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Cold spray onto carbon fiber reinforced polymers for lightning strike protection

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Abstract: Carbon fibre reinforced polymers (CFRPs) are more and more used in a wide range of industries, but their low electrical conductivity has limited their application. Especially in the aerospace industry, the low conductivity of CFRP used in aircrafts would result in a lightning strike problem. To make the polymer composites electrically conductive, a conductive media must be either embedded into or coated onto the composites. During the past few years, metallization of CFRP has attracted increasing interest, and cold spray is one coating approach to achieve this. In this work, metallic powders were cold sprayed onto the CFRPs used in aircraft by using a low-pressure cold spray system. The coatings as well as the coating/substrate interfaces were characterized and the deposition mechanism onto the CFRP substrate was determined.

1 Introduction

Carbon fiber reinforced polymers are increasingly used in a wide range of industries due to their low density and high specific strength, but their low electrical conductivity has limited their application. To make the polymer composites electrically conductive, a conductive media must be either embedded into or coated onto the composites. For example, for the latest generations of aircrafts and helicopters which make extensive use of CFRPs, embedded metal meshes or ply-integrated interwoven wires are the usual materials of choice for lightning strike protection [1]. However, these embedded structures are not only difficult to manufacture, but also difficult to joint with other pieces, and to repair if any damage occurs. Alternatively, cold spray is one coating approach to achieve this. This process enables selective deposition only onto the places where high conductivity is required (e.g. lightning zone 1# in the aircraft). The cold sprayed coatings are also easy to repair if there is some damages, since this process has already been successfully applied as a mature repair method for damaged part [2].

As traditionally used to produce metallic coatings onto metallic substrates, cold spray directly onto polymer substrates has been rarely successful. It has been reported that erosion of the substrates is the key problem, especially for these reinforced with carbon/glass fibres [3-5]. Furthermore, for CFRPs with thermosetting matrix, which degrade at elevated temperature rather than softening, it is hardly possible to take advantages of local thermal softening of the substrates, thus even more difficult to obtain coatings [6]. Therefore, more investigations are indeed needed to achieve directly cold spraying onto CFRPs and understand the deposition mechanism.

In this work, copper and tin were chosen as the coating materials because of their excellent electrical and thermal conductivity, good mechanical properties, good cold sprayability and relatively low cost. Copper is more conductive, and has excellent cold sprayability; tin is less conductive as compared with copper, but was reported to be most successful when cold spraying onto polymeric substrates. Various different combinations of gas pressure and gas preheating temperature were used for the cold spray process with a low-pressure system. .

2 Experimental methodology

Commercial-purity copper and tin powders were chosen as the coating materials. The feedstock powders used in this work are listed in Table 1. The particle sizes of the feedstock powders were measured with a Horiba LA-920 Laser Scattering Particle Size Distribution Analyser. The scanning electron microscope images and cross-section optical micrographs of the feedstock powders are shown in Fig. 1. It can be seen from that the both powders are not perfectly spherical; tin contains a larger number of relatively small particles and has a smaller average particle size.

Table 1. Feedstock powders used in this work.

Powder	Morphology	Supplier	D_{avg}	Hardness
Cu	Relatively spherical	Plasma Giken	29 µm	55 HV
Sn	Relatively spherical	CenterLine, SST	17 µm	11 HV

The CFRPs used in this work were provided by Bombardier Aerospace (Montreal, Canada). For the cold spray campaigns, sheet sections of dimensions 7 x 7 cm were used as the substrates. Prior to the cold spray experiments, these sections were degreased with acetone, and no other surface preparation methods were adopted. Unlike the metal substrates, which are usually grit blasted before cold spray, the CFRP substrates would be eroded during grit blasting.

Cold spray experiments were carried out at the McGill-NRC cold spray facility at National Research Council Canada, Boucherville. A commercially available CenterLine SST system (Supersonic Spray Technologies, CenterLine Windsor Limited, Canada) was used to perform the cold spray. The CenterLine system enables the so-called "downstream injection" mode, during which particles are introduced into the main gas stream immediately after the throat, the narrowest orifice of the nozzle, so that the risk of throat clogging in the nozzle can be alleviated when using a gas temperature higher than the melting point of the metal. Nitrogen was used as the carrier gas, and other cold spray process parameters are listed in Table 2.

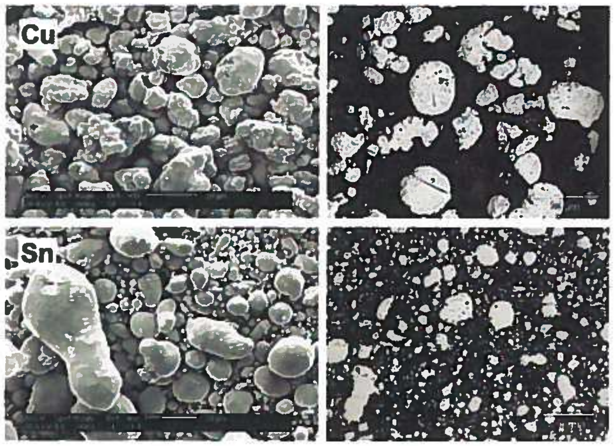

Fig.1. SEM images (left) and cross-sectional optical micrographs (right) of the feedstock powders.

Table 2. Process parameters for cold spray.

	Temp °C	Pressure MPa (psi)	Stand-off D mm	Gun travel speed mm/s	Feed rate g/min
Cu	425	0.34 to 1.38 (50 to 200)	18	25	~11
Sn	25 to 325	0.29 to 1.38 (42 to 200)	18	12.5 to 50	~13

3 Results

Figure 2 shows the deposition efficiency (DE) of spherical copper at various gas pressure conditions with a fixed gas temperature of 425°C. It can be seen that at all conditions performed, from 50 to 200 psi (0.34 to 1.38 MPa), the DE values are negative. This means that erosion of the substrate occurred and dominated despite the fact that the gas pressure was relatively low. It should also be noted that at 200 psi, the measured deposition efficiency was 7.24 per cent, but the actual erosion of the substrate was severe, more than 20 per cent of material, in thickness, was removed (the lightweight CFRP possesses a much smaller density, ~1.5g/cm^3, than metals, making the DE values look "small" in case the net weight change is caused by loss of CFRP). Due to the unsuccessful results of spraying copper, only tin was investigated thereafter in this work.

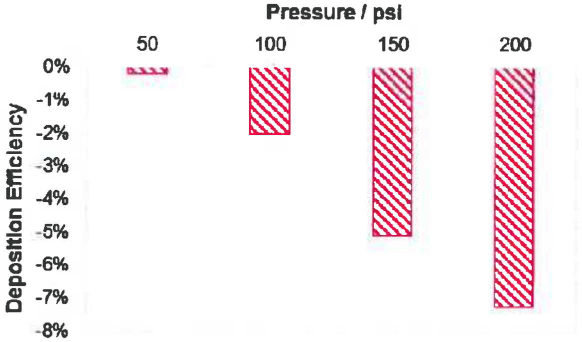

Fig. 2. Deposition efficiency of spherical copper at different gas pressure at 425°C.

The measured results of the DE of tin as function of gas preheating temperature and gas pressure are presented in Fig. 3. It can be seen that successful deposition of tin can be achieved with the low-pressure CenterLine system. When the gas temperature was fixed at 300°C, there was an abrupt increase in DE leading to a peak in deposition efficiency at a gas pressure of 60 psi (0.41 MPa), as shown in Fig. 3a. The deposition efficiency decreased to near zero when the gas pressure was increased to 150 psi (1.03 MPa), which is still low for conventional cold spray. On the other hand, when the gas pressure was fixed at 60 psi, there was a dramatic increase in DE when the gas temperature was increased from 280°C to 300°C, as shown in Fig. 3b. This abrupt change is possibly the indication of particle melting, since the gas preheating temperature, 300°C, is higher than the melting point of tin, 232°C. Whereas at relatively low temperature, DE was close to zero and even negative at 200°C due to slight erosion. The trend suggests that with further increase in gas preheating temperature, DE would continue to increase, so a trial spray at 325°C was performed, but the nozzle clogged despite the downstream injection mode was used.

The top morphology and cross-sectional microstructure of the tin coatings deposited under different gas pressures at 300°C are shown in Fig. 4 and Fig. 5, respectively. It can be seen clearly that good deposition and continuous coatings were achieved with tin when using the low-pressure system. At 42 psi (0.29 MPa, DE = 1%), the deposition of tin can be observed, but some uncoated area can also be found, indicating the deposition is non-continuous. At 60 psi (0.41 MPa), where the maximum DE (13%) was achieved, continuous coating was obtained and the top surface of the coating was relatively smooth. With increasing gas pressure, at 80 psi (0.55 MPa, DE = 7%), the coating was still continuous but some elliptical clusters emerge. These elliptical clusters have their longer axes in the vertical direction (aligned with gravity) and perpendicular to the gun travel direction. The reason of the formation of these clusters is unclear, but may be a combined effect of particle melting, particle bouncing and gravity. When the gas pressure was increased to 150 psi (1.03 MPa, DE = 0.6%), more and larger elliptical clusters and some grooves can be found. These grooves are essentially the carbon fibres coated with a thin layer of tin coating, which means erosion of the substrates nevertheless occurred despite the low-pressure.

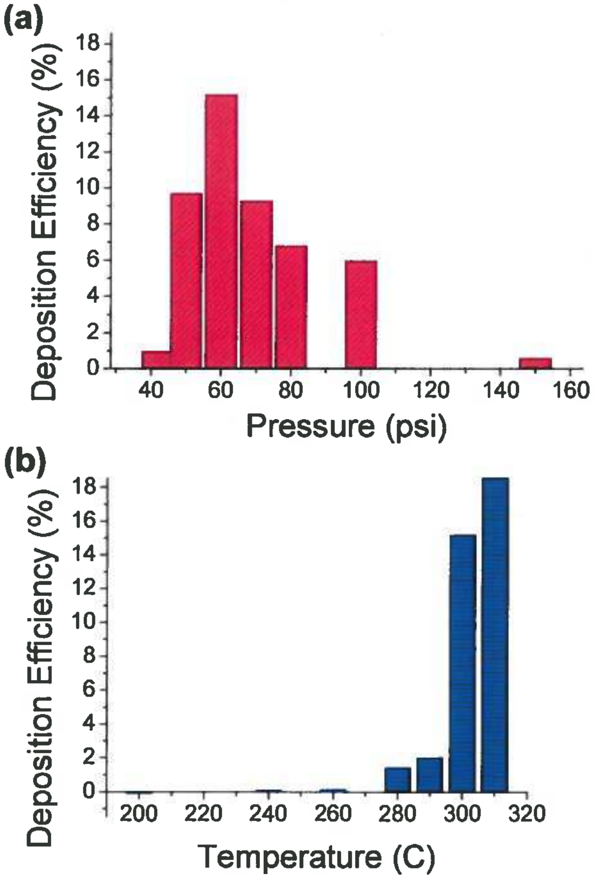

Fig. 3. Deposition efficiency of tin as a function of gas preheating temperature when sprayed at 300°C (a) and as a function of gas pressure when sprayed at 60 psi (b).

The cross-sectional micrographs in Fig. 5 are in agreement with the SEM top images. At 42 psi, although the deposition was non-continuous, the top surface of the CFRP remained smooth, without obvious signs of erosion. At 60 psi and 80 psi, the coatings were continuous, and the coating at 60 psi is approximately twice as thick as that at 80 psi, which agrees with the DE results. A close examination of the coating/substrate interfaces indicates that increasing gas pressure disturbed the smoothness of the interface, leading to waviness and irregularity at the interface. This might help to enhance mechanical interlock at the coating/substrate interface at low and medium gas pressure (e.g. 42 to 80 psi). However, further increase in gas pressure also led to erosion at the interface. At 150 psi, the deposition became non-continuous again, and signs of substrate erosion can be observed clearly: the surface epoxy was removed and the carbon fibres were exposed. The substrate erosion (removal) along with the tin deposition together resulted in a near-zero DE at this condition. It can be seen that in case that deposition and erosion occur simultaneously, the nominal DE is underestimated.

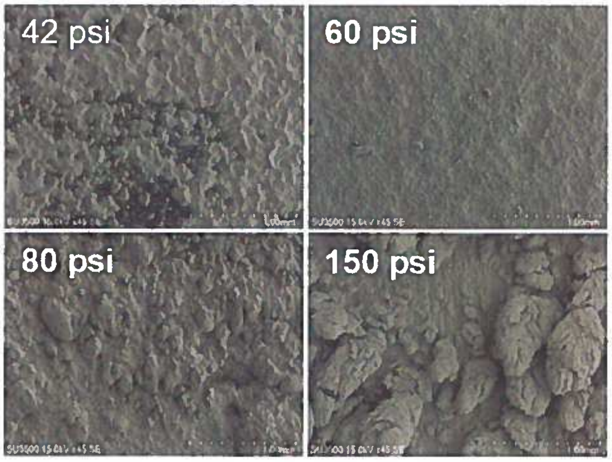

Fig. 4. SEM top images of the cold-sprayed tin coatings under different gas pressure at 300°C.

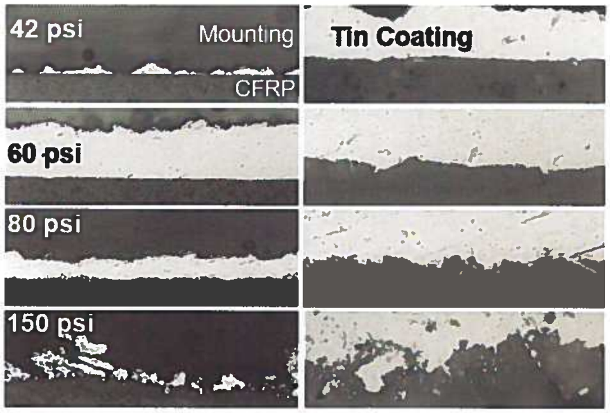

Fig. 5. Optical micrographs showing the cross-sections of cold-sprayed tin coatings under different gas pressure at 300°C at low magnification (left) and high magnification (right).

Figure. 6 presents the top surfaces of the samples after cold spray of tin at 60 psi at four different gas temperatures, 200°C, 240°C, 290°C and 310°C. Figure 6a shows the sample after spray of tin at

200°C, at which the gas temperature was below the melting point of tin and DE was slightly negative (–0.1%). It can be seen clearly that no coating was deposited. Fragmentation of the surface epoxy, an early sign of erosion, was also observed, but no significant removal of the epoxy occurred due to insufficient kinetic energy. A trace amount of tin can be seen within the cracks in the surface epoxy. When the gas temperature was increased to 240°C, just above the melting point of tin (232°C), a number of small tin clusters were deposited on the CFRP, and slight surface erosion can be observed from the cross-section, as shown in Fig. 6b (DE = 0.1%). Again, it indicates that deposition of particles and erosion of the substrates can occur simultaneously, which cannot be differentiated from DE values, so this may lead to an underestimated DE value. However, such underestimation is usually negligible when the erosion is slight considering the relatively low density of the CFRP (~1.5 g/cm^3). At gas temperature of 290°C, some small areas of the CFRP were coated with a thin layer of tin, but the deposition was still non-continuous in long range (Fig. 6d, DE = 2%). At 310°C, continuous tin coating was obtained, as shown in Fig. 6d (DE = 20%).

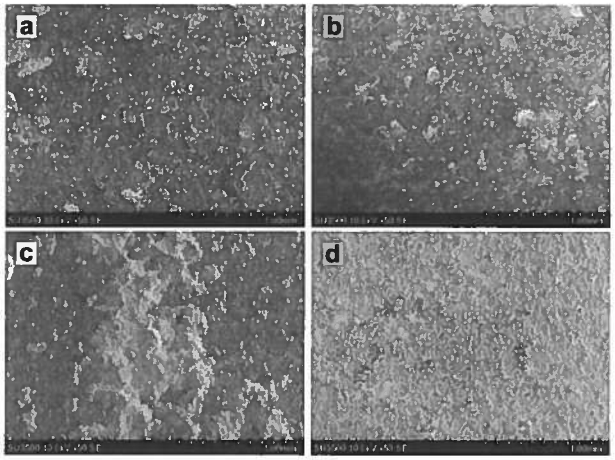

Fig. 6. SEM top images of the cold-sprayed tin coatings under different gas pressure at 60°C at (a) 200°C, (b) 240°C, (c) 290°C and (d) 310°C.

In particular, Fig. 7 presents a particle found at the top surface of the coating sprayed at 290°C. It can be seen the rim of this particle experienced noticeable change, as compared with the smooth surface of the starting powder. This may result from the melting of tin, considering the gas temperature is well above the melting point of tin. However, since the change was only found in the rim/outer surface of a particle while the particle as a whole basically remain spherical, it is reasonable to believe that only the outer surface of the tin particle melted while the core remained solid.

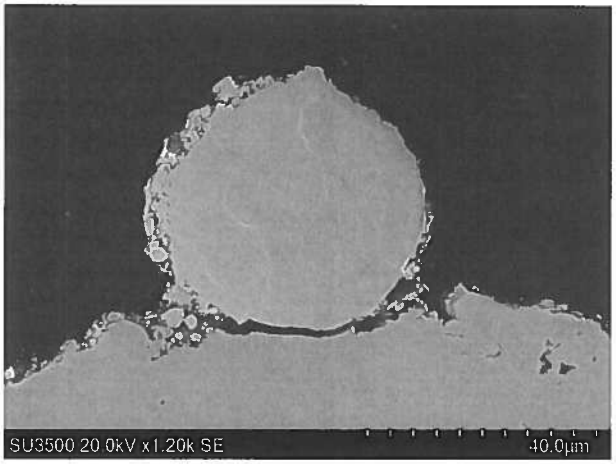

Fig. 7. SEM image showing a particle at the top surface of coating sprayed at 290°C.

4 Discussion

In this work, the unsuccessful trials with copper can be attributed to the failure in the development of the first layer. The copper particles cannot achieve mechanical interlocking with the CFRP substrates, but cause brittle fragmentation and material removal in the substrate surface. Even when spraying the relatively soft tin at 200°C, there were still difficulties in developing the first layer. When the gas temperature was increased to above 300°C, successful coatings were finally obtained by taking advantages of partial melting of tin particles. A “crack filling” mechanism is proposed to explain the success, as shown in Fig. 8. With this mechanism, when the tin particles enter the hot gas stream with a higher temperature than their melting point, the rims of these particles begin to melt. Due to the short residence time in the nozzle, the particles cannot wholly melt before they exit the nozzle, so the cores of each particles remain solid. When these partially molten particles bombard a brittle CFRP substrate, the impact generates a number of micro-cracks in the surface epoxy. Then the molten part of the tin particles get squeezed into these cracks and solidify, not only filling these cracks, preventing further erosion, but also achieving mechanical anchorage with the substrate and forming the first layer. Then the upcoming particles impact with this first layer and build up a coating, since the partially molten tin particles travelling at relatively low velocity cannot destroy the first layer whereas the velocity is still higher than the critical velocity for tin.

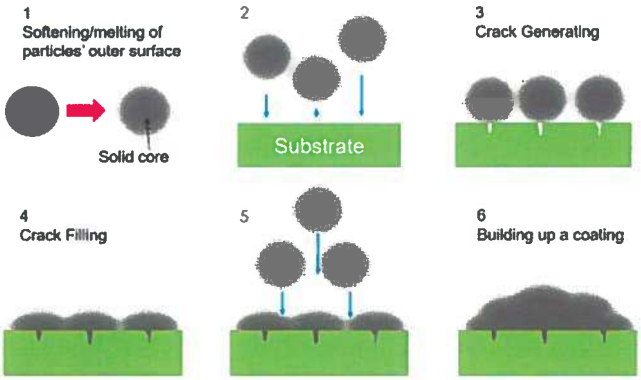

Fig. 8. Schematic of the crack filling mechanism.

5 Summary and conclusions

Continuous tin coatings were successfully obtained with the low-pressure cold spray system, whereas low-pressure cold spray of copper at various conditions still resulted in the erosion problem. Analysis of deposition efficiency indicates that medium gas pressure (60 psi) and high gas temperature (300°C and higher) are required for continuous deposition of tin onto the CFRP substrates. Examination of the coating morphology and microstructure reveals that tin particles partially melted when sprayed at gas temperature of 300°C and higher, and successful coatings were achieved by taking advantage of this partial melting. Accordingly, a "crack filling" mechanism is proposed to explain the deposition.

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