Experimental Study of Cold Sprayed Metallic Coatings on Thermoplastic Matrix Composites

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Abstract. In this research activity, the manufacturing of metallic coatings on polymer-based panels through the low pressure cold spray technique was studied. Aluminium particles were sprayed for the metallization and carbon fibre composite materials with thermoplastic matrix (PP, PA66) were used as substrates. Different deposition parameter combinations have been set to investigate the feasibility of the process; SEM analyses were carried out to study the coating surface morphology and the interface interaction between particle and substrate. The results showed that the CS process is an effective technique to create aluminium coatings on polymeric matrix composite materials: compact coatings can be obtained if the process parameters are properly set.

Introduction

Cold gas dynamic spray, or simply referred as cold spray (CS), is a process of applying coatings by exposing a metallic or non-metallic substrate to a high velocity jet (300-1200 m/s) of small (1-50 μm in diameter) particles accelerated by a supersonic jet of compressed gas [1,2]. Upon impact with a target surface, conversion of kinetic energy to plastic deformation occurs, the solid particles deform and bond together [3,4]. In contrast to the traditional thermal spray processes, in CS the particles are heated in the gas stream only to a fraction of their melting temperature, remaining entirely in a solid state prior to impacting the substrate [5]. Therefore, as a low-temperature technique, CS candidates as a potential method for the processing of temperature-sensitive materials [6,7]; moreover, the critical thermal deterioration phenomena as well as the structural variations of the substrates taking place in thermal spray processes, can be strongly reduced by CS [8]. In this scenario, this coating technology seems to be a suitable method for the metallization of polymer matrix composites (PMCs) for the improvement of the surface properties, strongly widening the applications of composite materials [9]. In fact, although PMCs are characterized by low density and high specific strength and stiffness, they suffer of a series of disadvantages such as low electrical and thermal conductivity, poor electromagnetic shielding, reduced erosion and radiation protection that limit their use in engineering applications [10]. In this regard, the surface metallization can give a strong contribution.

In the last decades, several researches were carried out on cold spray deposition process of metallic particles on metallic substrates [11,12]. Unfortunately, few researches have been done regarding the cold spray deposition of metallic particles on composite materials with polymeric matrix [13,14]. For example, Lupoi and O’Neill [15] analyzed the effect of the powder impact speed on the deposition characteristics of glass-fiber composite materials. Che et al. [16] pointed out the
beneficial effects on CS deposition efficiency of mixed metal powders for coated CFRPs substrates. Ganesan et al. [17] studied the influence of the substrate typology on the particle bonding mechanism finding that if the particles deeply penetrate into thermoplastic substrate, they can bond with the surrounding polymer matrix. Therefore, aiming to fulfil this lack of knowledge, in this research activity, carbon fibres laminates with thermoplastic matrix (polypropylene and polyamide matrices) were manufactured by the compression moulding technique and used as substrates for the CS metallization. AlSi12 particles were cold sprayed onto the polymeric surface under different process conditions in order to study: i) the feasibility of the process; ii) the coating surface morphology and the interface interaction between particle and substrate; iii) the effects of the main CS process parameters on the deposition mechanisms; iv) the influence of the fibre reinforcement on the CS coating formation.

Materials and Methods

The polymer matrix composite laminates used as substrates for the deposition process were produced by using a bidirectional carbon fibre fabric of 220 g/m² as reinforcement and polypropylene (PP) and polyamide (PA66) films, both with a thickness of 0.25 mm, as thermoplastic matrices.

The laminates were manufactured through the compression moulding technique under a pressure of 1.1 MPa at 220 °C for 15 minutes. The laminates so manufactured presented a thickness of approximately 2 mm. By using this approach, three kind of PMC samples were produced, as reported in Table 1; it can be seen that the PM-PA66 sample is free of fibre fabric.

A low pressure cold spray facility (Dymet 423) was used for the deposition process. Compressed air was used as carrier gas as a consequence of the low velocities required when spraying on polymeric substrates [16].

<table>
<thead>
<tr>
<th>Table 1. PMC samples typology.</th>
</tr>
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<tbody>
<tr>
<td>Matrix</td>
</tr>
<tr>
<td>CF-PP</td>
</tr>
<tr>
<td>CF-PA66</td>
</tr>
<tr>
<td>PM-PA66</td>
</tr>
</tbody>
</table>

Micron sized powders of aluminium alloy AlSi12 (particle mean size of 40 μm) were used for the spraying process to produce the metallic coating on PMC substrates. A preliminary experimental campaign, which is not here reported for the sake of brevity, was carried out by producing coating tracks 60 mm long and 5 mm width in order to determine the range of the optimal process parameters to be adopted for the next experimentation step, namely for the coating deposition on PMCs. In particular, the travel speed gun and the inlet gas pressure were set to 500 mm/min and 0.6 MPa, respectively, in agreement with the literature data [10]. As for the inlet gas temperature, its value was chosen by taking into account that the temperature of the gas flow on the target surface was below the melting point of the polymeric material and, at the same time, greater than the glass-transition one; this was done in order to avoid the deterioration phenomena of the substrate and ensure the softening, so that the metallic particles can penetrate the polymeric surface [15,17]. An inlet gas temperature equal to 150 °C was set in this experimentation for this purpose; moreover, the stand-off distance (SoD) was set in the range 20-35 mm.

Six laminates 100x100x2 mm³ were completely coated by using the best process parameters found in the previous step and specimens were cut, mounted and prepared according to the international ASTM standards for the metallographic observations. SEM analyses by using a Hitachi TM 3000 were carried out in the cross section of the coating samples to investigate on the adhesion mechanism between the substrate and the powders. The details of the specimens analysed are summarised in Table 2 along with the examined influencing process parameter; the cooling time represents the time needed for the coating cooling between each pass and the following one; the
time value was defined in agreement with the above mentioned preliminary campaign in order to ensure a stronger anchoring of the particles with the polymeric substrate. An exemplificative cold sprayed metallic coating on PMC substrate is reported in Fig. 1.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Specimen typology</th>
<th>SoD [mm]</th>
<th>Number of passes</th>
<th>Cooling time</th>
<th>Influencing process parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CF-PP₁</td>
<td>20</td>
<td>1</td>
<td>//</td>
<td>SoD</td>
</tr>
<tr>
<td></td>
<td>CF-PP₂</td>
<td>35</td>
<td>1</td>
<td>//</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CF-PP₃</td>
<td>20</td>
<td>6</td>
<td>NO</td>
<td>Deposition passes</td>
</tr>
<tr>
<td>3</td>
<td>CF-PP₃</td>
<td>20</td>
<td>6</td>
<td>NO</td>
<td>Coolning time</td>
</tr>
<tr>
<td>4</td>
<td>CF-PA66₅</td>
<td>20</td>
<td>6</td>
<td>NO</td>
<td>Fibre content</td>
</tr>
<tr>
<td></td>
<td>PM-PA66₅</td>
<td>20</td>
<td>6</td>
<td>NO</td>
<td></td>
</tr>
</tbody>
</table>

Fig.1. Exemplificative cold sprayed AlSi12 coating on PMC substrate.

Results and Discussion

The stand-off distance influence on the deposition process of aluminium particles sprayed on a PMC substrate was studied by comparing the SEM images of the cross sections of CF-PP₁ and CF-PP₂ specimens. In particular, the former was obtained by setting a 20 mm SoD and the latter by using a larger value equal to 35 mm. The results are reported in Figs. 2(a) and 2(b), respectively. It can be seen that a lower SoD guarantees a greater adhesion of the coating, namely, a greater deposition efficiency of the CS process. In fact, by looking Fig. 2(a), it is noticeable that the coating is thicker, more compact, denser and more homogeneous than the coating shown in Fig. 2(b), which seems to be discontinuous and almost non-existent. It is evident that a larger value of SoD (35 mm in this research activity) coupled with the above mentioned process parameters, does not ensure a high momentum of the particles upon impact with the substrate, resulting in poor and thin layer of the coating. This result was corroborated by the available literature [8], for which a higher momentum of the particles leads to the formation of a denser coating.

The influence of the deposition passes on coating quality was investigated by analysing the SEM images of the cross sections of CF-PP₁ and CF-PP₃ specimens, labelled as test number 2 in Table 2. As it is shown in Fig. 3(a), a thicker and more dense coating can be obtained for a single deposition layer with the particles that penetrate the surface and adhere to form the coating. Therefore, the results shown in Fig. 3(b) reveal that, although the coating was produced with a larger number of deposition passes, the coating build up on PMC substrates seems to be very difficult, if not impossible; the reason is that the coating build up is determined by the bonding strength between the first layer and the substrate. If the first layer is not firmly anchored, the shot peening effect of the upcoming particles can destroy the first layer making it impossible to build up a coating. Hence, there is no growth of the coating increasing the number of the deposition passes, confirming the results found in literature [18].
Fig. 2. SEM images of CF-PP₁ (a) and CF-PP₂ (b) specimen cross sections highlighting the influence of the stand-off distance.

Fig. 3. SEM images of CF-PP₁ (a) and CF-PP₃ (b) specimen cross sections highlighting the influence of the deposition passes.

With the scope to analyse the effect of the cooling of the coating between each deposition pass and the following one, the cross sections of CF-PP₃ (without cooling) and CF-PP₄ (cooled) specimens (see Table 2) were examined. The results are shown in Fig. 4. The analysis revealed absence of a significant height-difference between the two coatings, proving that the cooling did not affect the growth of the layer. In fact, with the relatively low inlet gas temperature and high travel speed gun set for the deposition, the coating cooling process is so fast that also by making continuous deposition, the coating has time to cool down. However, it is possible to observe in Fig. 4(a) that the continuous deposition guaranteed a greater deformation of the particles with a consequent better compaction of the coating.

Fig. 4. SEM images of CF-PP₃ (a) and CF-PP₄ (b) specimen cross sections highlighting the influence of the cooling time.

Aiming to point out the influence of the fibre reinforcement within the polymeric matrix on the CS deposition process, CF-PA66₅ and PM-PA66₅ specimens (the last is free of fibre fabric) were analysed by SEM observations. The results are shown in Fig. 5, where the coating thickness seems to be very similar for both the conditions. However, the comparison of the coating morphology highlighted that the coating of the specimen containing the carbon fibre fabric (Fig. 5(a)) is strongly
deformed and the aluminium particles have lost their morphology, resulting in a compact and quite dense coating. This is due to the fact that the fibres prevented the penetration of the particles. On the contrary, the coating particles on the free fibre specimen did not minimally deformed and the coating seems to be very discontinuous. Hence, this analysis proved the beneficial effect of the fibre content.

Fig. 5. SEM images of CF-PA66\(_2\) (a) PM-PA66\(_6\) (b) specimen cross sections highlighting the influence of the fibre reinforcement within the polymeric matrix.

Conclusions

On the basis of the above discussed experimental outcomes, the following conclusions can be drawn:

- Under optimized processing conditions, the cold spray technology seems to be an effective method to create aluminium coating on composite material substrates with thermoplastic matrix.
- A relatively low value of the SoD (equal to 20 mm in this research activity) ensures a greater adhesion of the metallic coating, namely, a greater deposition efficiency of the CS process.
- Thick and quite dense coatings can be obtained for a single deposition layer. The shot peening effect of the upcoming particles destroys the first layer making it impossible to build up a coating. However, in this regard, the continuous deposition can slightly improve the coating quality.
- Finally, the carbon fibre fabric within thermoplastic matrix was proved to give a beneficial contribution to the CS deposition process.

References


