A REVIEW ON COLD GAS DYNAMIC SPRAYING PROCESSES AND APPLICATIONS

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Abstract

The cold gas dynamic spraying (CGDS) method enables the application of coatings with various functional properties to nearly any substrate material, facilitates the restoration of geometric dimensions of parts damaged during use, and allows for the renewal of protective anticorrosive coatings without the need for complex structural dismantling. This review describes the latest developments in the processes and applications of CGDS technology.The ease and manufacturability of the process, along with the mobility of CGDS coating systems, make it suitable for use both in industrial settings with robotic systems and in "field" environments.

Keywords: anti-corrosion, cold gas dynamic spraying (CGDS), powder materials, protective coatings, repair technologies

1. Introduction

In mechanical engineering, there is an increasing demand for materials used in the production of parts and structures to have extended service life . A promising approach to meeting this demand is the enhancement of material properties through the application of functional coatings. These coatings improve corrosion resistance, wear resistance, and protection against mechanical damage, and they also allow for localized repairs without requiring the dismantling of the structure . Technologies that do not negatively impact the surface being treated are preferred. Cold gas dynamic spraying (CGDS) is one of the fastest-growing methods for applying protective coatings and imparting various functional properties to materials (Kablov et al.,2016; Vinogradov et al.,2017)

Coatings are formed by the cold gas dynamic spraying (CGDS) method through the initial acceleration of sprayed particles to supersonic speeds, followed by their collision with the substrate material, leading to plastic deformation (Abiev et al.,2004). The high velocity and substantial kinetic energy of the particles are achieved through the unique design of the Laval nozzle, enabling the formation of metallic coatings at temperatures well below their melting points (Koktsinskaya et al.,2014).

2. Literature Reviews and **Research Methods**

Coatings produced by the CGDS method exhibit improved adhesion to metallic surfaces and impart a broad spectrum of functional properties to various structural materials (Kosarev et al., 2003).

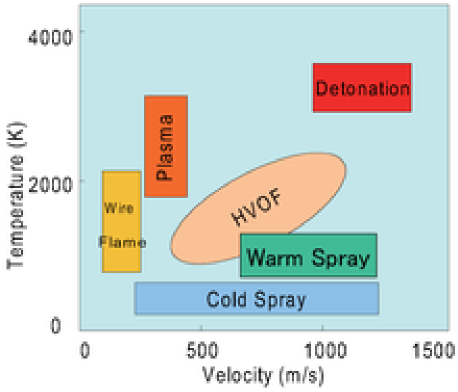

Figure 1. Comparison of particle temperature and velocity in various coating spraying methods

The method being examined differs from gas-thermal spraying systems like High Velocity Oxygen Fuel (HVOF) by featuring a high gas flow velocity and comparatively lower process temperatures. The lack of high temperatures during the CGDS process allows it to be utilized for thermally sensitive substrates (Alkhimov et al.,2000).

In HVOF, plasma, or detonation spraying methods, the working temperatures reach or surpass the melting point of metal particles, causing them to melt and compress upon cooling, which results in the development of residual tensile stresses in the coating. Conversely, in the CGDS process, the particles do not reach their melting point, and the spraying process induces compressive residual stresses due to the kinetic energy generated from the collision with the surface (Alkhimov et al.,2010).

Cold gas-dynamic spraying (CGDS) was the general term used for this process, although it may also be referred to as kinetic metallization or dynamic metallization (Katanoda et al.,2007). The phenomenon of coating formation using the CGDS method was first studied in Russia during the early 1980s. A team of scientists from the S.A. Khristianovich Institute of Theoretical and Applied Mechanics (ITAM) of the Siberian Branch of the Russian Academy of Sciences developed a technique for applying metal coatings by accelerating particles to supersonic speeds. This research resulted in the creation of two USSR patents, which covered the method and device for accelerating metal particles using high-pressure gas at temperatures much lower than the particles' melting points, allowing for the formation of a non-porous coating with strong adhesion to the substrate (Alkhimov et al.,1990).

In 1994, a patent for cold gas-dynamic spraying (CGDS) was granted in the United States. This process enabled the application of various materials-metals, alloys, polymers, and their mixtures-as coatings. Since then, numerous patents have been issued, but three have become particularly foundational in the field of CGDS (Alkhimov et al.,1990).

The primary objective of these inventions was to develop a method and device for spraying coatings to enhance the surface properties of products, such as reducing porosity, increasing hardness, strength, and corrosion resistance. This was achieved by introducing metal powders with particle sizes ranging from 1 to 50 microns into a gas stream to create a gas-powder mixture. The mass flow density of the particles varied from 0.05 to 17 g/(s·cm^2), depending on the spraying conditions. The gas flow velocity necessary for embedding metal particles into the substrate structure ranged from 300 to 1200 m/s. The acceleration of this gas-powder mixture imparts significant kinetic energy to the powder particles, and upon collision with the product surface, the particles undergo plastic deformation, forming strong adhesive bonds with the substrate.

The use of fine powders contributed to reducing micropore volume and creating a more uniform structure, which in turn improved the coatings' corrosion resistance, hardness, and adhesion.

Between 1980 and 2020, more than 150 patents were issued related to CGDS coatings. An analysis of selected protective documents and scientific-technical literature indicates that research into developing functional coatings applied via CGDS was being conducted in nearly all industrialized nations.

Over the past 20 years, the most significant advancements in CGDS coating technologies have been made in Russia, Germany, China, and the United States (Champagne et al., 2013).

In 2008, the United States issued the MIL-STD-3021 standard, "Spraying of Materials. Cold Gas-Dynamic Spraying," which outlines the CGDS process, coating testing methods, and were used in the restoration of military equipment through CGDS (Rokni et al., 2017).

This area of coating application was also being actively explored by developers in Japan, the Republic of Korea, India, Austria, and Australia (Irissou et al.,2008).

The key trends in the development of CGDS technologies include enhancing productivity and automating the coating process. This is being achieved through the development of new automated systems and the study of advanced powder materials to impart a wide range of functional properties to parts and products.

3. Results and Discussion

3.1. Features of the cold gas dynamic spraying process and formed coatings

3.1. 1. Design features of installations for spraying coatings by the CGDS method

The device for applying coatings using the CGDS method consists of a dosing feeder; a housing, which includes a powder hopper shaped like a drum with recesses on its cylindrical surface; and a mixing chamber fitted with a nozzle for accelerating the powder particles (Figure 2, a).

The nozzle connects the mixing chamber with a source of compressed gas. A powder feed controller regulates the desired flow rate during coating application, while a baffle installed at the bottom of the hopper prevents powder particles from entering the space between the drum and the housing of the dosing device, which could lead to the drum jamming.

The nozzle, which has a profiled passage, enables the gas flow to achieve supersonic speeds. To enhance process productivity and control the speed of the gas and powder mixture with the supersonic jet, the device includes a component for heating the compressed gas, complete with a temperature regulation system (Figure 2, b). Ideally, the heating system features a heating element made from a resistor alloy, which helps reduce the size and weight of the heating device (Moridi et al., 2014; Gärtner et al., 2006; Champagne et al.,2016; Marx et al., 2006).

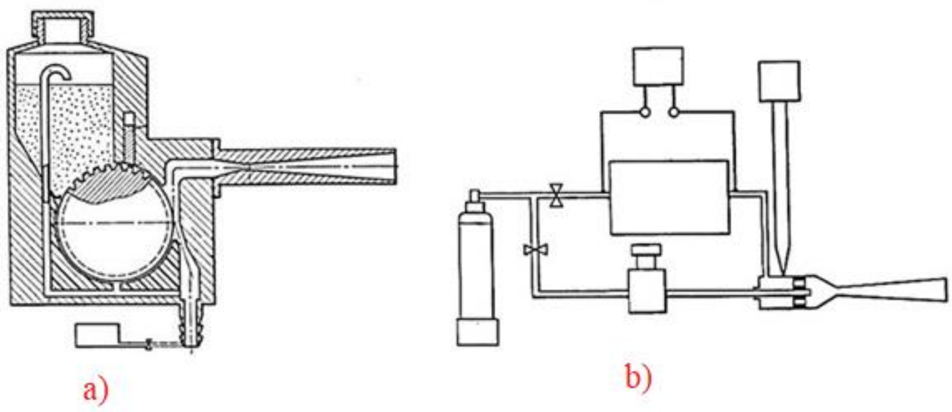

Figure 2. Device for coating the surface of the product: a – general view; b – a variant of the device having a gas heating module connected in parallel with a metering feeder

During low-pressure spraying, air (or nitrogen) is introduced into the supersonic nozzle at relatively low pressure (5–10 atm), heated to 550°C, accelerated to 600 m/s, and then directed onto a substrate made of metal, glass, or ceramics (Jodoin et al., 2006).

The incorporation of ceramic particles like silicon carbide (SiC) or corundum (Al_2O_3) into the metal powder mixture helps activate the substrate surface, enhance adhesion, and produce denser, non-porous coatings (Schmidt et al., 2009).

The performance and quality of CGDS coatings are influenced by the design features of the nozzle (Lupoi,2014). The optimal expansion ratio for particle acceleration is approximately 4 and 6.25 for nozzles with diverging lengths of 100 mm and 40 mm, respectively.

Beyond the traditional Laval nozzle, various modifications (cylindrical and rectangular) have been developed based on the part's configuration and the material of the raw material (Assadi et al., 2011).

To increase the kinetic energy of the sprayed particles, a system for heating the air has been designed. Compressed air is heated to temperatures ranging from 100 to 300°C in a heater before entering the nozzle, where it creates a vacuum and mixes with the sprayed material.

Figure 3. Equipment for applying CGDS: a – manual device; b– automated complexes

Currently, automated systems for applying CGDS coatings are being introduced in production environments to enhance work efficiency and improve coating quality on complex-shaped components.

3.1.2. Mechanism of CGDS coating formation

The initial powder used for CGDS coatings comprises particles with various sizes and masses, meaning not all particles were accelerated to the critical speeds necessary for embedding into the substrate surface and forming the coating. Larger particles often fail to reach these critical speeds and may bounce off the surface upon approaching it. The efficiency of spraying such particles can be as high as 95% (Li et al., 2014; Li et al., 2009; Rahmati et al., 2014).

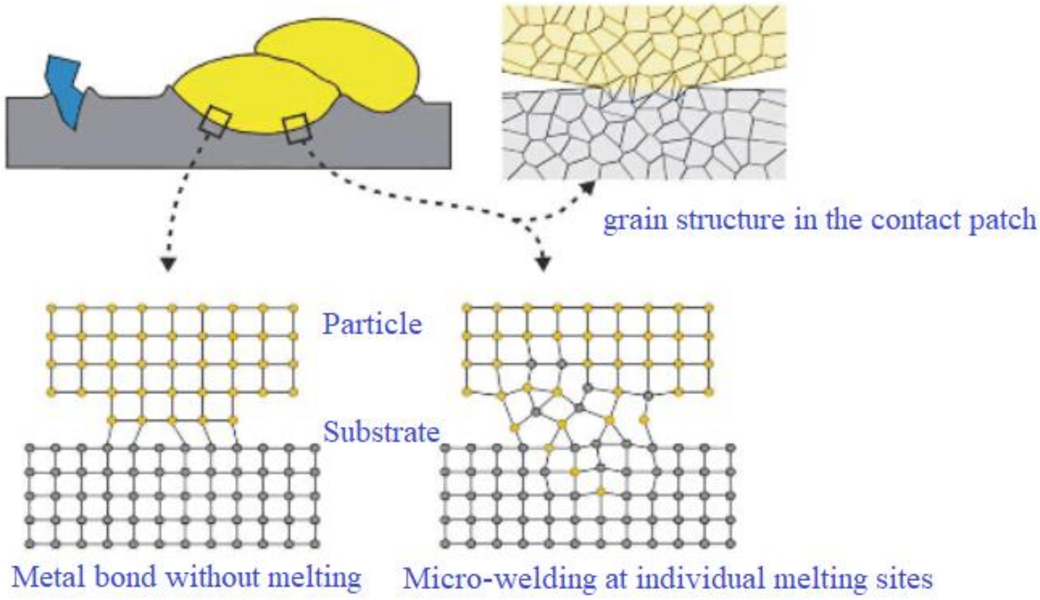

Figure 4. The process of coating formation during cold gas dynamic spraying

The particle velocity was the most crucial parameter in cold spraying, influencing adhesion, porosity, microhardness, and other properties of the coatings (Moridi et al., 2013). The CGDS process may involve erosive phenomena, which occured at particle velocities between 500 and 600 m/s. Surpassing these velocity ranges leads to plastic deformation of the particles and the development of an adhesive contact with the substrate material (Vucko et al., 2012).

Additionally, the critical particle flow rate was another essential parameter in CGDS coating application. When the powder flow rate exceeds this critical value, particles adhere strongly to the product surface and to each other, resulting in a dense and well-structured coating (King et al., 2020).

3.1.3. Materials Systems for CGDS

Currently, there is ongoing development of new powder materials and spraying technologies. A notable aspect of this technology is its ability to apply metal powders to materials that are incompatible with welding and brazing. Furthermore, this technology is utilized to enhance materials with various functional properties, including wear resistance, corrosion protection, and heat resistance .

Figure 5. The metal powder used in CGDS technology

3.2. Areas of application cold dynamic spraying

The technology of cold gas dynamic spraying of metals is highly effective for restoring defective areas of a wide range of parts and products. This effectiveness is largely due to the low heat input, meaning that the sprayed surface does not heat up, unlike during welding. As a result, defect elimination does not cause product deformation, internal stresses, or structural transformations in the metal, making this method particularly valuable in automobile repair.

The equipment is designed to provide a localized impact on the workpiece without affecting the defect-free areas. However, this technology is best suited for situations where there are no stringent requirements for the hardness and wear resistance of the applied coatings.

3.2.1. Application of Anti-Corrosion Coatings

To protect steel components from atmospheric corrosion, zinc coatings are most often employed. For parts that operate at temperatures between 300 and 500°C, coatings based on aluminum are applied. For protection at higher temperatures, nickel coatings are utilized. By providing cathodic electrochemical protection to steel parts, CGDS coatings made from zinc, aluminum, or their combinations offer superior anti-corrosion properties compared to paint coatings.

CGDS technology is effective for anti-corrosion protection of parts and enables coating of complex-shaped components as well as localized areas with corrosion damage (Figure 6).

Figure 6. Application of CGDS technology as an anticorrosive protection

3.2.2. Maintenance and restoration of Geometric Dimensions and Properties of Parts

The ability to apply CGDS coatings locally provides significant opportunities for restoring the geometric and linear dimensions of machine parts and assemblies. The low temperature during the coating application process prevents phase transformations and the development of internal stresses in the metal structure, which can otherwise lead to deformation of the part. This technology also allows for localized spraying on specific areas of the part's surface without impacting defect-free regions.

Figure 7. Examples of restoration of geometric dimensions and properties of products: a, b – recovery of abrasive shaft c, d – removal of cracks in cast iron engine

Figure 7 illustrates examples of how geometric dimensions and properties of parts are restored.

Sealing Liquid and Gas Leaks

The low porosity and gas permeability of coatings applied using CGDS technology make them highly effective for sealing and repairing leaks in pipelines; heat exchangers; pressure vessels; cryogenic system components; cooling systems; and more (Figure 8) .

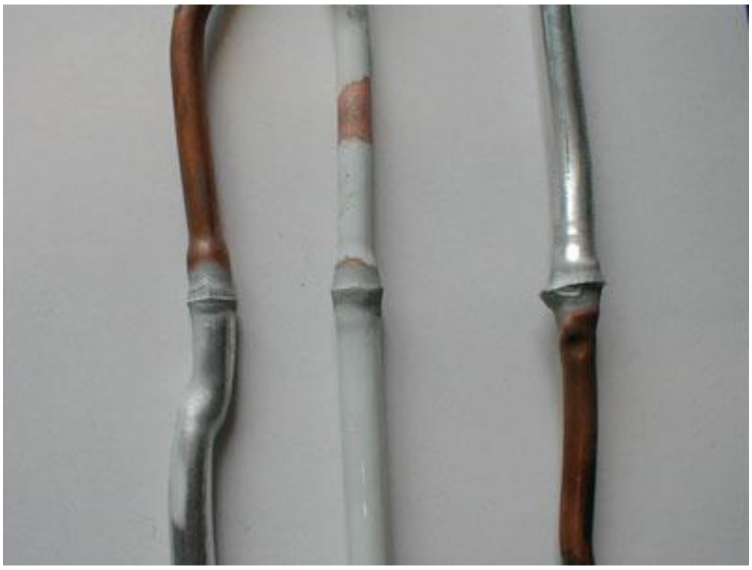

Figure 8. Hermetic connection of a copper tube with an aluminum one

3.2.3. Applications of Conductive Coatings

The low porosity and gas permeability of coatings applied through CGDS technology make them highly effective for sealing and repairing leaks in pipelines, heat exchangers, pressure vessels, cryogenic system components, cooling systems, and other similar applications (Figure 9).

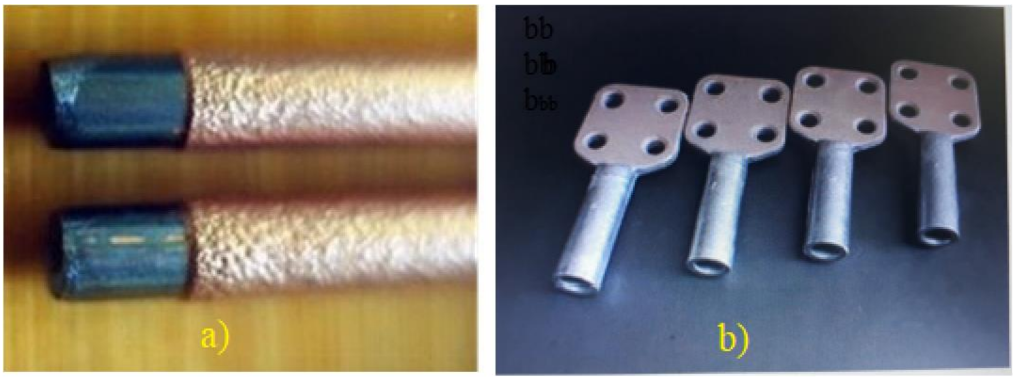

Figure 9. Examples of applying conductive coatings include copper plating of aluminum connecting elements (a) and steel electrodes (b).

3.2.4. Anti-Seizure and Anti-Friction Coatings

CGDS technology is effectively used to apply coatings directly to threaded areas of connections. Applying copper or zinc coatings helps prevent "seizing" of threaded connections. Additionally, sacrificial coatings ensure the tightness of the connection and protection from corrosion if moisture or corrosive electrolytes come into contact (Figure 10, a).

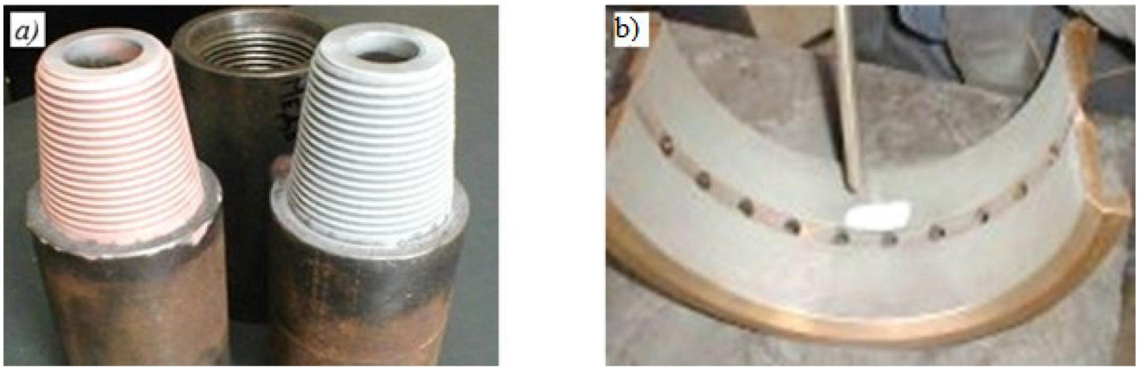

Figure 10. The use of CGDS as anti-pressure (a) and anti-friction coatings during bearing restoration (b)

CGDS equipment can also be employed to apply anti-friction coatings to sliding bearings. To improve wear resistance, both soft materials (such as babbitts and copper) and hard metal composites, based on the "tungsten carbide-cobalt" system, are used (Figure 10, b).

Additionally, potential applications of coatings include:

• **Protection against high-temperature corrosion**: Nickel and aluminum-based coatings are ideal for products operated at high temperatures, such as thermocouples.

• **Decorative coatings and microerosion treatment**: These coatings can be applied to metal, glass, and ceramic surfaces for aesthetic enhancement and surface treatment.

4. Conclusions

The appeal and advancement of coatings applied via CGDS stem from the straightforward application process and the unique properties of the resulting layers on the metal surface, which combine high adhesion with the ability to impart a wide range of functional characteristics to various materials. CGDS coating technologies show great promise for restoring the geometric dimensions of worn parts and creating protective anti-corrosion coatings on structural elements made of low-alloy steels.

Currently, the CGDS method is being actively developed in research institutes, universities, and corporations across more than 10 countries worldwide, as well as in numerous companies in Europe, Asia, and America. The primary trend in the CGDS field is the development of more compact and mobile systems for localized repair of mechanically damaged areas or the restoration of anti-corrosion protection. Ongoing research also focuses on developing powder compositions to impart various functional properties to materials.

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