Effect of HVOF particle deposition angle on particle deposition behaviour

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ABSTRACT. Power particles are mainly in solid state prior to impact on substrates from high velocity oxy-fuel (HVOF) thermal spraying. The combination state of particles and substrate significantly affects the coating quality. Finite element analysis (FEA) models are developed to simulate the impingement process of solid particle impact on substrates under different deposition angles. This numerical study analyzes the deformation behavior of particles and the reason under different deposition angles, and the shear-instability– based method is applied to the particles. The particles are given the properties of widely used WC-Co powder for HVOF thermally sprayed coatings. The numerical results confirm that in the case of vertical deposition, the deposition behavior of particles is better than that of non-vertical deposition. In the case of non-vertical deposition, the equivalent plastic strain of the right part of the particle central axis is larger than that of the left part of the central axis, and decreases gradually in a clockwise direction. The flattening process of particles is mainly controlled by the horizontal drag force. When the normal velocity of particles exceeds the critical deposition velocity, the particles will appear adiabatic shear instability phenomenon, with the matrix to produce an effective combination.

1. Foreword
As one of the surface treatment and protection technologies, HVOF has the advantages of high kinetic energy and low thermal energy output[1]. The prepared coating has the characteristics of high density, high bonding strength and less decarburization and oxidation. Therefore, HVOF spray is widely used in the fields of ship, paper, metallurgy, automobile and military industry[2]. The results show that the process of coating formation is essentially the process of particle flattening and stacking deposition. Therefore, it is of great significance to study the deposition behavior of single particle for improving the coating structure and enhancing the coating strength.

For the deposition deformation behavior of a single particle, G u s et al[1] conducted numerical simulation research for the deformation behavior of spray particles under different particle speed, temperature and shape. The results showed that the critical deposition speed is required for the successful bonding of particles and substrate, and the particles below the critical speed will rebound, peel off and compact the substrate. At the same time, increasing the particle velocity temperature can promote the temperature rise of particle flattening and particle substrate interface, and the non-spherical particles have higher critical deposition velocity than the spherical particles. On the basis of the research results in literature 1, Kamnis s et al[3]. discussed the deposition behavior of particles with different porosity on the substrate. The results showed that in a certain range, the
increase of the porosity of particles will promote the flattening deformation of particles, and the pores in particles will gradually change to the linear shape in the flattening process. Therefore, to increase the porosity of particles in a certain range can not only promote the momentum exchange of particles in the gas flame, but also increase the flattening degree of particles, and obtain the coating with excellent quality. Fan Chao Meng[4] and other researchers used the combination of numerical simulation and experimental characterization to explore the deposition deformation behavior of particles on the substrate and the deposition efficiency of particles under the cold spraying process. The research contents include the deposition mechanism of particles under different particle/substrate combinations and the relationship between deposition efficiency and particle velocity, which are in good agreement with the measured data.

The current research focuses on the influence of particle velocity, temperature, particle and substrate types on particle deposition behavior. In the actual spraying operation, due to the diversity of the surface structure, the angle between the spray gun and the substrate is not vertical, and the deposition angle of particles on the substrate may not be vertical. Therefore, in this paper, under the same deposition speed and different deposition angle, the deposition deformation behavior of particles on the substrate is simulated, and the influence of deposition angle on the formation of coating and the occurrence of adiabatic shear instability are discussed.

2. Finite element mode
The particle flight measurement experiment[5,6]and numerical simulation results[7-9]showed that the particle velocity of HVOF spraying can reach 300-800m/s, the particle temperature can reach 800-1500K, and the particle has the characteristics of high kinetic energy and low temperature, which can effectively protect the materials easy to oxidize and decompose. WC-12Co is widely used for surface strengthening and repair of mechanical parts due to its high melting point, high hardness and strong corrosion resistance[10]. 45# carbon steel is widely used in transportation, machinery manufacturing, national defense and military industry[11] for its high hardness and high strength, but the friction and vibration during the use process will aggravate the wear failure of 45# carbon steel. The preparation of WC-12Co wear-resistant coating on 45# carbon steel surface can effectively protect 45# carbon steel and extend its service life. Therefore, this paper uses LS-DYNA software to model and analyze the deposition deformation behavior of WC-12Co particles on 45# carbon steel at different deposition angles. In the calculation process, the transformation of strain strengthening, temperature rising melting, friction, plastic work and heat energy are considered.

Figure 1. Morphology of spray particles

2.1 Simulation model
Figure 1 shows the microstructure of Metco-WOKA-3102 series WC-12Co spray powder with good wear resistance[12], which is used in the HVOF spraying experiment. Its shape is nearly spherical and has good fluidity. The particle size distribution range of the powder is 15-45μm. According to the geometric parameters of the particles and the substrate, the two-dimensional finite element impact model of WC-12Co particles and 45# carbon steel substrate is constructed as shown in figure 2. The
particle diameter of WC-12Co is taken as the average value of particle size distribution as 30μm. The length and width of carbon steel substrate are 6 times of particle diameter, and the relatively large substrate size distribution can effectively avoid the influence of substrate boundary nodes on the central deformation area[13]. Due to the non-vertical deposition of particles, the two-dimensional finite element model does not have the condition of axisymmetric simplification.

In the process of spray particle deposition, the bonding time between particles and substrate is very short, taking ns as the measurement unit, and the heat conduction distance between particles and substrate is far smaller than the characteristic unit size of both[14]. Therefore, the heat transfer between particles and substrate can be ignored, in the other word, the heat insulation between particles and substrate is considered[15,16]. The hypothesis can be characterized by dimensionless parameters \( \frac{x^2}{D \cdot t} \) to prove its validity. The meaning of each parameter in the formula is as follows, \( x \) is the characteristic dimension of system unit, which equal to 3×10^{-5}m here, \( D \) is thermal diffusivity of the material, which equal to 2×10^{-6}-15×10^{-6} m^2/s here, \( t \) is time required for particle deposition, which is less than 100ns here.

When \( \frac{x^2}{D \cdot t} \) more than 1, the process is adiabatic. Conservative calculation of the dimensionless parameter value is 600, which is far greater than 1. The assumption that the particle deposition process is adiabatic is true. Therefore, the heat conduction equation of particles and substrate can be simplified as follows[17]:

\[
\rho c_p \frac{dT}{dt} = \beta \sigma \epsilon
\]

Because the mesh size has a great influence on the temperature rise and adiabatic shear flow of particles[18], the mesh refinement is carried out for the expected combination area of particles and substrate, and the mesh coarsening is carried out for the edge calculation area, which can ensure the calculation accuracy and reduce the calculation cost. In the process of mesh generation, the mesh size of the area where particles directly contact with the substrate is 0.5μm, and the mesh size of the edge area is 1.0μm. For the two-dimensional finite element impact model shown in figure 2, the non-reflective boundary condition is applied to the side of the substrate, and the rest of the surfaces are set to free state. The particle to substrate contact algorithm adopts Auto-2-D(ASS-2D) contact algorithm. In addition, the nodes of predicted maximum plastic deformation and their symmetrical nodes are set as monitor points to compare the deposition behavior of particles at different positions.

![Figure 2. Two dimensional finite element impact model](image)

2.2 Material model

In the calculation process, linear elastic model is used to describe the elastic response of WC-12Co particles and 45# carbon steel substrate, and Johnson cook plastic model is used to describe the plastic response. The model comprehensively considers the strain strengthening, temperature rise melting,
friction heat generation, transformation between plastic work and thermal energy in the process of particle deposition. The specific expression of Johnson–Cook plastic model\cite{19} is as follows:

$$\tau = \left[A + B\left(\varepsilon_p^\prime\right)^n\right]\left(1 + C\ln\dot{\varepsilon}^\prime\right)\left[1 - (T^\prime)^m\right]$$ \hspace{1cm} (2)

$$\dot{\varepsilon}^\prime = \frac{\dot{\varepsilon}_0}{\dot{\varepsilon}_0^\prime}$$ \hspace{1cm} (3)

$$T^\prime = \frac{T - T_r}{T_m - T_r}$$ \hspace{1cm} (4)

$\tau$ indicates the yield stress of material, $\varepsilon_p$ indicates the equivalent plastic strain of material, $\dot{\varepsilon}$ indicates the equivalent plastic strain rate of material, $T$ indicates the temperature of material, $T_r$ indicates the reference temperature of material, $T_m$ indicates the melting temperature of material, $A$ indicates the static yield strength, and $B$ is the strain hardening modulus, $C$ indicates the strain rate hardening modulus, $m$ represents temperature softening index, $n$ represents strain hardening index.

The first term of the expression $\left[A + B\left(\varepsilon_p^\prime\right)^n\right]$ represents the function relationship between material stress and strain in isothermal state; the second term $\left(1 + C\ln\dot{\varepsilon}^\prime\right)$ and third term $\left[1 - (T^\prime)^m\right]$ of the expression respectively represent the effect of material strain rate and material temperature on material yield stress.

The material properties of WC-12Co particles and 45\textsuperscript{th} carbon steel substrate are shown in Table 1.

| Material parameters   | WC-12Co | 45\textsuperscript{th} Steel |
|-----------------------|---------|-----------------------------|
| Density (g/cm\textsuperscript{3}) | 14.44   | 7.83                        |
| Young’s modulus (GPa)  | 650     | 210                         |
| Shear modulus (GPa)    | 256     | 83.33                       |
| Poisson’s ratio        | 0.27    | 0.26                        |
| Static yield strength (GPa) | 1.55   | 0.507                       |
| Strain hardening modulus (GPa) | 2.2     | 0.32                        |
| Strain rate hardening modulus | 0.031   | 0.28                        |
| Thermal softening index | 1.34   | 1.06                        |
| Strain rate hardening index | 0.45   | 0.064                       |
| Reference temperature (K) | 298    | 298                         |
| Melting temperature (K)  | 1680   | 1495                        |
| Heat capacity (J/kg·K) | 292    | 460                         |

3. Results and discussion

3.1 Dynamic deformation behavior of spray particle deposition

The deposition angle of particles $\theta$ is defined as the angle between the initial velocity of particles and the surface of substrate. In the calculation process, the deposition angle of particles is divided into
four cases, \( \theta = 30^\circ, 45^\circ, 60^\circ, 90^\circ \). Due to the adiabatic process of particle deposition, the temperature rise of particles and substrate is due to the transformation of plastic work and friction heat generation. For the energy flow in the process of particle deposition, there is the following relationship:

\[
E_{ke} = E_{kep} + E_{kes} = U_p + U_s + T_p + T_s
\]

(5)

\( E_{ke} \) is the initial kinetic energy of particles, \( E_{kep} \) is the internal energy of particles, \( E_{kes} \) is the internal energy of substrate, \( U_p \) is the elastic potential energy of particles, \( U_s \) is the elastic potential energy of particles, \( T_p \) is the temperature rise of particles, \( T_s \) is the temperature rise of substrate.

Figure 3 shows the deposition results of spherical particles with initial velocity \( V_p = 800 \text{m/s} \) and initial temperature \( T_p = 800 \text{K} \) at different deposition angles. Figure 3a is a schematic diagram of ideal vertical deposition effect. There is a certain degree of metal jet at the edge of particles and substrate, which can effectively increase the contact area between particles and substrate, and the combination of the two is dense, without obvious pores. Define the depth of the substrate crater as

\[
H = H_s - H_w
\]

(6)

Where \( H \) is the depth of the substrate deposition crater, \( H_s \) is the height of the substrate surface, \( H_w \) is the deepest height of the substrate deposition crater, and the particle flattening rate is defined as

\[
\eta = \frac{D_s - D_w}{D_s}
\]

(7)

\( D_i \) is the initial height of the particle, also is the particle diameter, \( D_s \) is the height after the particle deformation. According to the analysis of the broken line chart of the depth and flattening rate of the substrate deposition crater under different deposition angles in figure 4, with the decrease of the deposition angle of the particles, the deposition effect of the particles gradually deteriorates, and the depth and flattening rate of the substrate deposition crater gradually decreases. When \( \theta = 90^\circ \), the depth and flattening ratio of the substrate deposition crater are 6.50 \( \mu \text{m} \) and 0.49 respectively, and when \( \theta = 30^\circ \), the corresponding values are 2.13 \( \mu \text{m} \) and 0.32 respectively. In addition, the particle metal jet also disappears gradually, and the particle has obvious horizontal slip on the substrate, which leads to obvious gap on the interface of the two, reducing the bonding strength of the two.

![Diagram](image-url)
Figure 3. Schematic diagram of particle deposition behavior at different incident angles

Figure 4. Line chart of substrate crater depth and particle flattening rate under different angles

Figure 5 shows the equivalent plastic strain curve of particle monitor point under the condition of vertical deposition and non-vertical deposition. In the case of vertical deposition, the plastic deformation occurs first at the central axis of particles, and then moves upward. The change of the equivalent plastic strain at the symmetrical monitor point is the same. The equivalent plastic strain amplitude and the equivalent plastic strain rate at the particle edge (monitor 4 and 5) are larger than those at the particle central axis (monitor 1). In the case of non-vertical deposition, there are obvious differences in the change of the equivalent plastic strain at the symmetrical monitor point of particles. The farther away the symmetrical monitor point is from the central axis of particles, the greater the difference of the equivalent plastic strain is. The furthest distance between the monitor point 3 and the monitor point 5 is about the central axis, and the maximum difference of the two is 2.30. In addition, the equivalent plastic strain on the right side of the central axis (positive direction of horizontal velocity) is larger than that on the left side of the central axis (negative direction of horizontal velocity), and decreases gradually in a clockwise direction.
The reason is that the force applied to the particles in the process of deformation includes the vertical compressive stress and the horizontal drag stress. It can be obtained by observing the horizontal drag stress and the vertical compressive stress change curve at different monitor points in figure 6. With the advance of the deposition process, the vertical compressive stress rate of the monitor point on the left side of the central axis first decays and disappears, and the particles are mainly affected by the horizontal drag stress in the later stage of deposition. The maximum horizontal drag stress was found in monitor point 5 and the minimum in monitor point 3.

Therefore, the deposition effect of particles in vertical deposition is better than that in non-vertical deposition. In non-vertical deposition, the equivalent plastic strain on the right side of the particle's central axis is larger than that on the left side of the central axis, and decreases gradually in a clockwise direction.

3.2 Effect of deposition angle on yield stress/equivalent plastic strain of particles

This section will focus on the effect of deposition angle on yield stress and equivalent plastic strain of particles. The initial velocity of particles $V_0$ is 800m/s, the initial temperature $T_0$ is 800K, and the expected maximum plastic deformation monitor 5 is selected as the monitor point to represent the dynamic behavior of the whole particle.

Figure 7 shows the change curve of yield stress at the monitor point under different deposition angles. In the case of non-vertical deposition, the change trend of yield stress at the monitor point is similarly same. When $\theta = 30^\circ$, $45^\circ$, $90^\circ$, the peak value of yield stress at the monitor point is approximately the same, when $\theta = 90^\circ$, the peak value of yield stress is 28Mpa, when $\theta = 30^\circ$, the peak value of yield stress is 28.9mpa, the peak value of yield stress in the case that $\theta = 60^\circ$ is significantly higher than the other three cases. When $\theta = 90^\circ$, the stable value of yield stress at the monitor point decreases to 0.
Figure 8 shows the change curve of equivalent plastic strain at the monitor point under different deposition angles. With the increase of deposition angles, the equivalent plastic strain at the monitor point shows an overall upward trend. When the deposition is not vertical, the trend of equivalent plastic strain at the monitor point is the same. When $\theta = 45^\circ$, the peak value of equivalent plastic strain of particles is the largest, which is 2.68, and when $\theta = 30^\circ$, which is the smallest, equal to 2.33. The peak value of equivalent plastic strain at $\theta = 60^\circ$ is between the two. In the case of vertical deposition, the peak value of the equivalent plastic strain at the monitor point is 2.99, and the equivalent plastic strain curve has a "secondary growth".

The reason is that although the particles have large kinetic energy at $\theta = 60^\circ$, the peak value and stationary value of the yield stress at the monitor point are much higher than those in the other two cases, resulting in the lower equivalent plastic strain at the monitor point at $\theta = 60^\circ$. In addition, when the particles are deposited vertically, the temperature of the particles reaches the melting point (1640K), and the deformation mechanism of the particles changes from plastic deformation to viscous deformation, which makes the yield stress of the monitor point decrease to 0, and then leads to the "secondary growth" of the equivalent plastic strain of the monitor point.

In the process of solid particle deposition, adiabatic shear instability is an important indicator to measure the effective combination of particles and substrate[20-22]. When the normal velocity of particles is greater than the critical deposition velocity, that is $V_r \sin \theta > V'_r$, $V_r$ is the normal velocity of particles and $\theta$ is the deposition angle of particle[23-25]. In the process of deposition, the particles will produce suddenly increase of strain and yield, and then generate adiabatic instability jet, increasing the contact area between particles and substrate. From the observation of figure 8, it can be seen that the minimum value of the normal velocity component of the particles is $v_{min} = 400\text{m/s}$, and the equivalent plastic strain curve of the monitor point has a sudden increase, indicating that the normal velocity component of the particles is greater than the critical deposition speed, in the other word, when the initial temperature of the particles is 800K, the critical deposition speed of WC-12Co particles is less than 400m/s, which is consistent with the critical deposition speed calculated in literature 1.

Therefore, the change trend of equivalent plastic deformation degree and yield stress of particles under vertical deposition is better than that under non-vertical deposition. With the decrease of yield stress to 0, the equivalent plastic deformation of particles will appear "secondary growth"; when the normal velocity of particles exceeds the critical deposition velocity, the particles will appear adiabatic shear instability, generate adiabatic shear jet, and the initial temperature of particles $T_r = 800\text{K}$, the critical deposition rate of WC-12Co particles is less than 400m/s. In the actual spraying operation, vertical deposition should be selected as much as possible. When the non-vertical deposition occurs, the deposition angle $\theta = 45^\circ$ can be selected for spraying operation.
3.3 Effect of deposition angle on particle temperature

The influence of deposition angle on yield stress and equivalent plastic deformation of particles is described. In this section, the influence of particle deposition angle on particle temperature will be discussed. The initial boundary conditions and monitoring points are the same as those in the previous section.

Figure 9 shows the temperature change curve of the monitor point under different deposition angles. The temperature change trend of the monitor point under the four deposition angles is the same. When $\theta = 90^\circ$ (vertical deposition), the maximum temperature of the monitor point is 1652K, exceeding the melting point of 1640K, when $\theta = 60^\circ$, the minimum temperature of the monitor point is 1110K, when $\theta = 45^\circ$, it is between the two, it is 1605K. It can be seen from Fig. 8 and Fig. 9 that the equivalent effect of particles at $\theta = 60^\circ$ is higher than that at $\theta = 30^\circ$, but the temperature at the particle monitor point at $\theta = 60^\circ$ is lower than that at $\theta = 30^\circ$.

Because the temperature rise of particles comes from two parts: plastic deformation and friction heat generation. The friction heat generation at $\theta = 30^\circ$ effectively compensates for the plastic deformation heat generation, resulting in the temperature rise of particles at $\theta = 30^\circ$ being higher than that at $\theta = 60^\circ$. Therefore, the temperature rise of particles in the vertical deposition is higher than that in the non-vertical deposition; when spraying in the non-vertical deposition angle, considering the friction heat generation between particles and substrate, the surface roughness of substrate can be increased appropriately to promote the temperature rise and flattening deformation of particles.

4. Conclusion

In this paper, the linear elastic constitutive model and Johnson-Cook plastic model are used to analyze the influence of particle deposition angle on the deposition behavior of WC-12Co particles on 45\textdegree carbon steel substrate. The deposition behavior of particles on the substrate under the same particle velocity, the same particle temperature and different deposition conditions is compared and analyzed. The following conclusions are obtained:

1) The deposition angle of particles can be divided into 30\degree, 45\degree, 60\degree, 90\degree (vertical deposition). With the decrease of deposition angle, the deposition effect of particles on the substrate gradually deteriorates, and the flattening rate of particles and the depth of substrate deposition crater gradually decrease. When $\theta = 30^\circ$, the flattening rate of particles and the depth of substrate deposition crater are 0.32 and 2.13\micron respectively, the corresponding value is 0.49 and 6.50\micron respectively at $\theta = 90^\circ$; when the particles are not deposited vertically, the equivalent plastic strain on the right side of the central axis is larger than that on the left side of the central axis, and decreases gradually in a clockwise direction.

2) The change trend of equivalent plastic deformation and yield stress of particles under vertical deposition is better than that under non-vertical deposition. When $\theta = 30^\circ$, the peak values of equivalent plastic strain and yield stress of particles are 2.99 and 28Mpa respectively, and when $\theta =
90°, the corresponding value is 2.33 and 28.9mpa respectively. With the decrease of yield stress to 0, the equivalent plastic deformation of particles will appear "secondary growth".

3) When the normal velocity of the particles exceeds the critical deposition velocity, the adiabatic shear instability will occur and the adiabatic shear jet will be generated. When the initial temperature of the particles is 800K, the critical deposition velocity of WC-12Co particles is less than 400m/s.

4) In the case of vertical deposition, the temperature rise of particles is higher than that of non-vertical deposition. In the case of vertical deposition, the temperature rise of particles is 1652K. In the case of non-vertical deposition, $\theta = 45^\circ$ corresponds to the highest temperature rise, which is 1605K. When spraying in the non-vertical deposition angle, considering the friction heat generation between particles and substrate, the surface roughness of substrate can be increased appropriately to promote the temperature rise and flattening deformation of particles.

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