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Influence of substrate surface conditions on the plasma sprayed ceramic and metallic particles flattening

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Abstract

The influence of the substrate surface temperature and oxidation state on the flattening of alumina and stainless steel particles and the morphology of resulting splats were studied in the current work. Particles were sprayed by a d.c. plasma gun on polished plain carbon steel and low alloy steel substrates preheated by plasma jet at different temperatures in air or in an oxidation limiting nitrogen shroud system added around substrates.

Extensively fragmented splats of alumina and stainless steel were collected on substrates kept at room temperature. On substrates preheated to 573 (±20) K, the splat morphology of both materials transformed from splashed one to disk-shaped one. Optimal flattening degrees for stainless steel and alumina splats were measured for this substrate temperature, and the former particles exhibited flattening degree of the order of 1.2 times those of alumina. On plain carbon steel substrates, preheated in air at temperatures well above 573 K, the particle flattening degree decreased drastically and collected splats were extensively fragmented with bubbles like holes in them. The splashing and bubble formation in splats on preheated substrate were more dominating for low viscosity and higher Reynolds number stainless steel particles. The splat flattening–splashing and bubble formation were effectively limited by preheating substrates in the nitrogen shroud system. After a detailed characterization of substrate surface oxide layers, formed under different preheating conditions, it was concluded that splat morphology and flattening were only partially affected by the oxide chemical composition and thickness and were principally controlled by the surface roughness (more exactly its topography), induced by the oxidation.

Keywords: Plasma; Splat; Flattening; Morphology; Oxidation; Splashing; Atomic force microscopy; Mössbauer spectroscopy

1. Introduction

Thermal spraying is a group of processes in which finely divided surfacing materials are heated and accelerated simultaneously using a heat source and deposited in a molten or semi-molten condition on a prepared substrate. The coating is constructed by the impingement of heated and accelerated particles on the substrate where they flatten rapidly solidify and layer. The layering of these splats leads to the lamellar structure of deposits [1]. The microstructure and quality of coatings are much dependent on the splat morphology and inter-splat contact nature [2–4]. A good understanding of splat formation mechanisms is, therefore, necessary.

Factors governing splat formation can be distinguished into two major categories: impinging particle properties and substrate surface conditions. The former includes droplet temperature, velocity and physico-chemical state at impact (including its oxidation in flight), whereas the later groups substrate temperature, roughness, thermal properties, oxidation state, etc. Much attention has been given to correlate impacting particle parameters with resulting splats [5–8]. In other published works, investigations were carried out to

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establish a relationship between splat formation and substrate conditions including temperature [9–11], roughness [11–13], wettability [14], contact resistance [15] thermal properties [16], etc.

Given similar material and properties of sprayed droplets prior to impact, two types of splats have been observed on smooth surfaces ($Ra<0.05$ μm): disk-shaped ones and extensively fingered ones, initially reported by Turner and Budgen in 1926 [17]. In later works, the transition from splashed splats to contiguous disk-shaped ones has shown a strong dependence on the substrate temperature [18 19]. Extensively fragmented splats were collected on cold substrates. The splat fingers resulted from splashing parallel to the substrate surface called as flattening splashing. However, later on, Escure et al. [6] have shown that another type of splashing, quite different from flattening splashing, occurs at the beginning of the impacts. They called it impact splashing.

Origin of flattening splashing phenomenon in splats was studied by various authors. Houben [20] proposed a model based on shock wave generation, originate by impacting particle impulse energy that forces and expels out the lower layer of flattening particle forming splashed corona. However this model is well adapted to impact splashing but not flattening one. Mostaghimi and his co-workers [21–24] suggested that the solidification initiation in a splat, especially in its peripheral region, at the end of flattening process could obstruct the liquid flow causing jetting out of liquid from the top of the solidified periphery and resulting in splashed fingers. Interaction of flattening particle with pre-solidified splat was considered as another reason of splashing. A 3D model, based on Rayleigh–Taylor instability theory, was developed by these authors to predict the finger number around the periphery of splashed splat. These results showed the formation of fragmented splats when substrate–splat thermal contact resistance (R_{th}) was close to zero and splashing could be suppressed on increasing R_{th}. These results, however, diverge from other experimental findings. The calculation of R_{th} from the time–temperature evolution of flattening zirconia particles showed that when its value was below 10^{-7} m^2 K W^{-1} a disk-shaped splat was obtained while over 10^{-6} m^2 K W^{-1} splats were extensively fragmented [25 26]. These values were confirmed by Gougeon and Moreau [27], while working with molybdenum particles. Moreover, these authors reported that the liquid particle flatten to a maximum area due to its initial kinetic energy. Once the kinetic energy is completely dissipated, surface tension results in surface shrinkage causing jetting out of liquid from upper part. Fukumoto et al. [18] suggested that the splashing occurs more likely due to jetting away of liquid from the upper part of the flattening particle.

Splashing is characterized by considering Reynolds (Re) (Eq. (1)), Weber (We) (Eq. (2)), Sommerfeld (K) (Eq. (3)) [28] numbers and the flattening velocity (v_f) to impact velocity (v_p) ratio (a) (Eq. (4)) of impinging particle. Impact splashing, with tiny droplets ($d<1$ μm) entrained out of the flow boundary layer, is characterized by the Sommerfeld parameter K (Eq. (3)): if $K>58$ impact splashing occurs. A new criterion of flattening splashing (different from impact splashing) K_f (Eq. (5)) was introduced [29]. Fukumoto et al. [30], while conducting experimentation with free falling drops, established that the flattening splashing in splats occurred when $K_f>6$.

$$Re = \frac{\rho_p d_p v_p}{\mu_p} \tag{1}$$

$$We = \frac{\rho_p d_p v_p^2}{\sigma_p} \tag{2}$$

$$K = \sqrt{We\sqrt{Re}} \tag{3}$$

$$a = \frac{v_f}{v_p} \tag{4}$$

$$K_f = \sqrt{We_f\sqrt{Re_f}} = 0.5a^{1.25}Re^{-0.3}K \tag{5}$$

Flattening velocity of a particle is dependent on its impact velocity but more significantly on the substrate temperature and morphology and therefore a is a function of substrate temperature and impact velocity: $a=f(T_s, v_p)$.

Splats exhibit a drastic change from fingered ones to non-fragmented ones while increasing the substrate temperature over a certain narrow temperature range. The substrate temperature where splat shape changes was introduced as transition temperature ($T_s \sim T_t$) [31]. On substrates, kept at a low temperature, the splashed splats had porous bottom layer and uneven rapidly solidified zones whereas on substrates, preheated over temperature $\sim T_t$, splats exhibited a pore-free uniform finer columnar crystal structured bottom layer [14,30,32]. In the former case, nucleation at unevenly distributed areas in the bottom layer could have resulted in random localized solidified zones which were considered as a major factor impeding liquid flattening and promoting splashing. On the contrary it was found that in the later case, the solidification could have only initiated after almost complete particle flattening. A model, developed by Vardelle et al. [33], established that delayed nucleation of particle can be achieved for T_s approaching T_t that may favor solidification of the whole lower surface after complete flattening and leads to homogeneous splat cooling and disk-shaped morphology. Moreover, above T_t, a sharp decrease in K_f was measured [30].

These modifications in flattening and solidification of splats at T_t were found to be dependent on different parameters. Desorption, at elevated temperature ($T_s>T_t$), of condensates and aggregates present at substrate surface and improved wetting of particles on substrates were considered as major factors. Li et al. [34], while working with substrates covered with organic fluids, reported the formation of fragmented splats on substrates if this layer was not completely evaporated. Jiang et al. [35] reported a reduction in splat fragmentation with a decrease in adsorbed gas/