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Editorial

Advanced Cold-Spraying Technology

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Cold-spraying technology is a solid-state, powder-based coating deposition and additive manufacturing (AM) technology, which utilises a high-pressure gas stream to accelerate micron-sized particles through a de-Laval nozzle for supersonic speed and impact on substrates and to generate dense, high-quality deposits. Cold-spraying technology has many unique features (e.g., high deposition rate, high adhesion strength; solid-state bonding at low temperatures) contrary to other fusion-based techniques, thus opening up new opportunities in various industrial markets. After over thirty years of rapid development, cold-spraying technology has been successfully applied in surface repair, surface enhancement, functional coating, and AM in many fields, including the aerospace, weapon, energy and power, electronics, and medical equipment industries.

With the developments of fundamental understanding and practical applications in cold-spraying technology, this technology has attracted increasing attention around the world, pushing this technology to a more 'advanced' level. The supersonic projectile behaviours of micron-sized particles in cold-spraying allow investigations into fundamental material phenomena under extreme conditions, e.g., "size effects" in mechanics, dynamic recrystallisation, and phase transformation. In addition, the advanced hybrid cold-spraying process incorporates in-situ or post-mortem treatment techniques, which could resolve many inherent drawbacks of this technology (e.g., lack of ductility and insufficient cohesion) and further promote the deployment of cold-spraying technology. Moreover, the integration of artificial intelligence and deep learning technology in cold-spraying helps to realize better toolpath and process optimization, as well as process control for industrial production campaigns.

The advancement of cold-spraying technology still faces many challenges that need to be addressed, such as those related to (1) feedstock materials, (2) bonding mechanisms, (3) numerical and modelling issues, (4) composite coatings, (5) AM, (6) process control, (7) equipment, and (8) carbon emissions.

The stringent selection and availability of the feedstock material properties directly impact the advancement of cold-sprayed coatings. Metal and alloyed powders are primarily utilised as feedstock for the cold-spraying process because plastic deformation is required to form the coating during the deposition process. Some unique cermet powder can also be deposited using the cold-spraying process [1]. On the other hand, ceramic powders have poor ductility and can be rarely deposited by cold-spraying. The metallic powders used in the cold-spraying process can be manufactured by atomisation (gas or water) or through a crushing or electrolytic process. Atomised powders are more spherical and regular, while crushed powders are blocky with sharp edges and are irregular. Electrolytic powders usually have dendritic structures. The difference in shape and regularity affects the particle speed and influences the coating quality due to different deformation characteristics; however, this would differ from material to material.

Several bonding mechanisms are being proposed for cold-spraying due to the complex particle–particle/carrier gas interactions, which can influence the research direction of the community. Studies have shown that successful bonding requires the sprayed particles to have a specific amount of energy, a critical velocity, and an adequate temperature [2]. This will lead to high-strain-rate deformation and breakage of oxide films, coupled with microscopic protrusions, grain refinement and localised heating at the particle impact interfaces (particle–particle/substrate interfaces), resulting in possible metallurgical bonding [3–5]. According to Assadi et al. [2], when the particle impact velocity surpasses a critical velocity, adiabatic shear instabilities cause bonding at the particle impact surfaces. The adiabatic shear instabilities are shown to be accompanied by interfacial jetting of plastically deformed material that contributes to the removal of oxide films and production of clean contact surfaces that promote bonding [6]. However, Hassani et al. [7,8] demonstrated that adiabatic softening and adiabatic shear instability are not prerequisites for hydrodynamic jetting, but an interaction of strong pressure waves with the free surface at the particle edges that affects the bonding.

Modelling has been widely researched to understand the impact process of the particles. The approximations of the deformation mechanism, critical velocity, and stresses have been evaluated by numerical methods such as the Eulerian, Lagrangian, smoothed particle hydrodynamics, molecular dynamics and coupled Eulerian–Lagrangian methods [9–11]. These models allow investigations into the distribution of pressure, stress, strain, and temperature during particle impact [6,12–15]. However, some material phenomena are not considered in these models, for example, the role of cracks, stress relaxation, interactions between splats (impact onto an uneven surface or previously deposited layer), phase transformations, and microstructural changes.

Cold-spraying is a strategic method used to deposit composite coatings with comparable or improved properties compared to other methods. There is considerable freedom to combine powders of various properties to create a composite coating with phase retention and specific functional requirements [16]. Several composite structures that have been deposited include metal–metal, metal–ceramic, and metal–intermetallic composite coatings [17,18]. Some critical investigations into the tailoring of cold-sprayed composites focus on the following aspects: (1) the size, concentration, and distribution optimisation of multi-materials, (2) effect of process parameters on composite coating microstructure and properties and (3) control of the degree of phase transformation that may occur at the bonding interfaces between the multi-materials.

Cold-spraying is integrated with AM to build 3D components that have the opportunity to revolutionise the manufacturing industry, such as mass production, fabrication, and restoration of engineering components [19]. The key advantages of cold-spraying additive manufacturing (CSAM) compared to other AM techniques are rapid building times, higher process flexibility, unrestricted product size and suitability for repairing and restoring damaged components. Additionally, CSAM is helpful in producing highly reflective metals, such as Cu and Al, which are very challenging to produce using laser-based AM methods. However, there are several drawbacks for CSAM in its industrial applications that needs attention, such as the limited resolution of the printed parts due to the large size of the nozzle outlet diameter, semi-finished components with a rough surface that requires post-machining and some inherent defects caused by difficulties in regulating process parameters, which result in poorer properties in their finished condition.

Understanding the effect of cold-spraying process controls is required to determine the optimal input parameters for a range of coating/substrate material combinations. The coating properties are affected by feedstock properties, particle velocity, gas temperature, stand-off distance, gas pressure, process gas, spray angle, traverse speed, substrate conditions (temperature, hardness, roughness and material) and many other factors [4,20]. Each parameter has a critical linkage with each other, and every change provides a certain level of trade-offs. Deep insights into each parameter are needed to fully advance cold-spraying technology.

The selection and capability of cold-spraying equipment affect, to a certain extent, the potential to produce the required coating quality. The cold-spraying equipment can be categorised as low-pressure cold-spraying (LPCS, 5–10 bar) and high-pressure cold-spraying (HPCS, >10 bar) [21]. The LPCS is suitable for depositing low-melting-point and low-yield-strength materials, for example, aluminium alloys, babbitt alloys, magnesium alloys [22–25], etc. As for the HPCS system, it has higher potential to deposit materials that are difficult to deform, such as steel, titanium [26], Inconel, etc. [27–32]. Several companies have successfully developed commercial cold-spraying systems to meet the increasing demand for this technology, such as VRC from the USA, Impact Innovations from Germany, Plasma Giken from Japan, Centerline from Canada and Dycomet from Russia.

Advanced cold-spraying technology should also become a greener process, which could involve gas and feedstock recycling in the future. This is because the requirements for carbon emission limits in different industry sectors are becoming increasingly stringent. The cold-spraying process does not produce toxic or harmful fumes or by-products because of chemically inert gas propellants such as nitrogen or helium. However, the resources used to prepare/extract these chemically inert gases do pose some impacts on the environment. Powders used for the cold-spraying process are also complicated to produce, and this is still coupled with inevitable powder wastage during the spraying process, including rebounded powders and during overspray (spraying sequence not on the target). In addition, cold-spraying repair and remanufacturing applications should be further developed to reduce material waste. Cold-spraying can restore damaged metal parts and components to their original state without decommissioning the part, component, or structure. This technology can significantly reduce the cost and environmental impact of producing additional components to replace the decommissioned ones [33].

In conclusion, the advancement of cold-spraying technology will benefit numerous industries. The challenges need to be effectively and efficiently solved by strong collaboration between industry and academia, in order to accelerate the development of the fundamentals and applications of this technology.

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