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The Effect of Water Layer Covering Substrate Surface on the Deformation of the Impacting Particle Deposited by Liquid Cold Spray

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Abstract— Cold spray is a deposition method developed for manufacturing metallic coatings by impacting high-velocity metallic powders on a substrate surface at around room temperature. Because of the low temperature of impacted particles, no oxidation or phase transformations occur during spraying. However, the main limitations of cold spray are associated with considerable gas consumption to accelerate the particles and stringent powder size. To address these issues, liquid cold spray (LCS), as a pioneering technology, has been developed with the potential of utilizing water as the propellant for depositing coarse powders. In terms of producing the coatings, LCS is like conventional cold spray. In both techniques, the severe plastic deformation of the deposited particle and the substrate is the main cause of metallurgical bonding. However, the main difference is related to a thin film of water formed on the top of the substrate while LCS is being used. Thus, this research aims to examine the effect of the thin water layer on particle and substrate deformation by elastic-plastic finite-element modeling. Specifically, the deformation of an impacted 50 µm copper particle on a copper substrate covered with a water layer thickness of 3 and 6 µm was examined by the coupled Eulerian-Lagrangian (CEL) method. The results showed that having a 6 µm water film compared to the situation with no water covering the substrate decreased the particle flattening ratio and equivalent plastic strain of the substrate around 4% and 21%, respectively. This reduction in deformation can be related to the portion of the particle's kinetic energy devoted to passing the particle through the water layer. In the end, it is assumed that the particle velocity increased from 500 m/s to 600 m/s before its impact on a substrate covered with a 6 µm water film. The results illustrated that increasing the kinetic energy of the deposited particle can overcome the negative effect of water film and increase the deformation of the particle, particle flattening ratio, and substrate deformation.

Keywords; Liquid cold spray, cold spray, particle deformation, water layer, particle velocity

I. INTRODUCTION

Cold spray (CS) has been used significantly as a thermal spray or an additive manufacturing technique for producing metallic parts [1-2]. In CS process, metallic particles are deposited using a carrier gas such as nitrogen or helium before impacting the substrate surface [3]. Since the deposited particles impact the substrate surface at a very high velocity and around room temperature, no oxidation and phase transformation occur [4]. However, the main disadvantages of CS are the gas consumption, the need for small particle size, and the high porosity level of additive manufactured samples [4-5]. For reducing gas consumption, in our research center, some attempts have been made to develop a pioneering technology known as liquid cold spray (LCS) for depositing larger metallic particles using a water jet. In LCS process, the solid particle impacts at high velocity on a metallic surface. Hence, the cause of bonding between the deposited particle and the substrate is like conventional CS.

Both the deposited particle and the substrate would deform plastically during the impact, leading to bonding and producing the coatings [6]. To manufacture metallurgical bonding, breaking and ejecting particle and substrate oxide layer is necessary. After particle impacts the substrate, its deformation is higher in a ring-shaped region known as adiabatic shear instability leading to an increase in temperature. This temperature enhancement would activate thermal softening and ease material deformation. As a result, a material jet can be formed to eject the broken oxide layer [7]. Hence, particle and substrate deformation, which play a crucial role in this process, are defined by particle kinetic energy, type of material, substrate surface properties, particle size, and substrate temperature [4, 8]. All noted parameters' effects are summarized in the critical particle velocity definition. Conclusively, particle and substrate must be deformed significantly for producing bonding, which happens when particle velocity is higher than the critical velocity [4, 8].

Besides the advantages of LCS, the existence of the water jet creates a water film on the substrate surface, which might affect the particle critical velocity and particle and substrate deformation. Conclusively, this paper aims to use proper elastic-plastic modeling to understand the effect of water film on particle and substrate deformation while a 50 µm copper particle is impacted on a copper substrate using LCS. Then, the importance of impact velocity would be examined to reduce the possible effect of water film on particle and substrate deformation.

II. Numerical Methodology

A. Elastic and Plastic Modeling

First, it is necessary to introduce the utilized elastic and plastic model to understand the water film effect on particle and substrate deformation in LCS process. Elastic and plastic models are required to study a high strain rate deformation. Hence, for the elastic section, the Mie-Gruneisen equation of state (Eq. 1) and plastic section, Johnson-Cook Modeling (Eq. 2), have been selected. The full description of both noted models are reported in the literature [9-10].

$$P = \frac{\rho_0 c_0^2 \eta}{(1-s\eta)^2} \left(1 - \frac{\Gamma_0}{2}\right) + \Gamma_0 \rho_0 E_m. \quad (1)$$

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + C ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\left(1 - (\frac{T - T_r}{T_m - T_r})^m\right). \quad (2)$$

where, P is total pressure, $\rho_0 c_0^2$ is the elastic modulus at small nominal strains, c_0, s, Γ_0, and ρ_0 represent material constants, E_m is internal energy per unit mass, η (nominal compressive volumetric strain) is equal to $1 - \rho_0/\rho$, and ρ is pressure stress. ε_p, $\dot{\varepsilon}_p$, σ, $\dot{\varepsilon}_0$, T_r, T_m, and T represents equivalent plastic strain, plastic strain rate, flow stress, reference strain rate, reference temperature, melting point, and temperature, respectively. Constants in this model are A, B, C, n, and m [9-10].

B. Finite Element Method

A proper finite-element method such as coupled Eulerian-Lagrangian (CEL) is required to solve the noted models. In this examination, both particle and the substrate are assumed to be Lagrangian, and the water film is an Eulerian part. The initial assembly of the three noted parts is shown in Fig. 1, while a water film with a thickness of 3 µm covers the substrate. Also, a schematic picture of the same condition is represented in Fig. 2, illustrating the used dimension of the particle and substrate. This study has been carried out using ABAQUS/Explicit by considering the used material constants shown in Table 1 [6, 9]. The step has been defined as “Dynamic, Temp-disp, Explicit”, the friction coefficient is 0.3, and the simulation examines the particle and substrate deformation at the first 120 ns after the impact. Particle mesh size is 0.5 µm which falls into an acceptable value compared to the literature [11]. In the end, the mesh type for Lagrangian particle and substrate is C3D8RT (an 8-node thermally-coupled brick, trilinear displacement, temperature, reduced integration, and hourglass control), and for Eulerian water film is EC3D8RT (An 8-node thermally coupled linear Eulerian brick, reduced integration, hourglass control).

In this simulation, a 50 µm copper particle is deposited on a copper substrate. This particle size equals the smallest size of the copper particles used for manufacturing coatings by LCS in our research center. In the first step, three different conditions have been selected to study the water film effect. In all situations, impact velocity equals 500 m/s and particle and substrate temperature are 298 K. The particle velocity has been chosen above the reported value for critical velocity of a 50 µm copper particle in the literature [8]. The difference between the noted conditions is the water layer. First, the convention CS is assumed to be used, which means no water film covers the substrate. Then by using LCS, first, a 3 µm water film covers the substrate surface. In the end, it is assumed that a 6 µm water film is on the top of the substrate surface. It is worth noting that an accurate thickness of the water film will be studied in our ongoing computational fluid dynamic (CFD) research. Then, by assuming a 6 µm water film on top of the substrate, the particle velocity effect has been examined by changing the velocity from 500 m/s to 600 m/s while the initial temperature remains unchanged. All the noted velocities are higher than the critical value for a 50 µm copper particle noted in the literature [8].

TABLE 1. USED MATERIAL CONSTANTS IN THE FINITE-ELEMENT METHOD [6, 9]

Copper		Water	
Property	**Value**	**Property**	**Value**
Thermal Conductivity	386 $W/m.K$	Density	958 kg/m^3
Specific Heat	383 $J/Kg.K$	Speed of Sound	1490 m/s
Density	8930 kg/m^3	Viscousity	1 mPa-s
Shear Modulus	45 GPa	Thermal Conductivity	0.598 $W/m.K$
Melting Point	1356 K	Specific Heat	4.186 $J/g.°C$
Gruneisen's Constant	1.99		
Speed of Sound	3933 m/s		
Hugoniot Slope	1.5		
A	90 MPa		
B	292 MPa		
C	0.025		
m	1.09		
n	0.31		
Reference Strain Rate	1		
Transition Temperature	298		

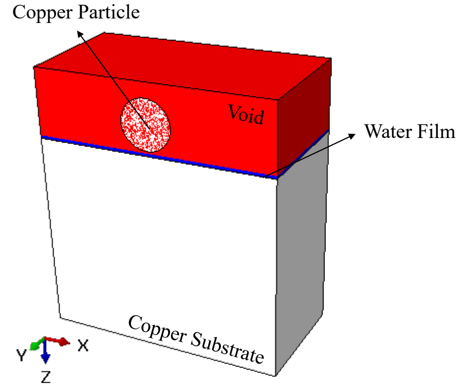

Figure 1. The initial condition of the used finite-element method in this paper.

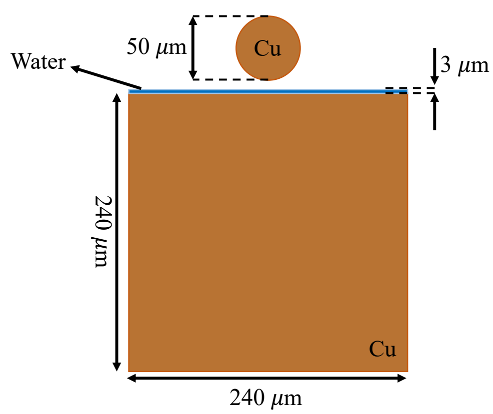

Figure 2. The initial condition examined the water film effect on particle and substrate deformation while a 3 µm water film covers the substrate surface.

C. *Flattening Ratio*

One way to study the particle deformation deposited by CS is the flattening ratio, which can be calculated using Eq. 3 below [12].

$$Flattening\,ratio = 1 - \frac{Deformed\ Height}{Particle\ Diameter}. \tag{3}$$

III. Results and Discussions

A. *Water Film Effect*

This section investigates the water film effect on particle and substrate deformation while a 50 µm copper particle is deposited with conventional CS and LCS. In all cases, particle velocity is 500 m/s and particle and substrate temperature are 298 K. First, it is necessary to examine the water film behavior after 120 ns of the initial impact of the particle on the substrate surface, Fig. 3. This figure shows the impacted particle would disperse the water film. As a result, the ejected water film from the surface would have a higher volume while water film thickness increases. Due to the water film behavior, it can be concluded that particle kinetic energy plays a significant role in passing the particle through the water film. In the three noted conditions, the initial kinetic energy is constant regardless of water thickness since the particle size and initial particle velocity remain unchanged. However, Fig. 4 demonstrates the changes in particle velocity by the passage of time. In all cases, particle velocity decreased because of the transformation of kinetic energy into deformation. However, by having a water film on the substrate surface, particle velocity decreased more, meaning that a portion of particle kinetic energy is devoted to passing the particle through the water film. Also, the significant drop at around 20 ns shows the time that particle and substrate started the deformation process. Thus, as the water film thickness increased, the particle would reach the substrate surface with lower kinetic energy, leading to less particle and substrate deformation, Fig. 5 and Fig. 6.

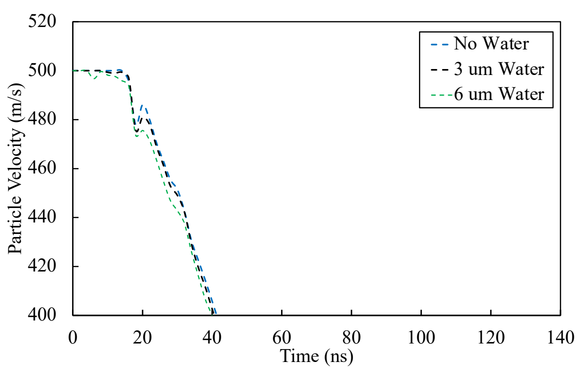

Figure 4. The changes of particle velocity by the passage of time.

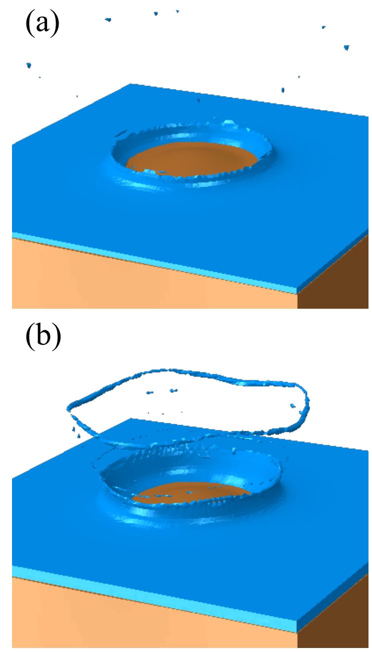

Figure 3. Water film behavior upon the impact of the copper particle by LCS while water film thickness is (a) 3 µm and (b) 6 µm.

Particle and substrate deformation have been examined to profoundly understand the water film effect. Fig. 5 shows that regardless of exiting the water film, both deposited particle and substrate deformed significantly after 120 ns of the impact. However, in Fig. 5, the water layer is cut from the pictures to focus on particle and substrate deformation. By comparing Fig. 5 (a)-(c), it can be understood that having water film and increasing its thickness can reduce the size of the deformed particle. For measuring particle deformation, flattening ratio can be used. When particle impacts on a surface with no water file, Fig. 6(a), the flattening ratio was 0.42. By having the 3 µm and 6 µm water film covering the substrate, the flattening ratio became 0.4 and 0.38, respectively. As noted, particle impacted the substrate surface with less kinetic energy while the substrate was covered with a water film. Thus, particle deformation would be slightly decreased. On the other hand, it is necessary to investigate substrate equivalent plastic strain (PEEQ) and temperature (TEMP) changes by the passage of time to examine the water film effect on substrate deformation. Fig. 6 demonstrates that substrate plastic strain decreased around 21% while a 6 µm water film covered the substrate compared to when no water existed on the substrate surface, meaning a decrease in substrate deformation. Since having a water film covering the substrate surface decreased substrate plastic strain and substrate deformation, less heat would be produced, which means maximum substrate temperature would reduce, Fig. 6. Conclusively, this decrease in particle and substrate deformation by having a water film covering the substrate is because a portion of particle kinetic energy would be devoted to passing the particle through the water film.

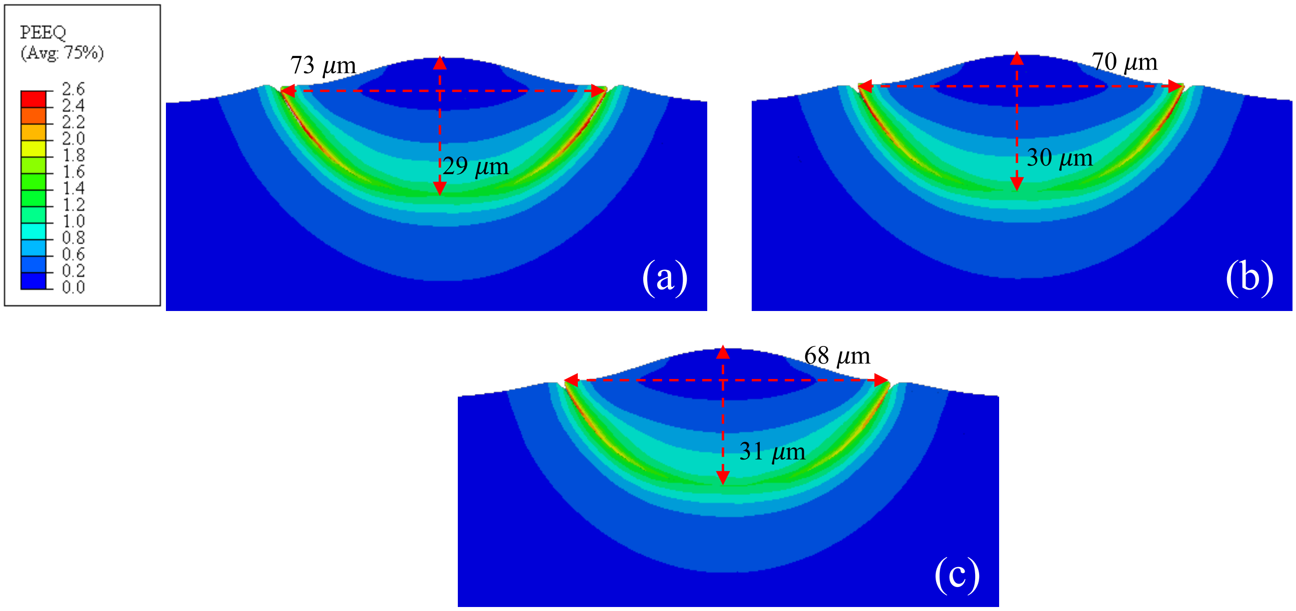

Figure 5. Examine the effect of water film covering the substrate surface on deposited copper particle deformation while the substrate is covered with (a) no water, (b) a 3 µm water film, and (c) a 6 µm water film.

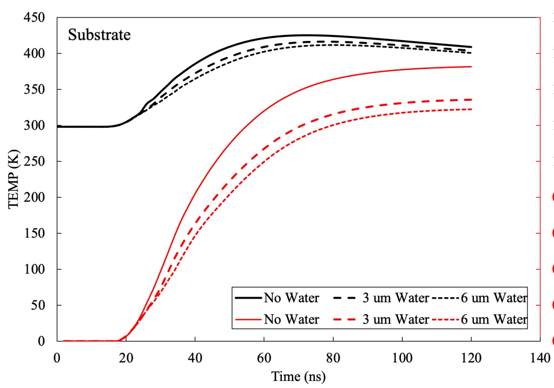

Figure 6. The effect of water film covering the substrate surface on substrate equivalent plastic strain and temperature changes by the passage of time.

B. *Particle Velocity Effect*

To overcome the negative effect of water film, this section assumes that a 50 µm copper particle is deposited using LCS on a copper substrate covered with a 6 µm water film. The temperature of the particle and substrate are 298 K. The particle velocity is assumed to change from 500 to 600 m/s. Fig. 7 illustrates that increasing particle velocity can enhance particle flattening ratio and particle penetration into the substrate. This enhancement in particle deformation can be shown by studying the particle flattening ratio of 0.42, 0.46, and 0.5 when particle velocity is 500, 550, and 600 m/s, respectively. The changes in equivalent plastic strain by the passage of time will be examined later to study substrate deformation. All these enhancements in particle deformation and reaching a higher flattening ratio than the obtained result for conventional cold spray (Fig. 6(a)) are rooted in enhancing the particle kinetic energy by increasing particle velocity upon its impact on the substrate surface. This shows that increasing particle velocity can increase particle deformation while the substrate surface is covered with a 6 µm water film.

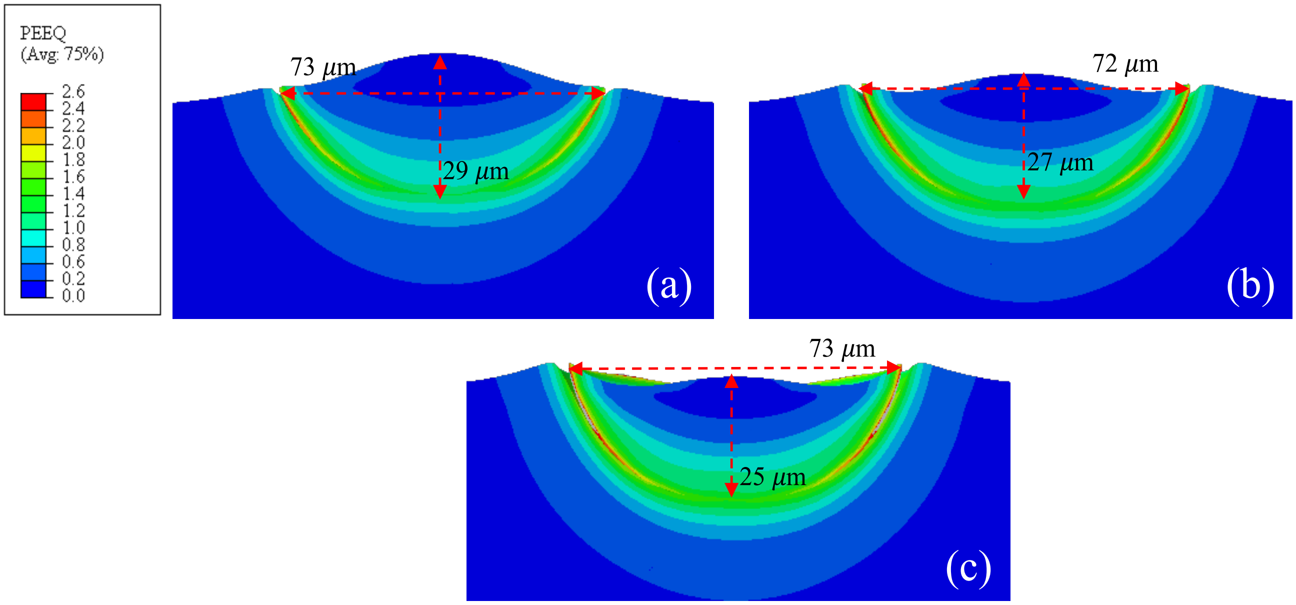

Figure 7. Examine the effect of particle velocity on deposited copper particle deformation after its impact on a copper substrate covered with a 6 µm water film while particle velocity is (a) 500 m/s, (b) 550 m/s, and (c) 600 m/s.

Then, it is necessary to investigate the particle velocity effect on substrate deformation while the copper particle is impacted on a copper substrate covered with water by studying substrate equivalent plastic strain (PEEQ) and temperature (TEMP). Fig. 8 shows that increasing particle velocity and kinetic energy can lead to a higher PEEQ value, which means the substrate has undergone more deformation. For instance, by increasing particle velocity from 500 to 600 m/s, substrate plastic strain rose from 1.2 to 1.6. Also, by having a particle velocity equal to 600 m/s, the substrate deformation becomes more comparing the substrate deformation while the copper particle is deposited using the conventional CS when no water covers the substrate surface. This shows that not only increasing particle velocity can eliminate the water film effect, but it can also increase the deformation even more than the condition with no water film. As a result of having higher deformation by increasing particle velocity, substrate temperature increased, Fig. 9. The maximum temperature is similar when particle impacts at 550 m/s compared to when the particle is deposited at the velocity of 500 m/s using conventional CS. However, by increasing particle velocity up to 600 m/s, maximum substrate temperature rises even more than when no water film covers the substrate due to a higher degree of substrate deformation. This enhancement in temperature is another proof of having higher deformation.

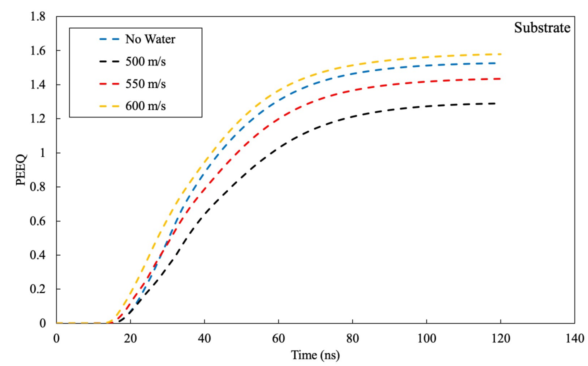

Figure 8. The effect of the particle velocity on the changes of substrate equivalent plastic strain by the passage of time while a copper particle is deposited on a copper substrate surface covered with a 6 µm water film.

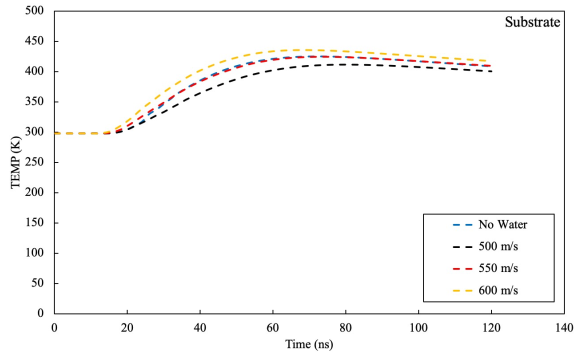

Figure 9. The effect of the particle velocity on the changes of substrate temperature by the passage of time while a copper particle is deposited on a copper substrate surface covered with a 6 µm water film.

To put it into other words, as the particle velocity increases, particle kinetic energy increases at the impact moment that the particle touches the substrate surface. As a result, both the particle and the substrate would go through a higher degree of deformation, leading to eliminating the negative effect of the existing water layer. As it can be seen in both Fig. 7 to Fig. 9, increasing particle velocity to 600 m/s can enhance particle and substrate deformation even more than the time that the copper particle is deposited using conventional CS. However, the primary missing point is the need for examining the possibility of enhancing particle velocity by using LCS experimentally.

IV. Conclusion

One of the main drawbacks of conventional CS is the high level of gas consumption and the impossibility of depositing a larger particle size to increase the deposition rate. A pioneering method known as LCS has been recently developed to address the noted concerns, making it possible to deposit large metallic particles using a water jet. However, the substrate surface is covered with a water film by using LCS due to the existing water jet. Hence, this paper aims to utilize a proper modeling method for studying water film effects on particle and substrate deformation. Then, this paper investigates the potential of particle velocity on eliminating the water film effect. Finally, the main conclusions of the noted study are listed below.

1. A partial part of particle kinetic energy would be devoted to passing the particle through the water film, which leads to an impact with the less initial required energy for the deformation.
2. A 6 µm water film would decrease particle flattening ratio by around 4%, meaning a decrease in particle deformation compared to when no water covers the substrate. Also, increasing particle velocity upon the impact on a substrate covered with a 6 µm water film would increase particle flattening ratio by around 16%, meaning an increase in particle deformation.
3. By comparing the substrate deformation between the conditions with no water film and a 6 µm water film covering the substrate, it was clear that substrate plastic strain decreased around 21%, meaning a decrease in substrate deformation. However, substrate deformation increased significantly by providing more kinetic energy and increasing particle velocity.

V. Proposed Future Work

After examining the potential of water film on particle and substrate deformation, experimental investigation can validate the obtained results by studying single splat deformation deposited by LCS. Furthermore, in terms of simulation, an estimation of the thickness of the water film could be achieved by using a proper CFD examination. Also, to make the investigation condition closer to the experiment, consider the water layer around the deposited particle.

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