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Cold gas dynamic manufacturing: A non-thermal approach to freeform fabrication

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Abstract

This paper reports on the development of a novel freeform fabrication technique using a cold spray (CS) system. In the CS process, metallic powder particles are accelerated in a supersonic gas jet and impacted with a substrate at speeds in excess of 600 m/s. The non-melting nature of its deposition mechanism ensures that the sprayed material is free from thermally induced tensile stresses, while the underlying substrate remains unchanged. The process is seen as a viable method for additive manufacturing because of its high deposition rates and controllable spray jet. A process was developed to investigate the potential of non-thermal freeform fabrication and was coined Cold Gas Dynamic Manufacturing (CGDM). Here, additive and subtractive techniques were combined to enable the production of complex geometries. Whereas most CS facilities concentrate on the application of wear or corrosion-resistant coatings, CGDM is dedicated to the production of freeform components, whilst still retaining an inherent coating ability. The process can produce functional forms using novel manufacturing strategies that are unique to CS. This paper presents information on the process, and details the various strategies employed during component fabrication. It was possible to construct components from many materials, including titanium, which exhibited freeform surfaces, internal channels and embedded devices. A breakdown of the process economics is also provided, with and without helium recycling.

Keywords: Cold spray; Embedded devices; Helium recycling; Moulds; Sacrificial materials; Titanium

1. Introduction

Rapid manufacturing (RM) technologies are commonly used to fabricate freeform components on a layer-by-layer basis. Each layer is created by the selective addition of material corresponding to a cross-sectional slice of the part to be built. By using this type of additive-manufacturing technology—as opposed to the traditional subtractive and formative fabrication techniques such as milling and forging—RM technologies enable the production of functional engineering components in a single step, where the time and cost of manufacture is independent of component complexity [1,2].

RM techniques are dedicated to the production of metallic components and can be broadly grouped by their material consolidation process. Whereas selective laser sintering (SLS) [3] employs a sintering process to consolidate the build material, processes such as direct metal deposition (DMD) [4], laser engineered net shaping (LENS) [5] and solid deposition modelling (SDM) [6] rely on melting and re-solidification. While many of these techniques are being employed commercially, they can all suffer the detrimental effects of high-temperature processing such as large residual stresses, poor mechanical properties, unwanted phase transformations and part distortion [7]. Several thermal spraying techniques have also been applied to the fabrication of free-standing components, including plasma spraying (PS) [8] and high velocity oxy-fuel (HVOF) spraying [9]; however, they too involve melting and solidification. Cold spray (CS) has been identified as a thermal spraying process with the potential to perform *non-thermal* freeform fabrication.

In CS, small-size particles are accelerated to supersonic velocities in a high-speed gas jet. When directed towards a substrate, if the particle impact velocity is above

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a material-dependent critical value, the ballistic impact events that result cause massive plastic deformation in both the incident particles and the underlying material. This process disrupts thin surface films such as oxides and exposes fresh, active material, which when brought into intimate, conformal contact under high localised pressures, undergoes adiabatic shear instabilities to form strong atomic bonds [10].

CS has until recently been used entirely for the application of surface coatings using metals, alloys and composites [11]. Unlike other thermal spray processes, CS operates with little or no heat. Because of this, the CS process has been frequently used to deposit temperature-sensitive materials such as nano-crystalline and amorphous materials [12,13], as well as oxygen-sensitive materials such as aluminium and titanium. However, it is the process' ability to rapidly develop thick coatings and complex free-standing shapes that distinguishes it from its thermally based counterparts (Fig. 1). By combining the additive properties of CS with the subtractive properties of high-speed machining, a process was developed to rapidly manufacture functional engineering components from many materials. So called cold gas dynamic manufacturing (CGDM), the process is compared to other RM techniques in Table 1.

2. CGDM principle and apparatus

The CGDM process is shown schematically in Fig. 2. A high-pressure (2 MPa) helium gas stream is fed to a gas heater (primary stream) and a powder feeder (secondary stream). The primary gas stream is heated to moderate temperatures ($\leqslant 600\,^{\circ}$C) and accelerated to supersonic velocities in a converging–diverging, or de Laval nozzle. This heating process increases the sonic velocity of the gas and compensates for the adiabatic expansion and cooling that occurs through the nozzle. At the same time, the secondary gas stream entering the feeder fluidises the powder and transports it to the nozzle. The particle stream is injected axially into the gas flow, a short distance from the nozzle throat. The high-velocity, powder-laden gas jet exits the nozzle and is directed towards a substrate. On impact, deposition occurs as a result of the massive plastic deformation and bonding that takes place.

The CGDM process is housed within a helium-tight build chamber. Within this chamber, the nozzle is fixed to the Z-column of a 3-axis machine tool whilst the substrate is mounted to the X–Y table. The path traversed by the nozzle is controlled by CNC and corresponds to the cross-sectional geometry of the part to be built; the part description is pre-programmed in a 3D CAD file. A high-speed

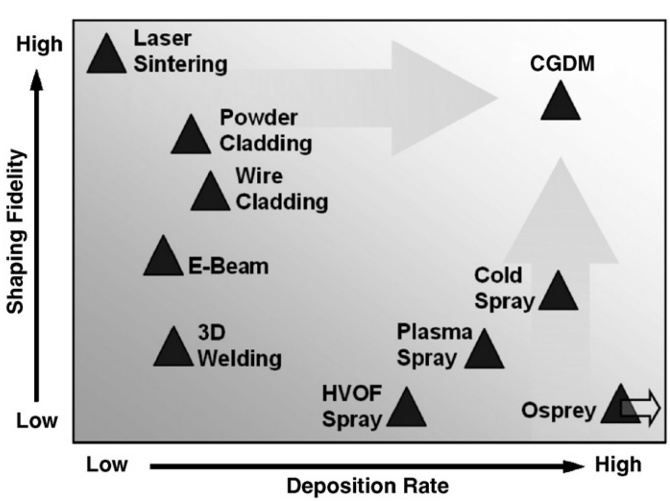

Fig. 1. Comparison of CGDM and CS with other additive manufacturing processes.

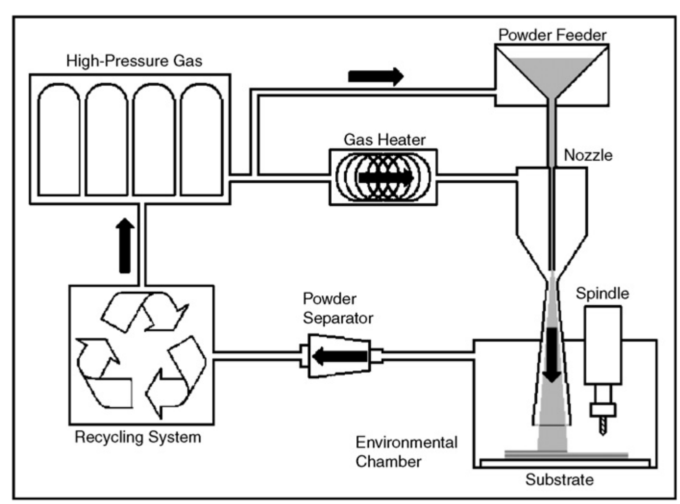

Fig. 2. Schematic diagram of the CGDM process including high-speed machining spindle and helium-recycling system.

Table 1
Comparison of the CGDM process with other RM processes

Process	Type	Accuracy	Layer thickness	Deposition/build rate	Deposition efficiency	Deposition materials
SLS [1,3]	Sintering	±50 um	≤75 um	Low	N/A	Steels, numerous
DMD [4]	Cladding	High	≤0.254 um	≤4.1 cm^3/min	N/A	H13, Al, numerous
LENS [4,5,14]	Cladding	±100 um	≤0.4 um	Low	≤14%	SS, Alloys, numerous
SDM [4,6]	Droplet cladding	±10 um (Machined)	Variable	≤30 g/min	N/A	SS, INVAR
PS [15]	Thermal spraying	Low	≤0.5 um	50–100 g/min	≤60%	Ceramics, numerous
HVOF [15,16]	Thermal spraying	Low	≤1.5 um	20–80g/min	≤70%	Carbides, numerous
CGDM	Cold spraying	±10 um (Machined)	≤0.05–10 um	≤10 cm^3/min	≤100%	Al, Cu, Ti, numerous

($\leqslant$50,000 rpm) machining spindle is incorporated to add component detail or improve surface finish. The exhaust gas and powder are extracted from the chamber via a high-flow rate blower. The powder is separated from the gas using vortex generation technology and the clean gas recycled and recompressed ready to be used again.

2.1. Deposition nozzle

Several factors affect the performance of the CS process, but none more so than the design of the nozzle; particle acceleration in the supersonic gas jet is critical for the successful deposition of material. The theory behind nozzle design for supersonic flow applications is well-established and can be found in many texts [17,18]. The design of nozzles specific to the CGDM process was presented by Pattison et al. [19]. During this research, a 2-MPa helium nozzle with a length of 180 mm was used.

2.2. Build Chamber

The chamber shown in Fig. 3 allows the exhaust products to be contained and recovered, whilst minimising contamination to the internal and external environment. Furthermore, it ensures that the atmosphere inside the chamber remains inert during processing. The chamber is fitted with bespoke optical apparatus that permits the indirect measurement of in-process particle velocities using particle image velocimetry [19].

While the CS process enables near-net shape deposition with reasonable accuracy and little overspray, fine features and good-edge definition are difficult to achieve [11]. Moreover, the as-sprayed surface finish is inferior to conventional milling techniques. Therefore, the spindle is located such that in-process machining can take place within the chamber. After each layer has been sprayed, the component surface can either be milled flat or provided with additional detail. At the end of spraying, the deposit is machined to net shape. The working volume of the chamber is 150 × 150 × 150 mm.

2.3. Helium-recycling system

Although the CGDM process generally uses helium, nitrogen may also be used. The advantages of using helium over nitrogen are well known [20]; however, due to its elevated cost per unit volume and higher flow rates, the cost of spraying with helium is significantly more expensive than with nitrogen [21]. In order to reduce these costs, a helium-recycling system (HRS) was developed specifically for the CGDM process. Unlike conventional membrane-based systems, which rely on fixed operating conditions, the CGDM pressure swing adsorption (PSA)-based system operates independently of gas input purity levels.

The HRS operates on a five-stage, batch procedure. Firstly, helium is delivered from a high-pressure storage vessel to the deposition nozzle at pressures up to 2.5 MPa. During spraying, the exhaust gas is retained by the chamber and extracted to a low-pressure storage vessel. This low-pressure gas is then compressed to a medium-pressure level (2 MPa) before it is ‘scrubbed’ of impurities (oxygen, nitrogen, etc.) and recompressed to the required storage pressure (15 MPa). Any helium that may have been lost during the spraying and purification processes is replaced; nitrogen may also be added at this point to achieve a desired mixture. The gas is then delivered back to the high-pressure storage vessel ready for spraying.

The chart shown in Fig. 4 represents the gas and powder costs associated with depositing 1 kg of copper and titanium, using both helium—with and without recycling—and nitrogen. Here, a cost ratio of 30:1 was applied to helium and nitrogen, whilst a ratio of 3:1 was applied to the cost of titanium and copper. Capital expenditure was not considered since it would be the same for helium and

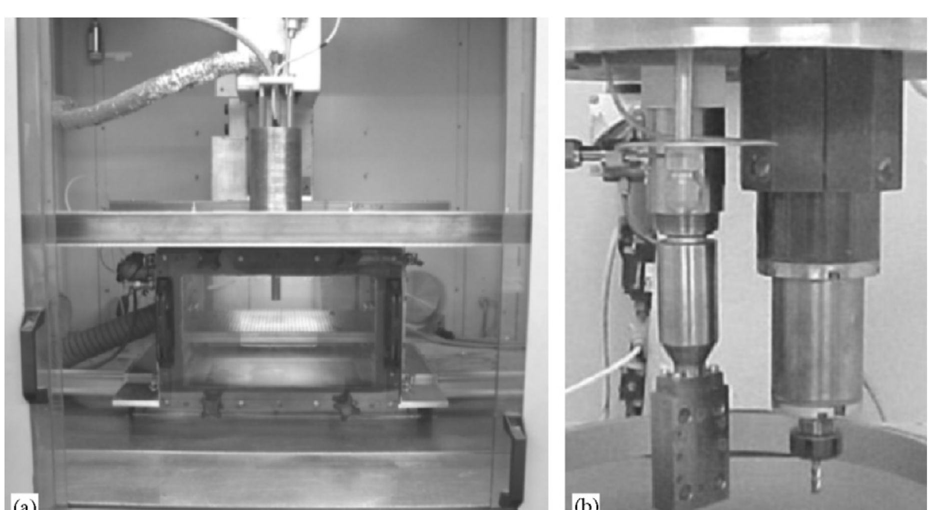

Fig. 3. Two photographs showing (a) the environmental chamber used to enclose the CGDM process and (b) the nozzle and machining spindle.

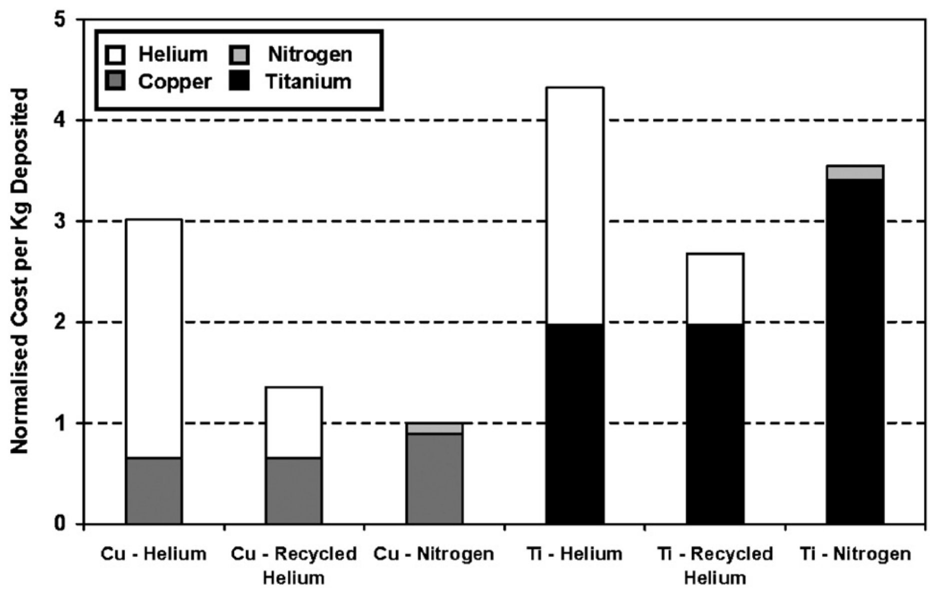

Fig. 4. Chart showing the cost of deposition in terms of gas and powder used. Data applies to a kilogram of chopper and titanium deposited with helium (with and without recycling) and nitrogen.

Table 2
Data used for the comparison of material costs in the CGDM process when using helium—with and without recycling—and nitrogen, to spray copper and titanium

	Gas pressure (MPa)	Gas Temp. (°C)	Throat diameter (mm)	Gas flow rate (l/min)	Deposition Cu (%)	Efficiency Ti (%)
Helium	2.0	350	2.0	1490	95	95
Recycled helium	2.0	350	2.0	1490	95	95
Nitrogen	3.0	350	2.7	1490	70 [22]	55 [22]

Note: a recycling efficiency of 70% was used.

nitrogen systems. The additional information used to produce this chart can be found in Table 2. When spraying with helium, the greater deposition efficiencies experienced generate powder-cost savings. However, these are small compared to the high gas costs. Recycling reduces the gas costs significantly but still cannot be justified for relatively cheap powders. When using high-cost, high critical velocity powders such as titanium, the increase in deposition efficiency can make the use of helium recycling more cost-effective. Thus, spraying with helium can be justified and makes the CGDM process economically feasible. At present, recycling efficiencies of 70% and above are regularly achieved.

3. Build strategies

Whereas CS is dedicated to the production of thin surface coatings, CGDM has been developed to deposit thick coatings and free-standing components. Here, things such as overspray and spray resolution, as well as multiple-layer deposition and edge effects become important. Starting from the deposition of simple multi-layer coatings and ending with the fabrication of complex components containing embedded devices, the strategies required to successfully deposit the necessary material are discussed.

3.1. Thick coatings

During deposition, the material laid down over a unit length may be controlled via the powder feed rate (PFR) and traverse rate (TR). If the PFR is low and the TR is high then thin, flat tracks are obtained. As the PFR is increased, and/or TR decreased, the tracks become rounded and eventually develop a sharp-triangular profile like that shown in Fig. 5(a). In this case, the triangular profile was produced by multiple passes of two different materials. This profile is a result of several factors. Firstly, the particle spatial density decreases with distance from the jet centreline [19]. Similarly, deposition efficiency decreases with distance from the centre of the jet due to the particle velocity profile across the nozzle exit and the increasing angle of impact [19,23]. This is exacerbated by particles

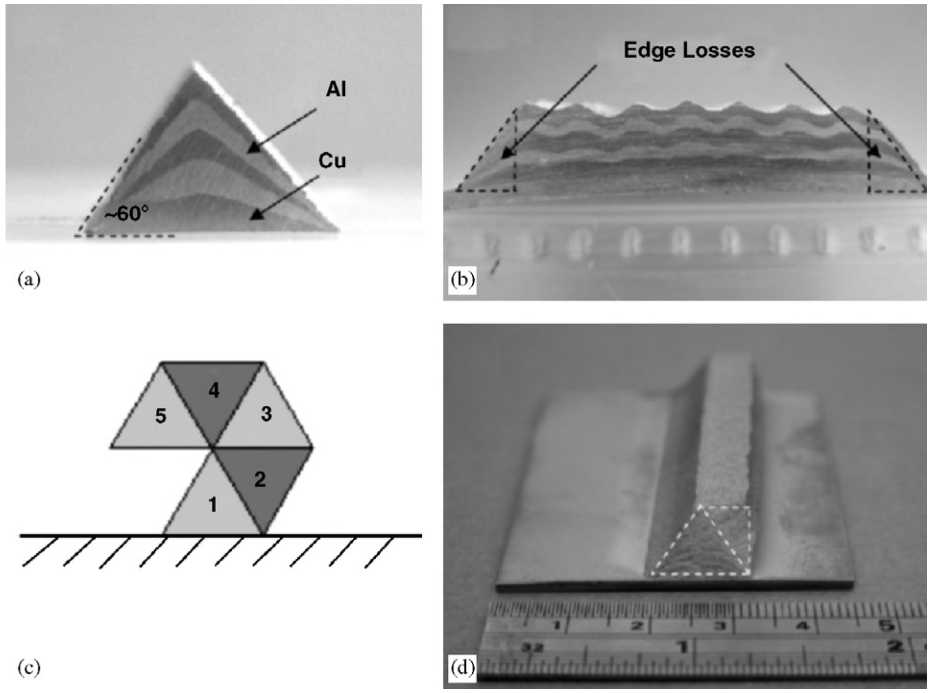

Fig. 5. Photographs showing (a) track growth, (b) layer building and edge losses, (c) the triangular tessellation scheme for the production of primitive shapes and (d) a vertical wall created using the same technique.

passing through the high-density blunt shock—formed in the jet–substrate impingement zone—such that particles with velocities only slightly above the critical velocity are further decelerated and effectively 'filtered' out, especially in the jet periphery [23,24]. When these factors combine, a greater degree of deposition is observed in the centre of the jet that eventually causes the track profile to become triangular. At that point, the angle of the inclined surfaces ($\sim 60^{\circ}$) is such that no further deposition can occur [23], except at the peak.

When laying down material for thin coatings (<1 mm), the profile of the deposited tracks are low and flat, and the overlap strategy is not critical. However, during multi-layer deposition, if a track overlap and/or build strategy is not employed then the resulting thick coating will have an uneven surface, Fig. 5(b). As a result, the build rate is reduced due to the drop in deposition efficiency associated with inclined surfaces. No matter what the build strategy, inclined surfaces at the edge of a coating or component are an unavoidable consequence of spraying with a 3-axis system. It, therefore, becomes impossible to create vertical walls without edge milling. In addition, to deposit a thick coating with an upper surface of prescribed area, the first layer must have a substantially larger area to account for the inclined edges. These regions of overspray need to be removed post-process and constitute edge losses.

3.2. Vertical walls

In order to create vertical walls without edge milling, a 4/5-axis system is required. The advantage of this type of system is that by tilting the nozzle so that it deposits normal to the inclined surface of a previous track, material may be deposited in the correct orientation to generate a vertical surface. Similarly, by tessellating the triangular track profile, shown in Fig. 5(c), it is envisaged that primitive shapes and even complex components could be fabricated with little or no machining. At present, the CGDM process utilises a 3-axis system; however, by adding a rotational stage to the chamber, a fourth axis was generated. In this case, it was the substrate that was tilted rather than the nozzle. Fig. 5(d) shows a photograph of a vertical wall created by this triangular-tessellation technique.

3.3. Multi-material deposition

One of the main advantages of the CGDM process is its ability to deposit a range of different metals under solid-state conditions. For example, if a laser-cladding process was used to deposit titanium onto a copper or aluminium substrate, the high temperatures required to consolidate the titanium would melt the substrate. In CGDM however, it is possible to fabricate components from materials with vastly different melting points, as shown in Fig. 6(a). Here a tri-metallic coupon was created by spraying aluminium, copper and titanium in a consecutive manner. Alternatively, by mixing different powders together and spraying them simultaneously, coatings and components can be created with bespoke compositions. The micrograph shown in Fig. 6(b) shows a component comprising an equi-atomic mixture of aluminium and titanium. With appropriate heat

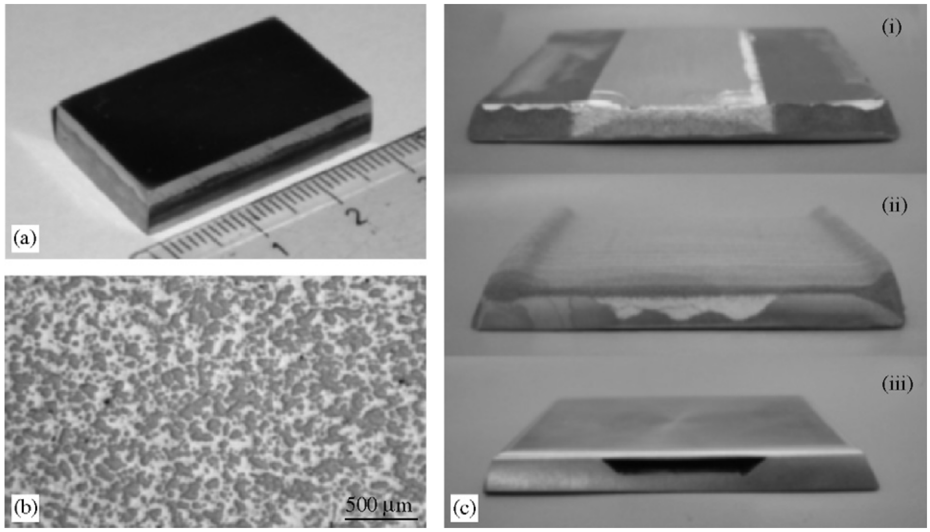

Fig. 6. Photographs showing (a) a tri-metallic coupon consisting of aluminium, copper and titanium, (b) a micrograph of an Al–Ti mixture as-sprayed and (c) a titanium component constructed with an internal channel.

treatment, this reacted to form a monolithic inter-metallic phase [25]. Similarly, by spraying different powders from separate powder feeders and controlling the PFR of each, the process has the ability to deposit functionally graded materials.

Since the CS process relies on having a solid surface onto which the material is deposited, components with internal geometries and overhanging structures cannot easily be formed. However, since the process can deposit materials with different physical properties, a build strategy may be implemented in which a sacrificial material is sprayed to support the build material [1,6]. During the construction of copper and titanium parts, an aluminium powder was deposited that could be removed post-process (by immersion in a sodium hydroxide bath) leaving the overhanging structure intact. Fig. 6(c) shows an example of a titanium part—complete with an internal channel—that was formed with a sacrificial support structure. The component was created by first depositing several layers of titanium to form a 5 mm-thick base; the top surface of this first tier was machined flat and a second tier, containing a central recess, was applied; a sacrificial layer of aluminium was sprayed into this recess and the entire top surface again machined flat, (i); a third tier of titanium was then deposited onto this new flat surface, (ii); finally the aluminium was removed and the entire component was machined to net shape, (iii). In this case, the deposition of different powders was performed in separate stages due to the capital cost of additional powder feeders.

3.4. Embedded devices and mould forms

The solid-state nature of CS lends itself to the deposition of metals onto composites and polymers. Given that the substrate does not have to be metallic, or have a very flat surface, the process is conducive to embedding devices within the deposited material. Provided the device is sufficiently hard so as to resist the particle bombardment, sensors such as thermocouples and optical fibres can be easily sprayed upon. In doing so, smart components could be created in a single step without the need for complex lithographic techniques. As an example of this, three-sheathed thermocouples were embedded within a titanium part without loss of functionality (Fig. 7(a)). The component was created in similar fashion as described previously. After the first tier of material was deposited, a second tier was laid down that contained three grooves; the transmitters were placed into the grooves and clamped in position; a third and final tier was added to complete the structure. Again the component was machined to net shape.

Material can be deposited into pre-fabricated moulds assuming their complexity is not too great; using a 5-axis system the complexity can be increased. Given that the CGDM process can deposit fully dense material, it is possible to create mould forms that can be heat treated without shrinkage and hence without the need for hot isostatic pressing (HIPing). A hemispherical mould form is shown in Fig. 7(b) that was created by spraying titanium into a hardened tool steel mould and removed via a sacrificial layer of aluminium.

3.5. Reinforcements

Due to the stiffness and compressive residual stresses that are present in cold sprayed material, tracks deposited by the technique can provide reinforcement to the underlying substrate. Since the process has the ability to spray tracks of variable width and thickness, the degree of reinforcement can be precisely controlled. Thus, stiffening ribs may be applied to existing components as and where required. In doing so, parts can be modified in situ and their properties enhanced without the usual downtime

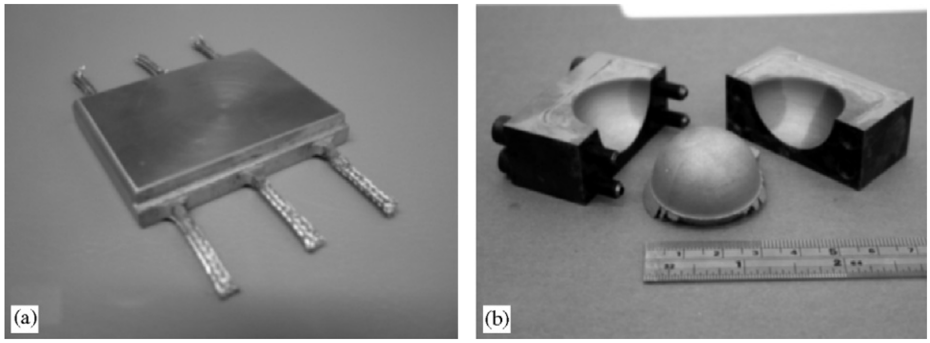

Fig. 7. Photographs showing (a) three sheathed thermocouples embedded within a titanium part and (b) a titanium hemisphere formed by a mould tool.

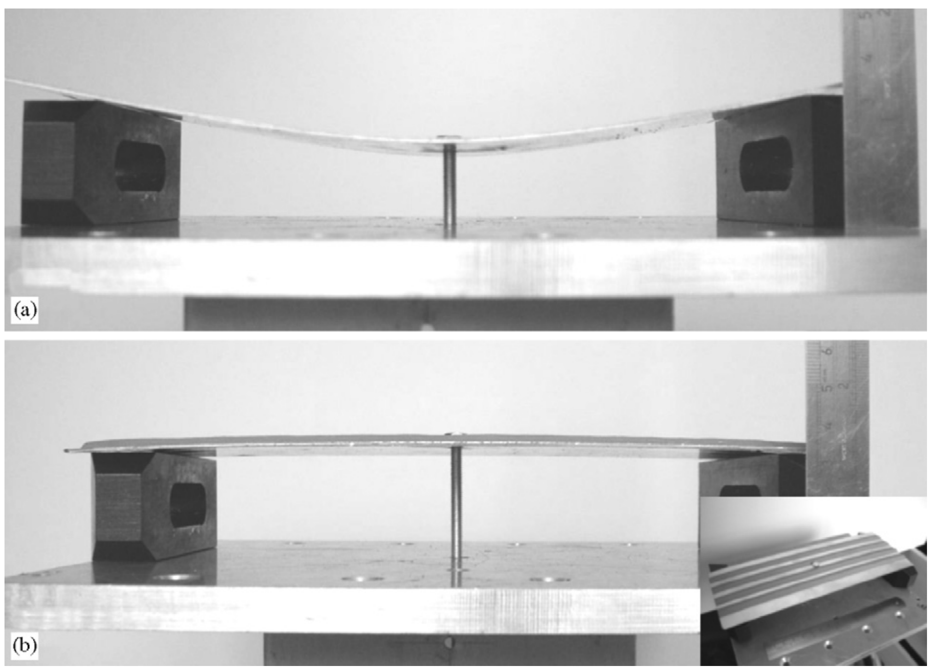

Fig. 8. Photographs showing (a) a 3-point bend test performed on a 1.5-mm aluminium plate and in (b) the same test is being conducted on a similar plate with four titanium reinforcing ribs sprayed on its upper surface (inset).

associated with component repair [26]. The images in Fig. 8 highlight the process' potential for adding stiffness to flexible components. Here, four titanium tracks—5 mm wide by 1 mm high—were sprayed along the length of a 1.5-mm aluminium sheet. During a 3-point bend test, the deflection caused by a 6.5 kg load was compared to an identical sheet without the reinforcement. The stiffening tracks reduced the deflection by ~15 mm.

4. Conclusions

At present, most RM techniques suffer from the detrimental effects of high-temperature processing such as large residual stresses, poor mechanical properties, unwanted phase transformations and part distortion. To address this issue, CS was identified as a process with the potential to perform non-thermal freeform fabrication. However, the dimensional accuracy and surface finish of parts produced by the process were incomparable with those produced by conventional machining techniques. Thus, the CGDM process was developed to exploit the benefits of both additive and subtractive techniques. Whereas most CS facilities concentrate on the application of wear or corrosion-resistant coatings, CGDM is dedicated to the production of freeform components, whilst still retaining an inherent coating ability. The process can produce functional forms using novel manufacturing strategies that are unique to CS. Metallic components were created that exhibited freeform surfaces, internal channels and embedded devices. Furthermore, by spraying multiple materials, the possibility of fabricating intermetallic and functionally graded components was demonstrated. Although these characteristics give the CGDM process a competitive edge, in order to produce fully functional engineering components, further work is needed to assess the mechanical properties of the deposited material. Moreover, in order to better understand and develop the process, the effects of the material and process parameters require further investigation.

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References

[1] D.T. Pham, R.S. Gault, A comparison of rapid prototyping technologies, International Journal of Machine Tools and Manufacture 38 (1998) 1257–1287.

[2] E.C. Santos, M. Shiomi, K. Osakada, T. Laoui, Rapid manufacturing of metal components by laser forming, International Journal of Machine Tools and Manufacture, in press.

[3] P. Fischer, M. Locher, V. Romano, H.P. Weber, S. Kolossov, R. Glardon, Temperature measurements during selective laser sintering of titanium powder, International Journal of Machine Tools and Manufacture 44 (2004) 1293–1296.

[4] J. Mazumder, D. Dutta, N. Kikuchi, A. Ghosh, Closed loop direct metal deposition: art to part, Optics and Lasers in Engineering 34 (2000) 397–414.

[5] R.R. Unocic, J.N. DuPont, Process efficiency measurements in the laser engineered net shaping process, Metallurgical and Materials Transactions B 35 (2) (2004) 143.

[6] A.H. Nickel, D.M. Barnett, F.B. Prinz, Thermal stresses and deposition patterns in layered manufacturing, Materials Science and Engineering A 317 (2001) 59–64.

[7] C. Amon, J. Beuth, H. Kirchner, R. Merz, F. Prinz, K. Schmaltz, L. Weiss, Material issues in layered forming, in: Proceedings of Solid Freeform Fabrication Symposium, 9–11 Aug. 1993, The University of Texas at Austin.

[8] A. Devansenapathi, H.W. Ng, S.C.M. Yu, A.B. Indra, Forming near net shape free-standing components by plasma spraying, Materials Letters 57 (2002) 882–886.

[9] J. Stokes, L. Looney, HVOF system definition to maximise the thickness of formed components, Surface and Coatings Technology 148 (2001) 18–24.

[10] H. Assadi, F. Gartner, T. Stoltenhoff, H. Kreye, Bonding mechanism in cold gas spraying, Acta Materialia 51 (2003) 4379–4394.

[11] J. Karthikeyan, Cold spray technology, Advanced Materials and Processes 163 (3) (2005) 33–35.

[12] L. Ajdelsztajn, B. Jodoin, G.E. Kim, J.M. Schoenung, Cold spray deposition of nanocrystalline aluminium alloys, Metallurgical and Materials Transactions A 36 (3) (2005) 657–666.

[13] C. Li, W. Li, Y. Wang, Formation of metastable phases in cold-sprayed soft metallic deposit, Surface and Coatings Technology 198 (2005) 469–473.

[14] M. L. Griffith, D. M. Keicher, C. L. Atwood, J. A. Romero, J. E. Smugeresky, L. D. Harwell, D.L. Greene, Freeform fabrication of metallic components using laser engineered net shaping (LENS), in: Proceedings of Solid Freeform Fabrication Symposium, 12–14 August 1996, The University of Texas at Austin, pp. 125–131.

[15] L. Pawlowski, The Science and Engineering of Thermal Spray Coatings, Wiley, New York, 1995.

[16] V.V. Sobolev, J.M. Guilemany, J. Nutting, High Velocity Oxy-Fuel Spraying, Maney, London, 2004.

[17] J.D. Anderson, Modern Compressible Flow, McGraw-Hill, New York, 1982.

[18] M.J. Zucrow, J.D. Hoffman, Gas Dynamics, vol. I, Wiley, New York, 1976.

[19] J. Pattison, S. Celotto, R. Morgan, W. O'Neill, Cold spray nozzle design and performance evaluation using particle image velocimetry, in: Proceedings of International Thermal Spray Conference, 2–4 May 2005, Basel, pp. 239–245.

[20] M. Grujicic, C.L. Zhaoa, C. Tonga, W.S. DeRosset, D. Helfritch, Analysis of the impact velocity of powder particles in the cold-gas dynamic-spray process, Materials Science and Engineering A 368 (2004) 222–230.

[21] F. Lauricella, S. Jaynes, Helium recovery: design considerations for cold spray systems, in: Proceedings of International Thermal Spray Conference, 5–8 May 2003, Orlando, pp. 113–116.

[22] J. Karthikeyan, C.M. Kay, J. Lindeman, R.S. Lima, C.C. Berndt, Cold spray processing of titanium powder, in: Proceedings of International Thermal Spray Conference, 8–11 May 2000, Montreal, pp. 255–262.

[23] D.L. Gilmore, R.C. Dykhuizen, R.A. Neiser, T.J. Roemer, M.F. Smith, Particle velocity and deposition efficiency in the cold spray process, Journal of Thermal Spray Technology 8 (4) (1999) 576–582.

[24] R.C. Dykhuizen, R.A. Neiser, Optimizing the cold spray process, in: Proceedings of the International Thermal Spray Conference, 5–8 May 2003, Orlando, pp. 19–26.

[25] T. Novoselova, P. Fox, R. Morgan, W. O'Neill, Experimental study of titanium/aluminium deposits produced by cold gas dynamic spray, Surface and Coatings Technology 200 (2006) 2775–2783.

[26] A. Rosochowski, A. Matuszak, Rapid tooling: the state of the art, Journal of Materials Processing Technology 106 (2000) 191–198.