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Research on the Adhesive Mechanism of Al + Ti Mixed Powders Deposited on Ti6Al4V Substrate by CS Using Abaqus/Explicit

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Titanium materials are widely used in aviation; their poor wear resistance and easy high-temperature oxidation defects limit their further application. Cold spraying technology is an excellent way to solve these defects, has essential significance for its surface research. This study reports the deposition mechanism of Aluminium (Al) + Titanium (Ti) mixed powders deposited onto Ti6Al4V by cold spraying technology using Abaqus/Explicit. Because of its high surface hardness, it is not easy to obtain effective deposition by direct spraying with pure Al powder. Hence, Ti powder as the intermediate coating was proposed between Ti6Al4V and pure Al powder. Since there are few reports on numerical simulation of mixed particles, most studies focus on single or multi-particles of the same material. The critical process of numerical simulation of mixed powders is emphasized in detail. Using the recovery coefficient is defined to determine the critical speed. The results show that it is feasible to determine the critical velocity of mixed powder through the smaller value of recovery coefficient from the perspective of energy. In this paper, the recommended critical speed of mixed powder is 500 m/s–900 m/s. It will

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provide theoretical guidance for researchers and is of great significance to further expand the application of other mixed powders.

Key words: Ti6Al4V, cold spraying technology, mixed powders, Abaqus/Explicit, recovery coefficient, critical speed.

Титанові матеріяли широко використовуються в авіації, але низька зносостійкість та утворення дефектів при високотемпературному окисненні обмежують їхнє подальше застосування. Технологія холодного напилення є чудовим способом для усунення цих дефектів, а також має важливе значення для дослідження поверхні. У цій роботі досліджено механізм осадження змішаних порошків алюмінію (Al) + титану (Ti), нанесених на поверхню стопу Ti6Al4V за допомогою технології холодного напилення та використання Abaqus/Explicit. Через високу твердість поверхні стопу нелегко досягти ефективного осадження при прямому розпиленні порошку чистого алюмінію. Тому порошок Ti був запропонований як проміжне покриття між поверхнею Ti6Al4V і порошком чистого Al. Оскільки інформації про чисельне моделювання змішаних частинок небагато, більшість досліджень сконцентровано на поодиноких або множинних частинках одного матеріялу. Детально подано критичний процес чисельного моделювання змішаних порошків. Коефіцієнт відновлення використовується для визначення критичної швидкости. Результати показують, що можна визначити критичну швидкість змішаного порошку через менше значення коефіцієнта відновлення з точки зору енергії. У цій статті критична швидкість змішаного порошку, що рекомендується, становить 500–900 м/с. Це може бути теоретичним посібником для дослідників, а також має велике значення для ширшого використання інших змішаних порошків.

Ключові слова: Ti6Al4V, технологія холодного напилення, змішані порошки, Abaqus/Explicit, коефіцієнт відновлення, критична швидкість.

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1. INTRODUCTION

Ti alloy applies widely in aerospace [1]. It belongs to hard materials, and it is not easy to obtain an effective cold spraying coating on its surface by direct use of soft materials. The critical velocity is vital to the excellent deposition of cold spray coating because the velocity is too small to obtain effective deposition; such a high velocity will erode the surface of the substrate. There are many research methods on the critical velocity of cold spraying, which summarize into three categories: The numerical simulation method [2–4], the theoretical formula calculation method [5, 6], and the experimental method [7, 8]. In addition, with the development of computer technology, new methods have been introduced into the field of cold spraying [9]. There is no unified standard for the theoretical calculation of the critical velocity of mixed powder; experimental methods usually obtain it. To reduce the number of experiments and avoid unnecessary waste, numerical simulation in advance is the means of scientific researchers.

However, there are few reports on the numerical simulation of the deposition process of mixed particles. In practical engineering applications, it is often a mixture of different materials to obtain optimal performance. Therefore, the numerical simulation of cold spraying of a mixed powder of different materials multi-particle is an urgent focus of discussion. This study represents the Al + Ti mixed powder deposited onto Ti6Al4V, and the research results have specific guiding significance.

2. EXPERIMENTAL/THEORETICAL DETAILS

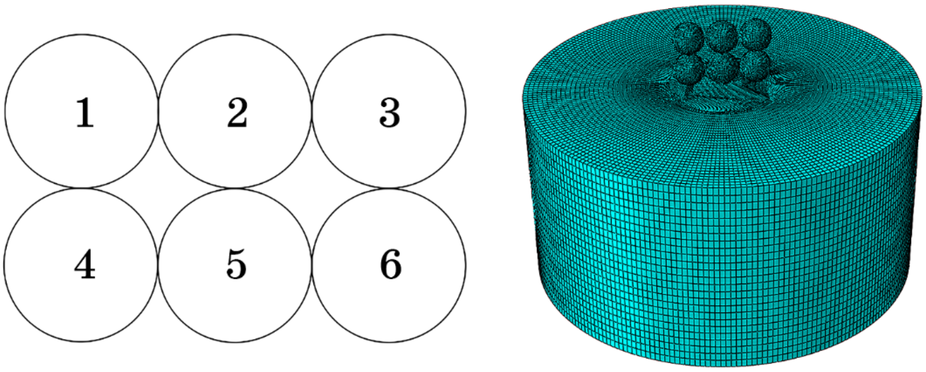
This study uses the Abaqus/Explicit method to analyze the critical velocity of Al + Ti mixed powder deposition onto Ti6Al4V from the energy perspective after the collision. The Abaqus/Explicit includes three algorithms, arbitrary Lagrangian–Eulerian, Couple Lagrangian–Eulerian, and Smoothed Particle Hydrodynamics (SPH). Recommend the SPH method for single-particle. However, for multi-particle mix powder simulation, it is not recommended to use the SPH method because of mutual infiltration in large deformation between powders, because it is challenging for the meshless method to achieve internal surface contact. Hence, using the Lagrange algorithm for multiple particles.

Due to the high hardness of Ti6Al4V, it is not easy to obtain a good coating if soft particles (aluminium) deposit on its surface [10]; this study considers sprayed with transition layer powder. The work [11] shows that the critical speed of aluminium particles deposited on the surface of the titanium matrix is 400 m/s–1050 m/s. Titanium can obtain a good coating as an intermediate layer [12]; this paper shows a titanium powder transition layer between aluminium powder and Ti6Al4V substrate, as Fig. 1 shows.

The material model needs to consider parameters such as plasticity, friction, and plastic damage, *etc*. Hence, the Johnson–Cook plastic model [13] was used, define Eq. (1)

$$\sigma = \left[A + B\varepsilon_p^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left[1 - (T^*)^m\right], \tag{1}$$

where σ is the equivalent flow stress, and are equivalent plastic strain rate and reference strain rate. ε_p is equivalent plastic strain. Parameters A, B, C, n, and m are material constants. T^* is the normalized temperature, as the Eq. (2) show



a *b*

Fig. 1. 1—Al, 2—Al, 3—Al, 4—Ti, 5—Ti, 6—Ti (*a*); three-dimensional model (*b*).

$$T^* = \begin{cases} 0; & T < T_{\text{trans}}, \\ (T - T_{\text{trans}})/(T_{\text{melt}} - T_{\text{trans}}) \nu & T_{\text{trans}} \le T \le T_{\text{melt}}, \\ 1 & T_{\text{melt}} \le T, \end{cases} \tag{2}$$

where T_{melt} is the melting temperature, T_{trans} is a reference transition temperature at or below which there is no temperature dependence of the response [14]. The main parameters of the simulation process are shown in Table 1.

The material failure model used in this paper is the Johnson–Cook dynamic fracture model. Considering the influence of static pressure, strain rate and temperature [15], it can be expressed in Eq. (3).

$$\varepsilon_f = \left[d_1 + d_2 \exp\left(d_3 \frac{p}{q}\right)\right]\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left(1 + d_5 T^*\right), \tag{3}$$

where ε_f is fracture strain, d_1–d_5 are material fracture constant, p is static pressure, q is miss yield stress.

The linear EOS_GRUNEISEN as the material state equation, it can be expressed in Eq. (4).

$$U_S = C_0 + sU_P, \tag{4}$$

where C_0 and s define the linear relationship between the linear shock velocity (U_S) and the particle velocity (U_P), the parameters as Table 1 show.

The time of analysis step is 50 ns, output parameter select energy. Particle surfaces need to select external areas and internal areas, which is the key factor for the success of the numerical simulation. The

TABLE 1. Material parameters of Al, Ti–6Al–4V, and Ti.

	Material	Al	Ti–6Al–4V	Ti
Essential parameters	Density, ρ/(g·m^{-3})	2.7	4.5	4.54
	Poisson's ratio ν	0.33	0.3	0.3
	Shear modulus, MPa	27	59.6	44
	Specific heat C_p, (J·kg^{-1}·K^{-1})	898.2	612	452
	Thermal conductivity coefficient λ, W·m^{-1}·K^{-1}	237.2	7.955	16.3
Johnson–Cook model	Yield strength, A/MPa	148.4	862	175
	Hardening index, B/MPa	345.5	331	380
	Strain index n	0.183	0.34	0.32
	Softening index m	0.895	0.8	0.55
	Strain rate, C	0.001	0.014	0.06
Material failure model	d_1	0.071	–0.09	–0.09
	d_2	1.248	0.25	0.27
	d_3	1.142	–0.5	0.48
	d_4	0.147	0.014	0.014
	d_5	1	3.87	3.87
	Melting temperature T_{melt}, K	916	1878	1811
	Transformation temperature T_{trans}, C	298	298	298
U_S–U_P state equation	C_O	5386000	5130000	4700000
	s	1.339	1.028	1.489
	Gammao	2.18	1.23	1.97

load parameter needs to fix the lower surface of the matrix. Considering the gravity of all particles and the value is 9810 mm/s^2. Unit type of the model is a hexahedral element ($c3d8r$) and hexahedral reduction integral is selected.

3. RESULTS AND DISCUSSION

Figure 2 represents the deposition of Al + Ti mixed powder impacting Ti6Al4V matrix at the speed of 300 m/s–1100 m/s. When particles collide with the Ti–6Al–4V matrix, particles 4, 5, and 6 collide with the substrate first and the effective plasticity strain of particles mainly

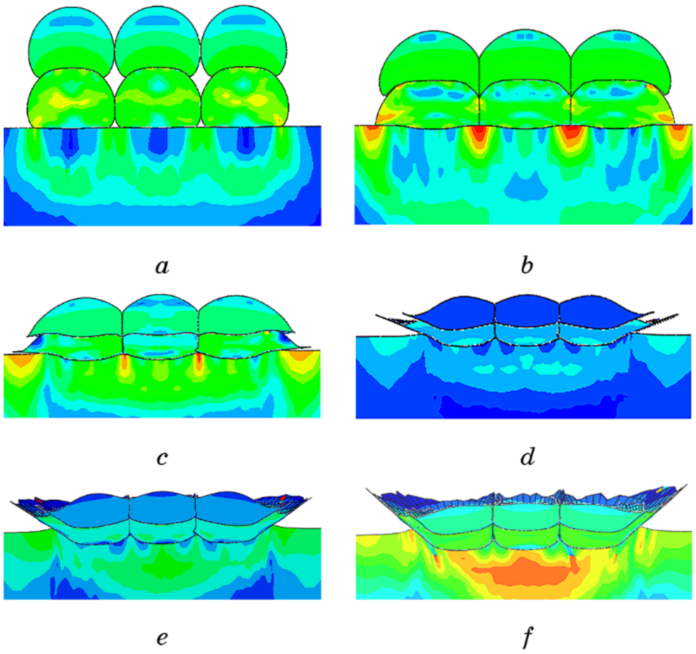


Fig. 2. Al + Ti/Ti–6Al–4V: *a*—300 m/s; *b*—500 m/s; *c*—700 m/s; *d*—900 m/s; *e*—1000 m/s; *f*—1100 m/s.

concentrate at the edge of the contact interface between particles and matrix, and the particles closely bond to the substrate and the particles change from spherical to flat. At 500 m/s, particles 1, 2, and 3 collide with particles 4, 5, and 6, respectively, and embed into their interstices. Particles 4, 5, and 6 collide with the matrix, there is a particular foundation pit, and the recovery coefficient is small. Hence as the lower boundary of the critical velocity. With the increase of velocity, the strong impact force of particles causes the matrix material to flow to the periphery, which makes the matrix material contact closely with the surface of particles 4, 5, and 6. Under the action of subsequent tamping of Al particles, the sedimentary layer deepens. The effective plastic strain increases as the velocity increases and the pits on the surface of the matrix deepen. In the whole process of particle deposition, the effective plastic strain of particles is much smaller than that of the substrate. When the velocity exceeds 900 m/s, the metal-plastic rheology appears on the surface of the matrix, and its plastic rheology inertia is greater than the viscosity resistance of the material, and the surface becomes unstable, suggested being the upper boundary of the critical velocity. Al and Ti particles are embedded in the softened Ti–6Al–4V matrix, resulting in mechanical bite-type bonding.

The kinetic energy (ALLKE) is transformed into plastic dissipation

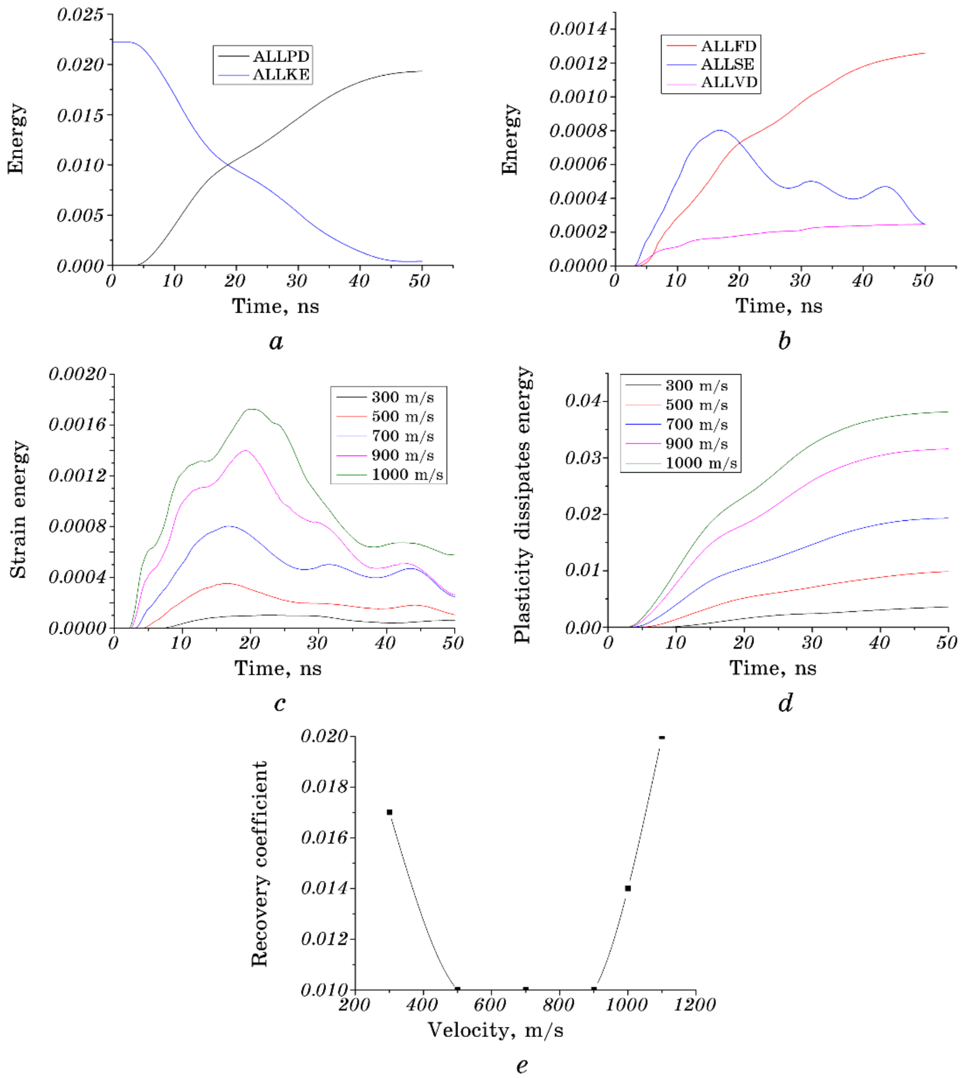


Fig. 3. *a*—ALLPD and ALLKE at 700 m/s; *b*—ALLFD, ALLSE, and ALLVD at 700 m/s; *c*—strain energy; *d*—plasticity dissipates energy; *e*—coefficient of recovery at different speeds.

energy (ALLPD), friction dissipation energy (ALLFD), elastic strain energy (ALLSE), and material Dissipation energy (ALLVD). Ignore the smaller energy in the energy transformation process, as shown in Figs. 3, *a*, *b*, which can be expressed as total energy ALLKE = ALLPD + + ALLSE + ALLFD + ALLVD. Plastic dissipation and frictional dissipation can also be known as bonding energy and strain energy storage called rebound energy [16].

Powder for deposition condition is that the bounce energy is less than the bonding energy define the ratio of rebound energy and bonding energy as the recovery coefficient. When the recovery coefficient decreases with the increase of the speed in a certain range, the deposited effect is better; when exceeding a certain speed the recovery coefficient increases, and determine the speed between the minimum values of the recovery coefficient as the maximum critical speed. As shown in Fig. 3, *c*, rebound energy increases gradually with speed, especially when the speed is 900 m/s–1000 m/s. Although the speed interval is 100 m/s, the rebound energy increases the most, exceeding the increased range of rebound energy between 500 m/s–700 m/s and 700 m/s–900 m/s. Fig. 3, *d* shows that the increased range of plastic dissipation energy is small in the range of 900 m/s–1000 m/s. Thus, the recovery coefficient is large. As shown in Fig. 3, *e*, the recovery coefficient in the range of 500 m/s–900 m/s is small; hence, recommend the critical speed, which is very consistent with Fig. 2. When the speed is less than 500 m/s or more than 900 m/s, the recovery coefficient increases, indicating that the rebound strength increases and the bond performance is poor.

4. CONCLUSION

Lagrange algorithm used to simulate the bonding process of Al + Ti mixed powder deposited onto Ti6Al4V is worth recommending. By using intermediate transition coating method (titanium coating) can solve the problem that aluminium powder is not easy to deposit on the surface of Ti6Al4V. Using recovery coefficient evaluates the critical velocity of mixed powder is feasible. This study recommends that 500 m/s–900 m/s as the critical velocity.

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