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Machining of hybrid structures produced through cold spray technology: A preliminary study

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Abstract. Cold spray is a recently developed manufacturing technology for creating metallic layers on a variety of materials. Metallic particles are accelerated and strike the target surface using a pressurized gas flowing at supersonic speeds. In the last years, cold spray has gained increasing interest in different industrial scenarios, in particular, in the aerospace sector. Given the many fields of application, the need to understand how coated substrates behave when it is necessary to carry out machining operations arises. In this work, low-pressure cold spray equipment was employed to produce metal coatings on epoxy-based glass fibre-reinforced substrates optimized for cold spray deposition employing a layer of polypropylene on the composite surface. An automatic multi-purpose machine was used to drill 4mm diameter holes in the coated specimens considering the rotational speed fixed and varying the feed rate. The machined areas were then analyzed to assess the surface quality of the drilled holes and the burr morphology, considering different feed rate values and different entry surface of the drill-bit.

Introduction

In response to the growing demand for engineered materials capable of responding to the various requests arising during their applications, interest in composite materials such as Polymer Matrix Composites (PMCs), whose properties are completely tailorable due to their anisotropic structure, has increased [1]. Numerous engineering disciplines have been lured to the notion of producing lightweight, high-performance structures, resulting in a recent growth in the use of PMCs for high-end applications [2].

As examined in the literature [3], the metallization of PMCs has been recognized as one of the most promising approaches for further broadening their areas of usage and mitigating the challenges associated with their inherent inadequacies (such as their poor surface characteristics and high sensitivity to heat). In reality, surface metallization can enhance PMC erosion behaviour, boost thermal and electrical conductivity, and assure lightning protection, all of which are important considerations for the aerospace sector [4] .

The functionalization of polymer composite materials using standard processes such as plasma-enhanced chemical vapour deposition (PE-CVD), sputtering, laser ablation and evaporation, and liquid phase deposition is complex and costly, and the resultant coatings are difficult to modify. In reality, these technologies have the following disadvantages: high equipment and processing costs or work-piece size restrictions, low adhesive force, poor stability, lengthy production cycle, distortion of the substrate surface caused by molten particles, and high-temperature flames in thermal spraying (TS) [5].

Because of its capacity to generate thick coatings without compromising the substrate, cold spray (CS) technology has emerged as one of the approaches for metallizing PMC surfaces [6]. In

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reality, CS employs kinetic energy to permit the deposition of micron-sized metallic particles (10-100 m in diameter) that do not melt and retain their original properties throughout the process [7].

Cold spray is a revolutionary powder deposition process that is increasingly being used to produce thick functional coatings from a variety of materials, including ceramics [8]. The name "cold deposition" refers to this method's ability to keep processed powder temperatures below the melting point of the particle's substance during the deposition process. As a result, the particles in the solid state strike the substrate at a relatively high velocity, distort, and bond together for coating creation and growth. As a result, CS may be sprayed on temperature-sensitive materials such as polymer matrix composites or plastics without causing considerable thermal degradation, surface deformation, oxide, vacancy development, or phase shift. Furthermore, these coatings reduce residual stress [9].

Cold spray offers resource efficiency benefits, which result in economic and environmental benefits that contribute to long-term sustainability [10]. Cold spray, for example, is a technique that may be described as a green manufacturing process since it releases no harmful emissions, has no discernible environmental impact, and is an important tool for sustainability in a variety of sectors. The heating source is electric and regulated at temperatures below the melting point of the substance being sprayed, thus there are no noxious fumes or other potentially harmful emissions. This prevents the melting of metal powder and the release of hazardous gases. In general, the benefits of cold spray for sustainable production fall into four categories: 1) the process has a minimal environmental effect; 2) repair rather than replacement; 3) better performance, which extends the useable life of components; and 4) an alternative to more polluting and/or less sustainable techniques [11].

Although cold spray has been extensively studied and optimized for the deposition of metal powders on metal substrates, little is known about the deposition of metals on composites, which is far more interesting because it would allow for completely tailored products from the core to the surface.

The majority of the investigations in the literature focus on CS deposition on thermoplastic-based substrates: because there is no other adhesion mechanism other than mechanical interlocking, deformation of the substrate and particles is required for adhesion to occur. This is only conceivable if the substrate is thermoplastic, as it is more ductile because of the weak links that exist between the polymeric chains. Thermosetting polymers, on the other hand, display brittle behaviour, with weakly adherent and inhomogeneous coatings.

However, thermosetting matrix composites are the most appealing in many industries (including automotive and aerospace) due to their high compatibility with fibres and strong mechanical properties. To address this issue, it was presented a unique method that may consist of putting a thermoplastic-based interlayer on the surface of a thermoset-based substrate to achieve excellent CS deposition [12].

However, the application of cold spray for additive, repairing, and coating manufacturing applications is still severely limited by the fact that, due to the poor control over the process, the products require post-processing procedures. Considering that the coatings obtained are substantially thicker than those created with typical coating processes, it is not viable to optimize the processing settings using literature data. In particular, since the drilling process of CS coating on composite involves layers of different materials, it is yet required to do in-depth research on the phenomena that take place during the process.

In this work, for the first time in the literature, a preliminary study on the drilling operations on metal coatings obtained by cold spray on thermoset-based composite substrates optimized for CS deposition is presented.

Materials and Methods

Substrate manufacturing.

By employing plain-woven glass textiles weighing 200 g/m2 and an epoxy infusion technique, square laminates of glass fibre-reinforced plastic measuring 100x100 mm were produced. A total of 16 0/90 cloth layers were piled to achieve a 5 mm thickness. A commercial epoxy resin optimised for infusion applications, with a glass temperature (Tg) onset of 85°C, was employed.

As was mentioned in the preceding paragraphs, several investigations have proven that it is challenging for the sprayed aluminium powder to adhere to the epoxy-based substrate [13]. The particle impact energy is what determines how well cold-sprayed metallic materials adhere to plastic (particle mass and velocity). Even with less impact energy, deformation of the particle is still necessary during the collision. Therefore, only a polymeric substrate that is softer and more ductile, like thermoplastic materials, can allow for the deposition of CS metal and the formation of coatings [12].

Therefore, a unique approach was here suggested based on Polypropylene (PP) film treatments carried out on the epoxy surface, therefore enhancing the metal anchoring, in order to build a metal coating on the composite substrates. Particularly, a heated plate press P 200 E was utilized to promote the PP-composite coupling and a commercial thermoplastic PP film with a thickness of 0.5mm was placed on the surface of each sample. The PP employed has a nominal Tg of -20°C and a melting temperature (Tm) of 170°C.

The dishes were heated to 200 °C, which is slightly higher than the temperature at which polypropylene melts, and then 5 bar of pressure was applied for approximately 5 minutes.

Cold Spray Deposition.

For the cold spray depositions, Dymet 423 low-pressure apparatus with nitrogen as a carrier gas was employed. In order to create the metallic coating on the PP layer, LPW South Europe provided micron-sized powders of the aluminium alloy AlSi10Mg (size range 15-45 μm).

Preliminary experimental results and literature findings served as the foundation for the method chosen for the coating production process [14,15]. Several coating tracks were first created by altering the process parameters in a wide range (inlet gas temperature: 150-600 °C, inlet gas pressure: 4-8 bar, stand-off distance (SoD): 10-80 mm). These coating tracks had a travel speed of the spraying gun equal to 8 mm/s. For the sake of brevity, this process was not described in this article. The optimal process parameters, employed for the deposition of the aluminium layer were determined according to the preliminary study (inlet gas temperature: 160°C, inlet gas pressure: 6 bar, SoD: 45 mm). During the deposition a K-type thermocouple was positioned on the substrate to assess the real process conditions.

To avoid degradation phenomena of the substrate and to ensure softening, the inlet gas temperature was specifically 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 to allow metallic particles to penetrate the polymeric surface. The proper gas pressure was chosen, taking into mind that the substrate will erode more quickly at higher pressures due to the significant shot-peening impact of the particles. Finally, in terms of stand-off distance, greater values of SoD result in particles rebounding, which results in a thin coating since the particles' velocity is reduced upon collision with the substrate. This finding was supported by the literature [16], which indicates that a denser coating forms when the particle momentum is higher.

A 60x60 mm coating was created on the composite substrate specimens' surface by spraying a single layer of Al-based particles. A PosiTest ATM was used to assess the adhesive strength of the coating obtained while complying to the ASTM D4541 standard. Using cyanoacrylate adhesive, aluminum dollies with 10 mm diameter were attached to the top of the cold-sprayed deposits. Using a drill bit, any extra glue or coating around the dolly was taken off. Dolly surfaces were

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examined with an optical microscope to measure the quantity of removed coating in order to determine if the test was successful.

Machining of the specimens.

Drilling operations were performed using a 5-axis machining centre (C.B. Ferrari) with a 4mm twist drill bit. As indicated in Table 1, 16 holes were drilled while maintaining the rotational speed constant at 1000 rpm and varying the feed rate.

Table 1. Drilling process parameters employed in this research activity.

Hole	Feed Rate [mm/min]	Hole	Feed Rate [mm/min]
1	20	*9*	20
2	40	*10*	40
3	80	*11*	80
4	160	*12*	160
5	200	*13*	200
6	400	*14*	400
7	800	*15*	800
8	250 *(mean value)*	*16*	250 *(mean value)*

Drilling operations were performed perpendicular to the surface of the substrate. As illustrated in Fig.1, the first eight holes were drilled considering the uncoated composite side as the entry surface, whereas the holes from 9 to 16 were drilled with the coated one as the entry surface.

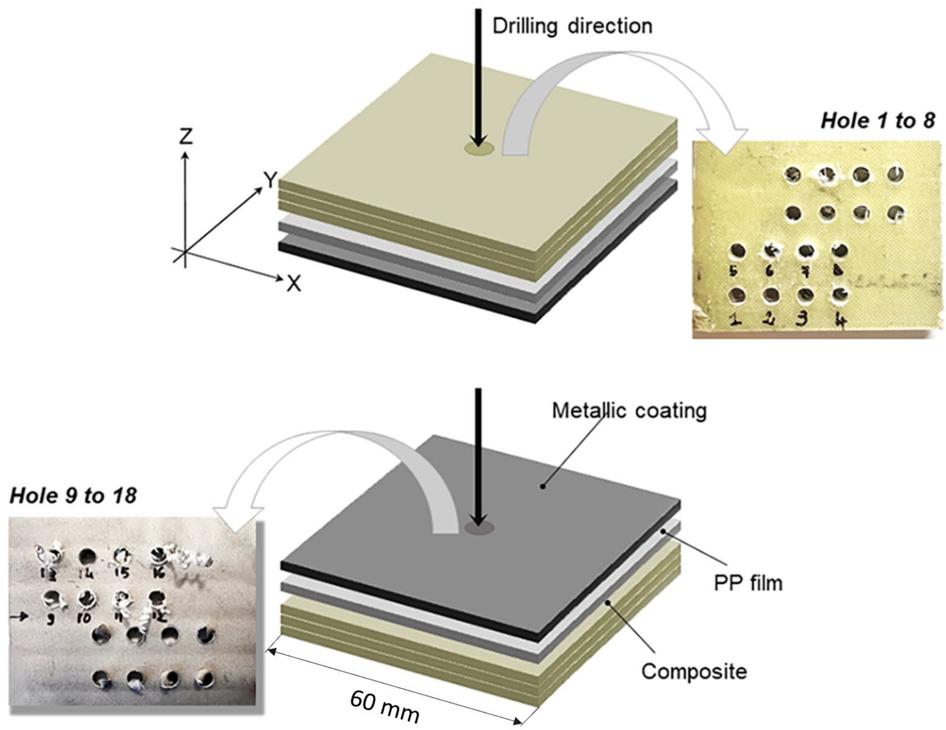

Fig. 1. Schematic illustration of drilling direction considered during the experimental tests.

Results and Discussion

As regards the holes obtained considering the epoxy-based composite as the entry surface the main results obtained by varying the feed rate are highlighted in Fig. 2. When the feed rate is increased it is possible to observe increasing delamination of the surface, defined as the inter-ply failure occurring during the drilling operation of the composite materials[17]. This phenomenon, as highlighted in Fig. 2, may be seen at the drilled-hole entry.

The plies separate from one another and form a peel-up delamination zone around the drilled-hole entry circumference when the drill penetrates the top surface of the laminate. This is caused by the contact between the composite material and the cutting edges of the drill, which creates a peeling force that acts in the Z direction through the slope of the drill [18]. In fact, when the thrust force is greater than the material's interlaminar bond strength, drilling-induced damage manifests as splitting between two adjacent layers.

Delamination is widely acknowledged as the primary mechanism of failure when drilling composite laminates and is regarded as a serious issue since it significantly lowers the material’s fatigue strength [19].

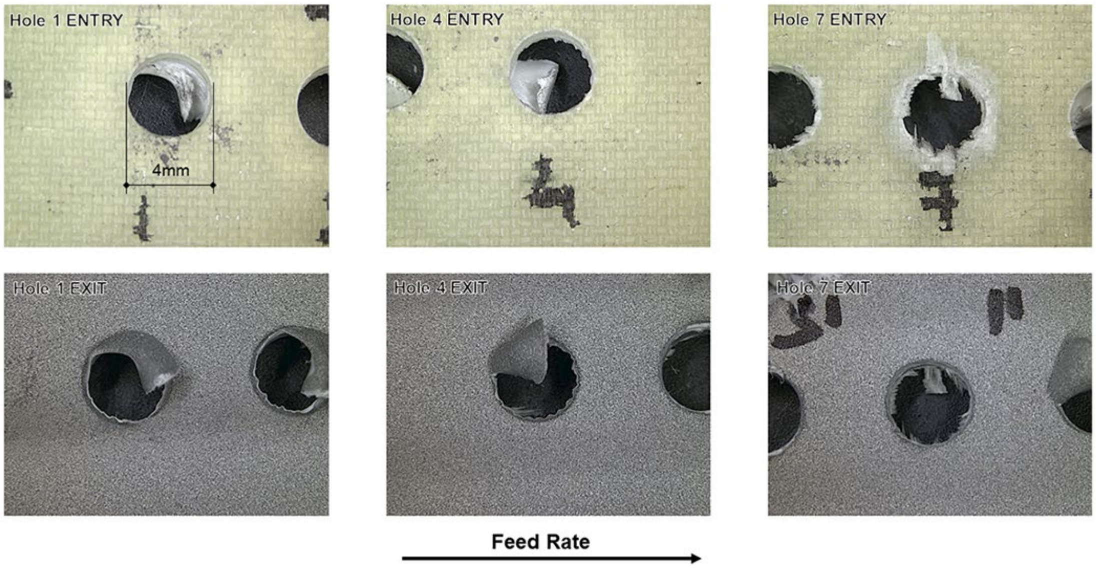

Fig. 2. Macrographs of the holes obtained considering the epoxy-based composite as the entry surface.

As the drill bit travels down the substrate's thickness, it will come into contact with PP film that has been cold-sprayed with aluminium powders. It is possible to observe the formation of burr, a push-out defect due to the deformation during the drilling process of the more ductile material compared to the epoxy-based composite . As the feed rate increases, this defect appears less evident. It is furtherly possible to observe, that the coating remains well adhered to the PP surface.

It, therefore, appears evident that the optimal feed rate value must take into account the opposing trend of delamination of the composite and push-down of the thermoplastic film.

As regards the holes obtained considering the coating as the input surface, the results obtained are portrayed in Fig. 3.

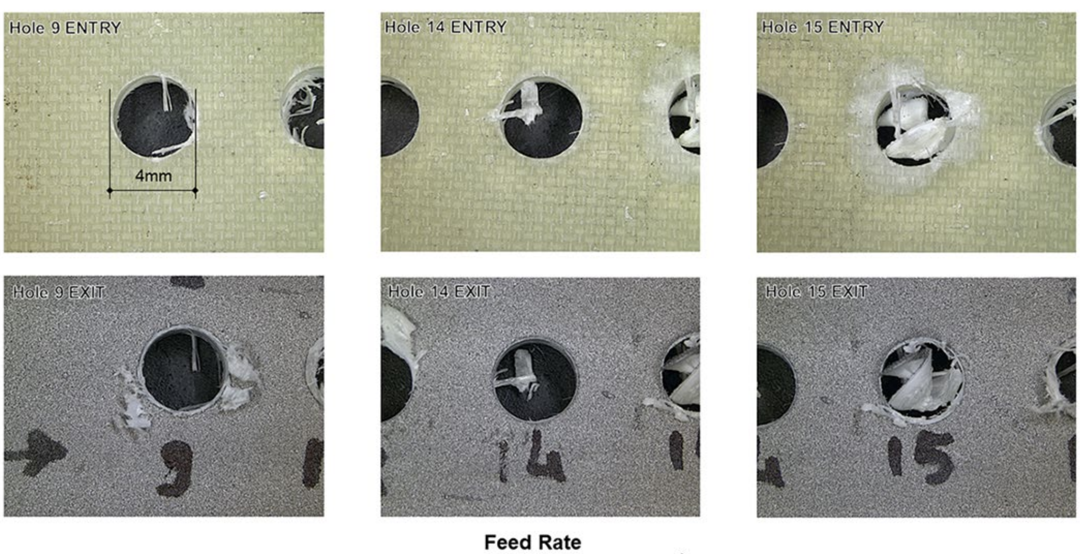

Fig. 3. Macrographs of the holes obtained considering the metallic CS coating as the entry surface.

Likewise the previous case, as the feed rate increases, the substrate might delaminate, in this case as a push-out delamination phenomenon. It should be noted that fiber breakage can be observed even at low feed rate values, as illustrated by observing hole 9.

However, in this scenario, we can notice the production of long continuous chips on the inlet surface, where the drilling bit penetrates the CS coating and the Polypropylene film, as shown in Fig. 4.

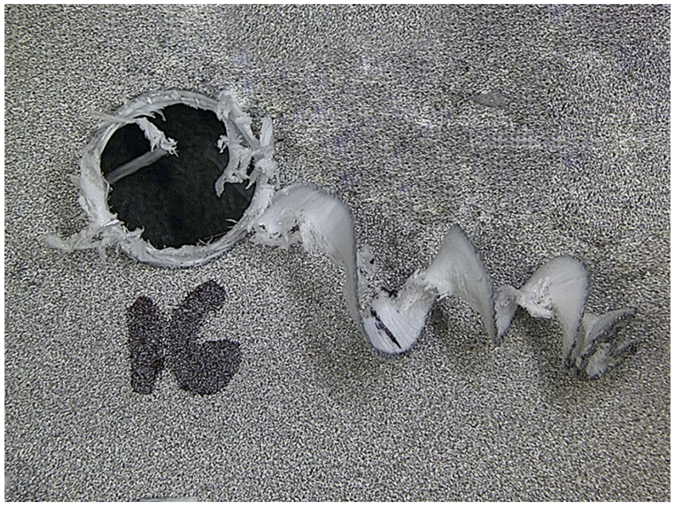

Fig. 4. Long continuous chip obtained with high values of the feed rate.

It is possible to assess that the feed rate strongly influences the length of the chips. Long continuous chips are undesirable as they could frequently tangle around the drilling tool and require hand removal, potentially affecting the operations [20]. In fact, low glass transition temperatures and low heat conductivity of the thermoplastic material are the main factors that contribute to tool clogging in thermoplastic composites. Due to friction, the tool temperature could rise above the glass transition temperature of the polymer during machining, causing the thermoplastic material to become rubbery and deposit on the tool's surface[21].

It is interesting to observe the presence of the CS coating on the surface of the chips created. In fact, the adhesion tests performed on the samples indicate that, despite the creation of the spiral chips, the coatings remain effectively adherent to the composite substrate. As depicted in the macrographic images of the dolly following the adhesion tests illustrated in Fig. 5, the coating is dense and homogenous. The measured average adhesion value is 5 MPa.

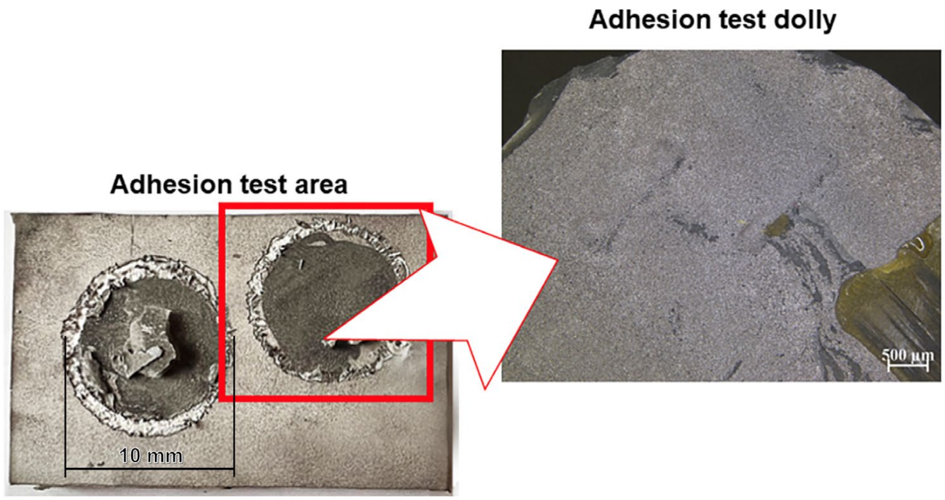

Fig. 5. Adhesion tests performed on the coated specimens. It is possible to observe the CS coating in the macrograph of the adhesion test dolly.

Confronting the results obtained by changing the entry surface of the drill, it is possible to assess that when the drilling operation starts from the composite laminate to the metal coating, no significant changes are observed in the composite to the coating/composite drilling sequence, when increasing the feed rate. However, the formation of long spiral metal/PP chips can be observed when the coating side is chosen as the entry surface, making further machining of the hole necessary and hindering the drilling operations.

Summary

The purpose of the work is to assess the influence of metal-based cold spray coatings on the quality of the holes and burr formation during drilling operations on composite laminates, optimized for CS deposition. The main findings of this work can be summarized as follow:

- the feasibility of drilling operations on cold spray coated samples was assessed
- the surface quality of the machined areas was analyzed by fixing the rotational speed and varying the feed rate
- The feed rate influences the delamination of the composite both at the drilled-hole entry (peel-up delamination) and exit (push-out delamination). Increasing the feed rate, the delamination effects worsen.
- it was shown that the machined-hole entry surface has a strong influence on the burr formation. In particular, long spiral chips are formed when the coating side is chosen as the entry surface.
- The coating remains well adhered to the surface during the drilling operations and remains adhered to the chips. This is further confirmed by adhesion tests performed on the coated surface.

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