The 9th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2024
3 – 7 June 2024, Lisbon, Portugal

MODELLING AND SIMULATION OF HIGH VELOCITY IMPACT OF PARTICLES IN COLD SPRAY ADDITIVE MANUFACTURING

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Key Words: *High velocity impact, High strain rate, Cold spray, Finite element analysis, Aluminium, Additive manufacturing.*

ABSTRACT

Cold spray additive manufacturing (CSAM) is an emerging technology with high deposition rate and high efficiency, that relies on the high-speed self-consolidation of powder particles to build up layers of material for diverse applications (e.g., coating, repairing and bulk component). In this paper, a comprehensive study is carried out on the modelling and simulation of high strain-rate deposition behaviour and interfacial bonding of highly deformed particles during the CSAM of aluminium powder. Both single particle and multi particles configurations are investigated using three-dimensional models with ABAQUS / Explicit solver. To capture the particle complex deformation mechanism, rate-dependent elastoplastic damage constitutive model is adopted. The initial temperature is set at room temperature, while the initial velocity is set at a critical value to ensure particle bonding. The developed model relies on coupled Eulerian - Lagrangian (CEL) approach. As a mean of solving high strain rate deformation problem, CEL combines the advantages of both frameworks to capture the complex particle-particle interactions with good computational accuracy. The evolution of particle shape, residual stress, equivalent plastic strain and temperature during the collision for both single and multi-particle models are presented. Through the particle impacting simulation, it is found that the strain localization mainly occurs at the interfacial region due to the thermal softening. The phenomenon of adiabatic shear instability and the resulting heat dissipation, which occur at the interface, are the main driving force behind the bonding between the particles and the substrate on the one hand, and between the particles on the other. They promote jetting splashing with inhomogeneous deformation. Through the multiple particles impacting simulation, it is possible to predict the compressive residual stress after collision induced by shot peening and bonding effects. It is also possible to predict the surface topology as well as the porosity. In summary, this research advances the understanding of particle deposition behaviour in CSAM through the development of multi-physics particle impacting models. The insights gained from two proposed models can contribute to the optimization of CSAM parameters, enhancing the precision and efficiency of the deposition process across a range of industrial applications.

1. INTRODUCTION

With the popularity of additive manufacturing (AM), it has become an indispensable field all over the world. And there are many categories of AM. Cold spray additive manufacturing, also called cold gas dynamic spray or kinetic spray, is a reliable and sustainable emerging deposition technology [1, 2]. Compare with other technology, the CSAM has higher deposition rate and higher deposition efficiency. With the help of high-pressure or low-pressure system and gas heater, various microparticles are accelerated to supersonic velocities, and then adhere to the substrate layer by layer, then deposit coatings in an entirely solid state [3-6]. For investigating the detailed bonding mechanism of deformed solid particles, various of works about simulation have been carried out during the past decade to improve our understanding on this issue [7, 8].

Therefore, this paper focus on the high impact of solid particles on Al/Al interface while modelling the cold spray additive manufacturing. Through the initial research, the numerical model based on CEL strategy has been successfully used to capture the complex particle-particle interactions of cold spray for Al/Al material welding. The key idea of this paper is to extend the investigation to an Al/Al consolidation. The contours of particle impacting results are also discussed.

2. METHODOLOGY

Coupled Eulerian Lagrangian method was regarded as a reliable approach to predict interface kinetics and it has the modelling capabilities of material flow behaviors during the consolidation process follow a fluid-like property. The schematic diagram in Figure below shows the details of the numerical model introduced in this study. The computation domain is given in Fig. 1. The simulations were performed using 3D model with Fig. (1) single particle and (b) multiple particles in commercial finite element software ABAQUS. Both single particle and multiple particle impact behavior are considered. Especially 100 Al 6061 particles with random arrangement were assembled with the Eulerian parallelepiped domain on top, as presented in Fig. 1 (c).

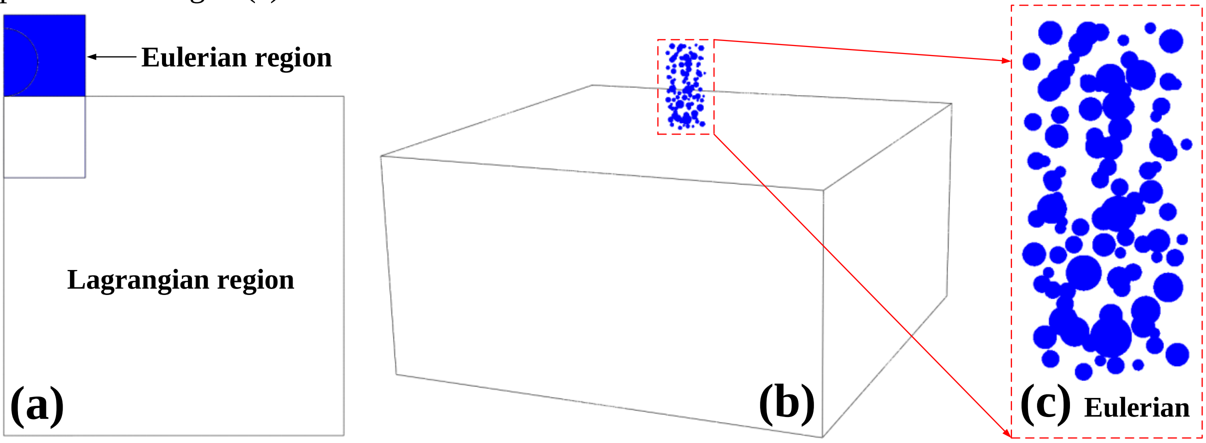

Fig. 1. Schematic diagram of 3D model: (a) single particle; (b) multi particle assembled model with the Eulerian parallelepiped domain on top and the Lagrangian substrate at the bottom; (c) random arrangement of Al 6061 powders.

For elastic exploration, a linear Mie-Gruneisen equation of state has been widely used in previous studies. The mechanical and thermal properties are assumed to be isotropic. As for the plastic examination, Johnson Cook plasticity and damage model with great advantage for presenting strain and strain rate hardening, thermal softening. The models above are represented by equations below:

$$P = \frac{\rho_0 C_0^2 \eta}{(1 - S\eta)^2}\left(1 - \frac{\Gamma_0}{2}\eta\right) + \Gamma_0 \rho_0 E_m \quad (1)$$

$$\sigma = (A + B\varepsilon^n)\left(1 + C\,ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_{reference}}{T_{melt} - T_{reference}}\right)^m\right] \quad (2)$$

$$\varepsilon_D = \left[D_1 + D_2 exp\left(D_3\frac{P}{S}\right)\right]\left[1 + D_4\,ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 + D_5\left(\frac{T - T_{reference}}{T_{melt} - T_{reference}}\right)\right] \quad (3)$$

In order to carry the simulation, the require material parameters [9] of constitutive model for the Al 6061 particle and Al 6061 substrate are shown in Table 1. The friction coefficient is assumed to be 0.3 and the basic meshing size near the impact area is 1.5 µm. The solution time in the calculation of single particle and multiple particle impact are 60 ns, 1500 ns, respectively. The mesh type of substrate with Lagrangian domain is C3D8RT. And the mesh type of particle with Eulerian domain is EC3D8RT. The interaction between particles, between particle and substrate is defined as “General” contact.

Table 1. Material parameters are used for simulating the impacting behavior of Al 6061 particle deposited on Al 6061 substrate.

Properties	Parameter	Al 6061	Unit
General	Density, ρ	2700	(kg/m^3)
	Specific heat	1009	$(J/kg \cdot K)$
	Thermal conductivity	155	$(W/m \cdot K)$
	Inelastic heat fraction	0.9	1
	Melting temperature	925	(K)
	Reference temperature	293	(K)
Elastic	Elastic modulus	69.11	GPa
	Poisson’s ratio	0.331	1
	Shear modulus	26	GPa
Johnson-Cook Plasticity	Yield strength, A	270	MPa
	Hardening index, B	154.3	MPa
	Strain index, n	0.239	1
	Strain rate, C	0.002	1
	Softening index, m	1.42	1
	Reference strain rate	1	$(1/S)$
Johnson-Cook damage	D_1	-0.57	1
	D_2	1.45	1
	D_3	0.47	1
	D_4	0.011	1
	D_5	1.6	1
Mie–Grüneisen Equation of State (EOS)	Sound speed, C_0	5240	(m/s)
	Slope of Up versus Us, S	1.4	1
	Grüneisen coefficient, Γ_0	1.97	1

3. RESULTS AND DISCUSSION

Interface features and contours of a single particle impacting behavior obtained from numerical simulation are shown in Fig. 2. From the morphology it could be seen that the deformed jet is only formed at the rim of the flattened single particle itself. Due to the adiabatic heat transformation at the interface between the particle and substrate, it will be no heat exchange and less effect effective plastic strain on the substrate as shown in Fig. 2 (d). It could be seen that the localized plastic deformation of substrate occurs at the periphery of the contact interface. At the same time, high temperature will promote the role of thermal softening effect. Then decrease the material hardening and promote the material flow. The temperature at the interface reaches almost 780 K that would provide favorable condition for consolidation. The specific kinetics of the jet formation are related to the high strain shearing, local strain localization, local temperature and pressure.

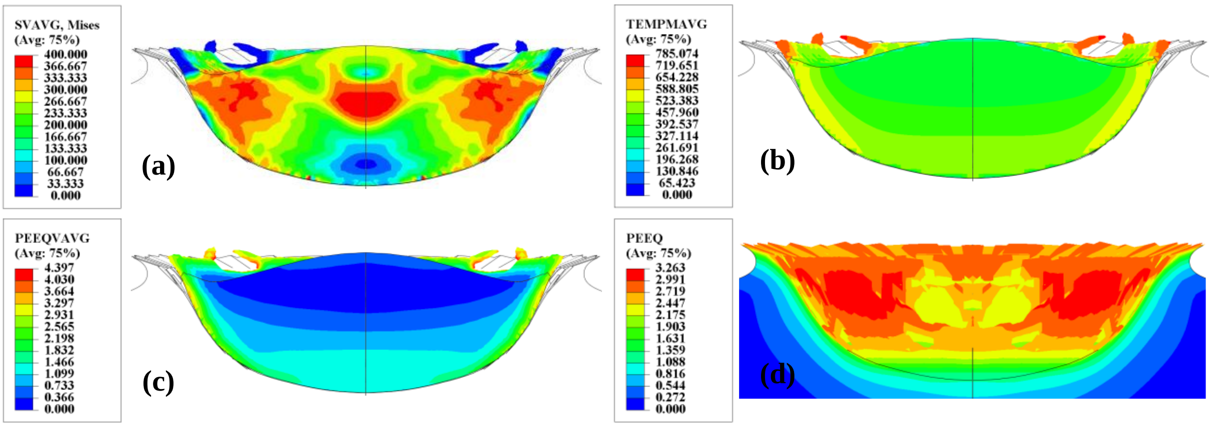

Fig. 2. Contours of a single particle impacting on the substrate modeled by CEL method at 12 ns with the critical velocity of 840 m/s: (a) Misses stress; (b) temperature; (c) effective plastic strain of Al 6061 particle; (d) effective plastic strain of Al 6061 substrate.

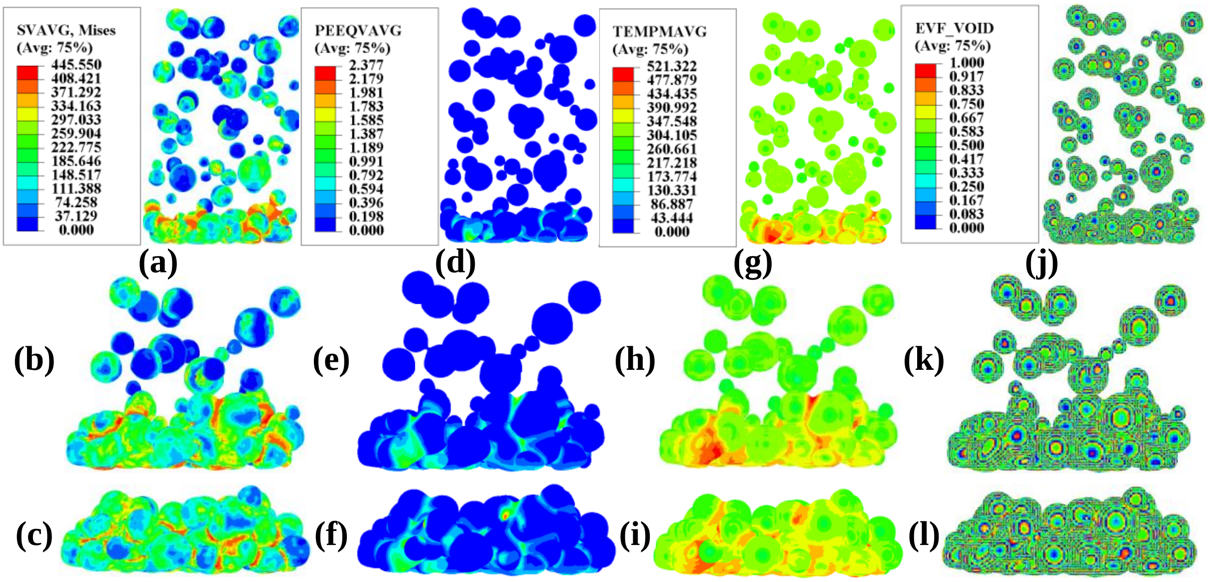

Fig. 3. Contours of multi particles impacting on the substrate modeled by CEL method at different time: (a) Misses stress at 500 ns; (b) Misses stress at 1000 ns; (c) Misses stress at 1500 ns; (d) effective plastic strain at 500 ns; (e) effective plastic strain at 1000 ns; (f) effective plastic strain at 1500 ns; (g) temperature at 500 ns; (h) temperature at 1000 ns; (i) temperature at 1500 ns; (j) volume fraction at 500 ns; (k) volume fraction at 1000 ns; (l) volume fraction at 1500 ns.

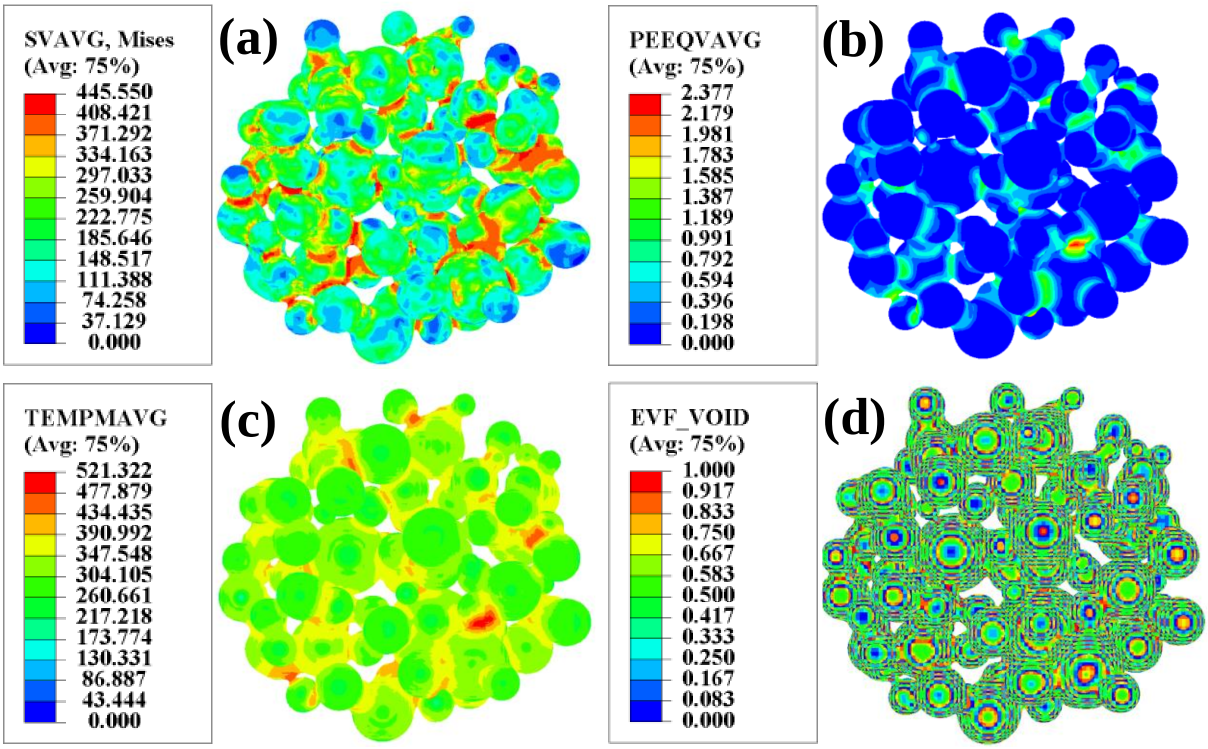

Fig. 4. The top view of Al 6061/Al 6061 deposit after consolidation, representing (a) Misses stress; (b) effective plastic strain; (c) temperature; (d) volume fraction of Al 6061 coating.

Contours of multi particles impacting behavior at different impacting time (500 ns, 1000 ns, 1500 ns) obtained from numerical simulation are shown in Fig. 3. Obviously, with the increment in particle impacting time, the multiple particles experience increasingly intensive and severe plastic deformation. The temperature of the former deposited particles is higher than the subsequent particles because of the subsequent impact of further deposited particles. And the temperature distribution of former particles is more uniform. Due to the severe plastic deformation, the high temperature can be also observed between the deformed multiple particles. Moreover, it is worth nothing that the subsequent particles have a compacting effect on the previous particles and result in better deposition effect. Such an enhanced peening-like effect with the help of high-pressure feed gas will promote the deformation and extrusion of oxide layer at the Aluminum particle surface.

Fig. 4 shows the contours of stress, effective strain, temperature and volume fraction of multiple particles in top view after consolidation. The value of residual stress in the region inside the impacting particles is lower than that of the surrounding area. Fig. 5 shows the contours of stress, effective strain, temperature of substrate in top view after consolidation. It is found that a crater was formed in the flat substrate. The maximum plastic deformation is focused on the surrounding of the contact region rather than the center point. The value of residual stress at the surrounding area of contact region is much higher than that of the center area.

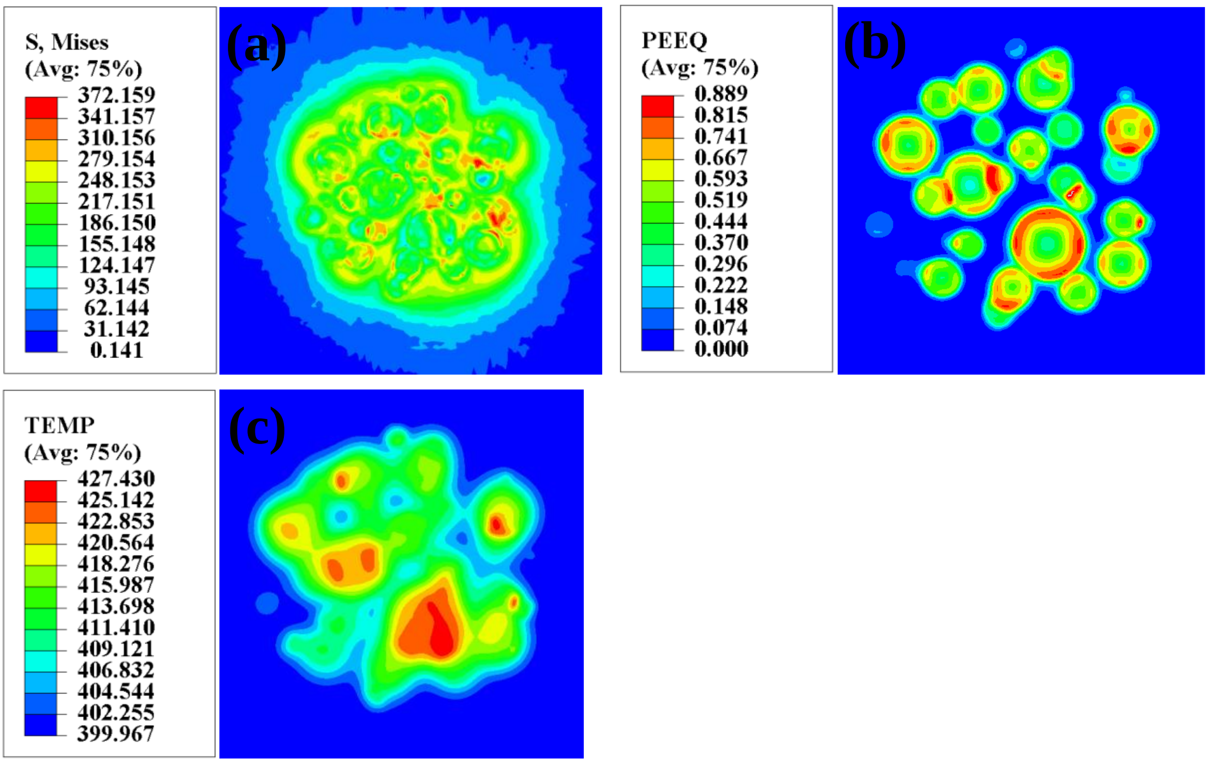

Fig. 5. The top view of Al 6061/Al 6061 substrate after consolidation, representing (a) Misses stress; (b) effective plastic strain; (c) temperature of Al 6061 substrate.

4. CONCLUSION

Based on the CEL simulation, the kinetics of particle impact of cold spray additive manufacturing process are investigated. The irregular interface observed are favored by the high strain shearing, large plastic strain and high pressure which is produced by the impact velocity and collision at the interface region. Through the investigation, there is a possibility of bonding mechanism for the entire high-speed consolidation could be better explained based on the simulation of single particle and multiple particles impacting behavior. Moreover, the 3D model could be used to further identify the suitable processing parameters and develop consolidate window under the various impacting conditions.

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