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Cold spraying: From process fundamentals towards advanced applications

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ABSTRACT

Cold spraying (CS) is a relatively new material deposition technique based on the phenomenon of high-velocity particle/substrate impact. In this process, the powder is accelerated to supersonic speed in specially developed supersonic nozzles in which air, nitrogen or helium is usually employed as a powder carrier gas. In the absence of melting, oxidation and thermal decomposition of a particle in-flight during CS, the deposited coatings demonstrate low residual stresses and preserve the initial phase composition of the source material, which are important advantages for spraying temperature sensitive powders including nanostructures and nanocomposites. In the present paper the review in the field of development of cold spray technology is performed. Different scientific and technological aspects of CS such as surface activation, nozzle geometry, powder preheating, powder injection, control of spatial resolution of particle flux and proper selection of spraying parameters are discussed.

1. Introduction

Cold gas-dynamic spray or cold spray is a coating deposition technology which uses metal powders as feedstock material. This technology was invented in the mid-1980s at the Institute of Theoretical and Applied Mechanics (Novosibirsk, Russia); however real development of this technology started only at the end of the 1990s [1]. Hundreds of patents and research articles devoted to the development of cold spray equipment as well as investigation of physical phenomena taking place in the cold spray process denote high scientific and commercial interest to this technology [2]. Cold spraying is recognized as a promising spray technique capable of producing thick metal and in some cases metal–ceramic coatings on metal or ceramic substrates at relatively low temperatures preserving the initial phase composition of feedstock material [3].

The principle of cold spray is based on particularities of the metal particle deformation behavior during high velocity impact with a solid obstacle. If the particle impact velocity exceeds a certain critical value, the impact energy from the particle–substrate provokes an intensive plastic deformation of the particle and, in some cases, the surface of the substrate. This process breaks thin films on the substrate and the particle surface establishing intimate contact between “clean” chemically active materials of the substrate and the particle which leads to the creation of strong bonding [3]. In order to accelerate and heat the particles, a high-velocity gas jet is delivered by a supersonic spraying nozzle. Particles, injected to the gas stream, accelerate and heat due to their interaction with the gaseous phase.

The comparison of cold spray with other thermal spray techniques in terms of particle impact velocity and temperature was discussed in detail by Ang et al. [4]. The particle temperature–velocity map presented in Fig. 1 shows that the process temperature in cold spray is significantly lower than that in any other thermal spray technology and does not surpass 1000 °C. At the same time the maximum possible impact velocity of cold sprayed particles exceeds the corresponding values of other techniques except for the warm spray.

Despite the relatively simple principle, the development and improvement of cold spray technology continue. A deeper understanding of the physical phenomenon involved in the particle accelerating/heating process as well as in the high velocity impact permits this technology to adapt to specific applications or even to find new application fields. In this paper the authors perform a review of some scientific and technological results obtained in the last decade in the field of cold spray and discuss potential interest for further development of the cold spray technology. Special accent was made on the “exotic” achievements and developments related with the gas dynamic features of the process.

2. Particle/substrate interaction and surface activation phenomenon

The physical nature of the forces responsible for the bonding mechanism in cold spray is not completely understood. However, it was defined with certitude that the probability of particle bonding is connected with the adiabatic shear instability phenomenon taking place at a high deformation rate in the near-surface zone of a particle during high velocity impact with a substrate under certain conditions.

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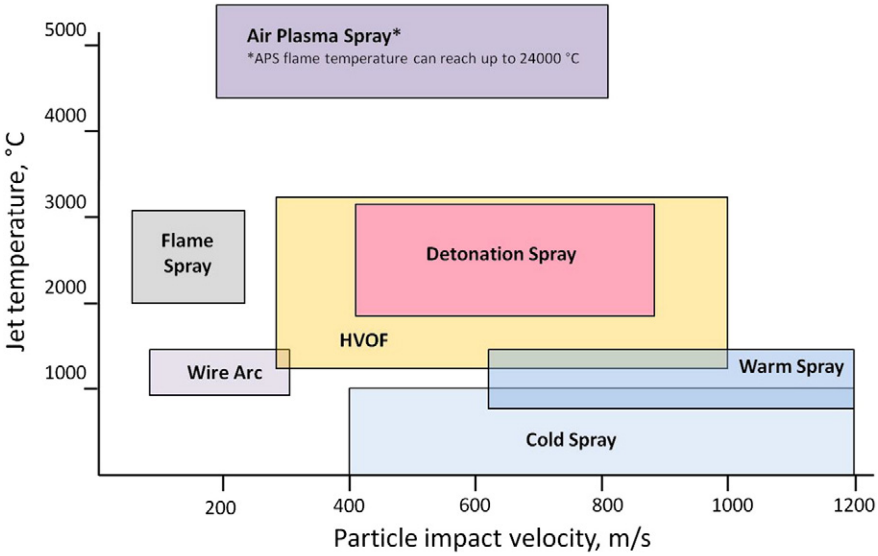

Fig. 1. Classification of thermal spray processes in accordance with particle velocity and flame temperature [4].

In particular it was clearly shown that if the particle impact velocity and temperature exceed some "critical" values, the metal particles with sizes between 5 and 100 μm could adhere to the substrate if they deform with the initiation of shear instability between the layers being in contact with the substrate surface [5]. The research team of Helmut Schmidt University (Hamburg, Germany) proposed an equation for this critical velocity permitting to calculate the value of velocity that particles should achieve in order to undergo this type of deformation if the impact temperature and particle material properties and size are known [5].

$$v_{cr} = 0.64\sqrt{\left[\frac{16\sigma_{TS}}{\rho_p(T_m - 293)} + c_p\right]\left(T_m - T_{pi}\right)}$$

Here c_p is the particle specific heat, T_m is the particle melting temperature, ρ_p is the particle density, σ_{TS} is the particle tensile strength, and T_{pi} is the particle impact temperature.

It is important to note that this equation does not take into consideration either the substrate properties (relief, thickness of oxide films, etc.) or the particularities of the particle surface, whereas experimental results show that surface conditions exert a significant effect on the particle–substrate bonding [3]. Some interesting information about the influence of particle surface properties on its deformation behavior and following bonding could be found in the work of Yin et al. [6]. In this paper the authors demonstrated that particles with increased oxide content require a higher critical velocity for adhesion.

Both mechanical interlocking and metallurgical bonding are commonly considered as two dominant mechanisms of the metallic bonding in cold spray. However the contributions of these phenomena strongly depend on the type of substrate and materials that was clearly shown by Hussain et al. [7]. Using the copper (powder)–aluminium (substrate) material system they clearly showed that in most cases, mechanical interlocking is able to account for a large proportion of the total bond strength, with metallurgical bonding only contributing significantly when the substrate had been polished and annealed prior to spraying [9]. Moreover, during the cold spray process the first coating layer is deposited on the substrate surface and the bonding mechanism depends on interaction particularities between particle material "A" and substrate material "B". The deposition of subsequent layers is made on previously deposited layers that means an interaction between particles and substrates both made of material "A". One can conclude that predominating adhesion mechanisms responsible for bonding between the first layer and the substrate and between subsequent layers could be different. Therefore, the optimal particle impact parameters necessary for the deposition of the first layer may not be the same as those for the deposition of subsequent layers. The cold spray deposition of metal–ceramic mixtures clearly illustrates that critical velocity strongly depends not only on the particle impact temperature and the material ultimate strength, but also on the surface properties. A number of works have been carried out during the past decade to better study this subject [8,9]. Shkodkin et al. [9] demonstrated an "activating" behavior of ceramic particles mixed with the metal powder. In particular they showed that the deposition of aluminium–alumina and copper–alumina powder mixtures occurs with non-zero deposition efficiency at significantly lower spraying pressure and temperature in comparison with the deposition of pure metallic powders. These results were used for the development of the so-called "low-pressure" cold spray technology [8].

This "activating" influence of ceramic powder could be clearly demonstrated experimentally if a nozzle with two injection points connected with two separate powder feeders is applied (Fig. 2). In this case, the composition of spraying mixture could be easily varied by changing the powder feeding rate. Switching between spraying of pure metal powder and metal ceramic mixture could be carried out by toggling the on/off switch of the feeder 2.

Fig. 3 shows the results of the experimental research performed by authors using the nozzle with the double powder injection system.

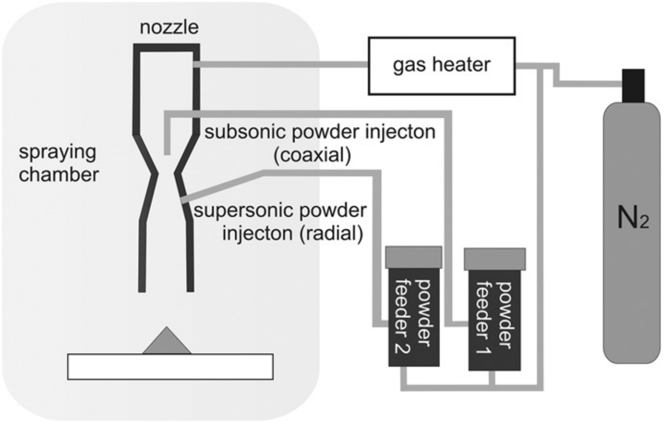

Fig. 2. Scheme of the cold spray system with double powder injection.