# Thermal Spray: A Case History for the Integration of Materials Science and Thermo-Fluid Dynamics

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## ABSTRACT

The thermal spray process involves the injection of particulates into a high flux environment so that momentum and heat transfer can take place. The particles are then accelerated within the gaseous effluent and within several milliseconds impact and splash against a suitably prepared substrate. In this fashion a coating rapidly grows over a time period that may range from minutes to hours.

The materials engineering concept comes into play when it is appreciated that the temperature, velocity, and chemical nature of the spray effluent controls the dispersion, impact phenomenon, and, therefore, the precise nature of the microstructure which is being formed *in situ* and in real time. Unsurprisingly, this is a somewhat random and chaotic process that is seeking practical and theoretical solutions so that some manner of engineering control can be employed.

This paper explores the scientific relationship between materials engineers and mechanical engineers so that a functional product can evolve. This relationship includes (i) the use of diagnostic equipment to monitor the spray process, (ii) the dynamic impact behavior of particulates, (iii) modeling of thermal fluxes and the resultant mechanical stress state, and (iv) the way in which the microstructure evolves. The eventual aim of this vast body of work is to enable real time feedback loops for the thermal spray process so that predictable and engineered structures can be manufactured.

## 1. INTRODUCTION

Thermal spray will be celebrating its centenary in 2003 [11]. It has a right to be classified as an “old” technology; yet its science, remarkably, is still in its infancy. The reasons for this apparent lack of advance are numerous and can be distilled to the fact that the engineering practice has exceeded its scientific comprehension. The upshot is that there is much room for improvement concerning the integration of thermal spray science [2] with respect to the current engineering practice so that future applications may grow.

The topics of interest where a synthesis of the mechanical and materials engineering may lead to greater understanding can be broken down into the following groups of specialization:

i. Enhanced understanding of the physical processes that give rise to generation of the heat source. For example, combustion processes in chemical flames, arc generation phenomenon within low pressure and high pressure electric discharges and the nature and formation of restricted, contained shock waves.
ii. The chemical environment of the heat source and how this local environment interacts with the thermal spray feedstock material.
iii. The temperature and velocity profiles of the heat source and of the feedstock materials. It is also vital to understand the stability of the thermal source with special emphasis on how this impacts the feedstock trajectory.
iv. A most serious lack of scientific evidence applies to the spatial distribution of feedstock particles throughout their transfer from the thermal spray feed device to deposition upon a substrate. Important materials transport behavior can be altered during this “residence time” of several milliseconds and therein lies an opportunity for process control.

v. Impact phenomena and materials flow of molten or semi-molten particles on roughened substrates needs to be quantified. An example of poor usage and correlations among physical parameters concerns the use of the roughness parameter, $R_a$[1], which is often used to describe surface conditions. This is an inappropriate and potentially misleading parameter because a numerical value of roughness does not present a clear physical representation of the surface. Thus, a single $R_a$ value can depict surfaces of widely varying areas and quite distinct physical conditions. The upshot is that any mechanical engineering model which attempts to relate the flow of material upon a substrate in terms of purely $R_a$ will be fundamentally flawed. Such physical relationships need to be investigated with more thoroughness with a view for integration into theoretical models.

vi. The microstructure of thermal spray deposits is created under an array of cooling conditions that may be as fast as $10^7$°C per second. Thus, the application of classical equilibrium kinetics is often not possible. In an alike fashion, the microstructure of thermal spray deposits is highly defective and anisotropic and this leads to some regions of the coating being oriented. Therefore, certain regions of the coating are highly oriented yet others are very chaotic and any model which does not take these microstructural attributes into account will not be representative of actual coatings.

vii. The physical properties of coatings need to be ascertained in a reliable fashion so that scientifically important and interpretive comments can be validated.

Only several of the above aspects will be touched upon in this present contribution.

## 2. THE NATURE OF THE THERMAL SOURCE

It has been demonstrated that entrainment of eddies of cold air influence the local temperature and velocity profiles of the transporting media [3], Fig. 1. Such entrainment of gaseous species has been demonstrated to cause *in situ* oxidation of the materials [4] which are intended to form the coating material and in many cases, therefore, this is undesirable. Furthermore, it becomes clear that any modeling that relies on orderly flow fields is unrealistic since it does not take into account the stochastic processes that physically occur. Few numerical models are able to replicate the virtually random conditions that are experienced within the thermal spray source.

One critical aspect that has heralded the emergence of this science has been the recent development of physics-based techniques [5,6] that can reliably measure the dynamic events occurring within these non-equilibrium effluents. Therefore, it is experimentally possible to measure the temperature, velocity, and particle size distributions throughout the thermal spray process zone. There is now active research to integrate these quantitative measurements to the modeling studies [7, 8].

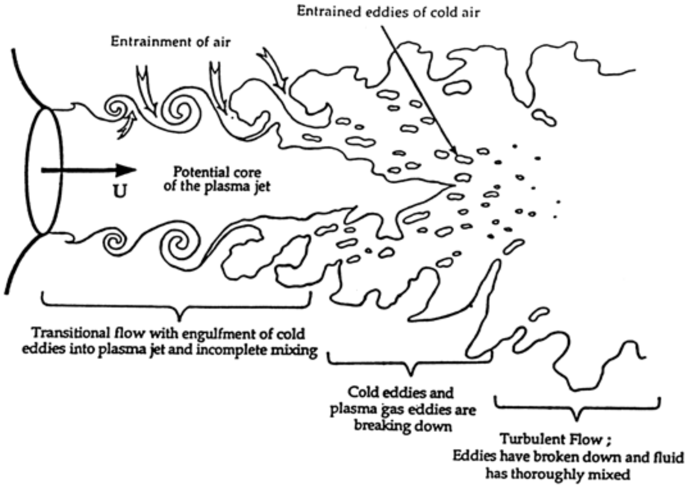

Figure 1: A schematic of the fluid dynamics which surrounds a plasma jet.

## 3. THE SPLAT PROCESS

The basic manifestation of the splat process has been described by many authors. Thus, splats may be described as “flower-like”, “star-like”, or “fragmented”. Visualization of the splats has, again, been limited by the available technology which has only recently become available [9]. Much work has cataloged the splash morphology under various conditions; e.g., [10,11, 12,13,14] including the properties of the substrate [15].

It is worthwhile to briefly review an early study [16] that focused intensely on the splat character of deposits and charted the morphology of A316 stainless steel particles impacting against a highly polished metallic substrate. Figure 2 [16] shows *“how the string type corona develops upon the radial flow of particle surface material”*. It becomes readily apparent that the idealized “saucer shape” or “pancake geometry” of spats, as often depicted in cartoons of the thermal spray microstructure, are more of the rarity than reality. The much

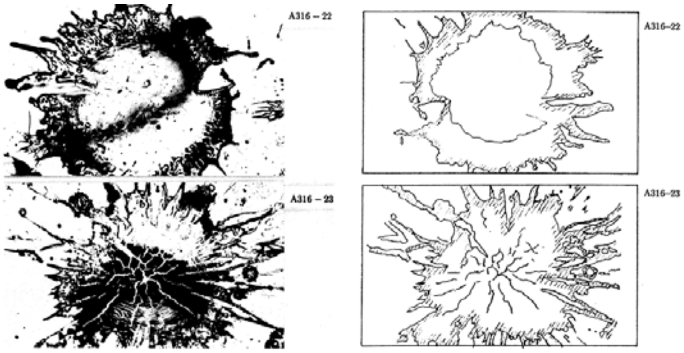

Figure 2: Experimental and schematic representation of a stainless steel particle impact.

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[1] It is not implied that existing studies are outmoded. Most surfaces for thermal spray are prepared by grit blasting. Therefore, R, may be a convenient term to use for this class of materials preparation technique since the surface profiles are to some degree similar.

more complex structures of particles that are observed in Fig. 2 are quite difficult to numerically model and it is suggested that the prime variables that need to be addressed include, (i) temperature, (ii) velocity, (iii) surface roughness of the substrate, and (iv) freezing time of the impacting particles.

## 4. SPLAT DEFORMATION

The more complete picture for the growth of a coating will incorporate the growth of a coating to a functional thickness. Thus, the profiles exhibited in Fig. 3 [16] are representative examples of contact zones between splats and a substrate. The physical model is observed to vary depending on the instantaneous contact parameters of the impacting particle and substrate.

The next step concerns the evolution of the subsequent layers of particles which now see a completely different surface; i.e., the roughness, hardness and temperature (among many physical properties) have been altered. The process therefore needs to be modeled in an iterative fashion whereby the boundary conditions are continuously changing and where the splat behavior will be different every time. The definition of the problem statement is these terms is, indeed, very challenging from the standpoint of the numerical analysis.

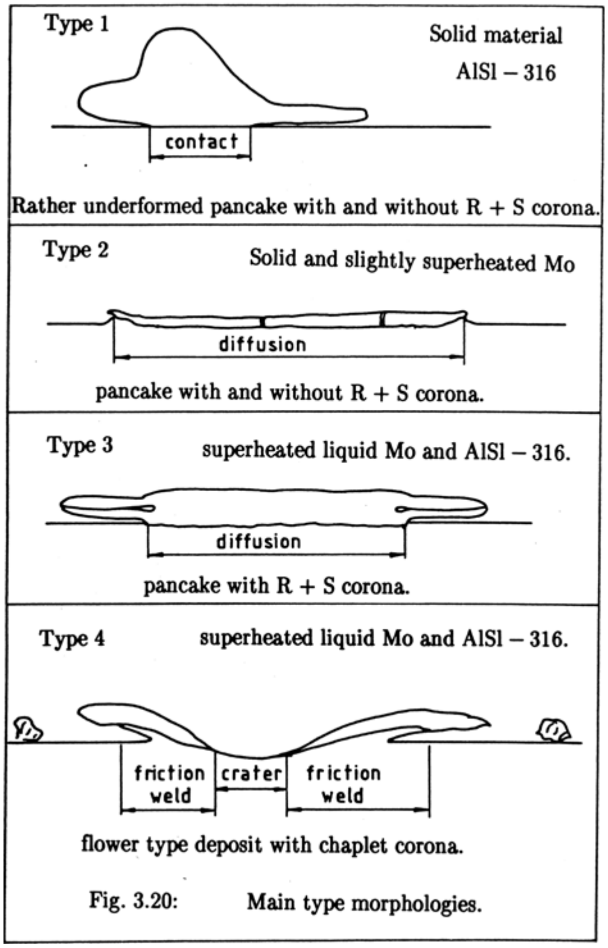

Figure 3: Models for splat / substrate interactions.

Another important aspect of such science is "How can the numerical models be verified by an independent technique?" For example there are no established rules that permit standard microstructures to be employed as calibration samples so that the computed model can be independently assessed.

Materials scientists are approaching these qualitative methods with statistical tools that may be employed to provide quantitative assessments of microstructures. Therefore, splat statistics such as thickness-to-diameter ratios, degree and size of porosity, as well as propensity of cracking have all been measured with an aim of acquiring a data base for the coating structure. Whereas these methods have been of immense scientific interest; their application to practical engineering problems have not been well documented.

## 5. A VISION OF THE FUTURE

Figure 4 shows some schematics and flow charts which indicate potential directions for thermal spray science.

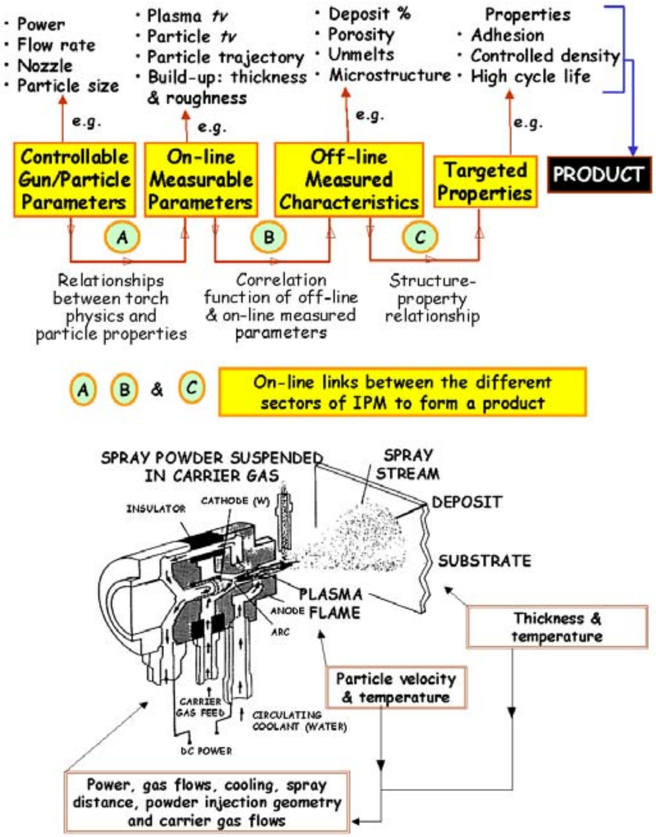

Figure 4: Schematics that depict the essential thermo-physical attributes of the thermal spray process. The top figure ("a") indicates important experimental and control parameters that are needed for integrated manufacturing processing (IPM). The bottom figure ("b") shows how a real-time feedback system would be integrated into a manufacturing cell so that "*designed-for*" coatings may be produced.

Figure 4a is a summary of many pertinent parameters that are required for current modeling studies. The gun parameters control the characteristics of the thermal spray effluent which then influence the splat behavior of the feedstock materials. The so-formed microstructure is then the controlling material characteristic that determines the nature of the material properties. The bottom of this figure shows that the parameter space groups of A, B, and C are all linked in some form so that any change in the processing parameters will ultimately influence the material properties.

Figure 4b shows a similar concept to that in Fig. 4a where the thermal spray process parameters are altered in real time so that "designed-for" microstructures can be achieved by adjusting the process variables under real time conditions. In this particular example; (i) on-line coating thickness and substrate temperature measurements and (ii) particle in-flight temperature and velocity data would be employed to adjust the (iii) thermal spray parameters. This processing concept is, at present, outside the realm of conventional processing capability since the mathematical models required for integrating the materials and processing sciences do not exist.

The long term vision is that dynamic processing methods such as thermal spray offer opportunities to manufacture unique microstructures that can be employed for emerging applications. Some prime limitations in advancing such concepts include the lack of numerical models that can simulate the entire processing - property envelope. This remains to be a scientific challenge that is worthy of further effort.

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