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Elastic moduli and elastic anisotropy of cold sprayed metallic coatings

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ABSTRACT

Resonant ultrasound spectroscopy is applied to analyze the elastic anisotropy of thick copper, aluminum, titanium, and nickel coatings prepared by cold spraying and to determine the respective elastic moduli. The results show that the coatings exhibit only weak deviations from perfect isotropy, and the obtained elastic moduli are comparable with those of the corresponding polycrystalline bulks. The increased internal friction observed in some of the studied coatings may indicate grain refinement and consequent grain boundary sliding.

1. Introduction

Cold spraying (CS, [1–7]) is a versatile and efficient method for deposition of relatively thick metallic coatings. Unlike the conventional thermal spraying methods such as plasma spraying [8–10], the CS process does not involve substantial heating or melting of the sprayed powders. Instead, the formation of the coating arises from a severe plastic deformation of the accelerated powder particles upon their impingement at the substrate [11,12]. Thereby, the oxidation or phase changes in the feedstock material are effectively reduced, as well as e.g. the magnitude of the secondary residual stresses arising from the thermal expansion mismatch [13]. As such, CS has recently received a lot of attention as a novel method applicable for sensitive metals and alloys that readily undergo chemical or structural changes at elevated temperatures. Among the sprayed metallic coatings, those prepared by CS frequently exhibit superior mechanical and physical properties [1,7], such as Young's modulus [14], hardness [15], or electrical conductivity [16], often comparable to those of the respective bulks. Further to that, the coatings deposited via high-temperature processes generally exhibit high levels of anisotropy [4], a property arising due to their heterogeneous lamellar or splat-like microstructure [4,17–19] and commonly regarded as undesired. In this paper, we show that the CS coatings do not exhibit any significant elastic anisotropy, as opposed to its high-temperature counterparts.

Resonant ultrasound spectroscopy (RUS, [20–22]) has been recently used to investigate elastic anisotropy of nickel coatings prepared by the high-velocity oxygen fuel (HVOF) and atmospheric plasma spraying (APS) methods [19] and of steel coatings [23] prepared by water-stabilized plasma (WSP) spraying. In all reported cases, the difference between the in-plane and out-of plane properties of the coatings were significant, with the values of the ratio $\alpha = E_{OOP}/E_{IP}$ between the out-of-plane Young's modulus (E_{OOP}) and the in-plane Young's modulus (E_{IP}) ranging from 0.36 (for APS [19]) to 0.87 (for WSP [23]). Here we apply this method to determine the elastic constants and the strength of anisotropy for pure copper, aluminum, titanium and nickel coatings prepared by CS. The main advantage of the RUS method is that it enables the determination of all independent elastic constants of an anisotropic solid from measurements of one small sample. In addition, the RUS enables also a direct assessment of the internal friction parameter of the examined material Q^{-1} [21], which may bring an additional information on the integrity of the sprayed material or on density and activity of defects in it [24].

2. Experimental setup

2.1. Examined materials

Four commercially available powders were selected for the experiment: Al, Cu, Ni, and Ti. Considering the aim of the study, i.e. evaluation of (an)isotropy of the cold spray technology as a method, the selection of the powders was made with the aim of having feedstock material of dissimilar properties. The powder particles (Fig. 1) differed in their

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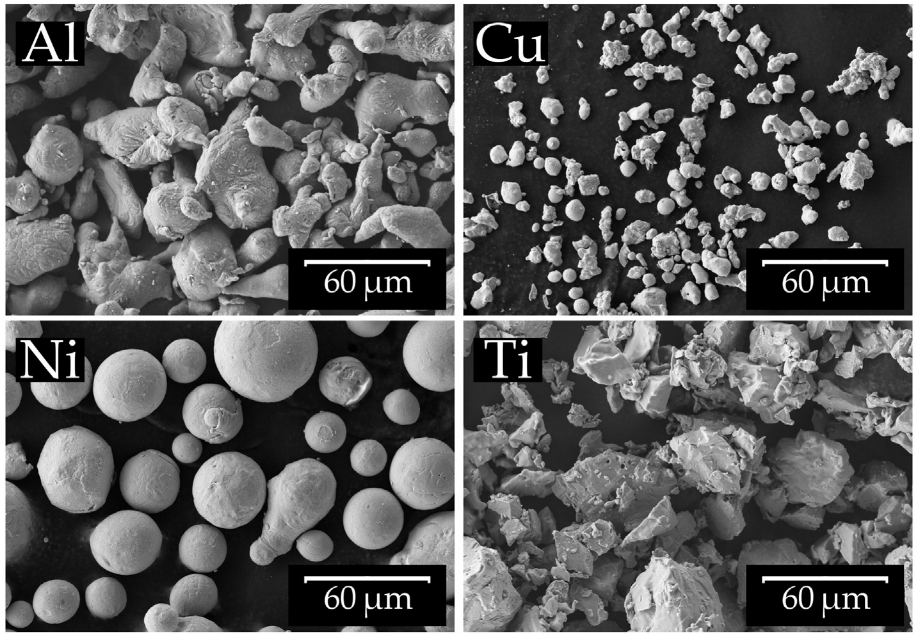

Fig. 1. Morphology of the Al, Cu, Ni, and Ti powders used for CS coatings fabrication.

apparent density (varying from 2.67–8.96 $g \cdot cm^{-3}$), morphologies (oval, fully spherical, angular; a consequence of different fabrication technologies), and average particle diameters (21–40 μm).

2.2. Coatings deposition

The analyzed materials were then deposited via high-pressure cold spray system (PCS-1000, Plasma Giken, Ltd., Japan) onto polycrystalline 6061 aluminum alloy substrates of commercial purity. The surface of the substrates was not grit-blasted prior to coatings deposition. However, chemical degreasing was used to remove any oil or contaminant films. The lateral dimensions of the coated areas were 150×50 mm and the robot arm movement and number of passes were set to reach a total coating thickness of at least 10 mm; the excessive thickness allowed subsequent cutting of the required samples. Further to that, the successive gun passes resulted in a further compaction of the underlying deposited layers, thereby lowering the inherent coating porosity. The spray parameters used in the deposition are proprietary to Plasma Giken and are not to be disclosed in the paper.

The properties of the fabricated coatings were studied using FE-SEM equipped with EDX mapping and EBSD detectors (Zeiss Ultra Plus) and XRD (X'Pert Pro X-ray diffractometer, Co-K $_{\alpha}$ source, K $_{\beta}$ absorption filter, X'Celerator detector; PANalytical B.V.). To determine oxygen content in the materials, Leco TC 600 thermoevolution analyzer was employed. Image analysis and the Archimedes methods were used to calculate the internal coatings porosity and Vickers microhardness was measured at 1 kgf load.

2.3. Resonant ultrasound spectroscopy

From each of the sprayed materials, a small sample of a rectangular parallelepiped-shape (approximately 3.5 × 2.5 × 1.5 mm^3) was cut from the region close to the center of the sprayed area. Taking advantage of the layers compaction via impingement of particles from successive gun passes, the samples were cut from areas close to the substrate-coating interface. All samples were oriented so that longest and the shortest edge of the sample were always perpendicular to the spraying direction and aligned with the directions of motion of the nozzle during spraying. However, it was assumed (as usual for the sprayed materials [19,23,25,26]) that all samples exhibit transversal isotropy, i.e. that all directions perpendicular to the spraying direction are equivalent, and the elasticity of the material can be fully described by five independent elastic coefficients. In the shorten Voigt's notation, these elastic constants are c_{11}, c_{12}, c_{13}, c_{33} and c_{44}, assuming that the spraying direction is aligned with x_3. The engineering constants E_{IP} and E_{OOP} introduced in the Introduction can be then recalculated from c_{ij} by simple algebraic relations (see e.g. [27]).

For each sample, a resonant spectrum of free elastic vibrations was obtained in the frequency range 0.1–2 MHz, using a contact-less, laser-based RUS setup [22]. The vibrations were excited by short (8 ns) infrared pulses from a Nd:YAG laser with nominal wavelength 1.064 μm and pulse energy 25 mJ (Quantel ULTRA, USA) and recorded by a scanning laser vibrometer (24 MHz frequency bandwidth) incorporated in a Polytec Micro-System Analyzer MSA-500, which enabled an identification of the modal shapes corresponding to individual resonant peaks. The experiments were performed at ambient temperature (295 K, temperature control ± 0.05 K) under a low pressure (10 mbar) nitrogen atmosphere.

The resonant spectra were complemented by pulse-echo measurements of phase velocity of longitudinal waves in directions perpendicular to the individual faces of the samples [27], i.e. in the in-plane (v_{IP}) and out-of-plane (v_{OOP}) directions. The schematics of the RUS method used within this study is shown in Fig. 2.

3. Results and discussion

3.1. Coating properties

The fabricated coatings exhibited well-sintered and relatively homogeneous structure (Fig. 3) with only negligible oxidation levels (<0.24 wt.% in all coatings). As the oxide content was found at particle rims only (via extended duration EDX mapping), it could be safely assumed that it was present in the original feedstock already and was incorporated into the coating during the spraying. As shown in Table 1, minimal porosity content only was detected in the coatings (ranging from 0.3–1.1%, decreasing towards interface) and the microhardness differed from 50 HV1 (Al) to 222 HV1 (Ti). The mass densities of the coatings as determined by the Archimedes method are further shown in Table 1.