Numerical Simulation of the Effect of Particle and Substrate Preheating on Porosity Level and Residual Stress of As-sprayed Ti6Al4V Components

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Abstract Nowadays, in the aerospace industry, additive manufacturing and repairing damaged metallic components like Ti6Al4V samples have grabbed attention. Among repairing techniques, solid-state additive manufacturing processes like cold spray are promising because of their unique benefits such as high deposition rate with almost no oxidation in the deposited materials. However, its main drawback is the level of porosity of as-sprayed samples. To increase density and inter-particle bonding, deposited particles must go through more degrees of deformation by increasing particle velocity and particle temperature. In order to increase these two parameters simultaneously, high-velocity air fuel (HVOF) can be utilized. For understanding the effect of using HVOF on particle deformation, a proper elastic-plastic finite-element-based simulation is required. The obtained outcomes show that enhancing particle velocity and providing more kinetic energy will increase particle deformation and sample density. Importantly, increasing particle temperature will seize particle deformation by thermal softening effect, i.e., enhancing as-sprayed sample density, while rising substrate temperature

by preheating will soften the substrate resulting in a decrease in particle deformation.

Keywords elastic-plastic simulation · high-velocity air fuel · particle temperature · porosity level · residual stress · solid-state additive manufacturing

Introduction

In the aerospace industry, a considerable amount of research has been devoted to developing new strategies to enhance the durability of different parts of the current aeroengines. Turbine blades, as an example, are manufactured by Ti6Al4V alloy because of its unique set of properties as high melting point and high tensile strength (Ref 1–6). The metallic Ti6Al4V components used in industry are susceptible to damage; therefore, the need for repairing is raised. Among repairing techniques, solid-state additive manufacturing methods like cold spray seem to be more promising because of their characteristics, such as high deposition rate and no oxidation. Nevertheless, cold spray as a solid-state additive manufacturing technique has a main drawback associated with high porosity levels in as-fabricated samples. These pores have been resulted from insufficient bonding, caused by inadequate particle deformation upon its impact on the substrate surface (Ref 7–13).

Particle deformation can cause bonding in a ring-shaped region known as “adiabatic shear instability.” To understand the formation of this area, at the first nanoseconds of the impact, a pressure gradient spread in both particle and substrate, creating localized shear straining at the gap between two bumping interfaces. The localized shear strain will become adiabatic shear instability by accumulating the impact pressure, which means that thermal softening is

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now overriding strain and strain rate hardening. This can cause a discontinuous increase in strain and temperature values (Ref 14–16). Besides, the out-flowing material jet is formed because of the viscous flow. Finally, this material jet can eject out the broken oxide layers, leading to bonding (Ref 14–15). However, Hassani-Gangaraj et al. (Ref 16) oppose the idea that localized shear stress is the cause of bonding. This investigation was mainly focused on the ineffectiveness of thermal softening on material jet formation. They proposed that material jet is produced because of solid pressure waves interacting with deposited particles' edges.

For realizing the importance of particle deformation more profoundly, some experimental investigations have been carried out. For instance, Chen et al. (Ref 11) deposited Ti6Al4V particles with cold spray by two different carrier gases: nitrogen and helium. He concluded that particle velocity is further increased by using helium compared to nitrogen. Hence, more deformation was observed in deposited particles resulting in a decrement in porosity levels. However, this reduced porosity level still can alter mechanical properties, and as a result, a post-heat treatment approach like annealing or hot isostatic pressure (HIP) is required. These heat treatment methods force the particles to go through the sintering process, reducing the porosity level significantly (Ref 11–12). Accordingly, to minimize the need for a post-heat treatment approach, particle's ability to deform must increase even more. For this purpose and because of the limitations on enhancing particle velocity, increasing particle temperature is proposed as a viable solution (Ref 17).

For considering particle temperature and having a high deposition rate simultaneously, high-velocity air fuel (HVAF) process can be employed as a solid-state additive manufacturing method. In the HVAF process, by combining air and a combustible fuel like propylene, combustion occurs. This combustion can increase both particle velocity and temperature instantaneously. Also, by contemplating flame temperature, particle melting point, and particle size, it is possible to deposit elevated temperature solid particles (Ref 14, 18–20). Moreover, it is essential to observe the effect of using HVAF on particle deformation and porosity level of as-sprayed samples.

For investigating the deformation of deposited solid particles, experimental approaches are incompetent because the deformation happens in tens of nanoseconds, follows dynamic rules, and is nonlinear (Ref 21–22). Hence, a proper set of elastic-plastic models capable of examining high strain rate deformations is required. For elastic exploration, Mie–Gruneisen equation of state (EoS) and for plastic examination, Johnson–Cook (JC) model have been used frequently (Ref 21–22). For solving the noted models, a finite-element-based method like Coupled

Eulerian–Lagrangian (CEL) is needed. Compared to other finite-element-based approaches like Arbitrary Lagrangian–Eulerian (ALE), CEL's advantage is based on assuming an Eulerian particle, which avoids the need of remeshing and having highly distorted elements (Ref 21). Xie et al. (Ref 21) compared CEL and ALE approaches by studying the impact of an aluminum particle on an aluminum substrate. They concluded that CEL could not study particle deformation numerically because only the mean value of each variable is reported for the Eulerian particle. However, it is the most accurate approach to analyze substrate deformation and predict the porosity level of as-fabricated samples (Ref 21).

Besides attempts to study particle deformation deposited by cold spray (Ref 11, 16, 21–26), the effect of copper particle temperature up to 700 °C was investigated when substrate is at room temperature. By rising particle temperature because of the thermal softening effect, the particle flattening ratio increases, and the material jet is produced only from the particle. On the other hand, by increasing copper substrate temperature up to 700 °C while the deposited particle is at room temperature, particle deformation decreases significantly (Ref 17). Furthermore, some attempts have been devoted to estimating the porosity level of as-fabricated samples. For example, the effect of particle temperature up to 523 K has been investigated while copper particles are impinging on an aluminum substrate. The results show that increasing particle temperature and velocity enhances the density of as-sprayed samples (Ref 27).

Conclusively, due to the lack of studies of the porosity level of as-sprayed samples produced by solid particles at elevated temperatures, this paper aims to numerically investigate the feasibility of using HVAF as a solid-state additive manufacturing technique. Therefore, the effect of particle and substrate initial temperature on particle deformation and porosity level of as-fabricated samples are scanned for fulfilling this goal. Accordingly, a proper elastic-plastic finite-element-based method based on Mie–Gruneisen EoS and JC model is used.

Numerical Methodologies

Mie–Gruneisen EoS

Mie–Gruneisen EoS is capable of handling the elastic sections of a high strain rate deformation. This model is developed based on crystal structure and a connection among internal energy, thermal vibrational energy, and the potential energy at zero temperature. It is worth noting that the relationship between vibration energy and thermal vibration pressure is dependent on vibration frequency and

volume but independent of temperature. Using the vibrational theorem and Gruneisen equation, the primary form of Mie–Gruneisen EoS can be illustrated via Eq 1 as follows (Ref 28–29):

$$P - P_H = \Gamma_\rho (E_m - E_H) \quad (\text{Eq 1})$$

where P is total pressure, E_m is internal energy per unit mass, P_H is Hugoniot pressure, and E_H is specific energy. Also, Γ_ρ is Gruneisen coefficient which can be calculated by Eq 2 (Ref 29):

$$\Gamma_\rho = \Gamma_0 \frac{\rho_0}{\rho} \quad (\text{Eq 2})$$

where Γ_0 and ρ_0 are material constants and ρ represented pressure stress. Also, the value for both Hugoniot pressure and Hugoniot energy can be found with the help of Eqs 3 and 4, respectively (Ref 21, 29).

$$E_H = \frac{P_H \eta}{2\rho_0} \quad (\text{Eq 3})$$

$$P_H = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} \quad (\text{Eq 4})$$

where η is equal to $1 - \rho_0/\rho$ and represents the nominal compressive volumetric strain. $\rho_0 c_0^2$ expresses the elastic modulus at small nominal strains. Furthermore, c_0 and s are material constants used for drawing an association between shock velocity (U_s) and particle velocity (U_p) (Ref 21). Finally, by considering all noted formula together, the final form of Mie–Gruneisen EoS can be formed as Eq 5 (Ref 21):

$$P = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} \left(1 - \frac{\Gamma_0}{2} \right) + \Gamma_0 \rho_0 E_m \quad (\text{Eq 5})$$

In the end, this model only can study the hydrostatic behavior; therefore, for examining the deviatoric behavior, a linear elastic model and shear modulus are required (Ref 22).

Johnson–Cook Model

Johnson–Cook model is a plastic model able to examine a high strain rate deformation. This model is represented by Eq 6 (Ref 22).

$$\sigma = \left(A + B \varepsilon_p^n \right) \left(1 + C \ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right) \left(1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right) \quad (\text{Eq 6})$$

where ε_p , $\dot{\varepsilon}_p$, σ , $\dot{\varepsilon}_0$, T_r , T_m , and T are equivalent plastic strain, plastic strain rate, flow stress, reference strain rate, reference temperature, melting point, and temperature, respectively. Constants in this formula are considered as A , B , C , n , and m . This model has been utilized noticeably for

examining the deformation of a deposited particle (Ref 21–22).

Coupled Eulerian–Lagrangian (CEL) Method

In the CEL approach, the mesh is unchanged through the analysis, so the submitted job will not get aborted because of highly distorted elements. Also, CEL can only study substrate behavior numerically because, for the Eulerian particle, only the mean value of each variable can be reported. On the other hand, because CEL can predict particles' final deformed shape, it is considered the approach used in this paper using ABAQUS to investigate Ti6Al4V particles deformation deposited by the HVAF process (Ref 21).

For carrying this simulation, the required material constants for the Ti6Al4V particle and the substrate are shown in Table 1 (Ref 30). Also, the changes of physical properties like density, heat conductivity, heat capacity, and shear modulus with temperature have been taken into account by the formulations noted in the reference (Ref 31). The friction coefficient is assumed to be 0.3 in all the conditions, and the mesh size of the particle and the substrate area under the impact is equal to 1 μm which has already been used in the literature (Ref 21, 32). The Lagrangian substrate's mesh type is C3D8RT (An 8-node thermally coupled brick, trilinear displacement, temperature, reduced integration, hourglass control). For Eulerian particle, mesh type is EC3D8RT (An 8-node thermally coupled linear Eulerian brick, reduced integration, hourglass control). The particle is extracted from the Eulerian part by defining a discrete field, and the interaction between particle and substrate is defined as "General" since there is no specific surface existing for an Eulerian

Table 1 Material constants are used for simulating the deformation of a Ti6Al4V particle deposited by HVAF (Ref 30–31).

Property	Ti6Al4V
Density, kg/m^3	4430
Shear modulus, GPa	41.9
c_0 , m/s	5130
s_0	1.03
Γ_0	1.23
A , MPa	862
B , MPa	331
C	0.012
m	1.1
n	0.34
T_m , K	1903
T_r , K	298
Conductivity, W/m·K	6.6
Heat capacity, J/Kg·K	536

section. The step used for carrying these simulations is considered as “Dynamic, Temp-disp, Explicit” and the time of studying particles deformation is chosen in a way that particle detachment is just about to begin. This is the reason that no particle detachment can be seen in the obtained results. In the end, the boundary condition for Lagrangian substrate is defined as “PINNED” for the bottom and perimeter and only the displacement in “Z-direction” is locked in the symmetric surface perpendicular to “Z-direction.” For the Eulerian part, the velocity of Z is assumed to be zero in the symmetric surface perpendicular to “Z-direction” (Ref 21).

Single Particle Impact

This paper’s first concern is devoted to examining the effect of particle temperature, particle velocity, and substrate temperature (Table 2) on the deformation of a 29 μm solid Ti6Al4V particle impacts on the substrate of the same material, as shown in Fig. 1 (Ref 33). The noted initial particle and substrate temperature has been assumed in a way that no melting will occur during the deformation to maintain the accuracy the noted elastic-plastic simulation. Also, in this examination, the flattening ratio will be utilized to understand particle deformation by using Eq 7 below. Also, the effect of noted parameters on substrate deformation will be investigated by the changes of equivalent plastic strain (PEEQ) and temperature (TEMP) for a specific node by the passage of time.

$$\begin{aligned} &\text{Flattenning ratio}(\%) \\ &= \frac{\text{The maximum hieght of a deformed particle}}{\text{The initial diameter of impacted particle}} \\ &\quad \times 100 \end{aligned} \quad (\text{Eq 7})$$

Multiple Particles Impact

After understanding the influence of particle and substrate initial condition upon impact on their deformation, the

porosity level of as-fabricated Ti6Al4V samples is investigated through modeling multiple particle impact. In order to make the modeling tractable, it is assumed that some agglomerated particles are impinging on the substrate by the pattern shown in Fig. 2. Based on actual Ti6Al4V powders, the Dv (10) and Dv (50) values shown in Fig. 3 will be utilized to capture the particle size distribution effect. Therefore, for different sets of particles and substrate initial conditions, once it is assumed only a unisize 10 μm particles are impinging and alternatively a combination of 5 and 10 μm particles are considered, Table 3.

Porosity Level Investigation

To investigate the porosity level of as-sprayed samples, a method based on extracting a constant cube shape from each as-fabricated sample is required. For each condition, with the help of Eq 8 and counting the number of total elements and the number of elements containing less than 85% void, the porosity level can be calculated. It is worth

Fig. 1 Preliminary state and computational mesh for examining the effect of particle and substrate initial conditions on the deformation of a deposited Ti6Al4V particle on a Ti6Al4V substrate by HVOF process

Table 2 The conditions utilized for investigating the effect of particle temperature, particle velocity, and substrate temperature on particle and substrate deformation upon the impact of a Ti6Al4V particle deposited by the HVOF process.

Condition	Particle temperature, K	Particle velocity, m/s	Substrate temperature, K
V1	873	600/650/700	673
V2	873/973/1073/1173/1273	600	673
V3	1073	600	473/573/673/773

noting that the benefit of utilizing this approach is based on considering the internal porosity in each as-fabricated sample (Ref 30).

$$\% \text{ of Porosity} = \frac{\text{Number of void elements}}{\text{Number of total elements}} \quad (\text{Eq 8})$$

Fig. 2 The initial condition for examining the porosity level, which (a) only 10 μm Ti6Al4V particles and (b) 5 and 10 μm Ti6Al4V particles are deposited by HVOF

Fig. 3 (a) Scanning electron microscope (SEM) image of Ti6Al4V powders and (b) particle size distribution of Ti6Al4V powders

Table 3 Various conditions for examining the effect of particle and substrate initial conditions and particle size distribution on porosity level of as-fabricated samples with Ti6Al4V powders.

Name of case	Particle size, μm	Particle temperature, K	Particle velocity, m/s	Substrate temperature, K
P1	10	873	600/650/700	673
P2	10	873/1073/1273	650	673
P3	10	1073	650	573/673/773
P4	5 and 10	873	600/650/700	673
P5	5 and 10	873/1073/1273	650	673
P6	5 and 10	1073	650	573/673/773

Results and Discussion

Model Validation

Before examining the effect of particle and substrate initial conditions on particle deformation, it is necessary to assure the accuracy of the simulation approach. It is assumed that a 29 μm Ti6Al4V particle is deposited by cold spray, which means that both particle and substrate temperatures are at 298 K. Also, particle velocity is assumed to be 741 m/s (Ref 33). After simulating the noted condition, the final deformed shape of both particle and substrate can be represented by Fig. 4. As illustrated, particle and substrate are significantly deformed, and the particle temperature (TEMPMAVG) and the substrate equivalent plastic strain (PEEQ) values are higher in the edges where adiabatic shear instability can occur. Also, a uniform ring-shaped area with the highest PEEQ can be achieved on the substrate surface. These prove that CEL can predict substrate deformation, particle final deformed shape, and adiabatic shear instability region as it has already been proven by Xie et.al (Ref 21).

On the other hand, by studying the changes of equivalent plastic strain and temperature for substrate and particle

Fig. 4 (a) Particle final deformed shape and (b) PEEQ distribution on the substrate surface after 20 ns of the impact of a 29 μm Ti6Al4V particle with the velocity of 741 m/s and the temperature of 298 K on a Ti6Al4V substrate at the temperature of 298 K

Fig. 5 Changes of (a) particle and substrate PEEQ and (b) particle and substrate temperature versus time

Fig. 6 (a) Changes in the ratio of artificial strain energy and internal energy by the passage of time

as shown in Fig. 5, it is observed that CEL is only capable of studying substrate deformation numerically, which is because of the fact that the value of equivalent plastic strain and temperature should reach a steady-state situation. On the other hand, for the Eulerian particle, only the mean value of each variable can be reported which is lower than the actual value. The initial zero value for particle equivalent plastic strain and temperature is based on the fact that

the material has not reached that specific node yet. Also, the high increase at the beginning of the impact in both equivalent plastic strain and temperature is because of the high strain rate (Ref 21).

Finally, it is necessary to make sure the mesh size is appropriate for the problem to be solved. For that, the ratio of artificial strain energy and internal energy should be less than 5% in the region where a steady-state is reached. This

is because at the beginning of the impact, due to noises, this ratio might be higher than 5%. In the case of the noted simulation, this ratio is around 3%, Fig. 6. This shows that the mish size was defined accurately to control the hour-glass and eliminate the propagation of zero-energy modes, leading to inaccurate outcomes (Ref 21).

Effects of Particle and Substrate Initial Condition on Particle Deformation

Particle Velocity

While using HVAF process as a solid-state additive manufacturing technique, an elevated solid particle will be imping on the substrate surface at high velocity (Ref 14). Therefore, it is necessary to examine the effect of particle

Fig. 7 The effect of particle velocity on kinetic energy.

velocity on its deformation. For this purpose, a solid Ti6Al4V particle with a temperature of 873 K and velocity of 600, 650, or 700 m/s is impacting on a Ti6Al4V substrate with the temperature of 673 K, condition V1 in Table 2. The results show that enhancing particle velocity will increase particle deformation significantly because of improving particle's kinetic energy required for the deformation, Fig. 7 and 8.

By boosting particle velocity, substrate deformation will also be affected, which means that the substrate will deform more, and its equivalent plastic strain (PEEQ) will increase. This increase will be more significant at the first five nanoseconds (ns) of the impact, which can be because of high strain rate deformation. In addition, due to the heat produced during the deformation, the final substrate temperature will rise as shown in Fig. 9. For instance, at 40 ns after the impact, when particle velocity increases from 600 to 700 m/s, PEEQ of the substrate will increase almost 22%, and the maximum temperature of the substrate will also increase by 50 K.

Particle Temperature

Another factor that can alter particle deformation is the temperature which has been taken into account by considering a 29 μm Ti6Al4V particle with the velocity of 600 m/s and temperature of 873, 973, 1073, 1173, and 1273 K impacting on a Ti6Al4V substrate with a temperature of 673 K, “Case V2” in Table 2. Since increasing a component temperature will seize the deformation with the help of thermal softening, a particle will deform more noticeably as its initial temperature is enhanced, Fig. 10.

Fig. 8 The final shape of a Ti6Al4V particle impacted with the initial temperature of 873 K on a Ti6Al4V substrate with an initial temperature of 673 K and particle velocity is (a) 600, (b) 650, and (c) 700 m/s

Fig. 9 The examination of particle velocity effect on the changes of substrate (a) PEEQ and (b) temperature by the passage of time

Fig. 10 The final deformed shape when a Ti6Al4V particle with the velocity of 600 m/s impacted on a Ti6Al4V substrate with the temperature of 673 K when initial particle temperature is (a) 873, (b) 973, (c) 1073, (d) 1173, and (e) 1273 K

Fig. 11 Effect of particle temperature on the substrate (a) PEEQ and (b) temperature by the passage of time

Moreover, when an elevated temperature particle is impinging on a substrate, the produced material jet is only formed of the particle itself. On the other side, a softer particle will apply less force on the substrate surface for its deformation, so it can be expected that substrate deformation is affected negatively by enhancing particle temperature. Also, because of having an adiabatic heat exchange system in the contact area of deposited particle and substrate, no heat will exchange, which means that particle temperature has a limited effect on the final substrate temperature as shown in Fig. 11.

When a solid particle is impinging on a substrate, adhesion requires to happen to produce a coating. Some researchers hypothesize that adhesion comes from a welding-like process which a localized melting occurs in the contact area. As a result, particles and substrate will diffuse into each other, and bonding will occur. On the other hand, if localized melting does not occur, the bonding can be the result of plastic deformation (Ref 21). In this simulation, in all conditions, neither particle nor substrate temperature exceeds the melting point. Therefore, it can be expected that only plastic deformation and having a pressure gradient is the cause of adhesion.

Substrate Temperature

In HVOF process, because of the existing flame, heating the substrate is inevitable. In addition, preheating the

substrate is an effectual factor to increase the adhesion of particles to the substrate. So, it is essential to take substrate temperature into account (Ref 14). For inspecting the effect of the noted variable on the particle and substrate deformation, it is assumed that a particle with the temperature equal to 1073 K and with the velocity of 600 m/s is impinging on a substrate surface with the temperature of 473, 573, 673, or 773 K, “V3” in Table 2. By having higher substrate temperature, particle deformation will decrease, and the importance of material jet becomes less critical, Fig. 12. This reduction in particle deformation is based on increasing substrate temperature, which cause the solid deposited particle impacts on softer surface. So, the particle will deform less and substrate deformation increases which can be understood by studying PEEQ and TEMP changes by the passage of time, Fig. 13 (Ref 17, 21). For instance, by increasing substrate temperature from 473 to 773 K, the value of PEEQ and TEMP will increase around 20 and 30%, respectively.

To put it in other words, a higher initial temperature enhances the role of the thermal softening effect. Thermal softening will decrease the material resistance to shear flow so that the elevated temperature part will deform more noticeably by the same amount of provided energy comparing to the cooler part. As a result, the plastic strain will increase, and more heat will be produced. This will increase the final temperature even to values higher than the melting point (Ref 27).

Fig. 12 The final deformed shape when a Ti6Al4V particle with the velocity of 600 m/s and the temperature equal to 1073 impacted on a Ti6Al4V substrate when its initial temperature is (a) 473 K, (b) 573 K, (c) 673 K, and (d) 773 K

Fig. 13 Effect of substrate temperature on the substrate (a) PEEQ and (b) TEMP by the passage of time

Fig. 14 Effect of particle velocity, particle temperature, and substrate temperature on a deposited Ti6Al4V particle flattening ratio

Flattening Ratio

Particle deformation is quantified by investigating the flattening ratio has been calculated via Eq 8 and reported as shown in Fig. 14. As illustrated, particle deformation will increase by enhancing particle velocity because of improving particle initial kinetic energy. For instance, by increasing particle velocity from 600 to 700 m/s, the flattening ratio improves by 13.5%. In addition, increasing particle temperature will lead to thermal softening, which will boost particle flattening ratio and deformation. For example, flattening ratio will increase by 49.4% when particle temperature raises from 873 to 1273 K. On the other hand, rising substrate temperature and having a softer substrate will decrease particle deformation and the flattening ratio (Ref 17). To be more specific, increasing substrate temperature from 473 to 773 K will decrease flattening ratio by 7.63%. Hence, it can be concluded that increasing particle temperature can increase flattening ratio and particle deformation more significantly comparing to increasing particle velocity. This shows that when particle velocity is high enough, particle deformation is affected

more noticeably by particle thermal softening compared to particle kinetic energy.

Porosity Level of As-Fabricated HVAF Samples

In this step, based on the conditions mentioned in Table 3, the effect of particles and substrate initial conditions on porosity level are examined. First, it is essential to visualize the density of as-sprayed samples. For that purpose, the conditions in which particle temperature is 1273 K, particle velocity is 650 m/s, and the substrate temperature is 673 K will be used as the example of as-sprayed samples to study the particle size distributions effect. As shown in Fig. 15, both final shapes are highly dense. However, for examining the internal porosity, i.e. Fig. 16, each deformed shape's outer surface is eliminated. This presents that when 5 μ m particles are in between 10 μ m particles, more porosity can be achieved, which is because of blocking the deformation of 10 μ m particles. Therefore, it is important to use an approach to count internal pores in as-fabricated samples for measuring porosity level, which has already been explained in previous section.

Based on the described approach, for the condition when only 10 μ m with initial temperature equals to 1273 K and velocity of 650 m/s are impacting on the substrate at the initial temperature equals to 673 K, a cube has been extracted, Fig. 17. Then, the porosity level is calculated and reported in Fig. 18. For both cases, the porosity level will decrease by enhancing particle temperature and velocity because of having particle thermal softening and improving particle kinetic energy, respectively. For instance, when only 10 μ m particles impact substrate, by increasing particle velocity from 600 to 700 m/s, the porosity level decreases by 75%. This value for the conditions in which both 5 and 10 μ m are impacting on the substrate is equal to 53%. Moreover, by increasing impinging particles temperature from 873 to 1273 K, the porosity level decreases

Fig. 15 The final deformed shape of conditions which Ti6Al4V particles temperature is 1273 K, particles velocity is 650 m/s, the substrate temperature is 673 K, and (a) only 10 μm particles and (b) 5 and 10 μm particles impacted on Ti6Al4V substrate

Fig. 16 Investigating the internal porosity of the conditions that Ti6Al4V particles temperature is 1273 K, particles velocity is 650 m/s, the substrate temperature is 673 K, and (a) only 10 μm particles and (b) 5 and 10 μm particles impacted on Ti6Al4V substrate

Fig. 17 (a) Cross section view of 18 particles with 10 micrometers deposited Ti6Al4V particles with a temperature of 1273 K and velocity of 650 m/s impacting on the substrate with initial temperature equals to 673 K, (b) Extracting a cube in the middle of the deposited part

Fig. 18 The porosity level of each condition is noted in Table 3 when only 10 μm or 5 and 10 μm Ti6Al4V particles are deposited on Ti6Al4V substrate by HVOF process

almost by 81 and 60 % when only 10 μm particles and a combination of 5 and 10 μm particles are impacting on the substrate, respectively. On the other hand, although enhancing substrate deformation will decrease particle deformation, but because of the peening effect, the porosity level remains almost unchanged (as described in 17, 34). To provide more details, by increasing substrate temperature from 573 to 773 K, the porosity level of as-sprayed samples once only 10 μm particles and a mixture of 5 and 10 μm particles drop almost by 34 and 14%, correspondingly.

It can be concluded that for enhancing samples' density, the most influential parameters are particle velocity and temperature. On the other side, increasing substrate temperature will have an insignificant effect on density

enhancement of as-sprayed coatings. Also, by adding 5 μm particles in between 10 μm ones, the porosity level will increase because the amount of inter-particle pores will rise. This can be related to the type of particle impact pattern, which will cause deformation blockage of 10 μm particles by 5 μm particles.

Residual Stress of As-sprayed HVOF Components

During cold spray process, the residual stress can be rooted in peening effect, thermal stress, and quenching. Peening effect occurs because of the impact of high-velocity particles. Thermal stress can be based on the mismatch of thermal expansion coefficient between particles and substrate, which can lead to have either tensile or compressive residual stress. In the end, quenching is defined by fast cooling rate of the deposited particles or substrate (Ref 27). While particles are impinging on already deposited layers, peening effect and quenching will define the final residual stress. The prominence of peening effect (compressive stress) or quenching (tensile stress) is based on the temperature difference between depositing particles and the temperature of already deposited particles, the ability to be plastically deform, and work hardening properties (Ref 35).

In this paper, for examining the residual stress, the pressure stress values at 34 ns after the impact have been selected on the symmetric axis (y-axis), Fig. 19. In the presented outcomes, the normal distance has been used, in which zero value is the contact area between deposited particles and substrate and -1 represent the bottom surface

of substrate. Also, it is worth noting that compressive stress is presented by positive sign and tensile stress is reported by negative sign. In the end, because the density of samples was higher when only 10 μm Ti6Al4V particles were impinging, only the residual stress in these as-sprayed samples will be investigated in this section.

First, in all conditions, the residual stress in substrate near the contact surface is compressive, which represents the importance of peening effect. To be more specific, when particle velocity increases from 600 to 700 m/s because of rising the impact kinetic energy, the peening effect becomes more significant. Therefore, the value of maximum compressive stress in substrate will increase from 461 to 521 MPa. On the other hand, increasing particle temperature will have more noticeable effect on particle itself because of thermal softening. This leads to the fact that increasing particle temperature from 873 to 1273 K while substrate temperature is 673 K will decrease substrate residual stress from 406 to 368 MPa. This can be related to the fact that increasing particle temperature will seize its deformation and decrease equivalent plastic strain of substrate and its deformation, Fig. 11. Finally, when substrate temperature increases from 573 to 773 K, because of thermal softening effect, its deformation will increase. Therefore, Ti6Al4V substrate residual stress near the contact surface will decrease gradually from 483 to 438 MPa. Having higher substrate temperature will increase the influence of thermal softening resulting in lower residual stress.

Fig. 19 Effect of (a) particle velocity, (b) particle temperature, and (c) substrate temperature on residual stress distribution in deposited 10 μm Ti6Al4V particles on Ti6Al4V based on conditions noted in Table 3

In the next step, it is important to study the effect of particle and substrate initial conditions on the residual stress of deposited particles. For initial deposited layers, by increasing all three variables, i.e., particle temperature, particle velocity, and substrate temperature, the residual stress will be compressive because of peening effect. On the other side, on the top layer of deposited particles, because peening effect is not significant, particles cannot deform expressively, so the residual stress will be tensile. To examine each variable's effect in more detail, when particle velocity increases from 600 to 700 m/s, because of providing more kinetic energy and particle deformation, the maximum residual compressive stress will increase from 843 to 871 MPa. Also, the maximum residual compressive stress will increase from 926 up to 1170 MPa when particles initial temperature increases from 873 to 1273 K due to thermal softening. In the end, increasing substrate temperature has a insignificant negative effect on porosity level, but a noticeable undesirable consequence on particle deformation, Fig. 14 and 18. Therefore, because of insignificant changes in porosity level, the changes in residual stress will also become unimportant. For instance, by increasing substrate temperature from 573 to 773 K, the maximum residual compressive stress increases only for 50 MPa. In the end, it can be concluded that particle temperature can increase compressive residual stress in a more noteworthy way comparing particle velocity or substrate temperature.

Conclusion

This paper targets to investigate the effect of using HVAF to enhance deposited solid Ti6Al4V particle velocity and temperature with the hope to increase the density of as-sprayed samples. Thus, a proper simulation method must be applied for fulfilling this purpose by considering the Mie–Grüneisen equation of state and Johnson–Cook for elastic and plastic parts of the simulation, correspondingly. Moreover, a finite-element-based approach known as coupled Eulerian–Lagrangian (CEL) is required to solve the noted models.

Applying the noted simulation shows that enhancing particle velocity will provide more kinetic energy for the deformation, which increases particle deformation. This can enhance the density of as-sprayed samples and increase the residual compressive stress in deposited particles. Also, providing more particle temperature will seize particle deformation because of thermal softening, which can increase sample's density more extensively alongside the residual compressive stress in as-fabricated components. On the other hand, by enhancing substrate temperature, the substrate will go through the thermal softening process and becomes soft. Therefore, the particle impinging on a softer

surface and its deformation will decrease noticeably. Although enhancing substrate temperature will decrease particle deformation, its effect on porosity level and residual stress is insignificant due to the pining effect. In the end, because of the chosen pattern when multiple 5 and 10 μm Ti6Al4V particles are impinging on a Ti6Al4V substrate, the enhancement in density will not be as significant as when only 10 μm Ti6Al4V particles are impacting. This can be because of deformation blockage role that 5 μm are performing.

So far, by the help of depositing Ti6Al4V particles by using cold spray, it has been shown that enhancing particle velocity by using helium as the carrier gas will lead to more particle deformation and density [11]. However, to the author's knowledge, the effect of particle and substrate preheating by using another thermal spray technique like HVAF as a solid-state additive manufacturing technique has not been investigated. Hence, to validate the outcomes noted above and to understand the effect of particle and substrate preheating, it is necessary to use HVAF process to manufacture Ti6Al4V samples by depositing powders represented in Fig. 3 above.

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