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Optimization of cold-sprayed AA2024/Al_2O_3 metal matrix composites via friction stir processing: Effect of rotation speeds

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A B S T R A C T

In this study, friction stir processing (FSP) was employed to modify cold-sprayed (CSed) AA2024/Al_2O_3 metal matrix composites (MMCs). Three different rotation speeds with a constant traverse speed were used for FSP. Microstructural analysis of the FSPed specimens reveals significant Al_2O_3 particle refinement and improved particle distribution over the as-sprayed deposits. After FSP, a microstructural and mechanical gradient MMC through the thickness direction was obtained. Therefore, a hybrid technique combining these two solid-state processes, i.e. CS and FSP, was proposed to produce functionally gradient deposits. The Guinier-Preston-Bagaryatskii zone was dissolved during FSP, while the amounts at different rotation speeds were approximately the same, which is possibly due to the excellent thermal conductivity of the used Cu substrate. Mechanical property tests confirm that FSP can effectively improve the tensile performance and Vickers hardness of CSed AA2024/Al_2O_3 MMCs. The properties can be further enhanced with a larger rotation speed with a maximum increase of 25.9% in ultimate tensile strength and 27.4% in elongation at 1500 rpm. Friction tests show that FSP decreases the wear resistance of CSed MMCs deposits due to the breakup of Al_2O_3 particles. The average values and fluctuations of friction coefficients at different rotation speeds vary significantly.

1. Introduction

Metal matrix composites (MMCs), in which hard ceramic particles are dispersed in a relatively ductile matrix acting as superabrasives, have widespread applications in areas of aerospace, automobiles and other engineering industries owing to their unique physical/mechanical properties and performance [1–3]. MMCs possess superior combinations of elevated-temperature capabilities, high thermal conductivity, high strength and stiffness, high strength-to-density ratio and low coefficient of thermal expansion [4,5]. According to the type of metal matrix, MMCs can be mainly divided into aluminum-based, copper-based, magnesium-based composites, etc. [5,6]. Up to now, MMCs can be produced using various methods, such as spark plasma sintering [7], squeeze casting [8], laser melting [9], composite electroforming technology [10] and thermal spray [11]. In these processes, high temperature (higher than melting point in most cases) is necessary to melt the matrix phase or enhance atomic diffusion for achieving excellent cohesion. However, high temperature frequently results in phase transformation, oxidation and decarburization of ceramic reinforcements or soft metal matrix, which can significantly deteriorate the mechanical properties and wear-resistance of MMCs [3,12]. Therefore, cold spray (CS) was proposed as an alternative technology to fabricate MMCs with eliminating the adverse effect brought by the high temperature [12–14].

CS, also known as cold gas dynamic spray or kinetic spray, has attracted increasing attention as a versatile solid-state coating and additive manufacturing technique [13,15]. With this process, metallic or dielectric substrates are exposed to high velocity particles accelerated by an expanding gas stream at temperatures lower than the melting point of spraying material [13]. These conditions identify CS as a 'low-temperature' and 'high-velocity' process with significant advantages such as lack of oxidation or phase transformation, which enables feedstock powder to retain its original properties [12,15,16]. These advantages allow CS a suitable technique to deposit particle-reinforced MMCs such as AA5056/SiC [17] and Cu/CNT/SiC [18].

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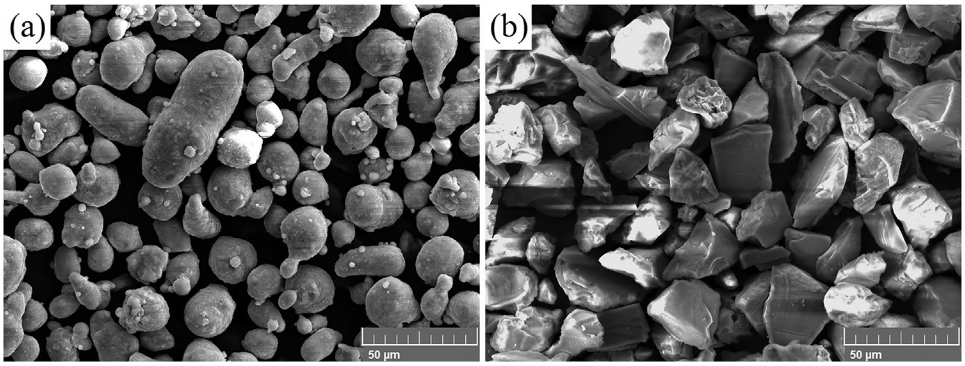

Fig. 1. Morphologies of (a) AA2024 and (b) Al_2O_3 powders.

However, there are often significant losses of strength and ductility of MMCs associated with CS. This can be attributed to two reasons: (1) The existence of interparticle interfaces [15,19]. Interparticle interfaces are the special existence in CS, which means a negative contribution to the final strength and ductility. For CS, the interfaces between particles are the main reason for poor performance of CSed deposits compared to the bulk material; (2) The existence of large size ceramic particles [19,20]. Investigations on particle-reinforced MMCs have shown that the strengthening effect is linked to the pinning of matrix dislocations by the dispersed reinforcements, which is referred to dispersion strengthening [21]. However, the dispersion strengthening shows a significant effect only when the particle size is very small (below 0.1 μm) [22]. Although ceramic particles can be broken during high-velocity impact, the refinement extent is very limited, which makes the existence of ceramic particles a negative factor for bonding in most cases [13,20].

To overcome the above negative effect, as the most commonly used post treatment in CS, heat treatment has a significant enhancement on CSed deposits with improving bonding between metallic particles [15,23,24]. However, its effect is limited on CSed MMCs, which may be due to the facts: (1) The bonding strength between metallic particle and ceramic particle can hardly be improved with atomic diffusion during heat treatment; (2) The dispersion strengthening is not improved, because ceramic particles retain unchanged large size during heat treatment. Therefore, an alternative post treatment is necessary to strengthen CSed MMCs.

As another solid-state process, friction stir processing (FSP) has been employed as a post treatment to refine and modify the microstructure of MMCs following conventional processes such as thermal spray, powder metallurgy and mechanical alloying [25]. In this technique, a non-consumable rotating tool, consisting mainly of a probe and shoulder, is plunged into a metal plate and then the tool is traversed in the desired direction [6,25,26]. During FSP, the metal is exposed to a combination of intense plastic deformation, mixing and thermal exposure, resulting in a modified microstructure [6,25]. FSP has been employed to co-fabricate MMCs to achieve homogeneous microstructure in reinforcement particle's spreading and dispersion with many conventional processes like thermal spray and mechanical alloying [20]. Besides, Gandra et al. [27] applied FSP to add reinforcement particles (SiC) into base materials (AA5083) in order to create mechanical property gradients along the thickness. Their investigations indicate that FSP could be a feasible method to produce gradient layers of composition and mechanical behavior.

In the past years, FSP has been applied to CSed deposits to refine the distribution of reinforcing particles and remove the weak interface between particles [19,28–30]. Among these investigations, Huang et al. [29] investigated the effect of FSP on AA5056 reinforced with SiC particles. Their wear study revealed that the presence of the refined reinforcing particles embedded in the matrix increased the average friction coefficient. Peat et al. [19,30] carried out a comprehensive understanding on the erosion performances of CSed MMCs modified by FSP.

The studies mentioned above have confirmed the positive modification effect of FSP on CSed MMCs with refining the distribution of reinforcing particles. In addition, it is also shown that a significant mechanical property enhancement of CSed metal alloys with ultrafine grains can be achieved by post-spraying FSP [31]. Therefore, in this study, FSP was employed to modify the CSed AA2024/Al_2O_3 MMCs. As an essential processing parameter, the effect of rotation speed was investigated. The microstructural evolution, mechanical properties and tribological performance were characterized and discussed.

2. Materials and methods

2.1. CS deposition and FSP treatment

Commercially spherical AA2024 powder (15–45 μm, Beijing Xing Rong Yuan Technology Co., Ltd, China) and irregular Al_2O_3 powder (15–45 μm, Beijing You Xing Lian Technology Co., Ltd, China) were used as feedstock (Fig. 1). Before spraying, two powders were simply mechanically blended with a volume ratio of 4:1. A 3 mm thick Cu plate was used as the substrate. The deposition was performed on a custom developed CS system. A conventional de-Laval nozzle, using helium as the carrier gas, was used to accelerate the powder particles. The inlet pressure and temperature were 0.8 MPa and 500 °C, respectively. The nozzle standoff distance was 25 mm and gun traverse speed was 20 mm/s. Following spraying, AA2024/Al_2O_3 MMCs deposit with about 5 mm thickness was obtained.

A commercial friction stir welding (FSW) machine (FSW-RL31-010, Beijing FSW Technology Co., Ltd., PR China) was employed to accomplish post-spraying FSP. Traverse speed of 100 mm/min and tool rotation speeds of 900 rpm, 1200 rpm and 1500 rpm were employed to modify CSed AA2024/Al_2O_3 MMCs. The used H13 steel tool with a threaded probe was designed to have a shoulder diameter of 10 mm, probe diameter of 2.9 mm and probe length of 3.4 mm. The rotating tool was tilted at 2.5°. The FSP direction was parallel to the CS gun traverse direction as shown in Fig. 2(b).

2.2. Characterization

The macro- and microstructural features of the CSed and FSPed samples were examined using both optical microscope (OM, OLYMPUS GX71, Japan) and scanning electron microscope (SEM, JSM5800LV, JEOL, Japan). X-ray analysis was carried out with an

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