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Investigation on relationship between mechanical properties and microstructural characteristics of metal matrix composites fabricated by cold spraying technique

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ABSTRACT

In this study, particulate-reinforced aluminum matrix composites were prepared by incorporation of 10 and 20 vol.% of copper. The metal matrix composite samples were fabricated using cold spray deposition technique. In general, the global properties of cold sprayed deposited materials are different from those of conventionally processed. This paper investigates mechanical properties of cold sprayed composites using available theoretical and experimental techniques. In order to determine the mechanical properties, both numerical simulation and analytical method were conducted. The microhardness and elastic modulus of Al–Cu cold spray coating were also determined using the Knoop hardness technique. Due to the different mechanical properties in transverse and longitudinal directions, the Knoop hardness was applied in both directions on the cross section of coatings. Image based numerical simulation was also performed on both transverse and longitudinal directions. Comparison between the results from the analytical models, experimental techniques, and numerical simulation helped us to better understand the influence of microstructural characteristic on the mechanical properties of cold spray deposited metal matrix composite.

1. Introduction

Metal-matrix composites (MMCs) are increasingly finding application in aircraft components, automotive industry, cutting tools, and sporting goods. In particular, aluminum matrix composites are very attractive due to their light weight and high strength to weight ratio [1]. Particulate-reinforced aluminum matrix composites have been used extensively for low temperature structural components in the aerospace and automotive industries. The two most important advantages of particulate-reinforced aluminum matrix composites when compared to fiber or laminate reinforced composites, are their isotropic mechanical properties and ease of fabrication into complex shapes. All types of reinforcements including SiC, B, B_4C, Al_2O_3, ZrO_2, graphite, copper, aluminides, and Kevlar have been investigated for use in aluminum-based MMCs [2]. In this study, the composite material consisted of aluminum matrix reinforced with 10 and 20 vol.% of copper particulates. Powder metallurgy and castings are among traditional and common methods used to fabricate particulate-reinforced metal matrix composites. This study uses cold spraying deposition technique to fabricate metal matrix composites instead of traditional methods.

Generally, coating techniques are used to apply a protective layer on the surface of materials. Here, a coating process has been employed as a manufacturing technique to fabricate metal matrix composites. A conventional cold spraying system includes the following steps; pre-heating solid particles below their melting temperature, acceleration of solid particles, impact of injected particles on the substrate, and deformation of solid particles (deposition formation). The fundamental feature of the process is “acceleration” of the preheated solid state particles to high velocities (typically 300–1200 m/s) while passing through a high pressure chamber of a converging-diverging nozzle. The coating will build-up after impact and flattening of injected powder particles on the substrate [3,4]. Cold spraying seems to be a promising technique to manufacture metal matrix composites compared to the other traditional techniques such as powder metallurgy and casting. It is a rapid, single-step manufacturing technique with less heat input resulting in less oxidation, no recrystallization, and minimum thermal stress build up in the fabricated metal matrix composites. However, since particles are injected in the solid condition, this technique is limited to spraying of ductile materials only. Aluminum and copper are two ductile materials which makes them suitable candidate to be deposited using cold spraying technique.

Mechanical properties of cold spray processed coatings are mainly based on their microstructural characteristics such as voids, pores, microcracks, and splat boundaries. Therefore, proper characterization of coating materials will significantly improve understanding of critical microstructural features which affect the

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physical and mechanical properties of cold sprayed MMCs. There is a huge need to develop an efficient microstructural based scheme to evaluate mechanical properties of coating materials. However, cold spray coatings exhibit a complex lamellae type microstructure. Due to the complex nature of the cold spray coating microstructure, it is difficult to establish an appropriate relationship between its microstructural characteristics and mechanical properties. It becomes more difficult taking to the account the multiphase nature of MMC materials.

There are a few published theoretical studies describing empirical relationships between the mechanical properties and microstructural characteristics of coating structures [5–7]. These studies only take into the account the volume fraction of the pores and voids in the coating microstructure. Models have also been developed to establish the same relationship for MMCs processed via conventional techniques such as casting and powder metallurgy [8,9]. Some studies proposed a microstructure-based finite element analysis to predicting the mechanical properties of particle-reinforced metal matrix composites [10–13]. However, no model can claim a complete success in accurate estimation of the mechanical properties of coatings [14].

The objective of this investigation was to characterize the mechanical behavior of aluminum matrix composite fabricated using cold spray method, reinforced with different volume fraction of copper particles. Generally, coatings are considered anisotropic and heterogeneous materials which exhibit different properties at different directions respect to the spraying direction. In this study, it has been tried to measure the mechanical properties of the cold sprayed aluminum matrix composites in both transverse (perpendicular to spraying direction) and longitudinal (parallel to spraying direction). The available models relating the microstructure to the elastic modulus, E, was used to estimate elastic modulus of the composite. Furthermore, the results of image based finite element analyses on the deposited composite are presented. To validate results obtained from analytical models and numerical simulations, experimental studies such as Knoop hardness test and resonant frequency are performed on the freestanding as-sprayed composite samples. Comparison between the obtained results from experimental studies, theoretical models, and finite element simulations gives us better understanding of the effect of microstructural characteristics on the mechanical behavior of aluminum composite fabricated by deposition technique.

2. Experimental

2.1. Materials

Commercially available powder of Al 99.5% with the irregular shape and the nominal particle size in the range of −45 to +5 μm, Centerline (Windsor) Limited, ON, Canada was used in this study. The aluminum particles were mixed with 10 and 20 vol.% of the copper particles (Cu 99.7%) with irregular shape and the nominal particle size in the range of −45 to +5 μm, Centerline (Windsor) Limited, ON, Canada.

2.2. Coating deposition

Fabrication of the metal matrix composite samples, consisted of aluminum matrix reinforced with various amounts of copper particulates achieved using the cold spraying technique. In this technique particles are heated under the melting temperature and accelerated toward the substrate. Coatings are formed layer by layer after impact of small solid particles. Bonding of particles is resulted due to the widespread plastic deformation and particle interlock at the interface boundaries [3,4]. Fig. 1 shows a schematic of cold spraying system.

Table 1
Operational spraying parameters.

Process parameters	Value
Temperature (°C)	350
Pressure (psi)	250
Nozzle stand-off (mm)	10
Gun traveling speed (mm/s)	20
Processing gas	N_2

Here, powder mixture was cold sprayed using SST-P Series cold spray system by Centerline (Windsor) Limited, ON, Canada using the parameters shown in Table 1.

2.3. Microstructural characterization

The two different Al–Cu powder mixtures were characterized using optical microscopy, SEM, and energy dispersive X-ray spectroscopy (EDS). Powders were slightly pressed, and mounted in epoxy before optical microscopy and SEM. The two different Al–Cu coating samples were cross-sectioned parallel to the spraying direction using a diamond coated blade and mounted using thermoset acrylic prior to the optical microscopy and SEM observations. The mounting process was carried out under low pressure to reduce pull out of particles during metallography. The coating cross-sections were ground and polished for microstructural observation. A Zeiss Axiovert 40 MAT (Focus Precision Instrument, Germany) was used for the optical microscopy. The coating cross-section was etched in 50 ml H_2O + 50 ml HCl + 10 g $CuSO_4$. Scanning electron microscopy was performed on powder mixtures and coating cross-sections by a JEOL JSM-6490LV SEM (JEOL USA, Peabody MA, USA) using an accelerating voltage of 15 keV. A Nanotrace EDS detector equipped with a NORVAR light element window (Thermo-Scientific, Madison WI, USA) was used for elemental analysis.

2.4. Mechanical testing

2.4.1. Knoop indentation test

In this study, Knoop hardness technique was conducted to simultaneously measure the Young's modulus of reinforcement and matrix phases of microstructure in both transverse and longitudinal directions. The elongated diamond shape covers wide area containing splats, splat boundaries, and voids which makes it suitable for coating structures. The Knoop hardness of each sample was measured using a Zwick microhardness machine under an applied load of 9.8 N for 25 s. Nine indentation tests were performed on each coating cross-section, with the long axis of the indent oriented perpendicular and parallel to the deposition direction. To obtain the Knoop hardness the following equation was applied:

$$\mathrm{HK} = \frac{L}{l^2 C_P}, \tag{1}$$

where HK is the Knoop hardness value in MPa, L is the applied load to indenter in kg, l is the length of major diagonal of the indentation in mm, and C_P is the constant relating l to the projected area. For a perfect indenter of 172° 30′ longitudinal angle, and 130° 0′ transverse angle, C_P equals 7.028×10^{-2}.

Also the elastic modulus, E, of the coating can be determined by Knoop indentation test using a model developed by Marshall et al. and Conway [15]

$$\left(\frac{b'}{b}\right) = 1 - 2[(1-\upsilon^2)\tan\gamma]\left(\frac{H}{E}\right), \tag{2}$$

knowing that b' is the diagonal of indentation after taking the indenter, b is major diagonal of indenter, υ is the Poisson's ratio