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Numerical Study on Simulating the Deposition Process of Cold Spray Multi-Particle Al-6061 based on CEL Method

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Abstract: *Cold spray is a solid-state deposition technique that improves the performance of part surfaces. Most scholars use the CEL framework to simulate the deposition of single particles on the substrate; Single particle depositions cannot fully characterize coating conditions. This article proposes to use the CEL method to simulate the deposition process of cold spray multi-particles on the Al6061 substrate. A multi-particle wrapped model is nested in a deposition model created by CEL to simulate the cold spray multi-particle deposition process. The Euler-Lagrangian method has the characteristics of high accuracy and robustness, and was selected as the method for multi-particle deposition model simulation; The CEL framework is a feasible method to simulate the actual cold spray multi-particle deposition process. The results show that the CEL framework can simulate the deposition of cold sprayed Al6061 multi-particles on the Al6061 substrate, observe the EVF Void value of the coating, and monitor the porosity of the coating after deposition. It is observed that the maximum substrate surface temperature after deposition is 528.2K and is located at the junction of particle and particle impact; By analyzing the temperature change curve of five points collected on the substrate over time, the curve appears multiple inflection points, indicating that heat transfer occurs between the particles and the substrate during the deposition process; the substrate first heats up and then cools down. During the multi-deposition process, the particles undergo plastic deformation and continuously squeeze the coating, thereby achieving interconnection between the particles and the substrate; Mechanical interlocking between particles forms a coating.*

Keywords: *coupled Eulerian-Lagrangian, Al6061, multi-particle, substrate, temperature.*

1. Introduction

Cold spray technology is a solid-state deposition technology that began in the 1980s [1]; After the particles are accelerated to 300–1200 m/s by the supersonic airflow in the nozzle, particles directly impact the surface of the substrate, eventually forming a uniform thin coating on the surface of the substrate [2], [3]. Cold spray technology is different from traditional surface technology. The process of cold spray deposition is a physical change; the particles undergo plastic deformation during the deposition process [4], [5], and the coating continuously compresses residual stress during the accumulation process. The compression characteristics of residual stress are helps improve the fatigue and strength characteristics of coating materials; residual stress is the result of particle/substrate and particle/particle interaction during the deposition process, and finally forms a dense coating on the substrate; cold spray technology is mainly used to improve performance of the part surface and achieve surface protection [6].

Methods to simulate the cold spray deposition process include: Smooth Particle Hydrodynamics (SPH) method, The Lagrangian method (ALE) and Coupled Eulerian-Lagrangian (CEL) method. The CEL method has the characteristics of high accuracy and robustness, and is selected as the method for multi-particle deposition model simulation; CEL is currently a better method for simulating the multi-particle deposition process of cold spraying, especially when particles undergo large deformation during the deposition process. At present, there are few studies on using CEL simulation method to simulate Al6061 particles in the deposition process. Rokni [7] experimentally analyzed the residual stress of single-particle Al6061 after deposition on an Al6061 substrate, observing the compressive residual stress state in the cold spray direction, and the

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transverse tensile residual stress state near the substrate/coating interface. Saleh [8] used the SPH method to simulate the impact model of single-particle Al6061 particles on the Al6061 substrate, and further analyzed the residual stress distribution by studying the deposition process of Al6061 particles on the Al6061 substrate. Lin [9] used the ALE method to simulate the evolution of residual stress during cold spraying of multi-particle Al6061 particles on the Al6061 substrate. Interfacial bonding is one of the important factors in the numerical simulation of residual stress evolution in cold spraying. Song [10] used the CEL method to simulate the deposition process of Ti6Al4V particles on the Ti6Al4V substrate to study the effects of temperature and speed on the porosity of the coating. It is both practical and economical. Most scholars use the CEL framework to simulate the deposition of single particles on the substrate; single particle depositions cannot completely characterize the coating. The CEL method is used to establish a multi-particle deposition model to simulate the real cold spray deposition process, which can better predict the coating performance.

This article proposes to use the CEL method to simulate the deposition process of cold spray multi-particles on the Al6061 substrate. A multi-particle wrapped model is nested in the deposition model created by CEL to simulate the deposition process of multi-particle Al6061 particles on the Al6061 substrate. By studying the particle/substrate and particle/particle depositions, the shape of the coating is observed. and the temperature distribution on the surface of Al6061 substrate after deposition.

2. Simulation model

This simulation model was jointly completed by Solidworks and Abaqus Expicit. Solidworks completed the modeling of 100 particle models with particle sizes of 20–70 um. A multi-particle wrapped model is nested in a deposition model created by CEL to simulate the deposition process of cold sprayed multi-particle Al6061 particles on the Al6061 substrate.

2.1 Multi-particles model and Euler domain

This article uses Solidworks to model multi-particle models of different particle sizes; or uses Catia/Python scripts to model multi-particle models of different particle sizes. Fig. 1 shows the appearance of 100 particle models with particle sizes of 20–70 um before deposition. Typical particle size distribution measured using a microvolume laser powder analyzer. The cumulative probability distribution of particle size is estimated by a lognormal function, as shown in Fig. 2 for the distribution of Al6061 particle size and number. This work adopts the assumption of uniform distribution to confine the affected particles to the central region of the dense grid of the substrate.

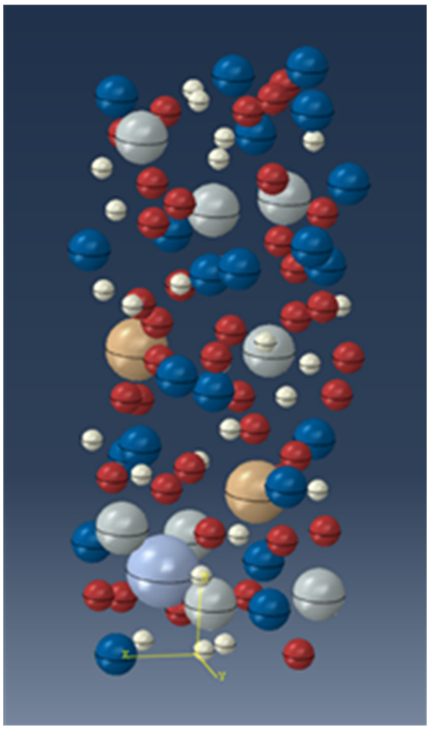

Fig. 1. 100 particle model with particle size of 20–70 um

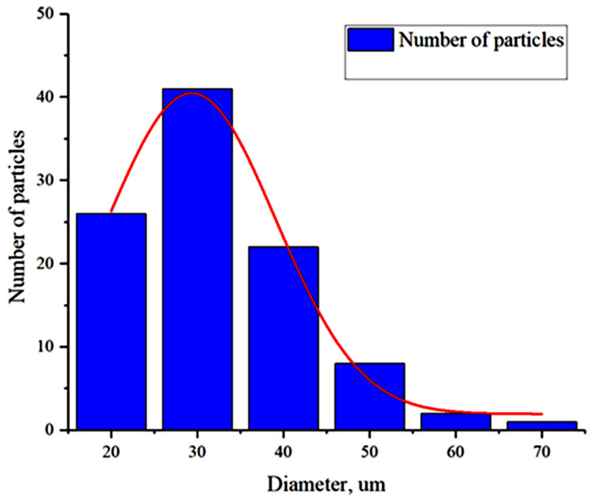

Fig. 2. Distribution of particle size and number of Al6061

It should be noted that the Eulerian domain must wrap all particles and the deposition area, as shown in Fig. 3. The blue area is the Euler domain. It should be noted that the Euler domain is set to a cuboid. The advantage is that it can generate a uniform hexahedral structure grid [11], reduce the time required for analysis, and ensure that the mass loss is reduced in the Euler domain grid, while at the same time it is convenient for the convergence of the results during the calculation process; some scholars set the Euler domain as a cylinder [9], [12]. The disadvantage is that the grid generated by the cylinder is mainly a tetrahedral grid, which is not easy to converge during the calculation process.

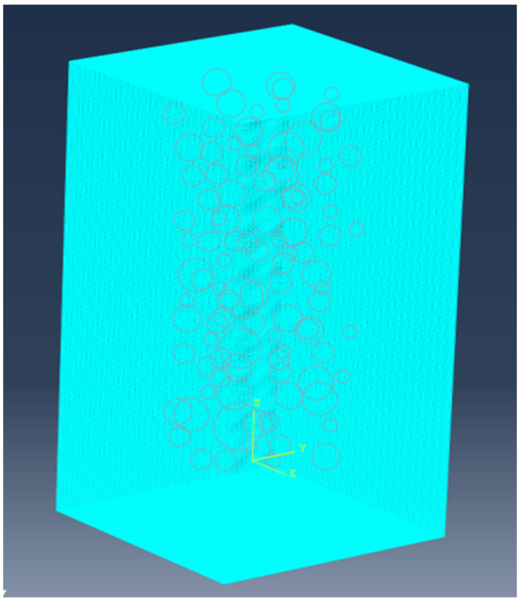

Fig. 3. Eulerlan domain containing multi-particles

Thermal coupling is added to the Euler domain grid, EC3D8RT: The node thermal coupling is purely Euler hexahedral element, reduced integration, hourglass control (using distortion and enhancement control), and at the same time, the nonlinear and large deformation effects of the material are considered during the simulation process.

2.2 Material model

The CEL framework can simulate the deposition process of cold sprayed Al6061 multi-particles on the Al6061 substrate. Assuming that the material is isotropic, an inelastic heat share parameter needs to be set, and its properties are shown in Table 1. Plastic hardening uses the Johnson-Cook (JC) plasticity model to describe the dependence of material behavior on rate and temperature [9], and adds a hardening J-C model representation that depends on the change rate.

The parameters of the J-C plasticity model are obtained by least squares curve fitting of the deformed particle shapes measured in the Advanced Laser Induced Projectile Impact (ALIPIT) test [13]. The ratio of plastic energy converted into heat is 0.9 [14]. The corresponding thermal response of a material is defined by its temperature-dependent thermal properties, such as specific heat, thermal conductivity and thermal expansion [15].

Table 1. Material properties for A16061

Properties	Parameters	Value
General	Density ρ, (kg/m^3)	2700
	Specific heat Cp, J/(kg·K)	1009
	Thermal conductivity coefficient λ, W/(m·K)	155
	Melting temperature Tm, (K)	925
	Inelastic heat fraction	0.9
	Elastic modulus, (Gpa)	69.11
	Poisson's ratio, ν	0.331
	Shear modulus, (GPa)	25.9
J-C Plasticity parameters	A, B, n, m, (Mpa)	270, 154.3, 0.239, 1.42
	Reference strain rate	1
	Reference temperature Tref, (K	298
	$C_1, C_2, \dot{\varepsilon}_c$	0.002, 0.0029, 597.2

2.3 Deposition model parameter settings

In the load predefined field, set the corresponding temperature field (k) and velocity field (m/s) for 100 particle models with sizes of 20–70 um. The velocity of all Al6061 particles is set to 585 m/s and the temperature is 400K. [16]. Ensure that all Al6061 particles can produce particle/substrate particles and particle/particle depositions evenly and orderly. As mentioned above, all Al6061 particles are wrapped in the Euler domain, so the essence is that all Al6061 particles flow in the Euler domain, and the deposition process including post-deposition will be completed in the Euler domain.

This work adopts the assumption of uniform distribution to confine the affected particles to the central region of the dense grid of the substrate. The analysis step time for the entire analysis process was roughly estimated based on the time it took for the particles furthest from the matrix to reach the substrate; a coupled temperature-displacement dynamic step with an appropriate time period was assigned to track the time from the start of the simulation to the complete stop of all particles. The entire multi-particle impact process has a total range of 900–1000 ns. Assign materials to all Al6061 particles in the Euler domain; use the volume fraction tool of the discrete field to set parameters for all particles in the Euler domain, and calculate the volume fraction of each particle in the Euler domain to ensure later calculations goes smoothly.

In this study, the multi-particle model is of the Eulerian type; the substrate model is of the Lagrangian type. The contact surface between the deposited particles and the substrate can be accurately and clearly observed. The grid of the substrate is divided from the inside to the outside, and the grid density decreases in sequence; The central area of the substrate is the main site for multi-particle deposi tion, so the grid in the central area should be as small as possible. The grid size in the particle impact area should be close to the grid size in the Euler domain. This is mainly to ensure that there is sufficient space in the subsequent analysis process. Better resolution. The grid model selects Lagrangian C3D8RT element type; eight-node thermally coupled hexahedral element, three-way linear displacement, three-way linear temperature, reduced integration, and hourglass control; the initial temperature field of the substrate is 400 K.

During the assembly process, the multi-particle model is wrapped in the Euler domain. The essence is that the particles flow at high speed in the Euler domain. The bottom of the Euler domain overlaps with the top part of the substrate to ensure that the multi-particle model after deposition is still in the Euler domain. within the range to ensure the integrity of the calculation results. As shown in Fig. 4, Half-section view of model assembly and meshing.

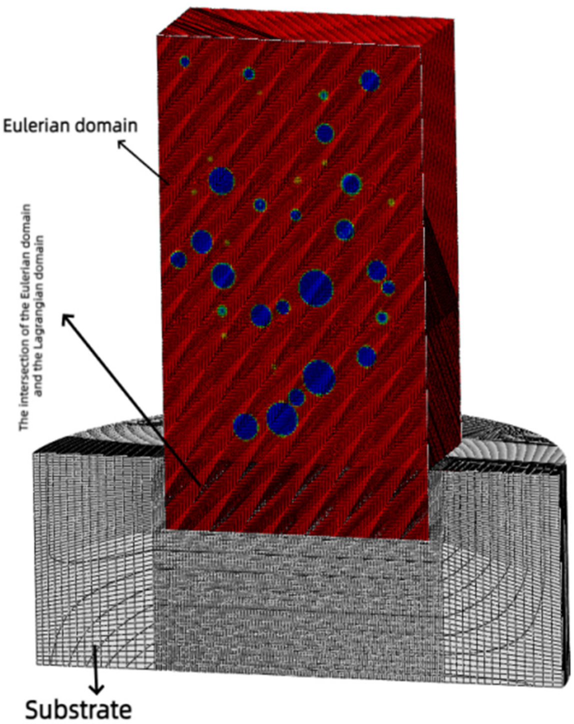

Fig. 4. Half-section view of model assembly and meshing

3. Results and discussion

Fig. 5 shows a cross-sectional view of the Euler volume fraction voids after multi-particles are deposited on the substrate. The EVF void value of the red area is 1, indicating a gap area, and the EVF void value of the blue area is 0, indicating that the element is filled with material. It can be clearly observed from Fig. 5 that there are still red areas in the coating after the deposition, and there are gaps in the model after the deposition. It shows that there are gaps in the model after the deposition. It can be seen from the figure that there is no gap in the contact between the model coating and the substrate after the deposition. It is said that the simulated deposition is successful.

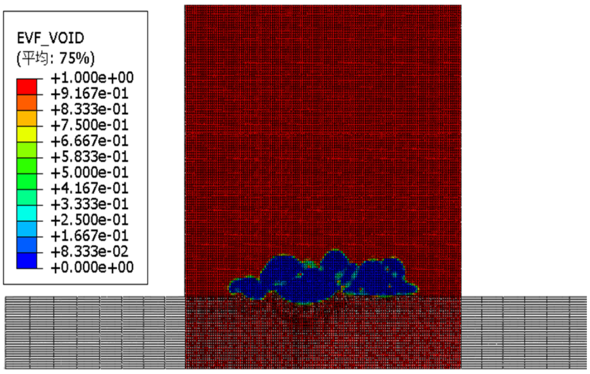

Fig. 5. Cross-sectional view of Euler volume fraction voids after multi-particle deposition on the substrate

As mentioned above, the grid in the Euler domain will not deform with the particles. The essence is that the particles flow in the Euler domain. This shows that the multi-particle deposition model established by the CEL method to simulate the actual cold spray process can be used to monitor and calculate the coating porosity, which cannot be achieved by the ALE method and the SPH method. Regarding the calculation of coating porosity from the multi-particle deposition model, a sample model can be collected in the coating and the average EVF pore percentage calculated as a numerical value for the porosity of the coating. In the actual cold spraying process, porosity always exists in the coating; eliminating porosity has always been an area of focus.

Fig. 6 shows the temperature cross-section of the Al6061 substrate after being deposited with Al6061 particles; the initial substrate temperature is 600 K; it can be seen from Fig. 6 that the maximum temperature on the surface of the substrate after deposition is 528.2 K, and the maximum temperature is located after the deposition of particles and particles. Because the particles deposited and squeezed during the deposition process, thus generating a large amount of heat; select 5 nodes from Fig. 6 and observe the temperature changes of these nodes before and after deposition.

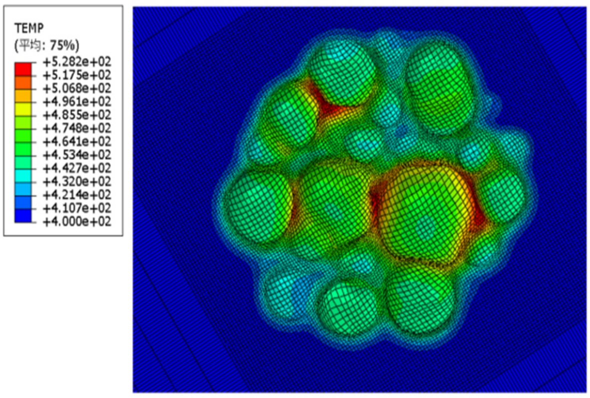

Fig. 6. The state of Al6061 substrate after particle deposition

As shown in Fig. 7, the substrate temperature points 1–5 temperature changes over time during the deposition process. From Fig. 7, it can be seen that the temperature curve of substrate points 1–4 temperature appears multiple inflection points. Each inflection point represents an occurrence at that location. Each impact causes an increase in the temperature of the substrate surface. Among them, two impact occurred at substrate points 1 and 4 on the substrate; three impact occurred at substrate points 2 and 3. The temperature curve of substrate points 5 temperature shows only one sharp increase in temperature, followed by a rapid decrease in temperature, which indicates that only one deposition occurred at Substrate points 5. point 1 and point 5 are located at different positions on the substrate; during the establishment process of the multi-particle model, the multi-particles in the Euler domain are randomly distributed, resulting in different numbers of particles perpendicular to the surface of the substrate. thus, each points have different number of impacts. The multi-particles generate a large amount of heat during the deposition with the substrate/Al6061 particles, and the temperature drops sharply after the deposition ends. Through the analysis of the simulation results of the multi-particle deposition model, it was found that during the multi-particle impact process, the matrix was squeezed into the gaps between the coating particles due to thermal softening, excessive plastic deformation and thermal expansion. After spraying, as the interface temperature dropped, the modulus of the substrate extruded into the coating gap due to plastic deformation returns to room temperature, thereby bonding with the substrate.

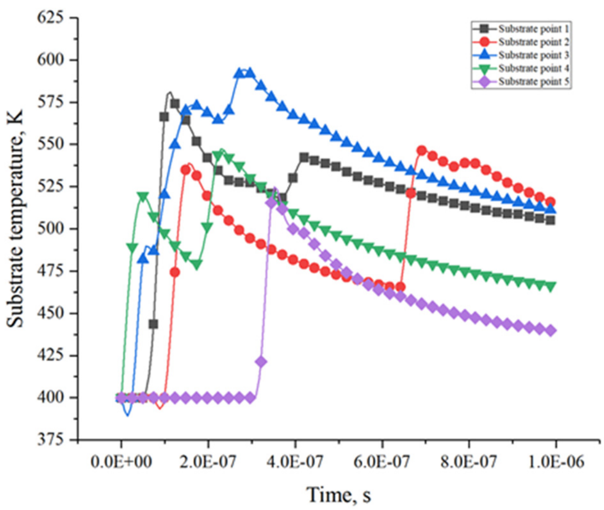

Fig. 7. Substrate points 1–5 temperature changes over time during the deposition process

As shown in Fig. 8, the mutual conversion between kinetic energy and internal energy of multi-particles in the entire collision model, almost all kinetic energy is converted into internal energy, and the process is stable, indicating that the entire deposition model has good stability. As can be seen from Fig. 8, the kinetic energy and internal energy curves of the model are symmetrical about $y = 0.529$. The loss of kinetic energy and thermal energy is not considered in the model, so all kinetic energy is converted into internal energy. It can also be seen from the Fig. 8, that in the multi-particle model, when the time reaches 980 ns during the deposition process, the entire deposition process ends, which is completely consistent with the total range stated above of 900–1000 ns. The curves of kinetic energy and internal energy changing with time tend to be horizontal as a whole, indicating that the entire deposition process is completely completed.

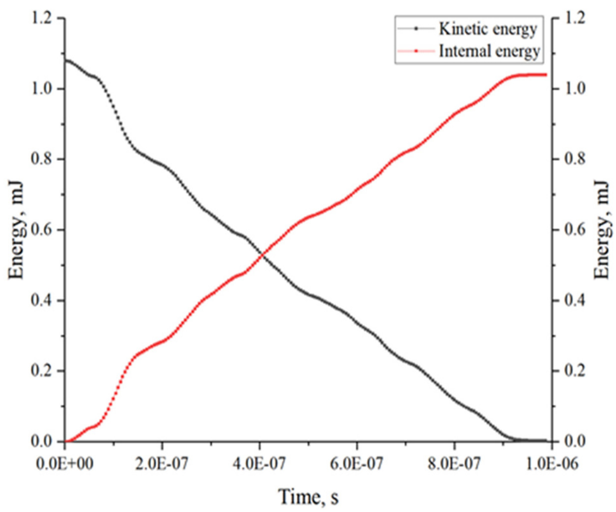

Fig. 8. ALLKE and ALLIE variation for the whole model during the entire simulation

4. Conclusions

This article proposes to use the CEL method to simulate the deposition process of cold spray multi-particles on the Al6061 substrate. A multi-particle wrapped model is nested in the deposition model created by CEL to simulate the deposition process of multi-particle Al6061 particles on the Al6061 substrate.

Using the CEL method to establish a multi-particle deposition model to simulate the actual cold spray process can be used to monitor and calculate coating porosity, which cannot be achieved by the ALE method and the SPH method. By calculating the value of EVF Void of the coating after simulated deposition, the calculated void ratio is used as the value to characterize the porosity of the coating.

The temperature changes and distribution of the surface of the substrate after deposition of the multi-particle deposition model; the maximum temperature on the surface of the substrate after deposition is 528.2 K, and the maximum temperature is located at the interface between particles after deposition. Observing the temperature change curves of five points on the substrate with time steps, the temperature curve of substrate points 1–4 temperature has multiple inflection points, indicating that multiple impacts caused the temperature to rise, and then the temperature dropped rapidly.

During the multi-particle deposition process, the matrix is squeezed into the gaps between the coating particles due to thermal softening, excessive plastic deformation and thermal expansion. After the spraying is completed, as the interface temperature decreases, the matrix is squeezed into the gaps in the coating due to plastic deformation. The modulus of the base material returns to room temperature, thereby bonding with the base material.

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Чисельне моделювання процесу осадження багаточастинкового алюмінію Al-6061 методом холодного розпилення на основі CEL

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Анотація. *Холодне розпилення – це метод твердотільного осадження, який покращує експлуатаційні характеристики поверхонь деталей. Більшість дослідників використовують систему CEL для моделювання осадження окремих частинок на підкладку; осадження окремих частинок не може повністю охарактеризувати умови нанесення покриття. У цій статті пропонується використовувати метод CEL для моделювання процесу осадження багаточастинкових покриттів холодним розпиленням на підкладку Al6061. Багаточастинкова модель вкладена в модель осадження, створену CEL для моделювання процесу осадження багаточастинкових частинок холодним розпиленням. Метод Ейлера-Лагранжа має характеристики високої точності та надійності, і був обраний в якості методу для моделювання моделі багаточастинкового осадження; фреймворк CEL є можливим методом для моделювання фактичного процесу осадження багаточастинкових частинок холодним розпиленням. Результати показують, що метод CEL може моделювати осадження холодним розпиленням мультичастинок Al6061 на підкладку Al6061, спостерігати значення EVF величини покриття і контролювати пористість покриття після осадження. Виявлено, що максимальна температура поверхні підкладки після осадження становить 528,2 К і знаходиться на межі зіткнення частинок і частинок; Аналізуючи криву зміни температури п'яти точок, зібраних на підкладці з плином часу, на кривій з'являються множинні точки перегину, що вказує на те, що в процесі осадження відбувається теплообмін між частинками і підкладкою; підкладка спочатку нагрівається, а потім охолоджується. Під час процесу багаторазового осадження частинки зазнають пластичної деформації і безперервно стискають покриття, тим самим досягаючи взаємозв'язку між частинками і підкладкою; механічне зчеплення між частинками утворює покриття.*

Ключові слова: *Зв'язаний ейлерівсько-лагранжіан, Al6061, багаточастинковий, підкладка, температура.*