COMPARATIVE ANALYSIS AND TESTING OF A DIFFERENT THEORIES CHARACTERIZING A DIAMETER AND THICKNESS OF PLASMA SPRAYED SPLATS

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ABSTRACT

Comprehensive comparative analysis of the known analytical formulae used for prediction of a thickness and diameter of the flattened and solidified particles (splats) have done taking into account the modelling collection of splats obtained under the conditions of complete control of the main regime parameters *(MRP)* prior to impact (velocity, temperature and size of a particle, temperature of a substrate).

INTRODUCTION

In the plasma spray technology, coatings are formed from separate particles of the melted material by their flattening and solidification at the interaction with a surface.

In this connection, it is necessary to obtain a comprehensive information characterizing the processes of a splat formation under the conditions of complete control of *MRP*. This is the only one way that may enable us to establish a feedback between the properties of the sprayed materials and the regime parameters of the process.

According to analysis fulfiled in [1], the following basic variants of "melted particle - substrate" interaction must be considered and discussed systematically: (1)--spreading and simultaneous solidification of the particle on the solid substrate, (2)—spreading and solidification of the particle with simultaneous partially melting of the substrate, (3)-spreading of a liquid particle over a partially melting substrate, (4)--spreading of a liquid particle over the solid substrate.

It is obvious that during this interaction in different zones of the flattening particle and the substrate different combinations of these variants defined by the concrete conditions may occur. These complex phenomena may be studied, at least, on the basis of two-dimensional unsteady-state boundary value problems which have to take into account the fluid flow and conjugate conductive-convective heat transfer, associated with the impingement, flattening and solidification of melted particles on the surface.

But, in practice it is necessary to have the analytical dependences providing the evaluation with a good accuracy the thickness and diameter of splats for the specific conditions.

At present there are known a several analytical approximations characterizing above-mentioned parameters of splats [2-5]. As indicated by analysis of these relationships the authors usually do not take into account the thermophysical special features of the examined problem and restrict themselves only to hydrodynamic approximation. These approximations are based on the assumption according to which the solidification of the particles takes place after their complete spreading. However, this directly indicates (in any case, for metallic particles) that during the stage of spreading of the melt the latter can be greatly supercooled below the temperature T_{pm} prior to the start of solidification. However, in this case, in our view, the hydrodynamic models of spreading have to take into account the local dependence of melt viscosity on temperature since the characteristic time of relaxation of viscosity of metals $(t_{\mu}<10^{-10}-10^{-9}\ s)$ to possible variations of local temperature is considerably shorter than the characteristic deformation time of the particle on the substrate $(t_d \simeq D_p/u_{po} \geq 10^{-7}\ s)$. Here D_p, u_{po} are the diameter of the initial particle and its velocity prior to the impact.

In our publications [6,7] it have undertaken the attempt to develop the new thermophysical fundamentals free of above-mentioned shortage.

The main difference between the theoretical approach developed by us and those described in previous publications (for example, see [2-5]) is that the solutions obtained can be used to predict the splat thickness in the vicinity of the stagnation point or, in other words, for the contact spot $(2r \leq D_p)$, for which the assumption on the unidimensional nature of the processes of conjugate heat exchange in the particle - substrate system, including phase transformations, is sufficiently substantiated. In this formulation, the parameter $\bar{h}_s$ is linked more closely with the *MRP* of the interaction $(D_p,\ u_{po},\ T_{po},\ T_{bo})$ and the thermophysical properties of the examined pair of the materials. For the conditions, typical of gas thermal spraying, it is almost independent of the processes taking place at the periphery of the spreading particle $(2r>D_p)$. Consequently, experimental verification of the reliability of the proposed model may be carried out accurately and efficiently. But, at the time when our first publications [6,7] appeared we knew of no collection of experimental data characterizing the thickness and diameter of splats produced under the conditions of complete control of the particle parameters prior to an impact.

In papers [8-11] we have started the cycle of experimental and theoretical study with the aim to create a representative collection of splats obtained under conditions of complete control of *MRP* for modelling materials (particle - tin, zinc, lead; substrate - stainless steel, copper) and on its base to check the possibilities of a different theoretical dependences describing the thickness and diameter of splats.

The main objects of the present paper are to continue the extention of the above-mentioned collection of the experimental data, to fulfil their theoretical generalization and to check the possibility of enumerated analytical dependences.

MODELLING EXPERIMENTAL STUDY

The principal diagram of the set-up used in our investigation is shown in Fig. 1.

Quartz pipe *(2)* with an outside diameter of *6 mm* (inner diameter of *3.5 mm*) was placed into resistance heater *(1)*. One of its ends was specially shaped by heating and subsequent drawing to produce an internal diameter of about *0.15 mm*. This construction could travel in the vertical direction to change the height from which the melted particle is dropped on substrate.

The investigated materials (tin, lead and zinc, purity near *99.9999*) was loaded into the pipe. The first gas line *(Ar)* was connected to the upper part protruding from the tube heater for protecting the melt material against oxidation and for creating the excessive pressure at droplet generation. The second gas line *(Ar)*, including bellows *(5)* and two valves, was connected with upper part of the heater. The heater consisted of a hollow copper cylinder with an internal diameter of *10 mm*, two heating sections made from nichrome wire with a diameter of *0.3 mm*, and two thermocouples *(8,9)*. The upper thermocouple *(8)* was placed at a distance of *80 mm* from the point of gas input and used for its temperature control at the initial section of the heater. The second thermocouple *(9)* was placed at the end of the outlet of the heating profiled channel at the lower part of the glass pipe where the melt droplet was generated. This thermocouple was used to control the temperature of gas blown through the coaxial gap between the glass pipe and the copper tube. The end section of the heater was covered by asbestos cement washer *(4)* with internal diameter of *4 mm* and formed the step. The melt droplet was generated in the gap behind the step. The adjustment device for the alignment of the tube with the material inside the heater was placed between the first and second heater sections.

To obtain the given size and velocity of the generated droplet the gas input system was arranged in the following way. With the help of the first gas line argon was blown onto the heated material. When a metal melt appeared inside the quartz pipe, the excessive pressure for formation of a single droplet at its lower end was created with the help of a vessel connected with the first gas line. When the droplet grew up to the necessary diameter it detached from the melt and accelerated in the gravity field and by the coaxial high-temperature jet generated with the help of the second gas line. During this process it was possible to control the particle velocity before its interaction with the substrate by changing the gas flow rate of the coaxial stream.

For accurate examination of the droplet size and velocity immediately before its collision with the substrate, our experimental set-up was supplemented with corresponding measuring apparatus [10].

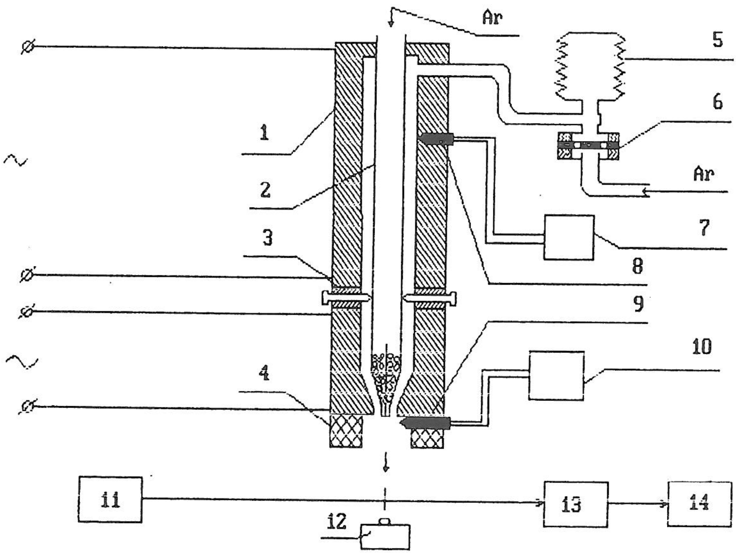

Fig.1. The principal diagram of the experimental set-up. 1-Ohm heater; 2-quartz tube; 3-device for the alignment of the tube with material inside the heater; 4-asbestos cement washer; 5-bellows; 6-valve; 7,10-blocks for temperature control; 8,9-thermocouples; 11-block for the formation of a light beam; 12-thermoregulated substrate; 13-registration block; 14-digital osciloscope.

EXPERIMENTAL VERIFICATION OF THEORETICAL FUNDAMENTALS

We shall now present the results of the extended modelling experiments which enabled detailed verification of the thermophysical fundamentals discussed above, concerning the formation of splats for metallic droplets with $0.3 \le D_p \le 3.6$ mm.

According to our approach [6-8], the dimensionless thickness $(\bar{h}_s = h_s/D_p)$ and diameter $(\bar{D}_s = D_s/D_p)$ of splats, in the case of flattening and solification of droplets on a solid substrate, $(T_{pm} > T_c < T_{bm})$ are characterized by the following formulae

$$\bar{h}_s = 1 - Pe \cdot Fo^*, \quad \bar{D}_s = 0.816/\sqrt{\bar{h}_s},$$

$$Fo^* = [c_\zeta(\sqrt{1+4Pe/c_\zeta^2} - 1)/2Pe]^2, \quad c_\zeta = P[\sqrt{1+4Q/P^2} - 1]/2,$$

$$P = \frac{1+0.8\lambda_{p,p}^{(l,s)} K_\varepsilon^{(b,p)} (\vartheta_{po} - 1)/Ku_p^{(l)}}{0.564\lambda_{p,p}^{(l,s)} K_\varepsilon^{(b,p)}}, \quad Q = \frac{2(1-\vartheta_{bo})}{\lambda_{p,p}^{(l,s)} Ku_p^{(l)}} \left[1 - \frac{1.259(\vartheta_{po} - 1)}{(1-\vartheta_{bo}) K_\varepsilon^{(b,p)}}\right],$$

where $\vartheta = T/T_{pm}$, $Fo = a_{pm}^{(l)} \tau / D_p^2$ is Fourier's criterion, $Ku_p^{(l)} = L_p/[c_{pm}^{(l)} T_{pm}]$

is a Stefan-Kutateladze's criterion, $Pe=D_p u_{po}/a^{(l)}_{pm}$ is the Peclet number, $K^{(b,p)}_{\varepsilon}=(\lambda^{(s)}_{bm}/\lambda^{(l)}_{pm})\sqrt{a^{(l)}_{pm}/a^{(s)}_{bm}}$ is criterion of the thermal activity of substrates' material to the material of particle, a is the thermal diffusivity, and $\lambda^{(l,s)}_{p,p}=\lambda^{(l)}_{pm}/\lambda^{(s)}_{pm}$ is the ratio of thermal conductivity of particles' material at melting point for liquid and solid states. Superscripts "s", "l" of the variables correspond to the solid and liquid state of the material, and subscripts "p", "b" correspond to the particle and the substrate. The additional subscript "m" characterizes the parameter of the corresponding material at the melting point.

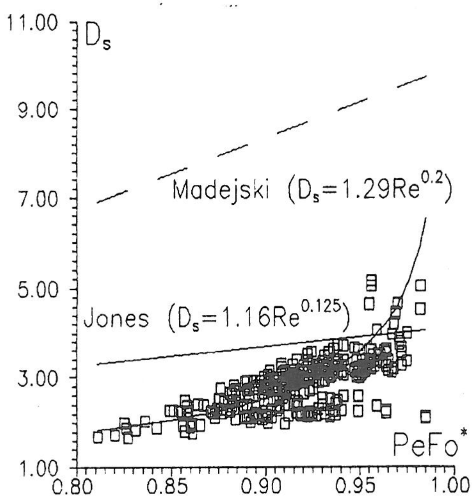

Fig.2. Comparison of the theoretical and experimental diameter of splats. (□-experimental data, solid curve corresponds to our solution, and dashed lines correspond to [2,3]).

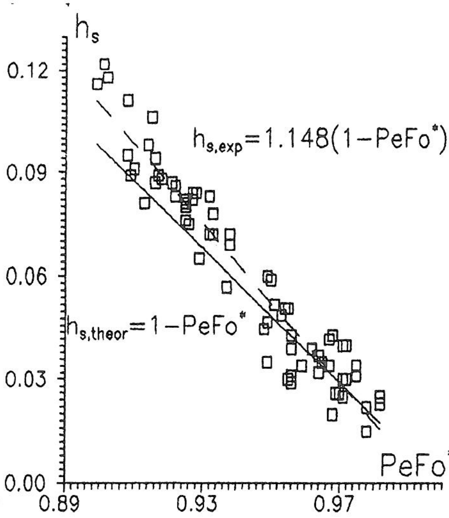

Fig.3. Comparison of the theoretical and experimental thickness of splats. (□ - experimental data, solid curve correspond to our theoretical solution, dashed curve is the best linear fitting of the experimental data).

Fig. 2 illustrates the results of a comparison of the theoretical and experimental diameters more that *300* splats. At the same time in Fig. 3 there are presented the results of comparison of theoretically predicted and directly mearsured thickness of splats. One can see, that the resultant theoretical solution obtained by us generalizes quite satisfactorily the experimental data without introducing any empirical constant, whereas the calculations carried out by use the well-known dependences derived by authors [2,3] usually differ quite appreciably from the results of the modelling experiments. But as it follows from Fig. 2, the branch of experimental data situated in lower right coner of Fig. 2 requires an additional theoretical considaration which will be carryed out by us in next publications.

CONCLUSION

For further verification and development of the theoretical models we have carried out extensive experimental investigations to facilitate a more detailed comparison of the thickness and diameter of splats under the conditions of complete control of the *MRP* of the process. The results show convincingly that for the the investigated droplets the resultant theoretical solution generalizes quite satisfactorily the experimental data without introducing any empirical constant, whereas the results computed by using the well-known dependences suggested by authors of [2,3], differ quite appreciably from experimental data.

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