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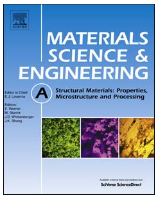

Additive manufacturing of an aluminum matrix composite reinforced with nanocrystalline high-entropy alloy particles

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ABSTRACT

In the present work, a metal-metal composite consisting of aluminum-magnesium alloy AA5083 matrix and nanocrystalline CoCrFeNi high-entropy alloy reinforcement particles in 12 vol% was successfully friction deposited in multiple layers. The layer interfaces or the reinforcement/matrix interfaces showed no brittle intermetallic formation – thanks to the inert nature as well as the high strength and hardness of the high-entropy alloy reinforcement particles. The composite showed significantly higher tensile and compressive strengths as compared to standard wrought-processed alloy AA5083-H112 and offered a much better combination of strength and ductility when compared to conventional aluminum matrix composites reinforced with ceramic particles. The current study establishes friction deposition as a viable technique for additive manufacturing of novel high-performance composite materials.

1. Introduction

In a recent study, additive manufacturing of a metal-metal composite, 6 vol% Ti_p/AA5083, was demonstrated using friction deposition [1]. Multi-layer friction deposits in this composite showed inferior Z-direction tensile ductility due to brittle intermetallic formation (Al_3Ti and TiAl) at the layer interfaces, caused by severe mechanical mixing or alloying of titanium with aluminum during the initial stages of friction deposition of each new layer. It should be possible to overcome this problem by employing a less reactive metallic reinforcement, which is also adequately strong and hard so that, during friction deposition of the composite, the reinforcement particles do not suffer excessive deformation.

High-entropy alloys (HEAs) are a new class of materials composed of multiple components (typically four or more metallic elements) in nearly equiatomic proportions [2–4]. Despite their unusual chemistry, they occur as simple solid solutions and display interesting and useful properties. According to Yeh [5], they derive their special properties from four core effects: (1) high-entropy effect, (2) sluggish diffusion effect, (3) severe lattice distortion effect, and (4) cocktail effect. With their inherently less reactive nature and sluggish diffusion behavior as well as very high strength and hardness, they make an excellent choice for use as reinforcements in friction deposited metal-metal composites.

Some work has already been carried out using HEAs as reinforcements in metal matrix composites, although not using friction deposition. Chen et al. [6] have successfully produced 10 and 20 vol% AlCoCrFeNi HEA_p/copper composites using powder metallurgy route. The HEA powder was prepared by ball milling and had a nanocrystalline structure. Sintering was done for 30 min at 800 °C and 70 MPa in vacuum. The composite samples showed no reaction products at the HEA particle/copper matrix interfaces. The HEA particles did not lose their nanocrystallinity after sintering. In compression tests, the composite showed significantly higher strength when compared to pure copper. In another study, using laser melt injection technique, Meng et al. [7] incorporated AlCoCrCuFeNi HEA particles into the surface of magnesium alloy AZ91D. Microstructural examination of the treated surfaces (~1 mm in thickness with 10 and 40 vol% HEA reinforcement particles) revealed no brittle intermetallic formation at the particle/matrix interfaces, although many of the HEA particles were found to undergo partial melting or dissolution. In sliding wear tests, the treated surfaces showed significantly higher wear resistance.

In the current work, for the first time, friction deposition was used for additive manufacturing of an aluminum matrix composite reinforced with nanocrystalline HEA particles. CoCrFeNi was considered as the candidate HEA system in view of its tolerance to aluminum (AlCoCrFeNi is an established HEA system). Thus, even if some aluminum diffuses into CoCrFeNi particles during friction deposition, the particles do not easily lose their high entropy character and it is less likely to result in undesirable brittle intermetallic formation at the particle/matrix and the layer interfaces.

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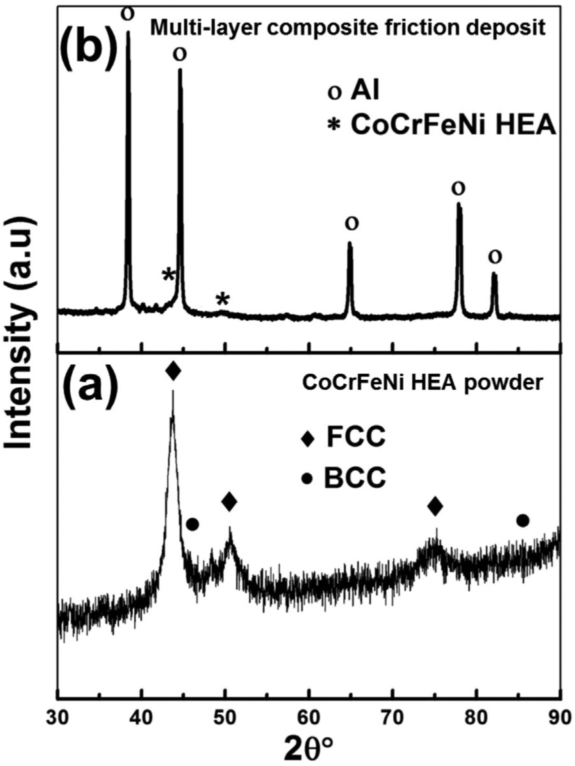

Fig. 1. X-ray diffractograms: (a) HEA powder, (b) HEA_p/5083 composite.

2. Experimental details

CoCrFeNi HEA powder was produced by ball milling pure elemental powders of Co, Cr, Fe, and Ni taken in equiatomic proportions (i.e., 25 at% each). Ball milling was carried out in a high energy ball mill (FritshPulverisette-P5) using tungsten carbide vial and balls for 15 h. A ball to powder ratio of 10:1 was used and toluene was employed as the process medium. The CoCrFeNi HEA powder had a major FCC phase and a minor BCC phase, as can be seen from the XRD plot shown in Fig. 1a. Using Scherer's formula, the crystallite size of the powder was estimated to be ~10 nm. The powder particles are irregular in shape and have an average size of 15 ± 5 µm, as determined using a laser particle size analyzer (Fig. 2a). As can be seen from Fig. 2b, many of the powder particles contained weakly-bonded sub-particles. More details about the CoCrFeNi HEA powder can be found in Refs. [8,9].

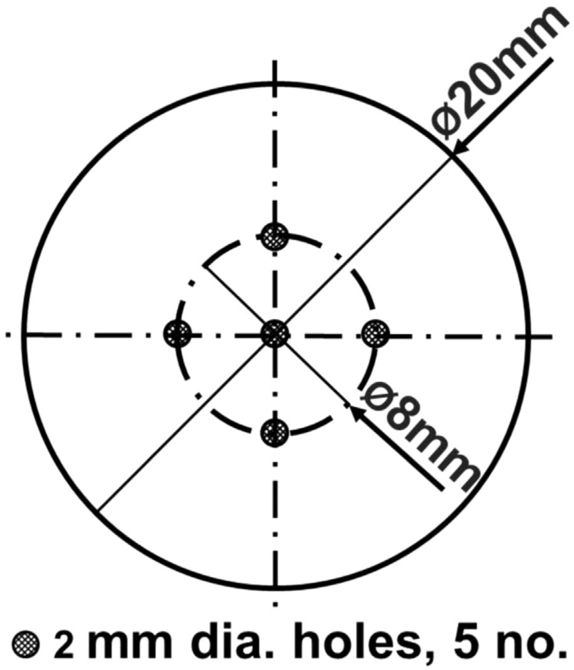

Fig. 3. Arrangement of holes in the consumable rod.

Friction deposition experiments were conducted on a 200kN direct-drive rotary friction welding machine (Eta Technologies, Bangalore, India) employing 20 mm diameter consumable rods of aluminum-magnesium alloy AA5083-H112 (nominal composition by wt%: Al - 4.43 Mg -0.60 Mn - 0.12 Si - 0.19 Fe). 25 mm diameter rods of the same material were used as the substrates. As shown in Fig. 3, 2 mm diameter and 50 mm deep holes were drilled in the consumable rods using spark electric discharge machining. Before friction deposition, the holes were tightly filled with the HEA powder (the targeted reinforcement volume fraction in the composite was 12 vol%). The process parameters used for friction deposition were: 800 rpm spindle speed, 8kN friction force, and 25 s friction time. Ref. [1] describes the process of friction deposition of metal-metal composites in detail. By friction depositing several layers one over the other (each layer is ~1 mm thick), cylindrical samples of 40 mm height and 20 mm diameter were obtained. For comparison, a few multi-layer monolithic friction deposits (i.e., without adding the HEA reinforcement particles) were also produced. In addition, a few single-layer composite friction

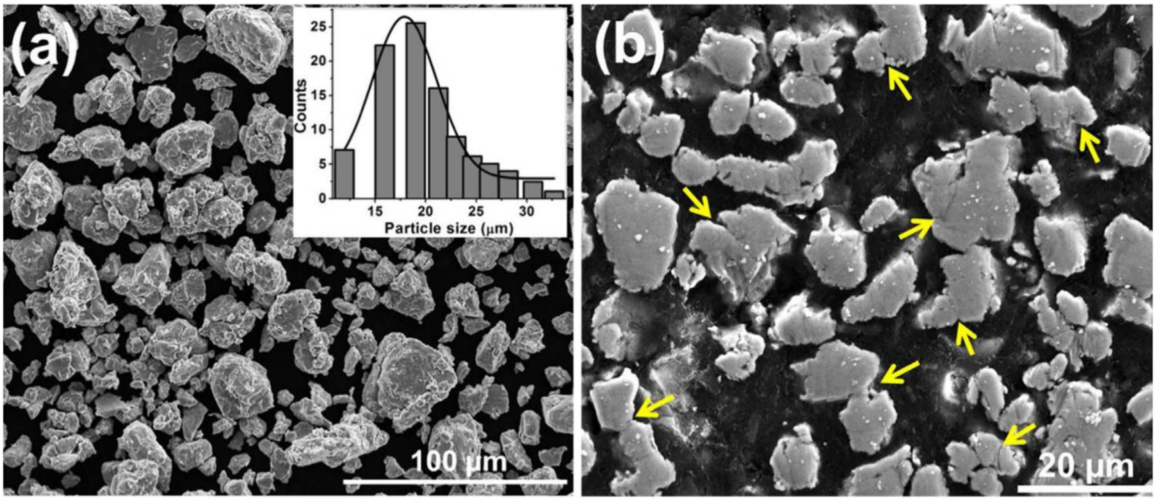

Fig. 2. SEM micrographs of CoCrFeNi HEA powder: (a) ultrasonicated loose powder, (b) mounted and metallographically polished powder. Inset in (a) shows the particle size distribution (based on laser particle size analysis). Arrows in (b) show some powder particles that are composed of weakly-bonded sub-particles.

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