Cold Spray Process

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COLD SPRAY has come to be understood, within the larger family of thermal spray processes, as a materials deposition process in which relatively small particles (ranging in size from approximately 5 to 100 μm, or 0.2 to 3.9 mils, in diameter, as shown in Fig. 1) in the solid state are accelerated to high velocities (typically 300 to 1200 m/s, or 980 to 3940 ft/s) and subsequently develop a coating or deposit on a surface (substrate) by an impaction process, shown schematically in Fig. 2. The deformable powder particles are accelerated to high velocities by injection into a high-velocity gas stream. A converging/diverging nozzle is used to develop the high-velocity gas stream. Various terms—including *kinetic energy metallization*, *kinetic spraying*, *high-velocity powder deposition*, *supersonic particle deposition*, *high-velocity particle consolidation*, and *cold gas-dynamic spray method*—have been applied to the general form of this technique.

The cold spray process was originally developed in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Science in Novosibirsk by A. Papyrin and colleagues (Ref 3–5). They deposited a wide range of pure metals, metal alloys, and composites onto substrate materials and demonstrated the feasibility of cold spray for a number of applications. A U.S. patent was issued in 1994 (Ref 6) and the European patent

in 1995 (Ref 7). Currently, a variety of cold spray research is being conducted around the world (Ref 2). These studies include gas dynamics, physics of high-speed particle impact, powder materials, novel application methods, and the development of specific applications. Cold spray now has been adapted as an established production tool in many industries for various applications, such as refurbishment of aircraft parts, production of sputter targets, production of protective and performance layers, and so on.

Figure 3 compares the particle velocity and gas temperature ranges of cold spray and other thermal spray processes (Ref 8). In the cold spray process, the gas and particle temperatures are much lower and the gas and particle velocity are much higher than in other thermal spray processes. There typically are four regions of particle/substrate interactions that can be defined by particle velocity. In the first region, the particle velocity (V_p) is too low for a given coating/substrate combination to form a coating, and the feedstock particles are reflected from or bounce off of the surface and do not form a contiguous coating or deposit. When the particles impinge at moderate velocities, solid particle erosion of the substrate surface occurs, but no coating is deposited. When the particles reach a critical velocity (V_{crit}), the particles begin to plastically deform, adhere to the

substrate, and form a coating. The critical velocity varies with particle and substrate material. As V_p increases, the particles undergo more deformation, typically leading to higher coating densities. At very high velocities, the solid particles start to erode the surface of the substrate. When this occurs, the particle velocity is called the erosion velocity ($V_{erosion}$).

The mechanism by which the solid-state particles deform and bond, both to a substrate and to each other, is now understood based on theoretical modeling and experimental studies. The kinetic energy of the impacting particles leads to a high rate of plastic deformation and results in adiabatic heating of the particles at the interface. When the temperature is sufficiently high, thermal softening occurs and the interface can melt. The molten, viscous material flows, forming a material jet. When the material jet resolidifies, it forms a bond between the particles and/or substrate. The velocity at which this jet forms is called the critical velocity (Ref 1, 9, 10). This is consistent with the fact that while various ductile materials, including metals and polymers, have been cold spray deposited, attempts to deposit brittle or hard materials, such as ceramics, have not been successful unless they are co-deposited with a ductile matrix material.

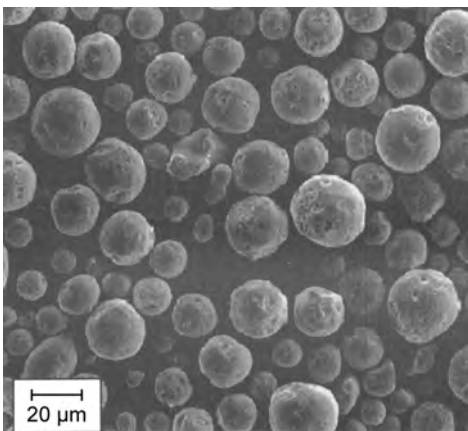Cold spray process parameters must be optimized for the selected powder/substrate

Fig. 1 Micrometer-sized copper powder used in cold spray experiments/applications. Source: Ref 1
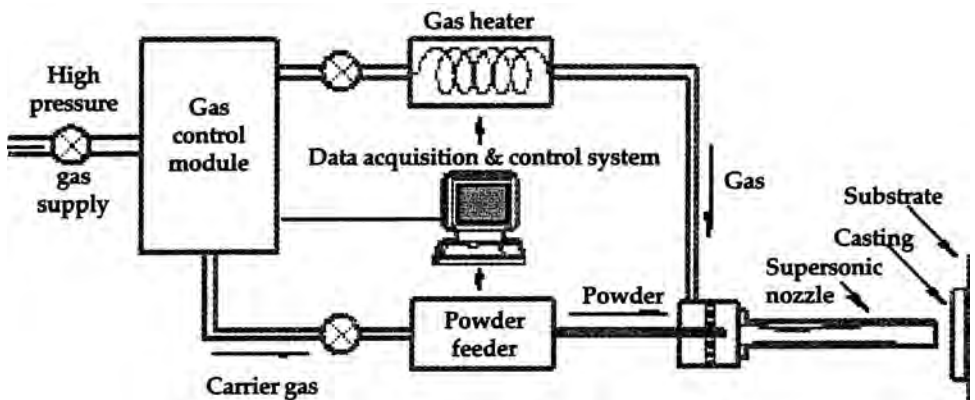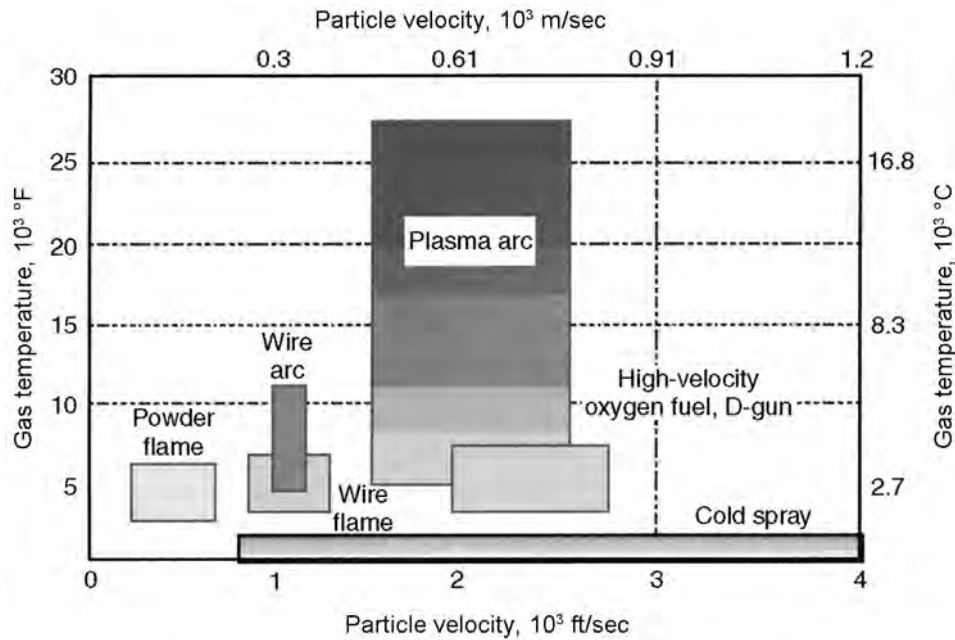

Fig. 2 Schematic diagram of a cold spray system. Source: Ref 2

Fig. 3 Temperature/velocity regimes for common thermal spray processes compared to cold spray technology. Source: Ref 8

Table 1   Typical range of gas-jet parameters for cold spray coating

Stagnation jet pressure, MPa (psi)	1–4 (145–600)
Stagnation jet temperature, °C (°F)	0–1000 (32–1832)
Gas flow rate, m³/min (ft³/min)	1–2 (35–70)
Powder feed rate, kg/h (lb/h)	2–8 (4–18)
Spray distance, mm (in.)	10–50 (0.4–2)
Power consumption, kW (for heating gas)	5–25
Particle size, μm	1–50

Operating gases: air, nitrogen, helium, and their mixtures. Source: Adapted from Ref 2

combination and spray device to achieve the desired coating properties. Process optimization is based on operational parameters of the particular application device (typically a gas nozzle) to achieve a suitable distribution of particle velocities for producing the desired physical properties of the deposit for any given material. Typically these parameters include the gas composition (N_2, He, air), gas preheat temperature, gas pressure, and nozzle geometry. Process parameters also may include equipment-specific hardware such as the pre-chamber length or nozzle cooling. A critical process parameter is the feedstock powder material itself—primarily particle size distribution and shape. Other powder particle attributes, such as oxide skins and thermomechanical properties (e.g., melting temperature, tensile strength, hardness, ductility, strain hardening, and density), also influence the ability to form a compacted layer. Operational parameters typically are selected to achieve the most suitable coating for its intended application at the lowest operational temperatures and gas flows.

The distinguishing feature of the cold spray process compared with conventional thermal spray processes is its ability to produce coatings with high-velocity rather than high-temperature particle jet. Although the process gas is preheated to temperatures in the range of 30 to 1000 °C (90 to 2000 °F) to compensate for the adiabatic cooling during expansion, the particle temperature remains below 200 °C (400 °F). Consequently, the deleterious effects of high-temperature oxidation, grain-growth evaporation, melting, recrystallization, tensile residual stresses, debonding, gas release, and

other concerns associated with thermal spray methods employing a liquefaction step are minimized or eliminated.

Cold Spray Equipment and Process Parameters

Figure 2 is a schematic of a typical cold-gas spray system. The process gas is introduced through a gas control module to a manifold system containing a gas heater and powder-metering device. The pressurized gas is heated to a preset temperature, often using a coil of an electrical resistance-heated tube. The gas is heated *not* to heat or soften spray particles but instead to achieve higher sonic flow velocities, which ultimately result in higher particle impact velocities. The high-pressure gas is introduced into the converging section of a de Laval-type nozzle (i.e., a converging/diverging nozzle), the gas is accelerated to sonic velocity in the throat region of the nozzle, and the flow then becomes supersonic (Mach numbers ranging from 2 to 4) as it expands in the diverging section of the nozzle. The powder feedstock is delivered by a precision metering device and typically is introduced into the high-pressure side of the nozzle in alignment with the throat orifice.

In a particularly novel adaptation of the technology, Kashirin and colleagues (Ref 11) have employed a downstream injection of the particles, thereby reducing the requirement of introduction into a high-pressure vessel. However, it should be noted that this technique results in a subsonic particle beam and hence requires

a peening agent to hammer the particles onto the substrate and form a coating. This low-pressure cold spray process yields coatings of select ductile materials with acceptable coating characteristics, as compared to the high-pressure process which yields coatings of almost any material with highest coating qualities. Typical gas-jet parameters for cold spraying are summarized in Table 1.

As shown in Table 1, process gases include nitrogen, helium, air, and mixtures of these gases. Nitrogen is a favored process gas because it can be used to spray some materials without promoting oxidation (Ref 12) and because it is much less expensive than helium. The nitrogen can be supplied from liquid nitrogen tanks, but it then must be compressed to the proper working pressure. For some materials, the velocities produced with nitrogen are not sufficient to produce good deposition efficiencies or high-quality coatings. Helium is capable of providing the highest gas velocities and therefore can be used in depositing the widest possible range of materials. Helium also may be diluted with nitrogen to improve the economics of the process, while providing particle velocities in excess of that achieved with nitrogen alone. In an effort to make helium more cost effective, gas-handling systems that permit the recycling of helium gas used in the cold spray process have been developed (Ref 13). Process economics for the recycling system strongly depend on production volume; that is, production volume must be sufficient to cover and provide a return on the cost of leasing or purchasing the recycling equipment.

Deposition Efficiency and Coating Properties

As with other thermal spray processes, cold spray process parameters such as those listed in Table 1 affect both the process deposition efficiency (DE) and properties of the prepared coatings. Reference 14, for example, describes a series of spray experiments that were conducted on various materials to determine how process parameters influence DE and mechanical properties. Typical results from these experiments are given in Fig. 4, which presents the variation of the DE with the different spray parameters for titanium metal. It was