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STUDY OF A DOUBLE-LAYERED SPHERE MELTING SUBJECTED TO CONDITIONS OF NOT UNIFORM HEAT FLUX

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ABSTRACT

This paper deals with solid/liquid transition in a double-layered micrometric composite spherical particle metal/ceramic injected into a high temperature plasma jet of argon-hydrogen. The analysis focuses on tracking the particle following its trajectory in order to consider its thermal heat history. The heat transfer equation is formulated by using the enthalpy method and its discretization is carried out by a technique of second order finite volumes in time and space. The obtained results show the significant effect of the geometrical parameters, the phase change and the coupled heat transfer.

NOMENCLATURE

C_p	[J/kg]	specific heat
d	[m]	diameter
ρ	[kg/m^3]	volumic mass
K	[W/mK]	thermal conductivity
$\overline{k}$	[W/m]	integrated heat conductivity
H	[W/m^2.K]	heat coefficient
H	[J/m^3]	enthalpy
L	[J/kg]	latent heat
Nu	[-]	Nusselt number
Pr	[-]	Prandtl number
Re	[-]	Reynolds number
R	[m]	particule radius
RTC	[m^{2}K/W]	thermal contact resistance
T	[K]	temperature
t	[s]	time
ε	[m]	emissivity
Grecs	***symbols***	
Δ	[-]	differential operator
Σ	[-]	contact (solid/solid)
Indices		
ext	[-]	external
int	[-]	internal
eb	[-]	ebullition
s	[-]	Surface of solid
c	[-]	centre
l	[-]	Liquid
f	[-]	Melting
p	[-]	Particle
0	[-]	initial

INTRODUCTION

In air plasma spraying, many parameters can influence the coating structure and its mechanical properties. That is reason why many studies have been devoted to modeling of the plasma jet and, its fluctuations, the cold air engulfment, the particle injection, the interaction between particles and plasma, the flattening of droplets onto the substrate and the coating formation (Fig. 1). In the most cases, the modeled particles were either metallic or ceramic. On the other hand, cermet composite coatings have interesting properties such as the improvement of the hardness of pure metals and the reduction of the brittleness of ceramic coatings. When both metal and ceramic particles are injected separately in the plasma jet, the behaviors of these two materials are quite different and their simulations give information about their flattening and layering onto the substrate. Unfortunately very few studies model cermet particles made by mechanofusion where a metal core is surrounded by a ceramic shell and, to our knowledge; the model is limited to the melting of the shell of the cermet neglecting the heat propagation. That is why this paper is devoted to the modeling of the behavior of mechanofused metal/ceramic cermets particles in a plasma jet with the propagation of melting fronts in both materials.

Powders mono material were largely studied [1-3]. Those composed of double-layered materials, were the subject of studies of feasibility by numerical simulation for the production of metal composite matrix coating (MMC) [4] and those of reference [5] in the case of an infinite plasma. Interest for a powder of this nature is motivated by:

(a) the possibility of producing MMC coatings having specific mechanics properties (fatigue, strength and wear) interesting for manufacture of light and reinforced structures [6].

(b) the limitation of the oxidation phenomenon encountered in metal powder projection under free air environment [7]. Indeed, the use of a process in controlled or confined atmosphere implies a higher cost for experimenters.

This work is dedicated to the heat treatment composite double-layered metal/ceramic powder (flow of injection less 1kg/h) in projection by plasma arc Ar-H2 75-25 % vol. The study identified certain parameters (size, thermal contact resistance, heating conditions) on the kinetics of the phase change.

Conductive cooling of heat-generating volumes has been approached by other researchers as a volume or area-to-point heat transfer problem [5]. Thermal tree theories have been developed to describe the distribution of low thermal resistant paths and heat transfer has been optimised for different thermal tree structures [6-8].

Even though thermal tree schemes present optimised heat transfer performance, it requires complex geometric layouts which at small dimensional scales can lead to high manufacturing costs. In passive power electronic modules, which typically have inductive, capacitive and transformative functions, restrictions imposed by the electromagnetic fields, dictates that only parallel-running internal embedded solid geometries can be considered. Such layouts, when placed in-line with magnetic field lines reduces the interference of a cooling insert may have on magnetic and electric field distribution. Three-dimensional thermal path networks are thus not suitable for such applications.

In a previous investigation [9], the thermal performance of a grid of discrete parallel-running rectangular solid inserts were studied and geometrically optimised in terms of fixed volume use. At the dimensional scale of interest in power electronics and electronics cooling, it was found that the geometric shape of embedded cooling inserts has a diminishing influence on thermal performance and that the fraction of volume occupied by the cooling system plays a much more dominant role [10]. With this in mind it may be appreciated that from an economic and manufacturing point of view, continuous cooling layers provides a more practical embedded conductive cooling configuration. This paper focuses on thermal characterisation of cooling layers and aims to provide some information on thermal cooling performance.

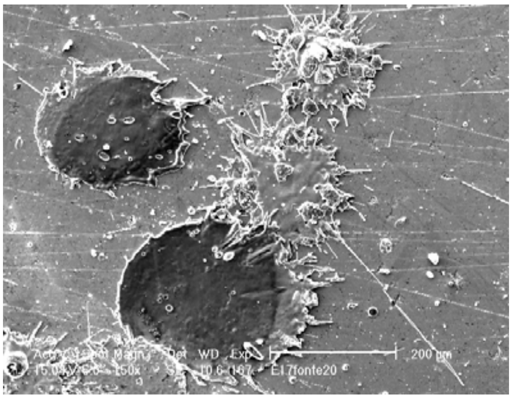

Figure 1: Splats of mechanofused stainless steel/alumina particles collected on a smooth cast iron substrate preheated at 200°C and plasma sprayed with the *Ar-H₂*, defined in Fig. 2 caption (white color stainless steel, grey color alumina).

MODEL AND SOLUTION METHOD

The studied configuration is a metal/ceramic double-layered sphere made up of two homogeneous and isotropic materials. The enthalpy model is adopted for the formulation of the conservation equation of energy including phase change [8-12]. In axisymmetric spherical co-ordinates:

$$\frac{\partial H}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left[k_p r^2\frac{\partial T}{\partial r}\right]+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left[k_p\sin\theta\frac{\partial T}{\partial\theta}\right] \qquad (1)$$

The enthalpy is used as a variable in order to allow the taking into account of the phase change. The front position of the face is given a posteriori. The initial conditions and the boundary conditions associated with the problem are:

$$T\big|_{t=0}=T_0 \qquad (2)$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} \; and \; \left.\frac{\partial T}{\partial \theta}\right|_{\theta=0,\pi}=0 \qquad (3)$$

$$\left[k_p \frac{\partial T}{\partial r}\right]_{r=R} = h_\infty (T_S - T_\infty) + \varepsilon\sigma\, T_S^4 \tag{4}$$

The heat transfer coefficient is connected to the Nusselt number by the correlation of Ranz & Marshall modified for plasma medium [2]:

$$h_\infty = \frac{\bar{k}}{d_p}\left[2 + 0{,}6\,\mathrm{Re}^{0{,}5}\,\mathrm{Pr}^{0{,}33}\right]\left(\frac{(\rho\mu)_\infty}{(\rho\mu)_S}\right)^{0{,}6}\left(\frac{C_{P\infty}}{C_{Ps}}\right)^{0{,}38} \tag{5}$$

One distinguishes two cases according to the way the surface is heated from the particle:

- uniform heating

$$h_\infty = h(T_\infty, T_{ps}) \tag{6}$$

- nonuniform heating with

$$h_\infty = h(T_\infty, T_{ps})(1 + Sin\theta) \tag{7}$$

The evaporation of the particle is not taken into account and the boiling of the alumina envelope starts when $T_{ps} = T_{boil}$. The boundary conditions (7) traduce the dissymmetry of the dynamic field around the spherical particle when the Reynolds number is higher than 2 (which is generally the case in plasma spraying). This condition has not ever introduced before (at the best of our knowledge) and it enables us to emphasize the presence of flux heat gradients which have their origin in the layer.

The condition of heat flux to the interface of two materials superimposed in imperfect contact is:

$$\left[k_a \frac{\partial T_a}{\partial r}\right]_\Sigma = \left[k_b \frac{\partial T_b}{\partial r}\right]_\Sigma = -\frac{\Delta T_\Sigma}{TCR} \tag{8}$$

in case of perfect contact, the temperature gap at the interface is null, which translates the continuity of the temperature field.

From the numerical point of view, the pure conduction model is solved by an implicit finite differences approach. The two phase Stefan problem is treated by an explicit numerical method improved, according to the correction proposed by Voller [11], to fit the step effect linked to the scale function *H (T)*. Constraints of the CFL type are corrected by using an accelerating convergence method namely [13] (i.e the initial numerical scheme is not stabilized at each time step but only after N time steps Δt for which the sum is maximized with the use of Chebychev polynomials. The time step *i* follow the equation:

$$\tau_i = \Delta t_{\exp}\left[(-1+\nu)\cos\left[\frac{2i-1}{N}\frac{\pi}{2}\right] + 1 + \nu\right]^{-1} \tag{10}$$

The choice of the parameters *N* and ν allows the acceleration of the explicit method by reducing the global computational time.

RESULTS AND DISCUSSIONS

This mathematical model is validated with the results of Kaldwell et al corresponding to a semi analytical integrale method, known as HBIM (Heat Balance Integral Method) [10]. Figure 3 shows the numerical forecast for the position of the melting front for a Stefan's number equal to 10 which is in good agreement with present results. A good agreement is obtained also on the evolution of the liquid fraction when compared to literature results of Khodadadi and al. [9] for a spherical domain subjected to Robin conditions.

When injected in the process, the particles follow several trajectories according to their sizes, speed of injection and the nature of the plasma flow nature and composition. This work proposes the study of the thermal behaviour of a composite particle length of a trajectory in a jet of plasma made up of argon and hydrogen.

The evaluation of the characteristics (*Re, Pr, T_∞...*) requires a resolution of an Eulerian problem for the jet flow and a Lagrangian for the particle movement. In the studied case, their determination was carried out by the use of software developed at the laboratory [14].

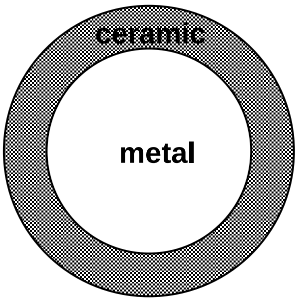

Figure 2: Composite double-layered configuration (metal/ceramic).

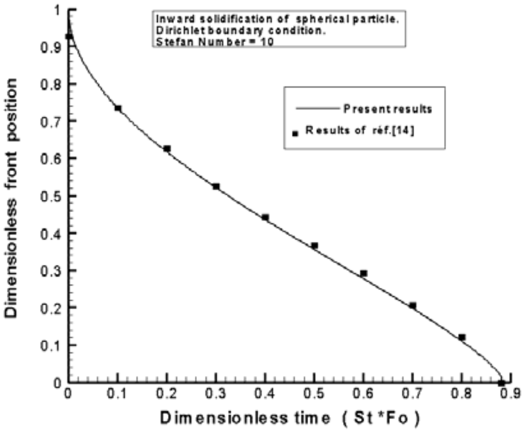

Figure 3: Present and literature computed results based on dimensionless parameter (Ste=10) for spherical inward solidification with Dirichlet boundary condition [10].

We consider initially, a composite particle double-layered Fe/Al_2O_3 of *60 µm* of diameter covered with *4 µm* of alumina and a thermal resistance of contact constant equal to 10^{-6} m^2K/W in uniform heating. Figure 4 shows the change of the temperature of the particle to different positions (centre, interface, and surface) and that of plasma gas seen by particle during its trip in the jet. The point of boiling of Al_2O_3 (*3800 K*) is reached just at the exit of the plasma dard and one can note the importance of the heat gradient in layer Al_2O_3 compared to that existing one existing in *Fe*. Before reaching the substrate placed with *100 mm*, there is an inversion of the field of temperature because particle crosses plasma plume with increasingly cold zones. The core of the particle is controlled by the TCR and if the latter is too high (10^{-5} m^2K/W), it insulates it completely and the heat coming from plasma is found trapped in the layer wraps. We also present on figure 5, evolution of the thermal gap at the interface of contact and the corresponding liquid fractions. In this example, alumina melts initially and particle arrives at the substrate in a completely molten state. When one consider weaker TCR below 10^{-7} m^2K/W, our numerical results show that it is rather the iron which begin early fusion and the volumetric expansion due to the phase change can produce thermo mechanical constraints such as they break the ceramic layer as observed in some experiments [7].

In the case of nonuniform heating, the model becomes two-dimensional result of one diffusion of radial and azimuth heat. A good knowledge of the modelling presented in this work makes it possible to bring brief replies to experimental observations [7], relating to the shredding of the particles. With this effect, figure 6 shows instantaneous numerical thermal field in the particle after a transient of *0.45 ms* and where one can note the development transverse heat gradients.

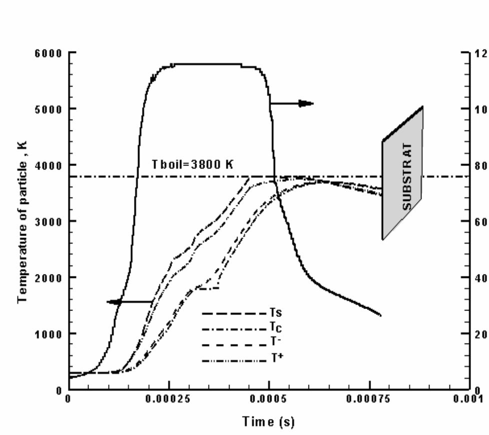

Figure 4: Evolution thermal field of a composite particle double-layered *Fe/Al2O3 (dp=60µm, 4µm Al2O3, RTC=1e^{-6} m^{2}K/W)* in uniform heating

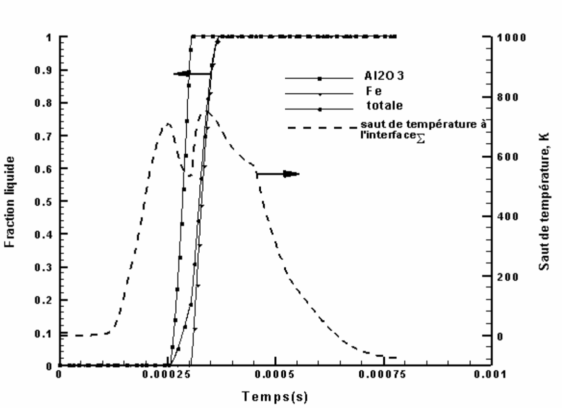

Figure 5: Evolution of thermal jump and liquid fractions of a composite particle double-layered *Fe/Al2O3 (dp=60µm, 4µm Al2O3, RTC=10^{-6} m^{2}K/W)* in uniform heating.

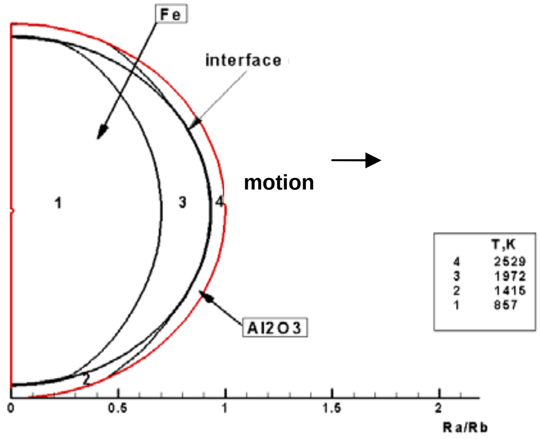

Figure 6: Instantaneous of the thermal field: *Fe/Al2O3 (d_p=60 µm, 4µm Al2O3, RTC=$1e^{-6}$ m^2K/W).*

CONCLUSION

A two-dimensional approach of the thermal transfer coupled with the phase change in a double-layered composite particle is developed. The physical model suggested finely translated the thermal behaviour of a double-layered grain in a plasma-producing jet as well as the various kinetics of phase shift along trajectory. The knowledge of such kinetics associated to TCR in the particle will allow operator to adapt the control parameters to ensure a better correlation with wished deposit characteristics.

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