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Numerical analysis of the effect of the gas temperature on splat formation during thermal spray process

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ABSTRACT

Thermal spray coatings are affected by various parameters. In this study, the finite element method with volume of fluid (VOF) procedure is used to investigate the deposition process which is very important for the quality of sprayed coatings. The specific heat method (SHM) is used for the solidification phenomenon. A comparison of the present model with experimental and numerical model available in the literature is done. A series of numerical calculations is carried out to investigate the effect of the surrounding gas temperature on the splat formation. The variation of the surrounding gas temperature has a significant effect on splat morphology and can affect the adhesion of the splat on the substrate.

1. Introduction

Thermal spraying is a surface treatment method, used generally for protecting surfaces against wear, corrosion and thermal barrier, providing by means of thick coatings (approximately 20 μm to several mm). Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites. The material is fed in powder or wire form, projected at high speed and heated to a molten state or semi-molten on a solid substrate in the form of micrometer-size particles. Coating quality is usually assessed by measuring its porosity, oxide content, macro- and microhardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities [1,2]. Optimization and control of the complex phenomenon in thermal spray processes has been reported in several works [3–6].

At impact, the liquid material is spread on the surface which then solidifies with a quenching speed of around 10^6–10^8 K/s. The flattering process continues until the kinetic energy of the particle hitting the surface is completely converted into viscous energy and surface tension. The properties of thermal sprayed coatings are essentially linked to the structure of a single splat and the quality of contact between the pilled-up splats. These properties of adhesion and cohesion and thermo-physical properties are related to the morphology of the individual splats and to the contact quality between these splats and the substrate. The formation of the splat depends on the parameters related of the suspended particle (its size, its velocity, its temperature, its melting state at impact and its thermo-physical properties) and on the parameters related to the substrate (its properties, its surface state, its preheated temperature and the presence of oxides). Understanding of melting and solidification of the substrate is essential for appropriate bond coat selection as well as avoidance of substrate damage [7–9].

Experimental works have been devoted for studying an individual splat for a better understanding of the different mechanisms which govern its faltering and solidification [10–12]. It is found that the preheated temperature of the substrate has an important role in determining the morphology of the splat. There is a critical preheated temperature of the substrate named the transition temperature, above which the splat has a regular disc form and bellow which it has a shredded form [8].

Other researchers have studied numerically the splat formation phenomenon [13–18]. These numerical models which use the volume of fraction method (VOF) take into account the hydrodynamic aspects of the splat formation and the heat transfer between the splat and the substrate. Xu et al. [19] experimentally investigated the corona splashing due to the impact of a liquid drop on a smooth dry substrate. It is suggested that splashing results from the compressibility of the gas and it can be inhibited by decreasing the surrounding gas pressure. The threshold of the gas pressure depends on the impact velocity, molecular weight of the gas, and

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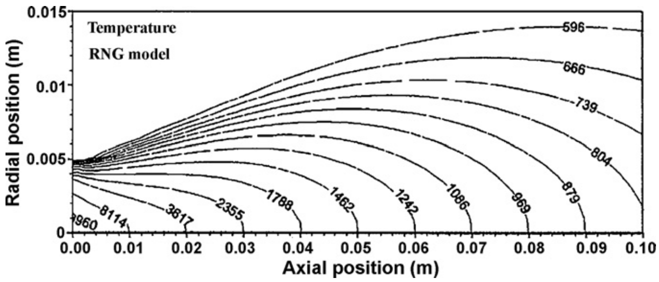

Fig. 1. Example of contourlines temperature of plasma spray jet (Ar-H_2) issuing into air [3].

the liquid viscosity. It can be deduced from this result that the temperature of the surrounding gas can influence the splat formation and morphology.

In thermal spray process, the surrounding gas can reach a high temperature in vicinity of the substrate (Fig. 1). However, this parameter has not been studied in these previous researches. Therefore, the aim of this work is to investigate the splat formation under different surrounding gas temperatures around the particle. The Galerkin finite element method is used to solve the set of governing equations using Ansys/Flotran code. The VOF method is used to track the free surface deformation. In this study, some pertinent parameters that influence the quality and the morphology of the deposit (the spread factor, the impact pressure and the temperature histories in the affected zone of the substrate) are considered.

2. Mathematical formulation

Numerical simulations are used for modeling the impact of the droplet. A set of the governing equations for the continuity, the momentum and the energy are adopted. The procedure is based on the use of the Galerkin finite element method [20] to solve system of equations and the VOF method to track the interface displacement [18]. The thermo-physical properties of the materials are given in Table 1 [18]. The physical domain with boundary conditions is illustrated in Fig. 2. The fluid flow is assumed to be incompressible. The dynamic and energy equations are coupled only by material properties which are temperature dependent. They are solved alternatively for every timestep until the final time is reached.

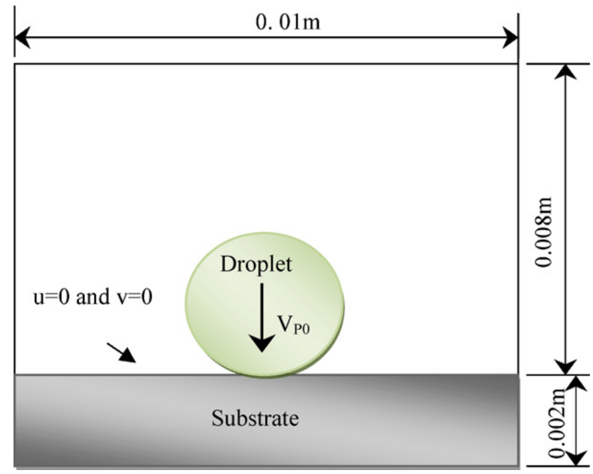

Fig. 2. Physical domain of a 3.92 mm droplet impacting a substrate.

2.1. Dynamic model

In the VOF method, the cell containing a fluid is governed by the following equations [18]:

$$\vec{\nabla}\cdot(\alpha\cdot\vec{V})=0 \tag{1}$$

$$\frac{\partial(\alpha\cdot\vec{V})}{\partial t}+(\alpha\vec{V}\cdot\vec{\nabla})\vec{V}=\frac{-\alpha}{\rho}\vec{\nabla}p+\alpha\nu\nabla^2\vec{V}+\frac{\alpha}{\rho}\vec{F}_b \tag{2}$$

where $\vec{V}$ is the velocity vector, ρ is the density, p is the pressure, α is called fraction of fluid volume, ν is the kinematic viscosity and t the time. $\vec{F}_b$ is the body force applied to the fluid.

The surface tension is an important parameter that contributes in the deformation of the droplet. It is considered as a volume force applied to the free surface of the liquid. The electrostatic forces between the molecules of the surrounding gas are very small compared to those of the liquid due to their molecular distances. The resultant of the forces is directed toward the inside of the particle. This force characterizes the liquid surface tension (σ in N/m). The liquid evolves spontaneously to minimize its surface tension (its free surface energy).

According to the VOF methodology, the fraction of fluid volume α is used for the all domain where its value indicates the presence or the absence of the fluid. We attribute the value of 1 for a point occupied by the metal and 0 in the other domain part. The mean

Table 1
Thermo-physical properties of aluminum and steel H13 [20].

Properties	Aluminum alloy 380		Steel H13	
Density [kg/m^3]	2570		7800	
Temperature of melting [°C]	570		–	
Melting heat [J/kg]	389		–	
Kinematic viscosity [m^2/s] as a function of temperature (°C)	T	ν	–	
	78	4.5E−7		
	2000	4.E−7		
Thermal conductivity of liquid [W/(m K)]	70		–	
Specific heat of liquid [J/(kg K)]	1000		–	
Superficial tension [N/m]	1.07		–	
Thermal conductivity of solid [W/(m K)] as a function of temperature (°C)	T	K	T	K
	100	144.5	27	17.6
	200	147.5	204	23.4
	300	152.5	427	25.1
	400	148.0	649	26.8
Specific heat of solid [J/(kg K)] as a function of temperature (°C)	T	C	T	C
	300	980	20	460
	300	1050	500	550
	479	1150	600	590