



Depositing Al-Based Metallic Coatings onto Polymer Substrates by Cold Spray

M. R. Rokni, P. Feng, C. A. Widener, S. R. Nutt*

M.C. Gill Composites Center, Department of Chemical Engineering and Materials Science, University of Southern California, 3651 Watt Way VHE-602, Los Angeles, CA 90089-0241, USA

* E-mail: nutt@usc.edu

Abstract: The feasibility of depositing aluminum onto thermoplastic substrates via cold spray (CS) was investigated. Dense coatings of 7075 Al and CP Al (commercial purity) were achieved on three substrates—polyetheretherketone (PEEK), polyetherimide (PEI), and acrylonitrile butadiene styrene (ABS) using an iterative optimization process. 7075 Al deposition yielded low deposition efficiencies (DEs) and low thicknesses but high adhesive strengths, while CP Al deposition led to high DEs and thicknesses but relatively low adhesive strengths. PEEK andPEI were more suitable substrates for cold spray than ABS, which suffered from surface erosion and substrate distortion. Two key factors were identified that influenced the DE and adhesive strength of the coating. The first factor was the bond layer, the initial few particle layers that fused with the substrate to allow subsequent buildup. The bond layer was influenced by the substrate hardness, yield strength, glass transition temperature, and impact strength, as well as the differences in thermal expansion coefficients of Al and the polymer substrates. The second factor was the CS process parameters selected, as the bond layer and the build-up layers may require different process conditions in order to optimize both bonding strength and coating strength, respectively.

Keywords adhesive strength, cold spray, deposition, behaviors, metallization of polymers, polymer substrate.





1. INTRODUCTION

Polymers are widely used in land and air vehicles because of their low density, ease of forming, and weldability [1]. In the last two decades, the use of polymers to reduce component weight has increased in various industries [1,2]. However, applications for polymers are limited by intrinsically inferior structural properties relative to metals, including low strength and modulus, poor erosion resistance, poor electrical conductivity, susceptibility to UV damage, and low service temperatures [2,3]. Metallization of polymers can be an effective approach to mitigate these shortcomings and broaden their applications. The objective of the present study is to investigate the feasibility of metallizing polymer substrates using a relatively mild process that does not damage or distort the polymer substrate.

Presently, few conventional methods are suitable for the surface metallization of polymers. These include PVD, CVD [4], electroplating [5,6,7], electroforming [8], and thermal spraying techniques [9,10,11], all of which have attendant limitations and drawbacks. For example, both PVD and CVD entail high equipment and processing costs, limitations on workpiece size, and they produce very thin coatings (< 10 μ m). Electroplating results in low adhesive strength, poor microstructural stability, limited coating thickness (< 100 μ m), and environmental hazards/costs. Electroforming has similar thickness limitations, long production cycles, and high molding costs. Finally, thermal spray involves high-temperature gas jets that deposit molten metal particles onto substrates, risking distortion and damage to substrates.

Cold spray (CS) produces uniform metallic deposits by accelerating solid powder particles in a supersonic gas flow to impinge on and deposit onto substrates. Until recently, CS was used primarily to deposit metal onto metallic substrates, primarily for repair of worn or surface-damaged components. Thus, metal-on-metal deposition via CS has been widely studied. However, few studies have been devoted to CS onto polymeric substrates





[3,10,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26]. Substrate erosion reportedly is a key problem with CS onto polymeric substrates, especially with thermoset polymers, which degrade at high temperatures [14,16]. Thermoplastics are of primary interest in this investigation because of printability, formability, and weldability.

In this work, the feasibility of metallizing thermoplastic polymer substrates by highpressure cold spray (HPCS) was investigated. CP Al and 7075 Al were chosen as the feedstock powders because they are compatible with cold spray and have low densities relative to other alloys. Powders were sprayed onto three thermoplastics—a low-cost commodity thermoplastic (ABS), and two high-temperature thermoplastics (PEI and PEEK). The resultant microstructures and mechanical properties (thickness and adhesive strength) were tested and analyzed. Then, the roles of different thermoplastic substrate characteristics and the effects of CS process parameters were evaluated. Also, the effects of the bond layer (initial deposit) on the substrate/coating interaction and on the coating build-up performance (particle/particle bonding) were determined. These observations are discussed to lay a foundation for developing applications to metalize polymers and polymer matrix composites (PMCs) to produce structural components.

2. EXPERIMENTAL METHODS

Polymer Substrates

Three thermoplastics—ABS, PEI, and PEEK—each 6.35 mm thick, were used as substrates. All three substrate materials are compatible with 3D printing. The substrates, physical dimensions, and properties are listed in Table 1. Differential scanning calorimetry (DSC, TA Instruments, DE) was used to determine the glass transition temperature (T_g) using a temperature sweep at a heating rate of 0.5^oC/min for the semicrystalline polymers. All tests





were performed at a heating rate of 10^{0} C/min. No surface preparation was performed prior to cold spraying.

Feedstock Powders

Gas-atomized aluminum powder (99.9% commercial purity Al, Alfa Aesar, Tewksbury, MA, USA) and 7075 Al powder (Ampel Inc, Elk Grove Village, IL, USA) were used as feedstock materials. The Al 7075 Al alloy is widely used for aero-structures and features a high strength/density ratio. CP Al was selected because of its high ductility and low yield strength. Prior to spraying, the powders were sieved with a no. + 270/- 635 wire mesh using a sieve shaker (AS 200 Analytical Sieve Shaker, Retsch GmbH, Germany) and baked in vacuum oven at 100°C to remove moisture and increase powder flowability. As a result, the powder diameters utilized ranged from 20 to 53 μ m.

Cold Spray Deposition

The 7075 and CP Al were deposited using an HPCS system (VRC Gen III, VRC Metal Systems, Rapid City, SD, USA). The pressure and temperature of nitrogen were maintained at 4.1 MPa and 350°C, respectively, at the heater exit. The three substrates were mounted side by side and sprayed at the same time. A simple optimization process was performed by adjusting select CS parameters, including gas pressure, gas temperature, stand-off distance, nozzle velocity, powder feed rate, and gas flow rate (Table 2) in a fixed "recipe" parameter set per condition. The CS samples from each recipe were evaluated quantitatively and qualitatively before adjusting process parameters. Deposition was performed using a nozzle stand-off distance of 75 mm, 90° deposition angle, medium powder feed rate (21.5 g/min), and a nozzle traveling speed of 350 mm s⁻¹. The CS gun consisted of a gas pre-chamber and a convergent–divergent accelerating nozzle. The nozzle has a throat diameter of 1.8 mm and an exit diameter of 7.8 mm. Powder was fed axially into the upstream of the nozzle from the back of the gun,





and then, the accelerating gas was introduced into the pre-chamber. Nitrogen was used as the process and powder carrier gas. Mass flow meters were deployed in both the gas control unit and the powder feeding unit to stabilize the spraying process. The gas heating unit consisted of three 15 kW high-power heaters in parallel, which are spiral-wound filament element types that can reach up to 800°C in the heater. Temperature measurements for the deposition were made at the nozzle body in the pre-chamber prior to mixing with the powder feed gas. Pressure measurements were taken within the CS system cabinet on the main gas side, before entering the heater. The CS control system was set to control both gas temperature and pressure, and also stabilized the powder gas flow and powder feeder in order to maintain consistent powder flow and particle velocities at the spray gun.

Microstructure Characterization

Feedstock powders and deposits were sectioned, mounted, and prepared by a combination of light grinding with increasingly fine SiC papers up to 1200 grit, followed by brief polishing (max. 3 min) on a felt pad down to a 0.5- μ m diamond suspension. The samples were also periodically examined under the microscope during the polishing procedure for signs of particle pullout. For more in-depth microstructure characterization through SEM imaging,

	Table 1.	Substrate	and powde	r material	properties
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Material	Hardness,	Yield strength,	T _g ,	CTE, μ strain/ ⁰ C	Impact strength,
	Vickers [27]	MPa [27]	⁰ C	[27]	J/m [25]
PEEK	26-29	87-95	143	50-60	80-85
PEI	22-24	73.5-81.1	217	84.6-101	50-60
ABS	6-12	18.5-40.7	105	171-198	144
7075 Al	31-35	100-110		22.9-24.1	
CP Al	14-16	24-26		22.9-24.1	





T_g, glass transition temperature, CTE, coefficient of thermal expansion

Impact strength was summarized from prior work, which was measured according to Izod Impact Testing (Notched) ASTM D256 standards

Table 2. Cold spray recipe development process for depositing Al onto the polymer substrates

Parameter	Recipe	Recipe	Recipe	Recipe	Recipe	Final	CP Al/CP	7075
	1	2	3	4	5	Recipe	Al [28]	Al/7075
								Al [29]
Gas pressure	3.1	3.5	3.5	3.5	4.1	4.1	4.8	4.8
(MPa)								
Gas	225	225	275	275	325	350	350	450
temperature								
(⁰ C)								
Stand-off	102	102	75	75	75	75	25	25
distance (mm)								
Carrier gas	N ₂	Не						
Spray angle	90	90	90	90	90	90	90	90
(⁰)								
Nozzle	200	300	300	350	350	350	500	700
velocity								
(mm/s)								
Powder feed	14.3	17.9	21.5	21.5	21.5	21.5	21.5	17.9
rate (g/min)								
Gas flow rate	771	856	822	872	962	947	1035	1071
(L/min)								





Polybenzimidazole (PBI) was the nozzle material for all recipes

select samples were also ion-polished (JEOL SM-09010, Tokyo, Japan). To measure porosity, the SEM images were analyzed using ImageJ.

Mechanical Properties Evaluation

Adhesive Strength

Adhesive strength was measured using a portable testing instrument (PosiTest ATA, DeFelsko, Ogdensburg, NY, USA) as per ASTM D4541 [30]. A 10-mm diameter Al pull-stub was bonded to the top surface of the CS deposit. Any excess adhesive or coating surrounding the pull-stub was removed with a boring drill bit. Upon activation, the device pulled the pull-stub at a rate between ~ 0.7 and 1 MPa per second until separation of the sample or adhesive failure.

Nanoindentation

Nanoindentation tests were conducted in the load control mode with a maximum load of 5 mN while using a Berkovich indenter. A line of 14 indents with 10- μ m spacing was made starting from the coating and into the substrate, and the Oliver and Pharr method [31] was used to determine the hardness and the modulus. While the elastic modulus data were measured by this method, there was no significant variation in the elastic modulus throughout the deposited coating. Thus, these data have been omitted.

Substrate Distortion

Distortion (d), which occurred only in ABS substrates during cold spraying, was evaluated by measuring the distance (d) between the highest point and the lowest point (as shown in Figure 1) of the distorted samples and then subtracting the thickness of the deposit (d_{CS}) and the sample prior to cold spraying (d_0). Distortion was calculated as $d = d - d_{CS} - d_0$. The deposit thickness was obtained by taking the average of 20 measurements of the sample cross section under a microscope (Keyence VHX-5000, Osaka, Japan).





3. RESULT AND DISCUSSION

Feedstock Powder

Figure 2 shows the nearly spherical morphologies of the CP Al and 7075 Al with some smaller satellite particles (less than 5 μ m in size) attached to the surfaces of the larger particles. Figure



Figure 1. Distortion $d = d - d_{CS} - d_0$ (where d_0 is the substrate thickness)



Figure 2. SEM micrographs of the feedstock 7075 and CP Al powders

2(b) and (e) shows a typical spherical powder particle of ~30 μ m from the two batches, with ~1-4 μ m nodular grain structure. However, the CP Al powder batch also contained some





elongated or irregular shaped particles. Details of the internal and surface microstructures of the CS powder particles have been reported elsewhere [12,32,33].

Coating Quality

HPCS yielded 7075 Al and CP Al deposits that were free of visible defects or pores and showed complete and uniform surface coverage. Figure 3 shows typical images of the 7075 and CP Al deposits on the thermoplastics, revealing low porosity (0.54% and 0.70% for 7075 and CP Al, respectively). However, Figure 4 shows that upon the first pass of deposition using the final recipe in Table 2, the PEI substrate developed cracks extending from the substrate surface (note the relatively low impact strength in Table 1). Figure 4(a) is shown to represent the declining deposit thickness near the sample edge, which is common for all samples. Aside from PEI cracking, obtaining continuous deposits with insignificant porosity demonstrates the suitability of the particular HPCS recipe for deposition onto the polymer substrates used in this study.

The approach to develop the final recipe is depicted in Table 2. The initial recipe (R1) did not work well for these depositions, yielding no deposition on the PEEK substrate. Key CS parameters, e.g., gas pressure and temperature, stand-off distance, nozzle velocity, powder feed rate, and gas flow rate, were then adjusted iteratively, based on evaluations of resulting deposits, to determine a more suitable recipe for depositing 7075 Al on PEEK. Ultimately, lower-pressure and lower-temperature parameters were ineffective, although desirable to protect the polymeric substrates. Thus, high-pressure and high-temperature parameters were utilized, but with a greater stand-off distance than would normally be used with a metallic







Figure 3. Typical cross sections of (a) 7075 Al and (b) CP Al coatings on PEEK substrates



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Figure 4. Cross sections of 7075 Al deposited onto (a) PEEK (black lines are scratches), (b) PEI (cracked), and (c) ABS substrates. The red lines indicate software coating thickness measurements substrate. The final CS recipe shown in Table 2 was then used for all ensuing deposition combinations.

Deposit Thickness

Figure 5 shows deposit thicknesses for 7075 and CP Al coatings on different substrates. Figure 5(a) shows that the 7075 Al deposits on PEEK reached a few hundred microns in thickness but did not increase substantially, while deposits on PEI remained the same with an increasing number of passes. The low thicknesses were attributed to the low DEs, which was calculated to be 32% and 19% for the 7075 Al on PEEK and PEI substrates. Because the process protocol yielded only modest thicknesses with 7075 Al, experiments were next performed with CP Al powder, a much softer alloy than 7075 Al, using the same CS parameters. Figure 5(b) shows that CP Al deposits on PEEK and PEI substrates yielded substantially greater thicknesses that increased with the number of passes. The DE was 74% for CP Al/PEEK and 49% for CP Al/PEI (versus 32% for 7075 Al/PEEK and 19% for 7075 Al/PEEK).

The behavior described above was attributed to a combination of the CS recipe and differences in substrate hardness. Table 2 shows that the CS parameters for 7075 Al/7075 Al deposition differed substantially from those in the final recipe used here, whereas the final CS recipe and CP Al/CP Al recipe were similar. The differences in process parameters imply that the harder 7075 Al particles erode the substrates, particularly during deposition of initial layer(s), and even when a base layer is deposited, impinging particles do not create build-up layers efficiently due to insufficient deformation upon impact. When depositing with CP Al, the particles erode the softer ABS but not the harder PEEK and PEI, and CP Al provided a





base layer on PEEK and PEI for subsequent buildup. Subsequently, the similarity between the final CS recipe and CP AI/CP AI recipe led to sufficient particle deformation upon impact, which resulted in the much thicker coatings. These findings indicate that a separate CS recipe may be required to build the initial layer(s), i.e., a "bond layer," according to the hardness difference between the particle and the substrate. Subsequently, modification of CS parameters for higher impact velocity/deformation may facilitate the "build" layers.

Furthermore, comparing Fig. 5(a) and (b), CP Al/ABS deposition yielded thicknesses similar to those of 7075 Al/ABS combinations, yet CP Al powder was expected to yield thicker deposits. Due to the low hardness and yield strength of ABS (relative to PEI and PEEK), particles penetrate deep into the substrate during the deposition process, which causes polymer



Figure 5. Coating thickness of (a) 7075 Al with 1, 3, and 5 passes, and (b) CP Al with 2, 4, and 6 passes material to dislodge between particles (see Figure 6). Also, the lower T_g of ABS could be a secondary factor causing erosion of ABS substrates and impeding formation of a bond layer to support the buildup of particles. As a result, the CP Al powder deposition did not yield deposits thicker than those of 7075 Al powder on ABS substrates.

Substrate Distortion

Figure 7 shows the ABS and PEEK samples after CS deposition of 7075 Al. ABS samples exhibit both concave and convex distortion caused by deposits, but PEEK and PEI







Figure 6. Cross-sectional image of CP Al deposited on ABS with 4 Passes

combinations do not. Similar results were observed after depositing with CP Al. This observation is attributed to the greater mismatch in CTE (coefficient of thermal expansion) and substantially lower T_g of the substrate in the Al/ABS pair compared to those of Al/PEI and Al/PEEK (Table 1). These two factors result in greater compressive and tensile stress (and strain) at different areas of the sample caused by uneven heating/cooling during cold spray. However, due to the lower CTE mismatch, higher substrate T_g, hardness, and yield strength in PEEK and PEI substrates, this behavior was not observed with these substrates. The measured distortions were d = 3.9 and 4.6 mm for 7075 Al/ABS combinations after 3 and 5 passes. The small difference in distortion between 3 and 5 passes indicates that the heat transferred to the substrate does not have a marked effect beyond 3 passes, primarily because a thin metal film is deposited on the substrate. As for CP Al/ABS combinations, $\delta = 3.2$ and 4.8 mm substrate Please cite this article as: Rokni, M.R., Feng, P., Widener, C.A. *et al.* "Depositing Al-Based Metallic Coatings onto Polymer Substrates by Cold Spray". *J Therm Spray Tech* 28, 1699–1708 (2019). https://doi.org/10.1007/s11666-019-00911-y





distortions were measured for 4 and 6 passes (Table 3). The distortion for the CP Al/ABS sample after 6 passes was relatively large, so the recipe was adjusted for this combination. As shown in Table 3, gas temperature and pressure are the main CS parameters that facilitate (a) particle/particle and particle/substrate bonding, and (b) thicker coatings with less distortion. These results indicate that CS deposition of metals onto polymer substrates requires judicious selection and control of CS parameters to achieve acceptable DE's and to avoid distortion of the structure.

Adhesive Properties of Coatings

Adhesion tests were conducted on Al/polymer substrate samples using flatwise tensile loading. Figure 8 shows typical SEM images of the fracture surfaces in the coating of cold-sprayed samples. The images show that inter-particle failure is the primary fracture mode in the coating. The fracture mode also indicates adequate particle to particle bonding and sufficient particle deformation within the coating, factors that result from appropriate choices of CS process parameters.

Figure 9 shows cross-sectional images of the deposit/substrate interface after adhesion tests. Failure occurred at the deposit/substrate interface (i.e., adhesive) for all samples, as no



Figure 7. Side view of 7075 Al deposit on top of ABS (distorted), and PEEK substrates after 1, 3, and 5 CS passes





	Recipe change	Thickness, μ m	Distortion, mm
First trial—2 passes	No change	45	0
First trial—4 passes	No change	130	3.2
First trial—6 passes	No change	100	4.8
Second trial—6 passes	Same recipe, 2nd	100	2.3
	attempt		
Third trial—6 passes	Temperature (⁰ C): 350	200	1.7
	$\rightarrow 250$		
Fourth trial—6 passes	Pressure (MPa): $4.1 \rightarrow$	50	Not measured
	3.8		

Table 3. Process of developing a CS recipe to minimize CP Al/ABS structure distortion



Fig. 8 Fracture surfaces of CS deposits (a) 5 passes of 7075 Al/PEEK and (b) 6 passes of CP Al/PEEK trace of the metal deposit was visible on the fracture surface. In certain areas of both 7075 Al and CP Al samples, metallic residue was observed at the interface where particles had penetrated deeply into the substrate. However, these particles were not directly connected to the rest of the deposit and thus were not considered part of the deposit. We attribute this fracture behavior to the process parameters selected, which resulted in deposits with strong particle–particle bonding.

The results of adhesive strength testing for different 7075 and CP Al/polymer combinations are presented in Figure 10. Comparing Figure 10(a) and (b), CP Al deposits showed generally lower adhesion properties than 7075 Al deposits. These values are in the same range reported previously for metallic coatings/polymeric substrates [12,14,16], but not as high as those reported here for 7075 Al/polymeric substrates (> 20 MPa). The difference





noted for CP and 7075 Al is attributed to two factors: (1) the hardness differences between the Al powder particles and the polymer substrates, and (2) residual stresses in the deposits. Although the recipe for CP Al deposits more closely resembles the typical CP Al recipe, the relatively soft CP Al particles do not penetrate the polymeric substrates as deeply as the harder 7075 Al particles. Additionally, the much greater thicknesses of CP Al deposits lead to greater residual stress at the interface than the thinner 7075 Al coatings [34]. These two factors contribute to the relatively low adhesion properties for CP Al/polymer combinations.

Figure 10(a) shows that with 7075 Al deposits, PEEK and PEI substrates yield much greater adhesive strength values than the ABS substrate. The greater CTE mismatch (stress/strain at deposit/substrate interface) between Al and ABS, as well as the lower yield strength and T_g of ABS (substrate surface damage), caused these combinations to yield the





Figure 9. Typical cross sections of (a) PEEK, (b) PEI, (c) ABS samples after adhesion test

Figure 10. Adhesive strength of (a) 7075 Al, and (b) CP Al cold-sprayed samples

lowest adhesive strengths. The adhesive strength values in PEEK and PEI samples were more

than two times greater than in ABS samples, although bond strengths were similar regardless





of the number of passes. These results indicate that 7075 Al adheres more strongly to PEEK and PEI than ABS.

The results reported here show that judicious selection of CS process parameters can lead to adhesive strength values nearly 4X greater than the highest values previously reported (~ 27 versus ~ 7.6 MPa, measured in tension) [24]. On the other hand, these values are much less than bond strengths reported for cold-sprayed aluminum alloys (typically 40-85 MPa) [12,33,35,36]. The lower bond strength values achieved here are attributed primarily to less plastic deformation of the particles, weaker mechanical interlocking with the deformed polymer substrate (compared to metal/metal depositions), and metal jetting (outward viscous flow of metal) at the softer polymer–substrate interface (see Figure 6). The lower bond strengths also indicate that conventionally accepted mechanisms occurring at metal/metal particle/substrate interfaces during HPCS [33,37] may not be duplicated in metal/polymer CS.

Among the three thermoplastics, PEEK substrates yielded superior results for the CS process. The resultant deposits were defect-free and exhibited great DE and adhesion properties. PEI also achieved relatively high thicknesses and adhesive strength levels, but PEI substrates cracked (Figure 4), which correlated with its relatively low impact strength (Table 1). ABS may require a much different process route due to the lower values of hardness and yield strength, and the large CTE mismatch with Al. HPCS on ABS resulted in distortion, and low thicknesses and adhesion properties. Modification of the CS recipe according to the above-mentioned material properties and in situ processing of the substrate may be required to optimize CS deposition of metals onto polymers.

Hardness of Deposits

Figure 11 shows the subsurface hardness distribution across the PEEK substrate and into the CS deposit (7075 Al). The hardness was measured by indenting the sample every 10 μ m in the transverse direction. The graph can be divided into three distinct regions (i.e., Regions I, II, Please cite this article as: Rokni, M.R., Feng, P., Widener, C.A. *et al.* "Depositing Al-Based Metallic Coatings onto Polymer Substrates by Cold Spray". *J Therm Spray Tech* 28, 1699–1708 (2019). https://doi.org/10.1007/s11666-019-00911-y





and III). Region I showed the lowest hardness values for the polymer substrate, as expected. Region II was the region where the first layer of particles deposited on the substrate (bond layer). The measured hardness in this region was 1.26 ± 0.18 GPa, approximately the hardness of 7075 Al powder [32,33]. This hardness is indicative of a low degree of plastic deformation



Fig. 11 Nanohardness traverse measurements across the deposit and the polymer substrate (work hardening) in this region, and indicates the absence of peening [38,39,40], as well as a cushioning effect of the relatively compliant polymer substrate.

The metal layers subsequently deposited are represented by Region III, which showed higher hardness values (1.5-1.8 GPa). The increased hardness in Region III is attributed to more particle deformation resulting from metal/metal particle interactions in the build-up layers of the deposit. The variations in hardness values in Region III can be attributed to the difference in the hardness of particle interiors versus particle/particle interface regions. Previous studies have demonstrated that particle interfaces experience more extensive plastic deformation during cold spray, and as a result, they contain fine and/or pancake grain structures [32,33,38,39]. However, particle interiors undergo less plastic deformation and exhibit larger grain sizes, resulting in lower hardness values.





4. CONCLUSIONS

Dense Al deposits (up to 3.1 mm thick) were produced on thermoplastic substrates by HPCS in just a few passes. Adhesive strengths up to 26.9 MPa were achieved, demonstrating the feasibility of rapidly metallizing polymers under relatively mild process conditions. The deposition efficiency and adhesive strength were governed primarily by two factors: bond layer microstructure and CS process parameters. The suitability of the bond layer was assessed by the amount of substrate damage and substrate distortion, which depended largely on the CTE mismatch, T_g, substrate hardness, yield strength, and impact strength. In practice, an appropriate CS process must achieve both (a) sufficient particle–substrate bonding for suitable bond layer formation and/or (b) extensive particle–particle bonding for acceptable build rates. These two factors can be used to guide future studies that seek to further optimize cold spray onto polymeric substrates, including composites. Optimization may require different CS recipes in sequence—one for the bond layer and a different one for the build-up layers.

The findings reported here have broad implications, demonstrating a pathway to coupling the exceptional formability and low density of thermoplastic polymers with the superior durability of metallic alloys. Ironically, both materials are compatible with additive manufacturing process routes, including 3D printing of polymers and CS of metals. For many engineering applications, polymers alone cannot satisfy all design and service requirements. Therefore, hybrid processes that combine the desired properties from different materials may present a possible solution and indeed are becoming increasingly popular. For instance, 3D printed polymer forms can be rapidly produced and subsequently metallized to impart metallike durability, including enhanced resistance to erosion, wear, and moisture. Thus, by combining 3D printing and cold spray deposition, 3D sandwich forms (polymer cores strengthened by hard shells) for structural usage can be rapidly produced. With additional





development, this hybrid process route could provide a method for rapid replacement of damaged parts and light-weighting of metallic components, resulting in competitive advantages.

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