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Dissimilar metal joining and structural repair of ZE41A-T5 cast magnesium by the cold spray (CS) process

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ABSTRACT

The ability to join aluminum to magnesium is important for many industries but is a challenge due to the formation of brittle intermetallic compounds (IMCs). This article presents a practical method to join and provide structural repair of cast ZE41A-T5 cast magnesium (Mg) by the cold spray (CS) process using 6061 Aluminum (Al). In this study, the CS process was used to deposit 6061 Al onto ZE41A-T5 Mg substrates, which were subjected to materials testing and characterization. Shear, hardness, and tensile testing were conducted to determine bond integrity at the dissimilar metal joint. Electron and optical microscopy were performed to analyze the interface and microstructure. A review of dissimilar metal joining techniques is provided for comparative purposes, and the unique bonding mechanisms of cold spray are discussed because of its relevance to the results obtained. Results showed that the cold spray process limited the formation of Mg_2Al_3 and $Mg_{17}Al_{12}$ intermetallic compounds and the bond strength of the dissimilar metal joints created by the cold spray process, had an ultimate tensile strength, hardness, and shear strength comparable to the weakest material being joined (Mg). This study serves to demonstrate the potential of the cold spray process to create high strength dissimilar joints and provide structural repair between Mg and Al.

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Aluminum; dissimilar; intermetallics; joining; magnesium; materials; spray; welding

Introduction

Magnesium alloys are being increasingly used in the fabrication of components in advanced aircraft because of their good mechanical properties, low density, and high strength-to-weight characteristics. Despite the obvious advantages of using these types of alloys on aircraft, magnesium is a very active metal electrochemically and is anodic to all other structural metals. Therefore, Mg will corrode preferentially when coupled with virtually any other metal in the presence of an electrolyte or corrosive medium [1]. Magnesium alloys are also very susceptible to surface damage due to impact, such as during handling, assembly, or repair. These alloys must be surface treated to prevent corrosion and oxidation and to increase surface hardness to resist impact damage. Therefore, there is a need to provide dimensional restoration and structural repair of magnesium parts that are damaged in service as a result of wear and/or corrosion.

The ability to join Al and Mg also represents a significant challenge for many industries, including automotive, petrochemical, and aerospace industries, and success would enable significant weight savings to be realized and subsequent energy efficiency in the automobile industry and the requirement for chemical plants and cryogenic applications [2,3]. Dissimilar welding of aluminum (Al) and magnesium (Mg) alloys would achieve weight reduction and high efficiency of production by a substitution of Mg alloys for Al alloys [4,5]. Magnesium is an engineering material of choice for such applications as transmission housings because of its low density, high stiffness, and high-specific strength [6]. The military and industry have numerous applications in aerospace, munitions, and vehicles that require the joining of dissimilar materials. Reduction in weight and improvement in performance are important in the design and manufacture of armored military vehicles, and therefore, a solution to this problem is important to enable the use of dissimilar material joints. The ability to provide structural repair of expensive gearbox housings that have experienced corrosion or wear during use would save millions of dollars a year for the military and commercial aircraft industry in replacement costs for new parts.

Researchers have attempted to join magnesium and aluminum using various joining methods with limited success. Fusion welding and solid state welding techniques were found to be unsuitable because of the amount of intermetallic compounds (IMCs) formed in the weld, which adversely affects the performance of the material, rendering it brittle [7,8]. The resultant joints have been poor or lacked sufficient structural integrity to be considered for applications demanding high or even moderate loading conditions. Diffusion welding has resulted in the formation of an interfacial transition zone of Mg-Al IMCs [9,10,11] Zhao et al. incorporated an interlayer

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of Zn to improve shear strength of joints and mitigate the formation of IMCs but only attained shear strength values of 75-83 MPa. Kostca et al. revealed the formation of $Al_{12}Mg_{17}$ and Al_3Mg_2 intermetallic phases after joining AA6040 Al to AZ31B Mg alloy by the friction stir welding process due to heat generated by adiabatic shear [10,12,13]. Magnetic-pulsed welding (MPW) [14], laser [10,15,16], TIG [17] electron beam [18], and resistance spot welding [19] have all resulted in the formation of IMCs to varying degrees depending upon the thermal energy imparted during each of these processes while joining aluminum alloys to magnesium alloys. When Al alloys are joined to Mg alloys and sufficient heat is generated, the resulting welds have reduced ductility due to the formation of an intermetallic layer at the dissimilar metal interface. The strength and ductility of the dissimilar metal joint can be adversely affected, depending on the processing parameters employed and the amount, size, distribution and type of IMCs formed [11,20]. Prior research has shown conclusively, that the formation of a large number of coarse Mg/Al intermetallic compounds cannot be avoided, by the aforementioned joining techniques. These intermetallic layers can have a size magnitude of over 500–900 μm [21] and can cause cracking and brittleness in the welds, making them unsuitable for use. Chen and Nakata have joined Al to Mg using friction stir welding, but the resultant joints had low strength (about 1/3 of the base material) and almost no ductility [13]. Low ductility was associated with the formation of intermetallic compounds, such as $Al_{12}Mg_{17}$ that form at the interface between the two dissimilar metals [13]. Cold metal transfer (CMT) dissimilar Al/Mg welding attempts have also been reported [22], but have resulted in poor mechanical properties and also brittle fracture of the IMC layer, occurring at the dissimilar metal interface. The addition of a zinc alloy interlayer between Mg and Al during the diffusion bonding process has been found to significantly improve the microstructure of the bond zone at the interface, but deleterious coarse IMCs were still formed at the interfacial region [9,11]. Somasekharan and Murr [21] fabricated numerous welds from Mg alloys and Al alloy 6061-T6 using friction-stir welding (FSW) with better results in that the formation of a large number of Mg/Al intermetallic compounds was avoided but not altogether eliminated. In another study by Toma et al, the microstructure of the interface layer between Al (4043) and Mg (RZ5) joined by CMT was found to contain high concentrations of Al-Mg intermetallics (Al_3Mg_2 and $Al_{12}Mg_{17}$) [23]. Taiki Morishige et al showed similar results to previous studies when attempting to use FSW between A5052-H Al and AZ31B Mg in that the resultant joint efficiency achieved was 61% due to the formation of $Mg_{17}Al_{12}$ and Mg_2Al_3 and ductility decreased with the increase of these compounds [24]. Finally, a comprehensive review of dissimilar welding techniques for Al to Mg alloys conducted by Liu et al, concluded that 'the IMC reaction layer could be significantly reduced due to the low welding temperature, but the formation of brittle Al-Mg IMCs cannot be completely avoided' [25]. In this 2014 review, Liu reviewed the results of friction stir welding (FSW), diffusion bonding, fusion welding, laser weld bonding, ultrasonic spot welding (USW), resistance spot welding (RSW), and magnetic pulse welding (MPW), and in all instances, the resultant joints contained some level of IMCs and mechanical tests of the joints fell significantly short of the strength of the substrate materials being joined [25].

Cold spray (CS) is a material consolidation process whereby micron-sized particles of a metal, ceramic, and/or polymer are accelerated through a spray gun fitted with a De Laval rocket nozzle using a heated high pressure gas (i.e., helium or nitrogen), such that the particles exit at supersonic velocities and consolidate upon impacting a suitable surface to form a coating or a near-net shaped part by means of ballistic impingement [26–31]. The particles utilized are typically in the form of commercially available powders, ranging in diameter from about 5 to 100 μm, and are accelerated at velocities from 300 to 1,500 m/sec by injection into a high velocity stream of gas (typically nitrogen or helium). Particles that are <5 μm do not have enough momentum to leave the gas stream and impact the substrate. Hence, submicron and nanoparticles cannot be deposited using cold spray in this fashion. However, Champagne et al. have shown that agglomerated nanoparticles or nanostructured powder within the feasible size range can be used, and CS has been shown to produce nanostructured coatings, as well as nanostructured bulk materials [32].

The high velocity gas stream is generated via the expansion of a pressurized, preheated gas through a converging–diverging de Laval rocket nozzle. The pressurized gas is expanded to supersonic velocities, with an accompanying decrease in pressure and temperature [33,34,35]. The particles, which can be carried from the pressurized powder feeder through a separate line or in the same line as the gas stream, are injected into the nozzle either prior to the throat of the nozzle or downstream of the throat. The particles are subsequently accelerated by the main nozzle gas flow and impact onto a substrate after exiting the nozzle. If the critical impact velocity of the accelerating particles is attained upon impact, the solid particles deform and create a bond with the substrate [36,37,38]. Adequate velocity is necessary for optimal particle consolidation and coating density, and several important CS process parameters, including gas conditions, particle characteristics, and nozzle geometry, affect the particle velocity. It has been well established that impacting particles must exceed the critical velocity to deposit; otherwise, they may rebound off of the substrate. The magnitude of the critical velocity can be estimated through the use of empirical relationships, which generally depend on particle material characteristics, such as density, ultimate strength, yield, and melting point, as well as the particle temperature [38].

As the process continues, particles collide with the substrate and form bonds with the underlying consolidated material resulting in an adherent, uniform deposit with very little porosity and high adhesive and cohesive bond strength. The term cold spray has been used to describe this process due to the fact that the temperatures are typically well below that of the melting temperature of the feed stock powders. The strength and modulus values of the cold spray material often exceed those of wrought materials, and the hardness of Al and Al-alloy cold spray is generally higher than for wrought alloys because of the extreme work hardening induced by the spray process.

Materials and Methods

Cold spray process parameters were developed and optimized by Champagne et al. and used in this study as listed in Table 1 [39]. Cold spray was performed at the US Army Research Laboratory, Aberdeen, MD and at Moog, Webster, MA. All specimens were produced using a VRC Metal Systems Gen 3 cold spray system. The substrates evaluated for this investigation were ZE41A-T5 cast magnesium alloy. Aluminum alloy 6061 was chosen as the joining material because of its compatibility with the substrate materials, the extensive experience with cold spraying 6061 Al, and the mechanical properties that have been established on similar substrates. Aluminum alloy 6061 has been used for many years by the Army aviation and its contractors in conjunction with magnesium alloys, including ZE41A Mg, without issues associated with galvanic corrosion.

A novel method of applying a cold spray layer (Fig. 1) onto one of the materials being joined is the key element for one of the methods to join dissimilar materials by cold spray. The cold spray layer consists of one of the materials or a compatible material to that being joined to the first material. For instance, to join a magnesium plate to an aluminum plate, first a cold spray layer of aluminum would be deposited onto the edge of the magnesium plate to serve as a transition layer, sufficient in thickness to accommodate a conventional MIG or TIG weld in order to join it to the aluminum plate. The type of aluminum chosen would be compatible to allow a conventional weld to be performed to the aluminum plate. The thickness of the cold spray layer would be sufficient enough to mitigate the formation of IMCs by providing enough insulation to prevent overheating and phase transformation. Without the cold spray layer, this would not be achievable without the formation of coarse intermetallics at the dissimilar metal interface. Other joint designs and methods incorporate only the cold spray process to join dissimilar materials.

Figure 2 shows a sequence of series of steps taken on a butt joint design that results in the joining of dissimilar metals while eliminating any evidence of a seam at the bottom of the deposit. This technique can be applied to damaged aluminum or magnesium parts that contain through holes as was demonstrated in this study. The elimination of the seam is important because it would serve as a stress concentration area and thereby limit the load bearing capacity of the joint. Figure 3 depicts a similar approach that was taken to repair a through hole by CS, whereas the sides of the hole were chamfered to allow a preferred angle for CS deposition and the use of a backing plate to cover the hole while a cold spray deposit is formed in much the same manner as previously described in Fig. 2. A mold release agent was used to prevent the CS deposit from adhering to the backing plate, such that it could be mechanically removed by a single impact [40]. Figure 4 is another method to fill in a through hole by CS that does not require a backing plate if the part to be repaired is of sufficient thickness to accommodate a layer by layer buildup of CS material along the chamfered edges. All these methods result in a seamless weld when repairing ZE41A-T5 Mg with 6061 Al by the cold spray process.

The triple lug shear test method was used to evaluate the bond strength of the cold spray 6061 Al deposit on the ZE41A-T5 Mg substrate. Triple lug procedure methodology is prescribed in military specification MIL-J-24445A. Mechanical drawings and a representative sample of a coated test coupon placed in the load frame subsequent to testing are shown in Fig. 5a–c, respectively. A deposit with a thickness of greater than 3.175 mm (0.125) inches is deposited onto the specimen, and three lugs are machined from the coating. The lugs are sheared from the test specimen using an Instron Model 1125 compressive load frame setup. Only one lug is sheared from the specimen at a time.

The test was carried out in accordance with MIL-J-24445A, using a strain rate of 1.27 mm/min. (0.05 in./min) at room temperature. Stoppers of different heights are placed below the specimen for each lug test to ensure the adjacent lug is not impacted after the shear of the lug being evaluated. Failure stress is reported based on the load at failure and the surface area of the lug base.

The 'glueless' bond strength test method was developed to evaluate the bond strength of cold spray deposits on a substrate. The traditional test method used throughout the aerospace industry has been ASTM C633, titled 'Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings'. This test procedure prescribes that a cold spray coating/deposit be applied to a 25.4-mm (1 inch) diameter substrate bar onto which a mating bar of the same diameter is glued to the top of the cold spray deposit. This approach offers a quick evaluation of adhesion strength of thin deposits, but limits the value of the ultimate tensile strength (UTS) that can be measured to approximately 69-90 MPa (10-13 ksi), which corresponds to the strength of the glue. However, high pressure cold spray material far exceeds these strength values and test results have been typically reported as glue failures with tensile strength values of the cold spray deposit designated as 'greater than 69 MPa'.

Since cold spray has advanced and now can achieve bond strength values much greater than 69–90 MPa (10–13 ksi), a test method for accurate and precise measurement at these strength levels was required. Therefore, to investigate the actual bond strength of cold spray deposits, a means of evaluating bond strength without using glue was developed at ARL. The test specimen and accompanying fixture were designed to uniformly pull the cold spray coating/deposit normal to the substrate interface

Table 1. Cold spray process parameters.

Feedstock powder:
Powder: 6061 Valimet −270/+635 mesh
Bake out: 1 h at 230°C in a laboratory air or vacuum furnace, or in other method for thermal processing
Cold spray nozzle:
Nozzle: PBI (polybenzimidazole) Celazole®
Surface preparation:
Substrate material: ZE41A-T5 Mg
Material surface preparation: Scotch-brite
Materials surface cleaning: alcohol + air
Gas, powder and robot controls:
Gas type: He
Gas pressure: 25 bar
Gas heater: 400C
Mass feed rate: 4.8 g/min
Robot program: Raster
Standoff: 1 inch
Raster speed: 200 mm/s

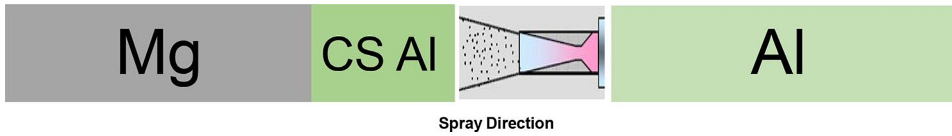

Figure 1. Cold Spray 6061 Al deposited on the edge of the ZE41A Mg, 'Buttering the Edge'.

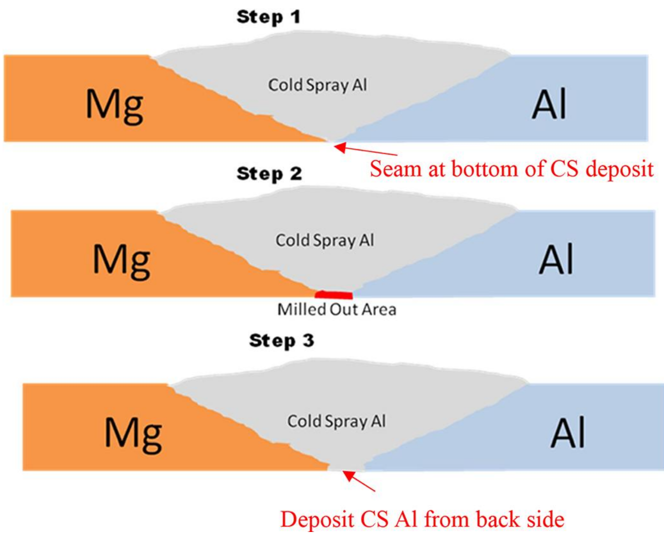

Figure 2. A butt joint design and sequential steps to join aluminum to magnesium by cold spray and eliminate any evidence of a seam.

in uniaxial tension with failure occurring in a 12.7-mm (0.5 inch) diameter section. A diagram of the specimen is shown in Fig. 6.

The spray conditions/parameters were optimized prior to this effort. The specimens were sprayed using a robotic arm to manipulate the cold spray applicator, and the substrate bars were placed in a circular array rotated using a single-axis rotary turntable. A spiral raster path pattern was utilized in order to reduce processing time and overspray. The robot was used to move the gun slowly across the specimens resulting in a spiral pattern to deposit each layer. The rotational speed and robot transverse were adjusted such that the relative velocity was equal to that of a typical raster cold spray pattern. The samples can be viewed in Fig. 7a, b before and after spraying. The as-sprayed specimens were machined to the required dimensions to form a cap and neck geometry. During testing, the specimen is secured in a two-plate fixture designed as shown in Fig. 8. The bottom section of the specimen and the overhead clamp are threaded to 25.4 × 305 mm (1 × 12 inch) for attachment to the load frame. The samples are pulled in tension using an Instron Model 1125 tension load frame. The test is carried out using a strain rate of 1.27 mm/min (0.05 in./min) at room temperature and approximately 50% relative humidity.

Results and Discussion

A total of 16 measurements of shear strength were recorded and the average maximum load to failure was 1,983 ± 10 kg (4,371 lbf ± 223 lbf), which equates to an average shear strength of 160.6 MPa ±8.3 MPa (23.3 ksi ±1.2 ksi). The 6061 Al cold spray deposits showed very high shear strength test results that are comparable to the shear strength of cast ZE41A-T5 Mg, which is reported as 160 MPa (23.2 ksi) [41].

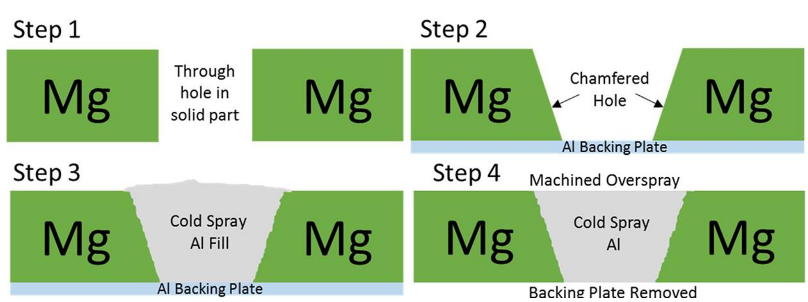

Figure 3. Steps taken to repair a through hole in Mg by CS using 6061 Al as the fill material.

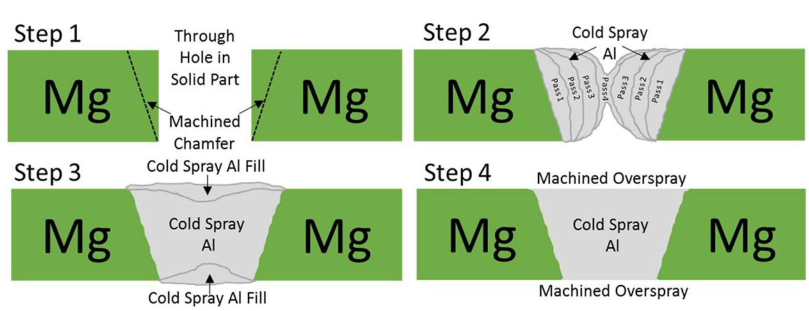

Figure 4. CS process to repair a through hole in Mg by CS without the use of a backing plate.

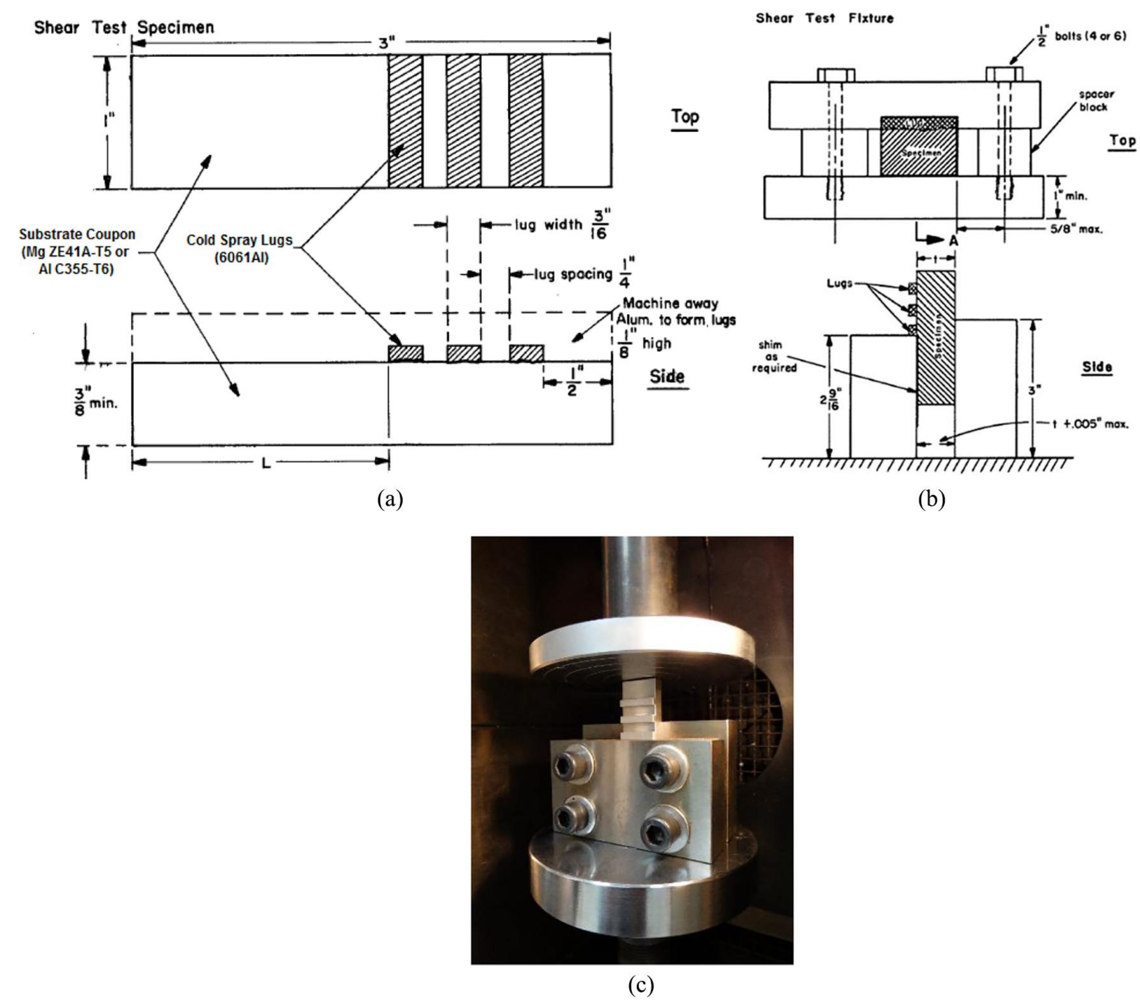

Figure 5. Schematic of the triple lug shear test specimen (a), test fixture (b) and photo of the actual load frame and testing set-up (c).

All of the samples of Mg ZE41A-T5 were tested at room temperature and fractured within the substrate material, as represented in Fig. 9.

The bond strength test results for a series of 6061 Al cold spray deposits on ZE41A-T5 Mg was obtained, and the average maximum load was 2106 ± 50 kg (4,644 lbf ± 110 lbf). These values correspond to an average ultimate tensile strength (UTS) of 163 ± 3.8 MPa (23.7 ± 0.6 ksi). Values as high as 184 MPa (26.7 ksi) with a corresponding load of 2,379 kg (5,246.7 lbs) were recorded. These values are commensurate with those reported by Champagne III *et al.* in their investigation of joining cast ZE41A-Mg to wrought 6061 Al by the CS process and friction stir welding [39]. They reported UTS values ranging from 130 to 164 MPa, but it is important to note that when 5056 Al was used as the cold spray

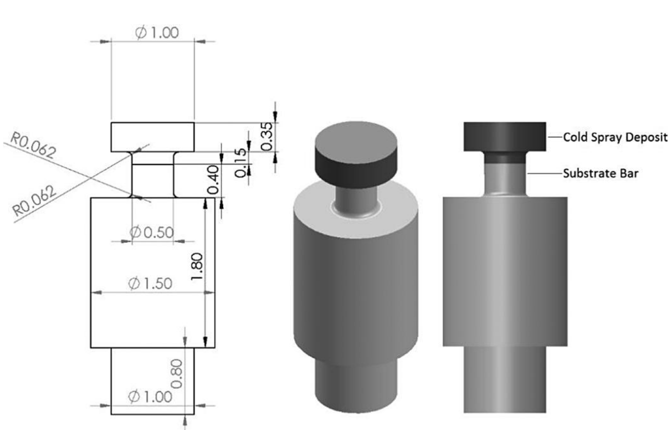

Figure 6. 'Glueless' bond strength test specimen mechanical drawing (dimensions in inches).

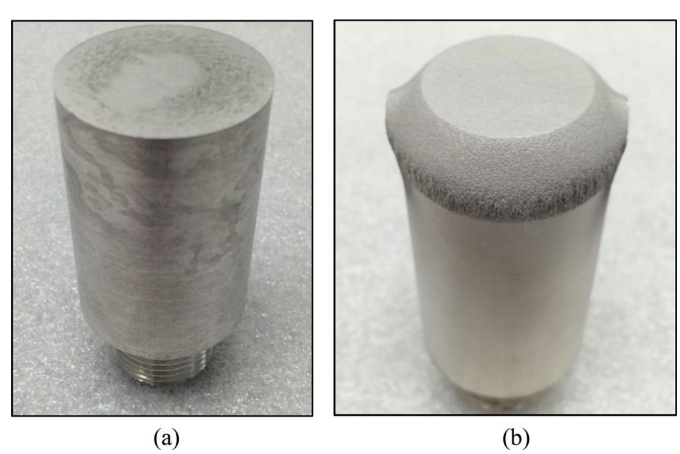

Figure 7. Uncoated ZE41A Mg 'glueless' bond strength test bar (a) and after spraying (b).

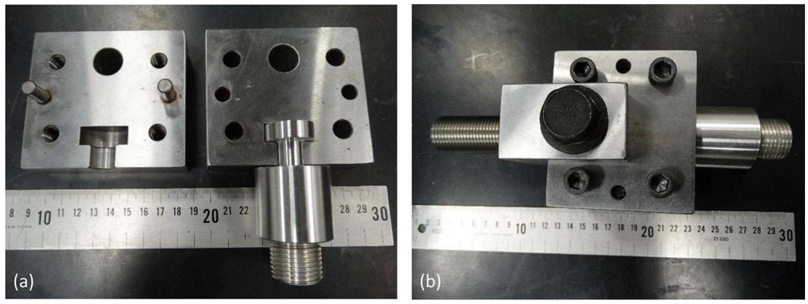

Figure 8. 'Glueless' bond strength test specimen fixture (a) and after being secured (b).

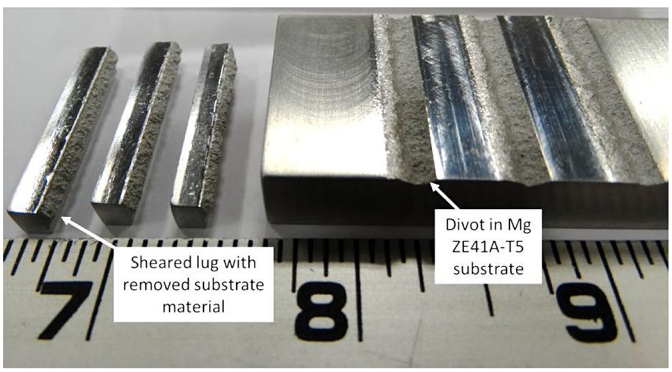

Figure 9. Representative specimen of 6061 Al triple lug shear test on Mg ZE41A-T5 substrate showing fracture beneath the substrate surface.

particulate material, the values of UTS increased and ranged from 181 to 198 MPa. Published values of the UTS of ZE41A-T5 Mg are 205 MPa [41].

Failure stress is reported based on the load at failure and the cross-sectional surface area at the failure point. A representative tested sample is shown in Fig. 10 with the failure shown at the deposit–substrate interface. The failure site varies from that of the shear test samples which was anticipated since the area of highest stress is at the interface within the tensile samples while it is slightly subsurface for the shear test samples.

Ultimate tensile strengths for adhesion of cold sprayed 6061 aluminum are reported well beyond the previous measurement limits using the ASTM C633 adhesion test. With testing capabilities no longer bound by the properties of the adhesive, the glueless bond test methodology can be transferred to a wide variety of cold spray deposit materials and substrates in assessment for structural repair applications.

Hardness was measured on standard metallographic specimens. The hardness was recorded over an average of a minimum of five evenly spaced indentations in accordance with ASTM E 384. Vickers hardness testing was performed using a 500-g load. The ZE41A-T5 Mg substrate had an average hardness value of 68 HV, while that of the cold spray 6061 Al was 105 HV.

Metallographic samples were taken to evaluate the microstructural features of the dissimilar metal joint between the 6061 Al cold spray deposit and the ZE41A-T5 Mg. Cross sections of the welded joint were taken utilizing a Leco cut-off saw, and one inch diameter metallographic samples were mounted in Bakelite and prepared incorporating a series of grinding steps starting at 180 grit and finishing with 2400 grit. Final polishing was accomplished using 3 um diamond paste followed by ¼ um diamond paste and completed using a 0.05-um colloidal silica suspension. The important aspects of the evaluation were that, as anticipated, no evidence of a heat affected zone (HAZ) was observed since the cold spray process is accomplished below any phase transformation temperatures and well below the melting point of both materials being joined (Figs. 11 and 12). Figure 11 represents an as-polished sample showing the interface of the ZE41A-T5 Mg and the 6061-T6 Al taken with the scanning electron microscope (SEM). The magnesium alloy ZE41A is a casting alloy having a combination of light weight, stiffness, and high strength and is currently used in the military and commercial aerospace industry for applications as high as 250°C for transmission housings. The major alloying elements are Zn and Zr, as well as the rare earth element cerium. This alloy has a thermally stable microstructure consisting of an α-Mg matrix, Mg eutectics, and various primary and secondary phases containing rare earth elements [42]. The ZE41A Mg cast alloy used in this study was heat treated to the T-5 condition, which is an artificially aged condition and the microstructure consists of α-Mg and β-Mg-Zn-RE according to Riddle et al. [43]. Figure 11 shows the β-Mg-Zn-RE grain boundary phase. Cerium is the rare earth alloying element for ZE41A and has a positive effect on creep resistance after aging. Additional precipitates formed within the grains and at the grain boundary that reduced grain boundary sliding [44]. Zirconium is used to refine grain size and zinc serves as a strengthening alloy

Figure 10. Bond test specimen showing failure at the coating–substrate interface.

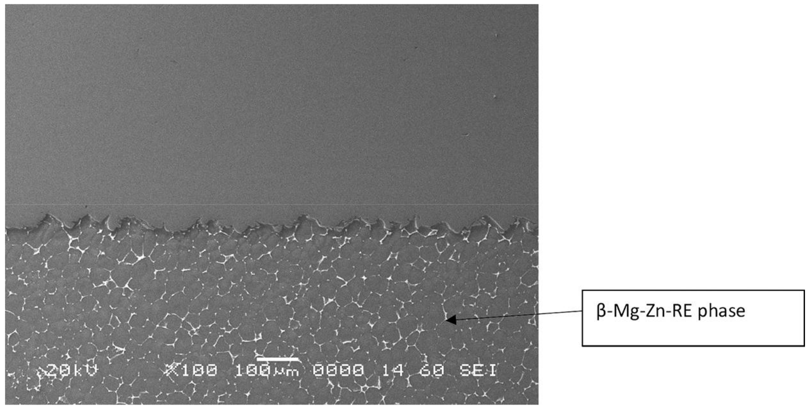

Figure 11. SEM of 6061 Al joined to ZE41A-T5 Mg showing a very dense deposit and no evidence of IMCs or other inherent defects at or near the interface. The weld has no heat affected zone and is free from porosity and defects often associated with conventional welds. The *β-Mg-Zn-RE* phase is shown at the grain boundaries of the Mg.

being found in solid solution and associated with the grain boundary precipitates. The CS layer near the substrate interface had a good deposition quality with no obvious evidence of porosity, triple junction voids, and lack of bonding between powder particles. This demonstrated suitable local particle deformation due to proper optimization of cold spray process parameters.

Figure 12 shows the same area but using optical microscopy and after being etched with Keller's reagent. There was no intermetallic layer or extensive IMCs formed at the dissimilar metal interface, which can have a size magnitude of over 500–900 µm [45]. The tremendous plastic deformation that occurred between the high velocity impacts of the spray particles results in very high strain rates, as shown in Fig. 13. Upon impact the plastic deformation disrupts and breaks down surface oxide layers on both the powder and substrate leading to a metallurgical bond, as well as mechanical interlocking (Fig. 13). Since the feedstock powder is deposited in the solid state, the microstructure is retained after deposition with the exception of dynamic recrystallization due to high strain levels. Localized temperature increases and strain concentration play a major role in the high speed deformation of the aluminum particles upon impact resulting in adiabatic shear. The large number of particles in flight can cause interactions between particles either before or during impact. Finally, deposited highly strained particles may be impacted immediately by other particles following the deposition of the next layer of impacting particles. This limited relaxation time after the deposition, in turn, can cause high strain hardening [46]. Roll-ups and vortices are formed as a result of particle penetration into the substrate material as a result of mechanical interlocking. Transmission electron microscopy was also performed to confirm these findings and the absence of coarse IMCs (Fig. 14). The spherical particles have undergone severe plastic deformation (SPD) and have become elongated through the cold spray deposition process and have formed pancaked structures at the interface. During the cold spray process, particles experienced enough deformation to remove the surface oxide to expose fresh material. Thermal softening due to the presence of SPD can enhance particle deformation

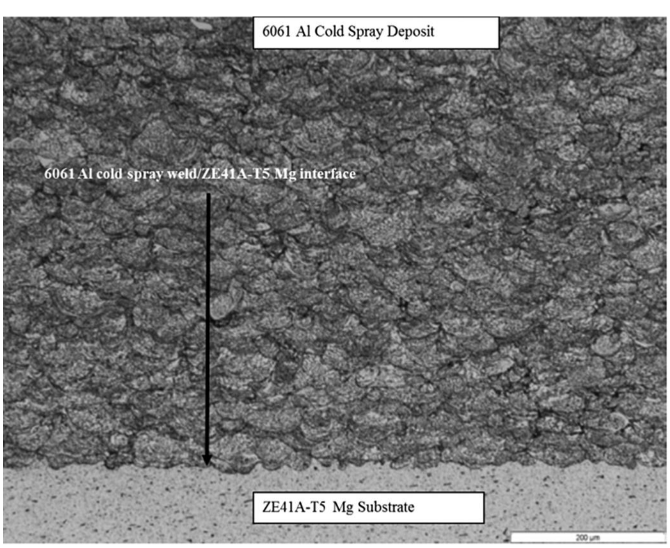

Figure 12. Etched microstructure of 6061 Al joined to ZE41A-T5 Mg showing no deleterious intermetallics at the interface or HAZ. Note the extensive degree of plastic deformation [39].

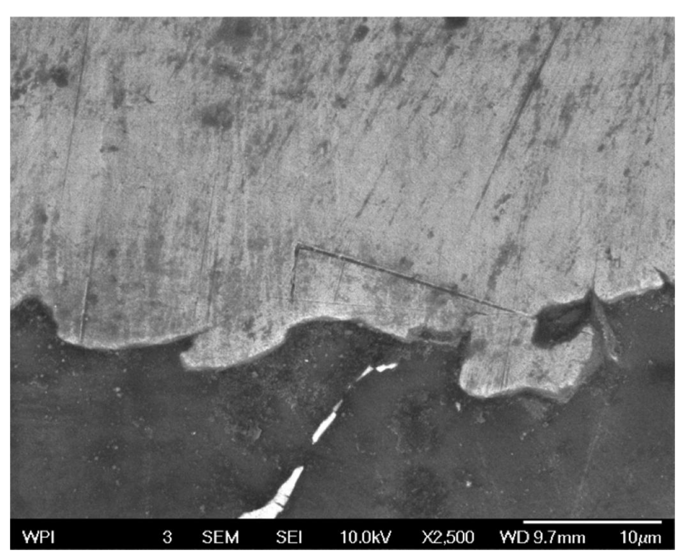

Figure 13. Enlargement of dissimilar metal interface between cold spray 6061 Al and cast ZE41A-T5 Mg. Note the mechanical mixing and adherent bond at the interface.

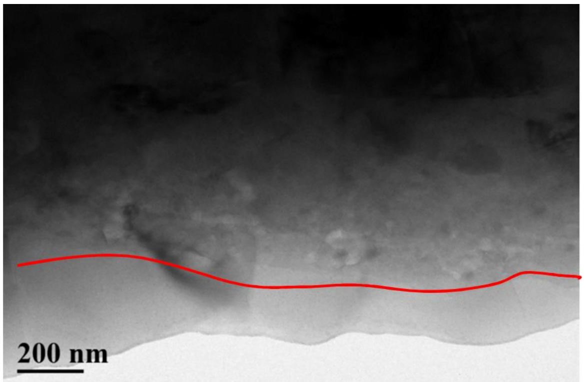

Figure 14. Formation of UFG structures at interface due to high strain rate deformation [39].

and interlocking of adjacent particles resulting in the intimate contact at the interface and consequently pancaked structures in the deposited material. However, the deformation for these particles was not enough to cause recrystallization or intermetallic phase formation [39]. It is evident in Fig. 14 that some of the particles have experienced sufficient deformation and heat during the impact that they have completely recrystallized at the interface, resulting in the formation of an ultra-fined grained (UFG) structure, but no evidence of coarse IMCs was found.

The materials, cast ZE41A-T5 Mg and 6061 Al, were chosen in this study because of their widespread applicability across several sectors of the aerospace and automotive industries. As previously discussed, the ability to join magnesium and aluminum has been attempted using various welding and joining processes to a limited degree. Many of the resultant joints have been poor or lacked sufficient structural integrity to be considered for applications, demanding high loads.

Magnetic pulse welding (MPW) is a solid-state welding technique comparable to explosive welding and produces a mechanically induced local weld, with a small fusion zone and no heat affected zone (HAZ). S.D. Kore et al. reported MPW was capable of eliminating the formation of IMCs and attaining a lap shear strength of 185 MPa when testing joints of AZ31-H24 having a UTS of 270 MPa and AL 3003-H14 having a UTS of 158 MPa [47].

However, Chen et al. showed that intermetallic compounds consisting of $Al_3Mg_2$and $Al_{12}Mg_{17}$ were formed at the weld interface as revealed by energy dispersive spectroscopy (EDS) line scans [48]. In another unrelated study, S. Chen et al. also confirmed the presence of an intermetallic β phase $Mg_{17}Al_{12}$ at the weld interface of dissimilar metal joints of Al and Mg [49]. Therefore, there is some disparity in the results obtained regarding the presence of IMCs when MPW is used to join Al to Mg. It does seem logical that IMCs would result because as S. Chen et al. point out that the interface layer is uniform due to local melting, intensive mixing of the melt, and a rapid rate of solidification intermetallic β phase $Mg_{17}Al_{12}$ [49]. Such elevated heat in this area would promote the formation of IMCs. Although MPW has shown to join dissimilar metals, it has yet to gain major acceptance in the welding industry [50,51].

Liu et al. conducted a review of dissimilar welding techniques for magnesium alloys to aluminum alloys in 2014 and have also reported that the formation of Mg2Al3 and Mg17Al12 IMCs is inevitable in the dissimilar Al/Mg joints under all conditions of the welding [52]. It is important to point out that Liu et el identified three primary approaches in an attempt to reduce or eliminate the formation of intermetallic compounds (IMC's) specifically: (1) using a solid state process, (2) improving IMC variety and distribution, and (3) reducing reaction and energy but even though the IMC reaction layer could be significantly reduced due to the low-welding temperature, the formation of brittle Al-Mg IMCs could not be completely avoided [52].

In this study, electron microscopy showed the absence of a coarse intermetallic layer of Mg2Al3 and Mg17Al12 being formed at the dissimilar metal interface and values of shear and tensile strength were obtained that were equal to or close to those of the weakest material being joined (Mg) when employing the cold spray process.

In comparison with diffusion bonding, Zhao et al. studied the use of an interlayer of Zn to improve the strength of the diffusion bond joint between Mg and Al. Zhao et al. reported values of shear strength between 75 and 83 MPa, which was twice that of the Mg–Al joints diffusion bonded directly but approximately half of that obtained for cold spray in this study, which were 160 MPa and as high as 184 MPa [9]. Xiangyu Dai, et al. have successfully joined Mg to Al using an arc-assisted ultrasonic seam welding technique incorporating a Sn/Zn composite interlayer to avoid the formation of brittle IMC's but only attained an average peak load of 2.5kN [53]. Mohammadi et al. studied lap FSW joints between dissimilar Mg AZ31B and Al 6061 alloy sheets produced while varying tool rotation and travel speeds. X-ray diffraction (XRD) analysis conducted by J. Mohammadi et al of the fracture surface of a debonded failure mode of the dissimilar metal joints indicated the presence of brittle intermetallic compounds, including Al12Mg17 (γ) and Al3Mg2 (β), which were attributable to decreased mechanical properties [54]. The highest values of lap shear tensile test results reported by J. Mohammadi et al were approximately 6.4 kN (1,459 lbs). Fernandus et al. attempted to optimize lap shear strength and bonding strength of diffusion-bonded dissimilar joints of AZ61A magnesium and AA6061 aluminum alloys and determined that the formation of intermetallics was responsible for the reduction of shear strength and bonding strength at the interface of the joints [55].

The high mechanical properties obtained in this study can be attributed to the high strength bond achieved by the cold spray process and warrant further discussion. Since the temperature of the gas stream is below the melting point of the particulate material during cold spray, the resultant consolidated material is formed in the solid state which made it feasible for joining low-melting temperature alloys, such as magnesium and aluminum. Since the adhesion of the impacted particles to the substrate, as well as the cohesion of the subsequent layers of CS deposit, was accomplished in the solid state, the cold spray joints were shown to maintain the microstructure, grain size, and elemental composition of the starting feed stock powder. The formation of a heat affected zone

(HAZ) was avoided, as well as deleterious tensile stresses that would occur during thermal contraction, associated with most welding techniques. Most importantly, the formation of Mg2Al3 and Mg17Al12 IMCs was avoided.

The CS process involves the acceleration of micron-sized particles which undergoes tremendous plastic deformation. Upon impact the plastic deformation disrupts and breaks down surface oxide layers on both the powder and substrate leading to a metallurgical bond, as well as mechanical interlocking, as was evidenced in this study (Figs. 13 and 14). The magnitude of the bond strength is directly related to optimization of the CS process parameters, condition of the feedstock powder, and surface preparation [39]. Since the feedstock powder is deposited in the solid state, the microstructure is retained after deposition with the exception of dynamic recrystallization due to high strain levels. The CS process is conducive to materials that can undergo high levels of strain with low energy input but also work hardens sufficiently to obtain the desired strength. Localized temperature increases and strain concentration play a major role in the high speed deformation of the aluminum particles upon impact causing adiabatic shear. Approximately 90% of the work of plastic deformation is converted to heat, and the flow stress of most metals is sensitive to temperature and decreasing as temperature increases. During impact of the solid feed stock powder particles, the oxide layers on both the powder and the substrate surface are disrupted and partially removed along with other impurities at the particle substrate interface causing the exposure of highly reactive un-oxidized metal and subsequent metallic bonding between particle and substrate material [56]. The feedstock powder forms an adherent metallurgical bond with the substrate as a result of the severe plastic deformation during particle impact [57,58]. The predominate bonding mechanism of the cold spray joint can be attributed to adiabatic shear, in combination with mechanical interlocking [56–59]. These attributes of the CS process were found to contribute to the exceptional strengths obtained from the dissimilar metal joint.

Conclusions

- CS did not result in the formation of an intermetallic layer at the dissimilar metal interface between cast ZE41A-T5 Mg and cold spray 6061 Al as confirmed by optical and electron microscopy. This is because the process is performed well above the melting temperature and the cold spray feedstock powder is consolidated in the solid state.
- Triple lug shear and tension testing results showed that CS is able to produce structural joints between dissimilar metals (ZE41A-T5 Mg and 6061 Al), with a bond strength equal to or superior to that of the substrate when tested in shear and uniaxial tension.
- Hardness testing has shown that the cold spray 6061Al was 105 HV while that of the cast ZE41A-T5 Mg had an average hardness value of 68 HV.
- This study has shown that CS can be used to form a dissimilar metal joint between ZE41A-T5 Mg and 6061 Al and be considered for structural repair.

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