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Cold spray additive manufacturing and repair: Fundamentals and applications

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ABSTRACT

Cold spray is a solid-state coating deposition technology which has recently been applied as an additive manufacturing process to fabricate individual components and to repair damaged components. In comparison with fusion-based high-temperature additive manufacturing processes, cold spray additive manufacturing (CSAM) has been shown to retain the original properties of the feedstock, to produce oxide-free deposits, and to not adversely influence underlying substrate materials during manufacture. Therefore, CSAM is attracting considerable attention from both scientific and industrial communities. Although CSAM is an emerging additive manufacturing technology, a body of work has been carried out by various research groups and the technology has been applied across a range of manufacturing areas. The purpose of this paper is to systematically summarize and review the CSAM-related work to date.

1. Introduction

1.1. Cold spray process principle

Cold spray is a solid-state material deposition process, which was originally developed as a coating technology in the 1980s [1,2]. In this process, high-temperature compressed gases (typically nitrogen, air, or helium) are used as the propulsive gas to accelerate powder feedstock (typically metals and metal matrix composites) to a high velocity (typically higher than 300 m/s), and to induce deposition when the powders impact onto a substrate (typically metals). In contrast to conventional high-temperature deposition processes, the formation of a cold spray deposit relies largely on the particle kinetic energy prior to impact rather than the thermal energy. The feedstock used for cold spray remains solid state during the entire deposition process. Deposition is achieved through local metallurgical bonding and mechanical interlocking which are caused by localized plastic deformation at the inter-particle and particle-substrate interfaces. This allows for the avoidance of defects commonly encountered in high-temperature deposition processes, such as oxidation, residual thermal stress and phase transformation [3–5].

Successful deposition of a cold sprayed deposit requires the feedstock particles to exceed a critical impact velocity [6–13]. In cold spray, the formation of a deposit consists of two different stages. The first stage involves the deposition of an initial layer of particles where bonding occurs between feedstock particles and the substrate material; the second stage is the deposition on top of the layer(s) previously deposited, where bonding occurs between feedstock particles. Each stage has a respective critical velocity, i.e. for particle/substrate bonding and for deposit growth. Particle impact velocity must satisfy both criterions for successful deposition. In general, a higher particle velocity will result in improved deposit quality. Note that when the powder and substrate are the same material, the critical velocity can be considered as the same for both stages. Fig. 1 shows an in-situ observation of a 45 μm aluminium particle impacting onto an aluminium substrate at different velocities, where particle deposition only occurs when the impact velocity is beyond the critical velocity [6]. Critical velocity is not a constant but depends on several factors including material type, particle size, and particle temperature. Larger particles or higher particle temperature upon impact helps to reduce critical velocity [6,10,12–15].

Feedstock for cold spray is typically gas-atomized spherical metal

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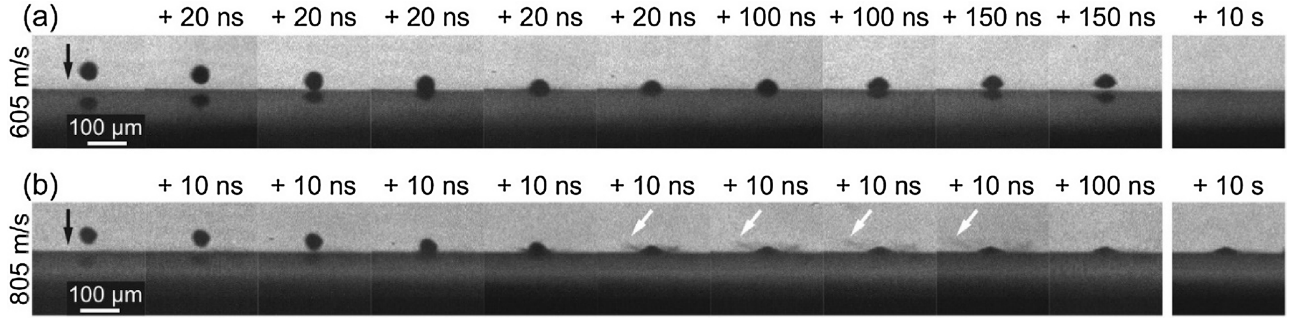

Fig. 1. In-situ observation of a 45 µm aluminium particle impacting onto an aluminium substrate at the velocity of (a) 605 m/s and (b) 805 m/s [6]. The critical velocity is between 605 and 805 m/s.

powders, and in some cases irregular powders [5]. The powder size must fall into a specific range, normally between 10 and 100 µm in diameter, to guarantee a sufficiently high particle impact velocity that is beyond the critical velocity [11]. Particles with diameters greater than 100 µm or lower than 10 µm are difficult to accelerate with the propulsive gas and thus usually fail to deposit [16]. For most metals, the most frequently used size-range is 20–60 µm; for low-density metals such as aluminium and zinc, the upper limit of the size-range can reach 100 µm [11].

1.2. Cold spray system nomenclature

The cold spray process can be divided into two categories, according to the pressure of the propulsive gas: high pressure cold spray (> 1 MPa), and low pressure cold spray (< 1 MPa). Fig. 2a shows a schematic of a high pressure cold spray system. Compressed gas is divided into two streams upon entering the cold spray system. One stream of the compressed gas (referred to as the propulsive gas) passes through a gas heater, where it is heated to a high temperature, At the same time, the second stream of the compressed gas (referred to as the carrier gas) passes through a powder feeder, where it becomes laden with the feedstock particles. These two gas streams are then mixed, before entering a de-Laval nozzle, where the gas expands to generate a supersonic gas and powder stream. In order to make certain there is successful injection of the powder into the mixed gas stream the carrier gas pressure must be slightly higher than the propulsive gas pressure. These high-velocity particles impact onto a substrate to form a coating or thick deposit at a temperature well below their melting temperature. Generally, high pressure cold spray systems can operate at the same pressures as low pressure cold spray systems, but the reverse is not true due to the special design of low pressure cold spray systems. Fig. 2b shows a schematic of a low pressure cold spray system. Two obvious differences in the low pressure system from the high pressure system are: the low-pressure compressed gas is normally replaced by a portable air compressor; the powder injection point is at the nozzle divergent section where the local gas pressure is sufficiently low to allow the release of powders from the powder feeder at the atmospheric pressure. These differences make low pressure cold spray systems more flexible and much cheaper in both equipment and processing costs than a high pressure cold spray system [3,5]. They are particularly suitable for the restoration of damaged components due to the portability of the simpler low pressure cold spray systems [17,18]. However, as the particle

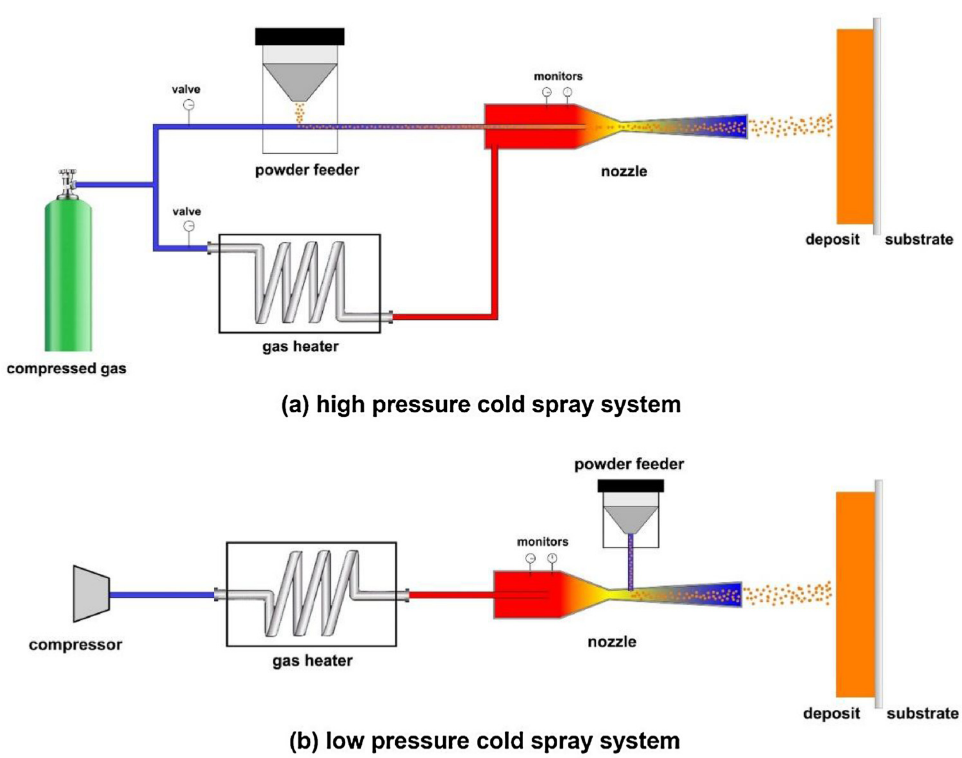

Fig. 2. Schematic of high pressure and low pressure cold spray systems.