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M. Grujicic
Clemson University

V. Sellappan
Clemson University

Laine Mears
Clemson University, mears@clemson.edu

X. Xuan
Clemson University

Norbert Seyr
BMW Group, Research and Technology

See next page for additional authors

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Authors
M. Grujicic, V. Sellappan, Laine Mears, X. Xuan, Norbert Seyr, Marc Erdmann, and Jochen Holzleitner

SELECTION OF THE SPRAYING TECHNOLOGIES FOR OVER-COATING OF METAL-STAMPINGS WITH THERMO-PLASTICS FOR USE IN DIRECT-ADHESION POLYMER METAL HYBRID LOAD-BEARING COMPONENTS

M. Grujicic, V. Sellappan, L. Mears
International Center for Automotive Research, CU-ICAR
Department of Mechanical Engineering
Clemson University, Clemson SC 29634

Norbert Seyr, Andreas Obieglo
BMW Group, Research and Technology, Knorrstraße 147
80788 München, Germany

Marc Erdmann, Jochen Holzleitner
BMW AG, Forschungs- und Innovationszentrum, Knorrstraße 147
80788 München, Germany

Correspondence to: [1]
Mica Grujicic, 241 Engineering Innovation Building, Clemson University, Clemson, SC 29634-0921;
Phone: (864) 656-5639, Fax: (864) 656-4435, E-mail: mica.grujicic@ces.clemson.edu

ABSTRACT

The suitability of various polymer-powder spraying technologies for coating of metal stampings used in polymer metal hybrid (PMH) load-bearing automotive-component applications is considered. The suitability of the spraying technologies is assessed with respect to a need for metal-stamping surface preparation/treatment, their ability to deposit the polymeric material without significant material degradation, the ability to selectively overcoat the metal-stamping, the resulting magnitude of the polymer-to-metal adhesion strength, durability of the polymer/metal bond with respect to prolonged exposure to high-temperature/high-humidity and mechanical/thermal fatigue service conditions, and compatibility with the automotive body-in-white (BIW) manufacturing process chain. The analysis revealed that while each of the spraying technologies has some limitations, the cold-gas dynamic-spray process appears to be the leading candidate technology for the indicated applications.

Keywords: Polymer Metal Hybrids; Polymer Metal Adhesion; Automotive Structural Components; Polymer Coating Processes

I. INTRODUCTION

Over the last decade, polymer metal hybrid (PMH) structures have been used in variety of automotive applications ranging from the instrument-panel cross-beams via the roof-panel-cross-support to the entire front-end vehicle modules. The main idea behind the PMH technology is to use a system level approach in order to combine the structural and non-structural functions of a number of components, into a singular fully-optimized sub-assembly (typically consisting of a metal-stamping core and plastic injection-molded overcoat containing multiple ribs). This approach generally yields, due to its underlying material/structure system-integration approach, greater system-level benefits relative to those obtained by simple merging/joining of the proximate parts/components.

The subject of the present work is the use of the PMH technology in load-bearing body-in-white (BIW) automotive components. An example of such a component is depicted in Figures 1(a)-(b). The component in question is generally referred to as the "*rear longitudinal beam***" which connects, on the front end, to the rocker panel, on the middle to the shock tower, while at the rear end it connects to the rear cross beam. The traditional all-metal design of this component is displayed in Figure 1(a) and includes three components: (a) main U-shape channel beam; (b) a reinforcement plate and (c) a cover plate. The latter two components are spot welded to the first one. It should be noted that the cover plate is slightly translated in Figure 1(a) in order to reveal the location of the reinforcing plate. The PMH rendition of the same component is depicted in Figure 1(b). The reinforcement plate has been replaced with an injection-molded thermoplastic rib-like sub-structure, while the thickness of the cover-plate (not shown in Figure 1(b) for clarity) is reduced.**

The main PMH technologies currently being employed in the automotive industry can be grouped into three major categories: (a) Injection over-molding technologies [1]; (b) Metal-over-molding technologies combined with secondary joining operations [2]; and (c) Adhesively-bonded PMHs [3]. A detailed description for each of

these groups of PMH manufacturing technologies can be found in our recent work [4]. Hence, only a brief overview of each is given below.

In the injection over-molding process, metal inserts with matching flared through-holes are stamped, placed in an injection mold and over-molded with short glass fiber-reinforced thermoplastics to create a cross-ribbed supporting structure. The metal and plastics are joined by the rivets which are formed by the polymer melt penetrating through-holes in the metal stamping(s). Such rivets then provide mechanical interlocks between the plastics and the metal. In the metal over-molding PMH technology, a steel stamping is placed in an injection mold, where its underside is coated with a thin layer of reinforced thermoplastics. In a secondary operation, the plastics-coated surface of the metal insert is ultrasonically welded to an injection molded glass-reinforced thermoplastic sub-component. In this process, a closed-section structure with continuous bond lines is produced which offers a high load-bearing capability. In the adhesively-bonded PMH technology, glass fiber-reinforced poly-propylene is joined to a metal stamping using Dow's proprietary low-energy surface adhesive (LESA) [4]. The acrylic-epoxy adhesive does not require pre-treating of the low surface-energy poly-propylene and is applied by high-speed robots. Adhesive bonding creates continuous bond lines, minimizes stress concentrations and acts as a buffer which absorbs contact stresses between the metal and polymer sub-components. Adhesively-bonded PMHs enable the creation of closed-section structures which offer high load-bearing capabilities and the possibility for enhanced functionality of hybrid parts (e.g. direct mounting of air bags in instrument-panel beams or incorporation of air or water circulation inside door modules).

While the aforementioned PMH technologies have demonstrated their potential and are being widely used in various non-structural and load-bearing automotive components, they nevertheless display some significant shortcomings. For example, in many applications, to maintain the structural integrity of the part, hole punching needed for polymer-to-metal interlocking in the injection over-molding process may not be allowed. Similarly, stamped-edges over-molding may be restricted. In the case of adhesively-bonded PMHs, the adhesive cost, long curing time and the ability of the adhesive to withstand aggressive chemical and thermal environments encountered in

the paint-shop during body-in-white (BIW) pre-treatment and E-coat curing may be an issue. Consequently, alternative lower-cost PMH technologies for structural load-bearing BIW component which are compatible with the BIW manufacturing process chain are being sought. One of such technologies, which is the subject of the present work, is the so called direct-adhesion PMH technology in which the joining between the metal and thermo-plastic sub-components is attained through direct-adhesion of injection-molded thermo-plastics to the metal without the use of interlocking rivets/over-molded edges or structural adhesives [4]. There are several potential advantages offered by this technology over the ones discussed above: (a) Polymer-to-metal adhesion strengths (ca. 35MPa [4]) comparable with those obtained in the case of thermo-setting adhesives are feasible but only at a small fraction of the manufacturing cycle time; (b) The shorter cycle time and the lack of use of an adhesive allow for more economical PMH-component production; (c) Unlike the adhesive-bonding technology, joining is not limited to simple and non-interfering contact surfaces; (d) Reduced possibility for entrapping air in undercuts of a complex surface; (e) No holes for the formation of interlocking rivets are required and, hence, structural integrity of the part is not compromised; and (f) Overall reduction in the constraints placed upon the design complexity of the PMH component.

In our previous work [4], it was shown that, in order to ensure a good load transfer between the polymer and the metal sub-components in the direct-adhesion PMH structures, a plastic overlay (with a large contact surface area with the metal stamping) is needed in addition to the plastic rib-like structure. An example of such an overlay is depicted in Figure 1(b). Furthermore, our previous work [4] has demonstrated that if the overlay is produced simultaneously as the ribbing structure using conventional injection molding, the weight of the resulting PMH component would be excessively high. The primary reason for this was the existence of a minimal injection-moldable part wall thickness, which in the case of short glass fiber-reinforced nylon 6 (the material most commonly used in the injection over-molding PMH technology) amounts to ~2mm (and becomes even larger as the need for drafting is accommodated). To overcome this limitation, it is suggested [4] that the overlay should be fabricated using one of the polymer-powder spraying technologies. Such

technologies enable fabrication of coating layer with ca. 0.5mm thickness and, hence, could substantially reduce the PMH-component weight. Once the overlay has been spray formed, the plastic ribbing structure can be injection molded against it.

In the present work, a brief overview of the main polymer-powder spraying technologies and an analysis of their suitability for use in the direct-adhesion PMH technologies aimed at load-bearing BIW components are presented. In order to carry out such suitability assessment a number of suitability criteria have been developed. Some of these criteria are related to the PMH-component manufacturability, others with respect to the long-term durability of the PMH-component while the remaining ones with respect to the compatibility of the PMH-component/process with the BIW manufacturing process chain. It should be noted that the far-reaching objective of the present work is to critically assess the potential of direct-adhesion PMH technology in BIW load-bearing applications. Hence, significant body of work dealing with polymer-to-metal adhesion developed within the electronic packaging field is not presented, since the approaches used employed very thin (10-100µm) metal and/or polymeric structures and were not compatible with the BIW manufacturing process chain.

As stated earlier, the objective of the present work is to assess the potential of different polymer-powder spraying technologies for use in direct-adhesion PMH load-bearing BIW components both from the component function standpoint and the stand point of compatibility with the BIW manufacturing process chain. In traditional all-metal BIW manufacturing practice, components are stamped in the press shop, joined (typically by welding) in body shop and the constructed BIW pre-treated and painted in paint shop. In the case of injection over-molding BIW PMH components, stamped metal subcomponents are "*hybridized*" with thermoplastic ribbing structure in injection molding shop. Hence to assess the suitability of various polymer-powder spraying technologies for BIW load-bearing applications, their compatibility with various processes taking place in press shop, injection molding shop, body shop and paint shop will be considered. Specific aspects of the BIW manufacturing process chain capability are discussed in the following sections.

It should be also noted that the present paper is part of the ongoing research which deals with a total life-cycle approach to the selection of materials, and

manufacturing/processing technologies in the light-weight engineering of the automotive BIW structural applications. Within such an approach, all the key BIW manufacturing process steps are considered. These steps include, metal-subcomponent manufacturing by stamping in the process shop, PMH component or thermoplastic-sub component manufacturing in the injection-molding shop, BIW construction by various joining processes in the body shop, BIW pre-treatment and painting in the paint shop, component performance and durability in service, and end-of-life considerations including disassembly, shredding, materials segregation, separation and recycling.

II. OVERVIEW OF POLYMER-POWDER SPRAY PROCESSES

In this section a brief overview is given of the major polymer-powder spraying technologies. Since the final goal of the present work is to assess the suitability of these technologies for plastic-overlay deposition needed in the direct-adhesion PMH technology, the spraying processing are presented using a common platform. Such platform includes the consideration of the following aspects of each process: (a) problem description; (b) variation of the process; (c) depositing materials (d) substrate materials; (e) depositing/substrate materials pre-treatment; (f) part post-treatment; (g) major advantages and (h) main limitations.

II.1 Cold-gas Dynamic Spray

Process Description: **The cold-gas dynamic spray process, often referred to as** *"cold spray"*, **is a high-rate coating and free-form fabrication process in which fine, solid powder particles (generally 1 to 50 μm in diameter) are accelerated to high velocities (ca.100m/s for polymeric materials) by entrainment in a (often supersonic) jet of compressed (propellant) gas. The solid particles are directed toward a substrate, where during impact, they undergo plastic deformation and bond to the surface, rapidly building up a layer of the depositing material. Cold spray as a coating technology was initially developed in the mid-1980s at the Institute for Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Science in Novosibirsk [5,6]. The Russian scientists successfully deposited a wide range of pure metals, metallic alloys, polymers and composites onto a variety of substrate materials. In**

addition, the Russian scientists demonstrated that very high surface deposition rates on the order of 5 m^2/min (~ 300 ft^2/min) are attainable using the cold-spray process.

In a typical cold-spray process, a compressed propellant gas of an inlet pressure on the order of 30 bar (500 psi) enters the device and flows through a converging/diverging DeLaval-type nozzle to attain a high velocity. The solid powder particles are metered into the gas flow upstream of the converging section of the nozzle and are accelerated by the rapidly expanding gas. To achieve higher gas flow velocities in the nozzle, the compressed gas is often preheated. However, while preheat temperatures as high as 900^o K are sometimes used, due to the fact that the contact time of spray particles with the hot gas is quite short and that the gas rapidly cools as it expands in the diverging section of the nozzle, the temperature of the particles remains substantially below the initial gas preheat temperature and, hence, below the melting temperature of the powder material. A simple schematic of the cold-gas dynamic spray process is shown in Figure 2.

The actual mechanism by which the solid particles deform and bond during cold spray is still not well understood. It is well-established; however, that in the case of metallic feed particles and the metallic substrates extensive localized plastic deformation takes place during the impact. This causes disruption of the thin surface (oxide) films and enables an intimate conformal contact between the particles and the substrate/deposited material. The intimate conformal contact of clean surfaces combined with high contact pressures are believed to be necessary conditions for particles/substrate and particles/deposited material bonding. As far as the bonding mechanism between the sprayed polymer and metallic substrates is concerned, the picture is much less clear. It is generally believed, however, that micron-scale mechanical interlocking between the two materials at the polymer/metal interfaces plays an important role.

Variations of the Process: **With the exception of some differences in the carrier-gas and powder delivery systems and nozzle designs, no distinct variations of the cold-gas dynamic-spray process could be identified.**

Depositing Materials: **A wide range of ductile (metallic and polymeric) materials can be successfully deposited by the cold spray while non-ductile materials such as ceramics can be deposited only if they are co-cold-sprayed with a ductile (matrix) material.**

Substrate materials: **Since a good combination of strength and ductility of the substrate is a critical component of the process, metallic materials are typically used as substrates.**

Pre-treatment: **To obtain higher jet speeds, the carrier gas is typically pre-heated to a couple of hundreds of degrees of Celsius. In the case of plastic powder materials, cleaning/degreasing and pre-heating of the substrate appear to have a positive effect in attaining larger deposition yields and higher polymer-to-metal adhesion strengths [7].**

Post-treatment: **Typically no post-treatment is needed for cold-sprayed parts.**

Advantages: **Because of its low-temperature operation, the cold-spray process generally offers a number of advantages over the thermal-spray processes when used for deposition of the polymeric materials. Among these advantages, the most important appear to be [8,9]: (a) The amount of heat delivered to the coated part is relatively small so that microstructural changes in the substrate material are minimal or nonexistent; (b) Due to the absence of in-flight oxidation and other chemical reactions, thermally- and oxygen-sensitive depositing materials can be cold sprayed without significant material degradation; (c) "Peening" effects caused by the impinging powder particles can give rise to potentially beneficial compressive residual stresses in cold-spray deposited materials [8] in contrast to the highly detrimental tensile residual stresses induced by solidification shrinkage accompanying the conventional thermal-spray processes; and (d) Cold spray of the polymeric materials offers exciting new possibilities for cost-effective and environmentally-friendly alternatives to the conventional solvent-based painting technologies.**

Disadvantages: **Due to visco-elastic (i.e. strain-rate dependent) nature of the thermoplastic materials and the mechanical-interlocking character of the polymer-to-metal bonding, a relatively narrow, material and particle-size dependent processing**

window is typically available for successful cold-spray deposition of thermoplastic coatings.

Other Significant Aspects of the process: **Per recommendations of one of the reviewers of the manuscript, additional aspects of each of the polymer powder spraying technologies in question are considered. These include, the maximum coating thickness, the ability for and the ease of real-time monitoring of the deposited-coating thickness and durability/robustness of the coating process. While these aspects of the polymer-powder spraying technologies are generally important and need to be considered, they are not deemed critical in the case of overlay fabrication for adhesively-bonded PMH components. Consequently, the aspects of the polymer-powder spraying technologies mentioned above will be discussed but will not be used to define the selection criteria for identifying the optimal polymer-powder spraying process.**

In the case of cold-gas dynamic spray process, a large range of coating thicknesses can be attained. The lower limit of this range is around 5-10μm and corresponds to the deposition of a one-particle thick coating, while the upper limit can be several centimeters, since cold-gas dynamic process is used also as a free-form fabrication process in addition to being used as a coating process. Real-time monitoring of the progress of deposition is typically not done. Rather, for a given set of process parameters and, the powder-particle size distribution and the substrate surface conditions, the deposition yield is predetermined and, hence the deposition thickness can be readily determined from the nozzle travel speed and the deposition time. The most critical aspects of the cold gas dynamic spray process which affects the performance is clogging of the nozzle.

II.2 Electrostatic Powder Coating Spray Process

Process Description: **Electrostatic-spray powder-coating process utilizes a powder-air mixture delivered to the spray gun from a fluidized-bed feed system. Within the gun, the powder is electro-statically charged and directed toward a grounded metal substrate being coated. A simple schematic of the electrostatic-spray powder-coating process is shown in Figure 3.**

Variations of the Process: **There are two basic variations of this process which mutually differ with respect to the way the electrostatic charge is applied to the powder: (a) within the "*corona*" electrostatic spray process, the powder is charged via an electrode subjected to a high negative DC voltage; and (b) in the "*tribo-charge*" electrostatic spray process, the powder is charged by friction accompanying the contact between the powder particles and the spray-gun inner lining.**

Depositing Material: **Currently, in excess of 90% of thermosetting coatings are deposited using the electrostatic spray process, while the process is also widely used for the deposition of variety of thermoplastic coatings (e.g. nylon, vinyl, poly-olefins)**

Substrate material: **Since electrical grounding of the substrate is a critical component of the process, metallic materials are typically used as substrates.**

Pre-treatment: **To remove the moisture, air is typically passed through a drying bed. Powder must be electro-statically charged. Standard cleaning/degreasing of the metal substrate is required. For thicker coatings (0.1-0.5mm), substrate preheating is necessary.**

Post-treatment: **Curing/fusion of the deposited powder is required and can be carried out at different temperatures (curing/fusing cycles as short as 20-60 seconds at temperatures around 200^{o}C are typically needed)**

Advantages: **High deposition efficiency since the over-sprayed powder is reclaimed, short cycle time, high adaptability to automation, suitable for a large variety of depositing and substrate materials.**

Disadvantages: **Difficulties in attaining uniform coating thickness in parts with complex geometries.**

Other Significant Aspects of the process: **Typical range of polymer-powder coatings deposited using the electrostatic spray process described above is 30-250μm. Real-time measurements of the thicknesses of the deposited coating is typically not done. Instead, various simple correlations are used between the process parameters and the properties of the polymer powder on one hand and the deposition rate, on the other. As in the case of cold-gas dynamic spray process, nozzle clogging is the phenomenon which most**

frequently affects the performance of the electrostatic polymer powder spraying process.

II.3 Fluidized-bed Powder Coating Process

Process Description: **In the fluidized-bed powder coating process, the coating powder is held in a container which is at its bottom separated from an air chamber (commonly referred to as "*plenum*") by a perforated plate. Compressed air is introduced into the plenum and through the perforated plate, into the coating-particle bed. As the compressed air passes through the bed it lifts the particles causing them to get suspended and to form a "fluidized bed" of the particle/air mixture. When the substrate is brought into a contact with the fluidized bed, coating takes place.**

Variations of the Process: **There are two basic variations of the fluidized-bed powder coating process: (a) a conventional process and (b) an electrostatic process. Schematics of these processes are given in Figures 4(a)-(b). Within the conventional fluidized-bed powder coating process, the part to be coated is preheated and lowered into the fluidized-particle bed. In the electrostatic fluidized-bed powder coating process, particles in the fluidized bed are charged using a high-voltage DC electrode. While the metallic part is electrically grounded and suspended above the fluidized bed, electrostatic interactions between fluidized-bed charged particles and the grounded substrate then causes particle acceleration toward the substrate and, in turn, to the formation of the coating on the part.**

Depositing Material: **Both versions of the fluidized-bed powder-coating process are widely used for the deposition of common thermoplastics (e.g. nylon, vinyl, poly-olefins, etc.) and common thermosets (e.g. epoxy, acrylics, etc.)**

Substrate material: **Typically metallic materials are used as substrates and in the case of the electrostatic fluidized-bed powder coating process, electrical grounding of the part entail a high-level of electrical conductivity of the part material.**

Pre-treatment: **With the exception of drying and electrostatic charging of the powder (in the case of electrostatic fluidized-bed process) no special powder pretreatment is**

required. Standard cleaning/degreasing of the substrate is required. In the case of the conventional process, the part is pre-heated and, often, pre-primed for improved coating adhesion.

Post-treatment: **Relatively short (3-5 min) post-coating heat treatment (at ca. 200^{o}C) is typically required to ensure smooth and less porous coating (in the case of thermoplastic) and complete curing (in the case of thermosets).**

Advantages: **One of the main advantages of the fluidized-bed powder coating process is uniformity in the coating thickness and the microstructure. Essentially perfect material-transfer efficiency is typically attained. Also, in the case of the electrostatic fluidized-bed process, no preheating of the substrate is required.**

Disadvantages: **Main limitations of the fluidized-bed powder coating process are: (a) suitable for relatively small to middle-size parts; (b) generally not suitable for coating of selected portions of the part; (d) in the case of the electrostatic process, the inside corners of the part are typically less coated due to the interplay of the so-called "***Faraday cage effect***".**

Other Significant Aspects of the process: **Typically, coatings in a 250-750μm thickness range are deposited using fluidized-bed coating deposition process. On-line monitoring of the deposition process is not usually done and, instead, the deposit thickness is assessed using previously established functional relationships between the deposition thickness and the process parameters and the deposition/substrate material properties. Coalescence of powder particles into larger clumps is typically the phenomenon that controls the quality of the coating deposited using the fluidized-bed polymer-powder coating process.**

II.4 Thermal Spray Powder Coating Process

Process Description: **Within the thermal spray powder coating process, powder particles in a 1-50μm size range are (at least partially melted) inside a spray gun and accelerated to high-velocities (ca. 40-100 m/s for flame, 400-800 m/s for HVOF, 80-300 m/s for plasma coating process) toward the substrate. Upon impact, the particles splatter onto the surface building a coating layer.**

Variations of the Process: **All the thermal spray processes are generally classified as combustion and electric processes. Among the combustion type thermal spray processes the ones most frequently used for the deposition of plastic are flame and high-velocity oxygen fuel (HVOF) spraying processes. Schematics of these two thermal spray processes are given in Figures 5(a)-(b). The fundamental difference between these two processes is that in the case of flame spraying the powder material is fed continuously to the tip of the spraying gun where it is melted in a fuel/gas flame and propelled to the substrate in a stream of carrier gas (typically air). Usually, acetylene, propane and methyl acetylene-propadiene are used as fuel. Within the HVOF process fuel and oxygen are pre-mixed, combusted in a confined space and accelerated to supersonic speeds in an n extended nozzle. While the powder particles are injected into the flame. Consequently, the resulting coating is characterized by a high-density, low-porosity and a high bond-strength.**

Among the electrical thermal spray coating processes, the one most frequently used for the deposition of plastic coatings is plasma-arc spray process. Within this process, powder particles are melted within the spray gun by an electric arc created between an internal central-line electrode and the gun nozzle (which acts as a second electrode). A pressurized inert gas is passed between the electrodes where it is heated to very high temperatures to form a plasma gas. As the powder particles are introduced into the plasma gas, they are melted and propelled toward the substrate. A schematic of the plasma-arc spray process is given in Figure 5(c).

Depositing Material: **A wide variety of metallic, ceramic and polymeric coating materials can be used.**

Substrate material: **Likewise, a variety of metallic, ceramic and polymeric materials can be used as substrate materials.**

Pre-treatment: **No particular pre-treatment of the polymeric powder is required while standard grit blasting, cleaning/degreasing of the substrate is normally required. Pre-heating of the substrate is generally not a pre-requisite for good adhesion bonding.**

Post-treatment: **Typically no post-treatment of the thermal spray coated parts is required.**

Advantages: **Among the main advantages of the thermal spray processes are: (a) no requirements exist with respect to substrate pre-heating; (b) a large variety of depositing and substrate materials can be utilized; and (c) low-porosity, high-density coating can be readily produced (particularly in the HVOF process).**

Disadvantages: **Potential for thermal degradation and oxidation of the coating material and the substrate appear to be the main concerns accompanying thermal spray deposition processes.**

Other Significant Aspects of the process: **In the case of thermal powder-coating spraying technology, a thickness range of 50-600μm is typically encountered. Real-time measurements of the thickness of the deposited material are typically not done. Rather, various correlations between the process/material parameters and the deposition rate are used to estimate coating thickness. The most critical aspect of the thermal powder-coating spraying technology is over-heating and thermal degradation of the deposited material.**

III. SELECTION OF THE POWDER COATING PROCESS

To select the most suitable powder coating process (among the ones discussed in the previous section), the standard decision matrix approach was used [10]. The decision matrix approach entails the definitions of constraints (i.e. the conditions which must be satisfied) and criteria (i.e. the conditions which are used to judge the suitability of a given solution alternative). To define the constraints and the criteria for selection of the powder coating process for the BIW load-bearing application at hand, the Quality Functional Deployment (QFD) approach was utilized [11]. The QFD approach provides guidance for converting the customer needs (i.e. quality) into the technical/engineering specifications (i.e. functions) of the product /process to be designed (selected, in the present case) or service to be offered. The needs of the customer (an injection-molding shop, in the present case) are simply defined as: "A polymer powder coating process is needed which will require little pre-treatment of

metal stampings and polymer powder, be easily integrated into the existing process chain within the shop, be readily automated and safe, have cycle time comparable with that for plastic-rib structure injection process, can be used to deposit relatively-high melting-point polymers, produce strong and durable polymer-to-metal bond, require little post-coat treating, and, above all be inexpensive." These needs are then converted into a list of specific engineering requirements, i.e. constraints and criteria, given below.

For the case at hand which involves thermoplastic-overlay fabrication at selected locations within the interior of a U-shape load-bearing BIW structural component, the following four constraints were identified:

1. **The process must be able to coat only pre-selected portions of the metal-stamping substrate without a requirement for extensive masking;**
2. **The process must be able to deposit relatively-high melting-point thermoplastics (e.g. nylon) which can withstand a typical 190^{o}C/30min E-coat curing treatment in the paint shop;**
3. **The process must ensure a minimal polymer-to-metal adhesion strength of ca. 5MPa; and**
4. **The total coating cycle time must be comparable with the injection molding cycle time (when coating is carried out just prior to injection molding) and thus have duration of several seconds, not minutes.**

Fulfillment of these constraints by the powder-coating process alternatives is presented in Table 1. It is seen that with the exception of the electrostatic spraying process and the electrostatic fluidized bed process which require post-coat heat treatment and with the exception of the conventional fluidized-bed process which entails extensive masking of the metal stamping, all the constraints are met by the remaining powder-coating spray technologies. While, in general, short cycle-time infra-red radiation-based post-coat heat-treating processing is available to remedy the aforementioned deficiencies of the electrostatic spraying and the electrostatic fluidized bed processes, high geometrical complexity of the BIW components and the need for a line-of-sight renders the infra-red radiation treatment not very effective. It should also be noted that, in the case of the cold-gas dynamic spray process no public-domain data could be located pertaining to the ability of this process to deposit nylon. To overcome

this deficiency, a simple computational analysis of the cold-gas dynamic-spray process involving formation of a nylon coat on top of a metallic substrate is presented in Section V. This analysis suggested that nylon can be cold-sprayed, provided the particles velocity and temperature are kept within well defined ranges. Based on all these considerations, it was concluded that all the powder-coating spray processes considered in the previous section except for the electrostatic spray process are viable candidates for the overlay fabrication. The next question to be answered is "Which of the processes is the most attractive alternative?" This question will be answered by constructing the appropriate decision matrix.

The decision matrix approach enables evaluation and ranking of competing alternative solutions to a problem using a list of weighted (ranking) criteria. The method is commonly used in situations involving the selection of a simple alternative solution and the decision involves consideration of a number of criteria. To construct the appropriate decision matrix the following steps are generally followed:

(a) An extensive list of criteria which are used to judge the suitability of an alternative solution is created via project-team brainstorming, input from the customer(s) and through the use of the QFD method;

(b) The list from (a) is critically evaluated and one or more list reduction tools (e.g. multi-voting) are used to obtain the final list of criteria;

(c) Next, relative importance of each criterion is assessed by assigning a relative weighting factor to each. Table 2 contains a list of the final criteria, their weighting factors and a brief justification for the assigned importance (i.e. the weighting factor) to each criterion. The results listed in Table 2 were obtained using pair-wise comparison between different criteria in order to assess their relative importance. As a result of each two-criteria comparison, score 0 is assigned to both criteria if they are judged equally important, score 1 is assigned to the more important criterion and score -1 to the less important criterion. The pair-wise comparison approach used in the present work is summarized in Table 3. The results appearing in the last column of Table 3 and the justification presented in the last column of Table 2 were used to assign the weighting factor for each of the criteria, Column 2, Table 2;

(d) Next, a two-dimensional matrix (the decision matrix) is constructed by listing the criteria with their weights along one (horizontal or vertical) direction and the alternative solutions along the other;

(e) Each alternative is then evaluated with respect to its ability to accommodate each of the criteria and the corresponding score is assigned. Most frequently, one of the following two ways for score assigning are used: (i) a fixed scale (e.g. 1-5. with a higher score denoting a superior solution) is used for each criterion and a score (e.g. 3) is assigned to given alternative. (e.g. cold-gas dynamic spray) for the given criterion (e.g. minimal need for metal-substrate pre-heating); or (ii) within each criterion, the alternative solutions are ranked and given a score based on their ranking (with score 1 being the least favorable alternative with respect to the criterion in question, score 2 being the second least favorable alternative, etc.). The first method of score assigning is used in the present work; and

(f) Lastly, scores for each alternative are multiplied with the corresponding criterion weighting factor and summed to get a total score for each alternative, last row, Table 4. The alternatives with the highest overall score are then closely examined to obtain the final single choice.

The decision matrix pertaining to the selection of the optimal powder spray coating technology for the fabrication of thermoplastic overlay at selected (interior) locations of a typical U-shape BIW load-bearing direct-adhesion PMH component considered in the present work is given in Table 4. The results displayed in Table 4 suggest that the cold-gas dynamic-spray process is the most suitable alternative for the fabrication of a nylon overlay in the interior of a U-shape BIW load-bearing direct-adhesion PMH component. A careful examination of the results displayed in Table 4 indicates that the main reasons for the cold-gas dynamic-spray process being identified as the best alternative are a relatively low cost and the ability of the process to deposit the thermoplastic material without causing any thermal degradation to it.

IV. COST ANALYSIS FOR THE OVERLAY FABRICATION

As discussed in the previous section, the cost is an important criterion in choosing the most suitable powder coating process for the direct adhesion PMH load-

bearing BIW applications at hand. In the decision matrix, Table 4, each of the alternative solutions was assigned a score in the criterion 7 using an estimated cost associated with the use of the coating process in question. While a detailed discussion of the procedure used in assessing the total manufacturing cost associated with the overlay fabrication process is beyond the scope of the present paper, a brief account of this procedure is presented in the remainder of this section.

In general, the total manufacturing cost, C_m, is segregated into contributing components as follows:

$$C_m = C_{mat} + C_{cap} + C_{tool} + C_{cons} + C_{power} + C_{op} + C_{maint} \quad \textbf{(1)}$$

where C_{mat}, C_{cap}, C_{tool}, C_{cons} , C_{power}, C_{op} and C_{maint} are respectively the material, capital equipment, tooling, consumables, power, operating and maintenance costs (for the coating deposition process in the present case).

The coating material cost, C_{mat}, is obtained by multiplying the weight of the coating with the unit-weight cost of the coating material and dividing the result by the powder-coating process deposition efficiency. The unit-weight material cost is determined using the so-called *"tiered-volume pricing model"*, **i.e. it is based on total planned production volume for the PMH component.**

The capital cost, C_{cap}, is assessed using the so-called *"straight-line depreciation"* **method. Within this method, the value of the capital equipment is assumed to depreciate linearly with time between its initial-purchase price and the** *"salvage"* **value. The C_{cap} is then computed by dividing the difference between the capital equipment initial-purchase price and its salvage value by the expected life time of the equipment (in years) and by the number of parts coated per year.**

Tooling manufacturing cost, C_{tool}, includes the cost of fixtures used to hold the part during pretreatment and coating. Since tooling is not perceived as a major cost component, is reusable and is not expected to be significantly different for the powder-coating alternative processes analyzed, C_{tool} was not assessed.

The cost of consumables, C_{cons}, includes the cost of material such as grinding/polishing medium, detergents, degreasers, fuel, oxidizing and carrier gases, etc., simple procedures were used to assess C_{cons}. For example, in the case of consumed

gases, the C_{cons}, is obtained by multiplying the gas mass-flow rate with a typical cycle time and the gas cost per unit mass.

The (electric) power cost, C_{power}, is taken to include five main components (where applicable): (a) spray-gun power consumption cost; (b) gas-compressor power cost; (c) part pre-treatment and/or post-treatment heating cost; (d) gas heater power cost; and (e) powder-delivery system energy cost.

The operating cost, $C_{op,}$ is assessed by multiplying a fixed labor rate with the total coating-deposition cycle time and an (indirect/overhead-cost) burden factor.

The maintenance cost, $C_{main,}$ was decomposed into the following two components: (a) the cost of labor and parts to service the equipment and (b) cost of downtime associated with lost production, idle employees, etc.

The results of the powder-coating cost analysis (per part coated) are presented in Table 5. The data used during the calculation of the results presented in Table 5 were obtained by consulting at least three equipment manufactures and/or service providers per each powder-coating process considered. The input received was averaged and the average values were used in the cost analysis. Some of the key input data used are listed in Table 6. It should be also noted that a number of assumptions/simplifications were used in the cost analysis and the most important ones among these can be summarized as:

1. **The part displayed in Figure 1(b) was used as a prototypical BIW load-bearing component, so the area (ca. 1370 cm^2) to be coated was assessed for this part;**
2. **An average coating thickness of 0.5 mm was assumed and the volume of coating material used assess as a product of the coating area and coating surface divided by the coating-efficiency factor;**
3. **400,000 parts are assumed to be coated per year over a period of eight years (typical production-life of a vehicle model);**
4. **The capital equipment needed is dedicated for coating the part at hand;**
5. **Comparable worker skills (and thus comparable labor cost) are required for each of the coating-process alternatives; and**
6. **Comparable metal-stamping surface pre-treatment requirements are entailed by each of the powder spraying process.**

To assess the robustness of the overall cost-analysis results (last row, Table 5), the input data were perturbed within reasonable limits and the cost analysis repeated. This procedure changed the numbers in the last row of Table 5, but not the ranking of the competing powder coating processes.

V. COMPUTATIONAL ANALYSIS OF THE COLD-GAS DYNAMIC-SPRAY PROCESS

As discussed previously, no public-domain data can be found for the cold-spray fabrication of nylon coatings. Nylon is of interest in the case of the overlay fabrication since: (a) it can withstand a typical 190°C/30min E-coat curing heat-treatment applied to the BIW in the paint shop and (b) since the injection-molded rib-like structure is likely to be made of the glass fiber-reinforced nylon, nylon overlay will guarantee good overlay/rib-structure adhesion strength.

To overcome the lack of data pertaining to cold-gas dynamic-spraying of nylon, a computational analysis of this process is being carried out in our ongoing work [12]. While a detailed presentation of this computational procedure used and the results obtained will be given in a future communication, a brief overview of the procedure and the results is given in the remainder of this section.

The (transient non-linear dynamics) computational analysis of the nylon-particles/metal-substrate interactions involves the solution of mass, momentum and energy conservation equations. The solution is obtained using a second-order accurate explicit control-volume computational analysis and the commercial code AUTODYN [13].

Due to the presence of large elastic strains accompanying thermoplastic coating formation during particle/substrate interactions, a multi-material Eulerian formulation of the transient non-linear dynamics problem is selected. Within the Eulerian formulation, a fixed computational grid is selected to discretize the computational space and the particles and the substrate materials are allowed to move through the grid and mutually interact. Materials models available in the AUTODYN material database were used to represent the constituent behavior of nylon and steel. The material models include three basic components; (a) an equation of state (defines the density and temperature dependencies of the pressure); (b) a strength model (defines the deviatoric

stress during elastic and elastic/plastic deformation steps); and (c) a failure model (defines the evolution of stress within material elements undergoing micro-structural damage/failure). Nylon is represented using a polynomial equation of state, a three-parameter visco-elastic strength model and a minimum (negative) hydrostatic pressure failure model. The material model for steel includes a linear equation of state, a Johnson-Cook strength model and a Johnson-Cook failure model.

The steel substrate is initially assigned roughness characteristics consistent with those observed in zinc-galvanized mild formable steel. The diameter of spherical nylon particles was selected from a narrow normal distribution with mean value of 10µm. All the particles were assigned the same initial velocities and their altitude with respect to the substrate top surface was assigned using a stochastic procedure.

An example of the initial configuration of the computational domain is displayed in Figure 6(a). The evolution of the materials in the particles and the substrate with time is displayed in Figures 6(b)-(d). The formation of the nylon coating is evident. Close examination of the particles/substrate interfaces reveal that the deposited thermoplastics forms a full conformal coating with the substrate. This finding suggests that nylon can be cold-gas dynamic-sprayed in such a way that good mechanical interlocking between the depositing material and the substrate may be achieved to ensure the necessary level of polymers-to-metal adhesion strength. The surface roughness evident in Figure 6(d) typically becomes quite small at longer simulation times.

It should be noted that the results of the computational analysis (like the ones displayed in Figures 6(a)-(d)) are greatly affected by the particle velocity, temperature and average size. If these are not properly selected, the depositing particles, following an impact with the substrate, either bounce back, incompletely coat the substrate, or break-up into several fragments and get scattered around. Neither of these scenarios is desirable from the standpoint of attaining a good polymer-to-metal adhesion resistance [12].

VII. SUMMARY AND CONCLUSIONS

Based on the results obtained in the present work, the following main summary remarks and conclusions can be drawn:

1. **A comprehensive review is provided of the public-domain literature dealing with various powder-coating processes suitable for the fabrication of an overlay within a U-shape body-in-white metal-stamping structural component which will be subsequently hybridized using the polymer-to-metal direct-adhesion injection-molding process.**
2. **After the product (overlay coating) requirements and the capabilities/attributes of the various processes were identified, a set of engineering-design tools (e.g. the quality functional deployment, decision matrix, etc.) were used to identify the screen-out non-suitable processes and to rank the remaining ones;**
3. **A detailed cost analysis is carried out while assessing the criteria used for ranking the candidate powder-coating processes.**
4. **Cold-gas dynamic-spray process was identified as a prime candidate for the BIW structural-component hybridization application at hand.**
5. **While no public domain data exist regarding the ability of the cold-gas dynamic-spray process to deposit nylon a transient non-linear computational analysis carried out in the present work suggested that such a process is feasible.**

III. ACKNOWLEDGEMENTS

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Table 1. Fulfillment of the requirements imposed by the PMH Direct-adhesion BIW load-bearing components onto the candidate powder coating technologies

Process	**Variations of Process**	**Constraints**			
		1	**2**	**3**	**4**
		Selective Coating without masking	**Nylon Compatible**	**Minimum Adhesion Strength** **5 MPa**	**Cycle Time in Seconds**
Cold-gas Dynamic **Spray**	**N/A**	Yes	Yes (Section V)	Yes	Yes
Electrostatic Spray	**Corona-Charge**	Yes	Yes	Yes	No (due to post-coat treatment)
	Tribo-Charge	Yes	Yes	Yes	No (due to post-coat treatment)
Fluidized Bed	**Conventional**	No (due to need for extensive masking)	Yes	Yes	Yes
	Electrostatic	No (due to need for extensive masking)	Yes	Yes	No (due to post-coat treatment)
Thermal Spray	**Flame**	Yes	Yes	Yes	Yes
	HVOF	Yes	Yes	Yes	Yes
	Plasma-arc	Yes	Yes	Yes	Yes

Table 2. Final list of ranking criterion, weighting factors and justification of importance of the criteria used in the decision matrix approach

Ranking Criterion	Weighting Factor	Justification of Importance
1. **Minimal need for metal-substrate pre-treatment (e.g. sanding, grit blasting, cleaning/degreasing, etc.)**	2	It is desirable, but not absolutely critical, to be able to leave drawing compound on the stamping to minimize the possibility for surface damage and not to have to introduce additional cleaning process step in the injection-molding shop.
2. **Minimal need for metal-substrate pre-heating**	3	Metal-substrate pre-heating is an additional process step in the injection molding shop and can degrade metallic-material properties.
3. **Minimal additional requirements for powder pre-treatment (e.g. screening, drying, etc.)**	2	Any additional powder pre-treatment would introduce a new process step in the injection molding shop and unnecessarily increase the overlay fabrication cost.
4. **Ability to coat uniformly intrinsic geometrical features of the metal substrate**	5	Uniform coating thickness is critical for ensuring a proper transfer of load between polymer and metal and for controlling the overall weight of the overlay.
5. **Minimal thermal/chemical degradation of the depositing and substrate materials**	5	Thermal/chemical degradation of the depositing and substrate materials can seriously jeopardize materials properties and, hence, functionality of the PMH component.
6. **Minimal need for post coating treatment**	3	If the post coating treatment does not seriously compromise the overall overlay-fabrication cycle time, it is a less critical requirement.
7. **Minimal overlay manufacturing cost**	5	In addition to reducing the component weight, the PMH approach should not compromise (if not reduce) the overall manufacturing cost.
8. **Maximal ease of automation**	5	Automation is a critical element of the effort to reduce the overall manufacturing cost.

Table 3. A pair-wise comparison matrix used to assign a relative weighting factors to the powder-coating process-selection criteria

Criteria	1. Substrate Pre-treat	2. Substrate Pre-heat	3. Powder Pre-treat	4. Uniform Coating	5. Material Degradation	6. Post-coat Treatment	7. Cost	8. Automation	TOTAL
1. Substrate Pre-treat	0	-1	0	-1	-1	0	-1	-1	-5
2. Substrate Pre-heat	1	0	1	-1	-1	-1	-1	-1	-3
3. Powder Pre-treat	0	-1	0	-1	-1	-1	-1	-1	-6
4. Uniform Coating	1	1	1	0	0	1	0	0	4
5. Material Degradation	1	1	1	0	0	1	0	0	4
6. Post-coat Treatment	0	1	1	-1	-1	0	-1	-1	-2
7. Cost	1	1	1	0	0	1	0	0	4
8. Automation	1	1	1	0	0	1	0	0	4

Table 4. Decision matrix for powder coating deposition process for PMH overlay fabrication. Weighting factors are given within parenthesis in the first column. Scoring is done on a 1-5 scale.

Criterion and Weight	**Alternative Solutions**			
	1	**2**	**3**	**4**
	Cold-gas Spray	**Flame Spray**	**HVOF Spray**	**Plasma-arc Spray**
1. Substrate Pre-treatment (2)	5x2=10	3x2=6	3x2=6	3x2=6
2. Substrate Pre-heating (3)	4x3=12	5x3=15	5x3=15	5x3=15
3. Powder Pre-treatment (2)	5x2=10	5x2=10	5x2=10	5x2=10
4. Uniform Coating (5)	3x5=15	3x5=15	3x5=15	3x5=15
5. Material Degradation (5)	5x5=25	3x5=15	2x5=10	1x5=5
6. Post-coat Treatment (3)	5x3=15	4x3=12	5x3=15	5x3=15
7. Automation (5)	4x5=20	4x5=20	3x5=15	3x5=15
8. Cost (5)	4x5=20	4x5=20	3x5=15	3x5=15
TOTAL	**127**	**113**	**101**	**96**

Table 5. Cost analysis for the alternative powder coating processes.

Cost Component ($)	Powder Coating Process			
	1	2	3	4
	Cold-gas Spray	Flame Spray	HVOF Spray	Plasma-arc Spray
C_{mat} **Material Cost**	0.3365	0.3883	0.3365	0.3883
C_{cap} **Capital Cost**	0.0356	0.0148	0.0238	0.0445
C_{con} **Consumable Cost**	0.2138	0.1438	1.027	0.0476
C_{power} **Power Cost**	0.0107	0.0296	0.0170	0.0391
C_{op} **Operational Cost**	0.2524	1.1649	0.5048	0.7766
TOTAL COST	**0.8490±0.1274**	**1.7415±0.2612**	**1.9068±0.2860**	**1.2961±0.1944**

Table 6. Parameters used in the construction of Table 5.

Parameter (Units)	Powder Coating Process			
	1	2	3	4
	Cold-gas Spray	**Flame Spray**	**HVOF Spray**	**Plasma-arc Spray**
1. Coating Efficiency (N/A)	0.6-0.9	0.6-0.7	0.7-0.8	0.6-0.7
2. Deposition Rate (kg/h)	20	5	10	7.5
3. Capital Cost ($)	1,20,000	50,000	80,000	1,50,000
4. Salvage Value ($)	6,000	2,500	4,000	7,500
5. Carrier-gas Pressure (MPa)	3	0.5	1	0.5-2
6. Gun Wattage (kW)	-	20-40	20-40	40-80
7. Powder-feeder Wattage (kW)	0.6-0.7	0.2	0.5	0.2
8. Carrier-gas, Oxygen, Fuel Flow Rates (cm^3/s)	Carrier-gas (Nitrogen) 10,000-15,000	Oxygen 700-800 Fuel (Acetylene) 210-220	Oxygen 10,000-20,000 Fuel (Acetylene) 2,000-4,000	Carrier-gas (Argon) 300-400

FIGURE CAPTIONS

Figure 1. An example of the: (a) All-metal and (b) PMH load-bearing automotive component.

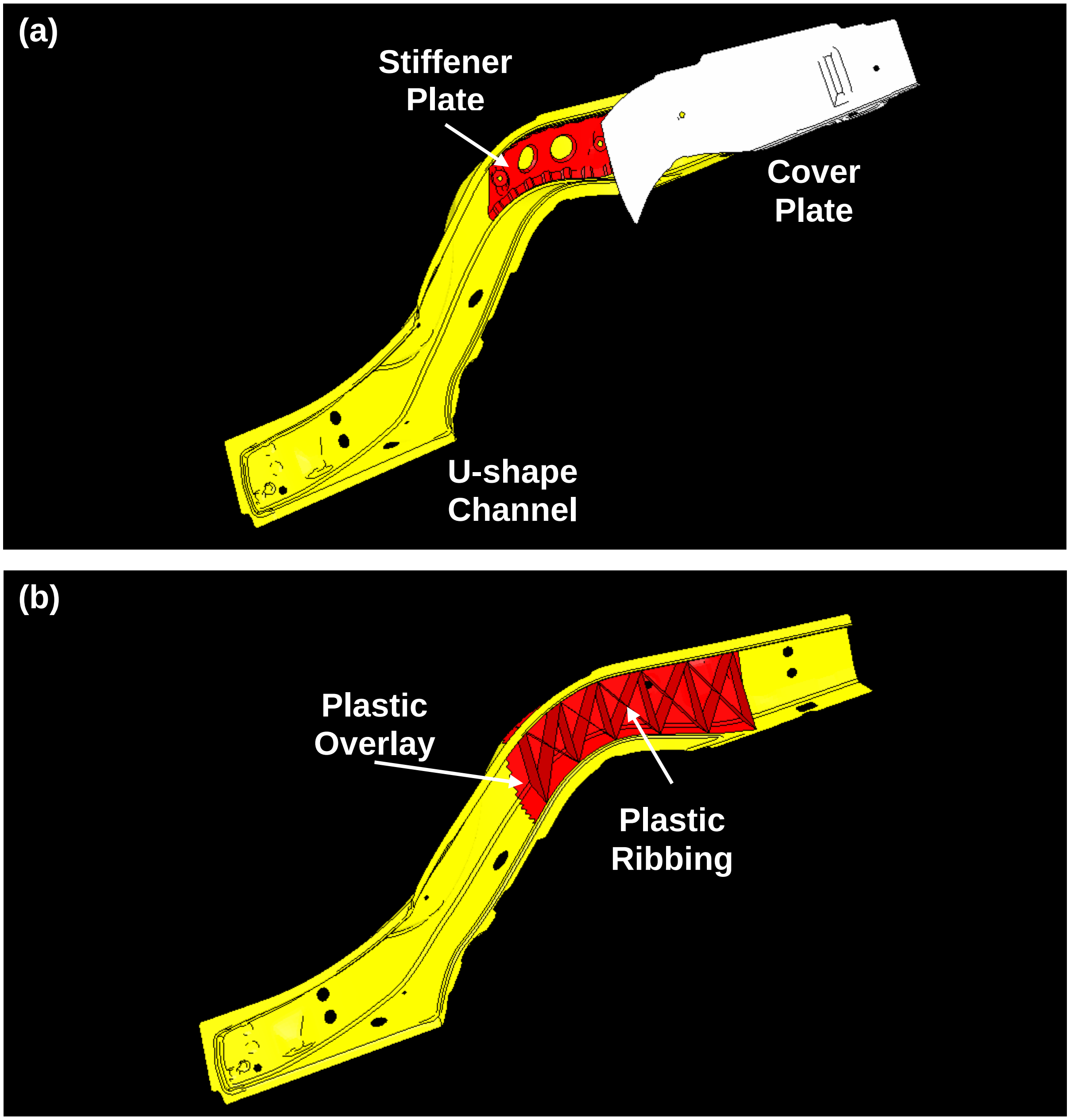
Figure 2. A schematic of the Cold-gas Dynamic-spray process

Figure 3. A schematic of the Corona Spray process.

Figure 4. A schematic of the: (a) Conventional and (b) Electrostatic Fluidized-bed process.

Figure 5. A schematic of the: (a) Flame; (b) High-velocity Oxy Fuel (HVOF) and (c) Plasma-arc Thermal Spray process.

Figure 6. Temporal evolution of the coating and substrate materials during cold-gas dynamic-spray: (a) 0ms; (b) 0.1ms; (c) 0.2ms; and (d) 0.3ms.



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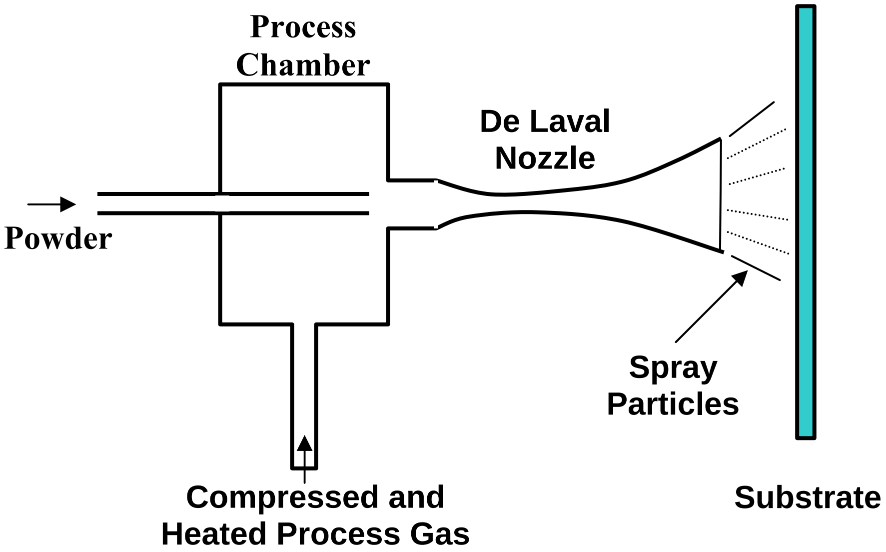


Figure 2. A schematic of the Cold-gas Dynamic-spray process.

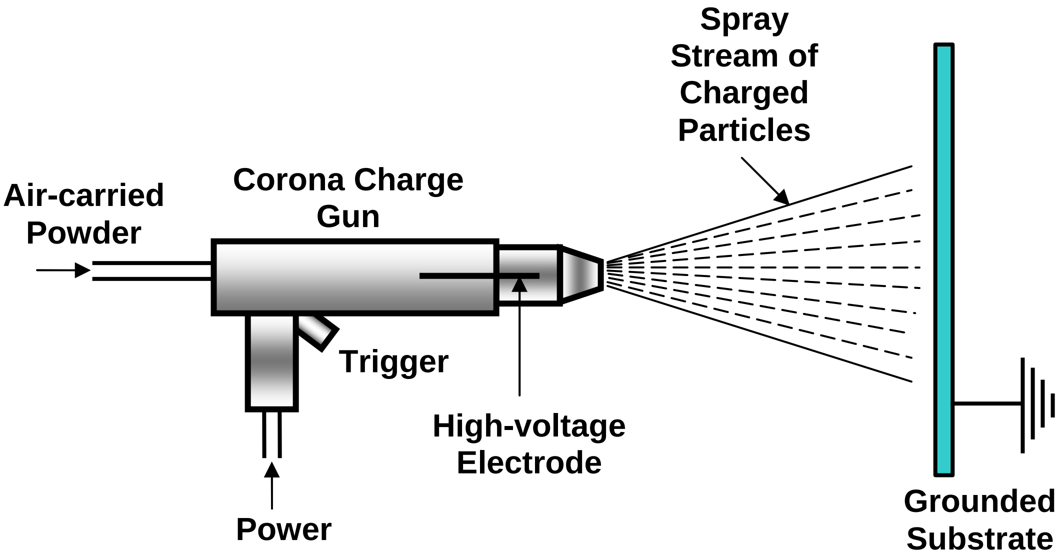


Figure 3. A schematic of the Corona Spray process.

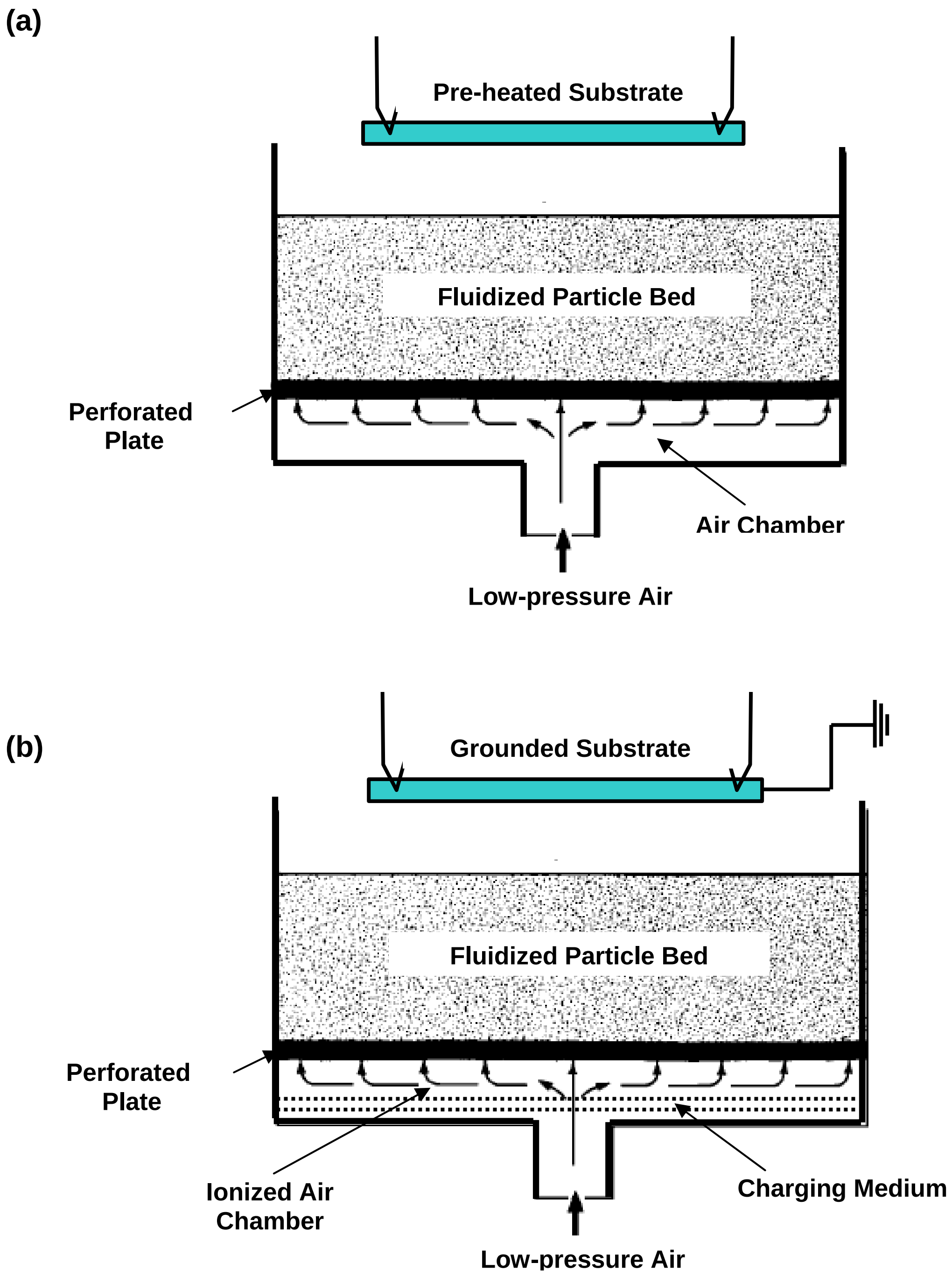


Figure 4. A schematic of the: (a) Conventional and (b) Electrostatic Fluidized-bed process.

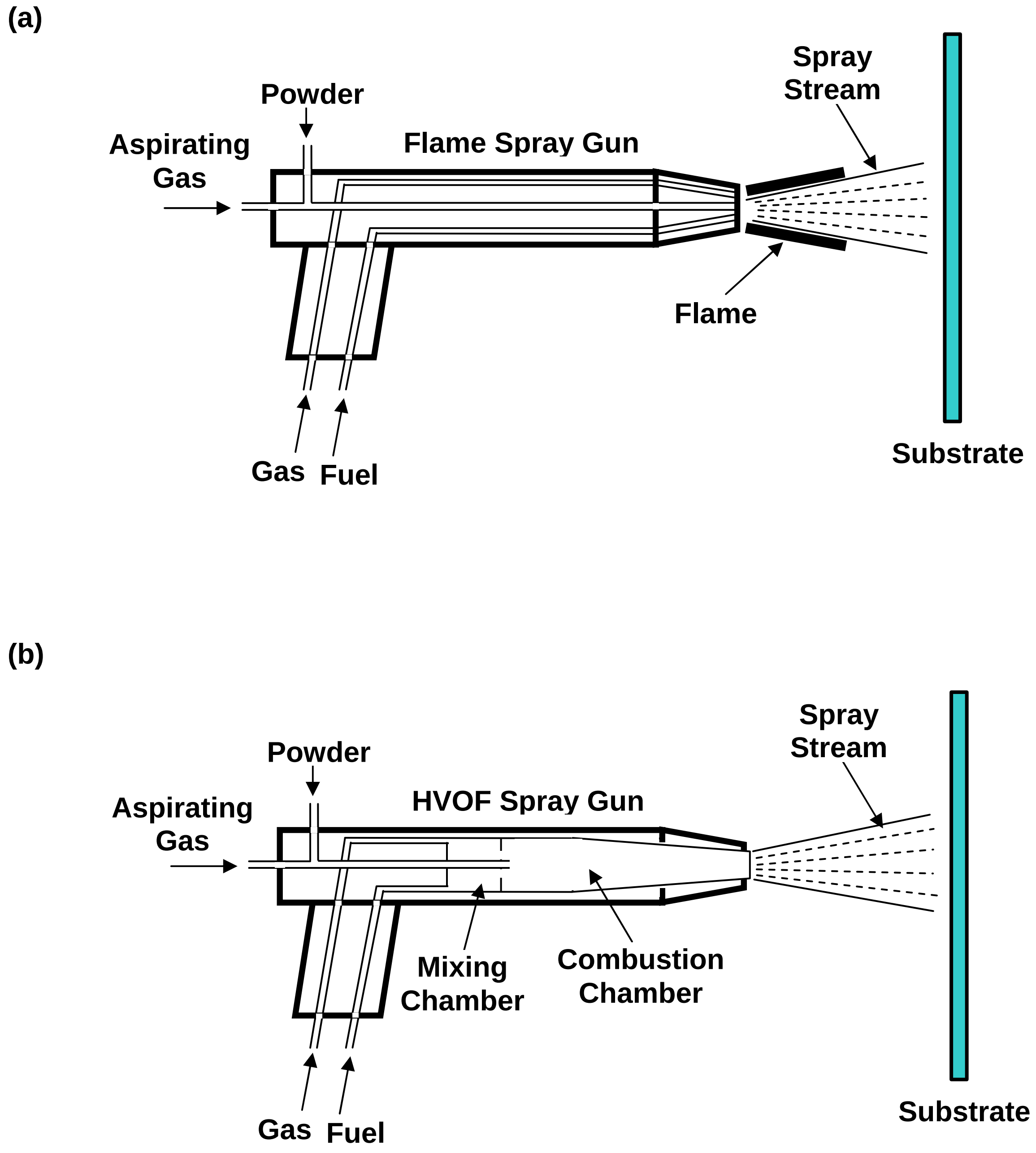
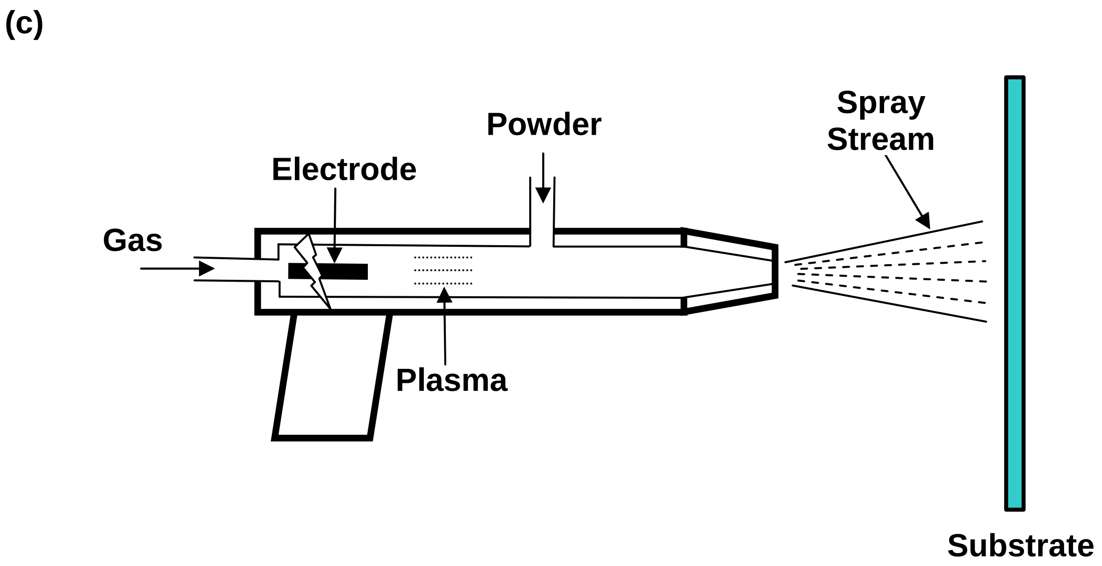


Figure 5. A schematic of the: (a) Flame; (b) High-velocity Oxygen Fuel (HVOF) and (c) Plasma-arc Thermal Spray process.



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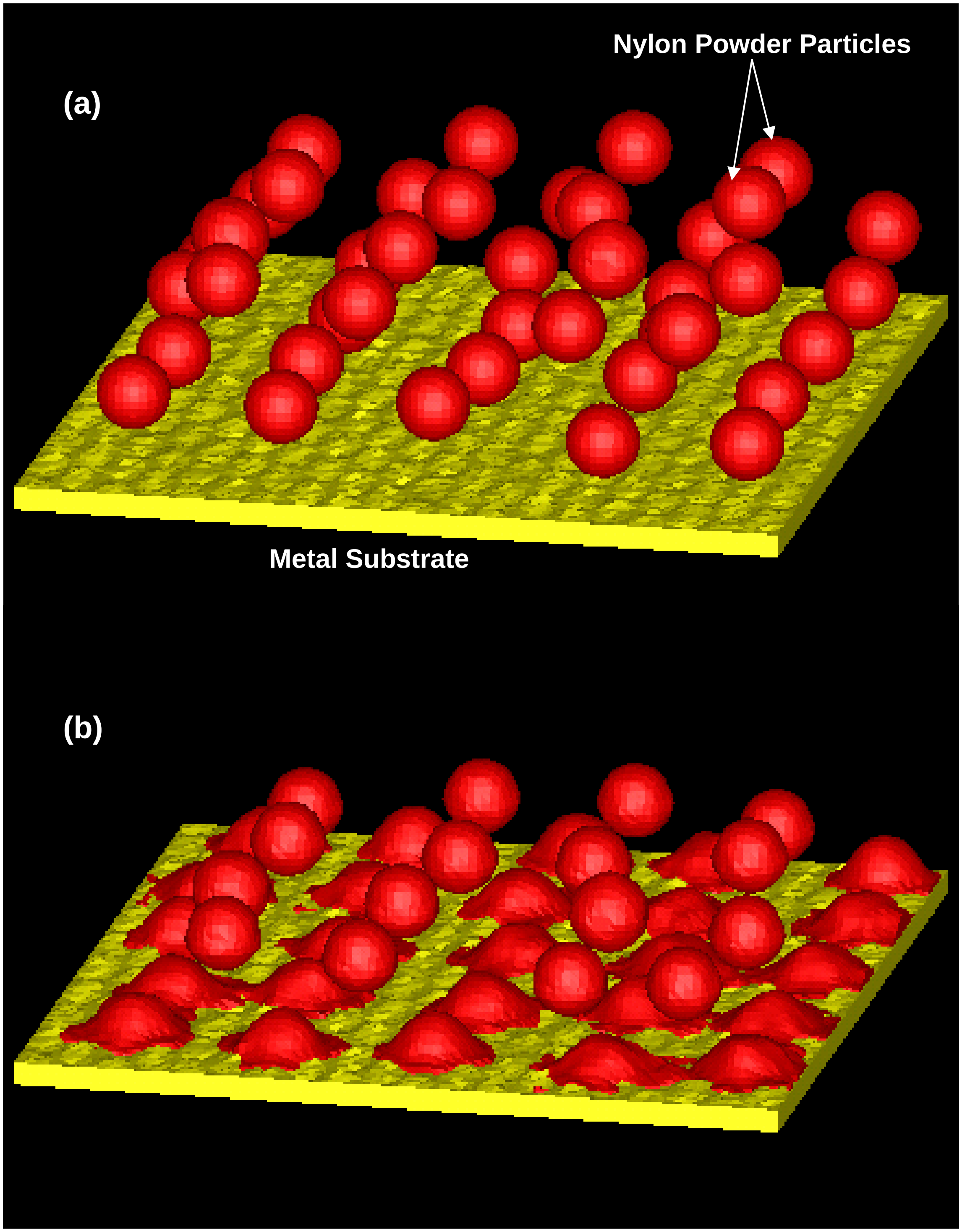

Figure 6. Temporal evolution of the coating and substrate materials during cold-gas dynamic-spray: (a) 0ms; (b) 0.1ms; (c) 0.2ms; and (d) 0.3ms.

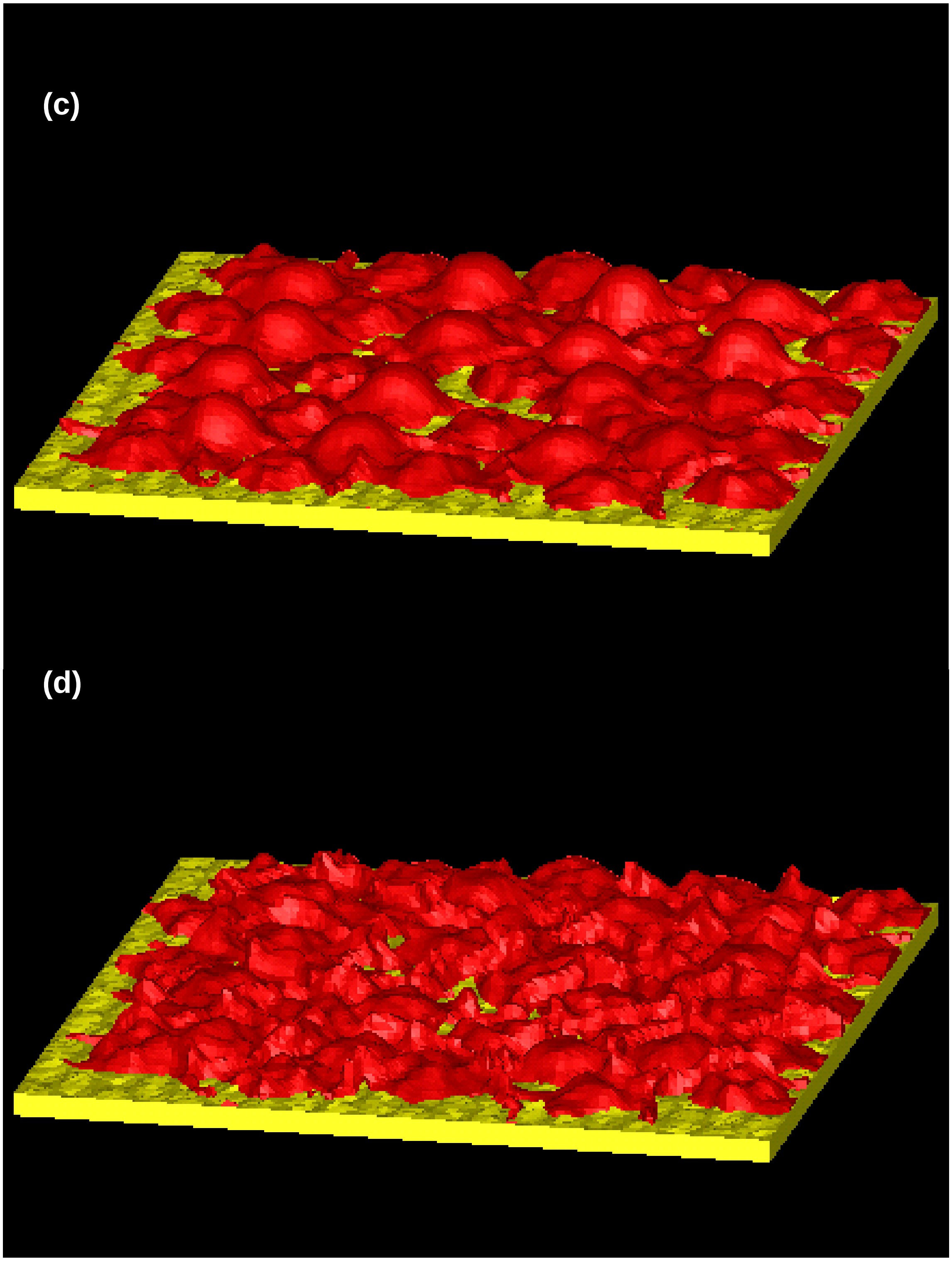

Figure 6. Contd…