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High velocity impact induced microstructure evolution during deposition of cold spray coatings: A review

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ABSTRACT

Cold spray is a fast growing coating process involving in high strain rate deformation of spray particles. Early investigations stressed the retaining of feedstock microstructures into deposits. However, in recent years, metastable microstructures including high density of dislocations, nanosized grains and localized amorphous phase have been frequently observed through detailed microstructure characterization and it was found that those metastable microstructures remarkably affect the coating properties. In this review article, the evolution mechanisms of metastable microstructure in a cold spray coating during deposition of spray particles were examined in terms of in-situ densification, residual stress, dislocation multiplication, grain refining, phase transformation and amorphization through typical materials. Feedstock microstructure design, in-process control and material selection are essential approaches to acquire the coatings with desired microstructure.

Contents

1. Introduction

Cold spray is a fast growing coating deposition process in the last decade due to its ability to deposit coatings without any change in chemical compositions compared with feedstocks and shows excellent flexibility to design the coating compositions through feedstock. Intensive investigations revealed that many different types of coatings can be deposited by cold spray. Typical coating materials include ductile materials such as copper [1–4], aluminum [5], zinc [6], nickel [7], titanium [8], iron-based alloys [9–11] and nickel-based superalloys [12,13], etc., metallic glass materials [14,15], intermetallic materials [16–18], ceramic particles dispersed metal matrix composites such as WC-Co [19–22], SiC/Al [23], bronze-diamond [24], cubic BN/NiCrAl [25]. Using small size particles of several micrometers down to submicrometers, ceramic coatings are also able to be deposited by vacuum cold spray [26,27] or previously so-called aerosol deposition process [28,29]. Owing to high deposition rate and efficiency, high adhesive and cohesive strength within the coatings, a deposit without thickness limitation can be produced and consequently cold spraying is also promising for the applications to fabrication of free-standing parts. During cold spray, to build up a deposit successively, upon the impact of a high

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velocity solid particle on a substrate plastic deformation is required for both particle and substrate, which creates a bond to make the particle adhere on the substrate. The features of high velocity and low processing temperature significantly limit the reaction of spray particles with the atmosphere gas species, which lead to negligible change of coating materials compositions, e.g. oxidation of metallic materials. Moreover, the low particle temperature without melting prior to impact also benefits to eliminate the melting-induced deteriorating effect on deposit microstructure such as grain growth and thus possibly retain the microstructure of spray materials into coating. Therefore, the cold spray process provides a possibility to design the deposit microstructure through feedstock powders.

Early investigations stressed the retaining of feedstock microstructures into deposits. However, recent investigations show that intensive plastic deformation of feedstock powder particle leads to various types of microstructure changes such as in-situ densification [8,30,31], residual stress developing [32–43], significant increase of dislocation density relating to work-hardening [4,8,44–64], grain refinement effects [65–79], phase transformation [22,80,81] and localized amorphization [6,69,82,83] as well. It is essentially necessary to understand all those impact-induced microstructure evolution mechanisms to design and create a deposit with desirable microstructures, because those phenomena influence significantly the coating properties and performances.

This review paper focuses on the mechanisms of microstructure evolutions taking place in cold spray deposition and their effects on mechanical properties of the sprayed coatings. After a brief introduction of deformation features of cold sprayed particles during high velocity impact, microstructure evolutions are addressed in order: mechanisms of in-situ densification, residual stress development, dislocation multiplication, in-situ grain refinement, phase transformation and localized amorphization. Subsequently, effect of the formed metastable microstructure on modifying the coating microstructure by post-spray annealing is discussed. Finally, a summary and some suggestions on how to utilize these microstructure evolution mechanisms to obtain desired microstructures are concluded.

2. Characteristics of impact induced plastic deformation in cold spray

Bonding of particles to a substrate during cold spraying is attributed to solid state cold-welding arising from the extremely high strain rate plastic deformation accompanied by the adiabatic shear instabilities at the particle/substrate interface [84–87]. The adiabatic shear instability results in high degree of plastic deformation around the contact boundary, usually leading to the jet formation. Investigations either by experimental or numerical simulation approaches [84–101] indicate that the plastic deformation in deposited particles is heterogeneous. As is shown in Fig. 1a and b, severe plastic deformation (strain > 10) occurs at the inter-particle interfaces while the upper region of particle undergoes only a limited deformation (strain < 0.5) in a very short duration (tens of ns). On the other hand, a rapid temperature rise occurs corresponding to the effective strain at the inter-particle interfaces [69,89–101]. A typical simulation result of a contour of deforming particle after a spherical Cu particle impacts on a flat Cu substrate in Fig. 1b shows the non-uniform strain and temperature distribution near the interface region [92]. Temperature rise observed at the highly deformed interface region appears with a distribution similar to that of the effective plastic strain. Moreover, the effective plastic strain and temperature rise are dependent on the particle velocity and the initial particle temperature. High degree deformation enhanced by adiabatic shear effect leads to the formation of metal jetting. The local maximum strain can be up to a value over 10 [84,90]. For Cu, the simulation investigations revealed that the peak temperature at the particle/substrate interface can be up to ~1150 K [92] and even exceeds the melting point when the particle impact occurs at high initial temperature [99]. Furthermore, the limited dimensions of the high strain rate deformation region lead to

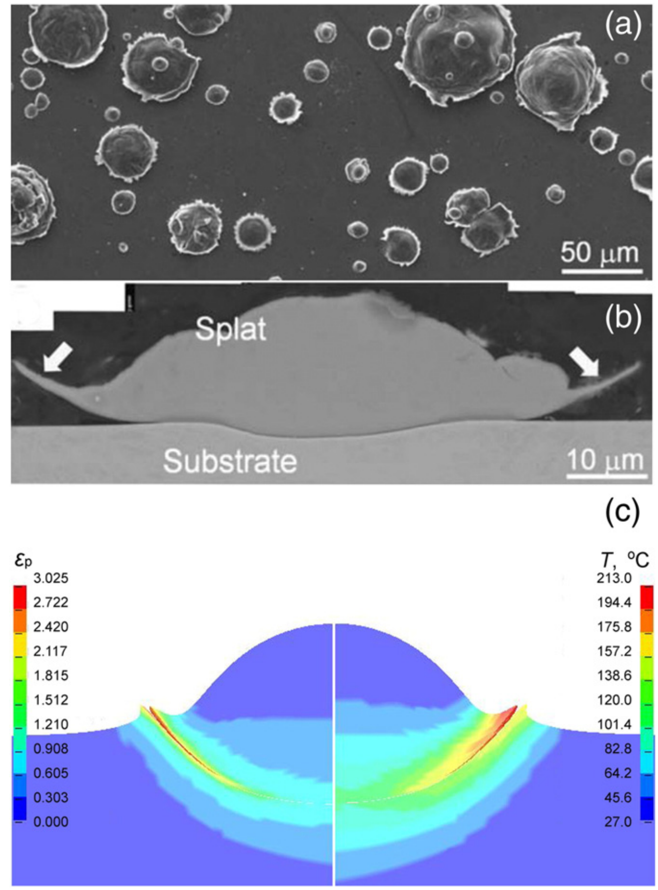

Fig. 1. (a) Top, (b) cross section view of cold sprayed Ti single particles and (c) contours of the effective plastic stain (left) and temperature (right) at 24 ns after a Cu particle impacting on a Cu substrate at a velocity of 500 m s^{-1} and a temperature of 27 °C. a and b are adapted from Ref. [72] and c is adapted from Ref. [92].

rapid heating up at ~10^{10} K s^{-1} and subsequent rapid cooling down at ~10^9 K s^{-1} at particle/substrate interface during single particle deposition [91]. Higher gas temperature results in higher peak temperature and longer duration. All above-mentioned effects are associated with the evolution of coating microstructure.

3. In-situ densification by tamping effect

In cold spray, former deposited particles are inevitably impacted and deformed by the following particles, which makes under-layer of the coating usually show denser microstructure than top-layer. The in-situ densification of following particles to the former deposited coating is termed as tamping effect. The tamping effect was firstly observed in cold sprayed Ti coating [8]. As is shown in Fig. 2a, the cross section of cold sprayed Ti coating reveals two distinguishable regions, the top porous region and the inner dense region. Apparently, the porosity in the porous region decreases from the coating surface toward the inner and reaches an apparently negligible level at certain thickness (Fig. 2b) [48]. This fact demonstrates that the density of the coating layer is gradually enhanced by accumulative deformation resulting from all approached particles over the layer. A solid particle in cold spray impacts the deposited particles to result in a certain level of deformation, which may not be able to completely fill all cavities exposed on the surface and some voids at inter-particle interface are remained. The following impacting particles force the deposited particles to deform gradually and to fill these voids. Such tamping effect becomes intensive with the increase of particle velocity. Therefore, the thickness of the porous layer decreases with increasing particle velocity and temperature [8]. The accumulative intensive deformation not only densifies the