

NUMERICAL ANALYSIS ON SUBSTRATE MELTING DURING PLASMA-SPRAYING CAST IRON ON ALUMINUM SURFACE

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Abstract. During plasma spray process, metallurgical bonding between the impinging particles and the substrate surface can provide substantial contribution for the improvement in the adhesion strength of the coatings. In this work, a one-dimension heat transfer model was used to investigate the integrated effect of cast iron droplet solidification, cooling, and melting and resolidification of aluminum substrate during spraying. The results indicated that the substrate surface temperature could be higher than its melting point during the splat deposition. This indicates that the substrate melting will take place under present condition. On the other hand, it is also found that initial substrate temperature has a profound effect on the development of melt undercooling in a splat, the splat bottom temperature, and the substrate surface temperature. A high initial temperature of the substrate promotes a deeper melting of substrate surface, which may lead to the metallurgical bonding formation between the cast iron splat and the aluminum substrate.

1. INTRODUCTION

In recent years, great interests were focused on the research of the protective coatings for the cylinder bores of aluminum alloy engines [1-4]. Plasma spray is an effective and relatively simple method to prepare these coatings. However, separating of the coatings from the substrate during operating, resulting from poor coating-substrate adhesion strength, limits the application of plasma sprayed cast iron coatings in engine fabrication [5,6]. During plasma spray process, metallurgical bonding between the impinging particles and the substrate surface due to substrate melting during droplet-substrate interaction can provide substantial contribution for the coating adhesion strength [7,8]. Understanding of melting and resolidification of the substrate is thus essential for the integrality of coating-substrate system.

In this work, a one-dimension heat transfer model was used to investigate the solidification, cooling of

the cast iron droplet, and the surface melting of the aluminum substrate during spraying.

2. MODEL OF THE SPLAT COOLING PROCESS

The formation of a plasma-sprayed cast iron splat can be simplified as a layer of liquid cast iron at initial temperature T_p and thickness of δ_1 is suddenly brought into contact at time zero with a much thicker aluminum substrate at initial temperature T_0 . The diameter of the splat is usually much larger than its thickness, thus permitting edge effects to be neglected. For simplification, the convection of melt is neglected. The physical property of the splat and the substrate, such as density, thermal conductivity and specific heats are all assumed to be temperature- and phase-independent, considering the scarcity of the available data. The splat top boundary is considered as an adiabatic boundary as well as that of the substrate bottom surface. With

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Table 1. Material properties used in calculation.

Parameters	Unit	Value
Splat density (ρ_1)	kg/m ³	7570
Splat specific heat (c_{p1})	J/kg K	480
Splat thermal conductivity (λ_1)	W/m K	39.2
Substrate density (ρ_2)	kg/m ³	2700
Substrate specific heat (c_{p2})	J/kg K	880
Substrate thermal conductivity (λ_2)	W/m K	238
Heat transfer coefficient (h)	W/m ² K	$10^6, 10^7, 10^8$
Initial splat temperature (T_p)	K	1623
Initial substrate temperature (T_0)	K	300~773
Splat thickness (δ_1)	μm	0.8, 1, 2
Substrate thickness (δ_2)	μm	1000
Substrate melting point (T_m)	K	933

these assumptions, the splat cooling and solidification can be considered as a one-dimensional heat transfer problem. The non-perfect contact heat transfer at the splat-substrate interface is represented by an interfacial heat transfer coefficient, h , which is assumed to be a constant.

One-dimension heat conduction equation for the splat and the substrate can be expressed as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \quad (1)$$

where ρ is the density, c_p the specific heat, λ the thermal conductivity, T the temperature, t the time, and x the distance normal to the substrate surface.

A finite-difference method was employed to evaluate temperature matrix in the splat and the substrate on the base of Eq. (1), together with the initial and boundary conditions. Table 1 presents the material data adopted in this numerical study.

In the case of this work, a non-equilibrium condition may exist since cast iron crystalline growth needs to start from the substrate surface, which is always at a temperature that is much lower than the equilibrium temperature. In other words, significant melt undercooling must be developed before growth could take place. On the other hand, a large melt undercooling may also accelerate the cast iron nucleation process. Therefore, there exists a competition between the cast iron nucleation on the substrate surface and the growth directly from the substrate surface, both are strong functions of the melt undercooling and the substrate surface temperature. At this moment, a detailed treatment of nucleation and growth kinetics of cast iron crystalline phase is very difficult. Here, only the initial

melt undercooling before nucleation or crystalline growth takes place will be considered. This can be drawn by removing the equilibrium solidification from our model and let the melt cool down continuously below the melting point without interruption.

3. RESULTS AND DISCUSSION

3.1. Splat cooling

Fig. 1 shows the calculated temperature distributions at various time instants in a splat. It is found that a positive temperature gradient exists in the liquid in front of solid-liquid interface during the entire time of splat solidification or cooling, which is consistent with the results of previous study [9]. If the melt is undercooled without solidification, a large temperature gradient develops within a thin layer of the melt close to the substrate (see Fig. 1 at $t =$

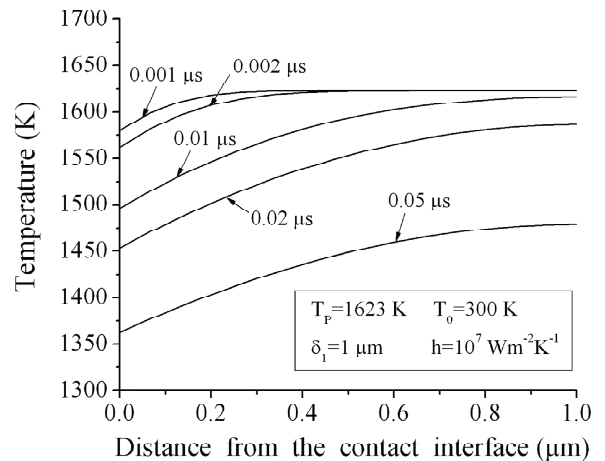


Fig. 1. Temperature distributions within cast iron splat at various time instants.

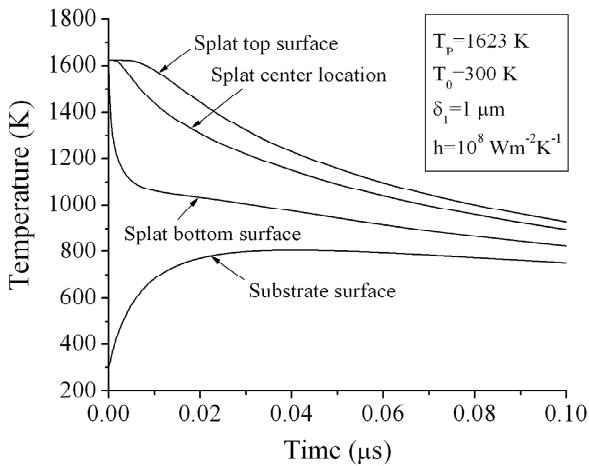


Fig. 2. Temperature histories of cast iron splat and substrate surface.

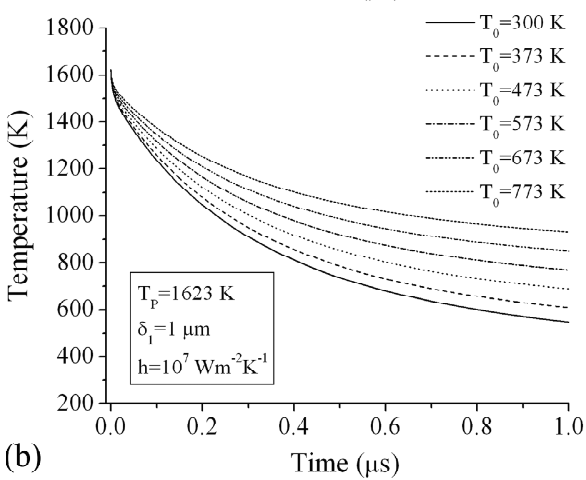
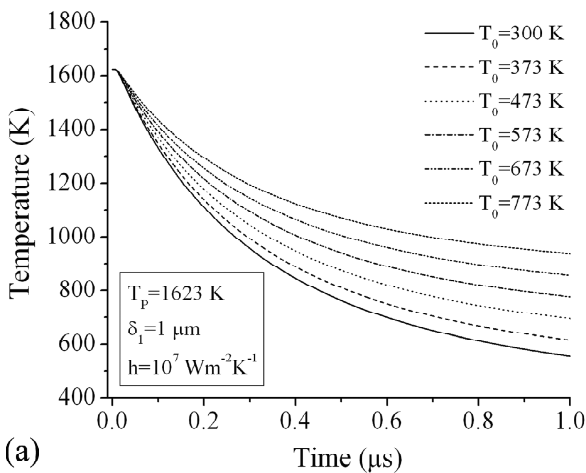


Fig. 3. Temperature histories of (a) splat top surface and (b) splat bottom surface at different initial substrate surface temperatures.

0.001 μ s). The temperature at the splat bottom surface drops very quickly first but will decrease slowly for a fairly long time. It is expected that grain growth from the substrate surface will take place at this moment if the compact contact of the splat with the

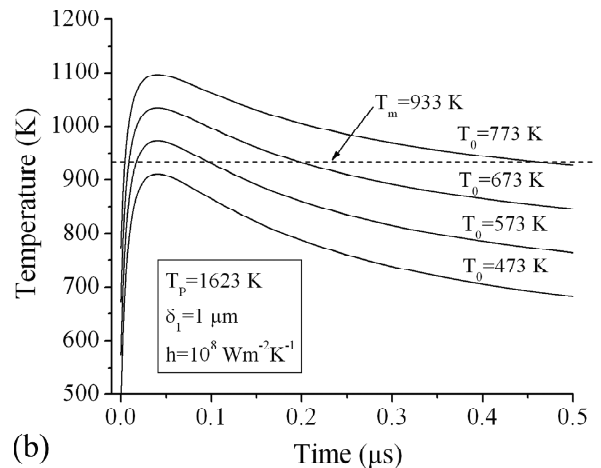
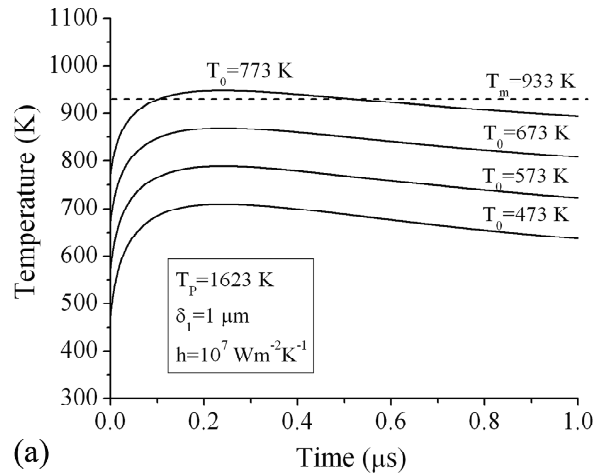


Fig. 4. Temperature histories of substrate surface calculated with different interfacial heat transfer coefficients.

substrate is possible. Of course, under such a high melt undercooling, cast iron nucleation is also possible. A high initial temperature of the substrate may help increase the substrate surface temperature where the melt is in contact with, and then stimulate the melting and resolidification of the substrate surface.

Fig. 2 shows the calculated temperature history of the splat top surface, splat center, splat bottom surface, and substrate surface when a splat is deposited on aluminum substrate at an initial substrate temperature of 300K. As one can see, the substrate surface temperature rises quickly to near 800K in about 0.02 ms, while the splat temperature at the bottom surface will drop to about 1050K.

Fig. 3 shows the effect of the initial temperature of the substrate on the temperature change of cast iron splat top surface (Fig. 3a) and splat bottom surface (Fig. 3b). The temperature of the splat top surface remains at the beginning of the cooling, and

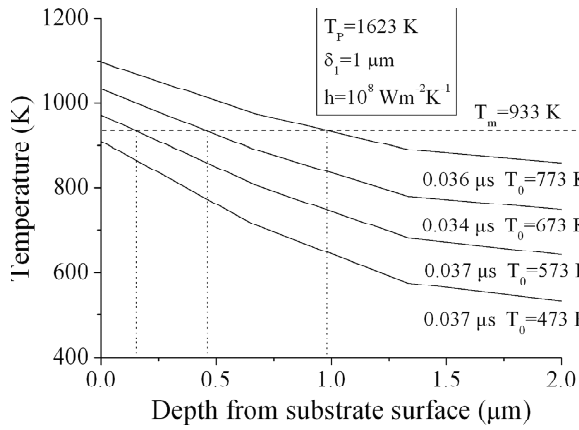


Fig. 5. Maximum melting depths in the substrate at different initial substrate temperatures.

then drops down fast, whereas the splat bottom surface drops very fast to a low temperature in a very short time and then remains at that temperature for a while before it slowly drops down. Specially, increasing the substrate initial temperature will increase the lowest splat surface temperature that can be reached, indicating a possibility of increasing the substrate surface temperature for next splat deposition.

3.2. Substrate melting

Fig. 4 shows the calculated temperature history of the substrate surface with different splat-substrate interfacial heat transfer coefficient. It is found that the substrate surface temperature increases quickly at first to a maximum value and then slowly drops down. It is also clear that the substrate temperature increases with the increase of the initial substrate temperature during the whole cooling process. From the figures, one also can found the time at which the melting of the substrate starts and resolidification ends at different initial substrate temperatures. Apparently, the initial substrate temperature is important for the substrate melting and resolidification.

For the results calculated in this work, the interfacial heat transfer coefficient was assumed to be constant during the entire process. In reality, the interfacial thermal contact resistance is generally a function of time due to temperature variation and solidification [10]. From Fig. 4, it can also be seen that the increase of the interfacial heat transfer coefficient results in a significant change of the substrate melting from melting at high initial substrate temperature to melting at low initial substrate temperature. Moreover, the decrease of

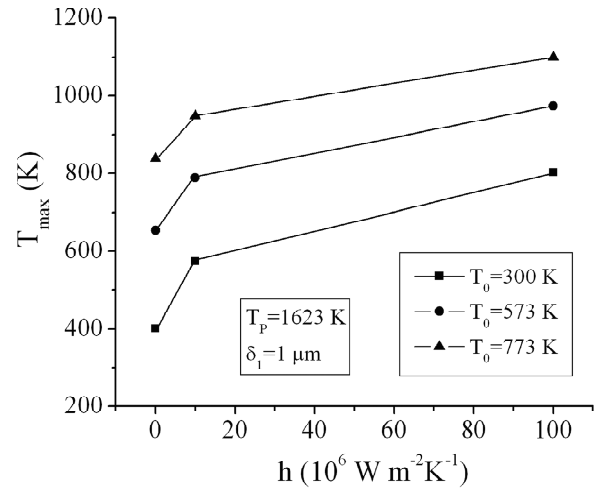


Fig. 6. Variations of maximum temperature of substrate surface with the interfacial heat transfer coefficient.

the interfacial heat transfer coefficient remarkably postpones the melting of the substrate surface.

The melting depth achieved in the substrate is an important parameter for splat-substrate bonding quality. Different maximum melting depths may also result in different microstructure and coating quality. Generally, a large melting depth might be useful to ensure a good bonding, but this may affect the microstructure of the substrate. Here, the maximum melting depth corresponds with the melting depth when the substrate temperature reaches maximum value. From Fig. 4b, it can be seen that maximum substrate surface temperatures appear at around 0.036 μs at different initial substrate temperatures. According to this, the maximum melting depths in the substrate at different initial substrate temperatures can be obtained, as shown in Fig. 5.

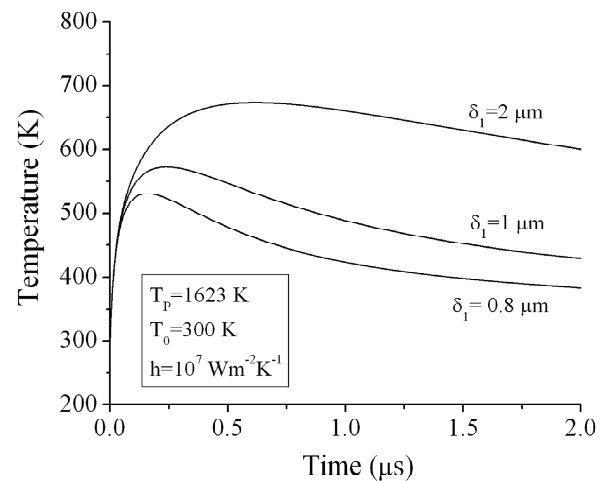


Fig. 7. Temperature history of substrate surface for three splat thicknesses.

It can be seen that the maximum melting depth increases from about 0.15 to 0.97 μm with the initial substrate temperature increasing from 573 to 773K.

From above analysis, the maximum substrate surface temperature determines the maximum melting depth. Thus, the factors that determine the maximum substrate surface temperature will influence the maximum melting depth. Fig. 6 shows the interfacial heat transfer coefficient dependence on the maximum substrate surface temperature (T_{max}). It is clear that the interfacial heat transfer coefficient has distinct effect on T_{max} . Therefore, the increase in the interfacial heat transfer coefficient will greatly increase the maximum melting depth. In addition, the splat thickness also affects the substrate surface temperature as well as the maximum substrate surface temperature during the deposition process, as shown in Fig. 7. It can be seen that the increase of the splat thickness contributes to the increase of the maximum substrate surface temperature. This indicates that the increase of splat thickness will lead to deep melting of the substrate surface.

4. CONCLUSIONS

A one-dimension heat transfer model was used to investigate the integrated effect of cast iron droplet solidification, cooling, and melting and resolidification of aluminum substrate during spraying. It is found that initial substrate surface temperature has a profound effect on splat cooling and the substrate surface temperature. The results also show that the substrate melting will take place at high initial substrate surface temperature. On the other hand, high initial substrate temperature, interfacial heat transfer coefficient, and the increase of the splat thickness promote a deeper melting of substrate surface, which may lead to the metallurgical bonding formation between the splat and the substrate.

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