

Advanced Diamond-reinforced Metal Matrix Composites via Cold Spray: Properties and Deposition mechanism

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Abstract: Diamond-reinforced metal matrix composites (DMMC) have great potential for wear-resistance applications due to the superior hardness of the diamond component. Cold spray as an emerging coating technique is able to fabricate coatings or bulk materials without exceeding the material melting point, thereby significantly lowering the risk of oxidation, phase transformation, and excessive thermal residual stress. In this paper, thick DMMC coatings were deposited onto aluminum alloy substrate via cold spray of **three feedstock powders: copper-clad diamond and pure copper, and their mixtures**. It was found that, due to its low processing temperature, cold spray is able to prevent graphitization of the diamond in the DMMC coatings. Further to that, the original diamond phase was almost completely retained in the DMMC coatings. In case of the coatings fabricated from copper-clad diamond powders only, its mass fraction reached 43 wt.%, i.e. value higher than in any previous studies using conventional pre-mixed powders. Furthermore, it was found that the added copper content powders acted as a buffer, effectively preventing the fracture of the diamond particles in the coating. Finally, the wear test on the coatings showed that the cold sprayed DMMC coatings had excellent wear-resistance properties due to the diamond reinforcement.

Keywords: Kinetic spray, microstructure, tribology, finite element analysis, modeling

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25 **1. Introduction**

26 Diamond is known to possess extremely high hardness, allowing it to be used as an excellent
27 wear-resistance material. However, for the same reason, it is difficult to be machined, which in turn limits its
28 direct applications. To overcome the limitations, diamond is normally applied in a form of thin,
29 wear-resistant coatings. Chemical vapor deposition (CVD) technique can be used to produce such films.
30 However, CVD films are restricted in terms of thickness, frequently suffer from low toughness, and tend to
31 crack or peel off completely from the substrate due to the large thermal and residual stress generated during
32 their solidification [1,2].

33 Diamond-reinforced metal matrix composites (DMMC) are novel materials in which the metallic phase
34 acts as a binder (yielding the DMMC deformable and machinable), while the reinforcement diamond phase
35 helps to improve the material properties. Currently, the common ways to fabricate bulk DMMC are powder
36 metallurgy [3–7] and pressure infiltration techniques [8–12]. These methods mostly require extremely high
37 processing temperatures to melt the metal binder, thereby significantly increasing the risk of the metal phase
38 transformation and diamond graphitization, which, in turn, may potentially yield inferior material
39 performance [5]. In terms of DMMC thin films for wear-resistance applications, various thermal spray
40 techniques such as oxy-acetylene thermal spray [13–15], HVOF [15], supersonic laser deposition [16,17],
41 and laser cladding [17] were applied. Analogous to the powder metallurgy and pressure infiltration
42 techniques for producing bulk DMMC, these thermal spray techniques also require high working
43 temperatures and the films/coatings therefore potentially face identical problems (in particular,
44 graphitization of the diamond content [17]). Higher diamond contents in the coatings is known to improve
45 the coating wear-resistance by reducing the wear rate [13]. However, in the thermally sprayed coatings, the
46 diamond content is usually much lower than the binder phase content. Combined, these disadvantages

47 significantly lower the wear-resistance properties of the thermally sprayed DMMC coatings. Therefore, it is
48 rather meaningful to develop a novel fabricating method of DMMC coatings that would avoid the risk of
49 diamond phase graphitization and simultaneously retain high diamond contents.

50 Cold spray as an emerging coating technique is capable to deposit metals, MMC [18–20] and even
51 ceramics [21,22], thereby attracting great interests over the last decades [23]. In this process, feedstock
52 materials in the form of micron-sized powders are accelerated by a supersonic gas passing through Laval
53 nozzle, and subsequently impact onto a substrate to form the coating [24–27]. During the deposition process,
54 the feedstock remains solid state without any melting; the coating is formed through a metallurgical or
55 mechanical bonding at the interface of adjacent particles and coating/substrate. Thereby, difficulties and
56 defects such as oxidation, detrimental thermal residual stress development, and phase transformations which
57 commonly appear in powder metallurgy, pressure infiltration, or thermal spray processes can be
58 considerably avoided [28]. Furthermore, the coatings in cold spray can be deposited onto various substrates
59 (such as metals, polymers, ceramics) and the respective thickness growth is almost unlimited for most
60 metals and MMC, allowing cold spray to act as an additive manufacturing technique for producing bulk
61 materials [29,30].

62 To date, very few attempts of cold spraying of DMMC coatings for improving the hardness and Young's
63 modulus have been carried out [31,32]. The state of the art suggests that the limitation for fabricating
64 DMMC (also applicable for other MMC) via cold spray is the feedstock powders. Typically, either
65 mechanically pre-mixed or ball milled feedstock is used. However, using the pre-mixed powders frequently
66 leads to a reduction of the diamond phase content in the coating as compared to the original feedstock due to
67 the its low deposition efficiency, while the ball-milling procedure in turn results in a serious fracture of the
68 diamond phase or its graphitization [31,32]. Aside from reducing the cost efficiency of the process through

69 the loss of diamond powder in such case, the coating performance is significantly lowered, too [16,17,33].

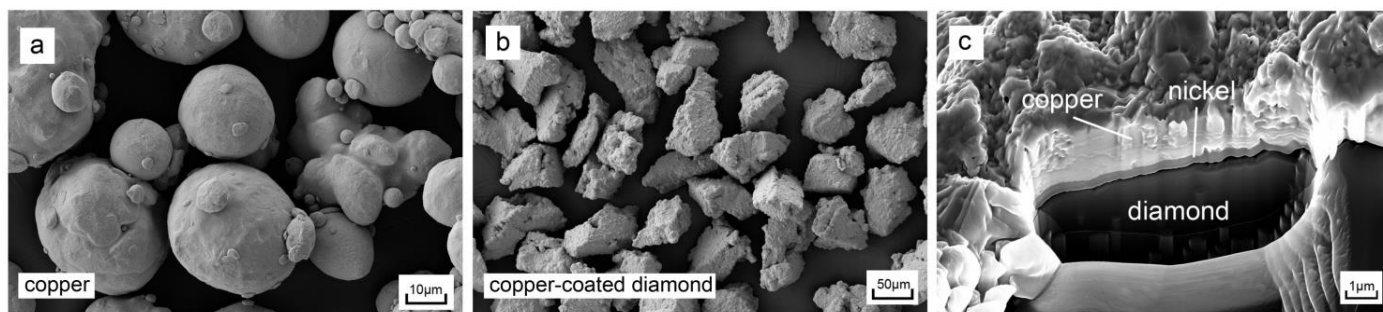
70 In this paper, DMMC coatings were fabricated via cold spray technique. In order to avoid the
71 disadvantages and problems associated with using the conventional pre-mixed or ball-milled feedstock, a
72 novel copper-clad diamond powder (and its mixture with copper powder) was used as the feedstock to
73 fabricate the coatings instead. In the previous work, this copper-clad diamond powder has been proven to
74 significantly increase the diamond contents in the coating [34]. As the base material, copper was selected
75 due to its ease of deposition and high deposition efficiency, allowing it to be an excellent binder in the MMC
76 coatings. Wear test of the fabricated DMMC coatings was further carried out to investigate the coating
77 wear-resistance capability. With copper not being a typical wear-resistance metal, the results better reflect
78 the role of the diamond reinforcement. In the future work, using typical wear-resistance metals such as
79 cobalt and nickel is planned.

80 **2. Experimental methodology**

81 **2.1. Coating fabrication**

82 Pure copper (-38+15 μm , > 99.9%, Safina, Czech Republic) and copper-clad diamond (-53+45 μm , PDA
83 C50, Element-Six, Ireland) powders and their respective mixtures were used as the feedstock. Fig. 1a-b
84 shows the morphology of both powders observed by SEM (Carl Zeiss ULTRA, Germany). The copper-clad
85 diamond powder particles typically consist of three different layers: a diamond core enclosed in a thin nickel
86 inter-layer and an outside electroless copper cladding, as can be seen from the powder cross-section shown
87 in Fig. 1c (FIB, DB235, FEI Strata, USA). The nickel inter-layer is used due to its superior bonding with
88 diamond as compared to copper. According to the supplier, the weight ratio of the diamond phase to both
89 metals in a single particle is approximately 1:1, and thus the diamond core diameter was calculated as
90 roughly between 40 and 47 μm .

91 The annotation of the produced coatings as well as the respective feedstock information and cold spray
 92 deposition conditions are provided in Table 1. The benchmark coating denoted as ‘P0’ was fabricated from
 93 pure copper powder only, i.e., no copper-clad diamond phase was present. The coatings were deposited onto
 94 common aluminum alloy substrates using an in-house cold spray system (Trinity College Dublin, Ireland).
 95 The system consists of high pressure nitrogen/helium gas from cylinders, gas heater, powder feeder, CNC
 96 working platform for controlling the substrate movement, Laval nozzle and a computer control system. In
 97 this work, nitrogen was used to produce P0 coating under previously optimized parameters, while helium
 98 was applied to produce the DMMC coatings. Each coating was fabricated with two gun passes at a robot
 99 arm traversal speed of 15 mm/s. A schematic of the cold spray coating fabrication process is shown in Fig. 2.



101 **Fig. 1** Morphology of the (a) copper and (b) copper-clad diamond powders used in this study. (c) cross-section of typical
 102 copper-clad diamond particle.

103 **Table 1** Annotation of the produced coatings, the respective feedstock composition and cold spray deposition conditions.

| Coating | Feedstock powders | Gas | Pressure | Temperature | Gun speed | Standoff |
|---------|--|----------------|----------|-------------|-----------|---------------|
| | | | [MPa] | [°C] | [mm/s] | distance [mm] |
| P0 | Copper | N ₂ | 3.0 | 350 | 15 | 45 |
| P1 | Copper + copper-clad diamond (8:1 by weight) | He | 2.0 | 25 | 15 | 45 |
| P2 | Copper + Copper-clad diamond (1:1 by weight) | He | 2.0 | 25 | 15 | 45 |
| P3 | Copper clad diamond | He | 2.0 | 25 | 15 | 45 |

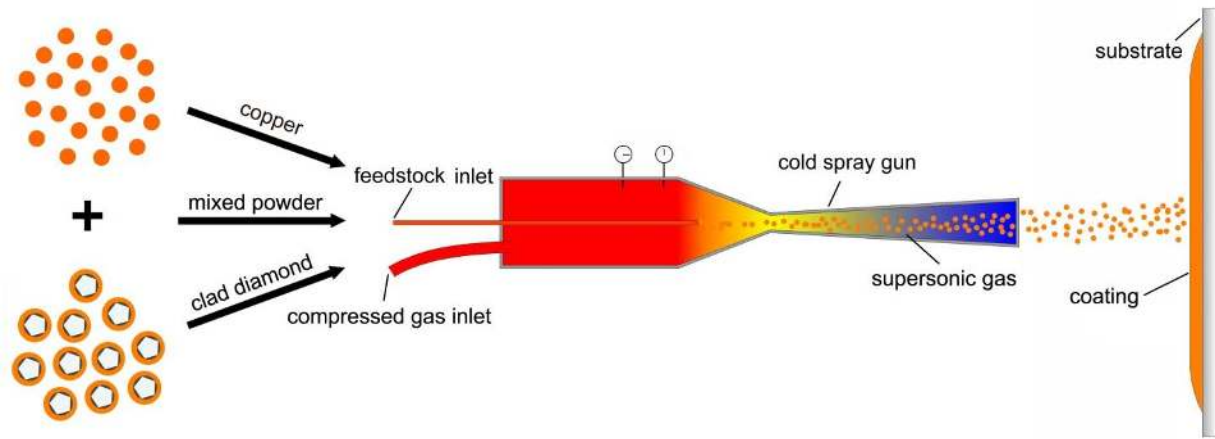


Fig. 2 Schematic of the DMMC coating fabrication via cold spray.

2.2. Materials characterization

To examine the phase content and the prospective graphitization of the diamond during the coating fabrication process, the as-sprayed coatings were examined by an X-Ray diffractometer (Siemens D500, Germany) with the Co ($\lambda=1.789 \text{ \AA}$) source at a current of 40 mA, voltage of 35 kV and scan step of 0.02° . To assess the coating microstructure via SEM, the as-sprayed coating samples were prepared using standard metallographic procedures with the final polishing applied by 0.05 \mu m Al_2O_3 solution. Fracture surface was also obtained by breaking the as-sprayed samples and the observed by SEM. The element analysis (primarily, the mass fractions of Cu and Ni) on the coating surfaces and polished cross-sections was performed with an EDS unit (Oxford Instruments INCA system, UK) equipping on the SEM system. Given its inaccuracy in measuring low molecular weight elements, the mass fraction of diamond was then calculated based on the results of copper and nickel. For each sample, five locations were randomly selected from the coating surface or polished cross-section and the measured data was then averaged.

2.3. Wear test

The wear properties were measured using POD-2 pin-on-disc system (Teer Coatings Ltd., UK) at room

121 temperature. For accurate measurement of the wear rates, the sample surfaces were polished using Al₂O₃
122 solution to 1 μm roughness prior to the test and the samples were then mounted on a carrier disc. A tungsten
123 carbide ball with a diameter of 5 mm was used as a counterpart under a constant load of 4 N. The disk
124 rotated at a linear speed of 10 mm/s for 15000 revolutions. To determine the coating and pin ball wear rates,
125 the material volume loss was calculated according to ASTM G 99 standard [26]. The amount of wear was
126 determined by weighing the specimens before and after the test. The respective wear rate was then
127 calculated as the volume loss per unit load and per traverse distance.

128 It was reported that the mean free path between reinforcement particles is an important parameter
129 affecting the coating wear-resistance property [25,35,36]. The mean free path was calculated by drawing a
130 total of 10 random lines on multiple coating cross-sectional images and counting the number of intersects
131 with diamond particles. Then, the mean free path could be calculated according to the following equation:

$$\lambda = \frac{1 - V_p}{N_L} \quad (1)$$

133 where N_L is the number of diamond particle intercepts per unit length of test line and V_p is the volume
134 fraction of the reinforcing particles.

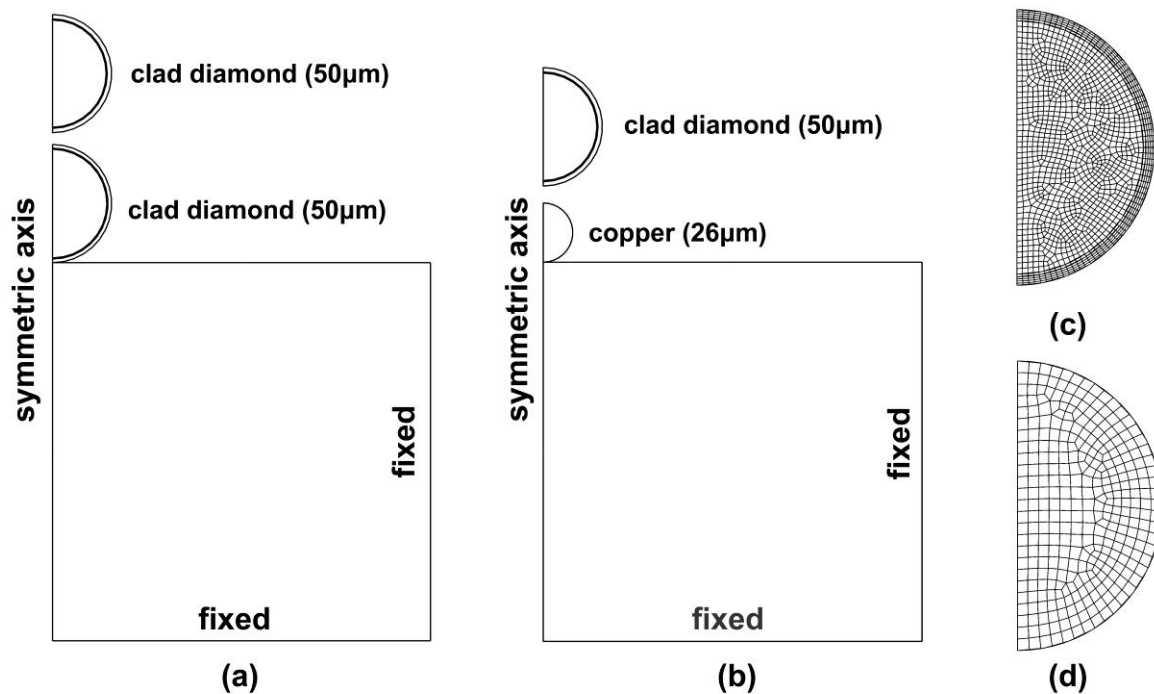
135 **3. Numerical methodology**

136 In order to study the powder particles deposition behavior during the coating formation process, finite
137 element analysis (FEA) of the inter-particle impact was carried out using ABAQUS. The impact process was
138 simplified as two particles successively depositing on the substrate in the same line. The contact pressure
139 between the two particles was then calculated and compared with the diamond fracture stress to evaluate the
140 diamond fracture behavior in the coating. Lagrangian algorithm with the dynamic explicit procedure was
141 applied to build the computational model. The aluminum alloy substrate was defined as a cylinder, having a

142 diameter and height of 320 and 160 μm , respectively. Based on the average size of the powders used in the
143 experiment, the copper particle was defined as a sphere with a diameter of 26 μm . For the preliminary
144 evaluation, the irregular copper-clad diamond powder was simplified as a sphere of an equivalent diameter
145 of 50 μm . Of that, the diameter of the diamond core and the thickness of the nickel inter-layer and copper
146 cladding were defined as 44.5, 0.4 and 2.4 μm , respectively, in accordance with the composition information
147 of the real powder. The metal materials including nickel, copper and aluminum alloy were modeled using
148 Johnson and Cook plasticity model. The diamond was considered as a linear elastic model with high elastic
149 modulus [37]. The model inherently does not allow considering the fracture of the diamond, but the
150 maximum contact pressure between the particles can be obtained. Detailed materials parameters applied to
151 both models can be found elsewhere [37,38]. Fig. 3 shows the computational domain, meshing and
152 boundary conditions of the used FEA model. Due to its symmetric character, the model was simplified as
153 axisymmetric in order to reduce the computational time. The geometry was partitioned by four-node bilinear
154 axisymmetric quadrilateral elements with reduced integration and hourglass control (CAX4R). The
155 axisymmetric condition was applied to the axis and the fixed boundary condition was enforced to the bottom
156 and lateral. The contact process was implemented by using the surface-to-surface penalty contact algorithm
157 with balanced contact pair formulation. The particle impact velocities for copper and copper-clad diamond at
158 the applied spray conditions (Table 1) and nozzle geometries were calculated as 600 m/s and 480 m/s in a
159 separate study (ANSYS-FLUENT 14.1 [39]).

160 The used FEA model inherently does not comprehend all experimental details and differs from reality in
161 several aspects, such as in-line impact, spherical particles or not taking into account the potential
162 out-of-equilibrium conditions of the particle materials arising from their fabrication routes (such as e.g. cold
163 working, internal stresses, etc). As such, the model could not work (and was not used) to properly explain

164 e.g. the deformation mechanisms or materials flow. However, the model's features suffice to achieve the
165 main aim, i.e. to calculate the level of stresses achieved at the contact and compare those with the diamond
166 fracture stress values.



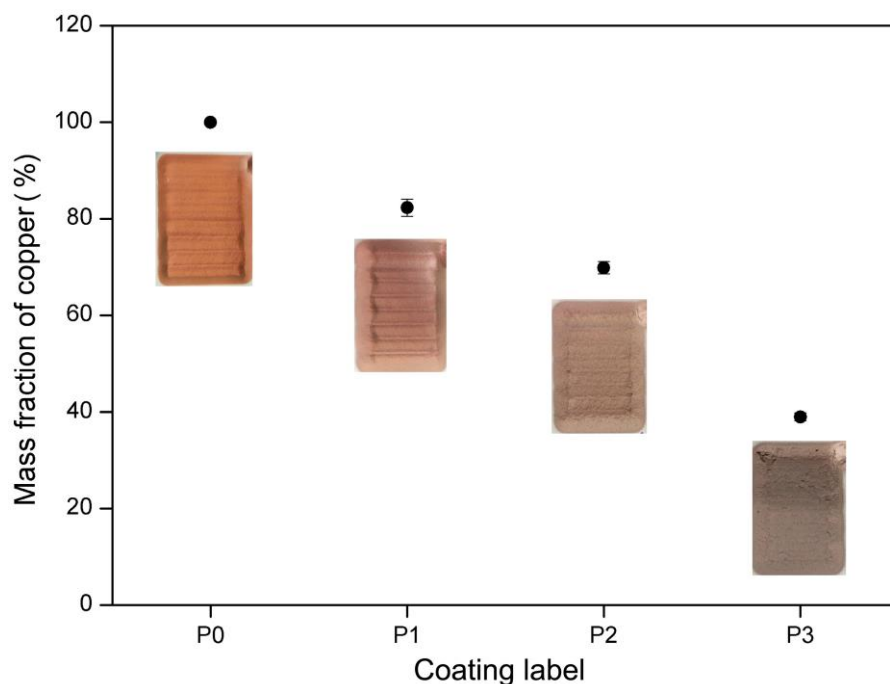
167
168 **Fig. 3** Computational domain, meshing and boundary conditions of the FEA two-particle subsequent impact model. (a) two
169 copper-clad diamond particles, (b) copper and copper-clad diamond particles, (c) mesh for copper-clad diamond powder and (d)
170 mesh for copper powder.

171 **4. Results and discussion**

172 **4.1 Chemical and phase transformations of DMMC coatings**

173 The cold sprayed coatings thickness exceeded 5 mm in all cases, i.e. order of magnitude higher than
174 what is possible to obtain using vapor deposition processes. As the mass fraction of the copper-clad diamond
175 feedstock increased (i.e., the copper content decreased, from P0 to P3), the coating color changed from
176 copper red to gray. Fig. 4 shows the copper content on the P0-P3 coating surfaces as determined by EDS as

177 well as the corresponding sample appearance.

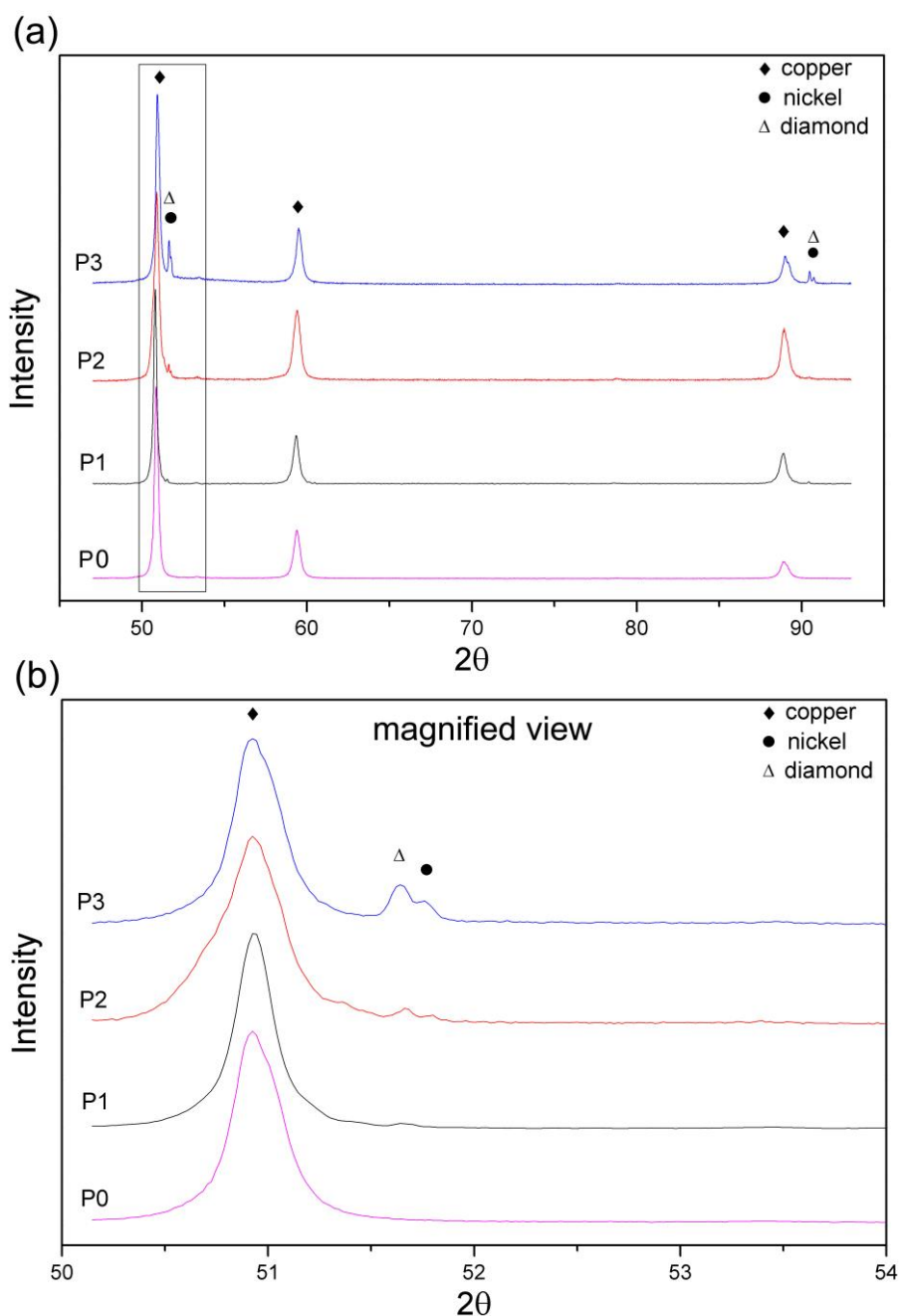


178

179 **Fig. 4** Copper content (wt%) on the P0-P3 coating surfaces as determined by EDS.

180 Graphitization of the diamond frequently occurs when fabricating the DMMC via sintering, infiltration
181 or thermal spray techniques due to the high processing temperatures [4,5,16,17]. The obtained XRD spectra
182 in Fig. 5 showed no graphite peaks, indicating that no graphitization occurred during the fabrication of the
183 cold sprayed DMMC. This fact clearly shows the advantage of cold spray over the other fabrication
184 techniques in preventing diamond graphitization. Moreover, the spectra presented in Fig. 5 further suggested
185 an increasing content of nickel and diamond phases from P1 to P3. This was supported by EDS cross-section
186 analysis of the diamond content (Fig. 6). The coating P3 that was fabricated from copper-clad diamond
187 powder only (50 wt% of diamond phase) contained 43 wt.% diamond, suggesting its fairly high deposition
188 efficiency in the process. In our previous work, even higher value of 56 wt.% was obtained by the EDS
189 measurements. However, it is rather safe not to attribute the difference to a change in deposition efficiency
190 as the higher value was obtained from coating fracture (i.e., not polished) surfaces [34]. In the previous cold

191 spray works where mechanically pre-mixed metal and diamond powders were used as the feedstock
192 [33,40,41], most of the diamond could not successfully deposit and thus the diamond mass fraction in the
193 coatings was generally low. The diamond fraction obtained in our works is higher than in any previous
194 studies using conventional pre-mixed powders. The excellent performance of the copper-clad diamond
195 powder clearly indicates that it is a promising feedstock for fabrication of cold sprayed DMMC coatings.



196
197 **Fig. 5** Comparison of the XRD spectra of the produced P0-P3 coatings (a) and local magnified view marked by black square in
198 Fig. 5a (b). Note the increasing content of Ni and diamond phases toward P3.

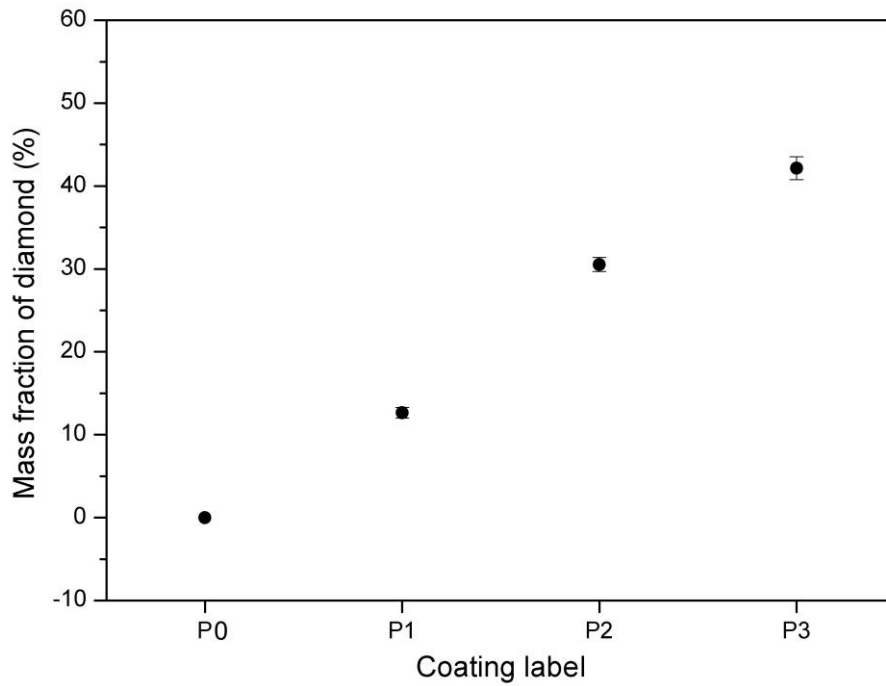


Fig. 6 Mass fraction of diamond on the coating cross-section.

4.2 DMMC coating microstructure

Fig. 7 shows the cross-sectional features of the DMMC coatings fabricated using different powders. It is known that a uniform distribution of the reinforcement phase in the MMC is of great importance to the final materials properties [42–44]. In this work, the cold sprayed DMMC coatings fabricated with the copper-clad diamond powders exhibited excellent uniformity, providing an essential condition for the high-quality materials properties. Besides, an obvious difference in the diamond mass fraction between each sample can be seen. The observed diamond contents in the coatings ($P3 > P2 > P1$) were well consistent with the EDS element analysis shown in Fig. 6.

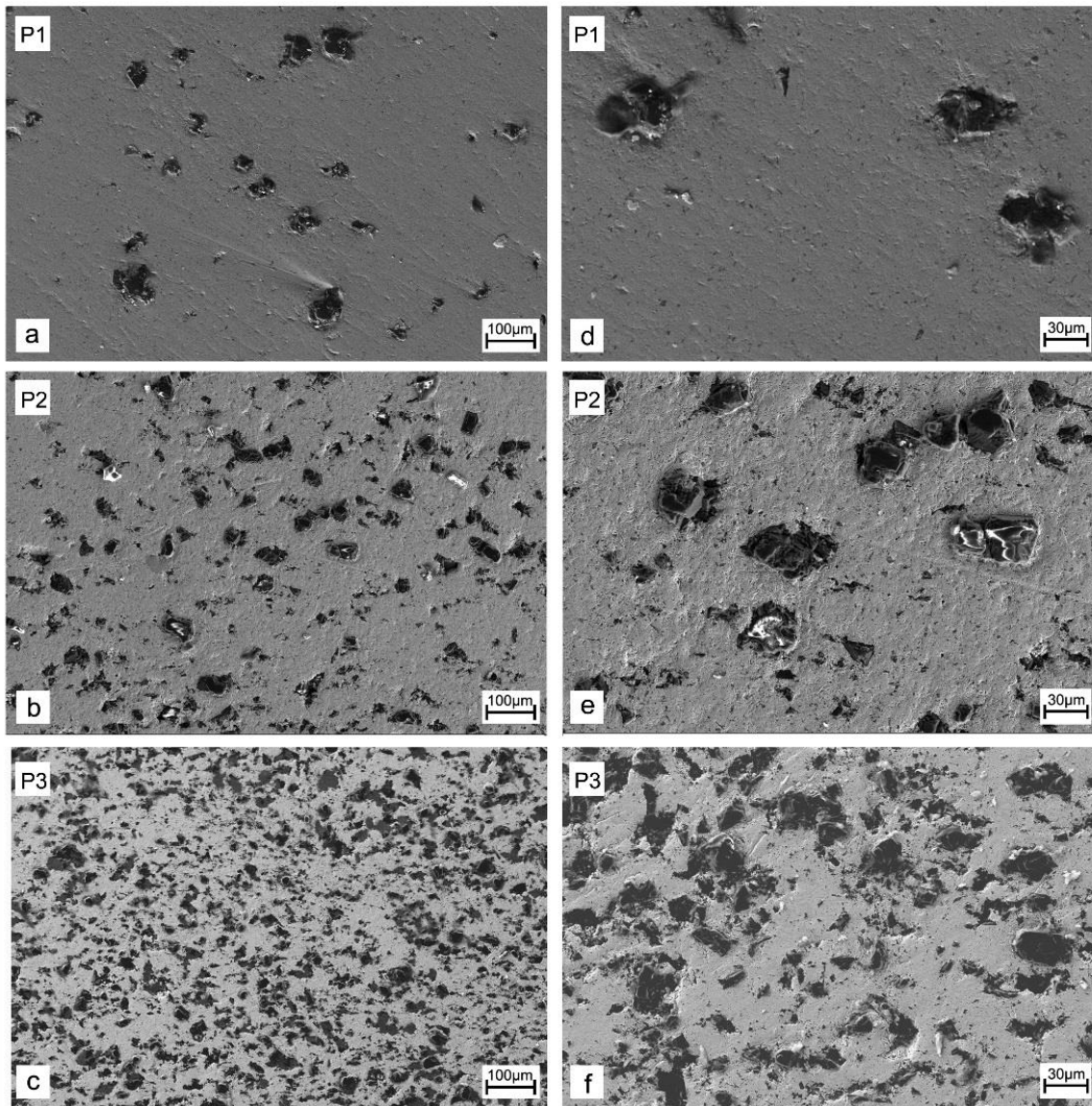


Fig. 7 Microstructure of the produced P1(a,d), P2 (b,e), and P3 (c,f) cold sprayed coatings.

The magnified images of the cross-section provided in Fig. 7d-f illustrate the diamond particles sizes in the produced coatings. Most of the diamond in the coating fabricated with the P1 and P2 powders had a diameter of approximately $40\mu\text{m}$. This value was quite comparable to the diamond core diameter of original feedstock ($-47+40\mu\text{m}$), which indicated that diamond did not exhibit substantial fracturing during deposition. In fact, the diamond phase in P1 exhibited almost no damage, while few cracks and several small diamond shards only could be found in P2. Assumedly, the matrix consisting of the free copper powder particles provided ductile component absorbing the impact energy and thereby effectively preventing the

218 diamond phase fragmentation. However, in the case of P3 coating, which was fabricated entirely using
219 copper-clad diamond powder only, the diamond phase was considerably smaller, containing a large number
220 of diamond shards with a diameter of less than 10 μm , suggesting the occurrence of fracturing. Despite the
221 fracture, previous works reported that tiny shards or fine particles may improve the toughness of cold
222 sprayed composite coating [19,20].

223 For well explaining the reason for inducing diamond fracture behavior in the pure copper-clad diamond
224 coating, Fig. 8 shows the predicted stress distribution at the moment of (i.e., at the precise moment when the
225 nominal stress reaches its maximum during the entire process) a copper-clad diamond powder impact (onto
226 either copper or copper-clad diamond particles), with room-temperature helium under 2.0 MPa pressure as
227 the propellant gas (i.e., identical to spraying conditions). For P1 and P2 coatings, the soft copper particles
228 could act as a ductile matrix to the copper-clad diamond particles, dissipating most of the impact kinetic
229 energy through the plastic deformation of copper. The predicted maximum impact stress in such case
230 (Fig. 8a) reached almost 3900 MPa, i.e. significantly lower than the diamond fracture stress calculated
231 elsewhere (5900 MPa, [37]). Therefore, the impacting stress was unlikely to damage the diamond in case of
232 impact into the copper matrix. The minor fragmentation of the diamond phase observed in P2 coatings
233 (considerably lower than in P3 coatings, nevertheless; cf. Fig. 7e and 7f) could be caused by a prospective
234 diamond-diamond contact given its higher content as compared to P1 coating. For P3, the outside metal
235 cladding was very thin and most of the energy was directly imposed on the inner diamond cores due to the
236 absence of softer buffer materials. The impact stress reached 8900 MPa (Fig. 8b). In this case, most of the
237 diamond was certainly fractured during the deposition, in accordance with the observed microstructure
238 (Fig. 7c,f).

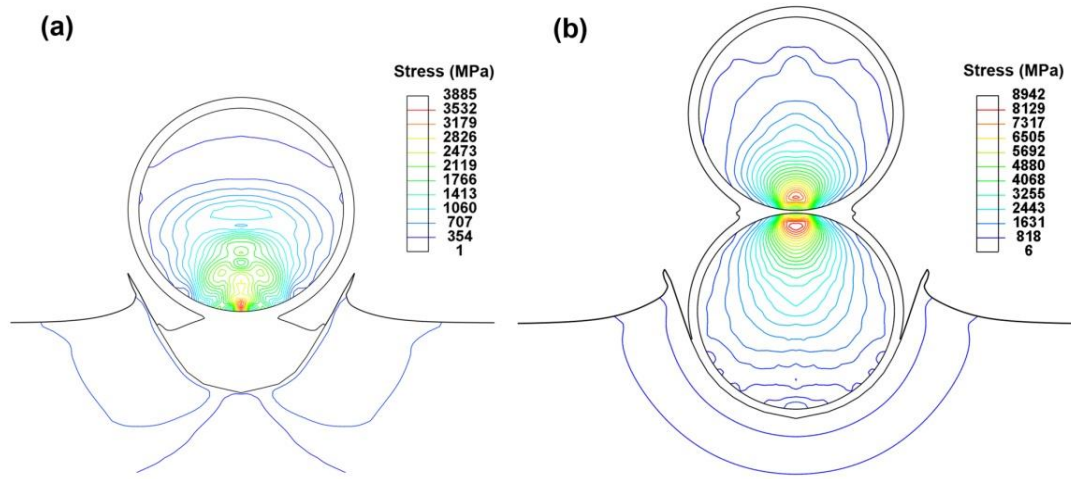


Fig. 8 FEA modeling results of the stress distribution at the moment of particle-particle impact with the inlet pressure of 2.0 MPa and helium as the propulsive gas. (a) copper-clad diamond onto copper, (b) copper-clad diamond onto copper-clad diamond

To further observe the coating microstructure and clarify the diamond phase behavior, coating fracture surfaces were observed using SEM (Fig. 9). The diamond particles in P1 coating were complete without any visible signs of damage, while the P2 coatings contained both undamaged and slightly damaged diamonds. However, for the P3 coating shown in Fig. 9c, the diamond phase observed a frequent cracking, producing small diamond shards surrounding the parent particles. In such cases, bonding occurred between the thin copper claddings only and the coating was formed through the fractured diamond sub-particles uniformly dispersing into the metal phase [34].

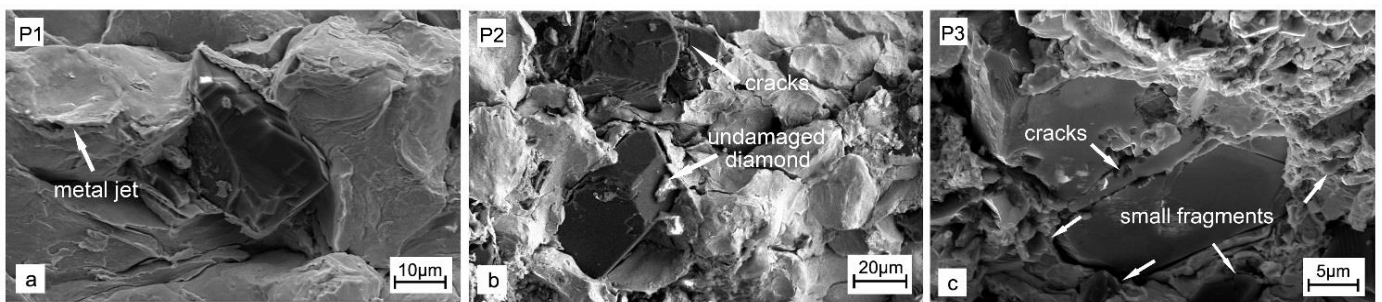
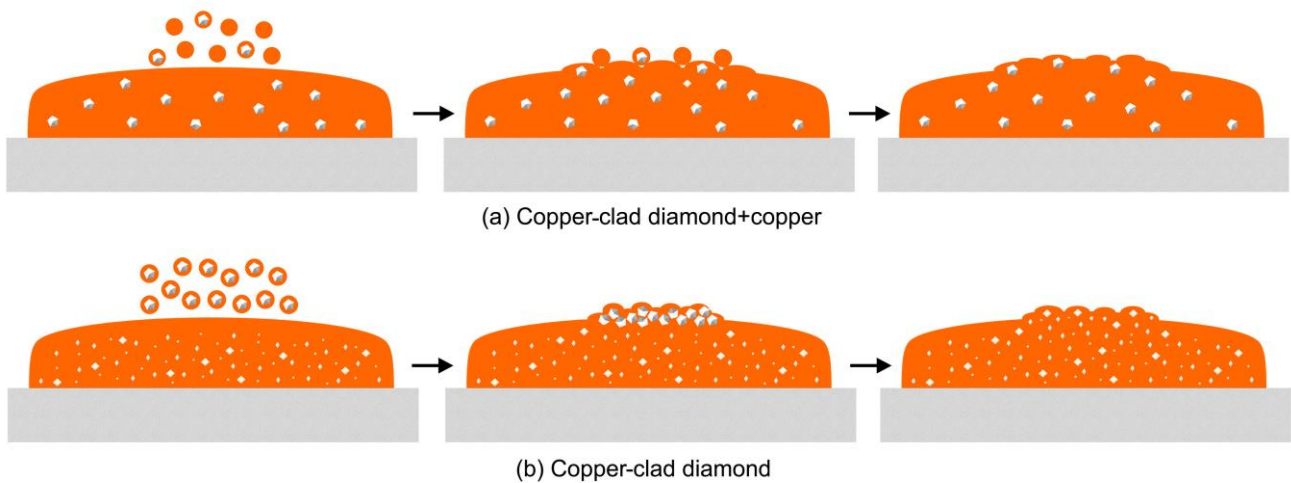


Fig. 9 Fracture surfaces of the produced P1-P3 coatings and the respective diamond phase fragmentation behavior

4.3 Coatings Deposition Mechanisms

252 Following the coating microstructure analysis, the following deposition mechanisms are suggested
253 herein. Fig. 10 shows the schematic of the deposition mechanisms for different coating types. For the
254 coatings produced using a mixture of copper and copper-clad diamond particles (Fig. 10a), the copper-clad
255 diamond particles have a limited chance to impact with each other only. Instead, they mostly impact onto
256 copper and, as a result, the metallic bonding in the coating mainly occurs between the copper particles only
257 or between the copper claddings of the diamond cores and copper particles. In addition, as the energy caused
258 by the high-velocity impact is mostly transformed into the plastic deformation of copper, the impact stress
259 imposed on the diamond phase does not reach its fracture stress threshold and the entire diamond content
260 therefore uniformly embeds and distributes in the copper phase.



261

262 **Fig. 10** Schematic of the deposition mechanisms for (a) copper-clad diamond + copper coating and (b) copper-clad coating

263 For the copper-clad diamond coatings (Fig. 10b), pure copper particles are absent in the deposition
264 process, leading to impacts of the copper-clad diamond particles with each other directly. Then, the metallic
265 bonding in the coatings only takes place between copper claddings. Although the copper cladding dissipates
266 part of the kinetic energy through plastic deformation, it is too thin (2-5 μm) to act as a buffer. Most of the
267 kinetic energy is dissipated via the interaction between the diamond cores rather than the plastic deformation

268 of the copper part. As a consequence, the impact stress imposed onto the diamond is large, exceeding the
269 diamond fracture stress, as discussed in the last section. Diamonds hence fracture into shards during the
270 deposition and disperse into the copper phase to form the DMMC.

271 **4.4 Coatings Wear Test**

272 The DMMC coatings experienced almost no wear during the test. Instead, the tungsten carbide pin ball
273 counterpart exhibited signs of damage. Also, a large amount of black debris worn from the tungsten carbide
274 pin ball was left on the worn track after the testing. As the debris surely affected the sample weight, the
275 coating wear rate measurement could not be taken as valid from this test. Fig. 11 provides the measured
276 wear rate of the tungsten carbide pin ball as a function of the calculated mean free path. It is clearly seen that
277 the mean free path decreased from P1 to P3, while the wear rate of the pin ball increased gradually. This fact
278 indicated that the coating wear-resistance performance steadily improved as the mean free path decreased, in
279 good agreement with the previous work [36]. The wear rate of the pure copper coating was also measured
280 for comparison reason. The copper coating was seriously worn after the test with the wear rate of
281 $0.0077 \text{ mm}^3/\text{N}\cdot\text{mm}$ while the pin ball did not experience any significant signs of damage. The comparison
282 clearly indicates the importance of the diamond reinforcements in improving the coating wear-resistance
283 properties. Moreover, in the previous works related to cold sprayed wear-resistance coatings (e.g.,
284 Al5056/SiC [45], CuSn8/AlCuFeB [46]), materials loss normally occurred on the coating surface, while the
285 wear of WC-Co pin ball was not reported. This fact further suggests the excellent wear-resistance properties
286 of the cold sprayed DMMC coatings obtained in this work.

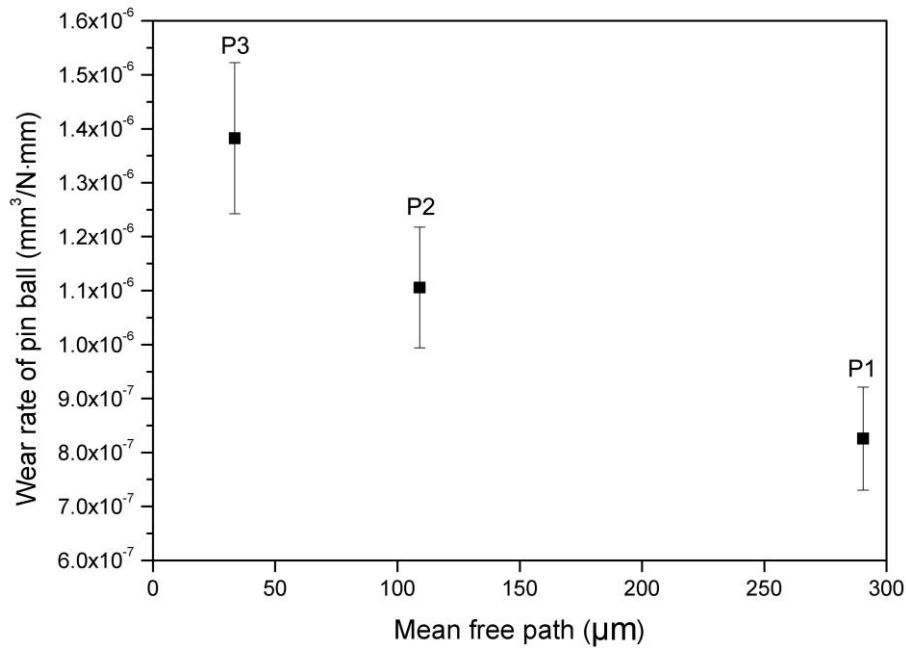
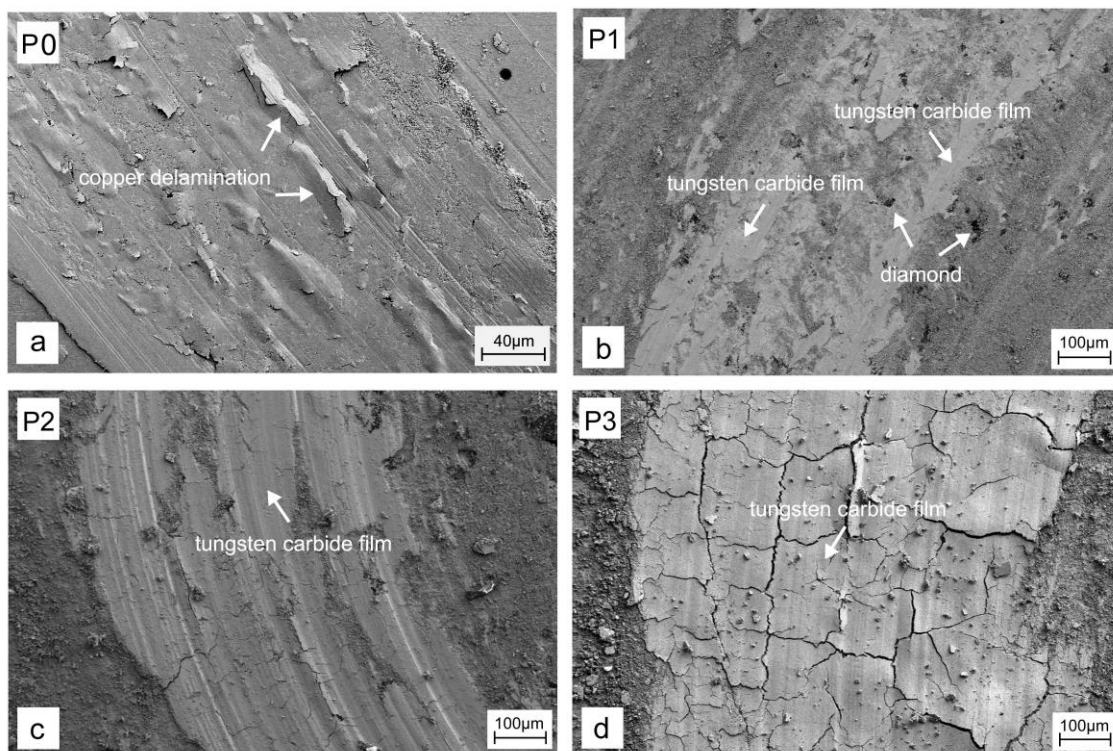


Fig. 11 Experimentally measured wear rate of the tungsten carbide pin ball against mean free path between diamond particles in the respective produced DMMC coatings.

To further investigate the coating wear mechanism, the worn surfaces and the corresponding EDS measurements are provided in Fig. 12. For the pure copper coating (P0), the worn surface was characterized by smooth profile with slight signs of delamination only. For P1 (having the lowest content of the diamond phase among P1-P3), tungsten carbide film worn off from the pin ball was detected on the worn surface. Also, the diamonds were not pulled off from but rather remained embedded in the P1 coating. They prevented the pin ball to wear the metal phase of the coating, but led to the serious abrasion of pin ball. With the pin ball continuously sliding on the coating surface, the tungsten carbide debris formed a thin film on the worn surface. As the diamond contents increased (P2), the area of the tungsten carbide film became larger (i.e., increased pin ball abrasion), lowering the area of the exposed coating materials. Therefore, the wear rate of the pin ball was higher than that of P1. In the case of P3 fabricated with copper-clad diamond powder only, a large amount of diamond resulted in the entire worn surface covered by the black and thick tungsten carbide film without any exposure of the underlying coating material whatsoever. The wear rate of the pin

302 ball was therefore the highest in all tests. It is known that copper is not a typical material for wear-resistance
303 coating due to its relatively low hardness [27]. Therefore, it is plausible to suggest that the wear-resistance
304 capability of the produced DMMC is attributed to the diamond reinforcements. The performed wear test
305 results clearly indicate the great potential of cold spray technique for producing wear-resistance DMMC
306 coatings.



307

308 **Fig. 12** SEM images and the corresponding EDS results of the worn surface of the cold sprayed P0-P3 coatings.

309 **Conclusions**

310 In this paper, a range of diamond-reinforced metal matrix composites (DMMC) were fabricated via cold
311 spray using copper-clad diamond powder or its mixture with pure copper powder. Copper-clad diamond is a
312 novel powder consisting of an inside diamond powder, a thin interbedded nickel layer and an outside
313 electroless copper cladding. The sprayed DMMC coatings fabricated using different powders had thickness
314 exceeding 5 mm, i.e. order of magnitude thicker than those typically produced by chemical vapor deposition

315 (CVD) processes. Due to the low working temperature, the coatings exhibited no phase transformations. In
316 the coatings fabricated from the mixed feedstock of copper and copper-clad diamond, the additional copper
317 powders acted as a buffer, dissipating most of the kinetic energy through the plastic deformation of copper,
318 thereby effectively preventing the fracture of the diamond phase in the coatings. When using pure
319 copper-clad diamond powder as the feedstock only, the impact stress imposed on the diamonds exceeded the
320 diamond fracture stress, leading to a frequent diamond phase fragmentation during the deposition. The pure
321 copper-clad diamond coating was then formed through the bonding between the copper claddings only and
322 the fractured diamond uniformly dispersed into the metal phase. In all coatings, the diamond in the feedstock
323 was fully transferred from the feedstock, with negligible losses only (e.g., reduction from 50 wt% to 43 wt%
324 in the copper-clad diamond coating) – a results never achieved in the previous cold spray works with
325 conventional pre-mixed powders.

326 Finally, the wear test on the DMMC coating clearly showed that the cold sprayed DMMC coating had
327 superior wear-resistance properties. With copper not being a typical wear-resistance metal, the results clearly
328 reflect the role of the diamond reinforcement in improving the wear-resistance capability. In the future
329 works, copper may be replaced by other wear-resistance metals, such as e.g. cobalt.

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