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Imaging Diagnostics Study on Obliquely Impacting Plasma-Sprayed Particles Near to the Substrate

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Real time close-up images of in-flight particles plasma sprayed onto a substrate and in freestream condition (without substrate present) are captured. Besides the images, particle behavior in terms of temperature, velocity, and heading are measured by the SprayWatch particle imaging diagnostics system. The monitoring and measurement of particle behavior have been performed for substrates inclined at various angles to investigate the effect of the substrate on particle behavior. The close-up images show that particles propelled from the torch travel with high momentum and are not affected by the substrate and inclination angle. Quantitative analyses of the particle average velocity and heading data with and without the different inclined substrates also lead to similar conclusions. The particle velocity is resolved into tangential and normal velocity components parallel and perpendicular to the substrate, respectively. The tangential velocity component controls the degree of splat elongation into elliptical shape from the circular shape seen in perpendicular impact. This is of practical importance in industrial spraying of engineering components of complex curvatures. A higher tangential velocity component also implies that more powders are lost through rebounding and overspraying and thus reducing the deposition efficiency. The normal velocity component decreases when substrate inclination increases, which tends to weaken the coating adherence.

Keywords imaging diagnostics, inclined substrate, particle parameters, SprayWatch system

1. Introduction

In a typical plasma spray coating process, fine particles of a given material are introduced into a high temperature and velocity of plasma plume to be accelerated, heated, and melted before impacting on the substrate. The microstructure and physical properties of coating deposited in the plasma spray process depend on many operational parameters. This is because the process parameters affect the particle in-flight characteristics, namely, velocity, temperature, and size, which subsequently affect the coating characteristics.

Considerable efforts have been undertaken in the areas of particle sizing, velocity, and temperature measurements to understand the behavior of the particles under different spray parameters and methods. Various diagnostics techniques were applied, such as phase-shift analysis (Ref 1) and telemicroscopic imaging of particle shade (Ref 2) to measure particle size. The Laser Two Focus (L2F) (Ref 3) and Laser Doppler Velocimetry (LDV) (Ref 4-6) have been used for particle in-flight velocimetry. The two-color pyrometry (Ref 4-6) was commonly used for particle temperature measurement. A combination of the above techniques were applied in the Dantec Phase Doppler Anemometer (PDA) (Skovlunde, Denmark) the Tecnar DPV-2000 system (St-Bruno, QC, Canada), and the Oseir SprayWatch (Tampere, Finland) particle imaging diagnostics system to allow for simultaneous measurement of particle characteristics (Ref 7-11). Using the above techniques and tools in their experiments, they highlighted the significant changes of particle behavior under different operating conditions. In all of the above, the measurements were carried out in the freestream condition, i.e., without the substrate being present. With the presence of the substrate, it is anticipated that there will be a blowback of gas and flow diversion, which will cause drastic changes in plasma flow. This will in turn cause changes in the entrained particle in-flight behavior that will ultimately affect the coating quality. After conducting an exhaustive literature review, it was found that there is a lack of research investigating on the possible changes of particle behavior caused by the presence of the substrate. In the industrial practice of plasma spraying, complex-shaped engineering components, such as turbine blades have surfaces of curvature, which present different angles of impact to plasma jet and particles. Investigations to evaluate the extent these substrates would interfere with the flow of gases, and hence their effect on the particles and coatings would be of importance.

This paper describes the monitoring and measurement of the particle temperature, velocity, and heading in the presence of different flat and inclined substrates. A recently available imaging diagnostics system, called SprayWatch is used to evaluate the influence of the substrate on the particle behavior. In the experiments, the flat substrates were inclined at 0°, 20°, 40°, and 60° from vertical plane and sprayed while subjected to diagnostics imaging by the SprayWatch system. The comparisons of results between with and without substrate present for different inclination angles are presented.

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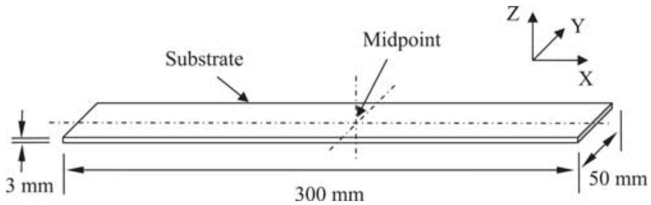

Fig. 1 50 × 300 × 3 (thickness) mm mild steel substrate used in the experiment

2. Experimental Method

2.1 Substrate Preparation

Figure 1 shows mild steel substrate with dimension of 50 × 300 × 3 (thickness) mm, which was cut from sheet material. Since the purpose of the substrate was to provide an obstruction, its already smooth surface was not subjected to further treatment.

2.2 Feedstock Powder

For the current study, agglomerated and sintered yttria-partially-stabilized (8%) zirconia (YSZ) supplied by Saint-Gobain Norton K.K., Singapore was used. The powder size distribution was measured by the Analysette 22 Compact Laser Particle Sizer (Fritsch GmbH, Industriestrasse 8, D-55743, Idar-Oberstein, Germany) to be between 22-125 μm in diameter with a mode of 37 μm. The powder was characterized as near-perfect spherical particles, as shown by scanning electron microscopy (SEM) photograph in Fig. 2.

2.3 Experimental Setup

The experiment setup presented in Fig. 3 shows the plasma spray torch and the SprayWatch charge coupled device (CCD) camera mounted on a traversing system. A model SG-100 plasma spray torch with an 8 mm diameter nozzle (Praxair Surface Technologies Inc., Appleton, WI) was used to spray powder at atmospheric pressure. A roto-feed powder hopper model 1264 (also from Praxair Surface Technologies Inc.) was used to introduce the powder radially and perpendicularly into the plasma torch at the rate of 9.6 g/min via the internal powder injector. Argon was used as the primary and carrier gas and the standard process conditions for the torch are given in Table 1.

The substrate was inclined by tilting the mounting fixture with the aid of spirit level and protractor. Four different inclination angles were chosen, starting from 0° to 60°, in steps of 20°. For each inclination angle, a fixture with a sharp pointer in front was mounted on the nozzle front face, as shown in Fig. 3, to assist in aligning the center of the plasma torch to the midpoint of the substrate. The plasma torch was elevated or lowered until the tip of the pointer was aimed at the midpoint of the substrate. The standoff distance was maintained for each case at 80 mm between the nozzle front face and the midpoint of the substrate. The substrate relative position to the torch remained fixed throughout the experiment.

During spraying, a deposit will quickly build up if both the substrate and the torch remained stationary. To prevent the excessive deposit buildup, which would cause unwanted deflection of the gas and particle flow, new substrate surface is constantly exposed by slowly feeding the substrate in its longitudinal (X axis of Fig. 3) direction or into the paper in Fig. 5 by means of the second traversing unit onto which the substrate is mounted. The feed movement of the substrate is perpendicular to the spray torch axis and does not affect the relative position of the torch and substrate i.e., standoff distance and inclination angle.

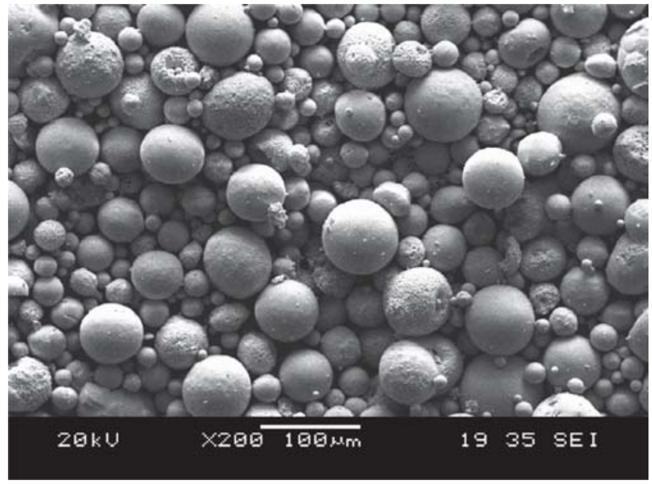

Fig. 2 Near-perfect spherical particles of yttria-partially-stabilized (8%) zirconia powder used in this study

Table 1 Experimental spraying conditions of Praxair Surface Technologies Inc. equipment

Parameter, unit	Magnitude
Powder injector angle, °	90
Torch diameter, mm	8
Current, A	900
Voltage, V	35
Primary gas flow rate (Argon), psi (slm)	80 (72)
Carrier gas flow rate (Argon), psi (slm)	30 (4.2)
Powder feedrate, g/min	9.6
Powder size, μm	22-125
Standoff distance, mm	80

2.3.1 SprayWatch CCD Camera Technical Information. The SprayWatch system consists of a CCD camera with a minimum exposure time of 10 μs and real-time image processing software. The CCD detector is 640 pixels high by 480 pixels wide, each pixel 9.9 × 9.9 μm^2 in size.

Besides providing a visual display of the spray plume, the system measures the primary parameters such as temperature, velocity, and number of in-flight particles in the spray, as well as the secondary parameters such as brightness, heading, and position. Particle temperature, velocity, and heading were monitored for different substrate inclinations.

The measurement of particle velocity is based on time of flight method while particle temperature measurement employs two-color pyrometry. The CCD detector in the camera is divided into two arrays to fulfill the needs of two different measurements. The left-hand array, as seen in Fig. 4, provides direct real-time visual display of the spray. Streams of particles constantly flowing across the pixel array are identified by the high

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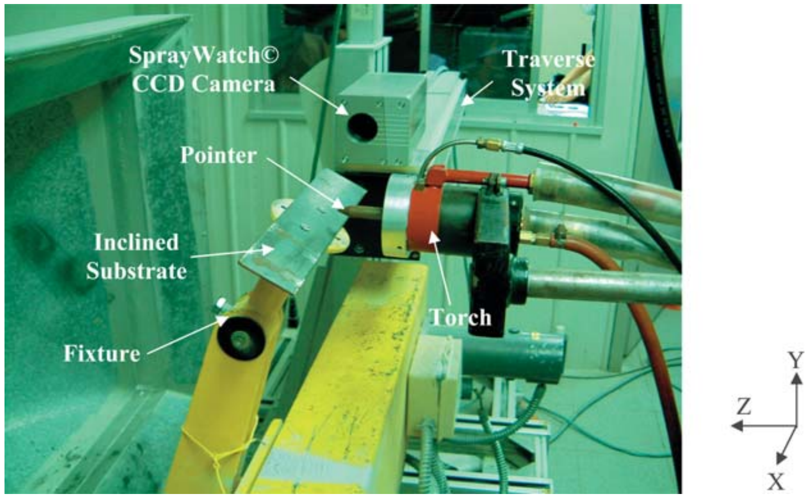

Fig. 3 Experiment rig showing the torch, substrate, SprayWatch CCD camera, and traversing system

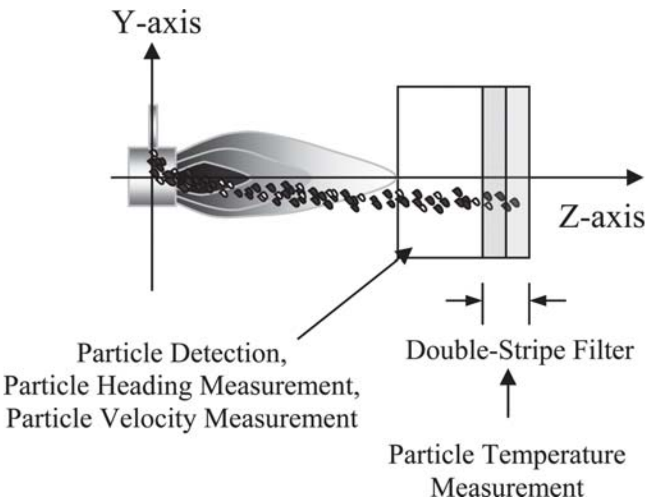

Fig. 4 Schematic illustration of particle behavior measurements in the two detector arrays in the SprayWatch system

brightness of their emitted light. The particle tracks are frozen at each frame. The time of flight and length of each track are used to deduce the velocity of the particle. The distance between beginning and ending points of each streak are measured by the number of pixels. The length of the exposure time (minimum of 10 μs) is the time of flight. Other measurements obtained from the two points are the particle heading and the particle count. The double-stripe filter on the right-hand side array seen in Fig. 4 is used for temperature measurement by means of two-color pyrometry.

A problem arises when imaging the spray at close vicinity to the substrate. To measure the velocities of the particles just before impact, the substrate must be placed at the boundary between the two arrays. The substrate thus blocks the particles from entering the right side temperature measurement array. Thus, the particle temperature cannot be recorded. More detailed explanations are provided in Sec. 4.1.

2.3.2 Translation of Target Area along Substrate Surface. The CCD camera was mounted on a precision XYZ traversing platform and pointed toward the plasma plume such that the sprayed particles crossing the camera's field of view before impacting on the substrate were in focus. The movement of the traverse allowed very precise survey of different parts of the substrate surface. For all measurements, the target area was set to 25.4 × 21.2 mm with 6 mm depth of field (DoF).

The target view of the CCD camera was first moved to position 1 in Δy and Δz directions, as illustrated in Fig. 5. Starting from position 1, a total of nine positions were imaged incrementally along the substrate surface to capture all the particles approaching the entire substrate. The distance between target positions was maintained at 5 mm, as shown in Fig. 5.

At each position, particles crossing the target area were imaged for approximately 10 s at the rate of 3 frames per second. In each frame, mean detected particle behavior was calculated by the data processing software. The average of the mean data of each frame over 30 frames taken in 10 s of measuring time provided the particle average behavior. The results presented in Sec. 4 are the averages of particle parameters.

The image captured at the substrate midpoint was referred at the position 5. At this position, the standoff distance between the torch to substrate would be at 80 mm, which was maintained as a constant distance for every angle of inclination of the substrate. This allowed for consistent comparison of measurements obtained for different substrate inclinations.

2.3.3 In-flight Particle Parameters Measurement. In this experiment, the CCD camera-torch axis distance was maintained at 350 mm. The measuring conditions of SprayWatch equipment are provided in Table 2. After the setup was established, the torch was ignited, and the powder was injected. The substrate was slid slowly in front of the plasma plume to obstruct the plasma jet. The camera was switched on to measure the particle temperatures, velocities, and headings at position 1 for approximately 10 s. In the meantime, the substrate was fed into the *X* axis away from the CCD camera unit to continuously expose new surface areas to the spray, the purpose being to avoid a deposit mound growing, which would affect particle trajectories and camera line of sight. The measurements were repeated for the other eight target views by traversing the CCD camera incrementally.

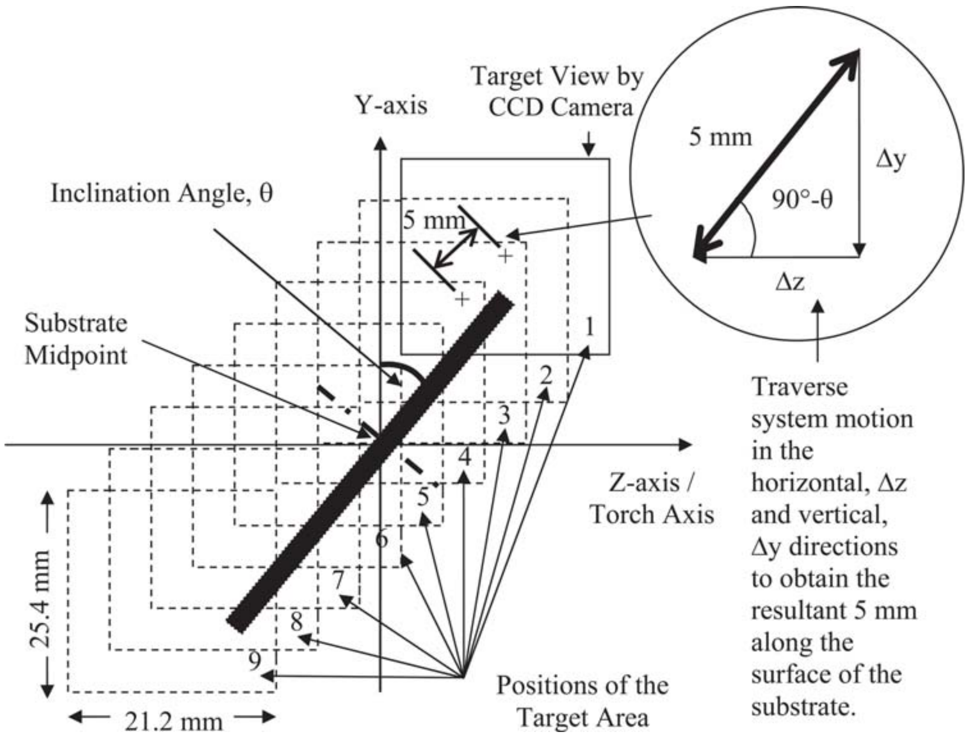

Fig. 5 Schematic diagram showing the incremental movement of the CCD camera and hence the target areas to capture the images of particles impacting the substrate at different angles of inclination. Position 5 is the image corresponding to torch centerline.

Table 2 Measuring conditions of the SprayWatch equipment

Parameter, unit	Magnitude
Resolution, pixels	640 × 480
Sensitivity, bits	12
Focus distance, mm	350
Exposure time, μs	10
Measurement time, s	10

After all measurements were taken, the substrate was removed from the plume allowing particles to spray freely into ambient environment. Nine measurements at each inclination were taken again by the camera retracing the same positions, as if the substrate was present. The measurement procedures for with and without substrate present were repeated for other substrate inclinations.

3. Definition of Particle Velocity Components

When a zirconia particle is fed through the vertical internal injection port with an initial velocity, its vertical velocity in the plasma jet is due to its initial vertical momentum while its horizontal velocity (parallel to the spray direction) is due to the drag force applied by the plasma gas. Thus, the trajectory takes a downward parabolic path. The resultant velocity of a particle at a given standoff distance is defined as U_p in this experiment. The particle will impact the substrate at an angle α, which defines the particle heading depending on the particle trajectory. The corresponding resultant particle velocity U_p can then be resolved into the tangential velocity U_{pt} (parallel to the substrate surface) and the normal velocity U_{pn} (perpendicular to the substrate surface) components. The velocity components of an impinging particle are illustrated in Fig. 6.

4. Results and Discussion

The basic sprayed particle parameters studied so far are the speed and direction of the particle. The particle temperature measurement under the presence of the substrate cannot be monitored correctly because the substrate shields particles from the temperature array preventing particle temperature from being taken. In Sec. 4.2, the images monitored at the substrate midpoint or position 5 for all the inclination angles are analyzed. Quantitative measurement results of particle behavior in the presence of substrate are discussed in Sec. 4.3.

4.1 Average Temperature of Particles

Particle average temperature can only be measured in freestream condition (Fig. 7a). In the setup with a substrate, which blocks the particles, the stripe filter region will not image any of the particles beyond the substrate (Fig. 7b). The particle temperature will therefore not be measured. Substrate temperature also cannot be measured by this method because it will require the substrate to be visible in both filter stripes and some modification of the software. In addition, when the particles en-

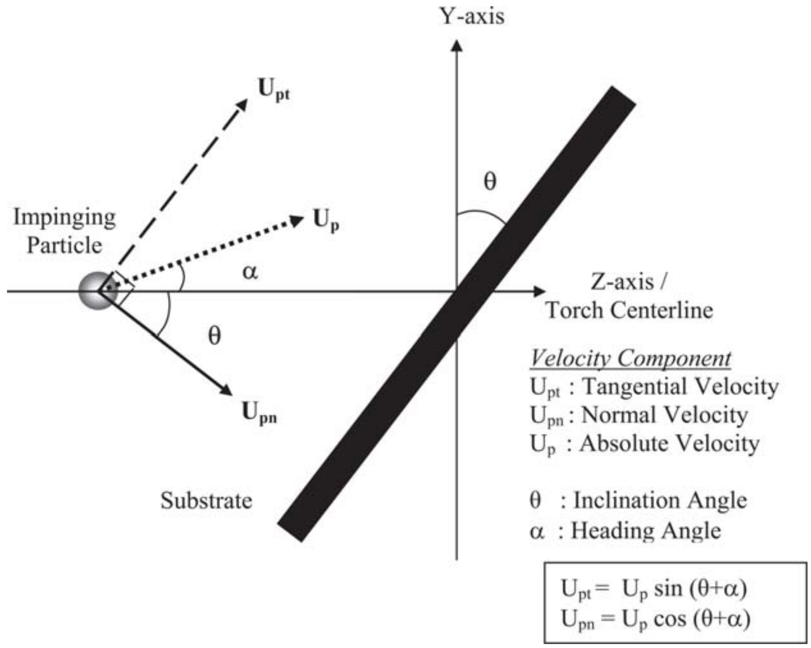

Fig. 6 Schematic diagram of a molten droplet impacted on a flat inclined substrate

ter the stripe filter region but are deflected by the substrate (Fig. 7c), the temperature measurement does not compute correctly because spray angle and divergence data are needed for temperature measurement. Hence, the temperature comparison will not be discussed for this study. However, the study provides important information on the velocity and heading of the particles.

4.2 Still Image Analysis

Examples of detected particle frames at freestream condition and with a substrate present at different inclination angles are presented in Fig. 8(a) to (e).

It can be observed that with the increase in substrate inclination angle, particles rebound toward the upper region of the substrate. For 0° inclination angle, the particles rebound vertically in both upwards and downwards directions, as shown in Fig. 8(b), whereas the rebounding particles from the substrate inclined at an angle of 60° are concentrated at the upper part of the substrate, as can be seen in Fig. 8(e). On the other hand, at substrate inclination angles of 20° and 40°, the rebounding particles behavior vary between the two extreme angles. In addition, more particles rebound from the substrate when the substrate inclination angle increases. Hence, fewer particles are available to form a coating and therefore, spraying at a higher inclination angle will result in lower deposition efficiency.

Deposition efficiency is defined as the ratio of the weight deposited on the substrate to the weight of powder ejected from the torch. Experiments were also conducted to evaluate the influence of the substrate inclination angle on the deposition efficiency. In this experiment, the substrates were weighed before and after 5 s of stationary spraying and the weight difference gave the actual amount of powder deposited on the substrate. The amount of powder delivered by the torch was calculated from the feedrate (g/s) and spray time (s). The feedrate was first obtained by spraying powder without igniting the torch and collecting the powder on a large plastic sheet on the floor over a fixed spraying time and with all other process conditions remaining the same. The weight of powder collected on the plastic sheet was calculated by the difference in the weight of the plastic sheet before and after spraying and this weight represented the amount of powder ejected from torch. Figure 9 shows the result of deposition efficiency at different substrate inclination angles. Indeed, the result shows a decreasing trend when the substrate inclination angle increases. This is previously mentioned to be caused by a high occurrence of rebounding particles at higher substrate inclination.

As a further observation in Fig. 8, the trajectories of the streams of hot particles propelled by the plasma jet are not affected by the substrate. This can be clearly observed from the paths of the particles with substrate present and the freestream particles in Fig. 8(a) to (e). All of them travel towards the substrate at high speed, with no sudden change in the particle directions right before impact. Thus, the presence of the substrate does not influence the particle flow or trajectory significantly.

4.3 Particle Behavior in the Presence of the Substrate

Besides presenting qualitative image analysis, quantitative data of particle velocity and heading are also collected by the SprayWatch system. Results obtained from measurements taken along substrate surface and at substrate midpoint in the case where the substrates present are compared with their freestream conditions and discussed in the following sections.

4.3.1 Average Velocity of Particles. Particle average velocities at the nine positions along substrate surface are presented in Fig. 10(a)-(d). At the location of 20 mm from midpoint of the substrate in Fig. 10(a) and (b), there are no measurement

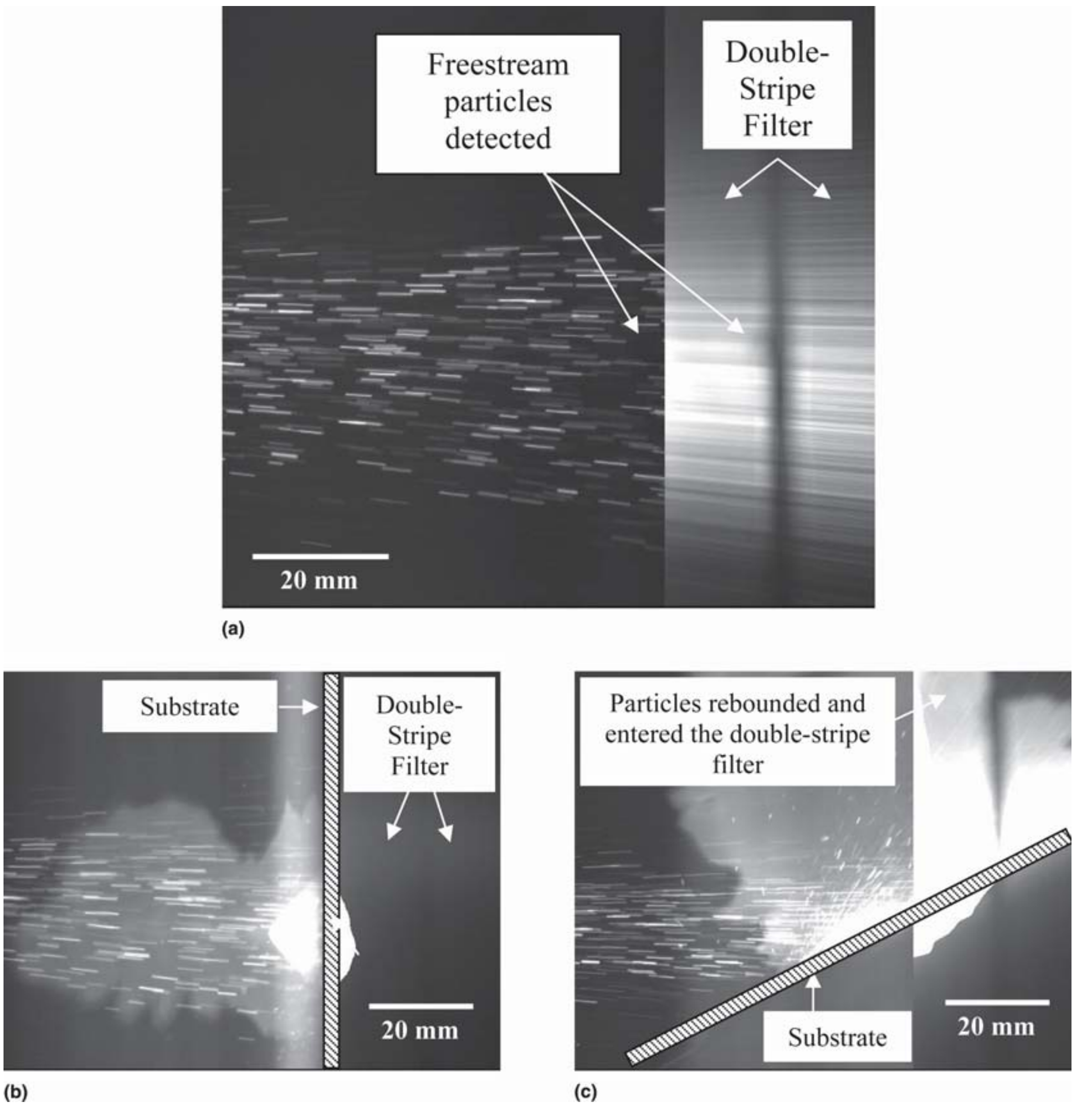

Fig. 7 Images of particles (a) passing through the visual display array (left) and the double-stripe filter array (right) in the freestream condition, (b) impacting on the perpendicular substrate, and (c) deflected by the substrate after impacting on the 60° inclined substrate. The substrates were added to the figures for clarity.

data because the location of 20 mm for perpendicular and 20° inclined substrates are too far above from the center of the plasma torch and no particle is detected and measured. In addition, it is noted that the particle average velocities measured in the freestream condition and with substrate introduced behave very similarly. No significant effect of substrate towards particle velocity is seen. This is because, as shown in Fig. 8(a) to (e), in-flight particles follow the similar trajectories and impact directly on the substrate, regardless of the presence of the substrate. Particles following the similar trajectories receive the same momentum from the prevailing plasma and thus show little difference in particle average velocity. The insignificant effect of perpendicular substrate on particle velocity was also noted in Ref 7. In the experiment described in Ref 7, a flat and perpendicular substrate introduced into the plasma spray had a minimal effect of less than 5% reduction of particle velocity. They suggested that particle motion was essentially ballistic and their velocities were not significantly affected by plasma flow divergence near the stagnation region.

However, there are two effects influencing the particle average velocity profile, namely, particle segregation and local standoff distance. In the case where the substrate is placed perpendicularly, all the particles impacting the substrate have to travel through the same standoff distance. The asymmetrical particle velocity profiles in Fig. 10(a) indicate that particles at the lower portion of the substrate experience lower velocities than particles at the upper portion. This is attributed to the effect of particle segregation caused by initial momentum of powder due to vertical injection. Larger and therefore heavier particles tend to penetrate deeper into the plasma plume due to their high initial momentum, whereas the lighter ones travel in the upper region of the spray jet due to their lower momentum, which allows only partial penetration into the plume. Thus, larger particles tend to be more numerous at the lower part of the spray

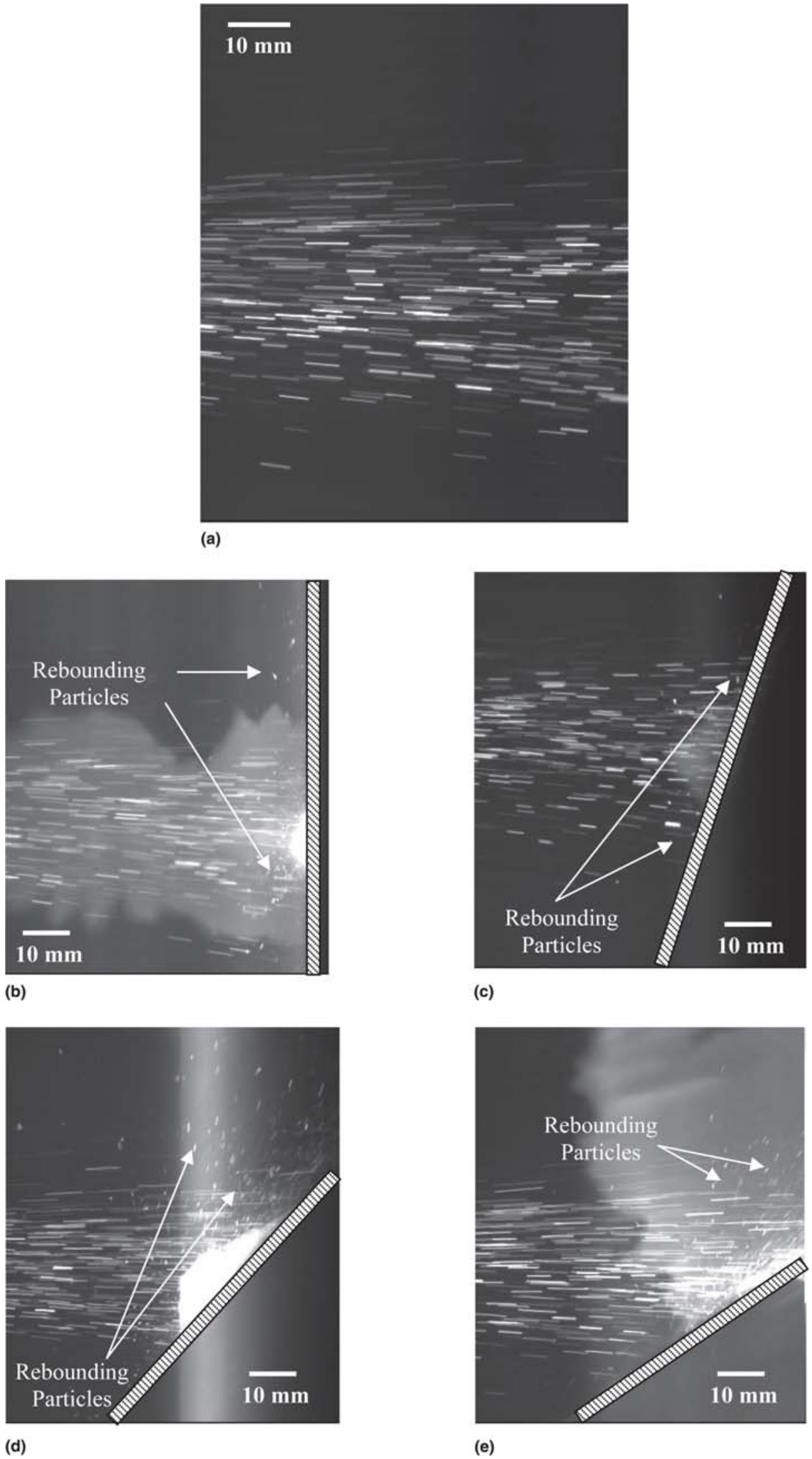

Fig. 8 Particles flow in (a) freestream condition and at different substrate inclination angles of: (b) 0°, (c) 20°, (d) 40°, and (e) 60°. Each frame is captured at the rate of 1/3 s with exposure time up to 10 μs

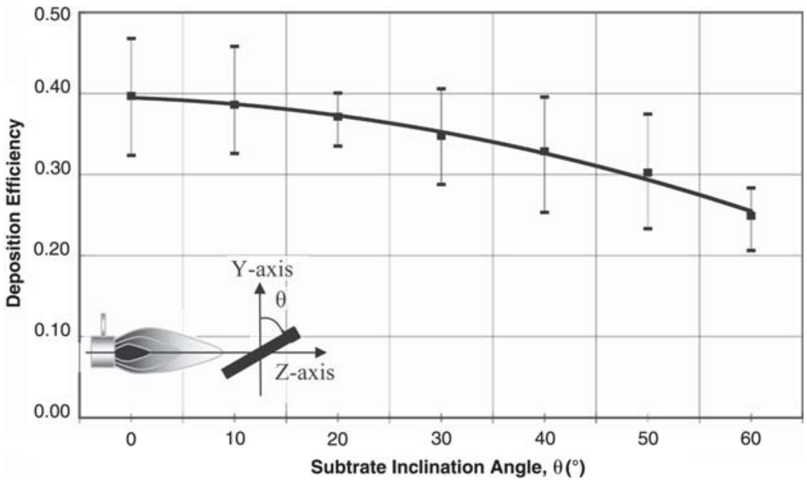

Fig. 9 Deposition efficiency showing decreasing trend when substrate inclination angle increases

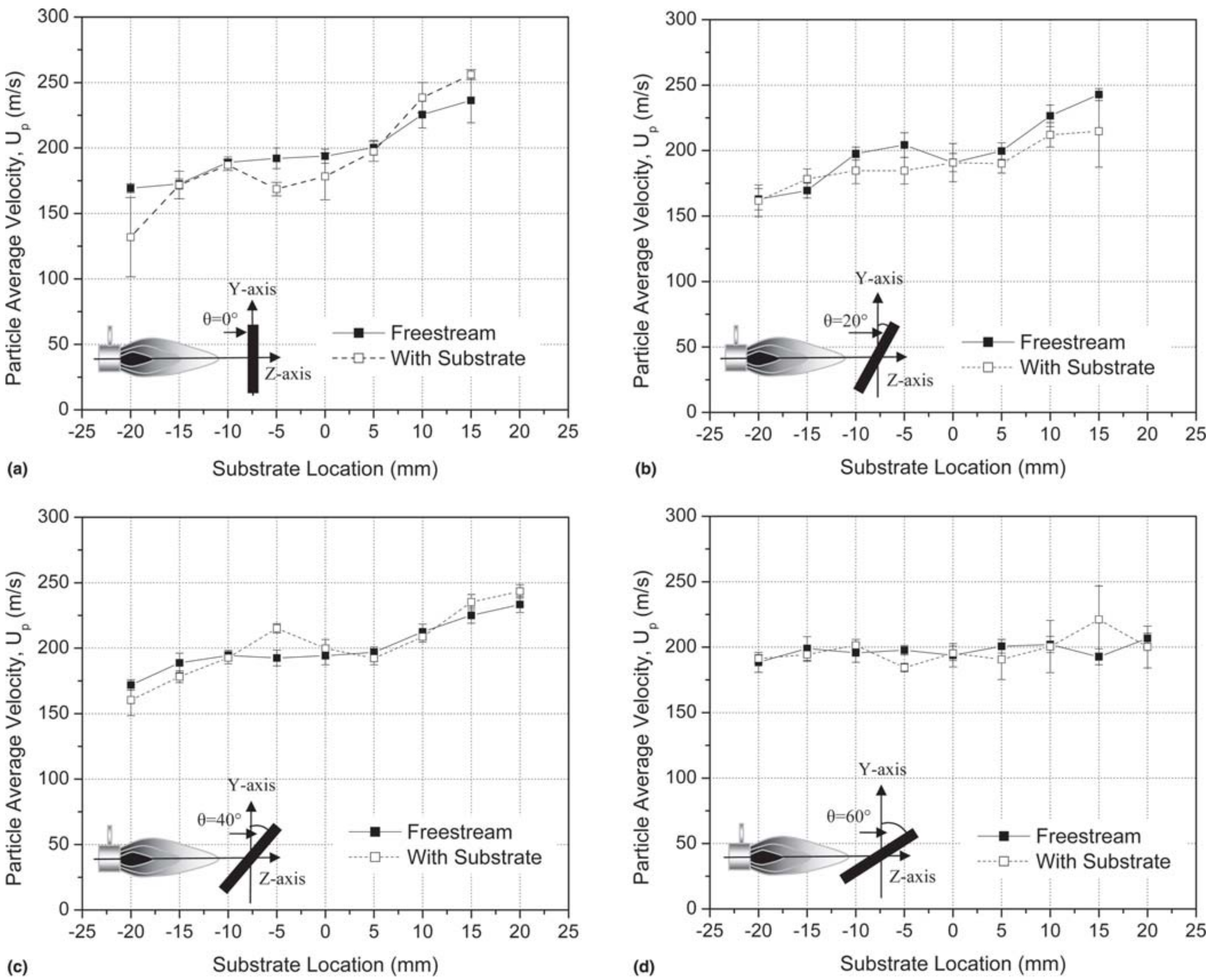

Fig. 10 Particle average velocity profiles along substrate surface for (a) 0°, (b) 20°, (c) 40°, and (d) 60° substrate inclinations compared to their corresponding freestream conditions

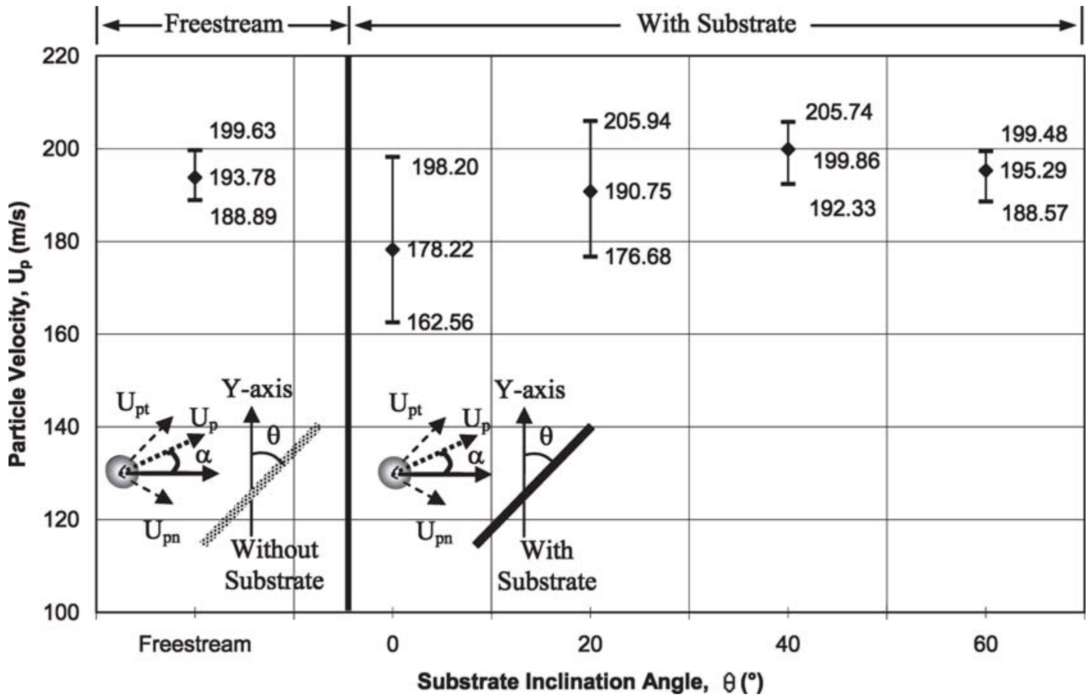

Fig. 11 Particle velocities U_p detected at the substrate midpoint for various inclination angles (right) compared with its freestream condition (left).

cone due to the vertical momentum initially acquired during their injection into the torch.

The second effect is related to the horizontal flight of particles between the torch and the substrate. The particles are initially horizontally accelerated by the drag force induced by the high-velocity plasma gases flowing past the particles. Further on in the flight, the gas velocity decreases due to expansion and atmospheric entrainment, thus causing a fall in the drag force and a decreasing velocity of the particle. The magnitude of particle acceleration is qualitatively dependent on particle diameter and mass. The cross-sectional area is a function of diameter squared, but mass depends on the diameter cubed. For instance, consider two particles, one smaller that the other by a factor of half in diameter. The smaller particle is accelerated towards the substrate by a smaller force (1/4 the larger particle force) due to its lower cross-sectional area, which is 1/4 of the larger particle. However, it also possesses lesser inertia because its mass is 1/8 of the larger particle. Therefore, the acceleration of the smaller particle will be greater than the larger particle by as much as twice when subjected to the same in-flight plasma gas velocity. Similarly, under the same condition of decreasing gas velocity, the smaller particles will decelerate more rapidly. Hence the inertia is dominant, which leads to smaller particles being accelerated and decelerated faster compared with the larger particles

The joint effects of initial vertical momentum and inertia cause the lower part of the substrate to be populated by larger particles with slower velocities. Conversely, the upper part of the substrate contains smaller particles with higher velocities. The effect of particle segregation on particle velocity was also reported in Ref 1, where the particle velocity was measured using Phase Doppler Anenometer (PDA).

From Fig. 10(a) to (d), it is noted that the increase of substrate inclination changes the particle average velocity from an inclined profile to a flat profile. At 60° inclination angle, the average velocity has a relatively flat profile throughout the substrate positions. This is due to the increase in local standoff distance between the nozzle exit and the upper part of the substrate. Because of the farther traveling distance to the higher part of the substrate, particles may have reached the peak acceleration and start to decelerate during their transition through the plasma plume. Moreover, the lighter particles do undergo more rapid deceleration and thus have lower velocities. At the lower part, particles are accelerated by the plasma gas before arriving at the substrate. Consequently, they reach higher average velocity.

Figure 11 shows the effect of different inclined substrates on average velocity recorded at the substrate midpoint. The mean velocities of most particles range from 178 to 200 m/s. At the 0° angle, the average velocity, which is 8% lower than the freestream velocity, is the most affected by the substrate. Nevertheless, the velocities for the rest of the inclination angles remain relatively undisturbed by the substrates. This again implies that particles are propelled from the torch with high momentum, which resists deflection by the plasma gas. Despite the different angles the substrate is oriented toward the torch, particles do not change their trajectories, and thus their velocities remain unaffected.

4.3.2 Average Heading of Particles. Particle headings along the substrate locations are shown in Fig. 12(a) to (d). There is a general trend between the particle headings defined by the α angle for freestream condition and with substrate for any inclination angles. With the substrate midpoint being the reference location, particle headings at the upper region for both conditions (freestream and with substrate) increase, while they behave in an opposite manner in the opposite section. This can be supported by the image analysis mentioned previously. Particle flux

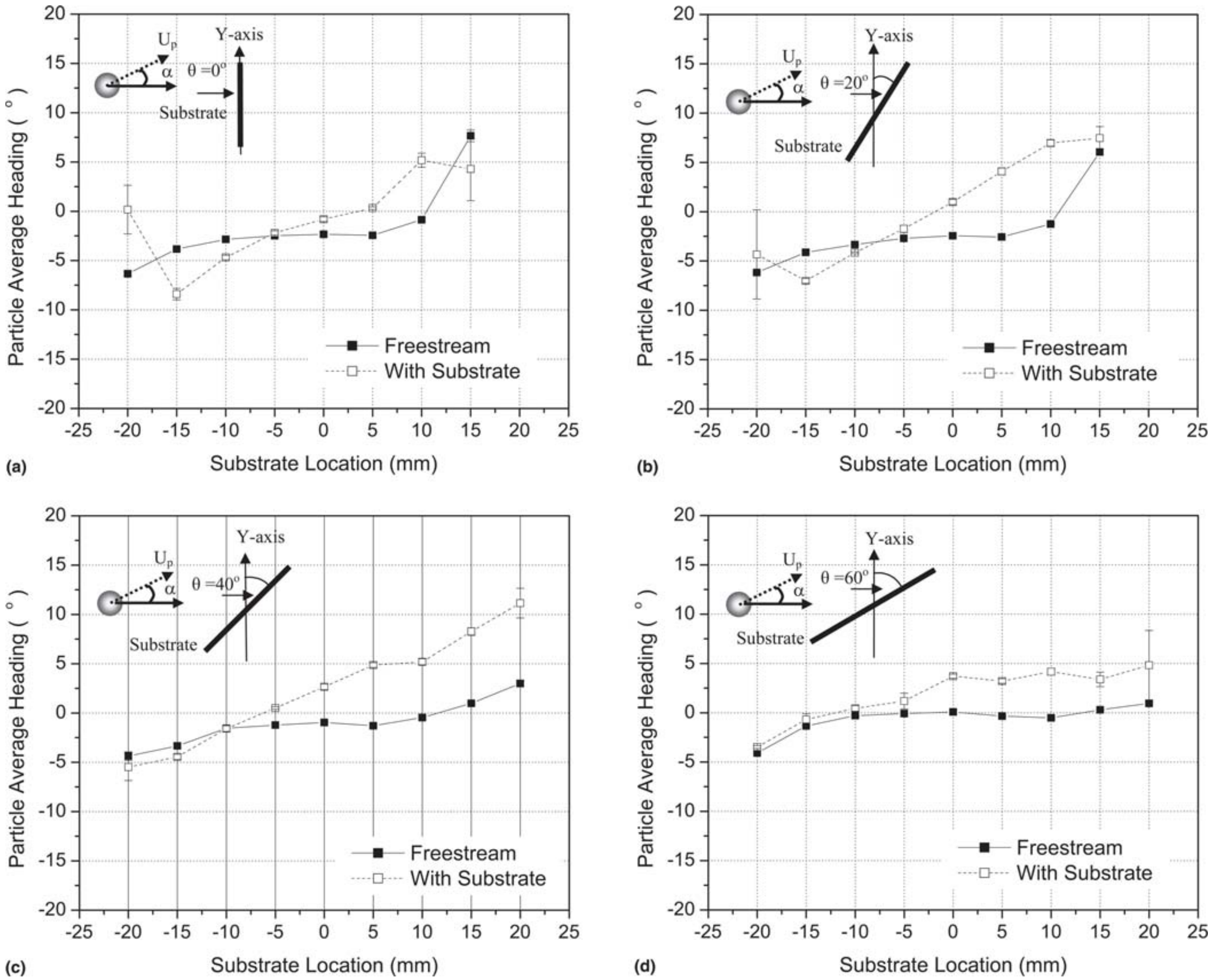

Fig. 12 Particle average headings measured with the presence of (a) 0°, (b) 20°, (c) 40°, and (d) 60° inclined substrates and their corresponding freestream conditions

moving in the upwards direction, i.e., above the horizontal reference will have a positive α angle whereas the downwards particles posses a negative α angle. This is an expected result due to the cone shape of the particle plume.

It is seen from Fig. 12(a) to (d) that particle average headings are slightly increased in the positive α angle directions for all inclination angles. This is due to the aerodynamic ramp effect of the inclined substrate, which deflects more particles to the upper region of the substrate than the lower part. However, the deviation is only between 5 to 10° and can be considered to be insignificant.

The particle average headings α toward the substrate midpoint at various inclination angles are compiled together in Fig. 13. In general, an increase in the substrate inclination angle has diverted the particle heading in a linear relationship. On average, an increment of inclination angle by 1° increases the particle heading by approximately 0.05°. This effect is insignificant as a substrate inclination from 0 to 60° results in only 4.5° change in the particle average heading. It is also noted that there are negative values of particle average headings for freestream and 0° inclination angle, indicating that the particles impact the substrate in a slightly negative α downwards direction. This is attributed to the initial downward momentum of particles when injected through the powder injection port.

4.3.3 Particles Tangential and Normal Velocities. Using the heading data (α) and the substrate inclination (θ), the particle velocity can be resolved into two components; tangential and normal velocities, which are parallel and perpendicular to the substrate, respectively. The tangential velocity component plays an important role in the splat spreading process and the normal velocity component determines the effective bonding of splat to the substrate or underlying splats. A high tangential velocity component tends to elongate the splat into an elliptical shape while an increase in normal velocity leads to high adherence strength between splat and the substrate. In the absence of tangential velocity, the splat tends to be circular in shape. A few

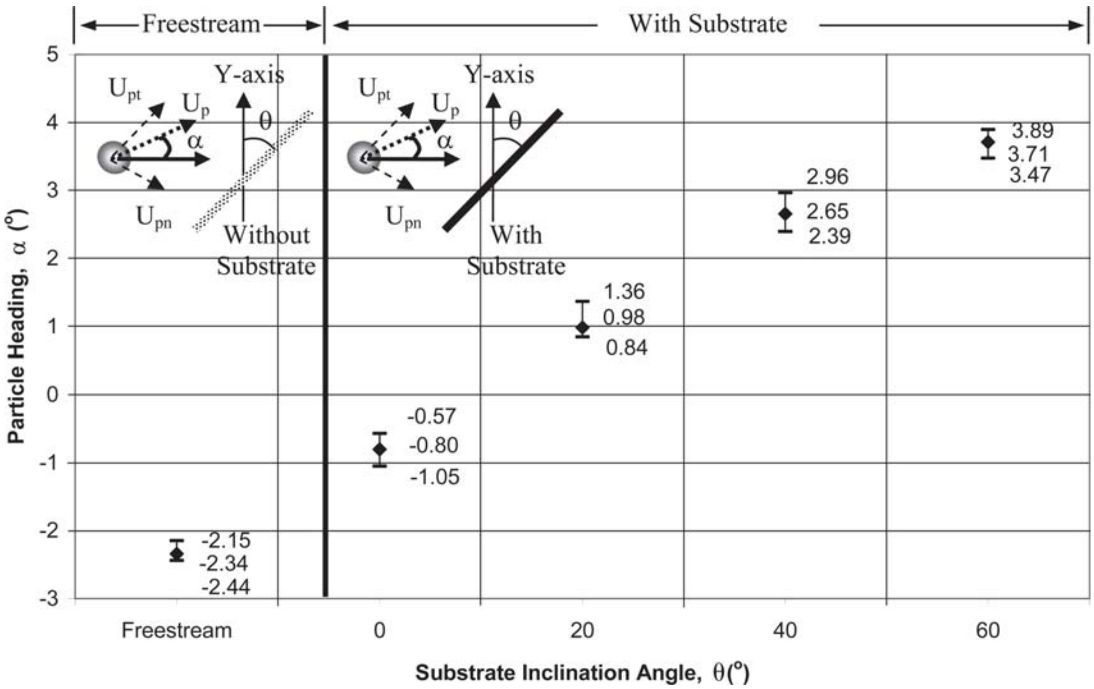

Fig. 13 Impacting particle headings at different substrate inclination angles at substrate midpoint.

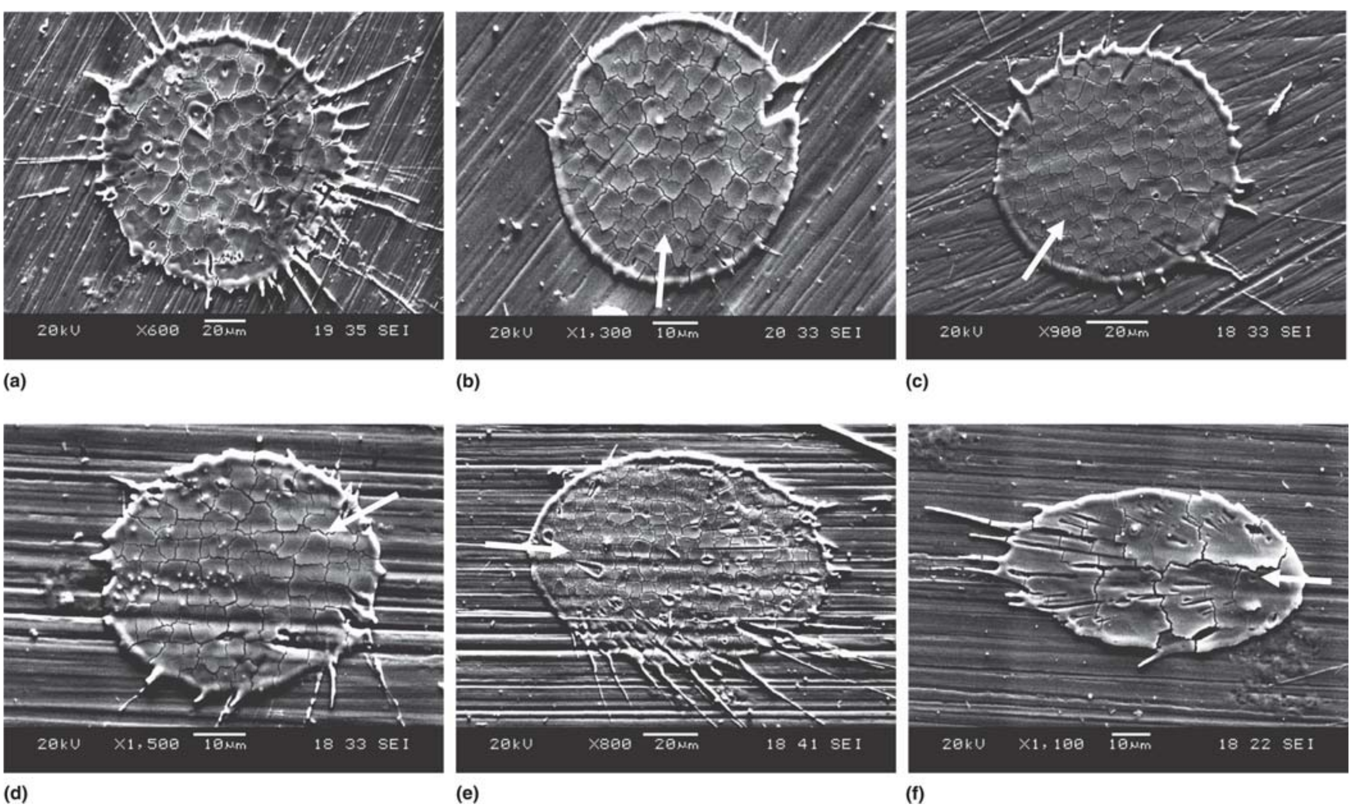

Fig. 14 Some examples of splats obtained from particles impacting at (a) 10°, (b) 20°, (c) 30°, (d) 40°, (e) 50°, and (f) 60° substrate inclinations. White arrows indicate the particle approach direction.

SEM photographs, as shown in Fig. 14, indicate the progressive elongation of splat from circular to elliptical shape as well as a higher tendency of peeling off the splat from the substrate when the substrate inclination angle increases. Therefore, it is necessary to investigate the effect of different substrate inclination on both the velocity components, as this can provide an insight on

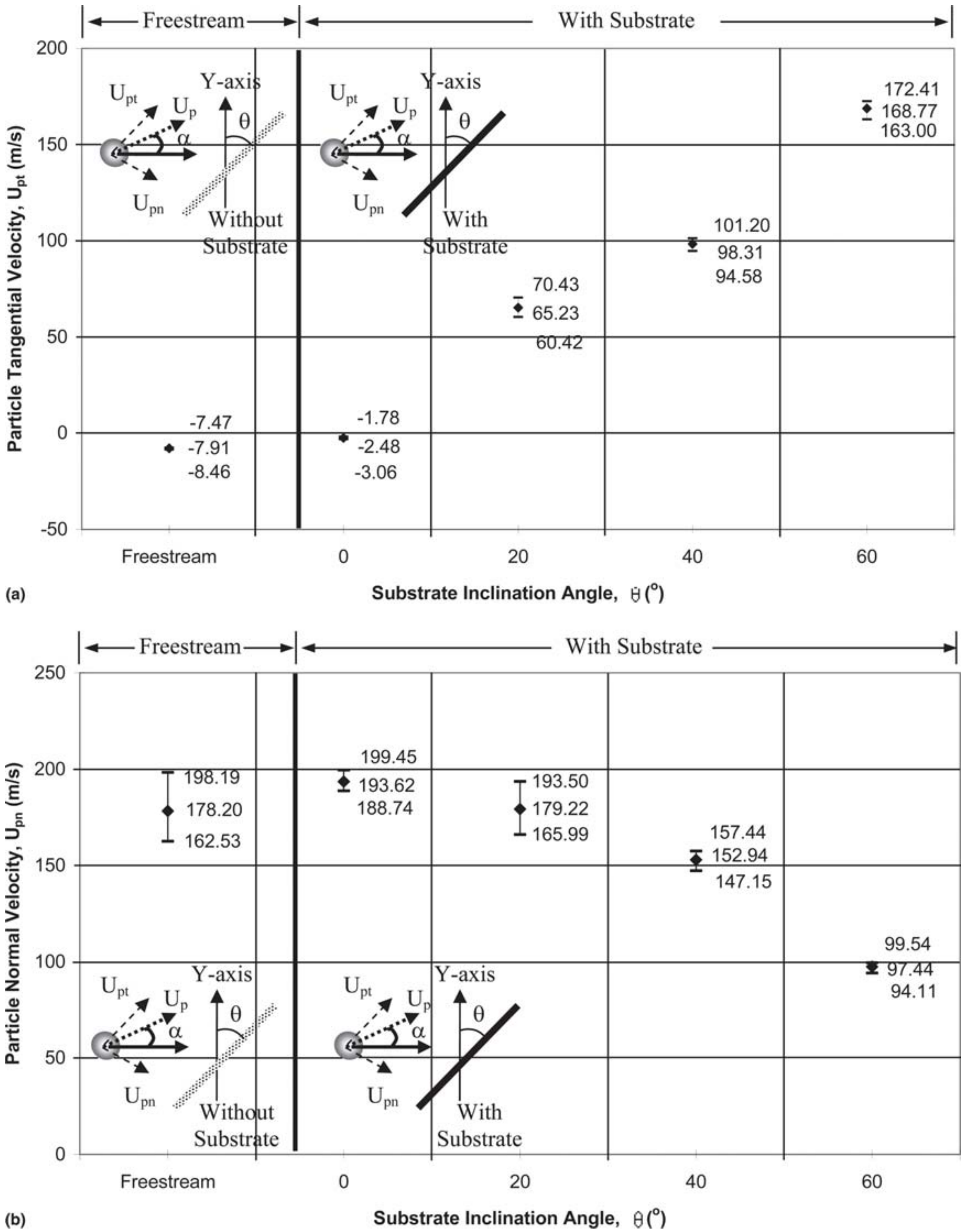

Fig. 15 (a) Particle tangential and (b) normal velocities components at various inclination angles

the changes of splat morphology and coating adherence with respect to substrate inclination.

The tangential and normal velocity components of the detected particle were derived from the average velocity, the particle heading angle α obtained from the measurement system, and the applied inclination angle θ. Because α is small compared with θ, the components are simply functions of the cosine and sine of θ. It is noted from Fig. 15(a) that the particle tangential velocity behaves in a linearly increasing trend as the substrate inclination angle increases. The plot indicates that the tangential velocity starts off at the value of 2 m/s downward at 0° inclination angle and rises until it reaches the maximum of 169 m/s at 60°. In general, the increment of 10° in substrate inclination angle has resulted in the increase of the particle tangential velocity by a maximum of 25%, hence highly sensitive towards the substrate inclination angle.

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In Fig. 15(b), it is expected that the particle normal velocity decreases with the increase of substrate inclination angle. Particle normal velocity (194 m/s) occurs for perpendicular substrate and gradually reduces to 97 m/s at 60° inclined substrate. There is an approximately 25% reduction in particle normal velocity for every increment of 10° in substrate inclination angle.

From Fig. 15(a) and (b), for the perpendicular substrate, the normal velocity component is higher than the tangential velocity component, indicating that the splat is in circular shape with sufficiently good bonding with the substrate. With increase of the substrate inclination, the normal component is reduced in exchange with the tangential component, which promotes splat elongation to an elliptical shape. The reduced normal velocity component results in poorly adhered splats on the substrate. Conversely, the increasing trend of tangential velocity component with respect to substrate inclination angle yields more rebounded particles after impacting, as can be observed in Fig. 8(b) to (e).

5. Conclusions

The in-flight behavior of particles when subjected to aerodynamic disturbance due to substrates at various inclination angles were experimentally investigated by means of SprayWatch CCD imaging diagnostics equipment. A qualitative evaluation of real-time images of the particles close to the substrate surface showed that due to high momentum possessed by the particles, there were negligible changes in their trajectories or headings right before impacting on the substrates despite of the presence of the substrates.

A more detailed quantitative evaluation of particle average velocity and heading data collected by SprayWatch also revealed that in general, particle average velocity behaved similarly regardless of whether the substrate was present. The average heading slightly increased positively for all inclination angles due to the aerodynamic ramp effect of inclined substrates.

For a better understanding of the effect of inclination angles, particle behavior such as velocity, heading, and tangential and normal velocity components at substrate midpoint were compared. Although the particle velocity and heading were negligibly affected, the inclination angle had an apparent significant effect on the particle tangential and normal velocity components due purely to the trigonometric manipulation and not as a result of substrate influence. The increase in the substrate inclination angle by 10° increased the tangential and reduced the normal components, both by approximately 25%. The increased tangential velocity with substrate inclination angle implied higher splat elongation to elliptical shape and large number of particles rebounded off the substrate resulting in reduced deposition efficiency.

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