COLD GAS DYNAMIC SPRAY DEPOSITION AS ADDITIVE MANUFACTURING OF ARCHITECTURED MATERIALS
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Resume
The paper is focused on the cold gas dynamic spray process as a useful tool for additive manufacturing of free-standing parts and in particular the production of architectured materials. The idea is demonstrated on samples of dual metal composition. The computed trajectory of channels was produced via a CNC milling machine and subsequently filled with another metal by the cold spray process. The microstructure of the deposited material and the interface with the substrate were studied. These types of produced architectured materials are discussed as potentially new structural materials.


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1. Introduction
Cold gas dynamic spray (CGDS) is also known as cold spray (CS), kinetic spray, supersonic particle deposition, dynamic metallization, high velocity particle or powder consolidation or kinetic metallisation. The most commonly used are CGDS and CS. CGDS is a member of the thermal spray process family (Fig. 1). In comparison with other methods of thermal spraying, CGDS is distinguished by its low temperature and supersonic particle speed. The temperature of the process gas (N, He) remains below 1100 °C, ensuring the absence of particle melting, and the supersonic speed gives the necessary energy to the particles for extensive plastic deformation and thereby metallic bonding and mechanical interlocking with a substrate and subsequently with the deposited coating material [1].

CGDS equipment usually consists of a source of process gas from which it is distributed into two branches, one for gas preheating (300–1100°C) and the other for powder mixing. The two branches are joined in a gun, and the gas and particle mixture is accelerated through a convergent-divergent nozzle to supersonic velocity (up to 1200 m·s⁻¹).

Due to the low gas temperature, CGDS offers unique advantages compared to other thermal spray technologies, including very high (almost theoretical) density of coating, production of compressive stresses, ultra-thick layers, small spray trace and precision deposition control, no or limited oxidation, deposition of thermally sensitive materials such as polymers and bioactive materials, no grain growth, and no phase transformation.

Typical materials applicable in CGDS are: a) metals, e.g. magnesium, aluminium, titanium, nickel, copper, tantalum, niobium, silver, gold; b) alloys, e.g. nickel-chromium, bronze, aluminium alloys, brass, titanium alloys, MCrAlY; and c) mixed materials (metal matrix combined with hard phases), e.g. metal
and ceramics, composites [3 – 5].

Thanks to the above behaviour, CGDS can be used in many areas, for example surface functionalisation, structural and dimensional restoration, and additive manufacturing (AM) (bulk manufacturing) [6 – 9].

1.1 Surface functionalisation

The first industrial application of CGDS was in surface engineering for the functionalisation of surfaces. CGDS coatings can offer protection against corrosion and high-temperature oxidation, and can improve the wear properties of engineering components. CGDS is also successfully employed in medical applications, where it is used to improve the biocompatibility of implants.

CS deposition offers the possibility of prolonging the lifetime of expensive parts in the aerospace industry. For example, the Boeing Company studied the improvement of H-47 Chinook Rotor Blade durability in conditions of sand and dust. For the successful protection of blades, a combination of niobium on a titanium substrate was chosen [10]. Solution for cost-effective protection against corrosion using the CS can be found. Bala et al. [11] presented NiCrTiCRe powder deposition on SA 516 boiler steel of Power Plant Boilers.

This deposition technology is also an ideal process for products requiring electrical conductivity [12]; Goris et al. [13] presented the use of CGDS as a tool for the production of an improved back-contact module of MWT solar cells.

1.2 Dimensional restoration

CGDS is also utilised in the restoration of objects; the ability to save on substrate material is highly appreciated by restorers. This process is applied both to antique technical objects, such as cars (body or engine defects) or aeroplanes, and to antique art objects, such as sculptures. In some cases, CGDS is the only applicable method of restoration [14].

The CGDS process also seems to be appropriate for repairing metal components and structures of aircraft. Matthews et al. [15] explored the possibilities of extending the limit of validity of aircraft structural components and restoring the structural integrity of corroded panels. They showed that CGDS is suitable for repairing corrosion damage and that the repaired structures have a dramatically increased fatigue life.
1.3 Art and decoration

For its specific benefits, CGDS can also be used for combining disparate materials such as metal and glass. This feature is used in art and decoration and creation of artistic works. Examples of “painting” with metal on a glass substrate can be found in [16].

2. Additive manufacturing (AM) by CGDS

An exciting possibility of the CGDS method is its utilisation in AM processing. In common AM techniques, the structure is produced layer by layer from powder, by laser or electron beam sintering. The resulting structure is actually formed in 2D+ regime by cladding one 2D layer upon another. The same principle is used in fused deposition modelling (FDM), stereolithography, or selective (laser, electron, arc) sintering based 3D printers.

A component or structure produced by CGDS has no tensile residual stresses, in contrast to those produced by selective laser melting (SLM) 3D printing. During CGDS deposition, compressive residual stresses are incorporated into the structure and increase the mechanical properties and fatigue resistance by cladding layers at a high velocity without melting. Bagherifard et al. [17] analysed free-standing samples of Inconel produced by CGDS and SLM. After heat treatment (HT), the mechanical properties of the CGDS samples were enhanced, and superior to those produced by SLM. Tensile test curves for the CGDS and SLM samples are depicted in Fig 2, with a comparison of states before and after HT. Note also that elastic properties of pure metals have been shown to be fully isotropic [18].

CGDS offers many advantages in the field of AM. Unlike common 3D additive printers, the powder particles stay in the initial state which opens the possibility for the AM of very specific materials (ODS alloys, etc.). The CGDS gun can be fitted on a robot arm with 6 or 7 controlled axes, which may extend the ingrained production habits of AM. In this configuration, the direction of powder deposition can be controlled, and thus real 3D structures can be produced [19].

It is possible to control the structure build-up process by layering the powder from many directions and by modifying the powder feed rate and transverse rate. If the feed rate is low and the motion of gun is quick, flat tracks are produced. On the other hand, when the feed rate is high and the transverse rate is low, the tracks are rounded; it is also possible for sharp triangular tracks to be developed in this way.

By combining the parameters, the deposition process can be finely controlled. Structures can be produced by layering thin coatings or by tessellating the triangular track profile as shown in Fig. 3.

![Graph](image-url)  
(a) comparison of SLM and CS samples before HT  
(b) comparison of CS samples before and after HT  
Fig. 2. Tensile test data.  
(full colour version available online)
Fig. 3. Photographs showing (a) track growth, and (b) layer building and edge losses [20].
(full colour version available online)

Fig. 4. Examples of one-layer internal reinforcing structural patterns.
(full colour version available online)

Fig. 5. Basic geometrical patterns applied for reinforcing the aluminium matrix by iron architecture.
(full colour version available online)
Furthermore, CGDS provides the possibility of combining metals to form an internal architecture within a component. Different powders can be deposited, either combined or separately, to produce a shape from two or more metals. In this way, multimaterial structures or components can be created. For example, engineering parts could be reinforced with stronger material only in places exposed to stress, thus allowing material and/or weight savings. This idea can be further extended, and via a combination of appropriate metal materials and geometrical patterns, internally architectured structures can be produced.

Schematic examples of such structures are depicted in Fig. 4. For example, a matrix made of a soft metal like aluminium could be reinforced by incorporating structural patterns of a hard metal. By creating these internal reinforcements layer by layer, new properties can be achieved, which could surpass the properties of the individual starting components.

3. Experimental

The aim of the experiment was to verify the use of CGDS technology as an AM process for forming reinforcing metal structures in the matrix of another metal. For this verification, aluminium alloy EN AW5754-H22 was chosen as the matrix, and pure Fe (99.9 %) was deposited by CGDS in reinforcing beams. The aluminium alloy was chosen as representative of common alloys and the pure Fe as representative of a powder with good spray effectiveness and higher mechanical properties (Young’s modulus, hardness). The CGDS method was used to prepare three kinds of sample, which differed in the geometry of the reinforcing beams. Two of the beams were linear, forming either squares or triangles, and the third was in the shape of a sinusoid in the x and y axes. The three beam geometries are shown in Fig. 5.

The production process consisted of two phases, depicted in Figs. 6 (a, b). First, grooves of 1 mm in width and depth were formed in the aluminium plate by means of a shank mill. The grooves were then filled using CGDS. Figs. 6 (c, d) indicate further steps of composite formation, however these were not used in this work. The device used was the Impact Spray System 5/11 from Impact Innovations, GmbH. The powder parameters and the parameters for spraying are listed in Table 1. Total spray thickness was 3 mm on average.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Parameters of CGDS process.</th>
</tr>
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<tr>
<td>Sample No.</td>
<td>3.1.1-3.</td>
</tr>
<tr>
<td><strong>Settings</strong></td>
<td></td>
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<tr>
<td>Parameters CS</td>
<td>Unit</td>
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<tr>
<td>Impact Gun</td>
<td>5/11</td>
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<td>Nozzle type/material</td>
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<td>Inlet pipe standoff</td>
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<td>Process gas</td>
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<td>Gas pressure</td>
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</tr>
<tr>
<td>Gas flow rate</td>
<td>m³·h⁻¹</td>
</tr>
<tr>
<td>Gas temperature</td>
<td>°C</td>
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<td><strong>General Parameters</strong></td>
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<tr>
<td>Standoff distance</td>
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<tr>
<td>Gun travel speed</td>
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<tr>
<td><strong>Powder</strong></td>
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<tr>
<td>Description</td>
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<tr>
<td>Supplier/Lot</td>
<td>Nanoval AO/068/GM</td>
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<tr>
<td>Particle distribution</td>
<td>µm</td>
</tr>
</tbody>
</table>
4. Description of results

Samples created with this method are shown in geometrical form in Fig. 7 as squares, sinusoids and triangles when viewing in order from the left to right. The samples were 100 mm × 170 mm in dimension. During CGDS deposition of the coating, material is simultaneously deposited both in and around the grooves in the substrate. Thus, the newly deposited layer retains the original geometry of the grooves. This occurs even with a considerable thickness of deposited material; at a coating thickness of 1 mm, the groove width was 1 mm. This effect could be used, for example, to form of a cooler layer on the surface of a thermally stressed component, similar to Dupuis et al. [7].

During the CGDS process, the milled groove was filled well. The groove bottom has a very good interface structure, while the vertical walls contain more defects. The defect types present in the microstructure of the deposited material can be sorted into three groups: a) large cavities, b) longitudinal cracks, and c) micropores.

On the walls parallel to the particle stream, coating deposition is difficult, and large cavities form. This is documented in Fig. 8. Impaired adhesion on the vertical walls continues even after the transition from the substrate to the coating layer. While the spray fills the grooves, material is simultaneously deposited on the surface of the substrate around the grooves, effectively increasing the groove’s height above the substrate. Thus, even after the deposited material has filled the matrix, the ‘new’ groove must be filled. Furthermore, the groove’s vertical walls, where adhesion of particles is difficult, are still being formed. This process continues throughout the spraying process and thus preserves the relief. The entire cross section of the sample relief and a detail of the spray interface are shown in Fig. 9.

Hardness HV1 of the substrate and the deposited layer were measured in several locations. The values do not differ depending on the location. HV1 of the aluminium substrate is 57 (s = 1.3) and HV1 of the Fe coating is 234 (s = 8.9) (measured in the groove, between the substrate and the longitudinal crack, and above the crack). From the hardness values of each component, one can deduce the other mechanical properties in general. The Fe coating is thus stiffer than aluminium and acts as a strengthening phase.

Another phenomenon observed in the CS structure were the longitudinal cracks passing through the deposited material at a constant distance (about 300 μm) from the surface of the substrate (Fig. 10).
Fig. 7. Milled patterns and parts of samples filled by CGDS of Fe.
(full colour version available online)

Fig. 8. Detail of milled grooves filled by CGDS of Fe.

Fig. 9. Entire cross section of milled groove and coating of Fe (left), interface of substrate and Fe coating (right).

Fig. 10. Longitudinal cracks passing through sprayed deposit (detail of two grooves).
Based on SEM analysis, it was found that this crack passes between the splats created during spray deposition (Fig. 11). The stress in this layer is higher than the mutual cohesion of the particles but not higher than the strength of the spraying material itself. The stress in the layer thus causes crack propagation between the particles and not through them. This implies that the cause of crack formation can be found in the spraying parameters, rather than due to defects within the sprayed Fe powder. Possible causes may be inappropriately chosen spraying parameters, or the relaxation of stress from the substrate (rolled sheet), etc. This will be the subject of further investigation.

The excess material of the deposited layer (approx. 3 mm above the grooves) was used for further analysis. The Fe coating was compared with electrolytic Fe powder by differential scanning calorimetry (DSC). A 10 K·min$^{-1}$ heating rate was used in Setaram SetSys apparatus. The resulting DSC signal curves of the analysis are depicted in Fig. 12. For the major transition reactions, both CGDS and electrolytic Fe samples showed the same DSC signal peak at the Curie point temperature (769.27 °C and 769.06 °C respectively) and almost the same DSC signal peak position for the gamma phase transition (919.14 °C and 919.74 °C respectively). This indicates that the material used for CGDS deposition and the resulting material of the analysed layer contain a low amount of impurities and oxides.

5. Conclusions

Grooved patterns created by CNC milling of the Aluminium EN AW5754-H22 substrate were covered with pure iron by CGDS deposition. The idea of creating an internal stiffener with a stronger metal (Fe reinforcement) in a less rigid matrix (aluminium alloy) was verified with these samples.

A high quality of coating was observed and the interface between the two metals was investigated on the surfaces perpendicular to the spraying planes. The homogeneity of the deposited material outside the groove area was found to be without any defects and showed very low porosity.

In the vicinity of the groove walls (parallel to the spray direction), a large number of defects were observed due to the inappropriate orientation of these walls to the particle stream. In grooves that had vertical walls better oriented towards the direction of spraying, better substrate-to-spray adhesion was observed (Fig. 9), and
consequently the intersection of the groove was completely filled. Further defects are probably caused by turbulent flow around the grooves during injection.

The DSC analysis shown high purity of the CGDS Fe layer, without significant oxidation.

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