13th International Conference on Aluminum Alloys (ICAA13)
Edited by: Hasso Weiland, Anthony D. Rollett, William A. Cassada
TMS (The Minerals, Metals & Materials Society), 2012

THE POTENTIAL OF THE COLD SPRAY PROCESS FOR THE REPAIR AND MANUFACTURE OF ALUMINIUM ALLOY PARTS

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Keywords: Cold spray, aluminium, repair, coating, metal matric composite

Being capable of producing deposits up to several centimetres thick, the cold spray process is emerging as an attractive technology for the manufacture and repair of high value aluminium and magnesium components. During the cold spray process fine aluminium or aluminium alloy powders are propelled at high velocities in the solid state at the target substrate. Due to the high velocity particle impacts, strong bonds are formed between the coating and the substrate and between particles within the deposited layer. Metallographic sections of cold sprayed coatings reveal microstructures characterised by very low porosity. With the objective of improving the abrasive wear and erosion resistance of cold sprayed coatings, ceramic reinforcements such as SiC, B_4C and Al_2O_3 have been introduced in the feedstock to produce composite coatings, and these composite materials have been deposited with thicknesses in excess of 25mm. Several applications employing commercially available equipment have achieved industrialisation.

Introduction

Many of the metallic alloys increasingly used in the aerospace sector have been designed to meet demanding engineering requirements (e.g. tensile strength, fatigue, fracture, creep, thermal cycling and oxidation resistance) and have bulk properties which must be retained following repair. Repairs fall into several categories depending on the nature of the damage:

1. Local material loss due to wear or corrosion, where restoration is required primarily to prevent further material loss (and to prevent further loss of structural integrity) and the repair must meet minimum specified requirements.
2. Substantial loss of material, considered significant with regard to component structural integrity and the repair must meet stringent metallurgical requirements.
3. Other repairs (e.g. fractured components and those needing thermal rejuvenation).

The first repair scenario is addressed using existing coating technologies (including those used in the original component manufacture) such as thermal spray, vapour deposition or electroplating. A classic example is the re-application of a thermal barrier coating (TBC) onto gas turbine components. The second repair scenario is more challenging, since it requires addition of material which is metallurgically bonded to form a dimensionally significant, structural element. Repair welding results in microstructural transformation of the adjacent substrate. Although it might be possible to restore the original condition by heat treatment, other limitations can arise e.g. formation of brittle intermetallic compounds, residual stresses and distortion. An example is the repair of high value Mg alloy components such as helicopter engine gearboxes and gas turbine engine fan case frames, which until now were considered non-repairable. This problem is also commonplace with many of the high strength Al, Ni and Ti alloys widely used in the aerospace sector. In these cases, there is a need for innovative repair technology, whereby material can be deposited at a high rate with the required properties. It is believed that a new technology, cold spray deposition, might meet this challenge. Although cold spray uses particulate feedstocks similar to thermal spray processes (HVOF, plasma) and powder welding deposition (laser, plasma transferred arc, powder welding), it differs from thermal spray and welding processes in two ways:

1. The coating material (powder feedstock) is not oxidised (as is for example the case in thermal spray) during deposition.
2. The coating material is not melted during deposition. The rapid re-solidification and transformed microstructure that occurs when welding or thermal spraying does not occur.

Cold Spray Deposition Process

Cold spray is a solid-state deposition process in which the kinetic energy of fast-moving solid particles is converted into interfacial deformation and localised heat upon impact with the substrate, producing a combination of mechanically interlocked and metallurgically bonded particles, Figure 1 [1]. Powder particles require a minimum critical energy (related to impact velocity and temperature) for effective bonding. Accumulation of multiple layers of cold spray particles can produce deposits in excess of 20mm thick, Figure 1.

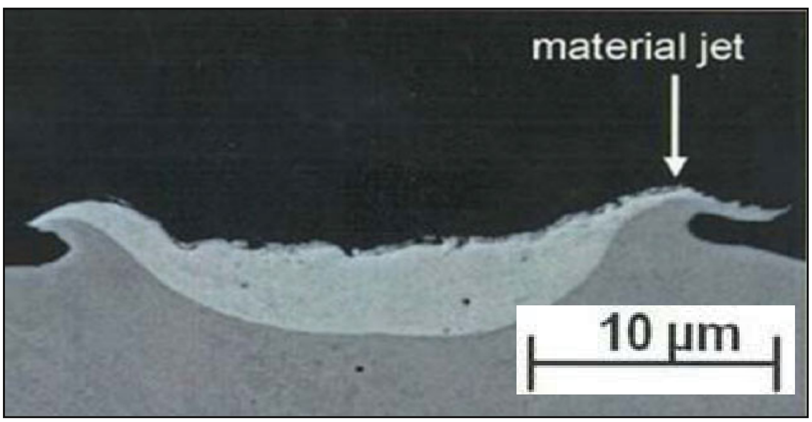

Figure 1. Cold spray particle deformation and bonding (left, [1]) and Al-MMC material deposited to a thickness of ~ 25mm (right).

Cold spray has low and high pressure process variants. High-pressure cold spray systems normally use N_2 as the propellant gas at pressures up to 55bar, Figure 2. The gases are accelerated to supersonic speeds (1200m.s^{-1}) by heating to 800ºC and passing them through a de Laval nozzle.

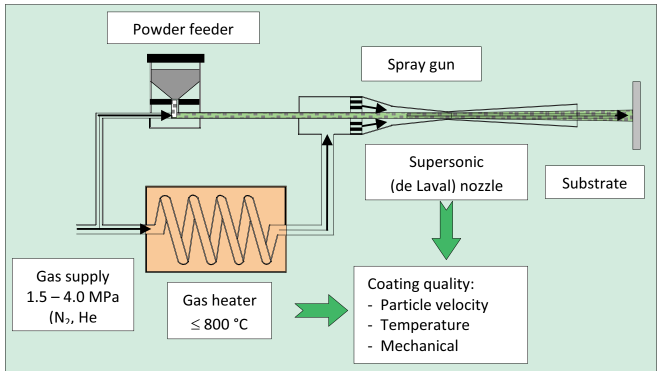

Figure 2. Basic schematic of cold spray process.

The feedstock powder is introduced in the high-pressure side of the nozzle, prior to the nozzle throat. The energy levels attained provide much higher deposition efficiencies and a wider range of deposited materials (e.g. stainless steels, Ni, Ta, Ti and Mo) but at the expense of higher equipment complexity, higher costs and limited portability. Helium is occasionally used when the required coating properties cannot be achieved with N_2. Further nozzle design and powder development is essential if coatings with the required properties are to be produced at affordable prices using N_2. If this is possible, cold spray costs will compete with thermal spray and will be significantly lower than laser powder deposition.

In low-pressure cold spray (5-20bar), pressurised air, N_2 or He is heated up to 550ºC and fed through a converging-diverging de Laval nozzle where gas accelerates to $600 m.s^{-1}$. The feedstock is introduced downstream of the nozzle throat in the divergent section. Low-pressure systems are suited to spraying ductile metals e.g. Al, Cu, Zn, or Sn. There are several commercial, low-pressure systems on the market, which are simple, portable and inexpensive to operate but are restricted to a maximum of 20bar delivery pressure for reasons of practicality and safety [2, 3].

Cold Spray - Technology Status

The key patent dates back to 1994, following which process and application developments initially focused on cold spray as a coating technology [4]. However, since 2005, several organisations, most notably the US Army Research Laboratory (ARL) and the Australian military have funded programmes to qualify the repair of Mg alloy helicopter gearboxes by cold spray [5, 6]. ARL has progressed gearbox repair to the extent that four new cold spray installations are planned in the USA during 2011-2012 for component repair [5].

With the exception of isolated commercial aerospace applications, such as the deposition of Al coatings on the internal surface of aircraft landing gear and the repair of Al propeller blades by Praxair in Germany, there are no reported technology-ready light alloy applications in Europe [7]. Unlike the USA where Military Standard MIL-Std 3021 has been in use since 2008, Europe has no cold spray process, materials or manufacturing-related standards [8].

Although significant effort has been expended in developing models for the cold spray deposition of simple ductile materials such as pure copper, there are little or no data relating to engineering materials such as Al, Ni and Ti alloys [9]. A better understanding of the relationships between nozzle design; gas supply pressure, flow rate and temperature; particle composition, morphology, size distribution and microstructure; and substrate preparation are required if a systematic approach to optimising cold spray characteristics is to be achieved.

Current Production And Near-Production Applications

The ARL has focused on the development and qualification of cold spray repair techniques to reclaim Mg components, with requirements to mitigate galvanic corrosion and corrosion pitting, the primary causes for removing the components from service [5]. Repairs to date have been confined to non-structural areas of the transmission and gearbox housings. The most severe of these has been associated with large, expensive transmission and gearbox housing assemblies for rotorcraft, which are removed prematurely from service because of corrosion, thus adversely affecting fleet readiness and safety. ARL has evaluated CP-Al, AA 4047 (Al-12Si), AA 5056 (Al-5Mg-0.1Mn-0.1Cr) and AA 5356 (Al-5Mg-0.1Mn-0.1Cr-0.1Ti) powders and validated the cold spray process in terms of the adhesive strength of CP-Al coatings deposited using different process gases, spray parameters and 1000 hour salt spray corrosion testing [5].

Australian coating and repair contractor, Rosebank Engineering (RBE) has worked towards obtaining cold spray approval to Military Standard MIL-Std 3021 and, in collaboration with the Australian Defence Agencies has developed a Certification Baseline matrix to enable acceptance of proposed applications, such as the corrosion protection and geometry restoration on Seahawk tail rotor and intermediate gearbox housing feet, main module sump and flight control pad; P3 NWS housing; F111 Spike tip and the Caribou MLG cylinder [6]. The acceptance protocol matrix comprises various cold spray powders, selected Al and Mg alloy substrates and tests including corrosion, tensile, shear, fatigue, residual stress, impact, hydrogen embrittlement and coating tensile strength testing. Preliminary tests demonstrated the potential for cold sprayed AA 7075 coating to extend the fatigue life of damaged structural components. The baseline specimen (AA 2024) lasted approximately 35,000 cycles; in contrast, the panel repaired with the cold sprayed AA 7075 coating showed no evident damage in the coating or crack growth in the 2024-T3 skin after 120,000.

Praxair Surface Technologies repairs commercial and military aviation engine and airframe components, and applies protective coatings to repaired parts [7]. It has published several articles on the application of cold spray as a repair process on C-160 propeller blades (coating materials AA 2224 and 2014), CH-53 landing gear housing (coating material AA 7075) and for structural frame repair on thin walls (<1.5mm), depositing AA 6061 and AA 5056 coatings with thickness exceeding 4mm,. These coatings showed very dense microstructures and an adhesive strength exceeding 60MPa. The choice of process gas significantly affected the fatigue strength of the AA 2224 coating, with the coating performing better than the base material (AA 2014) when helium was used. Similarly AA 7075 coatings deposited with He were also found to have fatigue strengths higher than the base material (AA 7075).

Applications Under Development

Boeing has evaluated cold spray repair of damaged ion vapour deposition (IVD) Al coatings, worn Al aircraft parts and damaged Alclad aircraft skins [10]. Work is on-going to confirm coating thickness range of 1-3mil (25.4-76.2µm), adhesion, fatigue hydrogen embrittlement and corrosion targets (1000 hours salt spray test) are met or exceeded. Pratt & Whitney Rocketdyne (PWR) has evaluated cold spray repair of a discontinuously reinforced aluminium alloy structural jacket used for space propulsion. It has also evaluated cold sprayed AA 6061 for fan case corrosion and structural repair, with coating structural requirements for shear strength, tensile bond strength, cyclic fatigue and corrosion resistance [11]. Although the as-sprayed AA

6061 coating showed low ductility due to the amount of work hardening, after full annealing treatment, the properties of the coating were comparable to those of AMS 4025 plate. PWR has published adhesive strength data of ~70MPa for cold sprayed Pandalloy® deposits on AA 6061 base material [11]. Neither development has been implemented in production or repair at present.

In parallel with the work undertaken at ARL, activities related to the repair of Mg alloy components are under way at the Pennsylvania State University, commissioned by the US Navy. Coating materials of interest are CP Al (99.8%), HP Al (99.95%), AA 5356 and AA 4047 to be deposited onto ZE41A-T5 Mg substrate and tested for corrosion [12]. European Aeronautic Defence and Space (EADS) believes that Al-MMCs are an attractive alternative for Ti-parts for applications including [13] structural struts in the space shuttle (AA 6061); the Hubble Space Telescope antenna mast (AA 6061); Eurocopter helicopters blade sleeves (AA 2009 + SiC); fan exit guide vanes in the PW4000 gas turbines (AA 6092 + SiC) and F-16 aircraft fuel access door covers and ventral fin (AA6092 + SiC). EADS has published no substantial data relating to these applications and it is not known if any of these potential applications has been implemented in production to date.

Cold Spray Deposition of Al-MMC Materials

The cold spray system installed at TWI is a commercial high-pressure system, capable of delivering gas pressures and temperatures up to 40bar and 800ºC respectively. Since its installation in 2007, TWI has focused on aerospace projects (repair of Mg alloy using CP-Al) and non-aerospace projects, e.g. Al alloy coatings for electronic devices and Al coatings for corrosion protection of carbon steels [14]. These projects have typically comprised definition and procurement of suitable powder feedstocks, development of spray procedures, preparation of application-related test coupons and coating of demonstration components or parts thereof [15]. CP-Al was cold sprayed onto Mg alloy and C-steel substrates resulting in adhesive bond strengths of 38 and 48MPa, respectively. These values exceed those of conventional wire flame spraying (7-10MPa) and twin wire arc spraying (15-25MPa). A typical metallographic section of a cold sprayed Al coating reveals a microstructure superior to wire flame spray with very low porosity and a well-bonded interface, Figure 3.

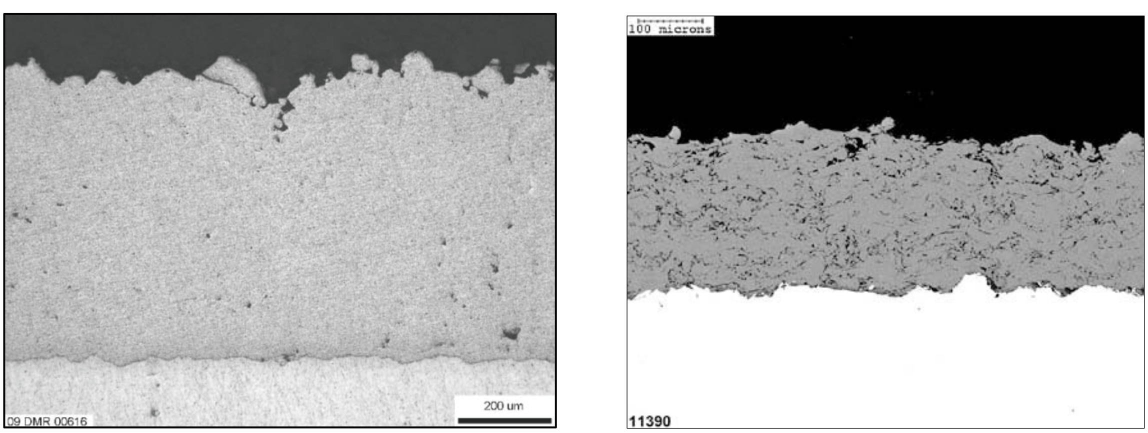

Figure 3. Metallographic cross-section taken through Al coatings deposited by cold spray (left) and wire flame spray (right).

Ceramic reinforcements such as SiC have been introduced in the feedstock with the objective of improving the abrasive wear and erosion resistance of cold sprayed coatings, Figure 4. Recently, the inclusion of Al_2O_3 in the coating was found to have no negative effect on the anti-corrosion properties of an Al coating [16]. With regards to the deposition of composite coatings, TWI has recently installed a second powder feed unit to facilitate controlled co-deposition of metallic and ceramic powder feedstocks and an adapter to the spray nozzle with axial powder feeding. Combined with the dual powder feeding unit, it has the option for one of the powders to bypass the gun 'pre-chamber' (where most of the heat transfer occurs between hot gas and powder particles), permitting the deposition of composite coatings where the materials have very different melting points (e.g. Al and ceramic).

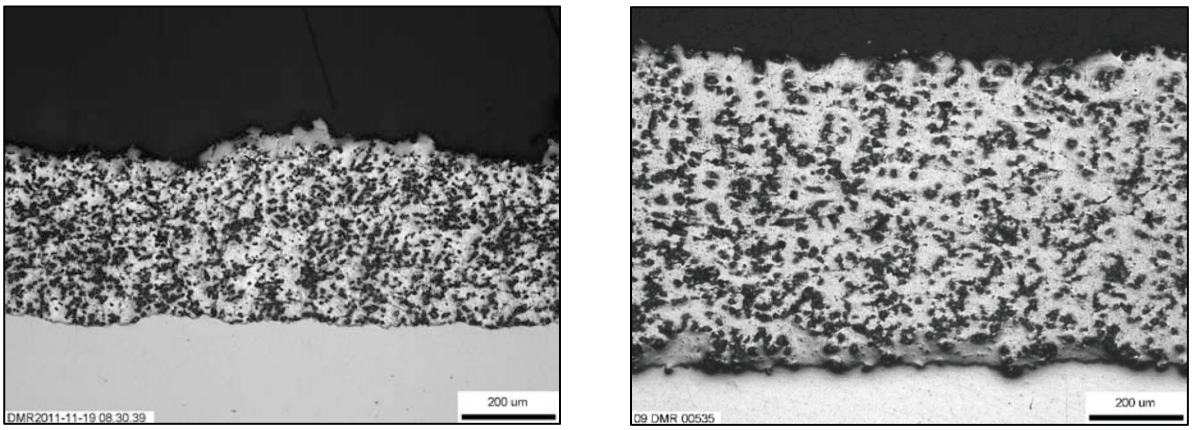

Figure 4. Metallographic cross-section of Al coatings co-deposited with SiC particles (left) and co-deposited with B_4C particles (right).

Conclusions

1. Cold spray is a new process that deposits dense coatings without thermal affect to the coating material or substrate. As such, it offers the potential for repairs with bulk material properties.
2. Published property data corrosion, wear, mechanical strength and fatigue are still quite limited and cold spray technology is at the transition between R&D and industrial implementation.
3. The co-deposition of Al-MMC coatings has been successfully demonstrated with over 20mm thick deposits possible.

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