Surface & Coatings Technology 333 (2018) 13–23

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Thermal spray metallisation of carbon fibre reinforced polymer composites: Effect of top surface modification on coating adhesion and mechanical properties

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ARTICLE INFO

Keywords:
CFRP composite
Zn coating
Arc spray
Filler layer
Adhesion strength

ABSTRACT

Thermal Spray (TS) processes are used to enhance the surface properties of Polymer Matrix Composites. However, poor adhesion and mechanical degradation are usually experienced. The main objective of this work is to investigate the effect of the modification of the top surface of Carbon Fibre Reinforced Polymer (CFRP) substrate on the TS deposition of metallic coatings. CFRP composite panels were manufactured with different upper layers: (I) pure epoxy overflow layer, (II) pure copper powder filler layer, (III) mixture copper and stainless steel powder filler layer, and (IV) aluminium mesh layer. The top layers of the CFRP substrates were manufactured during the forming process. Arc Spray, one of the TS processes, was used to deposit zinc coating onto the manufactured CFRP panels. The substrates were sandblasted before the TS process to enhance the adhesion of the deposited zinc to the substrate. The quality of the coatings including adhesion and mechanical properties was investigated using tensile adhesion and bending test, respectively. The porosity, microstructure, morphology and surface fracture of the metallised CFRP coupons were characterized using optical and electronical microscopy techniques. The results obtained revealed that pure epoxy top layer did not resist to sandblasting prior to TS process, contrary to the substrates with fillers and mesh top layer. Moreover, the aluminium based mesh layer improved the adhesion strength by about 50%. Bending test results indicated that coating on CFRP composites decreased their mechanical properties. However, the use of a metallic mesh layer reduced the degradation effect of spraying.

1. Introduction

Fibre-Reinforced Polymer (FRP) composites in general and Carbon fibre reinforced polymer (CFRP) in particular are used in a large variety of advanced engineering structures, ranging from aircrafts, helicopters and space crafts to boats, wind energy, offshore platforms, automobiles, sports goods, and chemical processing equipment [1]. The use of this class of materials continues to grow at an impressive rate. For example, currently, CFRP composites account for 50% of the total mass of the empty structure of new civil aircrafts [2]. A large number of metallic components are replaced by CFRP composites due to their high specific strength and their stiffness [3]. A key factor driving the increased applications of composites over the recent years is the development of new advanced forms of CFRP materials. Economic, environmental and technological considerations require that the equipment should be designed with increasingly stringent performance criteria, pushing materials to the limits of their competencies [4]. As any class of materials, to achieve a diverse range of applications, research will need to overcome some key challenges associated with advanced FRP composite materials and their manufacturing methods. Indeed, the development of FRP composites is limited by their physical properties and tribological behaviors such as their low wear resistance and their lack of thermal and electrical conductivities [5]. One of the solutions to overcome some of these limitations involves surface metallisation of the CFRP composites [6,7].

Among the available surface modification and coating deposition technologies, TS processes are widely used to deposit thick coatings in order to enhance the surface of components made from different classes of materials [8]. TS techniques include a group of coating processes in which a heat source is used to melt material in powder, wire or rod form and propelled the molten or semi-molten particles by expanding process gases toward a prepared substrate to create a coating build-up

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http://dx.doi.org/10.1016/j.surfcoat.2017.10.066
Received 20 July 2017; Received in revised form 12 October 2017; Accepted 25 October 2017

[9]. The materials capable of being thermal sprayed are almost limitless, making thermal spray coating technologies extremely powerful in providing engineering and design solutions for protecting components and enhancing their performance. Recently, TS deposition of metallic coatings onto FRPs constitutes a novel technology with promising applications, mainly in the field of aerospace technology. Several attempts have been made to use this manufacturing process to coat the FRP materials, and preliminary studies relating to the feasibility of functional metallic coatings on polymers have been conducted [10].

F. Alonso et al. [6] found that spraying functional plasma-sprayed erosion-resistant coatings directly onto CFRP is extremely difficult considering the high temperature flux, which results in substrate degradation. In contrast, low melting metals such Al, Zn, ZnAl and PbSn seem to be good candidate materials to avoid CFRP degradation [11–13]. A. Liu et al. [11,12,14] have reported some preoccupations with polymeric matrix degradation due to impingement of hot particles such as Cu and Ni (with melting temperature in the range of 1453 °C and 1083 °C respectively) via plasma spray. Unfortunately, most thermally resistant CFRP can endure only 371 °C for long periods, and 500 °C for short times, which insufficient for a coating deposition without substrate degradation. Similarly, it was observed that sandblasting of CFRP prior to coating improves adhesion strength, but at the same time, it results in noticeable damage of the carbon fibre in the CFRP material. However, zinc ($T_{melting}$ of Zn is 418 °C) was successfully sprayed by arc spray process. The Zn layer was used as bond coat in order to deposit the erosion-resistant coating: carbon steel skin and Ni−Cr−B−Si [14] and Al_2O_3 [11]. In another study, M. Ivosevic et al. [15,16] investigated the deposition of functionally graded coatings polyimide/WC−Co onto CFRP substrate using high velocity oxy-fuel (HVOF) process. The objective was to enhance thermal expansion compatibility between the CFRP substrate and the WC−Co topcoat layer. To avoid thermal degradation, a separate study suggested the use of cold spray [17–19]. The coating adhesion in cold spray process is provided, by mechanical anchoring of the plastically deformed sprayed particles at low temperature. The limitations of such a process are the severe contact stresses and the erosion of the substrate that are results of the high velocity of the sprayed particles [17].

The adhesion strength of the TS coating depends strongly on the nature of the substrate surface, the surface topography, and temperature [20]. It is well known that polymers have in common a low resisting temperature, high chemical inertness and low surface free energy [21]. Therefore, it is extremely difficult to achieve high adhesive strength levels of the coating on CFRP [22]. In addition, surface preparation of CFRP composites prior to spraying using sandblasting could damage the carbon fibres, hence, weakening its mechanical properties [23,24]. It is also essential to ensure mechanical anchoring (or interlocking) which is recognized as the main bond strength contributor in TS coatings [25]. E. Njuhovic et al. [26,27] investigated the influence of the sandblasting preparation of CFRP substrate with Al_2O_3 on adhesion strength. An increase of the adhesion strength was obtained by the increase of substrate roughness, which was mainly influenced by the blasting time and to a lower extent by the blasting distance. However, during sandblasting, the outer epoxy layer was removed from the CFRP Resulting in carbon fibres being exposed and damaged, leading to lower mechanical properties. If special precautions are not taken during spraying, excessive heat and high impact of sprayed particles can often deteriorate the composite substrate [6]. In order to avoid CFRP overheating, damaging the fibres, and enhancing the coating/substrate adhesion, a layer of filler such as sand [7,23] or metallic particles [18] have been added to the top surface of the CFRP substrate during the curing process. This layer will play a role of bond coat between the TS coating and the CFRP substrate. A. Lopera-Valle et al. [7,24] have added garnet sand to the surface of the FRP to roughen it and protect it from thermal degradation. They observed that the garnet sand layer promotes the adhesion of the flame-sprayed nickel-chromium-aluminium-yttrium (NiCrAlY) and nickel-chromium (NiCr) coatings, where no degradation of the polymer based substrate due to the high temperature exposure was observed. In another study, R. Gonzalez et al. [23] have investigated the effect of flame-sprayed Al−12Si coating on the leakage and burst pressures of FRP tubes covered with garnet sand. The application of garnet sand allowed the adhesion of the coating onto FRP and provided insulation against heat transfer to protect the fibres. Coated and uncoated FRP possess equal leakage and burst pressure values, which indicates that no mechanical degradation occurred after spraying. F. Robitaille et al. [18] presented a new method to deposit zinc coatings on CFRP using the Pulsed Gas Dynamic Spraying Process (PGDS). In order to protect the fibres from eventual damage, they co-cured copper particles as top layer of the CFRP substrate. No surface preparation was required before PGDS spraying, and successful dense Zn coating was obtained with satisfying adhesion strengths.

Based on the few studies reported so far, it is suggested that TS processes can be used to deposit a metallic coating on FRP substrates, although, they can present some challenges. Furthermore, zinc coating can be seen as a compatible bond coat or top coat for polymeric composites [11,14,15,18]. Filler particles layer may be added as a top surface layer or as a bond coat to protect FRP materials against erosion, fibre fracture and thermal degradation during the TS process [7,10,18,23,28]. The two key challenges for the widespread of TS processes as coating manufacturing method for FRP substrates are the increase of the coating/FRP adhesion and the reduction of the mechanical and thermal degradation of the substrate during the spray process [29].

The objective of this work is to demonstrate the feasibility of thermally spraying pure zinc (Zn) onto CFRP composites, and to investigate the impact of the top surface modification of the CFRP components on the CFRP degradation and coating adhesion. Pure Zn is chosen as the coating material owing to its low melting point (418 °C) to avoid degradation due to the heat of the CFRP substrate. Moreover, Zn has a good wettability on non-metallic surfaces, such as CFRP substrates [14]. In order to identify the suitable CFRP surface modification, various surface modification/bond coats have been tested. In fact, zinc was thermally sprayed, using arc spray process, onto CFRP with different top surface/bond coat modification including; (I) epoxy overflow, (II) pure copper powder filler, (III) mixture of copper and steel powder filler and (IV) aluminium mesh as shown in Fig. 1. The microstructural characterization of zinc coating, bond coats, and CFRP substrate was investigated to assess the manufactured metalized CFRP components. Furthermore, in order to determine potential degradation effects of the surface preparation and the spraying process, the uncoated and coated samples analysed using three-point bending test and fractography analysis to determine the failure mechanisms.

2. Experimental procedures

2.1. Material: Manufacturing of CFRP substrate

The CFRP substrate consists of an epoxy laminating system (EPOCAST® 50-A1 resin/hardener 9816, Huntsman Advanced Materials Americas Inc., Los Angeles, CA, USA) reinforced with a carbon-fibre plain weave TAFTAS (BMS 9-8 TY1 CL2, Hexcel, Seguin, TX, USA). In the preparation of the matrix, 100 parts by weight of Epocast 50-A1 resin were mixed with 15 parts by weight of Hardener 946 and blended mechanically for about 2 min (as recommended by the resin manufacturer). CFRP substrates were manufactured using bag moulding process and cured via an integrated heating system for 3 h at 60 °C. The CFRP manufacturing was conducted at the Algerian Airline Maintenance Centre (Algiers, Algeria). CFRP substrates ($250 \times 300 \times 2.6\ mm^3$) were elaborated from six layers of fabric oriented at the direction of 0° and 90°, alternately. The density of the used epoxy and carbon fibre are $1.21\ g\cdot cm^{-3}$ and $1.80\ g\cdot cm^{-3}$, respectively.

In order to promote the adhesion of the metallic coating onto CFRP substrates and to avoid the deterioration of CFRP substrates due to high