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Metallization of carbon fiber reinforced polymer composite by cold spray and lay-up molding processes

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ABSTRACT

With their high specific strength-to-weight ratio, carbon fiber reinforced composites are state of the art materials used in the aerospace industry, including fuselage parts. Studies have shown that it is complicated and costly to coat carbon fiber based composites using conventional thermal spray processes. For the purpose of producing metallic coated carbon fiber based composites, a new innovative technique which combines Cold Spray and lay-up molding of composites is envisioned. This paper presents a detailed description of the experimental approach developed to produce metallic coated carbon fiber reinforced composites and demonstrates the manufacturability of such components. Obtainment of a low resistivity metallized composite and production of an easily removable metallic layer from the mold during lay-up molding, and preservation of the mold integrity are essential for the production of such materials. The results produced show that it is possible to produce metallized composites of various shapes that are easily removable from the mold and have low porosity and high conductivity.

1. Introduction

Industries are constantly adapting to offer safer and more reliable products to consumers in a cost effective way. In the aerospace sector, technological improvements enable the integration of components which can offer weight reduction, leading to important fuel cost savings that are beneficial for the airline companies, the passengers and the environment. To ensure safer flights and obtain a competitive advantage over their competitors, aerospace companies are seeking novel ways to achieve this goal. Airplane fuselage, for example, is constantly being redesigned to offer weight reduction without encumbering its structural integrity. While historically made of aluminum alloys (especially 2000 and 7000 series), the aircraft's skin is being redesigned by the leaders from the industry who are incorporating in it a greater proportion of polymer fiber-reinforced composites; more specifically carbon fiber-reinforced polymers (CFRP). The strength-to-weight ratio and the mechanical properties of the aircraft skin are improved when using this new engineered material [1].

However, one important limitation of using a non-metallic fuselage is its lack of electrical conductivity [2]. With an aluminum fuselage, the surface is highly conductive, and in the event of a lightning strike, the electrical charge from the lightning will travel throughout the outer surface of the fuselage until the charge exits back into the surrounding air [3]. During a lightning strike up to 2.10^5 A can be delivered [4]. With a CFRP fuselage, the skin is highly resistive and will not permit electrical current and grounding as CFRP have a much lower electrical conductivity than aluminum alloys. Although carbon fibers are good conductors, the polymer matrix is an excellent dielectric and therefore reduces the overall electrical conductivity of the composite laminate. Lightning prone areas such as the turbine intake, wing tips and tail edges could melt from the local heating caused by the electrical discharge. As such, lightning strike damage poses both a safety and economic challenge for aircraft manufacturers and operators [5].

Current protective solutions improving the electrical conductivity of CFRP fuselages consist of riveting aluminum based conductive plates to critical areas and/or to insert a thin conductive metallic mesh placed on the outer surface of the CFRP structure [6]. The metallic wire mesh acts as a continuously-conductive path for direct or indirect electromagnetic interference effects and lightning strike energy. The mesh can be comprised of aluminum, copper or bronze wires, and can either be co-woven with the carbon fiber in a prepreg fabric ply, or bonded separately as the outermost laminate layer [7–9]. However, industry is seeking an alternative solutions because riveting plates are a labor intensive and costly procedure. The high cost and weight of these rivets/plates assemblies are in opposition to the weight reduction objective of aircraft manufacturers [10]. Cold spray process is considered to be one of the potential process to overcome such problem. This technique can be used to repair a damaged component. Note that this process offers also the possibility of field repair which has a big advantage for aircraft industry from an industrial point of view.

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To promote electrical conductivity, one could use coating processes, such as Thermal Spray (TS) processes to deposit thin conductive layers over the CFRP substrates. TS processes such Flame Spray and Plasma Spray are already used as local repair methods for CFRP airplane skins [11]. Unfortunately, the sprayed particles from the conventional TS processes have shown to have in-flight oxidation of the molten particles which results in changing the powder material properties in the metallic coatings. Oxidation increases the coating electrical resistivity. Furthermore, the impingement of molten particles on CFRP may result in the degradation of the substrate due to thermal effects and erosion which requires delicate and costly manufacturing operations during the repair. Colder spray techniques like the cold gas dynamic spray (CS) process, have the potential to solve the extreme temperature issue given that the sprayed particles remain in the solid state [12,13]. As its name implies, the CS process does not rely on thermal energy for the formation of coatings, but rather on kinetic energy: particles are accelerated above a critical velocity and plastically deform upon impact on the substrate to adhere and form a coating [14]. Although the carrier gas can be preheated, its rapid expansion leads to a considerable temperature decrease within the spray gun and therefore heat transfer to the particles is minimal. As such, coating formation is attributed solely to the severe plastic deformation resulting from the high-velocity impact of the particles on the substrate. Coatings produced from the CS can be characterized as oxide free due to the inert nature of the carrier gas (N2 or He) and the relatively low process gas temperatures [15,16]. The numerous differences of the CS with respect to other TS processes make it a potential process to possibly lay down conductive metallic coatings over CFRP substrate. Regrettably, erosion/degradation of polymer-based composite caused by the large particle impact velocity is a severe and challenging drawback of this technique [17–19].

Since it is hard to produce CS metallic coatings on CFRP due to the low coating adhesion strength and substrate erosion that damages the CFRP during the spray process, the reverse molding technique is developed and used to produce metallic coatings on CFRP. The procedure is to coat a substrate that is usually used as a mold. Subsequently, the coating will be transferred on a CFRP during its manufacturing process. This work was motivated by the need to develop a method for applying thin oxide-free conductive metallic layers over key aircraft composite parts. This metallic layer (75 μm to 125 μm) should ensure minimum electrical resistivity less than (8.40×10^{-8} Ωm) to allow electrical charges from the lightning to travel throughout the outer surface of the fuselage until the charge exits back into the surrounding air. The investigations have been focused on producing a coating with low adhesion on a metallic mold, then molding a composite over the coating. By removing the coating (bonded to the composite) from the mold, a conductive composite component was produced. Various geometric profiles were produced. With the mold surface roughness and feedstock powder used to produce the coating, the surface adhesion of the coating to the mold was investigated in order to optimize coating debonding from the mold. The coating properties such as density, resistivity and thickness were varied to demonstrate the potential of the proposed technique.

2. Experimental procedures

2.1. Materials

In this study different powder size distribution, type and morphology was investigated. Pure Copper (Cu) feedstock powder was used. The selected copper powder is supplied by Centerline (Windsor) Ltd. under the product name SST-C5003. Its dendritic shape is an indicator that it was manufactured by electrolytic forming. The production process quality control ensures a minimum purity of 99.7 wt%. As seen in the SEM image of Fig. 1, the powder is highly branched and has a rough outer surface. As per ASTM B417 and ASTM B212, the density of the powder was measured by the distributor to be 2.07 g/cm^3 [20,21]. The size distribution test (ASTM B214) was conducted and the sieve results are presented in Table 1 and demonstrate that the majority (90% of mass) of the particle are below 44 μm; confirming the range (5 μm to 45 μm) specified by the distributor. This powder has shown to produce coating with very low porosity and acceptable adhesion to the Invar substrate. Due to the dendritic shape, the sprayed copper particles showed strong mechanical bonding between themselves.

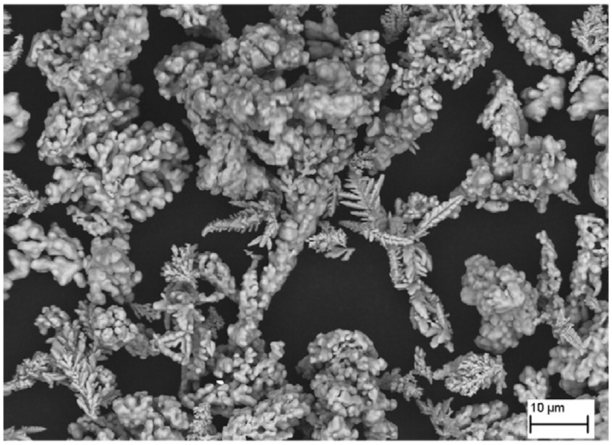

Fig. 1. SEM image of centerline SST-C5003 pure copper powder showing its dendritic shape.

2.2. Substrate

Invar (36% Ni–64% Fe) is used as the substrate. This alloy is used as a mold for CFRP manufacturing due to the similarity in its thermal expansion coefficient with CFRP. This prevents the development of internal stresses during curing of the composite. The similarity of thermal behavior of both mold and composite results in a low degree of component distortion [22].

For the feasibility study of the proposed approach, the sprays were conducted on flat as well as curved (1 × 3 in.) coupons prepared from 25 mm thick Invar plates. The flat coupons were cut by water jet and then wire electric discharge machining (EDM) was used to cut the curved pieces to shape (see Fig. 2). It is reported that in coating processes, the surface finish of a substrate has a critical importance in coating adhesion [23,24]. To explore the effect of the surface roughness on the coating quality and its adhesion to the substrate, three surface finishes of the Invar coupons were used. For the first surface finish, the substrate is ground with a surface grinder (Model NB from Churchill) and rotating grinding wheel (SiC 46 grit AA60-N6-V10 from Carborundum). The second and the third surface finishes are obtained using a grit blasting process to roughen the surface of the substrate using two types of grits: 80 grit aluminum oxide and 20 grit copper oxides.

2.3. Spray process & CFRP lay-up (inverse) molding process

In the present study an SST-EP cold spray system (CenterLine (Windsor) Ltd., Windsor, ON, Canada) [25] was used to produce Cu coatings on Invar substrates. Nitrogen gas was used as the driving flow that is fed into a converging/diverging polymer nozzle where it

Table 1
Size distribution result based using sieve method (ASTM B214).

Size (μm)	Content (wt%)
Size < 44	90.10
44 < Size < 74	8.50
74 < Size < 149	1.38
Size < 149	0.00