Protective Plasma Sprayed Coating for Thermo-Sensitive Substrates

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Abstract. Plasma spray is one of the surface treatment techniques that consist on the deposition of a thin coating onto a targeted substrate. Coating is built up by successive accumulation of layered splats resulting from impact and solidification of molten particles into thin ''splats'' onto the substrate. The process of droplet impact, spreading and solidification is then a crucial process in coating formation. This technique may be also used for thermo-sensitive materials such as wood by applying a metallic coating for protective or decorative purposes. However, when applying a ceramic coating which provides a high protection against hot temperatures like fire, wood may be damaged because of the high temperature at which the ceramic molten particles arrive at the substrate. In this paper, a numerical simulation based on the Finite Elements Method is carried out in order to simulate the process of the first splat formation onto a wood substrate under traditional plasma spraying conditions. The computations are carried out on a fixed eulerian structured mesh using the level set method to track the interface between the molten particle and surrounding gas. The effects of operating conditions as well as the droplet characteristics that allow applying ceramic coating onto a wood substrate without any damage to this thermo-sensitive material are investigated.

1. Introduction

Wood, which is an organic and heterogeneous material, represents an integral part of our usually life. It has been used for thousands of centuries extensively in several engineering and industrial applications especially the construction. Its importance has been started since its utilization by humans for building shelters, huts, boats, etc. and until now is still a crucial material not only in construction, but also for furniture such as chairs, doors, frames, beds, etc. [1]. Furthermore, wood currently attract particular attention owing to large demands for sustainable development. However, this material may be further damaged by several factors such as moisture, microbial growth, UV light also the fire that represents an important danger to this material leading to lose its basic properties, environmental quality and then its durability. To conquer all these problems, several treatments are available: impregnation [2], retification [3], drying [4],etc. In the other hand, a relatively new technique in the domain of wood surface treatment which has become increasingly popular due to its increased performance is the plasma spray technique [5,6]. This technique consists of the deposition of a metallic or ceramic hard coating having a physical thickness on the substrate to be covered. This coating is obtained by injecting the powdered material to be deposited into a plasma jet where the particles are heated and propelled at high velocity and high temperature toward the surface to be covered where they impact, flatten rapidly and solidify in the form of individual splats. Coating is built up over the original surface when millions of these splats are accumulated on the top of each other layer by layer. However when treating wood by plasma spray, it receives two thermal solicitations: the first one is the direct flow of the plasma jet and the other one is the average temperature at which the molten particles of the material to be deposited impact onto the substrate. The direct flow of the plasma jet may be avoided by blowing a cold high flow of air which cools the surface of the substrate and deflects the hot jet, while the thermal effect of the molten particles resulting from the thermal energy released from the droplets to the substrate leads to increase the surface temperature. Therefore a pyrolysis temperature front can propagate in the wood leading to destroy its structure and thus its durability [7].

In this study, a numerical simulation based on the Finite Element Method is performed to simulate the process of a ceramic splat formation resulting from spreading and solidification of a ceramic molten droplet (alumina) onto a wood substrate and also to investigate the effect of droplet characteristics such as initial temperature on the substrate which can help to optimize the conditions of the coating deposition and thus to avoid damage when treating the wood substrate. The choice of a ceramic coating such as alumina is due to its improved properties such as the superb resistance to high temperatures environment like fires.

2. Numerical formulation

Fig. 1 shows the geometry and the initial configuration of the problem; a *20 µm* molten alumina particle impacts onto a rigid substrate at a normal incidence with an initial velocity V_i. The fluid flow is modeled by using the full Navier-Stokes equations for incompressible flow (Eq.1 and Eq.2):

$$\rho\frac{\partial u}{\partial t}+\rho(u\nabla)u=-\nabla p+\nabla.\mu(\nabla u+(\nabla u)^T)+\rho g+F_{TS}+F \quad (1)$$

$$\nabla.u = 0 \quad (2)$$

here u is the velocity, p, ρ and μ are respectively the pressure field, density and dynamic viscosity of each fluid, g is the gravitational acceleration and F_{TS} represents the surface tension forces. The Navier Stokes equations are coupled with the Level Set method [8] in order to track and follow the evolution of the interface between the two fluids (liquid and surrounding gas). In this method, the interface is represented by a certain level set or iso-contour of a globally defined function: the level set function ϕ. This function ϕ is a smoothed step function that equals *(0)* in a domain and *(1)* in its complementary part. Across the interface, there is a smooth transition from *(0)* to *(1)* and the interface is represented implicitly by the *0,5* iso-contour (Fig.1). The interface moves with the fluid velocity u, this is described by the following equation:

$$\frac{\partial\phi}{\partial t}+u.\nabla\phi=\gamma\nabla.(\varepsilon\nabla\phi-\phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}) \quad (3)$$

The terms on the left-hand side of Eq.3 give the correct motion of the interface, while those on the right-hand side are necessary for numerical stability. The parameters ε and γ determine the thickness of the region and the amount of re-initialization or stabilization of the level set function respectively. Consequently, the change in properties for the different phases is captured by the following equation:

$$\alpha=\alpha_{gaz}+\phi(\alpha_{liquide}-\alpha_{gaz}) \quad (4)$$

α may be the viscosity, the density or thermal conductivity.

For reasons of symmetry, only the droplet half is modeled and the flow is modeled by using a 2D axi-symmetric rectangular computational domain with a fixed and uniform grid (Fig.1).

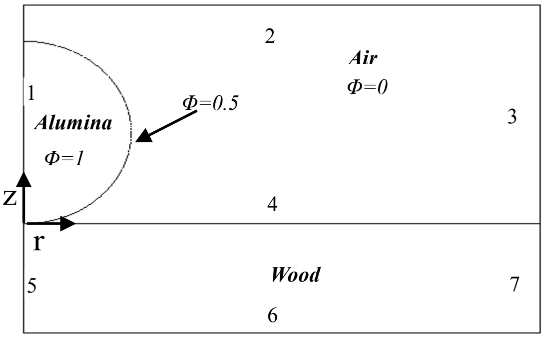

Fig.1. Initial configuration and computational domain. Numeric labels 1 to 7 refer to boundaries for which conditions are set on table 1.

The heat exchanges between the molten particle, air and substrate are modeled by using the energy equation (Eq.5):

$$\rho\, Cp\frac{\partial T}{\partial t}+\nabla\cdot(-\lambda\nabla T)=-\rho\, Cp\; u\nabla T \quad (5)$$

where T, ρ and Cp denote respectively temperature, density and specific heat. The term on the right hand side is introduced to include the convective heat effects. The energy equation is solved in all the geometry of the problem. As the droplet spreads on the cold substrate, it cools down and solidifies, so to tack into account the latent heat related to the solidification, the specific heat Cp in the energy equation (Eq.6) must be changed as follow:

$$Cp = Cp_{solide} + \frac{\Delta H}{T_m} . f + \Delta H . \delta \quad (6)$$

where f is a smooth Dirac delta function with nonzero values in a range of temperature equal to ΔT and its integration over temperature is equal to unity, ΔH the latent heat of the transition, T_m the melting temperature. ΔT is the temperature gap between liquidus temperature ($T_m+\Delta T$) and solidus one ($T_m-\Delta T$) and δ is a Gaussian curve given by (Eq.7):

$$\delta = \frac{\exp(-(T-T_m)^2/(\Delta T)^2)}{\Delta T\sqrt{\pi}} \quad (7)$$

The source term F in (Eq.1) is defined in (Eq.8) and serves to slow down the velocity of the fluid at the phase-change interface and eventually arrests its motion as the droplet cools down.

$$F = \frac{(1-\beta)^2}{\beta^3+\eta} . C . u \quad (8)$$

In (Eq.8) C is the mushy zone constant (should have high value to produce a proper damping), η arbitrary constant (should have small value to prevent division by zero), u the spreading velocity and β is the volume fraction of the liquid phase, given by (Eq.9):

$$\beta = \begin{cases} 0 & T < T_m - \Delta T \\ \dfrac{T - T_m + \Delta T}{2\Delta T} & T_m - \Delta T \le T \le T_m + \Delta T \\ 1 & T > T_m + \Delta T \end{cases} \quad (9)$$

To take into account the discontinuity of temperature at the interface due to the non perfect contact between the droplet and the substrate, the thermal contact resistance (TCR) is introduced and set to 10^{-7} $m^2.K/W$ [9]. The boundary conditions and the thermo-physical properties of different materials used in this study are listed respectively in table1 and table 2.

Table 1. Boundary Conditions for Simulation of Droplet Spreading and Solidification.

Boundary	Navier-Stokes Equations	Heat transfer Equation
1	Axial symmetry	Axial symmetry
2,3	No slip condition	Insulation
4	No slip condition	TCR
5	Not active	Axial symmetry
6,7	Not active	Insulation

The numerical model is solved using an Eulerian approach and a Finite Element Method implemented in Comsol software. Its validation was presented in our former papers [10].

3. Results and discussion

Fig. 2 displays different stages of the process of impact, spreading and solidification of a micrometric alumina droplet (*Di=20µm*) onto a rigid wood substrate. The initial temperature of the droplet is set to *2400 K* very close to the solidification point *2323 K* of the ceramic material (alumina) while the temperature of the substrate is set to *300 K*. The average impact velocity selected was chosen to be low (*50 m/s*). These droplet conditions are chosen in order to minimize damage that could be happen to the wood substrate.

The droplet has a spherical shape before impact, and as soon as it hits the substrate ($t = 0$ *µs*), it begins to spread on the substrate, cools dawn and solidify. The droplet is completely solidified at about *48 µs*. It should be noted that the morphology of the splat formed is associated with the initial droplet conditions such as temperature, velocity, size as well as the thermo-physical properties of the substrate.

Table 2. Properties of Different Materials Used in this Study.

	Alumina	Air	Wood (red oak)	Copper	Units
Density, ρ	2900	1.3	545	8000	Kg/m^3
Viscosity, μ	0.012	1.7e-5	-	-	Pa.s
Surface tension, σ	0.6		-	-	N/m
Thermal conductivity, k	5	0.0262	0.23	400	W/(mK)
Heat capacity, Cp	1425	1004	2385	385	J/(kg.K)
Latent heat, ΔH	770	-	-	-	J/kg

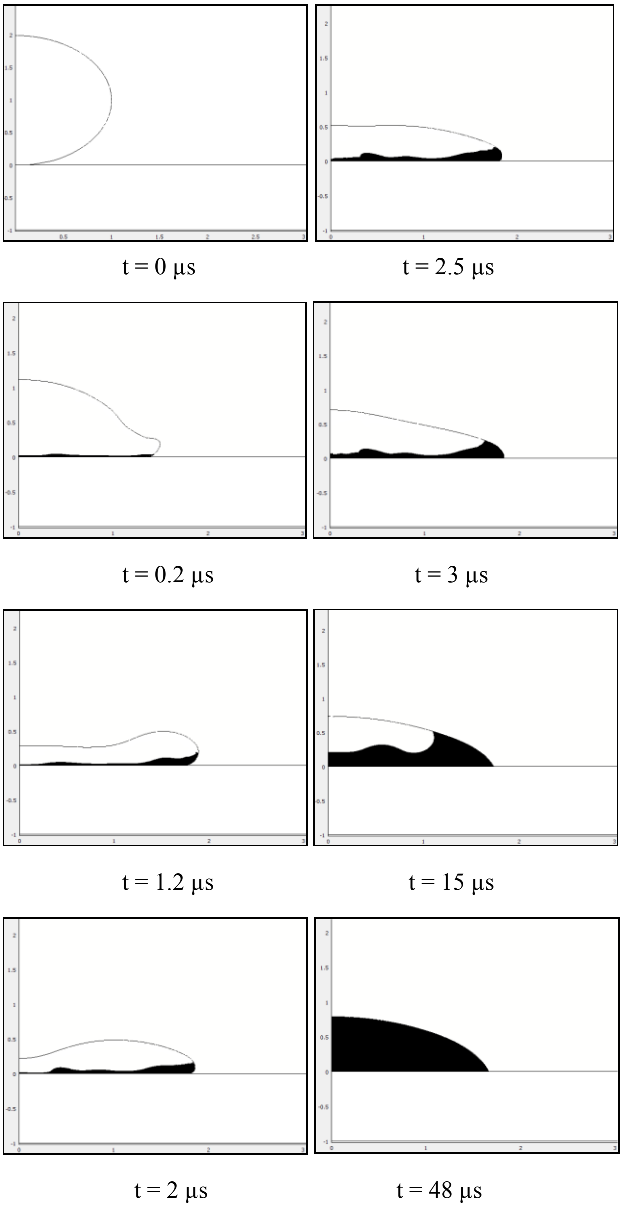

Fig.2. Process of impact, spreading and solidification of a micrometric alumina droplet onto a wood substrate.

Due to the heat released from the molten droplet during the deposition process, the temperature of the wood surface increases rapidly and exceeds the wood pyrolysis temperature $T = 750\ K$ before the end of the droplet spreading ($t = 2.5\mu s$) which can lead to burn the wood as shown in fig. 3. This figure shows the temperature evolution at $1\mu m$ depth in the wood during the deposition of the molten ceramic droplet for different initial temperatures of the droplet ranging from undercooling (*2400 K*) to superheating (*2800 K*).

The temperature evolution in the substrate during the droplet deposition is almost the same for the three droplets while the maximum temperature reached differs from one droplet to another: the higher the initial temperature of the droplet, the maximum temperature reached will be.

The wood absorbs much heat released from the molten droplet; this heat is transferred slowly from the top part of the wood substrate to the rest part because of the low thermal conductivity of the wood. The heat is accumulated at the top of the wood which explains the significant increase of the temperature at the top of substrate leading to the wood burning during the deposition of the ceramic droplet. Therefore, a ceramic coating cannot be deposited directly on wood substrate by using plasma spray technique even for small and undercooled droplets.

To avoid wood damage occurring during ceramic coating depositing, it's necessary to use a thin sub-layer (or intermediary layer) of another material having a relatively low fusion point, on the wood that helps to form a barrier and also inhibiting the thermal degradation of the wood substrate.

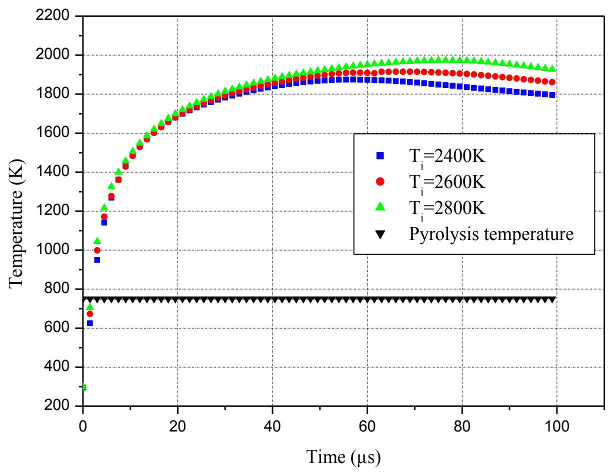

Fig.3. Temperature evolution at 1 μm depth in the wood during the spreading and solidification of a molten alumina droplet on wood substrate for different initial temperatures.

In this study a copper layer is used with different thicknesses ranging from $2\ \mu m$ to $6\ \mu m$ to know the optimal thickness should be used. Fig. 4 represents the temperature evolution at $1\mu m$ depth in the wood during the spreading and solidification of the alumina droplet for different initial temperatures on wood substrate with and without protective copper layer.

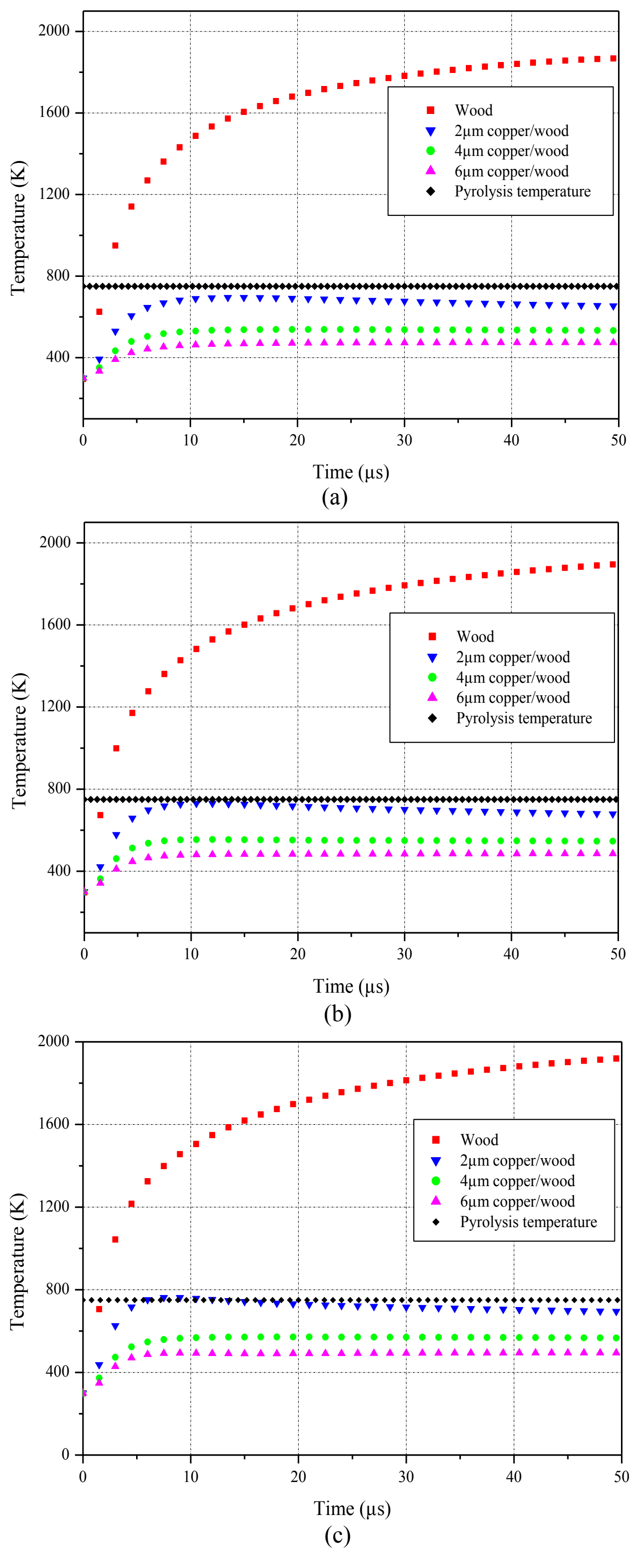

Fig.4. Temperature evolution at 1µm depth in the wood during the deposition of the alumina droplet with different initial temperature a) Ti = 2400 K, b) Ti = 2600 K and c) Ti = 2800K on wood substrate with and without protective copper layer.

As shown in this figure, when a copper layer with a thickness of $2\ \mu m$ is placed on the wood substrate, the temperature in the wood increases rapidly at the first instants of the ceramic droplet spreading but it stays under the pyrolysis temperature only for the undercooled droplet (*Ti = 2400 K*) (fig.4(a)). However, for droplet with an initial temperature of *2600 K*, the surface wood temperature reaches almost the pyrolysis temperature (fig.4(b)) while for the superheated droplet (*Ti = 2800 K*) it exceeds the pyrolysis temperature (fig.4(c)) which can lead to destroy the wood properties. Therefore a $2\ \mu m$ layer copper is suitable to protect the wood from the high temperature during the plasma treatment but only for the small and undercooled droplets, while for heated (*Ti = 2600 K*) and superheated (*Ti = 2800K*) droplets, a thickness of $4\ \mu m$ must be deposited on the wood substrate before applying the principal coating.

On the other hand, it should be noted that the process of lamella formation resulting from spreading and solidification of the molten droplet varies with the nature of substrate. Fig. 5 shows the thermal history of the socle of the alumina droplet during the spreading and solidification onto a wood substrate with and without a sub-layer of copper. As shown in this figure, when the spreading is on the wood substrate, the temperature of the droplet decreases very slowly due to the low conductivity of the wood, therefore the lamella takes more time to cool down and it is completely solidified at about 48 µs, while when the wood substrate is coated by a sub-layer of copper, characterized by a good conductivity, the temperature in the droplet decreases very rapidly, solidification starts at about $t = 0.1\ \mu s$ before the end of the spreading process and the lamella is completely solidified at about $4\ \mu s$.

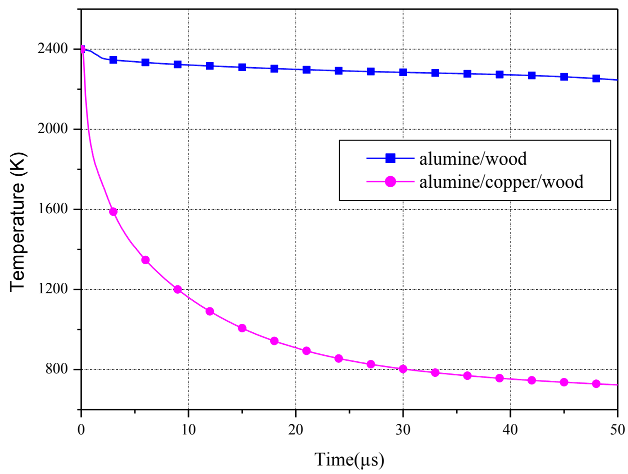

Fig.5. Thermal history of the alumina droplet socle during the process of spreading and solidification on the wood and on the wood coated by a sub-layer of copper.

4. Conclusion

In this study, a numerical simulation based on the Finite Element Method was carried out to analyze the process of spreading and solidification of a molten ceramic droplet (alumina) onto a wood substrate which is a thermo-sensitive material.

Results show that ceramic coating can be applied successfully onto a wood substrate by plasma spray technique without any damage if the wood is coated firstly by a protective sub-layer of another material such as copper with a properly thickness (2 μm for undercooled droplets and *4 μm* for heated and superheated droplets) before spraying the principal ceramic coating.

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