle velocity, 0.5% for particle temperature, and 5% for jet intensity. The experimental standard deviation of the mean value u_A can be evaluated as:

$$u_A = \frac{\sigma}{\sqrt{N}} \qquad \text{(Eq 1)}$$

where N is the total number of measurements in the buffer (i.e. 16 in this case), and σ is the measured standard deviation. Combing the contributions of Type A and Type B results in an estimate of the uncertainty (u_C) associated with an individual measurement data point:

$$u_C = \sqrt{{u_A}^2 + {u_B}^2} \qquad \text{(Eq 2)}$$

Results and Discussion

Figure 2 displays the particle velocities and temperatures (i.e. PSPs) acquired with the Accuraspray from one example run. Additionally, the total jet intensity recorded with Accuraspray is displayed. In this example run, the process parameter set E was applied and the first measurement procedure used (i.e. it was waited for 30 s for the particle jet to stabilize after powder injection before starting the measurement). The figure displays only the parts of the signal where the correlation signal of the Accuraspray was greater than 0.8. The correlation signal serves as an indicator of the validity of the measurement (Ref 12). The periods without signal recording correspond to the times where the gun was away from the sensor system and was

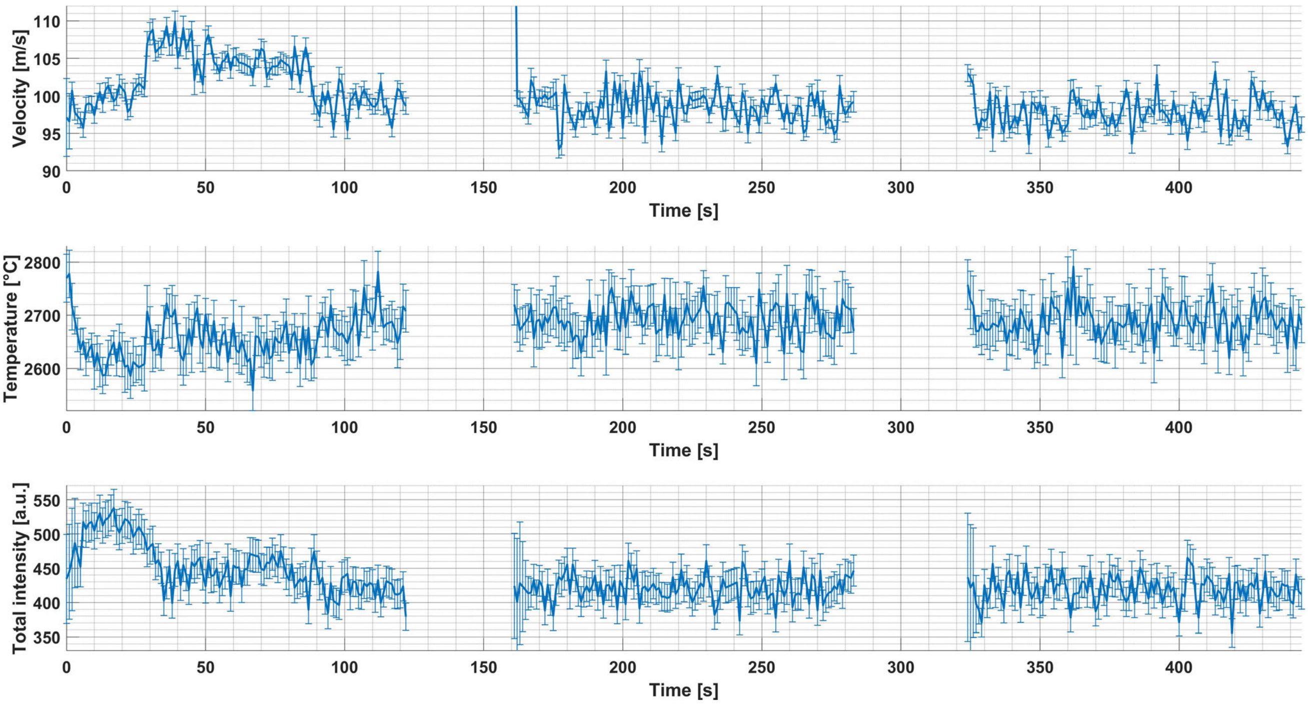

Fig. 2 Example of particle velocities and temperatures as well as total jet intensity acquired with Accuraspray during one run where parameter set E and the first measurement procedure was used. Added is the estimated uncertainty of each measurement point (at a 95% level of confidence)

coating the substrate. The uncertainty of each data point is also shown (at a 95% level of confidence).

Despite the measurements being noisy, it is noticeable that the particle velocities started at a low value, then increased, and later dropped to a quasi-steady value, while the temperature started at a high value, decreased quickly, and then slowly increased before similarly settling around a quasi-steady value. This was in spite of the fact that the process input parameters were kept at a constant level, indicating that there were transient instabilities present at the start of the process, possibly related to the plasma gun and/or powder feeder.

Moreover, Fig. 2 shows that moving the gun to the sensor for PSPs measurement during the coating influences only the first few data points (i.e. seconds of measurement). They are declared to be valid despite most likely being outliers, e.g. the large spike in the velocity at the beginning of the measurement after the first two layers being coated (at 161-s mark). The total jet intensity could serve as an additional indicator to identify such outliers, because its uncertainty is larger at those data points compared to the rest of the measurement. These observations indicate that it is possible to acquire valid data points of the PSPs during coating by moving the gun periodically to the sensor system for a short measurement duration instead of having to have the sensor system installed on the robot arm. However, care should be taken to identify and exclude artefacts resulting from the gun movement.

From noisy measurements it is difficult to assess the state of the particle jet during the run, e.g. to correlate it to the resulting coating properties or use it for the purpose of process control. Therefore, the measurements are usually averaged over a certain measurement period. Shinoda et al. (Ref 16) used a 20-s measurement duration. This is equivalent to applying an SMA filter of length of 20 samples to the data. Figure 3 shows the outcome of performing such signal processing on the raw signals from Fig. 2, with estimation of the uncertainty in the filtered average value (at a 95% level of confidence). While applying a causal filter delays the signal, it does not affect the evaluation of the (quasi) steady state. The filter was initialized with zeros and applied in a way to not be triggered when the correlation value is below 0.8, e.g. between the coating periods with no signal, to prevent artefacts arising from invalid data. The uncertainty of the average value is estimated as a combined uncertainty of the previously addressed uncertainty due to the measurement device (Type B uncertainty) and the experimental standard deviation of the mean based on the pooled estimate of standard deviation (Type A uncertainty).

From Fig. 3, it can clearly be seen that there was an initial transient state in the signal before it reached a

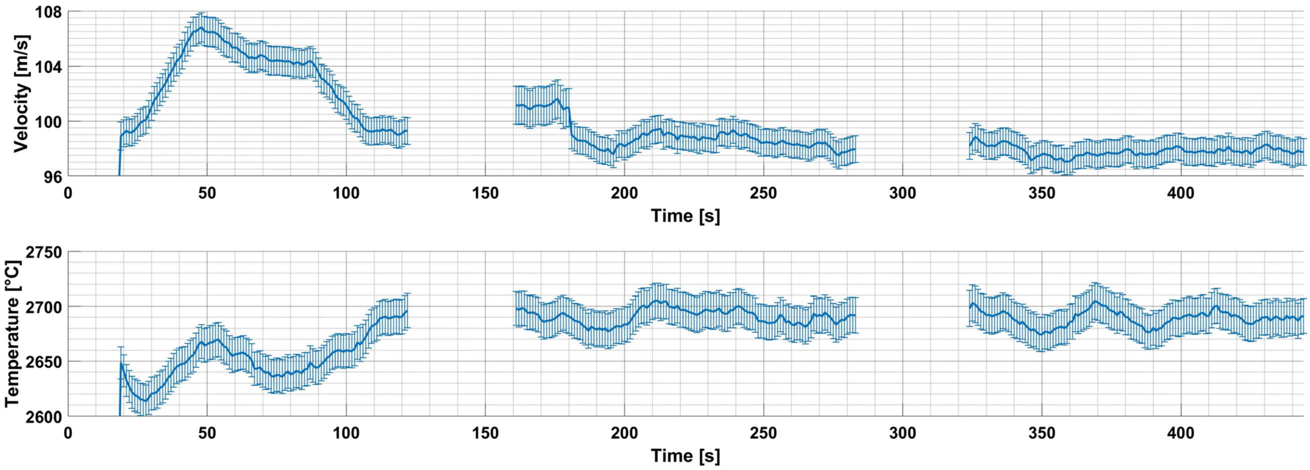

Fig. 3 Particle velocities and temperatures from Fig. 2 filtered with an SMA filter of length of 20 samples with estimated uncertainty of the averaged values (at a 95% level of confidence)

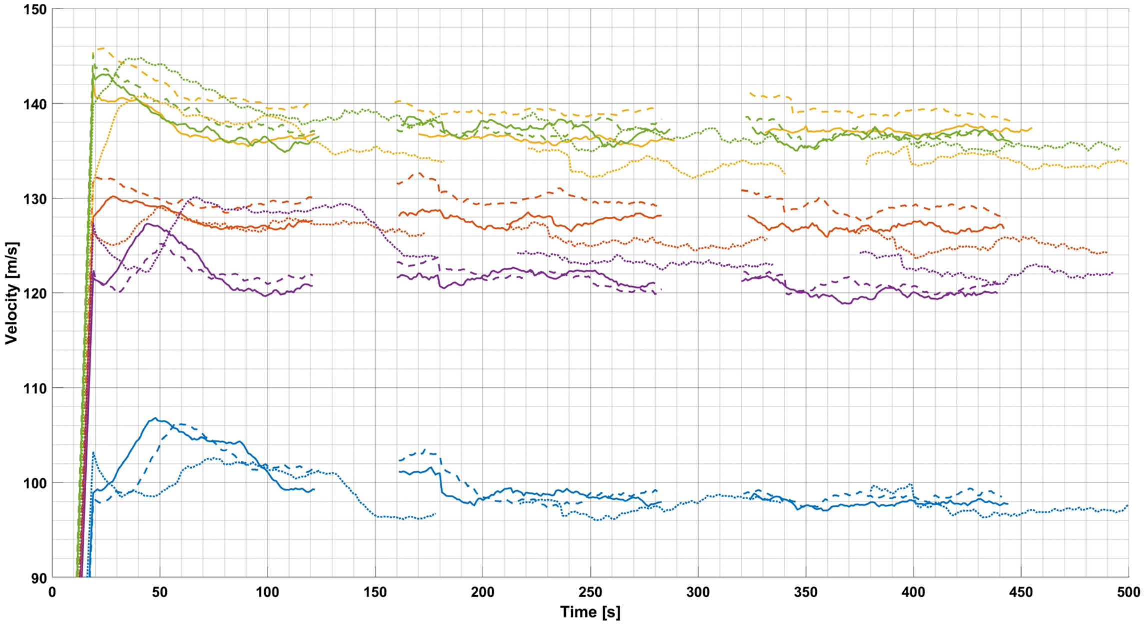

Fig. 4 Recorded particle velocities of experiments conducted with the first and second measurement procedure, filtered with an SMA filter of length of 20 samples. The line colors correspond to the process parameter sets used in the experiments (Table 1). The line styles differentiate the three repetitions of each experiment; the full and dashed lines marking the experiments conducted with the first measurement procedure, and the dotted lines the ones with the second measurement procedure

(quasi) steady state. Therefore, measuring the PSPs for a period shorter than ca. 100 s would provide an estimate of the jet state in the transient period that is significantly different from the steady state. This could lead to an incorrect go/no-go decision in process control used in industry. Moreover, the figure shows that the first couple of layers could be coated with significantly different PSPs than the subsequent layers if the coating is started before the particle jet stabilizes. This could potentially cause microstructural differences in the coatings.

Similar signal trends were observed also in the other runs. Figure 4 and 5 shows particle velocities and particle temperatures, respectively, recorded during experiments conducted with the first and second measurement procedure. The displayed signals are filtered with an SMA filter of length of 20 samples. The line colors correspond to the process parameters used in the run (Table 1): A—orange, B—yellow, C—purple, D—green, and E—blue. The line styles differentiate the three repetitions of each run; the dotted line marking the experiments conducted with the second measurement procedure (i.e. with particle jet being

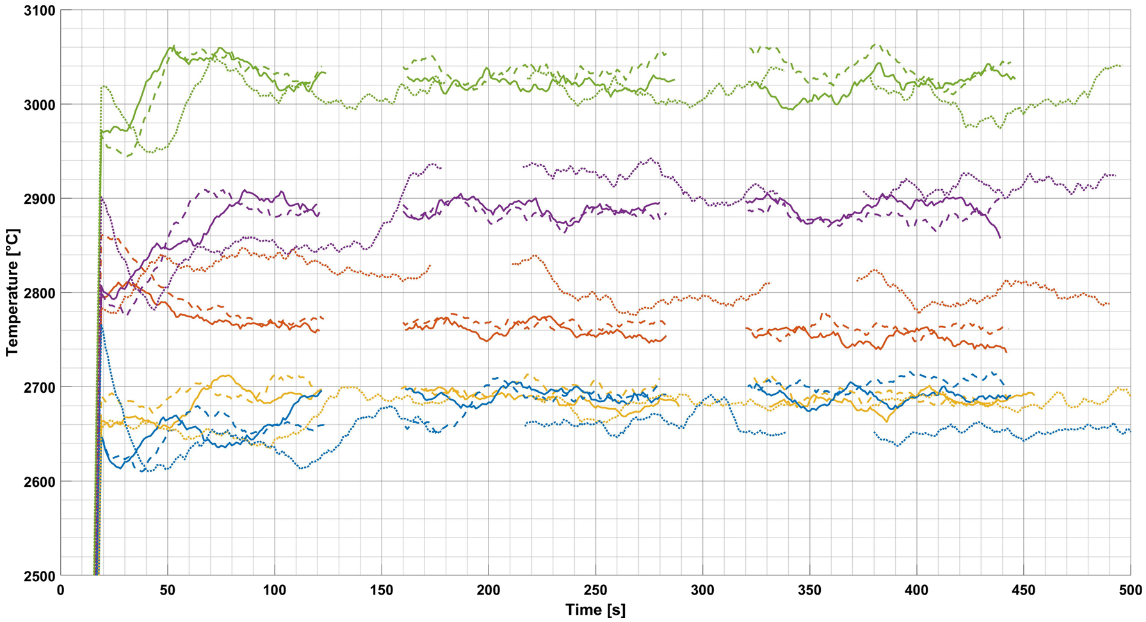

Fig. 5 Recorded particle temperatures of experiments conducted with the first and second measurement procedure, filtered with an SMA filter of length of 20 samples. The line colors correspond to the process parameter sets used in the experiments (Table 1). The line styles differentiate the three repetitions of each experiment; the full and dashed lines marking the experiments conducted with the first measurement procedure, and the dotted lines the ones with the second measurement procedure

recorded since particle injection, and initial recording lasting 180 s). The measurements are aligned according to their first valid measurement data points, and only valid parts of the signals are shown. The measurement uncertainties are omitted for clarity.

From Fig. 4 and 5, it can be seen that the particle jet needs different amounts of time to stabilize for different sets of process input parameters. Moreover, there also seems to be discrepancies among runs with the same process parameters. Further, it can be seen that even the signals that were acquired from the start of particle injection (marked with the dotted lines) produce valid measurement points from their beginning (i.e. the correlation was above 0.8). This shows that there is no reason for an initial waiting for the particle jet to stabilize before starting the PSP measurement. The measurement should always start at the beginning of particle injection to gain the most information about the particle jet.

Figure 3 also shows that even for a signal filtered with the SMA filter of length of 20 samples, there are still statistically significant differences in the evaluated PSPs even after the initial transition period. This makes it ambiguous how to assign a representative value to describe the PSPs during the run, e.g. to establish a model for process control. The possible discrepancy in the data needs to be included in their uncertainty evaluation, which compromises the potential for process control. However, it is possible to get an improved estimate of the PSPs by applying different signal filtering. The data processing should extract only the relevant information for the targeted application. For example, when using the PSP data in a run-to-run control application, the PSPs of a coating run are compressed to a single value assigned to that run. For the data compression, it is necessary to eliminate the aliasing artefacts caused by downsampling of the signal. Hence, the bandwidth of the signal needs to be limited at least by the duration of a single run, i.e. the frequency of the downsampled signal. Therefore, a cutoff frequency corresponding to the duration of one run can be used to filter the acquired PSPs. In the experiments in this study, the coating duration of one run was about 10 min. The signals filtered with a low-pass filter with the cutoff frequency corresponding to this coating duration (i.e. 1.7 mHz) are shown in Fig. 6 for the example run.

From Fig. 6, it can be seen that the filtered signals reach a steady value—within the evaluated uncertainty—after the initial transition. This value could be used as a representative descriptor of the particle jet state during a particular run. For the data processing, the filter was again not triggered at invalid data, which results in filtering of a non-uniformly sampled signal and consequently introduces some minor artefacts. To validate the approach without the influence of the effects of non-uniformly sampled data, the experiments were also conducted with the third measurement procedure. The acquired signals filtered with the same filter with a cutoff frequency corresponding to the coating duration (i.e. 1.7 mHz) are shown in Fig. 7 and 8, for particle velocities and particle temperatures, respectively.

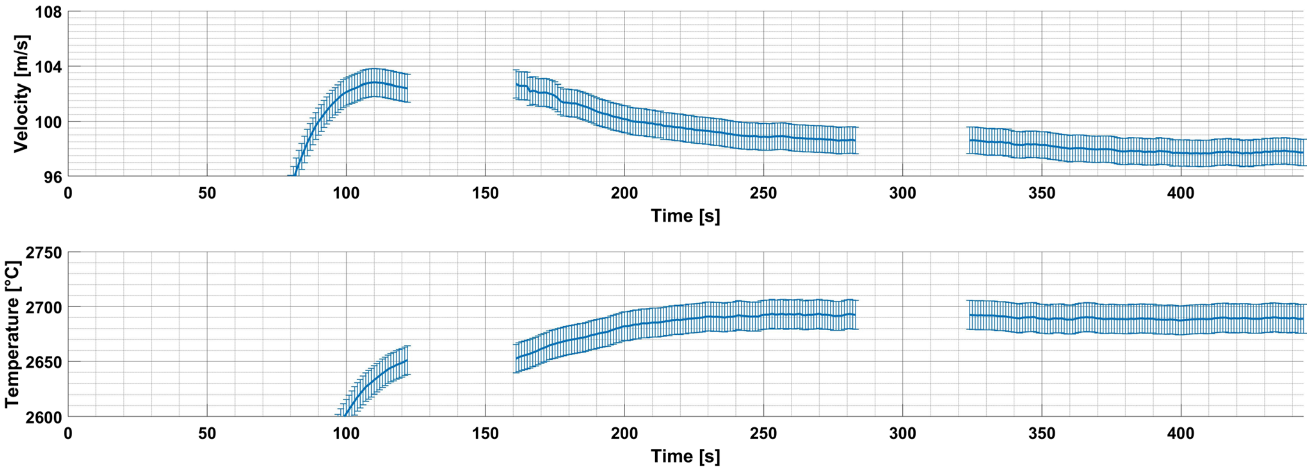

Fig. 6 Particle velocities and temperatures from Fig. 2 filtered with a low-pass filter with the cutoff frequency corresponding to the duration of the coating run (with the estimated uncertainty at a 95% level of confidence)

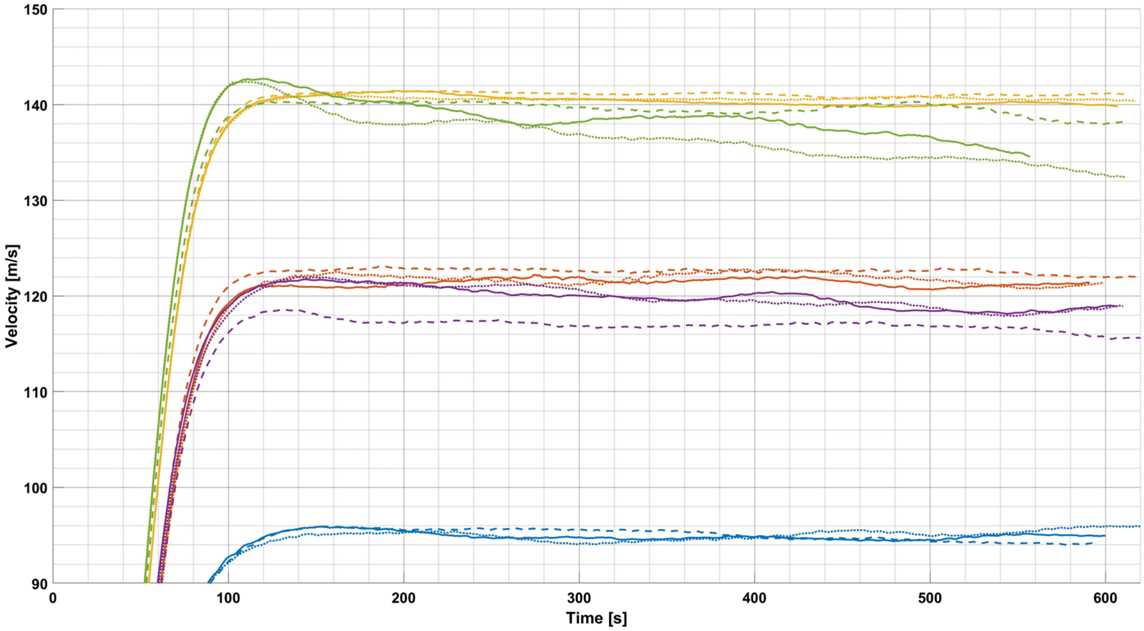

Fig. 7 Recorded particle velocities of experiments conducted with the third measurement procedure, filtered with a low-pass filter with the cutoff frequency corresponding to the duration of the coating run. The line colors correspond to the process parameter sets used in the experiments (Table 1) and the line styles to their repetitions

The line colors correspond to the process parameters used in the individual runs (Table 1) and the line styles to their repetitions. The measurements are aligned according to their first valid measurement data and their uncertainties omitted for clarity.

Figure 7 and 8 shows that with appropriate signal filtering, it is possible to acquire a stable signal and thus produce a representative descriptor of PSPs during a run. Further, it can be seen that certain parameters sets (e.g. set D) produce relatively instable process conditions since there has been a significant change in their PSPs even during a single run. Moreover, these experiments provide an insight into the repeatability of the PSPs between multiple gun ignitions, as there are significant differences between repetitions of individual parameter sets. This can be seen more clearly in Fig. 9, which shows for all conducted experiments the particle velocities versus particle temperatures at the steady state—evaluated at the 5-min mark from powder injection. In addition, Table 2 shows the calculated coefficients of variation, i.e. relative standard deviations, of particle velocities (CV_V) and particle temperatures (CV_T) at the steady state of all experiments. These data could potentially be used to improve on the current go/no-go process control applications by

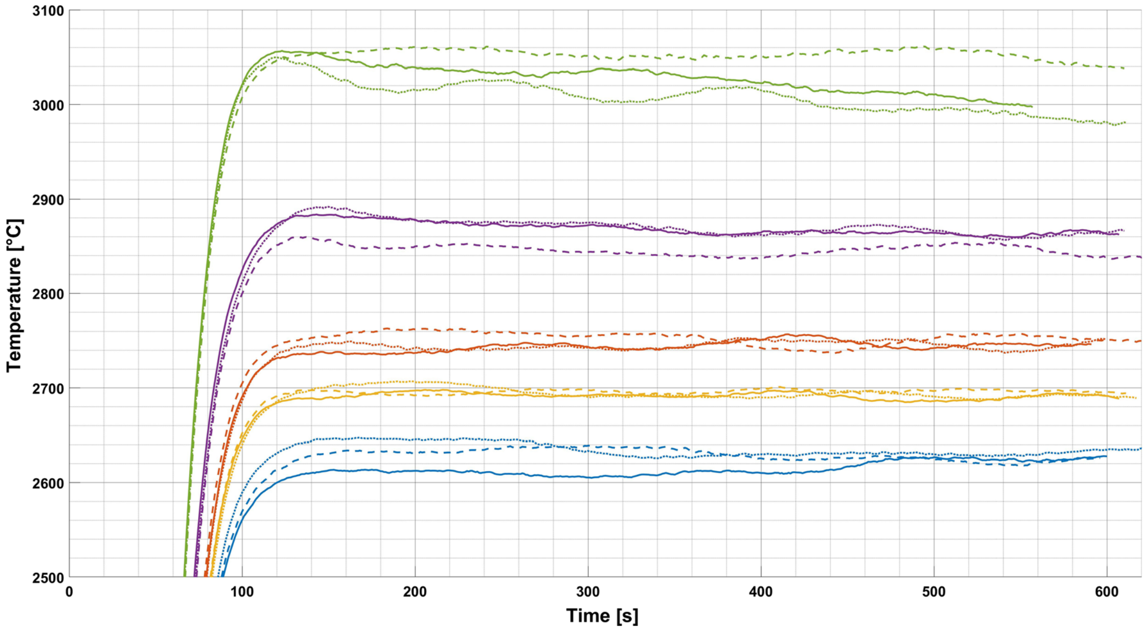

Fig. 8 Recorded particle temperatures of experiments conducted with the third measurement procedure, filtered with a low-pass filter with the cutoff frequency corresponding to the duration of the coating run. The line colors correspond to the process parameter sets used in the experiments (Table 1) and the line styles to their repetitions

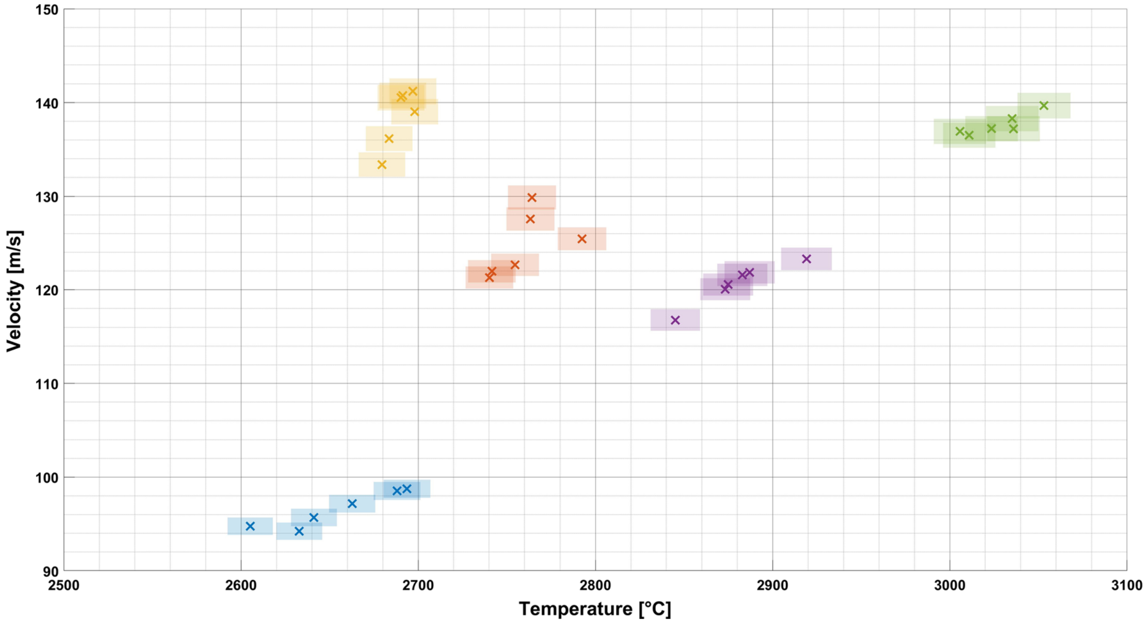

Fig. 9 Particle velocities versus particle temperatures at the steady state, evaluated at the 5-min mark based on signals filtered with a low-pass filter with the cutoff frequency corresponding to the duration of the coating run (with estimated uncertainties at a 95% level of confidence). The colors mark the different process parameter sets used in the experiments (Table 1)

establishing well-defined process windows based on the mean PSP values and their standard deviations. However, care should be taken to acquire a representative number of data points and identify conditions with unacceptable PSPs for the targeted application.

Conclusions and Outlook

This study revealed the importance of the measurement procedure used and the subsequent data processing applied for the evaluation of the in-flight particle state, with the

Table 2 Coefficients of variations of particle velocities and particle temperatures between different runs for different parameter sets

Process parameter set	A	B	C	D	E
CV_V [%]	2.8	2.3	1.9	0.9	2.0
CV_T [%]	0.7	0.3	0.9	0.6	1.3

focus on process control applications. This was demonstrated on the example of atmospheric plasma spraying of yttria-stabilized zirconia where a commercially available sensor system Accuraspray-G3C was used for measuring the ensemble particle temperatures and velocities as descriptors of the PSPs. The experimental results showed a longer stabilization time of the particle jet to reach a (quasi) steady state of PSPs than what is practically considered in industry applications. The steady state needs to be correctly detected to prevent incorrect go/no-go decisions in process control. Moreover, if the coating is started before the particle jet stabilizes, the first couple of layers are coated with significantly different PSPs than the latter layers, possibly resulting in microstructural differences in the coatings.

Furthermore, the approach of monitoring PSPs during a coating run without installing the sensor system on the robot arm but instead periodically moving the coating gun to a stationary sensor system was investigated. It was demonstrated that such a measurement procedure could acquire valid PSP data during the coating run even with a short measurement duration, thus minimizing the effect of the measurement on the coating process.

Lastly, it was demonstrated how different data processing methods affect the evaluation of the acquired PSPs. The processing applied should extract only the relevant information for the targeted application. For a run-to-run process control application, the acquired data can be filtered with a low-pass filter with a cutoff frequency corresponding to the duration of the coating run. This provides a representative descriptor of PSPs that can be used, e.g. for defining the process window for go/no-go process control.

In order to achieve improved process control, the causes of certain observations (i.e. different particle jet stabilization times and the influence of the gun movement on the PSP measurement) need to be further investigated. Moreover, future studies should focus on identifying appropriate data processing solutions for individual applications (e.g. with different guns and powders) and incorporating them in more complex run-to-run control techniques as well as their extrapolation to layer-to-layer control schemes, enabled by periodic monitoring of PSPs during a coating run. All these control approaches would benefit from an increase in the temporal resolution of the acquired PSP data since it would provide a better insight into the variability of the particle jet state. This could be achieved already by improving the data logging rate to equate the sensor's actual sampling rate, removing the aliasing artefacts resulting from the initial signal downsampling.

Acknowledgments The work conducted in this study was part of the project ACTIV financed by Innosuisse—Swiss Innovation Agency, Grant Nr. 37896.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich.

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