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Feasibility of steel powder deposition on composites through cold spray

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ABSTRACT
The deposition of steel powders on glass fiber reinforced polymer (GFRP) with the Cold Spray technique is investigated. Metallization of composite materials is still challenging when high-strength and dense powders, such as steel, are used due to excessive erosion of the polymer or disruption of the fibers during the deposition. To overcome these issues, low-pressure cold spray equipment has been used for the experimental campaign shown in this paper. Different coatings were obtained by using nitrogen as the carrier gas and different sets of pressure and standoff distance. Optimization of the process parameters, including the stratification of the laminate, has been carried out. Results of an initial study of the feasibility of the process and the influence of the different chosen spray conditions are exposed. In particular, the bonding mechanisms of steel powders and their morphology are discussed.

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Introduction

Fiber Reinforced Polymers (FRPs) consumption in engineering fields is gaining interest due to their several advantages comparing to other materials, such as metals or ceramic.[1,2] FRPs are commonly used in the aerospace and the military industries because of their low density, high strength and stiffness and other outstanding properties, for example, easy formability and manufacturing.[3] Composite materials are easier to be manufactured in complex shapes with a combination of lower superficial roughness and appropriate resistance to corrosion.

In recent years, the metallization of plastic surfaces is gaining interest to combine the advantage of plastic materials with the benefits of the metals.[4] Some important characteristics, e.i. thermal and electrical conductivity, resistance to abrasion and temperature, can be attained through the metallization of polymer and composite surfaces.[5] The characteristics of metalized composites are required for different applications, such as microelectronics,[6] lightning protection[7] or biocompatible elements.[8] Although the metallization of these materials can be obtained by several techniques, for instance, physical vapor deposition (PVD),[9,10] chemical vapor deposition (CVD)[11] and plasma-enhanced chemical vapor deposition (PECVD),[12] the thickness of the deposits could not exceed a few micrometers, the cost of the equipment is high and the temperatures achieved during the process are still an issue. A suitable alternative to these techniques is the use of a thermal spray process, with which metal coatings are successfully deposited onto numerous substrates.[13,14] However, the high gas temperature during thermal spray deposition can cause degradation of the polymer. To avoid this last phenomenon, caused by the high reached temperature, Cold Spray technology can be used.[15,16] Even if the cold spray deposition on metal substrates has been extensively studied in the last decades, the deposition on a polymer or composite substrate is a relatively new cold spraying application. Compared to other techniques, the cold spray results suitable for this type of application: i) bonding is made possible only by mechanical interlocking mechanism and no chemical reactions are necessary between the particles and the substrate[17]; ii) less heat input is required comparing to thermal spray processes so that the powders remain solid and can retain their primary properties during deposition.[18] On this basis, cold spray appears to be the most appropriate technique to deposit coatings on temperature-sensitive materials, i.e. polymers and polymeric composite, without reaching the melting or degradation temperature of the material.

Anyway, differently from the classic deposition of metal powders on metal substrates, some issues can be observed when spraying on polymer or composites, such as the absence of appreciable particles' deformation[19] and substrate erosion or fibers disruption.[20]

In this case, to guarantee a successful deposition, it is necessary to identify the nature of the substrate. As Ganesan et al.[17] have affirmed, cold spray coating deposition mechanisms are different for thermoplastic and thermosetting substrates. On the thermoplastic substrate, the particle can easily penetrate the polymer, due to its ductility under high temperature, and mechanical interlocking is easier to happen. On the other side, thermosetting substrates, due to their brittle nature, tend to be eroded and thick coatings cannot be deposited. Consequently, the deposition of metal powders on thermoplastic materials can be more achievable. Due to the high research interest, more than a few studies have been conducted on the deposition of metal coatings on different thermoplastic substrates, such as PEEK,[21–24] ABS[19–21,25] or PVC.[26,27] To understand the coating mechanisms occurring on the polymeric substrate, in previous works it was proposed that cold

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spray is a two-step process, one for the first layer and the other for the development of the buildup layers.[28] It is obvious that each step has its window of deposition and the overall window is determined by the overlap of these two windows.[19] However, it is found to be extremely difficult to determine the first window of deposition considering that the polymers' properties largely depend on temperature, impact energy and powders properties.[26] Che et al.[25] stated that the buildup of a thick coating on a thermoplastic polymer and its properties, such a good adhesion strength, is strictly dependent on the properties of the metal powder and the bonding strength of the embedded particles of the first-sprayed layer. It was noticed that deposition of lighter materials, such as tin or aluminum, is easier to achieve while the deposition of harder materials, such as copper is still challenging and, in most cases, the need for a softer interlayer is required.[29] As verified by R. Lupoi et al.,-[30] powder type has been found to have the main role in the deposition on these types of substrates and the powder cold sprayability is still objected to study. To analyze the feasibility of the process, these authors were able to define the impact energy of different metal powders on thermoplastic substrates with a High-Pressure Cold Spray equipment. Experimental results with aluminum, copper and tin powders were analyzed and it was demonstrated that deposition on thermoplastic substrates becomes achievable when spraying lighter material with lower impact energies. On the other hand, stainless steel 316 L, such as copper, was predicted to cause erosion of the substrate because of its higher strength but no experimental experiences have been found in the literature.

For the first time, in this paper, the deposition of steel 316 L powders on a thermoplastic substrate is discussed. To limit surface damage, steel 316 L powders were deposited directly onto FRPs laminates by using a low-pressure cold spray system instead of a high-pressure system.[15] Also, most works in literature did not investigate the influence of the laminate stratification and the consequent effects of the polymer matrix and fibers parts. Based on these considerations, the authors set up the experimental campaign aiming to explore the interaction between firstly sprayed powders and the polymer and the influence of the process parameters on the deposition. To understand how the composite substrate affects deposition and how it differs from a polymer substrate, protective polymer layers on the top of the fibers are used. The authors aim to explore how the thickness of these protective polymer layers can affect the deposition, namely the fibers' influence. Two different panel types used as substrates are manufactured with two different stratifications. Polypropylene (PP) is used as a thermoplastic matrix while glass fibers are used as reinforcement. The coated samples were sectioned, mounted and prepared through several phases of grinding and polishing. The coatings were observed in different directions with SEM microscope, Confocal Microscope and Optical Microscope. The aims of this work are: (i) to analyze the feasibility of the process with steel powders, (ii) to investigate the influence of the composite stratification on the deposition of the first layer of powders, (iii) to find the optimum set of process parameters (gas inlet pressure and standoff distance).

Materials and methods

Manufacturing of the substrate

For the deposition, FRPs were selected as the substrates. Polypropylene (PP) was chosen as a thermoplastic matrix while bidirectional glass fiber fabric of 160 g/mm^2 was taken as reinforcement. To control the laminate dimension, sheets in polypropylene (PP) and glass fibers fabric were cut in a rectangular shape of 150 mm x 100 mm. Composite laminates were realized with a compression molding technique. For each laminate, 15 different sheets were used, alternating fibers and matrix sheets. Then, the whole composite has been placed in an oven and heated at 210°C for 15 minutes. To limit the damage of the fibers, a polymer layer has to be placed on the top of the substrate.[22] The authors decided to consider as a process parameter the layer thickness of the superficial matrix layers. The building strategy of the FRP to obtain protective polymer layers of different thicknesses for the fibers on the top of the substrate is investigated. As shown in Fig. 1 two different types of laminates have been produced by superimposing matrix and fiber layers in different ways: in the first case, a single matrix layer is placed on the top of the panels while in the second case two matrix layers are used. The actual matrix layer thickness was calculated as the mean value of five different measures performed in 5 different points of the panel, as shown in Fig. 2, and the results are summarized in Table 1.

Cold spray deposition

Spherical steel 316 L powders, obtained with gas-atomization by LPW South Group, were chosen as feedstock material. The average size of the powder was identified through the ImageJ software. In Fig. 3a SEM image of the powder is exposed.

The deposition was accomplished with a low-pressure cold spray machine Dymet 423 and nitrogen was used as the carrier gas. A composite nozzle, which consists of a converging-diverging fixed nozzle and an interchangeable divergent part, has been used for the deposition and all the geometry features are summarized in Table 2. A detailed scheme of the nozzle and his parts is presented in Fig. 4. The advantage of having a movable and interchangeable divergent part is attributed to the opportunity to avoid the substitution of the whole nozzle in case of damage, and to limit the change to the most damaged part of the nozzle, which is usually the divergent part, more subjected to wear phenomena by gas and heat flows. Consequently, costs and waste of materials are reduced. The process was automated by a numerically controlled pantograph while the nozzle moved at a set speed and a set standoff distance when spraying onto the substrate. The panel was placed on a platform while the working gun was placed vertically above the substrate at a fixed standoff distance.

To analyze the interaction between the cold sprayed powder and the polymer and study the bonding mechanism, only one spray layer is deposited on the panel.[31] For each set of process parameters, a single track of about 100 mm length has been deposited. The spray conditions are summarized in Table 3. The inlet gas temperature was set at 150°C and maintained constant at the set temperature. Different propellant gas pressures (0.5 MPa, 0.6 MPa) and different standoff distances

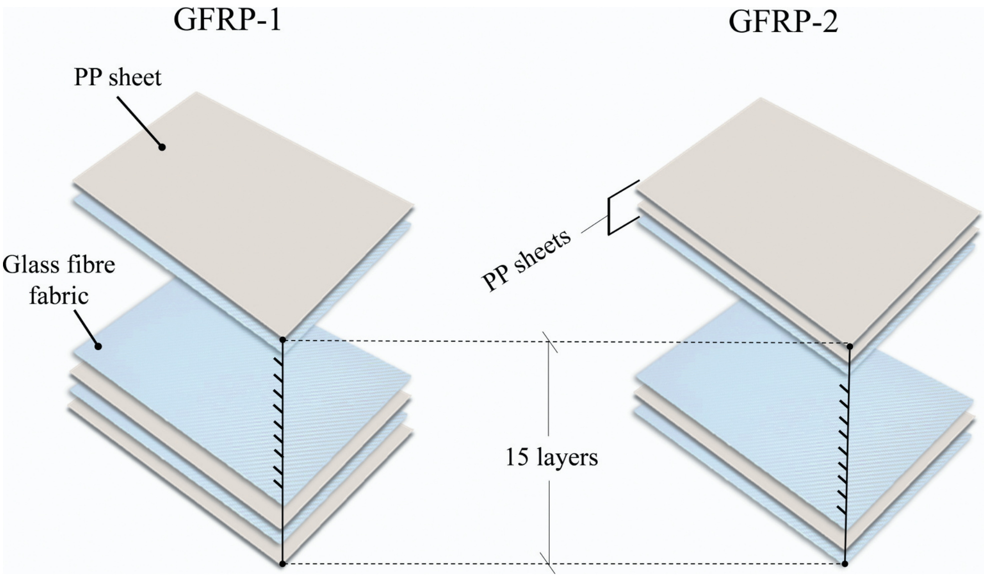

Figure 1. Scheme of laminate stratification.

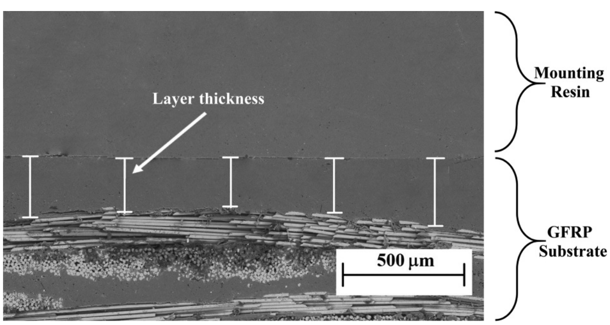

Figure 2. Mean substrate layer thickness: white lines indicate the thickness of the superficial layer.

Table 1. Indication of the mean value of the polymer thickness for the two typologies of FRPs.

Panel typology	Mean substrate layer thickness [μm]	ID Panel
Single configuration	149	GFRP-1
Double configuration	254	GFRP-2

(20 mm, 25 mm, 35 mm) were used to investigate their influence on the deposition. The substrate temperature was about 110°C, below the PP melting temperature, and it was measured with a k-type thermocouple.

For the experimental campaign, 12 different steel coatings were produced and characterized by different spraying conditions by varying the SoD distance and the gas inlet pressure. Table 4. summarizes all the obtained samples with different parameter combinations.

Table 2. Nozzle geometrical features.

	FIXED NOZZLE			MOVABLE DIVERGENT NOZZLE	
	Inlet section	Throat	Outlet section	Inlet Section	Outlet section
mean radius [mm]	4.5	1.25	1.7	2	2.5
mean length [mm]	0	7	19	19	139

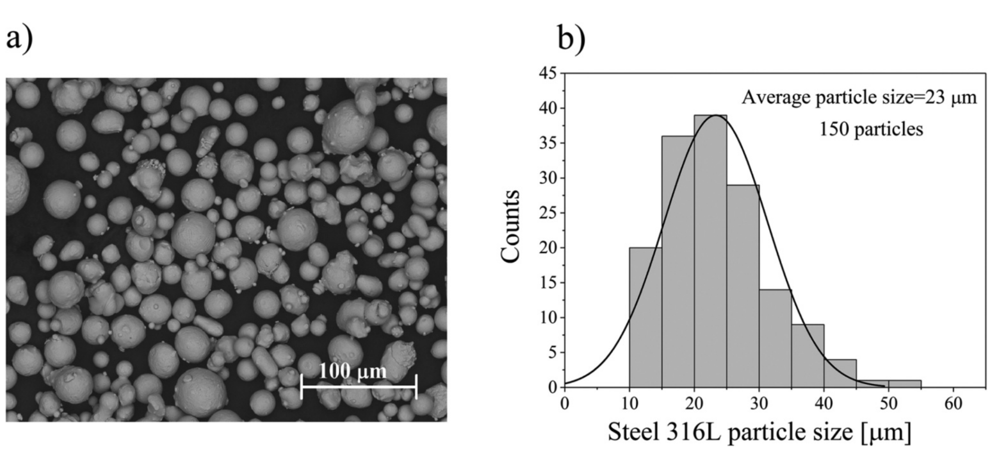

Figure 3. SEM observation for steel 316 L powders morphology (a) and size distribution (b).

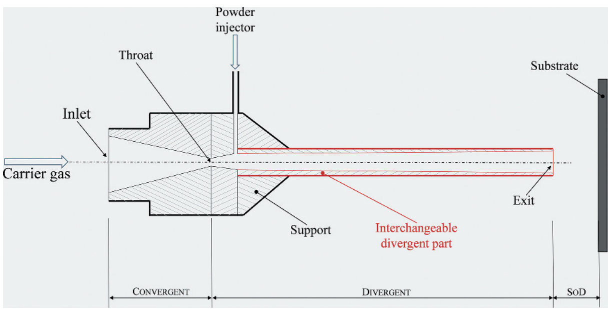

Figure 4. Scheme of the convergent-divergent nozzle.

Table 3. Process parameters for deposition.

Parameters	Values
Inlet Gas Pressure	0.5–0.6 (MPa)
Inlet Gas Temperature	150 (°C)
Gun Traverse speed	7.5 (mm s^{-1})
Standoff distance	0 – 30 – 35 (mm)

Table 4. Experimental campaign investigated in the article.

Powder	Carrier Gas	Substrate type	Pressure [MPa]	SoD [mm]	Sample
				20	1
			0.5	25	2
		GFRP-1		35	3
				20	4
			0.6	25	5
Steel	Nitrogen			35	6
316 L				20	7
			0.5	25	8
		GFRP-2		35	9
				20	10
			0.6	25	11
				35	12

Coating characterization

The experiments aim to evaluate the surface coverage of the coating, the powder morphology and the penetration depth of the particles. After the deposition, each sample was cut perpendicularly to the sprayed surface with a hacksaw to obtain a small specimen of about 1 cm width. As pictured in Fig. 5., observations of the specimens were taken in two different directions: cross-section direction, perpendicular to the cutting direction and top-view direction, parallel to the cutting direction.

Firstly, top-views of the coatings were observed by a Scanning Electron Microscope (SEM – Hitachi TM 3000) and Confocal Microscope (Leica DCM3D Scan). Afterward, each sample was mounted, prepared trough different grinding and polishing phases with sandpapers and diamond suspensions and then metalized. The cross-sections of the coatings were observed with the same SEM and an Optical Microscope (Askiop 40 by Zeiss).

To qualify the effectiveness of the deposition, the amount of coated surface should be evaluated. The effective coated area was calculated from SEM acquisition by creating a binary mask of the surface and evaluating the pixel threshold (ImageJ), where particles are identified in white while the polymer substrate in black (Fig. 6). The percentage coverage of pixels was then quantified and the surface coverage was visually calculated as the mean value of three different acquisitions.

Coating height was estimated by the analysis of both the Confocal Microscope and the Optical

Microscope acquisitions, the first from the top-view direction while the second from the cross-section direction. Top-view observations were carried out through the generation of a three-dimensional surface taken from a random area of the coated surface. After the creation of the surface, as seen in Fig. 7, results have been exported to LeicaMap software for the profile extraction. Subsequently, maximum height was measured as the mean value of the 3 maximum profile values.

To compare the coating height before and after the sample preparation, further analyses with the Optical Microscope in the cross-section direction were required.

The coating height values were visually measured from the substrate surface up to the highest point of the coating in three different acquisitions and then a mean value is determined.

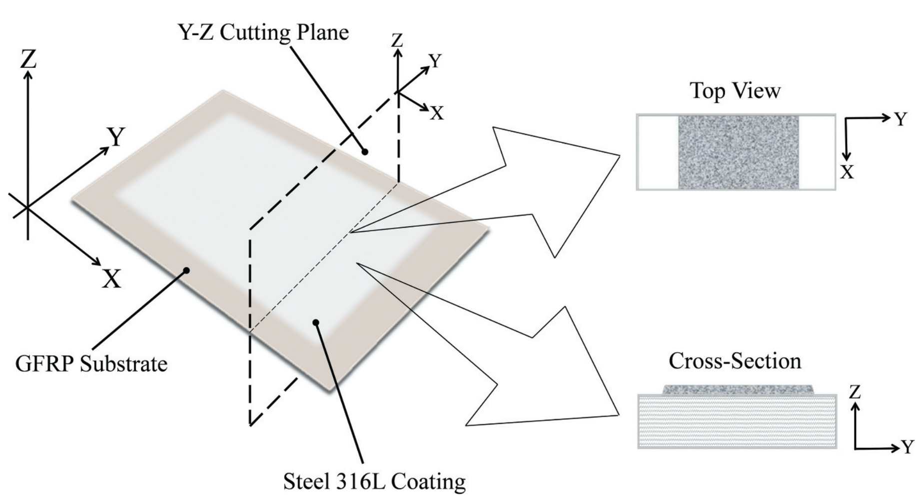

Figure 5. Scheme of sample characterization.

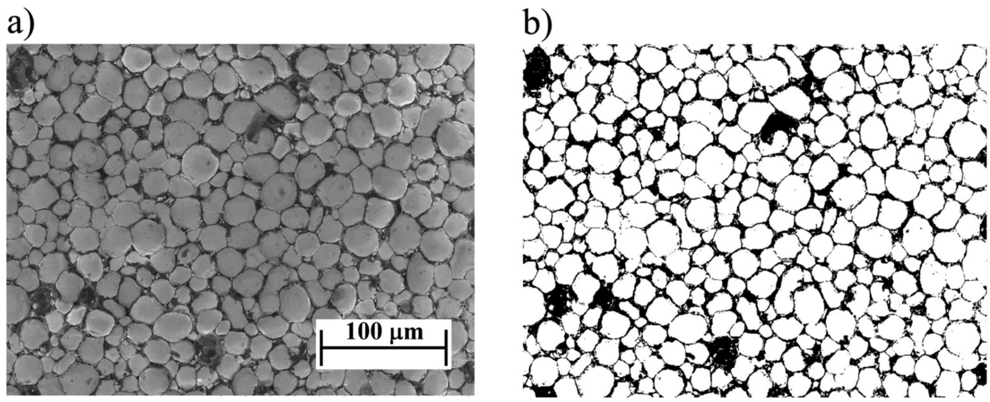

Figure 6. Top view acquisition with SEM (a) and ImageJ (b).

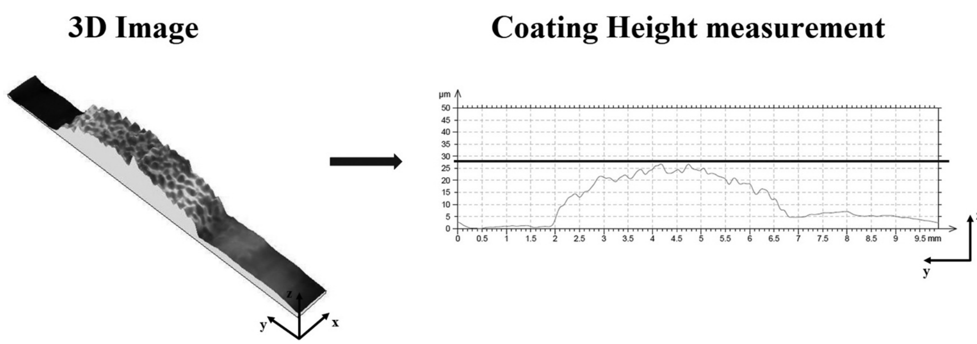

Figure 7. Profile extraction with LeicaMap for maximum coating height analysis.

To estimate the penetration depth of the steel 316 L particles, coatings were examined with SEM acquisition in a cross-section direction. As done in the previous study,[32–34] this length was identified from the substrate surface down to the deepest point of the coating and its value was taken as the mean of ten different measurements in several points of the coating.

The above-mentioned techniques are commonly used in the literature.[32,35]

Results

Surface coverage

The deposition efficiency of the various samples of the experimental campaign has evidenced low values of less than 10%, which ties well with previous studies.[17,22] Anyway, for each set of process parameters, similar deposition efficiencies values are given and the influence on the other process parameters is not relevant. For this study's purpose, to evaluate the feasibility of the process and the effectiveness of the deposition throughout the single track, two different zones of each steel 316 L coating, indicated as boundary (the external part of the track) and bulk (center part of the track), have been separately observed from the top-view direction.

As shown in Fig. 8, the bulk region (Fig. 8b) is characterized by a good amount of deposition, the surface appeared widely coated with the presence of few voids between the particles. Anyway, the absence of appreciable powder deformation limited the particle-particle interaction and as a consequence, the

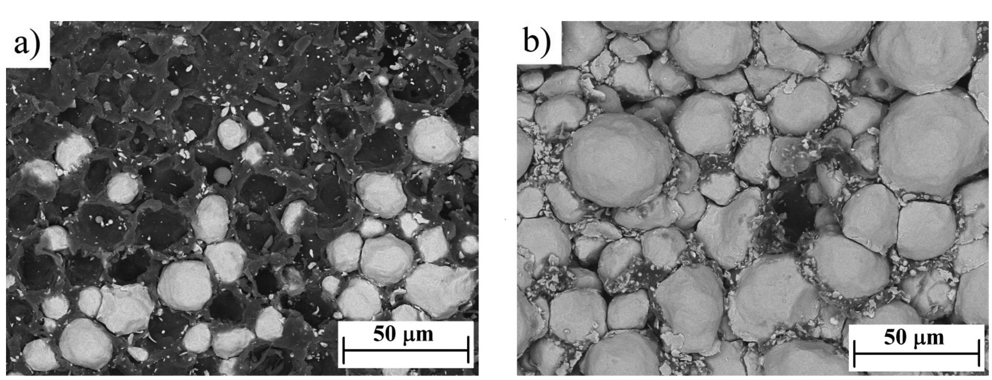

Figure 8. SEM magnification of steel coating on GFRP-2 S.O. = 25 mm p = 5 bar a) boundary b) bulk.

coating is not completely compacted and homogeneous, showing uncovered spaces in the deposit.

On the other hand, at the boundary region (Fig. 8a) the number of deposited particles appeared to be extremely lower compared to the bulk region and a lot of "impact craters" can be spotted on the surface. This fact does not suggest that the deposition cannot occur in the boundary zone but that these craters may be caused by the low impact velocity of the steel particles: particles impact onto the surface, deform or crack the surface and then rebound without stacking into the substrate due to the poor adhesion.[20] This behavior could be attributed to the variation of the mean particle velocity profile[36] which sharply drops when retreating from the nozzle axis. It could be assumed that the particle energy does not reach the minimum critical value and, as evidenced by the sequence in Fig. 9, changing the SoD or the gas pressure parameters did not produce any notable improvement in the amount of the deposition in the boundary region. Hence, it is obvious that the presence of the impact craters mainly depends on the properties of the chosen metal powder, such as density and size distribution, which directly affect the powders' velocity.

Considering all the above-mentioned observations, from bulk to boundary region the powder morphology and the deposition behavior appeared to be similar for each set of process parameters and each panel type. In all the cases, the particles retain their original shape, deformation of the powder has not occurred and the borders of the particles are distinct and defined. Anyway, it is critical to note that throughout the single track, the coating is obtained without evident damages or erosion of the substrate.

Since the cold spray deposition is usually obtained with different overlapped spray passes and different strategies,[37] only the bulk of the coating gains major interest. In the following outcomes, only the bulk sections were considered for the surface coverage characterization. All the results were summarized in Fig. 10 and graphed against SoD and pressure. As evidenced, surface coverage values in bulk sections are extremely high, leading from a minimum of 82% to a maximum of 93%. When increasing the substrate layer thickness, a clear trend of increasing surface coverage is evident. Another significant trend reveals that the surface coverage increases when increasing the gas pressure.

Overall, these results indicate that when using a thicker polymer layer thickness and higher gas pressure, deposition is improved. On the other side, no clear trend has been noticed when increasing the SoD distance. Therefore, it does not seem to be an obvious relation between surface coverage and SoD influence.

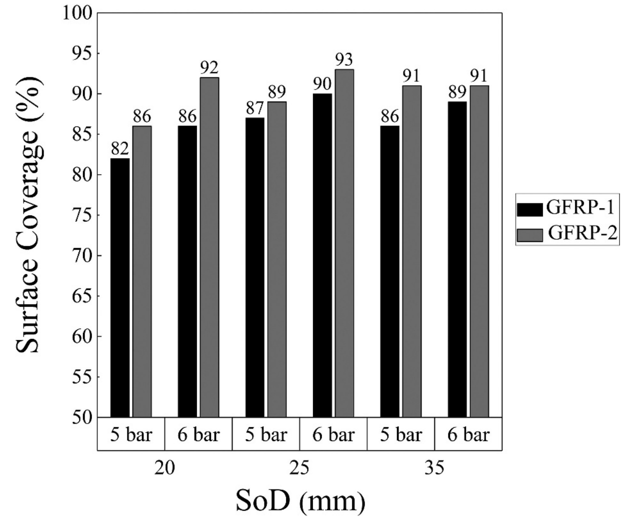

Figure 10. Surface Coverage measurements.

Coating height

To understand the quality of the mechanical anchorage and how it affected the powder embedment, an analysis of the coating height is necessary. Nevertheless, it was noticed that the measurements of the coating height significantly changed from different acquisitions taken before and after the metallographic preparation of the specimen. As reported in Fig. 11, coating height values were compared for both sets of results. What is obvious is that, when considering coating height after the deposition, values are higher while they tend to be reduced after the specimen preparation. The main consideration from these results is that the reduction of the height is characteristic for each sample and no clear trend can be observed when increasing the SoD distance on the gas inlet pressure. This suggests that the coating removal can be attributed to the low anchoring force and the combination of both the process parameters and differences in substrate-particles hardness. Probably, the hardness and stiffness of the substrate were too low to cause deformation or the particle velocity was well below critical velocity. The metallic particles are not able to deform so the bonding is only activated by the polymer deformation. The interface between the coating and the substrate resulted from a polymer flow that surrounded particles that led to mechanical anchoring of these particles into the substrate while their shape remained mostly unchanged. Anyway, besides the lack of particle deformation, the absence of interparticle interaction can play a main role in the coating homogeneity. All these phenomena can be better pictured in Fig. 12 with SEM magnification of the coatings' cross-section. As

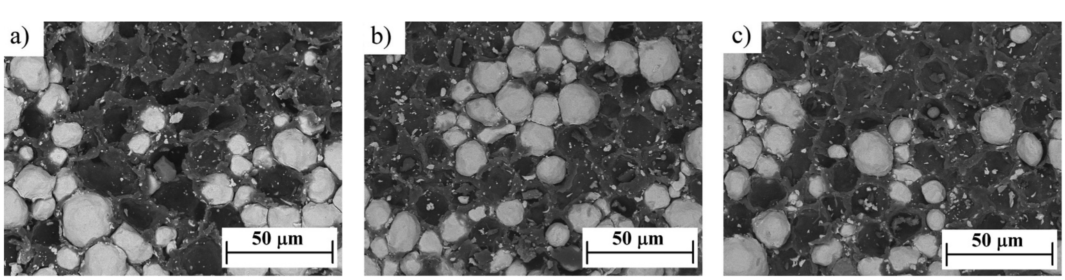

Figure 9. SEM magnification of boundary zones of steel coatings on GFRP-2 at p = .5 MPa and a) S.O. = 20 mm, b) S.O. = 25 mm, c) S.O. = 35 mm.

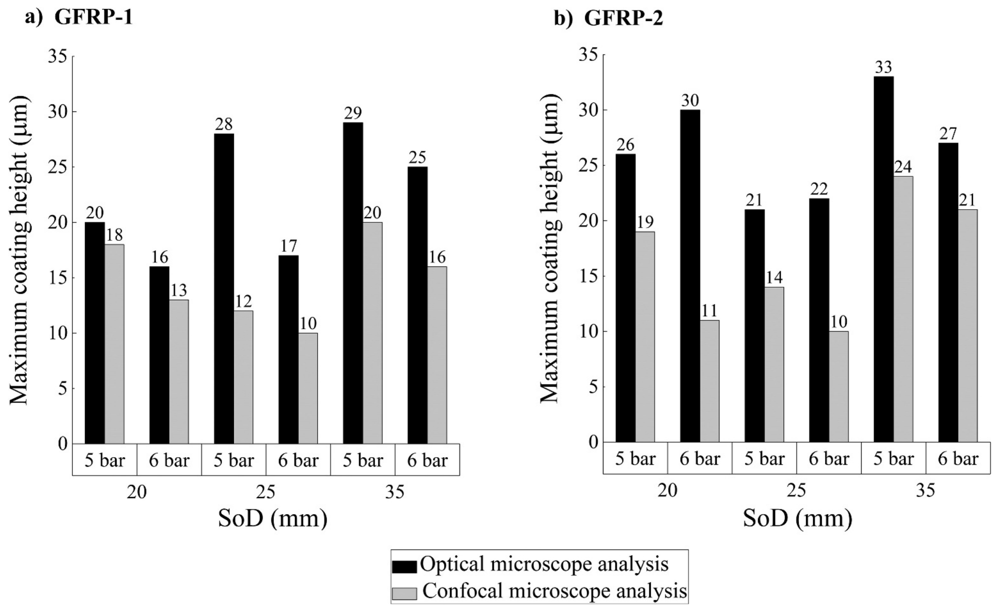

Figure 11. Coating Height measurements.

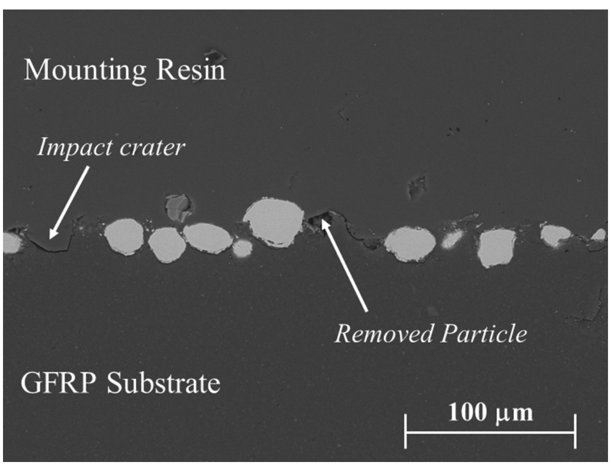

Figure 12. SEM observation of substrate and coating damages.

consequence, different defects are evident: some particles are mechanically removed from the substrate during the cutting phase, as evidenced by the crater, while others are removed during the polishing phase, as evidenced by the voids.

Penetration depth

As already seen in other works, deeper penetration of the particles can be considered as a symptom of good bonding and it is enhanced when the particles are harder or denser than the material of the substrate.[33,35] When particles penetrate the substrate, the deformation of the polymer substrate around them resulted in their capture and the formation of the polymer cavity may prevent particles to fall out and lead to greater mechanical interlocking.[34] Hence, the combination of hard steel 316 L powder on a soft polymer substrate should be considered more auspicious for the deposition.

Penetration depth measurements are graphed against the SoD and pressure in Fig. 13. To understand the combined effect of pressure and SoD, experiments were carried out at 0.5 MPa and 6 MPa inlet pressure. By increasing inlet gas

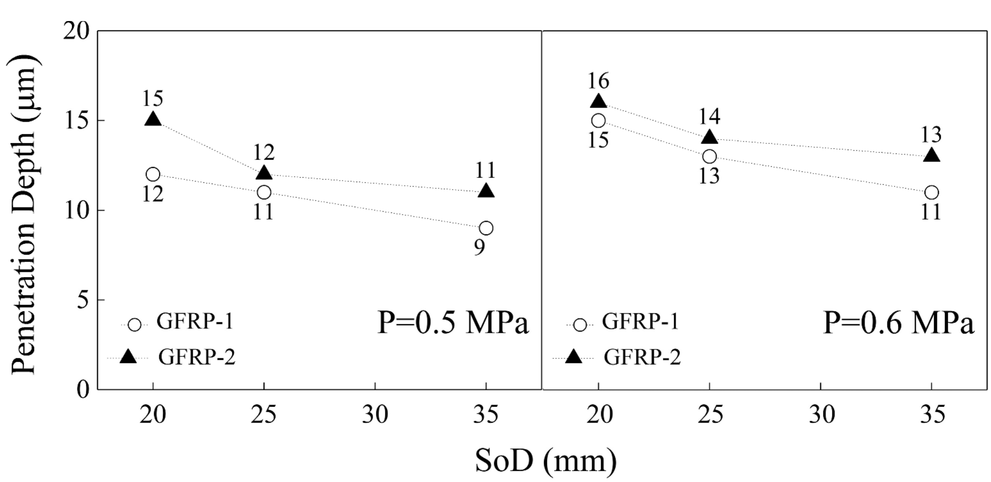

Figure 13. Penetration Depth measurements.

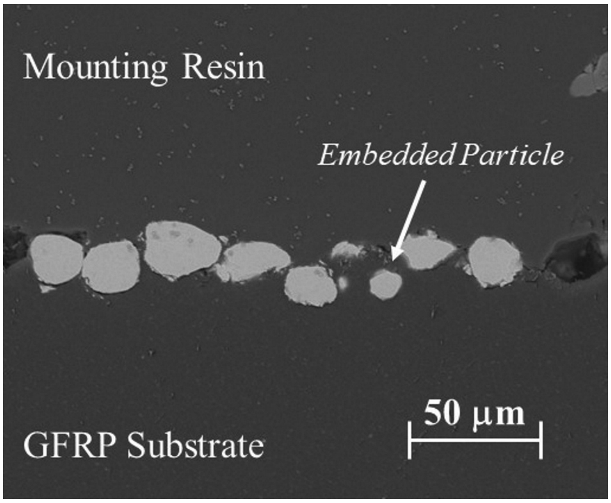

Figure 14. Sem magnification of cross-section of steel coating.

pressure, particle penetration is increased. However, in both cases, increasing standoff distance resulted in a lower embedment.

On the other hand, few differences in the response of the two substrates can be noticed. A similar tendency against SoD and pressure could be observed on both the substrates, except the more pronounced depth of penetration on the GFRP-2 substrate as compared to the GFRP-1 substrate. Although there is a high difference between the properties of PP and the steel 316 L, the particles are not driven deep into the substrate and rather, most of them, remain partially off the surface.

Even if it is demonstrated that bigger particles can reach lower value critical velocity,[38] in the present case it seems that only small particles can embed more into the substrate. As seen in Fig. 14, smaller particles penetrate deeper into the substrate and get anchored, with an evident interaction with the polymer. This embedment is due to a combination of particle size and velocity. Contrarily, for larger particles, the interaction zone around them can barely be observed. Particles did not penetrate the substrate but instead they superficially attached, which implies the already discussed inadequate anchorage.

Discussion

Deposition mechanism

In previous studies, Ganesan et al. found out that, when spraying denser powder with a higher yield stress, the realization of the coating is not easy to attain and, in some cases, an interlayer of softer powders, such as tin, is required,[30] especially when using high-pressure cold spray equipment. Despite these considerations, this work showed that the deposition of steel powder can be achieved utilizing a low-pressure Cold Spray system. Even if no damages of the surface were detected, preliminary observations indicate that steel powders do not sufficiently deform in contact with the polymer surface, leading to a non-homogenous and non-compacted first sprayed layer. This behavior can also be attributed to the spherical shape of the powders; the particles just stuck into the substrate, similar to what was observed by King et al.[34] for copper particles: spherical powder, thanks to their shape, showed deeper penetration but cannot guarantee homogeneous and well-compacted coating, while irregularly shaped particles have more contact points with the substrate and, consequently, higher homogeneity can be reached. Without significant particle deformation, the bonding can only be achieved by the substrate deformation, but it must be to the right amount to limit polymer damage or erosion.

As observed in the “surface coverage” section, the major issue encountered with the deposition of steel powders is that a significant quantity of particles is lost at the boundary zones of the sprayed tracks. This attitude may be chargeable to the particle rebounds, as confirmed by the appreciable presence of the impact craters on the surface. A simple explanation can be detected in the differences in the particles’ profile of velocity. As known, the particle velocity is maximum at the central axis of the nozzle and then it decreased by withdrawing from it.[36] In these external zones, the particle velocity drops well below the critical velocity to cause the deformation[39] and to guarantee deeper powder penetration and an appropriate bonding. In fact, in Kromer et al. work,[27] particle embedment was considered only if the particle penetrated in the polymer deeper than its radius. As already observed from top-view observations, these phenomena are enhanced in the boundary region of the single track but they are also present in the bulk region where a lot of impact craters can be spotted also in the cross-section. A closer look at the impact craters is shown from SEM magnification in Fig. 15. The depth of the crater is not so deep and it is below the particle diameters, which make the particle easier to be removed even if the deformation of the polymer substrate has occurred: the polymer after the impact undergoes deformation and the creation of material jetting is indicated by the arrows in Fig. 15. Indeed, significantly fewer particles remained adhered to, leaving more craters on the sample.

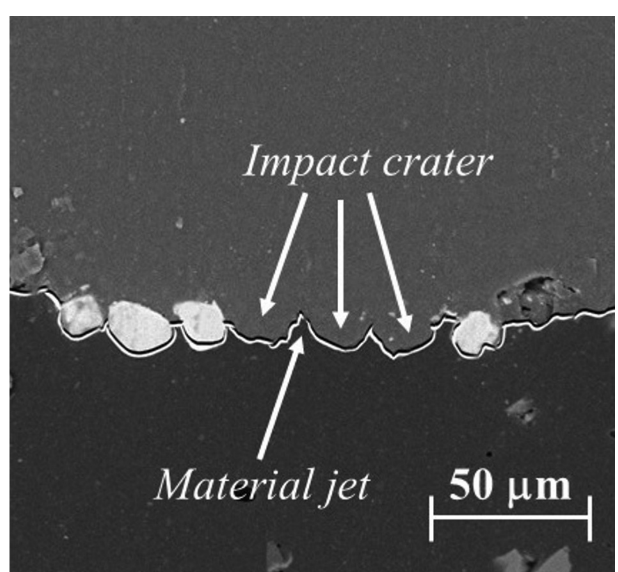

Figure 15. Identification of impact craters on the GFRP substrate.

In all the cases it can be assumed that the powder velocity is not high enough to reach the minimum critical velocity to successfully deposit the metal powders onto the polymer substrate.

Therefore, with the chosen powder size distribution, most of the impacted particles did not have any steady contact with the surface and hence they could peel off. It is also clear that the phenomenon of the impact craters is shown for each panel type, suggesting that the effect of the powder velocity is more prominent than the effect of the substrate properties.

Consequently, deposition has to be considered in terms of powders properties, i.e. powder size. To overcome these issues and to reduce the presence of these craters, it could be useful to use powders with a smaller range of size distribution.

Effect of the laminate stratification

In the *Results* section, it is deduced that different stratification of the composite substrate produced specific results. Even though it was possible to achieve deposition on both panel types, GFRP-2 panels performed better than GFRP-1 in terms of penetration depth and surface coverage. The GFRP-1 has a specific substrate layer thickness value below which the effect of the fiber stiffening is more concentrated. From all the observations, it derives that, with a lower value of the substrate thickness, the particles will be less incorporated by the polymer flow and a higher percentage of voids in the coating is observed. These results are supported by the fact that when the matrix superficial layer is thicker, particles do not suffer from the fibers stiffening effect and the power embedment is facilitated. Similar findings have been exposed by Gillet et al.[22] which stated that, when using two protective PEEK films on the fibers instead of one, the samples exhibited a more homogeneous and well compacted coating-substrate interface. That behavior can be addressed to a higher contribution of the elastic modulus and elastoplastic behavior when spraying on a double PEEK substrate, which is opposite when spraying on a one PEEK layer substrate. Anyway, differently from the above-cited works, these findings demonstrate that, in the case of steel powders, the mechanical properties of the substrate, i.e. stiffness, are not suitable to deform the powders and to give to the coating a certain homogeneity. Although there are differences in the mechanical properties of the two panels, the influence of the fibers is not predominant. In this condition, the interactions between the cold spray process parameters and the properties of the composite should be reconsidered to achieve a good coating.

Effect of the process parameters

The carrier gas influence on the coating formation was analyzed by considering constant SoD and matrix layer thickness. Even if results were quite similar for both pressure conditions, for higher pressure at 0.6 MPa penetration depth of the powder and surface coverage of the substrate are increased.

It is well known that higher particles in-flight velocity are obtained for higher gas inlet pressure.[40] About this, Chen et al.[23] recently reported the effect of both pressure and velocity on the deposition of a single Cu particle on PEEK. It was found that when increasing gas pressure, the copper particles penetrated deeper into the polymer with the enhanced formation of wrinkles and jets. This phenomenon may be attributed to higher kinetic energy which causes both more mechanical penetration and more thermal softening due to kinetic energy dissipation. Such a result was observed also by Giraud et al.[41] who stated that by increasing the carrier gas pressure the particle penetration into the polymer increases with growth in powder velocity: the substrate softens when exposed to higher process gas pressure and higher impact velocity, causing enhanced polymer squeezing effect and, consequently, enhanced powder embedment. The particles are driven deeper into the substrate in contrast to the lower gas pressure.

Regarding the influence of the SoD, it has been observed that this parameter mainly affects the penetration depth of the powder, as already seen in Stenson et al. work.[33] At SoD of 20 mm, the obtained penetration depth resulted to be at the maximum value: the particles could easily embed into the substrate rather than rebounding. When increasing the standoff distance, the penetration depth decrease. This is because the particles' impact velocity tends to rise for lower values of standoff distance.[42] There is a range of SoD where the gas velocity is lower than the particle velocity and both particle velocity and particle impact velocity start to decrease. Consequently, when increasing the SoD distance, the drop in the impact velocity causes less penetration of the metallic powder. Additionally, at SoD of 35 mm, the impact velocity is the lowest, the particles are not embedded into the substrate and rather remain on the surface.

Considering all the results, optimum conditions were determined to be 0.6 MPa for inlet gas pressure and 20 mm for SoD.

Conclusions

Preliminary investigation of cold spray deposition of steel 316 L powders on glass fibers reinforced polymers has been carried out. The findings reported and discussed in the previous section are highlighted in the following conclusions:

- Steel powder was successfully deposited on the GFRP substrates employing a low-pressure Cold Spray technique.
- Visual inspection of the coatings evidenced a uniform distribution of sprayed powders on the surface. However, powder deformation is minimal due to the relatively high density and the high strength of the steel powders.
- Because of the powders' profile velocity in the nozzle, at the boundary zone of the single sprayed track, a significant quantity of particles cannot reach the critical velocity and bond to the substrate. This phenomenon is confirmed by the appreciable presence of the impact craters on the surface.
- It was yielded that the thickness of the superficial matrix layer influenced the embedment of the particles but not affected the deformation of the powder. Cross-section observations highlighted that steel particles did not experience significant particle deformation while

penetrating the polymer and seem to be scarcely sensitive to the spraying parameters.

- It was proved that the standoff distance influences the powder embedment: when the SoD increase, the penetration depth decreases.
- Concerning the inlet pressure of the carrier gas, it was proved that it directly affects both the penetration depth of the particles and, in particular, the increase of inlet gas pressure could facilitate the powder embedment into the polymer surface with consequent reduction of powder deformation.

Further work is still needed to quantify the influence of the matrix layer thickness and the presence of the fiber. Based on the results, the parameter optimization process could be carried out to optimize future studies on the cold spray application onto polymeric substrates, including composites. Also, mechanical characterizations of the coatings, such as adhesion tests, have to be carried out.

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