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COLD SPRAY COATING: AN EMERGING SPRAY ECHNOLOGY

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Abstract- Number of traditional thermal sprayed coating process such as HVOF, plasma spray are based on the melting or partial melting of coating material, and then spraying on substrate to cool down the molten material to produce coating. Due to the high temperature during the development of these coatings, may lead to high level of oxidation, which limits the broader penetration of thermal spray coatings for commercial applications like for temperature sensitive materials. These limitations forced the researcher to develop the cold spray (CS) technology. In cold spray technology high velocity is used instead of high temperature. The coating particles are dumped by means of supersonic velocity collision at a temperature which is very less than the melting point of the spray particles. In CS the coating takes place in solid-state. The cold spray coating process belongs to the broad family of thermal spray technology, and is a prospect of deposition of coating. The aim of this paper is to focus on sum up the fast growing common knowledge on the cold spray process under the light of open literature.
Keywords: Cold Spray, Coating, Thermal Spray Coating.

1. INTRODUCTION

The key criterion in cold spray is that the material deposition occurs at a certain minimum velocity of the particles, which is known as the critical velocity. If the impact velocity is less than the critical velocity, no bonding occurs between particle–substrate and particle–particle and spraying particles rebound. On the other hand if we go on increasing the impact velocity then at a certain velocity erosion of substrate material stars and this velocity is known as erosion velocity. Wu et al (2006) and Wu et al (2006A) [1,2] reported that if particle impact velocity is less or more than critical, the particles would bounce back or erode the substrate surface. Deposition efficiency (DE) is very important factor in cold spray process. Deposition efficiency is the ratio of weight gain by the substrate to the weight of all particles injected on the substrate during cold spray process. Deposition efficiency depends upon the different factors such as critical velocity, delay time, angle of impact, spray powder morphology and substrate material properties such as plastic strain, yield stress, pressure etc. [3]. The materials deposition efficiency versus impact velocity for a definite impact temperature is schematically represented in Fig. 1. Deposition of spraying particles takes place only in a definite velocity range for a specified particle size and temperature and is known as ‘‘window of deposition.

2. BONDING MECHANISM

The bonding mechanism in case of cold spray can be expressed on the basis of local adiabatic shear instabilities at particle–substrate and particle–particle interfaces as a result of thermal softening. The particles having more effective plastic limit as compared to substrate can easily go through adiabatic shear instability, whereas particles having less effective plastic limit as compared to the substrate did not go through adiabatic shear instability and liberates deformation energy to bounce back particles. However different researchers have different approach for the bonding mechanism in cold spray process, so there are still some conflicts for real mechanism. Still much more studies are required to ascertain the mechanism of bonding during this process at micro level. Two kinds of bonding takes place during cold spray: (i) bonding between spray particles and substrate material on which the final adherent strength between coating and substrate material depend (ii) bonding between spray particles and deposited spray particles, which built up the thicker coatings. For better understanding of the bonding mechanisms many authors did modeling of particle impact and estimated the critical velocities for different materials and some others tried to explore the bonding mechanism at micro level using different practical techniques such as SEM, TEM, XRD, BSEI, focused ion beam and high resolution transmission electron microscopy etc. With the commonly recognized and accepted model up to now; during the collision of particles, the solid particles undergoes plastic deformation, upset thin surface films (oxides), and sequentially get conformal contact with each other and get in touch with high pressure, enhance bonding with the substrate surface. Numbers of other bonding mechanism were proposed such as physical bonding, metallurgical bonding and mechanical bonding.

3. FACTOR AFFECTING THE CRITICAL VELOCITY

In cold spray process, the deposition efficiency depends mainly upon the critical velocity of the particles. The particle velocity must be more than the critical velocity to obtain better DE and good quality of coating. The particle velocity/critical velocity depend upon number of factors as follow:

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3.1 Spray material

The critical velocity is different for different spray material. Many authors (Karthikeyan, 2004, Ghelichi et al, 2009, Li et al, 2003, Li et al, 2005 and Li et al, 2010) [4,3,5-7] observed the critical velocity for cupper, iron, nickel and aluminum was in the range of 560–580, 620–640, 620–640 and 680–700 m/s respectively. Gartner et al (2006) [8] determined experimentally the critical velocity of different material as shown in Fig.2.

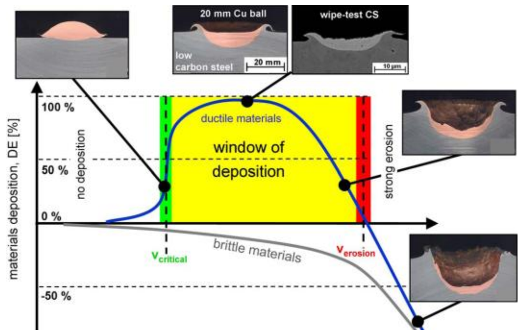

Fig. 1 Schematic diagram of the materials deposition efficiency (DE) as a function of impact velocity for a certain impact temperature [17].

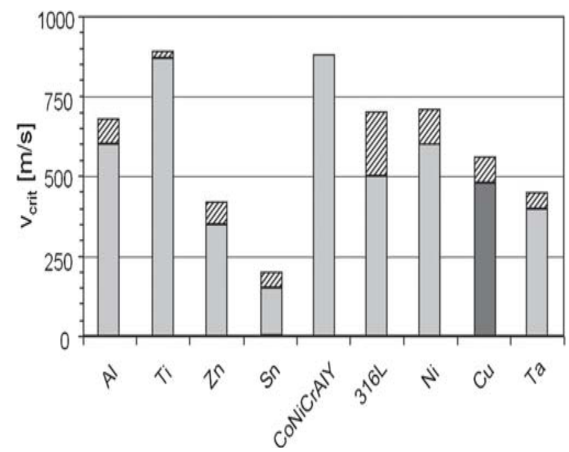

Fig. 2 Experimentally determined critical velocities of various spray materials. The error bar accounts for differences caused by the range of available powder purities [8].

3.2 Particle diameter

Li et al (2005) [6] reported the mathematical relation between velocity of particle size as $V_p = k/d^n$, Where V_p and d represents particle velocity and diameter of the particle respectively. k and n are the coefficients related to driving gas conditions for a certain material. Li et al (2006) [9] shows the dependency of velocity of Cu-particles on particles diameter with different spray parameters of pressure and temperature as shown in Fig.3. In Figure 3, the curves C1, C2 and C3 are for nitrogen and C4 is for helium. All the curves shows that the velocity decrease with increase in size of particle under all spray conditions and there is large increase in particle velocity with smaller size of particle typically less than 20µm.

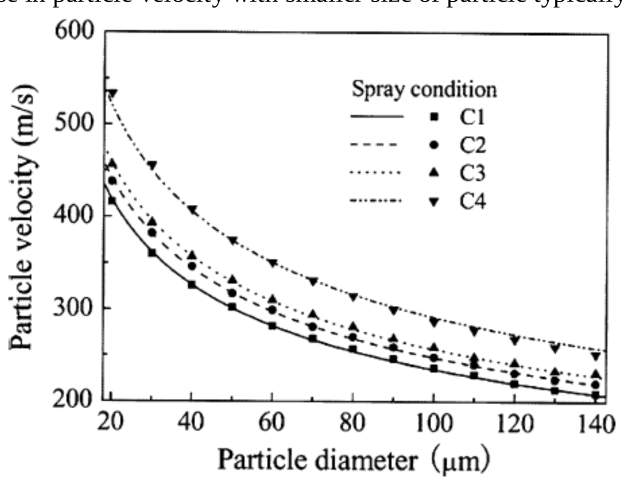

Fig. 3 Shows the variation of particle velocity with particle size under different spray condition [9].

3.3 Temperature of gas

With increase in gas temperature in clod spray process the velocity of gas increases at the throat of nozzle as velocity at the throat of nozzle is given by $V_t = (\gamma RT)^{0.5}$, where γ, R and T are ratio of gas specific heats, specific gas constant, and gas temperature respectively [10]. Hence the velocity will increase with increase in gas temperature but it will decrease the critical velocity because of thermal softening effect as depicted in figure 4. Lima et al (2002) [10] reported that with increase in temperature, the gas density and viscosity decreases which results in lower drag force of gas, responsible to accelerate the particles, hence this area needs to be further explored. Moreover the risk of oxidation and/or nitridation is more at high gas temperature which may defeat the purpose of applied coatings [11].

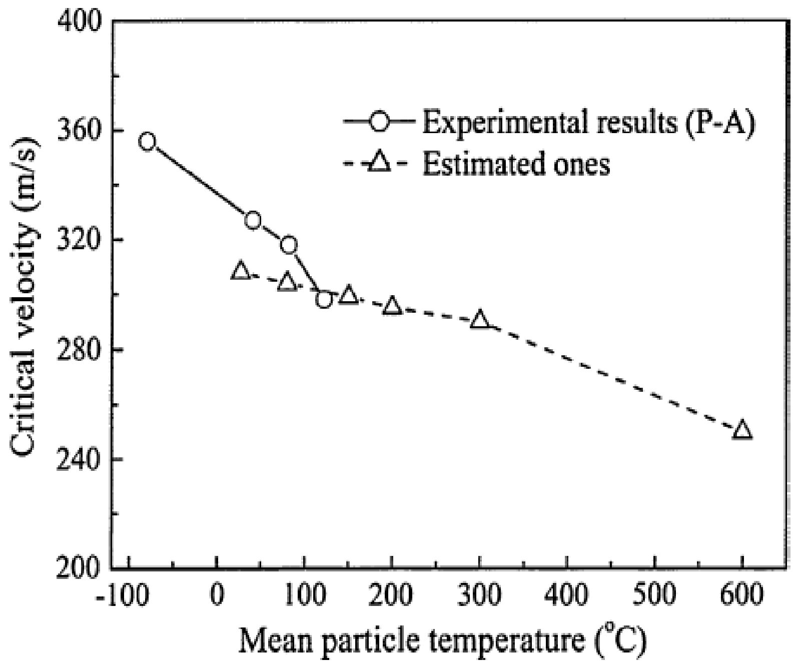

Fig. 4 Shows the variation of critical velocity with mean particle temperature [9].

3.4 Nature of carrier gas

Pre-heated nitrogen and helium gas is being used in cold spray process. Some of the material cannot be deposited with nitrogen gas as it requires high velocity. Hence helium gas is used to get the highest possible velocity among inert gases. Yoon et al (2006) [12] observed higher deposition efficiency with helium gas than nitrogen during cold spraying of NiTiZrSiSn amorphous powder. The cost of helium gas is ten times the cost of nitrogen. Due to this high cost of helium it is not used for commercial applications unless recycled. However a helium recovery system is being used in Canada which is able to recover the helium gas with sufficient purity (>99 %). With this recovery system the 85% gas can be recovered which make it a cost-effective operation [11]. A mixture of helium and nitrogen gas is also being used as carrier gas. This increases the heat transfer rate to particles, but on the other hand it reduces the velocity due to high atomic weight and coatings formed have low density and hardness [13]. However, Balani et al (2005) reported that coating formed by cold spray process using 1100 Al as coating powder and 1100 Al as substrate with He–20vol.%N_2 as carrier gas are more corrosion resistance than 100% Helium as carrier gas.

3.5 Oxygen contents

The critical velocity depends upon the oxygen content in spraying powder. Li et al (2010) [7] reported that the critical velocity for Cu-powder increases from 310 m/s to 610 with increase in oxygen content from 0.02 wt% to 0.38 wt%. Whereas the critical velocity of nickel-based Monel alloy powder changes from 583 m/s to 632m/s with increase in oxygen contents from 0.016 to 0.108 wt% as shown in Fig. 5. This increase in critical velocity with increase in oxygen content may be attributed to the energy required to break and extrude the oxide scale formed in the presence of oxygen contents.

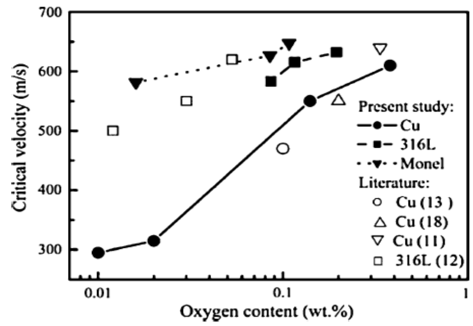

Fig. 5 Effects on Critical velocity with change in oxygen contents [7].

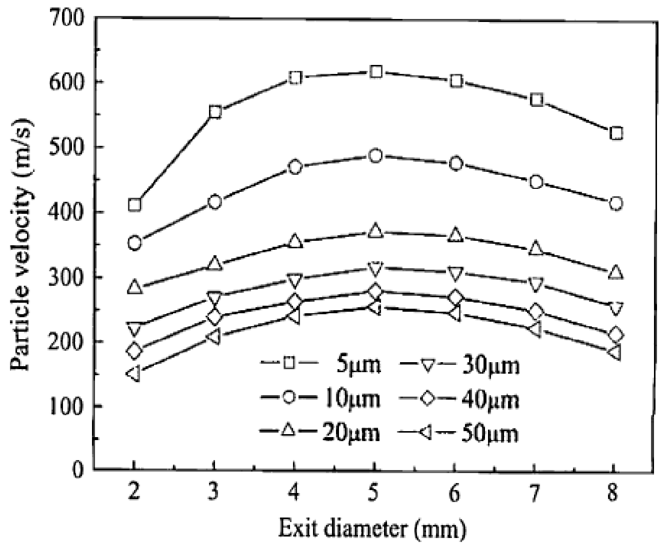

Fig. 6 Nozzle exit diameter Vs velocity of particles of different sizes [6].

3.6 Nozzle design

Nozzle is the component of cold spray machine where the spraying particles accelerated to high velocity. Hence its design is very important to optimize the velocity of particles with other parameters such as pressure and temperature. With the improvements in nozzle design using fluid dynamic models, it is now possible to design of optimized nozzle geometries to obtain high deposition efficiency and good quality of cold spray coatings for more economical process conditions. The velocity of particles depends upon nozzle inlet diameter, throat diameter, exit diameter, the entrance convergent section length and the divergent exit length. Singh et al 2012 [14] and Singh et al 2013 [15] reported that with increase in length of nozzle from 83 to 221mm, the velocity of Cu-particles increase approximately 33% which increased the deposition efficiency from 10% to 80%. Li et al (2005A) [16] reported the effect of nozzle exit diameter on velocity of particles of different sizes using nitrogen at a pressure of 2 MPa and temperature of 330^{o}C as shown in Fig.6.

4. CONCLUSIONS

The binding of sprayed particles on surface in cold spray process depends on velocity of the particles. Velocity of particles plays significant role in cold spray particles. Further the velocity of particles depends upon the different factors such as spray materials, particle diameter, and temperature of gas, nature of carrier gas, oxygen content and nozzle design. So one must consider the different factors for selecting velocity of spraying particles in cold spray process, so as to get good deposition efficiency.

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