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Formation mechanism and microstructure characterization of nickel-aluminum intertwining interface in cold spray

Yingchun Xie[a], Shuo Yin[b,*], Jan Cizek[c], Jan Cupera[d], Enyu Guo[e], Rocco Lupoi[b,*]

[a] National Engineering Laboratory for Modern Materials Surface Engineering Technology, The Key Lab of Guangdong for Modern Surface Engineering Technology, Guangdong Institute of New Materials, Guangzhou 510651, PR China

[b] Trinity College Dublin, The University of Dublin, Department of Mechanical and Manufacturing Engineering, Parsons Building, Dublin 2, Ireland

[c] Institute of Plasma Physics, Czech Academy of Sciences, Za Slovankou 1782/3, 182 00 Prague, Czech Republic

[d] Netme Centre, Institute of Materials Science and Engineering, Brno University of Technology, Technicka 2896/2, 616 69 Brno, Czech Republic

[e] School of Materials, The University of Manchester, Manchester M13 9PL, UK.

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A B S T R A C T

Experimental investigation was carried out to explore the formation mechanism of nickel-aluminum intertwining interface in cold spray, and to characterize the microstructure of deposited nickel particles at the intertwining interface. Shear stress was found to induce the intertwining interface through elongating and breaking of the nickel particles at the coating-substrate interface. The in-situ temperature measurement indicated that the temperature at the intertwining interface did not exceed the recrystallization temperature of nickel during the entire deposition process, suggesting that the nickel particles at the intertwining interface were in solid state rather than thermally softened viscous state. Electron channeling contrast (ECC) and electron backscatter diffraction (EBSD) imaging revealed a development of elongated subgrain (200 nm < D < 1 μm) and localized equiaxed ultrafine grain (D < 200 nm) microstructure within the highly deformed and fractured nickel particles at the intertwining interface. Such microstructures were induced by the dislocation accumulation due to the high strain/strain-rate plastic deformation and grain refinement caused by adiabatic temperature rise, respectively. Moreover, equiaxed ultrafine grains were also found to localize within a shear band near the center of the nickel particles, which experimentally confirms the existence of shear stress at the intertwining interface.

1. Introduction

Cold spray is an emerging coating and additive manufacturing technology, which was developed in the 1980s. In this process, micro-scale powders are accelerated by a supersonic gas passing through a de-Laval nozzle and subsequently impact onto a substrate to form a coating or bulk deposit [1]. Metals [2], metal matrix composites [3] and even ceramics [4] can be deposited onto various substrates via cold spray without exceeding their melting points. Thereby, defects encountered in the related high-temperature deposition processes such as oxidation, thermal residual stress and phase transformation, can be effectively avoided [5–10].

Microstructure evolution of cold sprayed metal coatings has been intensively studied during the past decades. It is well known that a significant grain refinement down to elongated subgrains (200 nm < D < 1 μm) and ultrafine grains (D < 200 nm) occurs near the inter-particle interface during the deposition process due to the impact-induced high strain/strain-rate plastic deformation [11–19]. The formation mechanism of the elongated subgrains is attributed to the dislocations pile-up that produces an array of dislocation walls, further transforming into subgrain boundaries [11]. At the highly deformed inter-particle interfacial regions where adiabatic shear instability phenomenon occurs, the elongated subgrains are further broken into smaller pieces and rotated by additional shear force due to dynamic recrystallization, ultimately leading to the formation of equiaxed ultrafine grains [11]. Such grain refinement phenomenon was observed in cold sprayed Ni [11], Cu [12,13], Ti [14,15] and Al coatings [16–19].

Bonding mechanism of the materials in contact has also been a major research focal point due to its crucial importance in the cold spray field. It has been well recognized that a successful inter-particle and coating-substrate bonding only takes place when the particle impact velocity exceeds a so-called "critical velocity" [20,21]. The well-documented metallurgical bonding resulting from a nano-scale chemical reaction at the interface is known to be the dominant mechanism for both inter-particle and coating-substrate bonding [5,7,8,22,23]. In

* Corresponding authors.
E-mail addresses: yins@tcd.ie (S. Yin), lupoir@tcd.ie (R. Lupoi).

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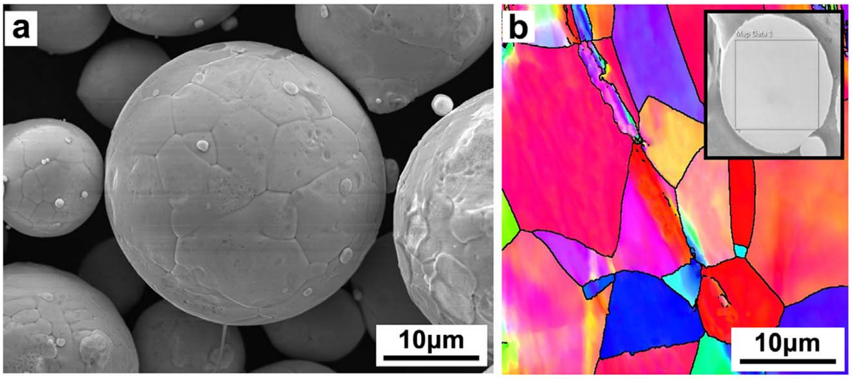

Fig. 1. Nickel feedstock characterization: (a) surface morphology observed by SEM, and (b) grain structure observed by EBSD.

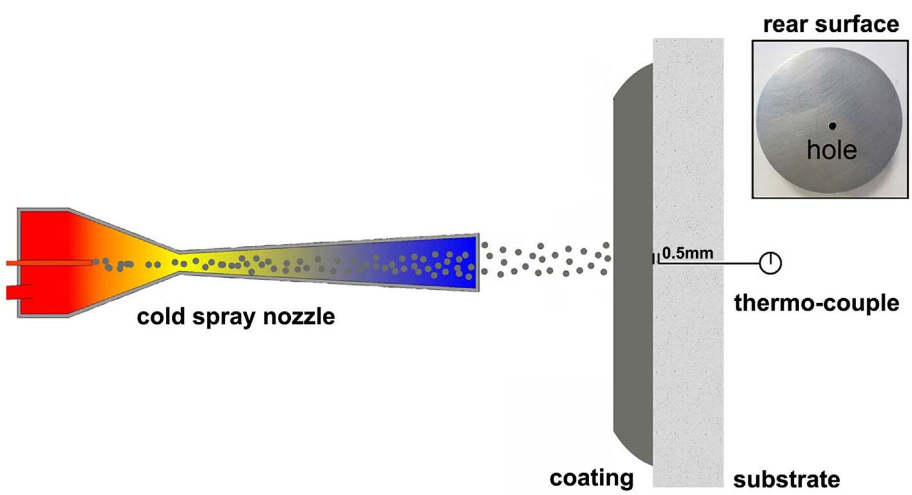

Fig. 2. Schematic of the interfacial temperature measurement setup and a digital photo of the 25 mm cylindrical substrate rear surface with the drilled thermocouple inlet. The front surface of the substrate was polished.

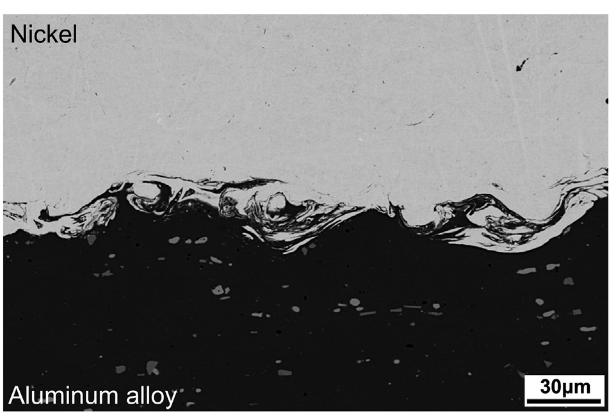

Fig. 3. General view of the intertwining nickel-aluminum alloy interface observed by SEM.

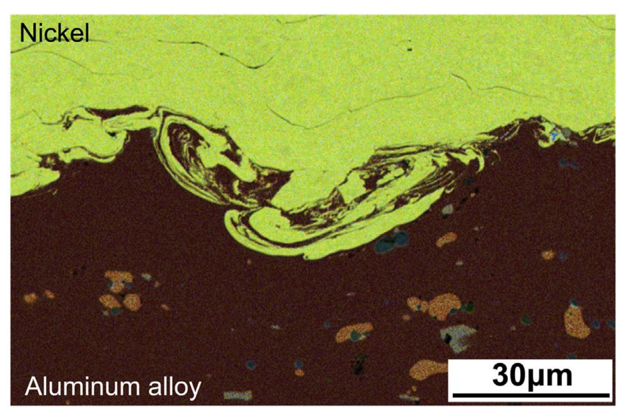

Fig. 4. Magnified view of the intertwining nickel-aluminum alloy interface colored by EDX mapping.

this respect, adiabatic shear instability and an intimate metal-to-metal contact arising from the impact-induced oxides removal are the prerequisites for the occurrence of such chemical reaction [20,24]. Another important mechanism contributing to the overall coating-substrate adherence is commonly present in cases when the substrate material is softer than the particle material: mechanical interlocking. Non-chemical bonding in its nature, the interlocking is represented by hard particle material being embedded into and trapped by the soft substrate material [5,8].

Apart from the two major bonding mechanisms, another bonding phenomenon in the form of particle elongation, fracture and mutual intertwining at the coating-substrate interface was observed in very limited cases when hard coatings were deposited onto soft substrates [25–29]. Although it has been years since the first report of such structure [25], only few studies addressed this interesting bonding phenomenon in more detail till now [27,29]. These studies mainly ascribed the formation of such intertwining interface to the so-called 'Kelvin-Helmholtz instability (KHI)' phenomenon in which two viscous materials move in parallel at different velocities to generate interfacial perturbation. This hypothesis seems to explain the formation mechanism of the vortex structure at the intertwining interface. However, some essential conditions for inducing the KHI may not be satisfied at cold spray coating-substrate interfaces. For one, KHI requires both materials to be in a viscous state. In cold spray, however, the low deposition temperature disallows the large-scale transformation of materials from a solid state to the viscous state. Note that the adiabatic shear