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Mechanical and microstructural behavior of nanocomposites produced via cold spray

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ABSTRACT

Cold spraying is an innovative coating technology mainly based on the high speed impact of metals and ceramic particles on different substrates. Through the employment of low temperature gases (Air, He, N_2) spray particles (usually 1–50 μm in diameter) are accelerated to a high velocity (typically 300–1200 m/s) that is generated through a convergent–divergent de Laval type nozzle. Severe plastic deformation of particles impacting on the substrate occurs at temperature well below the melting point leading to the unique mechanical properties experienced by such kinds of coatings. In the present paper the main processing parameters affecting the microstructural and mechanical behavior of metal–metal cold spray deposits are described. The effect of processing parameters on grain refinement and mechanical properties were analyzed for different particles (Ti–$TiAl_3$, Al–Al_2O_3, Ni–Cr_3C_2, Ni–BN, Cu–Al_2O_3, Co–SiC). The results belonging to the properties of the formed nanocomposites were compared with those of the pure parent materials sprayed in the same conditions. Many experimental conditions have been analyzed in terms of particle dimensions and composition, substrate temperature and composition, gas temperature and pressure, nozzle properties. In particular, those conditions leading to a strong grain refinement with an acceptable level of the mechanical deposit properties such as porosity, adhesion strength and hardness were underlined.

1. Introduction

Cold spraying is a coating technology based on aero and high-speed impact dynamics of small particles (usually 1–50 μm in diameter). A coating is formed through the intensive plastic deformation of particles impacting on a substrate at a temperature well below the melting point of the spray material. It can be considered a safe and green technology because of the absence of a high-temperature gas jet, radiation, and explosive gases. An example of a key application of the cold spray process is the recovery of costly aircraft parts during overhaul and repair. Cold spray also can be used in the development of unique materials and for the production of actual parts [1,2]. Cold spray can be used to produce a new class of materials that could not be achieved by conventional ingot metallurgy. Even if it has great application potentials in aerospace, automobile manufacture, chemical industry, etc., there are still many fundamental aspects to be uncovered. Since adhesion of the metal powder to the substrate and deposited material is achieved in the solid state, the characteristics of cold spray deposits are quite unique. Cold spray can potentially provide with restoration, sealing, surface modification, wear resistance, thermal barriers, heat dissipation, rapid prototyping, aesthetic coatings, fatigue resistance and many other applications without the undesirable effects of process temperatures or metallurgical incompatibilities among materials. It can also be used to increase the heat resistance of a material. Research, aimed to improve the cold spraying technology, is still being conducted worldwide today. This technique appears very promising in the production of nanostructured composite due to the possibility of depositing materials starting from very fine particles and tuning the final properties by modifying processing parameters leading to severe plastic deformation. Different papers have been published in recent years describing microstructural and mechanical properties of cold sprayed nanocomposites coatings. The potential of preparing cold sprayed nanostructured composites is largely described in [3,4]. The advantages of cold sprayed coatings with regards to corrosion resistance is shown in [5,6]. In [7–9] the authors describe the microstructural behavior of the deposited material by varying the reinforcing particle dimensions. The effect of post spray heat treatment on the microstructural and mechanical properties of deposits is largely described in [10,11]. The strengthening mechanisms acting in cold spray nanocomposites are described in [12]. The present paper mainly focuses on the microstructural and mechanical

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behavior of nanocomposites produced by varying processing parameters in order to optimize adhesion strength, grain refinement and porosity reduction of deposited materials.

2. Experimental procedure

Different cold spray deposits were prepared by employing CGT Kinetics 4000 series cold spray system with a tungsten carbide MOC de Laval nozzle, with rectangular cross section 2×4 mm throat and 2×10 mm exit. The deposits were prepared on different substrate materials by employing different particles characterized by various dimensions. The different particles mixtures employed to prepare cold sprayed coatings were Ti–$TiAl_3$ (sprayed on Ti6Al4V substrate), Al–Al_2O_3 (sprayed on AISI316 steel substrate), Ni–Cr_3C_2 (sprayed on IN718 alloy substrate), Ni–BN (sprayed on IN718 alloy substrate), Cu–Al_2O_3 (sprayed on AISI316 steel substrate), Co–SiC (sprayed on Co substrate). For all cases ceramic–metal mixtures were employed as feedstock. The mean starting particles dimensions were in the range 3–60 μm. The sprayed materials were obtained by previously prepared powder mixtures. The cold spray parameters in the present study were: gas type, gas temperature and pressure, nozzle–substrate distance, all influencing the particle velocity, in particular particle velocity was tuned by varying gas pressure and temperature and nozzle substrate distance. The monitored properties were: deposit grain size, adhesion strength and porosity. Particle velocity was modified by varying gas conditions and nozzle–substrate distance. The mean grain size of the deposits was measured through X-ray diffraction by using a Rigaku Ultima + diffractometer by employing Hall–Williamson plotting; for selected deposits, transmission electron microscopy observations were performed by employing a JEOL 2011FX TEM. The porosity was calculated through a statistical analysis performed on Zeiss EVO40 SEM observations, for each sample 5 different images of 200×200 μm^2 were analyzed. The adhesion strength between substrate and coatings was performed by employing a standard ASTM C633-01 test.

3. Results and discussion

3.1. Properties vs. processing parameters

The results in terms of mechanical and microstructural properties of cold deposits have been analyzed as a function of the deposited materials on different substrates. The first main parameters affecting the final properties of the deposited samples resulted in the adhesion of the deposit and the deposit porosity. A similar influence, on the adhesive strength of coatings and particle velocity, can be underlined for the effect of working gas pressure and temperature. The higher the pre-heat temperature is, the higher is the thermal energy retained by the particles impacting on the substrate. The gas pre-heat temperature can also affect the substrate. The deposition of the coatings was carried out with a single step at a high transverse velocity. In Fig. 1 the variation of grain refinement as a function of particle velocity and gas temperature is shown for Al–Al_2O_3 (starting particle dimensions 25 μm) and Ni–BN (starting particles dimensions 30 μm) materials. The pictures refer to a presence of the respective reinforcements of 10%. It should be underlined that in the Al–Al_2O_3 composite the grain size decreases with the increase of particle velocity and the decrease of gas temperature. It can be underlined that the difference in grain size between the parent material and the corresponding composite is more pronounced for the Ni–BN system. The aspect is probably due to the difference in the material properties especially in melting and recrystallization temperatures. Stress localization at the matrix–particle interfaces play a crucial role in dynamic recrystallization in such kind of materials [13]. For the Ni–BN composite the same dependence on particles speed was observed but the grain size shows a minimum in correspondence to intermediate temperatures. The grain size increases as the gas temperature increases. As in the previous case, the presence of reinforcing particles play an important role in dynamic recrystallization but with a different trend as a function of particle velocity and temperature.

During impact, pressure elastically deforms the ceramic particles. Such deformation energy should be transferred to the ductile matrix which dissipate it through microstructural modifications (recovery, recrystallization, twinning, e.g.); the capability of the matrix to dissipate such energy govern the ceramic particle fracture. In the case of insufficient energy dissipations ceramic particle fracture occurs leading to very different behavior from a microstructural and mechanical point of view. The main strengthening mechanism in such materials is, in fact, the effect of ceramic particles in grain refinement of the matrix at the nanoscale [14]. Such effect is amplified by the shot penning of further impacting particles which normally leads to higher density of the coatings closer to the bulk surface. Mechanical properties of cold spray coatings strongly depend on particles bonding on the substrate; such bonding is dependent on mechanical properties of the substrate and particles and on the processing parameters employed during spray. Some authors emphasize the enhancement of shear instability as

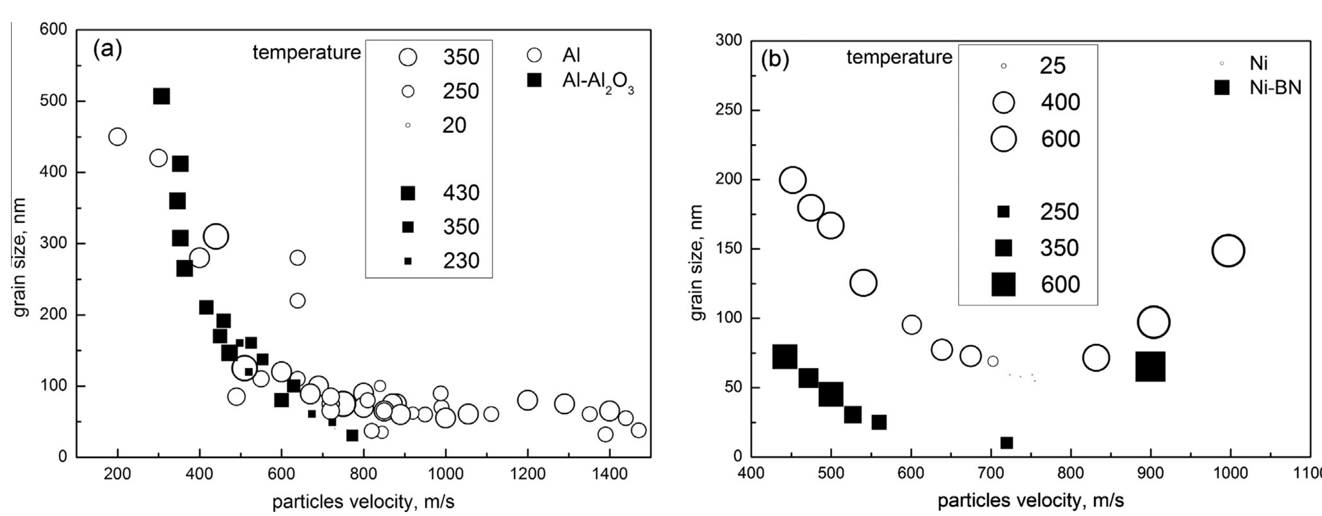

Fig. 1. Grain size dependence on particles speed and temperature for Al–10% of Al_2O_3 particles and Ni–10% of BN particles.