In-Flight Measurements of Particle Temperature and Velocity with a High-Speed IR Camera During Cold Gas Spraying of In718 and TiAlCrNb

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Abstract Unlike other thermal spraying methods, it is difficult to determine the temperature of the particles during cold gas spraying due to the relatively low radiation. In the present study, the velocities and in-flight temperatures of metal particles were measured during cold gas spraying. A state-of-the-art high-speed infrared camera was used to study the behavior of two different base materials, In718 and TiAlCrNb, both used as structural materials in gas turbine engines. The experiments aimed to improve the fundamental understanding of the process, in particular the heating of the particles, and to compare the experimental results with theoretical calculations of the particle temperatures.

Keywords cold spray · cold spray meter · infrared camera · particle temperature · particle velocity

Introduction

Cold gas spraying is a promising method for additive manufacturing and repair applications in the aerospace industry. In contrast to other thermal spray techniques the relatively low process temperatures offer several advantages, (i) minimization of oxidation, (ii) low thermal stress, and (iii) prevention of unwanted (or unintended) phase transformations (Ref 1, 2).

Reliable predictions for successful bonding in cold gas spray have been investigated for around 20 years. A simple equation for the required critical velocity depending on certain material properties (density, yield stress, melting temperature) as well as the initial particle temperature was given by Assadi et al. in 2003 (Ref 3). Further improvements on this approach were done by Schmidt et al. (Ref 4, 5) who developed a general window of deposition for the cold gas spray process. In their work, an equation for the critical velocity depending on particle impact temperature, and the properties of the feedstock material, namely density, heat capacity, and yield strength, was derived (Ref 5). In addition, Schmidt et al. also investigated the influence of the particle size on the critical velocity and gave simple dependencies for Cu and 316L steel (Ref 5). A new dimensionless parameter \( \eta \) (ratio of particle impact velocity and critical velocity) was introduced by Assadi et al. (Ref 6) and so-called parameter selection maps were developed to simplify the determination of reasonable conditions for the experiments. It should be noted that the critical velocity in their study is still based on the description by Schmidt et al. (Ref 5). An alternative description to the parameter selection map is the so-called cold spray coating diagram (CSCD) introduced by Kamaraj and Radhakrishnan (Ref 7). Here, the ratio of particle temperature and melting temperature \( \left( \frac{T_p}{T_m} \right) \) is plotted against the particle velocity \( v_p \). By including available experimental data, e.g., adhesion strength or deposition efficiency, and the experimentally observed bonding mechanisms, e.g., surface melting or adiabatic shear instability, a complete picture of the material dependent coating diagram can be created. During the past 10 to 15 years, alternative models for the critical velocity and the bonding process have been developed by,
calculations of the critical velocity, see, e.g., (Ref 4-6), it is usually obtained by calculations using either simplified numerical models (e.g., the isentropic model (Ref 4, 6)) or computational fluid dynamics simulations (CFD) (Ref 4, 5, 33-35). A comprehensive review on the modeling in cold gas spray was published by Yin et al. (Ref 36) comparing cases where the particle temperature distribution is no longer uniform within the sprayed particles and found that for materials with low heat conductivities (e.g., Al2O3) a difference between the core and the surface temperature exist. In a more recent study Raoelison et al. (Ref 38) analyzed the particle temperature distribution in cold sprayed particles in more detail and formulated a criterion for the uniformity of the particle temperature, named RUTp (Ref 38). The criterion depends on gas velocity, particle size and the ratio of the thermal conductivities of the particle material and the process gas.

A first attempt to obtain particle temperatures experimentally in-flight during cold gas spray was undertaken by Nastic and Jodoin (Ref 33), who used a high-speed IR camera to analyze sieved Ti-particles with a diameter of around 150 µm. The highest temperature was assumed to be the particle temperature. Two different methods, particle streak velocimetry (PSV) and particle track velocimetry (PTV), were utilized to determine the particle velocities. In their study, the obtained particle velocities (below 200 m/s) and temperatures (less than 100 °C) were below the necessary conditions for successful coating deposition, means outside of the deposition window.

In the present study, we will focus on in-flight particle diagnostics of Inconel 718 and TiAlCrNb (AE Alloys™) particles that exceed the critical velocity and could be used for potential applications in future. For this purpose, a high-speed IR camera is used, an improved model compared to the one used by Nastic and Jodoin (Ref 33), and further details will be provided later. The influences of the emissivity and particle size on the particle temperature are discussed. The quality of the experimental results is evaluated by comparing the particle velocities and temperatures to predictions of the KSS software (Ref 39). Furthermore, for the IN718 feedstock, a comparison between the results of a cold spray meter (CSM) and those obtained by the IR camera is presented.

Experimental Methods and Data Analysis

Two different powders, In718 (Inconel 718) and TiAlCrNb (Ti-48Al-2Cr-2Nb), were used in the present study. The In718 powder was provided by AP&C (Canada) and the characteristic values for d10, d50, and d90 are 27, 35, and 45 µm, respectively. The second feedstock was a gas atomized TiAlCrNb powder customized for the cold gas spray process. The particle size of this powder was measured as d10 = 17 µm, d50 = 32 µm and d90 = 48 µm using the laser diffraction method (LA-950-V2, Horiba Ltd., Tokyo, Japan).
Japan). The spherical morphologies of the two feedstocks with some satellites at the particle surfaces and the particle size distributions are shown in Fig. 1(a), (b), and (c).

Figure 2 shows the IR camera (FAST M2K) and cold gas spray experimental setup used in this study. An impact 5/11 system (Impact Innovations GmbH, Rattenkirchen, Germany) was used for the cold spray experiments. The cold spray gun is equipped with a water-cooled SiC-D24 convergent-divergent De-Laval-nozzle. During the experiments, a gas inlet temperature of 1100 °C and a gas inlet pressure of 50 bar (N₂) were chosen. A further increase of the particle temperatures was achieved by attaching a longer pre-chamber with a length of 170 mm to the cold spray gun. As a result, the injected particles spend more time in the hot gas. The particle velocities are not affected by a longer pre-chamber length. For the experiments, the IR camera was focused at a spray distance of 60 mm. In the present study, there was no substrate in front of the cold spray gun, which avoids the bow shock effect.

As reported in (Ref 33), there are two methods to measure the velocities of the particles with an IR camera, namely particle tracking velocimetry (PTV) and particle streak velocimetry (PSV). In the PTV method, two consecutive frames are analyzed. The same particle has to be present in both frames and then the travel distance of this particle can be obtained from the measured starting and final position in the respective frames. With the known time between two consecutive frames (1/ acquisition rate) the particle velocity can be calculated. Due to the low acquisition rate of 10 kHz the PTV method was not applicable in the present study. The time between two frames is 100 μs and particles with a velocity of more than 400 m/s would fly through the entire field of view within that time interval. In the second method (PSV), the starting and final positions of the particles are determined in the same frame. During the exposure time of the image, the particles travel a certain distance and emit infra-red energy. The length of the “streak” of infrared energy is the travel distance of the particle, more precisely, the length of the
streak is the travel distance plus the particle diameter. Since the exposure time is known, 2 μs in the present work, the particle velocity could be calculated. In the present study, the PSV was used to determine the particle velocity distributions of In718 and TiAlCrNb. In the post-treatment of the In718 data, the particle velocities were filtered into 3 groups: (i) \( v_1 < 400 \text{ m/s} \), (ii) \( 400 \leq v_2 < 1000 \text{ m/s} \) and (iii) \( v_3 \geq 1000 \text{ m/s} \). The reason for the filtering will be discussed later in more detail (see Sect. “Results and Discussions”).

Nastic and Jodoin (Ref 33) also described the basics of the temperature measurements with an IR camera. The total infrared energy measured by the IR camera is a sum of three different contributions, (i) infrared energy emitted from the particle, (ii) infrared energy of the surroundings reflected by the surface of the particle, and (iii) the emitted infrared energy of the surrounding atmosphere (this contribution is neglected in the temperature calculations). As a result, a semi-empirical Planck law was derived that expresses the signal detected by the infrared camera [Eq 31 in (Ref 33)]:

\[
W_{\text{tot}} = \frac{R}{\exp \left( \frac{B}{T_p} \right) - F} + \left( 1 - \frac{R}{\exp \left( \frac{B}{T_p} \right) - F} \right) \exp \left( \frac{B}{T_p} \right) - F
\]

(Eq 1)

here, \( \varepsilon \) stands for the emissivity (depending on wave-length of the measured signal and the particle temperature) of the particle material, \( T_p \) is the particle temperature, \( T_{\text{ref}} \) stands for the temperature of the surroundings, \( R \) is a function of integration time and wavelength band, \( B \) is a function of wavelength only (\( B = h\nu/k_B \)) and \( F \) is a positive value close to 1.

Therefore, for the particle temperature calculations, the spectral hemispherical emissivity value of the particles has to be known. Due to its use in the aerospace industry, nuclear reactors or cryogenic storage tanks the emissivity of In718 has been studied quite intensively (Ref 40-50). In the literature, usually values for the total hemispherical emissivity (Ref 40, 43, 47) or the spectral emissivity (directional, effective or normal) of In718 (Ref 41, 42, 44-46, 48-50) are given. Furthermore, it should be noted that the emissivity depends on several factors like surface roughness (Ref 41) or surface oxidation. Values for total hemispherical emissivity values of as-received In718 with a temperature of 700 to 1400 K lie between 0.2 and 0.3 (Ref 40). After oxidation or surface treatments like sand-blasting, the total hemispherical emissivity values increase up to 0.5 or 0.7, respectively (Ref 40). Based on these, the interval for the emissivity of In718 was chosen between 0.5 and 0.9. While the emissivity of In718 was reported extensively, no emissivity data could be found for TiAlCrNb alloy in the literature. Therefore, emissivity for this alloy was chosen based on the studies reported on TiAl. Belkskaya (Ref 51) measured emissivity of TiAl alloys with up to 10 at.% Al as 0.18 to 0.32 between 800-1400 K temperature range. It was suggested that the emissivity of the investigated titanium alloys depends weakly on the composition. Krishnan et al. (Ref 52) on the other hand determined emissivity of TiAl alloys with higher Al contents (40.3-95 at.%), which is closer to the composition investigated in this study, at near melting temperatures (1400-2000 K) and reported values between 0.10 to 0.34. In this study, in contrast to the work of Belkskaya, the emissivity of TiAl alloys was found to exhibit nonlinear variations both with composition and temperature. In both studies, the measurements were made under vacuum or protective atmosphere implying that oxidation effects were not considered which leads to an increase in emissivity values. Therefore, a large emissivity range between 0.1-0.7 was used in the present work for the analysis of the TiAlCrNb measurement data collected by the IR camera.

The software of Telops requires the particle diameter as well as the emissivity to be chosen before running the analysis. Due to this limitation of the software, it was decided to use a fixed particle diameter of 30 μm and investigate the influence of the emissivity. For each chosen emissivity value the same particles were identified and analyzed by the software. This assumption enables a link between the particle temperatures of a particle of fixed size but with different emissivity values, i.e., the particle temperatures for lower or higher emissivity values can be extrapolated according to Eq 2:

\[
T_{p_2} = \frac{C_4}{\lambda} \left( \ln \left( \frac{\varepsilon_{p_2} - \varepsilon_{p_1}}{\exp \left( \frac{\varepsilon_{p_1}}{\lambda T_p} \right) - 1} \right) + 1 \right)^{-1}
\]

(Eq 2)

here, \( \varepsilon_{p1} \) and \( \varepsilon_{p2} \) are the emissivity values of a particle with temperatures \( T_{p1} \) and \( T_{p2} \), respectively. Furthermore, \( C_4 \) and \( \lambda \) are constants (\( C_4 = h\nu/k_B \approx 1.438775 \times 10^{-2} \) mK and \( \lambda = 4 \) μm, see (Ref 33)).

For comparison, the particle velocities were also measured with a cold spray meter (CSM) from Tecnar. A laser beam (wavelength 790 nm, power 3.3 W, divergence 70 mrad) is aligned with the particle beam and the reflected laser light is detected by an optical sensor which is equipped with a double-slit mask. Using the time of flight and the known dimensions (80 μm between the slits, width of the slits is 80 μm) of the mask the particle velocity is calculated with an accuracy in the order of 0.5%. For each experiment, 10,000 particles were evaluated. Furthermore, the particle diameters were estimated from the measured
energies assuming that the scattered radiation intensity corresponds to the surface area of a spherical particle. Before, a calibration coefficient has to be determined from a measurement of reference particles with a known volumetric mean particle diameter and the same emissivity. The particle size is obtained with an accuracy of 7-15%, and that it is greatly dependent on the validity of the hypothesis of sphericity of the particles.

During the experiments, several videos with around 100,000 frames were recorded and a smaller subset of around 21,500 frames was analyzed automatically for different pre-set parameters, e.g., particle radius, material emissivity, distance to the object, and surrounding conditions (e.g., humidity and temperature). An acquisition rate of 10 kHz and an exposure time of 2 μs were chosen. The field of view was set to 320 × 40 pixels. Since the pixel size of the camera is 30 × 30 μm, the field of view has a size of 9.6 × 1.2 mm.

Additionally, the KSS software was used to calculate the particle i temperatures and particle velocities from the injection point to the substrate surface via a 1-dimensional model (Ref 39). Several parameters can be set for the calculations. These parameters can be divided into several groups: (a) nozzle parameters (nozzle types and injection point), (b) gas parameters (temperature, pressure, gas type and gas composition), (c) injection parameters (fraction of carrier gas, carrier gas temperature and particle injection velocity). In the literature section of the software several publications are listed, divided into the following 6 groups: (i) basics of the calculations of the KSS software (Ref 4, 6, 53), (ii) basics of fluid dynamics in cold spray (Ref 34), (iii) critical velocity and bonding mechanisms in cold spray (Ref 1, 3, 5), (iv) hardening of powder particles (Ref 54), (v) further literature (Ref 55, 56), and (vi) book chapters (Ref 57, 58).

As the KSS software takes the bow shock effect (Ref 59) into account, two different particle velocities, namely max and impact velocities, calculated in the software were considered and compared to the values determined by the IR camera and CSM methods where no bow shock occurred as no substrates were present. For comparison, calculations at a spray distance of 200 mm were performed with the KSS software and the in-flight particle velocities and temperatures at 60 mm downstream the nozzle exit were determined. These calculations were performed since during the experiments no substrate was placed in front of the cold spray gun.

Results and Discussion

Particle Velocity and Temperature—Comparison Between the CSM, High-Speed IR-Camera and KSS Software

In Fig. 3, the measured particle velocities (a, c) and particle temperatures (b, d) of the In718 and TiAlCrNb powder, respectively, are plotted. For the temperature measurement by the IR camera the emissivity of 0.5 to 0.9 for In718 and 0.1 to 0.7 for TiAlCrNb was considered for the analyses. The solid and dashed lines in Fig. 3(b) and (d) are described by Eq 2 (see “Experimental Methods and Data Analysis” section). The data were obtained using a particle diameter of 30 μm.

Overall the software from Telops identified over 20,000 particles for the selected analysis parameters and each powder. As already mentioned in the experimental section, the analyzed In718-particles were divided into three different classes based on the measured velocity (Fig. 3a, b). In the first group (v < 400 m/s) 4.1%, in the second group (400 m/s < v < 1000 m/s) 84.5%, and in the third group (v ≥ 1000 m/s) 11.4% of the detected particles were found. The average velocity of the slow particles (< 400 m/s) was 310 m/s. The standard deviation of the particle velocities in fig. a (400 ≤ v < 1000 m/s) is 107 m/s. For the fast particles the standard deviation is much larger (around 300 m/s) and for the slow particle the standard deviation is a little smaller. For the particle temperatures in Fig. 3(b) the standard deviations are around 150 °C (for the black points).

An analysis of the individual video frames as shown in Fig. 4(a), (b), and (c) revealed that these slow particles were located at the right or left edge of the field of view of the IR-camera (Fig. 4b, marked by a white arrow). Therefore, only a part of the particle track was visible in the image so that a very low particle velocity was supposed. Moreover, the obtained average particle temperature was low (T_{average} = 387-470 °C, depending on emissivity), since a smaller area was evaluated and hence a smaller amount of infrared energy was detected by the IR camera. As it can be seen from Fig. 3(b), the fastest particles also possessed the highest temperatures. The average velocity of this group was 1359 m/s and the average particle temperature ranged from 723.9 °C (ε = 0.9) to 928 °C (ε = 0.5). This observation is also explained in Fig. 4(c). Here, it can be seen that the impression of fast particles is caused by overlapping particle tracks, which is apparent in the presented example since the width of the labeled particle (white arrow in Fig. 4c) changes suddenly. The overlap originates from particles flying at the same height, but at different distances from the camera thus leading to...
an overestimation of the particle velocity and the particle temperature, since a larger area is used for the calculations. For the analysis only the “good” particles were considered and examples can be found in Fig. 4(a) (white arrow) and Fig. 4(c) (orange arrow). In Table 1, exemplary values of particle velocities and temperatures (particles in Fig. 4a-c) for an emissivity of 0.7 are listed for the different cases mentioned above. A comparison of the results obtained with the IR camera and a CSM will be discussed later for In718, but first the measured particle velocities and temperatures for TiAlCrNb are summarized and evaluated. As the first (v < 400 m/s) and third (v ≥ 1000 m/s) group of particles in In718 data analysis were found to be under-and overestimations stemming from the analysis procedure, only data for the second group (400 m/s ≤ v < 1000 m/s) of particles are shown for TiAlCrNb in Fig. 3(c) and (d). Accordingly, similar to the In718, the particle velocities are independent of emissivity (Fig. 3c) and have an average value of 875 m/s. The average particle temperatures were found to be in the range of 612 °C ≤ Tp ≤ 1370 °C revealing the importance of true emissivity for such thermal measurement. Impact temperatures of 32 μm particles (d50), determined by KSS are given in Table 2. A comparison to IR camera data of 30 μm particles as shown in Fig. 1(d), yields at emissivities between 0.3-0.4 the most comparable results between the two different methods.
A comparison of the particle velocities of In718 measured by IR-camera, CSM and predicted by the KSS software are depicted in Fig. 5(a). The calculations were performed with the KSS software (Ref 39) using the same spray parameters as in the experiments. The left and right edge of the gray box in Fig. 5(b) and (c) represent the \(d_{10}\) and \(d_{90}\) values of the In718 feedstock, respectively. The in-flight particle temperatures were determined using a spray distance of 200 mm in the KSS and the particle temperatures and velocities 60 mm downstream of the nozzle exit are plotted for comparison. As mentioned in “Experimental Methods and Data Analysis” section, during the measurements with the CSM, 10,000 particles were detected. To improve the comparison between the results of the CSM and the IR-camera the same filtering method was applied. Here, 208 particles (2.1%) exhibit a particle velocity of less than 400 m/s and 58 particles (0.6%) fly faster than or equal to 1000 m/s. Overall 9736 particles were analyzed for the velocity distribution in Fig. 5(a) and the comparison between both methods reveals that the IR-camera measurements (Fig. 5a) lead to higher particle velocities. Both distributions are plotted in number fractions. The average particle velocity for the CSM measurement is about 745 m/s and around 770 m/s for the high speed IR-camera. It should be noted that the experimental error for the particle velocities obtained with the IR camera is relatively large which is related to the limited spatial resolution of the images. As mentioned in “Experimental Methods and Data Analysis” section, the pixel size used for the evaluation is 30 \(\mu m\). Assuming the minimum inaccuracy of one pixel on

| Powder     | Particle diameter, \(\mu m\) | \(v_{\text{inv}}\), m/s | \(T_{\text{inv}}\), \(^{\circ}\)C | \(v_{\text{max}}\), m/s | \(\eta\) |
|------------|-----------------------------|------------------------|-----------------------------|------------------------|--------|
| In718      | 27 (\(d_{10}\))             | 726                    | 726                         | 735.2                  | 1.47   |
|            | 35 (\(d_{50}\))             | 689                    | 792                         | 694.4                  | 1.53   |
|            | 45 (\(d_{90}\))             | 650                    | 841                         | 653.2                  | 1.57   |
| TiAlCrNb   | 17 (\(d_{10}\))             | 845                    | 603                         | 883                    | 1.23   |
|            | 32 (\(d_{50}\))             | 773                    | 777                         | 789                    | 1.34   |
|            | 48 (\(d_{90}\))             | 731                    | 858                         | 740                    | 1.40   |
each side of the particle track already leads to an uncertainty of 60 µm for the traveled distance of an individual particle. If the traveled distance is divided by the short exposure time of 2 µs, the resulting minimum error for the particle velocity is 30 m/s. Thus, it can be stated that the results of CSM and IR-camera are in good agreement within the experimental errors.

For the theoretical velocity distribution calculation using the KSS software, the experimentally determined particle size distribution of the In718 powder was considered and for each diameter value the particle impact velocity was calculated. Afterward, the number fraction of each particle size was taken into account and an average velocity was calculated resulting in a predicted value of 696 m/s (Fig. 5a). Overall the impact velocities range from 562 m/s (for particles with 77 µm diameter) to 777 m/s (for particles with 17 µm diameter). A more detailed comparison revealed that approximately 5.5% (CSM) and 6.1% (IR-camera) of the analyzed particles are slower than the predicted 562 m/s, but around 38.4% (CSM) and 57.1% (IR-camera) of the measured particle are faster than the highest predicted velocity of 777 m/s. The KSS software takes the bow-shock effect (Ref 59) into account, but in the experiments no substrate was placed in front of the particle jet, so that no bow-shock effect occurred. Mainly, fine particles are influenced by the shock-waves in front of the substrate reducing the impact velocity. In addition to the impact velocities and impact temperatures the KSS software also enables to analyze the particle velocities and particle temperatures along the entire particle track, in this case the nozzle axis. The maximum particle velocity ($V_{\text{max}}$) occurs at a short distance, approximately 2.5 mm, in front of the substrate. At this distance the KSS software starts to take the bow shock effect (Ref 59) into account. In the software the effect is realized by an abrupt change of the gas velocity down to 50 m/s, which stays constant until the particle hits the substrate. Consequently, the bow shock effect leads to a deceleration of the particles, in particular for particles with a diameter of less than 20 µm. Some examples can be found in Table 2 for the $d_{10}$, $d_{50}$ and $d_{90}$ values of the used feedstocks. A more pronounced reduction in particle velocities due to bow shock effect can be seen for TiAlCrNb feedstock in contrast to the In718. This can be attributed to smaller $d_{10}$ value of TiAlCrNb feedstock and about two times lower density of TiAlCrNb ($\sim 3.97$ g/cm$^3$) than that of In718 ($\sim 8.19$ g/cm$^3$) meaning lower inertia of the TiAlCrNb particles when compared to same size of In718 particles. If impact velocities of the $d_{10}$ size TiAlCrNb particles calculated by KSS (845 m/s) are compared to particle velocities measured by IR camera (875 m/s assuming a particle diameter of 30 µm, Fig. 1e) it can be seen that KSS yields lower velocity even for the smaller particles. A better comparison of the predicted and measured particle velocities consequently can be reached when the bow-shock effect is excluded and the maximum particle velocities are considered instead of the impact velocities. A study by Mauer et al. concluded that during CSM measurements corrections for the bow shock effect are reasonable and were found to be larger than predicted by the KSS software (Ref 29). Observed differences between the measured and calculated particle velocities the authors also linked to the powder morphologies which potentially deviated from ideal spheres. Nevertheless, IR camera measured particle velocities still exceed the KSS determined $v_{\text{max}}$ values of $d_{50}$ size particles (or $d_{10}$ for IN718) for both materials. It should be noted that the KSS software is using just a 1-dimensional model for the calculations and more precise calculations could be done by CFD simulations.

The drag force acting on the particles depends on several factors, including the drag coefficient. Due to the nature of Newton’s law the particle acceleration is proportional to the drag coefficient. The most common expressions for spherical particles used the literature on cold gas spray are the ones of Schiller-Naumann (Ref 60), Alexander and Morsi (Ref 61) and Henderson (Ref 62). As it can be seen in Fig. 1(b), some TiAlCrNb particles show a deviations from the ideal spherical shape. Recently, Ozdemir et al. (Ref 21) investigated the impact of particle shape on measured particle velocities in more detail. In their study, the shape of the feedstock powder was analyzed with a light microscope and significant deviations from the spherical shape were found. The sphericity $\psi = s/S$, first introduced by Wadell (Ref 63) (s = surface area of a spherical particle of equivalent volume, S = surface area of the particle under investigation), is 1 for a perfect sphere and smaller than 1 for all other shapes. Haider and Levenspiel (Ref 64) developed a drag coefficient for non-spherical particles depending on sphericity. Detailed 1-dimensional and 3-dimensional CFD simulations by Ozdemir et al. (Ref 21) for different particle shapes revealed that the discrepancy between the CFS simulations and the velocimetry data originated from the used Schiller-Naumann drag-coefficient (Ref 60) which is valid for spherical particles. A better agreement between theoretical and experimental particle velocities was found using the drag coefficient of Haider and Levenspiel. Since the calculations in the KSS software were performed for spherical particles an underestimation for the particle velocity of non-spherical particles is expected, in particular for TiAlCrNb.

**Effect of Particle Size on the Particle Temperature and Velocity**

Similar to the influence of emissivity, the effect of the particle size was investigated. In this case, the emissivity is
kept constant and the particle diameter is changed prior to the image analysis with the Telops software. Again, the same particles were analyzed and identified with the software. Due to the change of the particle size, the obtained particle velocity decreases with increasing particle size, as presented in Fig. 6(a). Independently of the particle size, the same area is evaluated in the frames and the travel distance of a particle is calculated between the center of the particle at the start and finish position. Therefore, the total particle track is the sum of two particle radii and the travel distance. As a consequence, the particle velocity decreases by 20 m/s when the particle diameter increases by 40 µm (40 µm/2 µs = 20 m/s), see Fig. 6(a). To avoid an influence of the velocity filtering process on the results it was decided to use the filtered data set for a particle diameter of 30 µm as a reference. The same particles were analyzed for all the other data sets which were obtained using different particle diameters in the software. If each obtained data set would be filtered individually, some particles with velocities close to the lower (400 m/s) and upper limit (1000 m/s) would be excluded or included in the analyzed data set, respectively, depending on particle size, e.g., a particle with 30 µm diameter and a velocity of 402 m/s in data set A has a velocity of 392 m/s in data set B where a particle diameter of 50 µm was used for the analysis.

Based on Eq 1 a formula linking the temperatures of two particles with the same emissivity but different particle diameters can be derived. Assuming that exactly the same area of the image (same particle track) is evaluated for different per-set particle diameters leads to the conclusion that the total measured infrared energy is identical. The following relationship can be derived based on this assumption.

\[
T_{p2} = \frac{C_4}{\lambda} \left( \ln \left( \frac{R_{p2}^e}{1 - \varepsilon} \right) \frac{R_{p1}^e - R_{p2}^e}{\exp \left( \frac{C_4}{C_4 \varepsilon R_{p1}^e} \right) - 1} + 1 \right) ^{-1}
\]

(Eq 3)

Here, \( R_{p1} \) and \( R_{p2} \) are the radii of the particles with temperatures \( T_{p1} \) and \( T_{p2} \), respectively. The emissivity \( \varepsilon = 0.7 \), \( C_4 \) and \( \lambda \) are constants (\( C_4 = h\epsilon/k_B = 1.438775 \times 10^{-2} \) mK and \( \lambda = 4 \) µm, see Ref 33. The particle size dependence of In718 according to Eq 3 is plotted as a solid line in Fig. 6(b) and is in good agreement with the experimental data obtained by the image analysis. As mentioned in “Experimental Methods and Data Analysis” section, for In718 the \( d_{10} \) and \( d_{90} \) values are 27 and 45 µm, respectively. Within this particle diameter range, the calculated particle temperature decreases from 620 to 440 °C with increasing particle size.
Linking Particle Temperature and Diameter Measurements

As described above, a specific value for the particle diameter $d_0$ is needed to be used for the evaluation of the measured particle temperatures. Thus, particle diameters must be determined in advance. This can be done, e.g., by the laser diffraction method. A particle sample is suspended in a carrier fluid. A parallel laser beam passing through the suspension flow is scattered at the particles depending on their diameters. The corresponding diffraction patterns are detected and evaluated applying Fraunhofer’s or Mie’s diffraction theory. Since the particle size in a powder is statistically distributed, the result is a density distribution $q_d$ as a function of the particle diameter $d$. If this is integrated, the cumulated frequency curve is obtained and some characteristic values like $d_{10}$, $d_{50}$, and $d_{90}$ are read to describe the average particle size as well as the width and symmetry of the distribution. The averaged measured particle diameter $d_{50}$ can be used for the initial evaluation of the measured particle temperatures setting $d_0 = d_{50}$. The result is a density distribution $q_T$ as a function of the particle temperature $T$. This distribution results from different thermal histories on the one hand and the statistical distribution of the particle diameters on the other hand. However, the temperatures were evaluated with the correct diameter only for particles with $d = d_0$. To improve this situation it is proposed to repeat the temperature evaluation setting different values of the diameter $d \neq d_0$ (this can be easily done using Eq. 3) and to weight the results with the frequency $q_d$ at this value of $d$ in the diameter distribution. Then, these average values of these weighted temperature distributions $q_{T, \text{avg}}$ are added up by integration with respect to the temperature $T$ to obtain the particle temperature distribution $q_T$.

Finally, the resulting temperature distribution $q_T$ is normalized so that its integral with respect to the temperature $T$ is unity. This distribution should represent the effect of the particle size on the particle temperatures in a better way than simply evaluating the temperature measurements setting only one diameter $d_0 = d_{50}$.

For the reference data set used for this method a particle diameter of 30 µm and an emissivity of 0.7 were chosen. By applying Eq. 3 the particle temperature distributions were calculated for different particle diameters $d = d_0$ considering the experimentally determined particle size distribution, see Fig. 7(b). The obtained temperature distributions were weighted by the number fractions of the particles size distribution (see Fig. 1c) and the average particle temperatures were calculated. The resulting average particle temperature were taken and a new particle temperature distribution was created. This new distribution was normalized and the results are shown in Fig. 7d for two different emissivity values. The influence of the emissivity can be calculated using Eq. 2.

Conclusions

The present study is built on the work of Nastic and Jodoin (Ref 33) and represents another step forward toward more accurate in-flight particle temperature measurements during the cold gas spray process. Accurate and reliable particle diagnostics are essential for the development and refinement of models and enable a comparison between the existing theories and experimental observations.

The in-flight measurements of particle temperature and particle velocity with a high-speed IR Camera lead to the following conclusions:

- The measured particle velocity distributions of the CSM and the IR camera are in good agreement with each other considering the larger experimental error of
the IR camera. An increase of 8% (CSM) and 11% (IR camera) compared to the calculated results of the KSS software were found for In718.

• For both materials the experimental results revealed a high dependence of particle temperature on emissivity. For low emissivity values, 0.3 for In718 and 0.3 to 0.4 for TiAlCrNb, the measured particle temperatures are comparable to the predicted temperatures for particles with a diameter of 35 and 32 μm, corresponding to the $d_{50}$-values of the respective feedstock.

Despite the great progress some challenges remain for the future including further improvements of the camera resolution to distinguish different particle sizes more precisely and to enable better correlation between the measured particle velocities and particle temperatures. Furthermore, it is important to accurately determine the particle emissivity values of the feedstock since the exact value is crucial for the correct calculation of the particle temperatures.

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