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Effect of the thickness of cold sprayed aluminium alloy coating on the adhesive bond strength with an aluminium alloy substrate

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ABSTRACT

The variation of adhesive bond strength of cold sprayed 7075 and 7050 aluminium alloy coatings on 7050-T7351 Al alloy substrate with coating thickness was determined through shear and tensile tests. Generally, without heating the substrate, the shear bond strength decreases with the increase in cold sprayed coating thickness. The thickest 7075 cold sprayed coating produced on rectangular substrates, which were used to measure the shear bond strength, was 1.6 mm. Although thicker coating was produced on the end of the cylindrical substrates, which was used to measure the tensile bond strength in accordance with the ASTM C633 standard, increasing the coating thickness from 1.2 mm to 2.9 mm led to reduction in tensile bond strength from 10 MPa to 5.1 MPa. However, further increasing the coating thickness to 3.7 mm improved the bond strength due to the heating effect resulted from impact of the late stage spray on the pre-formed coating layers. When the rectangular substrates were heated at 175 °C during cold spray, not only much thicker coatings were produced, the shear bond strength was also significantly increased. Hence, heating cold sprayed substrate is considered as an effective approach to produce thick and highly bonded coatings.

1. Introduction

7xxx series (e.g. 7075 and 7050) aluminium alloys are widely used in civilian and military fighter aircraft structure, such as the wing box structure (upper wing skin), spars, stringers, framework and pressure bulkhead [1] and fuselage bulkheads [2]. These structures carry high loads and are normally classified as fracture critical components of the aircraft, i.e., one single failure of such component from fatigue and/or corrosion damage will cause a safety damage of flight condition. In addition to the aircraft safety, the fatigue and corrosion damage also involve substantial costs resulted from damage inspections, maintenance and replacement. Considering the fact that the high costs are involved in replacement of failed components and often the long lead time, aircraft engineers prefer to seek more effective on-site repair solutions instead of replacement of the failed component.

In past decades, a number of processes, such as thermal spray [3] and laser cladding [4–6], have been developed for aircraft structural repairing. However, those processes normally involve local melting and solidification of metals, which may introduce oxidation of metals during repairing process. Because oxides can act as crack initiator, these impurities in aerospace components must be minimised. Hence, it is of high demand in developing new repairing process that overcomes the limitations of the thermal spray and laser cladding process. Since the cold gas dynamic spray (also called cold spray) process was invented [7,8], it has attracted increasing interest in surface deposition and spray forming of metallic materials and metal-based composites. As an additive manufacturing process, cold spray can also be considered as one of the most promising alternatives for damaged structural component repairing [9,10] due to its high deposition efficiency, dense deposition and compressive residual stress [7–9].

In a cold spray (CS) process, fine (generally from 5 to 50 μm) metal or ceramic powders are accelerated to a supersonic speed in conventional cold spray process or to sonic speed in kinetic metallization process (developed by Inovati in US) by a high pressure gas (~4 MPa) at a gas temperature less than 800 °C. The accelerated particles at high speed collide with the substrate, forming coating layers via severe plastic deformation at a high strain rate (up to 10^9/s) at solid state. Hence, it is especially suitable for those thermo-sensitive aerospace materials like magnesium, aluminium, titanium and their alloys due to the native feature of the low temperature process. In 2004, US Army Research Lab at Aberdeen Proving Ground reported the trial of cold spray process to repair aerospace components [11]. It has been demonstrated [12,13] that cold spray process has been quite successful in repairing corrosion, wear damage, and manufacturing defects of magnesium and aluminium parts, including helicopter transmission gearboxes, flap transmission housings, constant speed drive output housings, nose wheel steering actuators and landing gear components.

In repairing aircraft structural components using CS technology, it normally requires relatively thick deposition ranging from 0.5 mm to

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8.0 mm depending on corroded or worn depth and size of the component in order to fully restore its functions, such as dimensional accuracy, load-bearing capacity and properties [11]. Another major concern related to structural repairing is the bond strength between the repaired portion and the original substrate. This is critical in the performance and durability of the repaired parts, as low bond strength may lead to failure resulted from the coating peeling off, cracking or/and corrosion along the interface. Although considerable work [14–18] has been done in understanding the mechanisms of cold spray bonding and factors that control the bond strength, there is fewer work [9,10] studying the effect of cold sprayed coating thickness on the bond strength. Particularly, in the case of thick coating, it is critical to understand whether the high bond strength associated with CS technology can still be retained. Moridi and co-workers [9] reported the bond strengths of cold sprayed 6082 Al coatings on the same substrate with two different coating thicknesses. It was found that the thicker coating corresponded to lower bond strength. However as stated by the authors, the results of bond strength tests are not admirable because of the limited capability of their cold spray process. The present work focuses on investigating how the thickness of 7050 and 7075 cold sprayed coatings deposited on 7050-T7351 aluminium alloy substrate affects the adhesive bond strength between the coating and the substrate.

2. Experimental procedure

2.1. The kinetic metallization process for coating deposition

Two types of 7050-T7351 aluminium alloy substrates were used for determining the adhesive bond strength (details are in Section 2.2). One is cylindrical and another is rectangular. As-received wrought block (about 150 × 150 × 500 mm) was cut into a number of 25.4 mm in diameter and 50 mm long cylindrical samples for determination of the adhesive bond strength through tensile test according to the ASTM C633 Standard [19]. In the case of the failure of tensile test, such as fracture not along the interface between the coating and the substrate, and therefore the adhesive bond strength cannot be measured, a lug shear method (using rectangular substrate) developed by Zhang and co-workers [18] was used. Thus, a number of 10 × 10 × 40 mm rectangular substrates were also prepared using the same 7050-T7351 aluminium alloy. For both the tensile and shear tests, cold sprayed coatings with various coating thickness from 1.0 to 9.0 mm were produced at one end of the cylindrical samples and at the middle of the rectangular samples, as schematically shown in Fig. 1. Before cold spray, all the surfaces of the substrates were ground using #600 SiC sand paper. Two types of aluminium powders, 7050 (LPW Technology, UK) and 7075 (Valimet Inc., USA), were used as feedstock. The nominal chemical composition of the 7050 powder is 6.2wt%Zn–2.3wt%Mg–2.5wt%Cu and it is 5.6wt%Zn–2.5wt%Mg–1.5wt%Cu for 7075 powder. Examination of the powders in scanning electron microscopy shows spherical and elliptical shape particles as shown in Fig. 2. The mean particle size of 7050 powder is 18 ± 12 μm and it is 10 ± 6 μm for the 7075 powder. Obviously, the powder particle sizes of both powders, particularly in the 7050 powder, are non-uniform, showing a mixture of both large (~12–40 μm) and micro-satellite particles (less than 5 μm in size). Previous research work [20,21] has shown that particle shape, size and size distribution significantly affect the deposition efficiency, bond strength and coating density of cold spray. However, as the present work focuses on the effect of coating thickness on the adhesive bond strength of the cold spray coating, the same 7050 and 7075 Al alloy powders were used throughout the work.

Cold sprayed coatings were deposited on the substrates using kinetic metallization (Inovati, Santa Barbara, CA, USA) approach with helium as carrier gas. The differences between the convenient CS and the kinetic metallization was described previously [18,22]. Based on previous work on investigation of the effect of cold spray processing parameters on the bond strength and coating density [23] and after further optimisation with the present Al alloy powders to produce thick coatings, the cold spray processing parameters used are listed in Table 1. This enables the deposition efficiency of both types of powders on the 7050-T7351 aluminium alloy substrate to be higher than 80%. Thickness of the coatings was controlled by numbers of the cold spray nozzle travelling passes and the nozzle travelling speed. Thick coatings were produced through high number of passes with the lowest nozzle travelling speed. The 7075 coatings were deposited on the substrates without heating for the shear and tensile bond strength tests. In order to investigate the effect of substrate temperature on bond strength, the 7050 coatings were deposited on substrates that were heated to 175 °C during cold spray. This temperature was selected based on the typical two-stage ageing process of 7050 Al alloy at 200 °C and then at 120 °C [24]. For comparison, 7050 coatings were also deposited on substrates without heating.

2.2. Measurement of bond strength

According to the ASTM C633 standard, tensile adhesion strength between the coating and the substrate can be determined. Because adhesion strength refers to the bonding between the coating and the substrate, the term of "adhesive bond strength" is used in the present work. To measure the adhesive bond strength, cold sprayed coating deposited at one end of the cylindrical substrate was machined and ground and then was glued to another cylindrical substrate using 3 M N460 off-white epoxy glue. A special "V" shape clamp was used to ensure the alignment between the axial directions of the cylindrical substrates and the normal to the cold sprayed coating. After curing at 60 °C for 2 h, tensile test was done in an Instron 4505 tensile testing machine. If the tensile fracture occurs along the interface between the cold sprayed coating and the substrate, the fracture strength is the tensile adhesive bond strength. If the fracture occurs within the coating, it implies that the adhesive bond strength is higher than the fracture strength of the coating, which can be regarded as cohesive strength of the coating.

As stated above, to ensure that the adhesive bond strength is determined even in the case that the tensile adhesive bond strength is higher

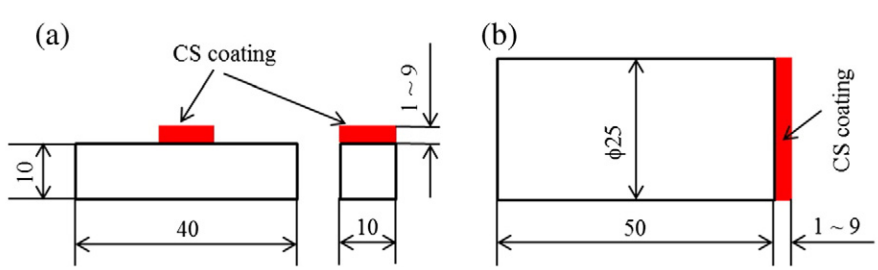

Fig. 1. Schematic illustration of the rectangular sample of cold sprayed substrate for measurement of shear adhesive bond strength (a) and the cylindrical sample substrate for measurement of tensile adhesive bond strength (b), together with schematic cold sprayed coating as illustrated in red. Dimensions are in mm.

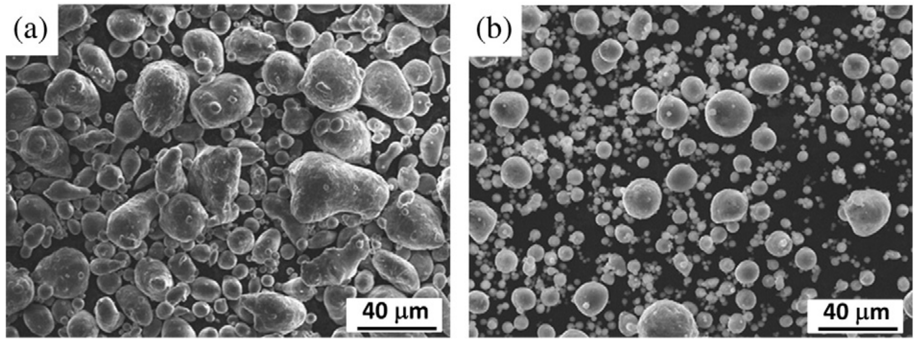

Fig. 2. Feedstock morphology of (a) 7050 Al alloy and (b) 7075 Al alloy powders.

than the tensile cohesive strength of the coating when the ASTM C633 standard is used, shear adhesive bond strength was measured using the lug shear test method [18] as shown in Fig. 3. A coating strip of 10 × 10 mm in variable thickness ranging from 0.7 mm to 9 mm was deposited on one of the long surfaces (50 × 10 mm) of the rectangular substrate. The adhesive bond strength measurement was conducted by pressing the coated strip through a 10 × 10 mm square hole with sharp edges on a steel die. Then, the coating was sheared off along the coating/substrate interface. Although the cold sprayed coating becomes conical shape for thick coatings, its influences on the lug shear test are marginal because the dimensional tolerance between the rectangular substrate used and the lug shear testing device designed (as shown in Fig. 3) is less than 50 μm. This ensures that the fracture of the shear is along the coating/substrate interface. The shear adhesive bond strength was calculated using the peak load divided by the contact area of the coating to the substrate. For each coating thickness, four samples were tested under both the tensile and shear testing conditions. The adhesive bond strength for each coating thickness was averaged based on the four measurements.

The fracture surface after tensile and shear tests was characterised through scanning electron microscopy (SEM) to understand the fracture mechanisms of the CS coatings, such as cohesive or adhesive failure mode.

3. Results and discussion

3.1. CS coatings on 7050 substrate

Although the optimised cold spray processing parameters as listed in Table 1 were used in order to produce thick Al alloy coatings on 7050-T7351 aluminium alloy substrates, it was found that there is still a coating thickness limit, over which the CS coating peels off. The thickness limit on the rectangular substrate differs from that on the cylindrical substrate. The cause for such influence of geometry of substrate on the thickness limit of cold spray is unclear. It is highly likely related to coating positions and heat dissipation. On the cylindrical substrate, the coating is at the end of the cylinder. Thus, heat generated from the impact of aluminium particles on the substrate can be uniformly dissipated. However, on the rectangular substrate, the coating is deposited at the middle of the surface. The heat along the edge of the coating can be released much faster than within the centre. This could lead to higher thermal stress in the coating on the rectangular substrate compared with the cylindrical substrate. As thermal stress is accumulated with thickening of the coating, the thickness limit of 7075 CS coating on the non-heated rectangular substrate is lower (only 1.6 mm) than that on the cylindrical substrate (3.6 mm). Probably due to the higher Zn and Cu contents, which lead to higher hardness, deposition of 7050 powder on the rectangular 7050 substrate was even more difficult than depositing 7075 using the present cold spray processing parameters as listed in Table 1 without heating the substrate. Even rising gas temperature to 450 °C, the thickness limit was only close to 2.0 mm, which was also associated with very low deposition efficiency. Because the present work focuses on investigating the effect of coating thickness on the adhesive bond strength, to eliminate the influence of other factors, coatings with various thicknesses need to be produced using the same processing parameters as listed in Table 1. Thus, in order to produce thick 7050 coatings, following the most recently published work [25], the substrates were heated to 175 °C during cold spray. As a result, very thick coatings up to 8.7 mm were obtained. Heating the substrate has very similar effect as the laser-assisted cold spray process [26,27]. Heating softens the substrate first, promoting plastic deformation and enhancing the contact between the particles and the substrate. After the first layer of the coating is built, the heated substrate can retain the high temperature of the deposition resulted from the impact between the particles and the substrate, or even can increase the temperature of the deposition. Hence, the residual stresses within the first deposition layer can be effectively released, enabling further deposition [25]. Thus, thick coating is obtained. In addition, heating may cause growth of oxide film on the surface of the substrate prior to the coating deposition. But, it is believed that it does not influence the subsequent CS deposition. First, the heating temperature is relatively low and the time is short (less than 5 min) before the first CS layer is deposited. The oxide files could not be significantly thickened. Second, CS involves collision of high speed metal and/or ceramic particles to the surface of substrate, resulting in severe strain at high rate on the surfaces of both the substrate and the particles. Such strain breaks the oxidation film on the surfaces, leading to contact of "fresh" surface between the substrate and deformed particles, creating metallurgical bond [17,18]. Watanabe and co-workers' results verified

Table 1
The cold spray processing parameters for deposition of the 7050 and the 7075 coatings using kinetic metallization approach.

Powder	Shape of substrate	Powder feed rate, (g/min)	Heating temperature (°C)		Pressure (kPa)		Nozzle	
			Substrate	Gas	PFU	TCU	Speed (mm/s)	Standoff distance (mm)
7050	Rectangular	11	170	204	689	620	100	16
7075	Rectangular	11	25					
	Cylindrical	16						

Note: PFU—powder fluid unit.
TCU—temperature control unit.

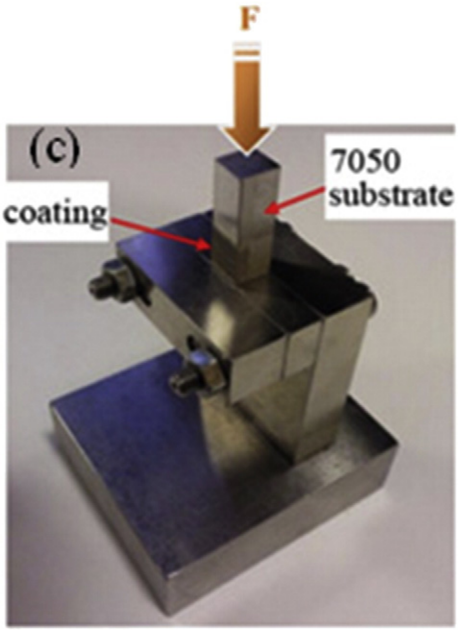

Fig. 3. Photograph of the lug shear test fixture [18].

that substrate oxidation and contaminant exportation resulted from substrate heating during cold spray are not the key factors of the adhesive bond strength.

3.2. Microstructures

The microstructures of the CS 7050 and 7075 coatings are very similar as shown in Fig. 4. But, the 7050 coating is associated with higher porosity than the 7075 coating. According to previous work [20,21], this can be considered as a result of difference in particle size distribution between these two types of powders. From Fig. 2, it can be seen that the currently used 7075 powder contains particles with relatively uniform size and the fraction of small particles is relatively low. However, the particle size in the 7075 powder is highly inhomogeneous with high fraction of small particles. Previous work [22] indicated that using proper proportion of coarse and fine particles in cold spray, higher density deposition can be achieved. Hence, the 7075 coating has higher density. In addition, as stated above, the higher hardness of the particles in the 7050 powder due to the higher Zn and Cu contents may also contribute to the lower density of the CS coating. Except for the density, the CS coating thickness, shape and pre-heat temperature of substrate have no noticeable influence on the microstructural morphology of the CS coatings. But, in the case of thick 7075 coating (1.2 mm thick), partial detachment from substrate was detected as indicated by the arrow in Fig. 4(d).

3.3. Bond strength

Fig. 5 shows the variation of shear and tensile adhesive bond strengths of the CS 7075 coatings on the non-heated 7050 substrates with coating thickness. The overall tensile bond strength is higher than the shear bond strength. Similar to previous work of Moridi and co-workers [9], increasing the CS coating thickness reduces the shear adhesive bond strength. A 1.9 mm thick CS coating on the rectangular substrate peeled off before the shear test, giving zero bond strength. The tensile adhesive bond strength also decreases with increase in the CS coating thickness when it is less than 2.9 mm, at which the lowest tensile bond strength of 5.2 MPa is achieved. Further increasing the CS coating thickness to 3.7 mm, the tensile bond strength rises to 9.3 MPa from 2.9 MPa. The decrease in bond strength with thickening of the CS coating is attributed to the accumulated internal residual stress. Cold spray is associated with considerable plastic deformation of powder particles, surface of substrate and the pre-deposited coating layers, which lead to high residual stress within the coating [28]. As the CS coating is thickened, the residual stress within the coating is accumulated, causing reduction in the adhesive bond strength. However, the tensile bond strength increases when the CS coating is further thickened to 3.7 mm as shown in Fig. 5(b). It might be attributed to the

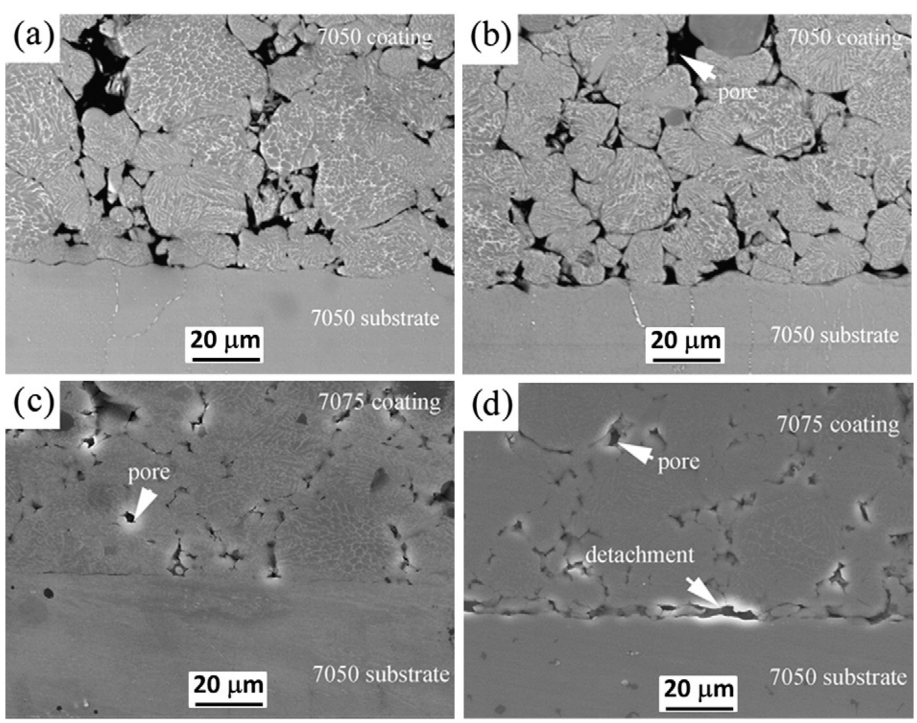

Fig. 4. Optical microstructures of the CS coatings on 7050 substrate. (a) 0.5 mm thick 7050 coating on pre-heated substrate; (b) 8.7 mm thick 7050 coating on pre-heated substrate; (c) 0.7 mm thick 7075 coating on the cylindrical substrate without heating; and (d) 1.2 mm thick 7075 coating on the rectangular 7050 substrates without heating.

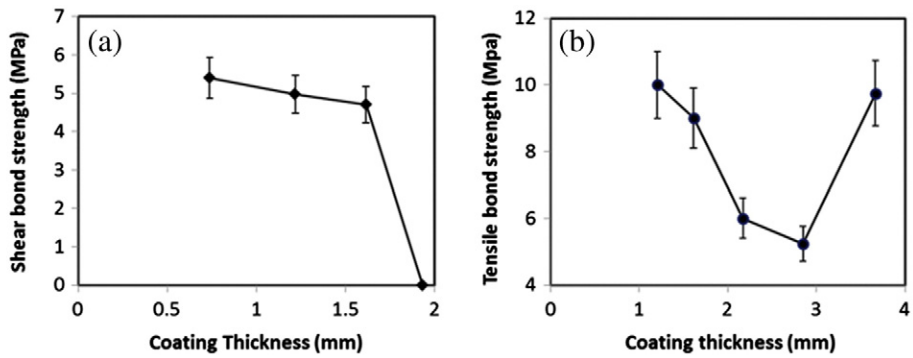

Fig. 5. Variation of (a) the shear adhesive bond strength and (b) the tensile adhesive bond strength, of the 7075 coatings on the 7050 substrate with the coating thickness.

annealing effect of the warm spraying gas on the pre-deposited coatings although the detailed mechanisms are yet to be investigated.

In the case of 7050 coatings on non-heated rectangular substrates, as shown in Fig. 6, the variation of the shear adhesive bond strength with coating thickness is similar to that of the 7075 coatings. Increase in coating thickness leads to reduction in shear bond strength. The coating peeled off at 1.58 mm thick. But, the overall shear bond strength of the 7050 coating is lower than that of the 7075 coating on the same substrate. The lower bond strength of the 7050 coating is related to the lower density of the CS coating as shown in Fig. 4, which is considered as results of the inhomogeneity of feedstock powder as illustrated in Fig. 2 and the higher particle hardness due to the higher Zn and Cu contents. However, heating the rectangular substrate to 175 °C during cold spray not only enabled much thicker coatings up to 8.7 mm, but also significantly improved the shear adhesive bond strength of the 7050 coatings. As shown in Fig. 7, with the CS coating thickness increasing from 0.8 mm to 3.7 mm, shear adhesive bond strength correspondingly increases from 8.7 MPa to 16.5 MPa. Further increase in the coating thickness marginally affects the bond strength. As mentioned before, heating the substrate during cold spray is similar to the laser assist cold spray process [26,27]. First, heating softened the substrate, promoting the deformation of substrate surface upon impact of the powder particles. Second, heating the substrate also helped release the residual stress within the coating through a process like annealing even within a short time [25], which contributes to the improvement of bond strength. Watanabe and co-workers [25] investigated the effect of A5083 substrate temperature on the shear adhesive bond strength of Cu CS coatings. It was reported that heating the substrates at 200 °C during cold spray effectively improved the bond strength. However, pre-heating the substrate and performing the cold spray at room temperature (the pre-heated substrates were cooled down to room temperature before spraying) had no influence on bond strength. Hence, although the actual mechanism of how the substrate heating influences on bond strength of CS coating is yet unknown, substrate heating during cold spray is an effective technique to increase the bond strength of CS.

3.4. Fracture surface

After bond strength test, fracture surfaces on the 7050-T7451 aluminium alloy substrates were examined in SEM. Figs. 8 and 9 show the typical fractographic morphologies of the rectangular substrate and cylindrical substrate after the 7075 coatings were sheared and pulled off, respectively. Both the rectangular and the cylindrical substrates show very similar fractography. Although adhesive failure mode dominated fracture, some cohesive features can be observed as some coating materials can be clearly identified in all samples, as indicated by arrows in Figs. 8 and 9. Generally, adhesive failure refers to the fracture purely along the interface between the coating and the substrate and cohesive failure implies the occurring of fracture within the coating. In the case of cohesive failure, the adhesive bond strength is higher than the cohesive strength of the coating. Mixed adhesive and cohesive failure is normally featured with observation of remained coating materials on the fracture surface of the substrate. In the present work, on the fracture surface of the rectangular substrates as shown in Fig. 8, the fraction of remained coating materials is almost the same for all coating thickness ranging from 0.7 mm to 1.6 mm. This indicates that the variation of bond strength is marginal, which is consistent with the results in Fig. 5(a). On the cylindrical substrates, when the coating thickness is below 2.2 mm, the amount of remained coating materials on the fracture surface reduces with increase in coating thickness, implying more significant adhesive failure. But, in the case of thick coating

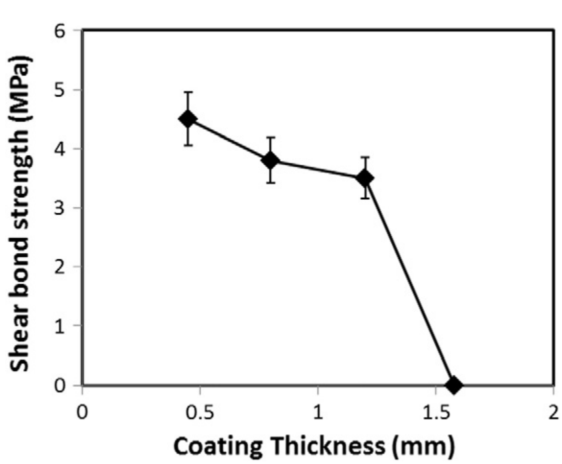

Fig. 6. Variation of the shear adhesive bond strength of the 7050 coatings on the 7050 substrate with the coating thickness.

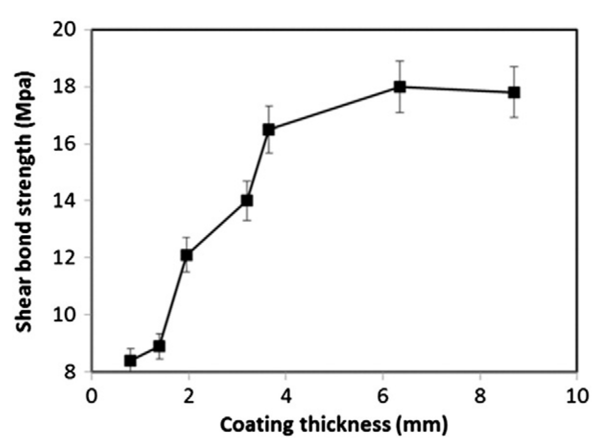

Fig. 7. The shear adhesive bond strength of 7050 coatings as a function of coating thickness on the rectangular 7050 substrates that were heated at 175 °C during cold spray.

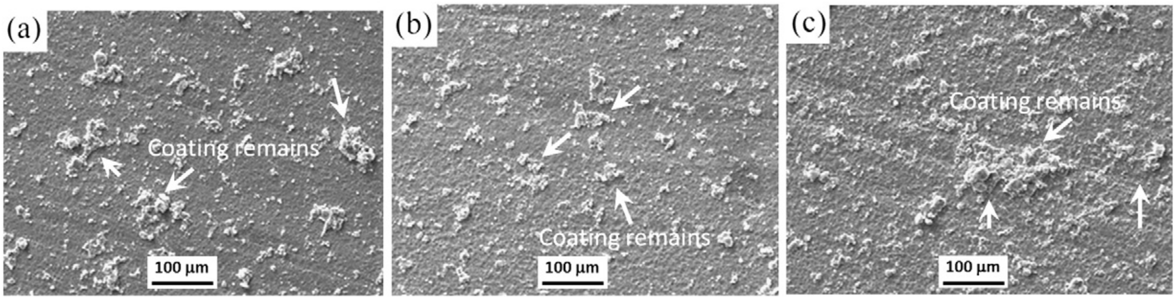

Fig. 8. Fractographic morphology of the fracture surfaces of the rectangular 7050 Al alloy substrates after the 7075 coatings with a thickness of (a) 0.7 mm; (b) 1.2 mm and (c) 1.6 mm were sheared off.

of 3.7 mm, where high tensile bond strength was obtained, the cohesive failure effectively contributed to the fracture, which is evidenced by the large amount of remained coating materials on the fracture surface, as shown in Fig. 9(c). This fractographic analysis is consistent with the variation of the tensile adhesive bond strength with coating thickness as shown in Fig. 5(b).

Fracture surface of the heated substrates of 7050 coating also shows the mixture of adhesive and cohesive failure modes as shown in Fig. 10. However, unlike the coating on un-heated substrates, for thicker coating over 6.0 mm, the fracture surface shows predominated cohesive feature as evidenced by the large amount of remained coating materials on the fracture surface as indicated by the arrows. This corresponds to the increase in shear adhesive bond strength as shown in Fig. 7.

4. Conclusions

The effect of the cold sprayed coating thickness on bond strength was experimentally investigated through deposition of the 7050 and 7075 aluminium alloy coatings on the 7050-T7351 Al alloy substrates. The following conclusions can be drawn.

(1) The shear adhesive bond strength (measured using the lug shear method) of the 7075 and 7050 cold sprayed coatings on unheated 7050 substrate decreased with the increase in coating thickness. The thickest 7075 coating and 7050 coating produced on the rectangular substrates without peeling off were 1.6 mm and 1.2 mm, respectively.
(2) Using the 7075 Al alloy powder, much thicker cold sprayed coating was produced on the cylindrical substrates than that on the rectangular substrate. The tensile adhesive bond strength (measured in terms of the ASTM C633 standard) also reduced with increase in coating thickness and the lowest bond strength was obtained at the coating thickness of 2.9 mm. However, further thickening led to increase in tensile bond strength, possibility due to the annealing effect resulted from the heat generated from the impact of powder particles at the late stage spray on the pre-formed coating layers.
(3) Heating the 7050 substrate at 175 °C during cold spray not only led to producing very thick 7050 cold sprayed coating up to 8.7 mm, but also effectively improved the shear adhesive bond strength. Increasing the coating thickness led to further improvement of the

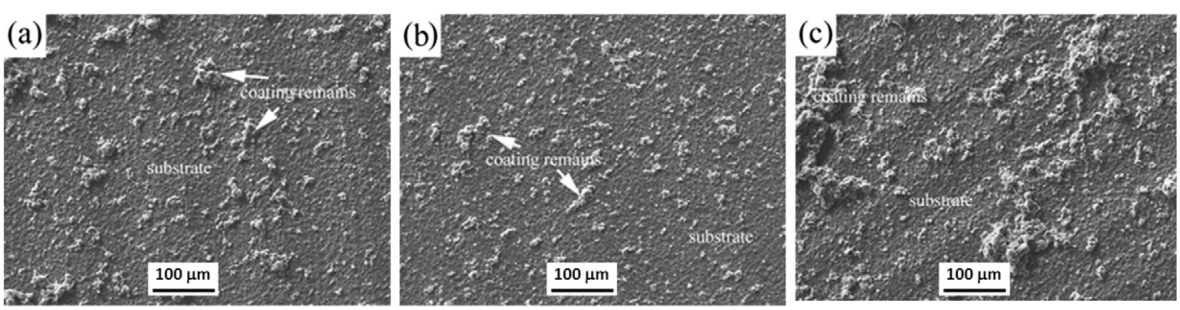

Fig. 9. Fractographic morphology of the fracture surfaces of the cylindrical 7050 Al alloy substrates after tensile adhesive bond strength test of the 7075 coatings with a thickness of (a) 1.2 mm; (b) 2.2 mm and (c) 3.7 mm.

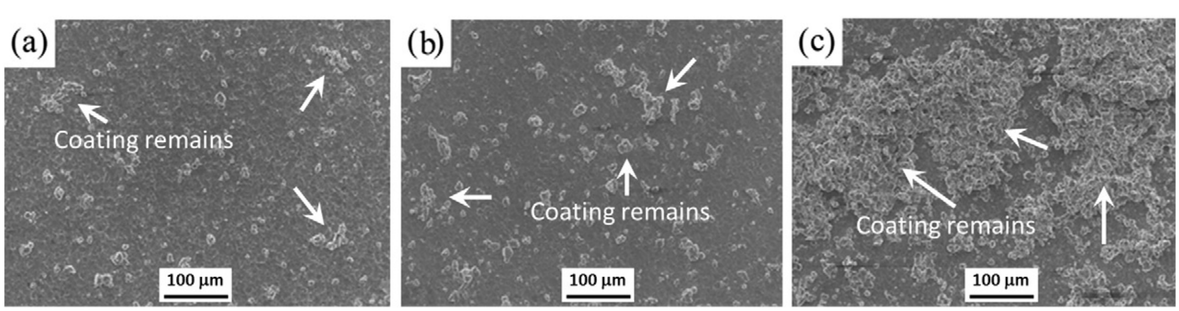

Fig. 10. Fractographic morphology of the fracture surfaces of the 7050 Al alloy heated substrates after the shear adhesive bond strength test of the 7050 coatings with a thickness of (a) 0.5 mm; (b) 3 mm and (c) 6 mm.

shear bond strength. Thus, substrate heating during cold spray can be considered as an effective and practical approach to produce cold sprayed coating with high adhesive bond strength.

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