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SIMPLIFIED 2D THERMO-MECHANICAL MODELING OF SPLAT FORMATION IN PLASMA SPRAYING PROCESSES

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ABSTRACT

The particles projected by arc plasma are generally of micrometric size (ranging in general between *10* and *100 μm*) in conventional projection and their impact velocity ranges from *50* to *350 m/s*. characteristic times for the formation of a splate are very short: less than *5 μs* for the duration of spreading of the particle melted with a solidification which can start before the end of the spreading stage and continues in general between *0.8* and *10 μs* after the impact.This work is devoted to studying numerically this complex coupling. The model is firstly validated in comparison with available results of particles spreading (large size and low impact velocity < *1 m/s*).

1. INTRODUCTION

Thermo-mechanical and service properties of plasma sprayed coatings strongly depend on the momentum, heat and mass transfer phenomena during the spraying, including particle trajectory distribution within the plasma jet controlling particle velocity and temperature distributions upon impact of the molten or semi-molten particles which determine the coating formation and hence its properties. A thorough review of the heat, mass and momentum processes in plasma spraying has been performed [1, 2]. These authors describe all the phenomena involved in coating formation by plasma spraying. The plasma jet is mostly produced (*95 %* of plasma spray processes) by Direct Current (DC) arc. The plasma jets produced by DC spray torches exhibit unusual properties: high flow velocities (up to *2000 m/s* at the nozzle exit but still subsonic), high temperatures (up to *14 000 K*), steep temperature gradients (up to *108 K/m*) and low gas density (*1/50* to *1/30* that of the cold gas). They are laminar in their core and turbulent in their fringes. In addition, the plasma jets are continuously fluctuating in length and position because of the continuous movement of the arc root at the anode wall at frequencies ranging between *3* and *20 kHz*. This results in some sort of piston flow.

Micron-sized (*5-100 μm*) particles are introduced into the high-temperature plasma stream by means of a carrier gas flow through injectors. The injection parameters (the momentum of injected particles must be about that imported by the plasma flow) influence the particle trajectory, the deposition efficiency and coating properties. When particles penetrate the plasma jet core, they are first heated and accelerated. Then, in the plasma plume, they decelerate and slowly cool down. Particles injected in DC plasma flows have a residence time in the millisecond range and receive heat fluxes as high as $108\ W/m^2$ [3]. As a result of the high gradients within the plasma jet, particles following different trajectories will have different accelerations and heating rates. A better understanding of interactions between particles and plasma has been achieved due to intensive research through both measurements and modelling. The modelling of particle acceleration and heating in the flow uses the conventional equations for spherical droplet motion in flows with heat transfer, including some effects specific to the thermal plasma environment [3].

To improve this understanding for the surface treatment, a simplified model is presented of splat formation. It is based on the Navier-Stokes equations, to describe the transfers and fluid flow and an additional constitutive equation (surface tension and contact angle). The fluid is supposed to be Newtonian, and the drop flow is considered incompressible. The only tension applying to the free surface is regarded as normal with this one. The equations are discretized by finite elements. The free deformation of the interface is tracked by a level set function used to determine the density and the viscosity on both sides of adjacent surface separating the droplet and the surrounding atmosphere.

The particles data at the impact (temperature and velocities for a given diameter) result from an available laboratory tool Jets&Poudres [5] for usual conditions of plasma projection of zirconia particles.

2. MODELS AND SOLUTION METHODS

2.1 DYNAMICAL MODEL

The application of the fundamental principle of dynamics, the assessment of the forces within each Newtonian fluid leads to the momentum equation:

$$\rho\left(\frac{\partial u}{\partial t}+\nabla.(uu)\right)=-\nabla p+\rho g+\nabla\left(\mu\nabla u+\nabla u^{T}\right)+F_{TS}$$

$$\nabla u=0 \qquad (1)$$

where ρ and μ is respectively the density and the viscosity of the fluid, g the gravity. Term F_{TS} represents the forces of surface stress, it is related to the concept of interface between two fluids non miscible. This force is represented by

$$F_{TS}=\sigma.k.\delta.n_i \qquad (2)$$

Where σ , K and δ are respectively the coefficient of surface tension, the local average curve of the interface and the Dirac function.

The model chosen here is of the model type to a fluid. Indeed this model adapts well to the discretization on Cartesian fixed grid. This kind of model was used by several authors to simulate the deposition on dry substrate [6, 7] or the impact on liquid film [5]. It is advisable to define a function which geometrically determines the position of the phases in the field. That is to say the phase function ϕ defined by $\phi = 1$ in the fluid 1 zone, $\phi = 0$ in the zone containing fluid 2 and $0< \phi < 1$ in the zone of two fluids interface.

The phase function ϕ is advected according to the velocity of the interface ***u***. This evolution is described by the kinematic equation which connects the function to the interface velocity ***u***:

$$\frac{\partial\phi}{\partial t}+u\nabla\phi=0 \qquad (3)$$

A physical property of the medium λ is expressed according to the presence of each fluid by:

$$\lambda=\lambda_1+(\lambda_2-\lambda_1)\phi \qquad (4)$$

2.2. THERMAL MODEL

The medium under phase changes is represented as two fields separated by an interface which is the area of melting/solidification. The temperature evolution of each medium is solved separately; the interface corresponds to a condition known as Stefan, derived from the heat flux balance at the interface:

$$k_s\nabla T_s n-k_l\nabla T_l n=\rho L_f V_f n \qquad (5)$$

l and s represent the phases respectively liquid and solid and V_f is the velocity of the solidification front. The difficulty of this method lies in the need for determining the position of the solidification front, which is often carried out either an evolutionary grid [7-9] or on fixed grid by taking into account the Stefan condition (enthalp method) [10, 11].

3. VALIDATION OF THE MODEL AT VARIOUS IMPACT VELOCITIES

There are not analytical formulations which make it possible to describe accurately the evolution of the impact and the spreading out of a drop, to validate the impact simulation, we compared the results obtained with those of the reference [11].Moreover we used the analytical formula [12] in order to compare the degree of maximum spreading out obtained $\xi_{\text{max, is}}$ defined as the relationship between the maximum diameter of the spread out droplet and the initial diameter of the drop.

$$\xi_{\max}=\sqrt{\frac{w_e+12}{3(1-\cos\theta)+4\left(w_e/\sqrt{R_e}\right)}} \qquad (6)$$

with *We* and *Re* are respectively the numbers of Weber and Reynolds of impact, and θ is the static contact angle.

Let us consider in Cartesian coordinates axisymmetric 2D the impact of a drop on a substrate. The axis of the drop is taken as a symmetry axis reduce the computational cost.. The boundary condition with the interface drop-substrate is a non slip condition one (figure 1).

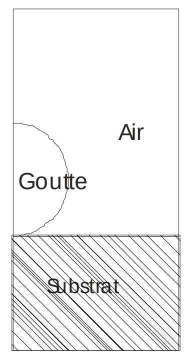

Figure 1*:Geometry of the studied system*

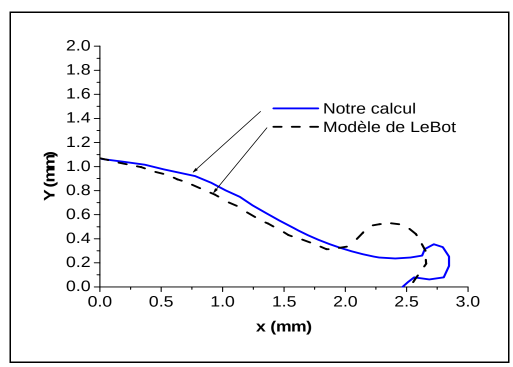

Figure 2*:Spreading out of the drop at the time 0.01 S*

The numerical simulation is carried out for the impact of an indium drop of *2 mm* of diameter, initial velocity of $0.1\ m.s^{-1}$ and whose characteristics are summarized on the following table:

Surface tension (N.m)	Viscosity (Pa.s)	Density (kg.m 3)	Re	We
0.005	1.35 10-3	7300	1081	29

The time step used is constant (5.10^{-6} s). The Navier-Stokes equations in incompressible flow are solved by the method of *Lagrange*, and the advection equation by the `*level set* method.
In the simulation presented here the maximum spreading out of the drop is about $\xi_{max} = 2.11$.In the simulation presented in [4] the maximum degree of spreading out of the drop reaches a value of $\xi_{max} = 2.17$, that is to say a relative variation of 2.7%, whereas the analytical expression proposes $\xi_{max} = 2.07$, which thus gives a relative variation of 1.9%. That Pasandideh-Make-up et al.[5] consider realistic such dispersion of the results lower than 15%.
The comparison of two model was also made by the phase function ϕ (the interface between the liquid drop and the air), figure 2 shows the results of the two models at the time 0.01s. For low velocities the results are thus coherent with those of the reference [11], and the analytical expressions of the reference [12].
For high velocities (> 100 *m/s*), we compared the results of the model suggested with those obtained by *Bertagnolliall* [13].The numerical simulation carried out corresponds to the impact of a zirconia particle of *20 µm* diameter and initial temperature of *3400 K*, and animated a velocity of $180 m.s^{-1}$ with the impact. The characteristics of this drop are given on the following table:

Surface tension (N.m)	Viscosity (Pa.s)	Density (kg.m ^{3})	Specific heat (J/Kg.K)	Thermal conductivity (W/m.K)
0.5	42 10^{-3}	5550	500	2

Figure 3, compares the spreading out of the zirconia drop in the model suggested and that of *Bertagnolli*. The impact and the drop shape evolution are similar during the impact. At the time 0.5μs, the drop shape stabilizes and takes the form of final spreading.

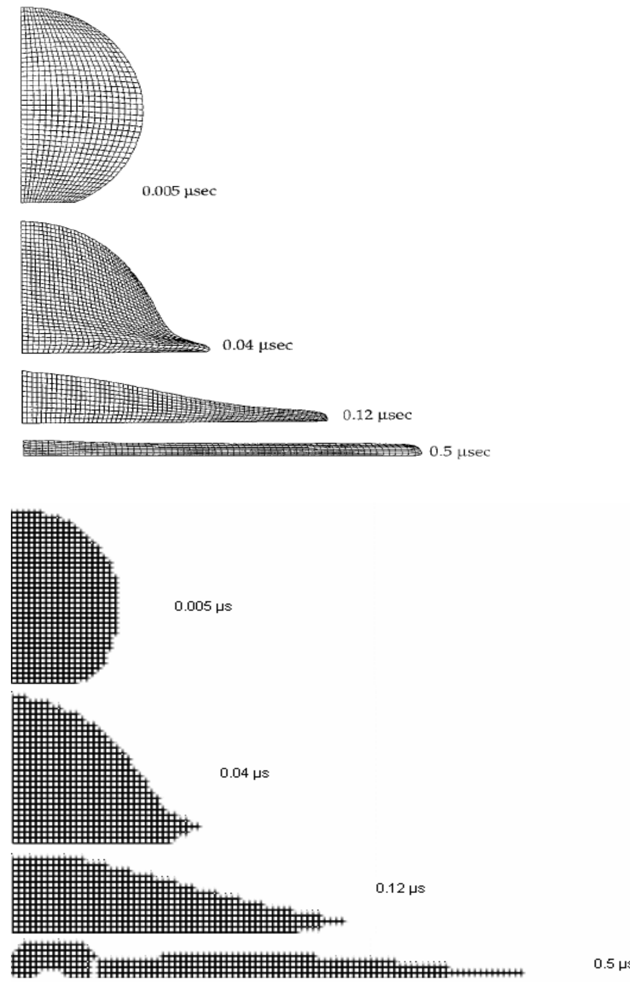

Figure 3*: spreadingwith grid of the zirconia drop a) [MauroBertagnolli], b) present results.*

The parameters used in this validation are those treated by *Madejski* , *Bertagnoll*and *Yoshida* [14] and. The model of *Madejski* is founded on the assumption of a cylindrical deformation of the drop, the maximum degree of spreading (equation 6) is then estimated by:

$$\xi = M R_e^{0.2} = M\left(\frac{\rho V d}{\mu}\right)^{0.2} \quad (7)$$

According to *Madejsk*i, *M* is a constant coefficient equal to 1.2941 whereas according to *Yoshida* et al., *M* is equal to 0.925. The model of *Madejski* overestimates slightly with that of *Yoshida*. The results of the model presented are very close to those obtained by *Bertagnolli*. On figure 4 are represented the rates of spreading out predicted by these various models. the *Yoshida* results and of the *Madejski* one. Consequently the simulation results of the drop impact on a substrate at a high velocity are coherent with the theoretical calculations and the other models for low velocities or high velocities.

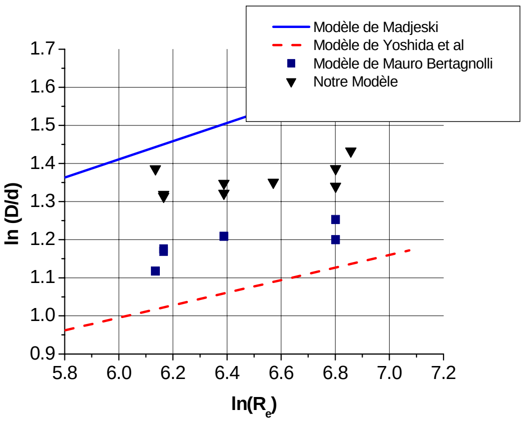

Figure 4*:Degree of spreading out according to the Reynolds number*

4. EXPLOITATION OF THE MODEL SUGGESTED FOR DROPS OF ZIRCONIA MELTED AT HIGH VELOCITIES OF IMPACT.

In plasma projection, the behavior of particles melted with the impact is the fundamental element to include/understand the microstructure of the resulting layer. Indeed the layers are created by the stacking of plates formed by the spreading and the solidification of molten individual droplets. The particles projected by plasma arc are generally of micrometric size (ranging in general between *10* and *100 µm*) in conventional projection and their impact velocity extends from *50* to *350 m/s*.

This study is devoted to a drop of zirconia preheated to *3500 K*, and of *20 µm* diameter, projected for two velocities of *100* $m.s^{-1}$ and *150* $m.s^{-1}$ on a substrate of steel preheated to *700 K*.

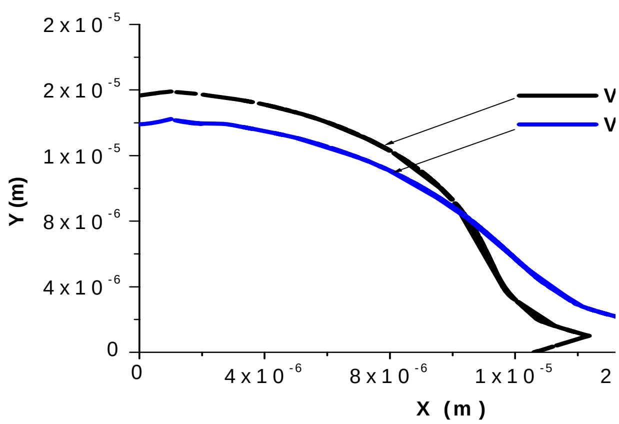

Figure 5*:Spreading out of the drop at the instant 0.05 µs.*

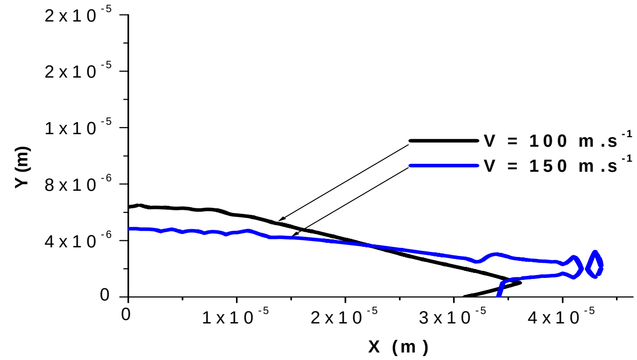

Figure 6*:Spreading out of the drop at 0.3 µs.*

Figure 5 and 6 show various instants of a zirconia drop (of *20 µm)* spreading on the substrate with several impact velocities (100 and 150 $m.s^{-1}$).The drop is spread out more especially as velocity is higher. It is spread out and solidified on the steel substrate in a time lower than *1 µs*. At the time *0.3µs*, the splashes appears starting from the animated drop at a velocity of 150 m/s, the breaking of the fluid film appears with the birth of secondary droplets ejected from the surface of the substrate.

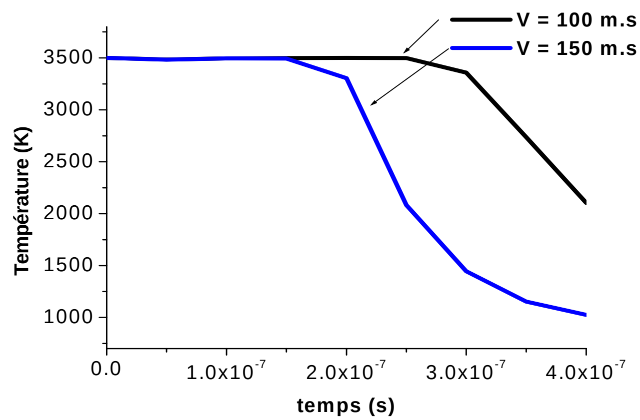

Figure 7 *: Change of the temperature at the point X=0Y=5.e-5m*

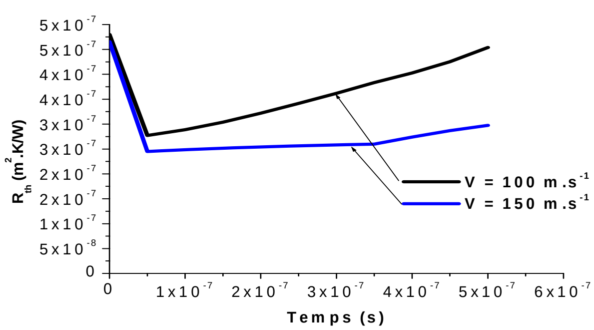

Figure 8: *Evolution of the thermal contact resistance*

Figure 7 shows that the zirconia drop is solidified more quickly as the impact velocity is larger. That seems ascribable to the faster time of spreading out which thus increases heat exchange between the drop and the substrate. Thus the impact velocity increase influences directly over the time of spreading out of the drop and the maximum diameter reached by the plate.

When the liquid runs out on surface it tends to follow the surface form. The more the latter is rough, the more the liquid will have difficulties to flow through the forms. Thus the liquid which runs out perpendicular to these obstacles will be projected vertically thanks to its inertia.

At the first moments which follow the contact of the drop with the substrate, the surface of contact and thus of exchange increases quickly and the thermal resistance R_{th} decreases from 5.10^{-7} to $3.10^{-7}\ m^2\ K/W$ (figure 8).After partial spreading out, the surface of contact between the substrate and the drop increase, whereas the temperature of the drop remains quasi-constant. At this time, the temperature of the substrate ceases increasing whereas the drop surface temperature; the corresponding thermal contact resistance increases to reach a maximum at the end of the spreading stage. Let us add that during the impact the drop is crushed on the surface of the substrate by generating a strong pressure. The liquid drop fills all the cavities on the surface of the substrate, the thermal contact resistance is minimum until the pressure falls down, and then the thermal contact resistance increases.

5. CONCLUSION

The 2D model of the droplet impact illustrates way it is valid the temporal and dimensional sizes relating to the phenomena of crushing of droplet under plasma spraying. Solidification is taken into account when the drop reaches a temperature lower than the melting point what contributes to solidify the matter quickly and decreases the kinetic energy of the system and in deadened consequence the velocity of spreading out. Many theorists suppose that the droplet is crushed in super melting state. It would be thus interesting to continue the investigations by taking into account of subcooling state in order to represent it correctly and to integrate it in the global code. The immediate prospects for this work relate to the development of 3D simulation of the impact of drops, but that forces a significant CPU in order to manage the number of mesh used.

REFERENCES

[1] Fauchais P., Understanding plasma spraying, J. Phys. D: Appl. Phys. 37, R86–R108, 2004.

[2] Pfender E. and Chang C.H., Plasma spray jets and plasma particular interactions: modelling and experiment, in: Coddet C. (Ed.), Proc. of ITSC 98, ASM International, Materials Park, OH, USA, pp.315-327, 1998.

[3] Pfender E., Particle behaviour in thermal plasmas, Plasma Chem. Plasma Proc. 9(1), pp. 167-194, 1989.

[4] J. Cedelle, Etude de la formation de lamelles résultant de l’impact de gouttes millimétriques et micrométriques : application a la réalisation d’un dépôt par projection plasma » Thesis, University of Limoges, 2005.

[5] B. Pateyron et al http://Jets.poudres.free.fr

[6] Pasandideh-Fard M., Mostaghimi j. (1996) “Droplet impact and solidification in a thermal spray process: droplet-substrate interaction”, Thermal spray : Practical Solutions for Engineering Problems, C. C. Berndt (Ed.), Pub. ASM International, Material Park, Ohio-USA, p. 637-646.

[7] C. Le Bot. "impact et solidification de gouttes métalliques sur un substrat solide", Thesis, Univ. Bordeaux I, 2003.

[8] D. Gueyffier S. Zaleski. Full Navier-Sokes simulation of droplet impact on thin liquid films de digitations lors de l'impact d'une goutte sur un film liquide. Third international conférence on Multiphase Flow, Lyon, France, p. 1-7, 1998.

[9] D. Delaunay. "Transferts de chaleur par conduction associés à un changement de phase". Ecole d'été G.U.T: Transfert de chaleur et de matière avec changement de phase, p. 327-372, 1990.

[10] M. El Ganaoui, A. Lamazouade, P. Bontoux and D. Morvan Computational solution for fluid flow under solid/liquid phase change conditions, Int. J. Computers and Fluids, vol.31, issues 4-7, pages 539-556, 2002.

[11] C. Le Bot, S. Vincent, E. Arquis. "Impact and solidification of indium droplets on a dry substrate". Int. J. Thermal Sciences, Volume 44, Issue 3, pp. 219-233, 2005.

[12] Madejski J. (1976) "Solidification of droplets on a cold surface" Int. J. Heat Mass Transfer., 19, pp.1009-1013.

[13] M. Bertagnolli, Thermomechanical Simulation of the Splashing of Ceramic Droplets on a Rigid Substrate Journal of computational physics 133, 205–221 (1997)

[14] T. Yoshida, T. Okada, H. Hideki, and H. Kumaoka, Plasma Sources Sci. Technol. 1, 195 (1992).

[15] Kh.Fataoui "Développement de modèles thermomécaniques de construction de dépôts obtenus par projection thermique. Modèle mécano thermique de l’étalement de la gouttelette".Thesis, University of Limoges, (2007).

[16] Pepper D., “The finite element method : basic concepts and applications”, Hemisphere Pub. Corp. Library of Congress Cataloging-in-Publication Data. ISBN: 1-56032-104-0. 1992.