NUMERICAL SIMULATION ON DEPOSITION PHENOMENA OF IMPACT PARTICLE IN COLD SPRAYING PROCESS

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Abstract. Cold spraying is a new coating technique that makes a thin layer on the solid surface of various mechanical components using tiny material particles. Differing from the conventional thermal spraying methods, there are some advantages for example, oxidation and thermal deformation of the target substrate is unlikely to occur. While the fundamental researches and applications of a cold spraying have been carried out, deposition phenomena in cold spray has not been fully clarified yet. In this paper, numerical simulations on the first step of the film forming process are conducted by a MPS (Moving Particle Semi-implicit) method. Thereby, the numerical result of the height of the particle deposition is well accord with the experiment. The characteristic phenomena is reasonably reproduced. That is, an impinging particle whose speed is lower than the critical velocity rebounds from the substrate, meanwhile, an impinging particle whose speed is higher than the critical velocity adheres on the substrate.

1 INTRODUCTION

Cold spraying is a new coating technique that makes a thin layer on the solid surface of various mechanical components using tiny material particles. These particles are accelerated by pre-heated supersonic gas such as helium or nitrogen, then they impact and accumulate on the target surface. The temperature of supersonic gas used in cold spray is relatively low than conventional thermal spraying methods such as flame spraying and plasma spraying. Differing from these conventional methods, the deposition process of cold spraying relies purely on the kinetic energy rather than the combination of thermal and kinetic energies of spray particles. Therefore, there are some advantages that oxidation and thermal deformation of the target substrate is unlikely to occur, and a dense film can easily be formed.

However, deposition phenomena in cold spray has not been fully clarified yet. Schmidt et al. [1] indicated the relation between particle temperature and velocity in a cold spray process. According to this study, the particle speed has to exceed the critical velocity. The critical velocities vary considerably with the target substance and its temperature. A multistep process has also been suggested by Steenkiste et al. [2]; (1) substrate cratering and first-layer build-up,

(2) particle deformation and realignment, (3) metallurgical bonding and void reduction, and (4) bulk deformation. The first step of this process is very important for forming a film by cold spray technique, because it determines the guality of coating film.

The deposition process of the particle impingement in a cold spray is completed within a few tens of nanoseconds, so the observation of this process is too hard to achieve. Moreover, expensive operation gas is needed to perform such experiments. Therefore, it is expected, by using numerical simulations, these problems can be solved, and the detail of deposition process in various conditions can also be observed. The observation of the process was conducted by the numerical simulation by means of coventional grid-base methods like FEM (Finite Elemet Method)[3]. However, there are hard problems that come from mesh regeneration by using the grid-base methods. While, in the case of particle dispersion, the particle method has a further advantage over conventional grid-base methods, that is, it does not need any mesh.

In this paper, numerical simulations on the first step of the film forming process is conducted by a MPS (Moving Particle Semi-implicit) method, and the deposition phenomena of an impinging particle in cold spray process is reproduced. This numerical method is validated by comparing the computational results with the experiment result in the shapes of the particle deposition. Next, by using this simulation method, we observe the deformation behavior of an impinging particle on a substrate which is consisted of titanium.

2 NUMERICAL PROCEDURES

The present numerical procedures are based on the particle method proposed by Chikazawa et al. [4]. The method is proposed for thick elastic structures based on the concept of MPS (Moving Particle Semi-implicit) method which provides particle interaction models for differential operators.

2.1 Elastic modeling

Governing equation for two-dimensional isotropic elastic structure is followed as :

$$\rho \frac{Dv_\alpha}{Dt} = \frac{\partial}{\partial x_\beta}\left[\lambda \varepsilon_{\gamma\gamma}\delta_{\alpha\beta} + 2\mu\varepsilon_{\alpha\beta}\right] \tag{1}$$

where v_α is the velocity vector, t is the time, ρ is the density, x_β is coordinate, $\delta_{\alpha\beta}$ is Kronecker delta, $\varepsilon_{\gamma\gamma}$ is the volumetric strain, and $\varepsilon_{\alpha\beta}$ is strain tensor, respectively. λ and μ are constants that are expressed by :

$$\lambda = \frac{\nu E}{(1+\nu)(1-\nu)} \tag{2}$$

$$\mu = \frac{E}{2(1+\nu)} \tag{3}$$

where E is Young's modulus and ν is Poisson's ratio.

In the MPS method, each particle interacts with its neighboring particles using a weighting function such as the following equation.

$$w_{ij} = \begin{cases} \frac{r_e}{|\mathbf{r}_{ij}|} - 1 & |\mathbf{r}_{ij}| < r_e \\ 0 & |\mathbf{r}_{ij}| \geq r_e \end{cases} \tag{4}$$

where $\mathbf{r}_{ij}$ is a position vector from particle i to j, and r_e is the radius of weighting function. The interaction area is limited by r_e. The particle number density at particle i is defined as :

$$n_i = \sum_j w_{ij} \tag{5}$$

The particle number density is constant at inside particles if the configuration of particles is uniform. This constant value is denoted by n^0.

In the MPS method, model for one differential operator, such as divergence, is as follow

$$\nabla \cdot \mathbf{u} = \frac{2d}{n^0} \sum_j \frac{\mathbf{u}_{ij} \cdot \mathbf{r}_{ij}}{|\mathbf{r}_{ij}|^2} w_{ij} \tag{6}$$

where $\mathbf{u}_{ij}$ is a vector and d is the number of space dimensions.

2.2 Elastic-plastic modeling

Computational approach for plastic structures is basically depend on the method to calculate elastic structures. In this study, a stress-strain curve obtained from the experiment is divided parted into color-coded intervals as shown in Fig. 1. If one strain ε_{ij} between particle i and j is equal to or more than ε_n and equal to or less than ε_{n+1}, Lame's constants λ and μ are calculated by substituting Young's modulus obtained from the interval into Equations (2) and (3).

3 COMPUTATIONAL CONDITION

3.1 Computational domain and boundary condition

Figure 2 shows the schematic of the computational objective in this study to simplify the process of particle impingement in cold spraying. In the initial condition, the diameter of a single particle D_0 is 20 mm, the thickness of a substrate H is 24 mm and the width of a

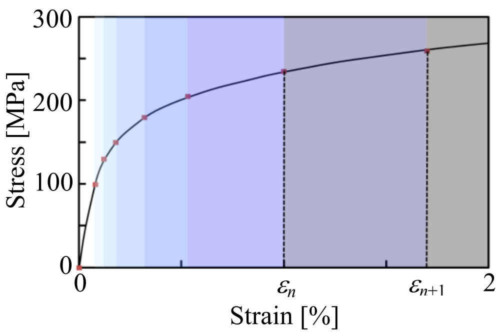


Figure 1: Stress-Strain Curve

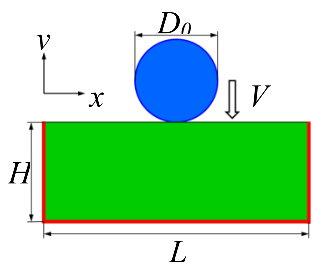


Figure 2: Computational Domain

substrate L is 64 mm. The impingement particle is initially contiguous the substrate. In Fig. 2, the blue part is the impingement particle, the green part is the substrate, the red part is a fixed boundary, and the stress in the red part is zero. The impingement direction of the single particle is vertical to the substrate. In this study, the impingement particle consists of 600 particles and the substrate consists of 2,400 particles. The diameter of all particles is 0.8 mm.

3.2 Computational conditions of particle and substrate

The computational results are compared with the experiment data measured by Schmidt et al. to validate the shapes of the particle deposition deformation. The computational conditions of the particle and the substrate are based on the experiment conditions. The particle material and the substrate material are copper and carbon, respectively. The speed of the particle is 350 m/s. The particle material and the substrate material are titanium. The critical velocity can be calculated by the following equation,

$$V_{crit} = \sqrt{\frac{F_1 \cdot 4\sigma_{TS}\left(1 - \frac{T_i - T_R}{T_m - T_R}\right)}{\rho} + F_2 C_P (T_m - T_i)} \quad (7)$$

where V_{crit} is the critical velocity, ρ is the density, σ_{TS} is the tensile strength, T_i is the impact temperature, T_R is the reference temperature, T_m is the melting temperature and C_p is the specific heat. Moreover, the empirical factors F_1 and F_2 are 1.2 and 0.3, respectively. In Equation (7), the first term in the right side means the interaction between the strength of material and the dynamic load, and the second term means the energy balance between the thermal dissipation and the kinetic energy. From this equation, the critical velocity is about 540 m/s, when the impact temperature T_i is 20 degrees Celsius. Thus, we observed the deformation of the impingement particle with V=100 m/s (lower than the critical velocity) and V=600 m/s (higher than the critical).

4 RESULTS AND DISCUSSION

4.1 Validation of Particle Shapes

Figure 3 shows the *y*-direction strain change of a copper particle against time. This figure 3 indicates that the strain is linearly-increasing with time. It is found that the strain is maximum at around 30 μs and is approximately constant while 35~40 μs. This tendency would be caused to remain the plastic strain of the impingement. The strain is obtained from the rebounding elastic strain energy to the restoration of the particle to the initial shape.

Next, Figure 4 indicates the *y*-direction speed at 35 μs after the particle impingement on the substrate. The movement of the particle near the surface of the impacting particle can be seen in Fig. 4. In the near contact surface between the particle and the substrate, the speed within the impacting particle is slower than the initial speed. As a result, it is thought that the deformation behavior of the particle impingement is settled. Therefore, it is regarded that the impacting particle adheres on a substrate at 35 μs.

Figure 5 compares the shapes of the particle deposition between the computational and the experiment results. Comparing the *x*-direction shapes in Fig. 5, the sticks called material-jet occur in both of results. However, it is found that the sticks of (a) is shorter than that of (b).

The reason is why the frictional force between the particle and the substrate is not considered in this simulation unlike the experiment. On the other hand, comparing the *y*-direction shapes in Fig. 5, the height of the particle deposition of (a) is in well accord with that of (b). The error is comes from that the collision between the particle and substrate is assumed a completely-elastic collision. The deformation of the impingement particle to vertical direction is resonably reproduced in our simulation.

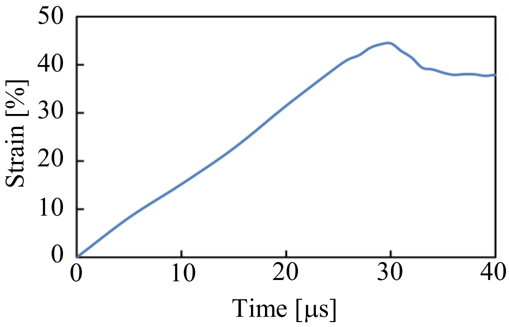


Figure 3: *y*-Direction Strain Change of Particle against Time

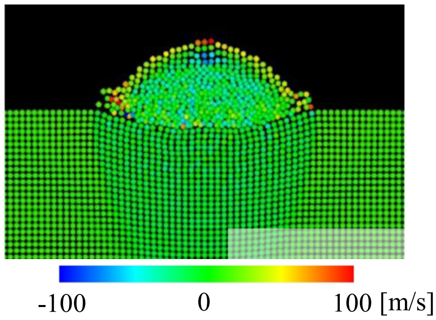
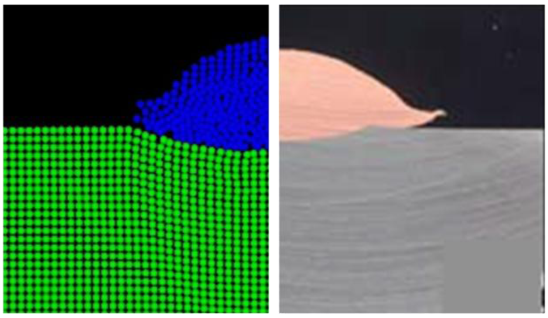


Figure 4: Speed Distribution at 35 μs



(a) Computation (b) Experiment

Figure 5: Shapes of Particle Deposition

4.2 Deformation Behavior of Particle and Substrate

Figures 6 and 7 show the deformations of the particle and the substrate consisting of titanium in the speed of a particle impingement with 100 and 600 m/s, respectively. First, in Fig. 6, it can be observed that the impinging particle found contacts with the substrate and then rebounds from the substrate. That is, the impinging particle whose speed is slower than the critical velocity does not adhere to the substrate. Next, in Fig. 7, it can be observed that an impinging particle dents into a substrate. Comparing the shapes of the particle after 30 and 35 μs, the *y*-direction strain at 35 μs is smaller than that at 30 μs. This is similar to the phenomena around 30~35 μs in Fig. 3. Therefore, it is confirmed that the impinging particle whose speed is faster than critical velocity adheres on the substrate.

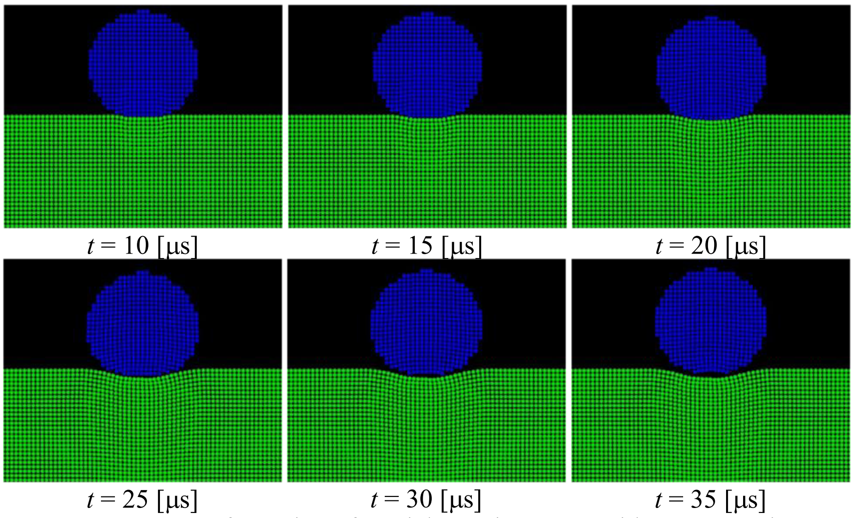


Figure 6: Deformation of Particle Impingement with *V* = 100 m/s

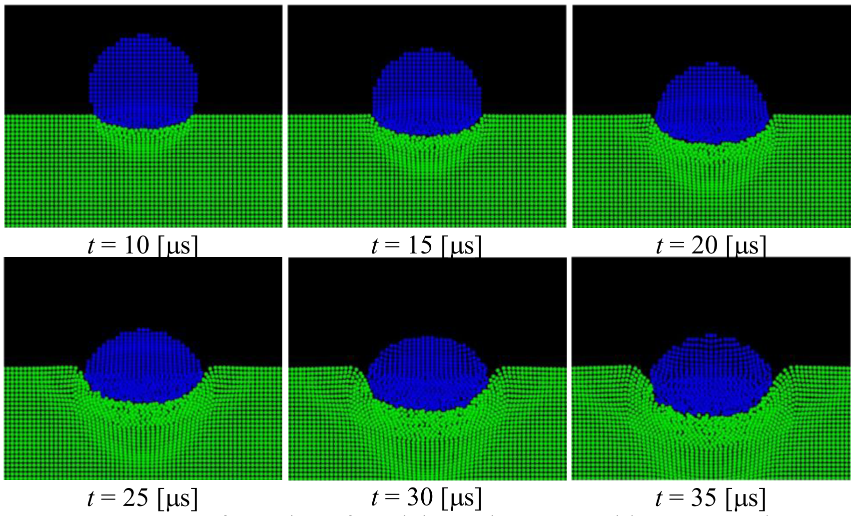


Figure 7: Deformation of Particle Impingement with *V* = 600 m/s

5 CONCLUSION

Numerical simulations on the first step of the film forming process by cold spraying were conducted by the MPS (Moving Particle Semi-implicit) method. The following knowledges are obatained. By using MPS method, the shapes of the particle deformation is resonably reproduced. The impinging particle whose speed is lower than the critical velocity rebounds from the substrate, meanwhile, the impinging particle whose speed is larger than the critical velocity adheres on the substrate. Through the present study, we confirmed that the MPS method is promising in simulating a cold spray process.

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