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Fiber traction printing--a novel additive manufacturing process of continuous fiber reinforced metal matrix composite

XinWang, Xiaoyong Tian, Dichen Li

State Key Laboratory of Manufacturing Systems Engineering, Xi'an Jiaotong University, China

Abstract

Metal matrix composites (MMCs) are materials which have been widely used in the aerospace and automobile industries since the 1980s and have been classified as hard-to machine materials. This manuscript proposes a novel additive manufacturing process of continuous fiber reinforced metal matrix composite -- fiber traction printing (FTP). The composites with complex structures can be directly manufactured via FTP which utilizes the wetting force and capillarity force to control the flow of melting matrix. The craft is proceeding without extra pressure device and atmosphere protection device and substantially decreases the cost. This manuscript introduces the proof-of-concept prototype and the ability to control the flow of melting matrix and fiber distribution through this process yields a flexible manufacturing route to fabricating 3D metal matrix composite parts with full density and complex geometries.

Keywords: metal matrix composite; 3D printing; additive manufacturing;

Introduction

Manufacturing technologies in extreme environments have drawn more and more scientists' attention especially for space exploration.[1] In particular, 3D printing techniques have potential to be deployed in the space environment to enhance safety levels by providing replaceable parts and decrease launch mass.[2-7] Hence, metals or materials with higher performance are required. Nevertheless, the conventional metal based 3D printing methods, such as SLS, EBM and SLM,[8] are challenging to be operated in space[7-9] and shrinking and balling of molten droplets occur in microgravity due to the large surface tension.[9,10] Thus, a 3D printing method utilizing fiber pulling process is proposed in this paper in order to prepare metal matrix composites (MMC). Fiber Traction Printing (FTP) is an additive manufacturing method taking advantage of wetting behavior between fibers and metal matrix to pull the molten metal out of printhead and then deposit the composite filaments layers upon layers. The wetting forces are used to overcome the surface tension of metal, thus molten metal can homogeneously enfold the fiber and spread along fiber direction. To demonstrate the fundamental mechanism of this approach, we will show a proof-of-concept FTP prototype of a simple and low temperature C_f/Sn-Pb composite system as a representative example with an experimental platform. Sn-Pb alloy is a class of solder alloy system,[11,12] and the ability to print these metal matrix composites will also offer insight into many applications such as printed electronic interconnects and three dimensional electronic circuit architectures in space for the future.[13]

Materials and Method

Alloy wires of 2mm diameter with a normal composition of $Sn_{50}Pb_{50}$ (at. %) and carbon fibers were used as raw materials. One of the simplest methods of measuring the quantities for estimating the adhesion properties of materials (i.e., the adhesion work, the surface energy, and the interfacial tension between certain liquids and a surface) requires the determination of the contact angle θ between the liquid and the surface.[14] According to the preliminary experimental results, the molten $Sn_{50}Pb_{50}$ cannot wet the carbon fiber. Hence, in order to improve the adhesion property, carbon fibers were treated by electroplating two layers of metallic coating successively, 1μm Ni coating which is used to improve the bonding strength between Cu coating and carbon fiber, and 2μm Cu coating. To identify the wetting behavior, a $Sn_{50}Pb_{50}$ ingot cube with 2mm side length was put on a plate covered with Cu/Ni coated carbon fibers in the vacuum furnace (Fig. 1(a)). The wetting angle was almost 109.6-degree when the temperature was 300℃ (Fig. 1(b)), and the phenomenon is non-wetting because of the oxidation of Cu coating. Oxygen contamination (even at ppm levels) can have a dramatic effect on the surface tension of metals.10 Hence the soldering flux was utilized to modify the Cu/Ni coated carbon fibers. The major ingredient of the soldering flux is rosin which eliminates the oxide layer and improves wetting behavior. The fibers were covered with cream-state soldering flux homogeneously and it had a great influence (Figs. 1(c) and 1(d)).

Based on the above wetting mechanism, FTP of $C_f/Sn_{50}Pb_{50}$ composites are carried out using a continuous fiber reinforced composites 3D printer (COMBOT-I from Shaanxi Fibertech Technology Development Co., Ltd, China). As the coated fibers are pulled out of the nozzle, solidification of metal matrix adhering to the fibers rapidly occurs, which forms homogeneous cylindrical composite filament (Figs. 2(a) and 2(b)). In order to achieve a precise feature size, the pulling rate should match to the solidification rate[15]. Therefore, the pulling rate in the range of 1-7mm/s is adopted according to the experimental results. When the pulling rate is large, the wetting is incomplete and the fiber is partial exposed. On the contrary, the uniformity decreases when the pulling rate is low. The temperature is in the range of 230-245℃.

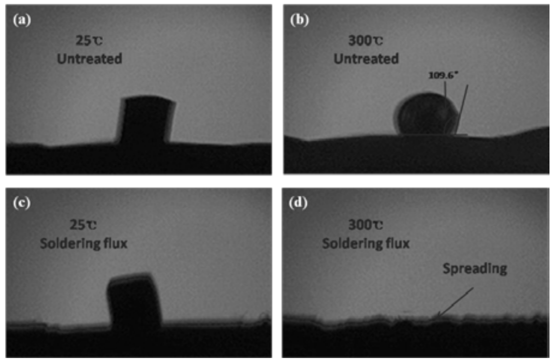

FIG. 1. Wetting angle test of Sn50Pb50 alloy on Cu/Ni coating carbon fibers (a) fibers without soldering flux at 25 ℃, (b) fibers without soldering flux at 300 ℃, (c) fibers with soldering flux at 25 ℃, (d) fibers with soldering flux at 300 ℃

Results and discussion

The approach of FTP is a dynamic wetting behavior of cylindrical surface in non-equilibrium condition.[16,17] Hence the wetting behavior of a fixed point on the fiber will change with the position and circumstance of the molten cavity.

Two bunches of composite filaments were printed (Fig. 2 (b)) at 230℃ and 245℃ respectively with the speed of 1mm/s. The tension strength of the 230℃ specimen is 60.4Mpa, the fracture surface (Fig. 2 (c)) shows that the Cu/Ni coating still adheres to the fibers. The tension strength of the 245℃ specimen is 124.1Mpa, while the fibers and coatings are separated in the fracture appearance (Fig. 2 (d)). It clearly shows that the adhesion property of the 245℃ specimen is better than the 230℃ specimen.

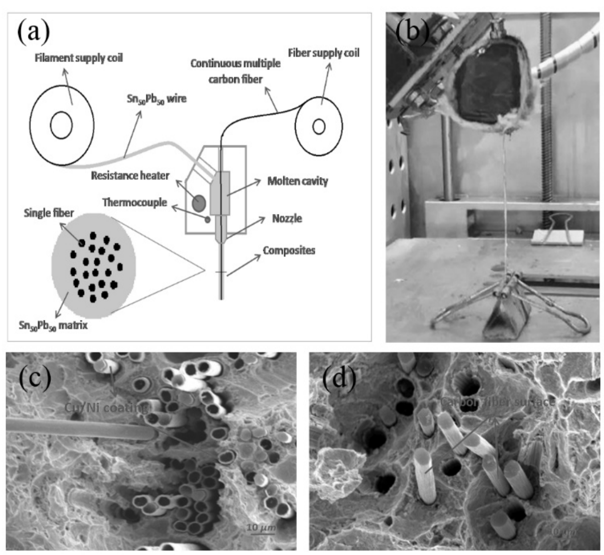

FIG. 2. (a) Schematic diagram of printhead in FTP system. (b) The actual printing process of composite monofilaments. (c) The fracture appearance of spice printing at 230℃. (d) The fracture appearance of spice printing at 245℃

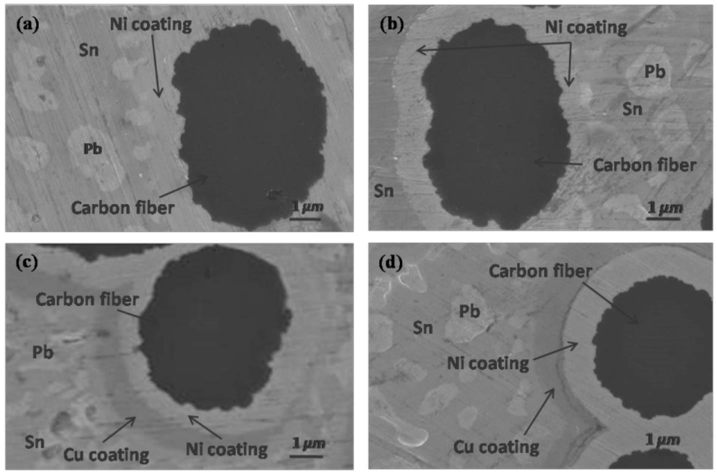

FIG. 3. Microstructure and EDS analysis of the interfaces in polished cross-sections of composite filaments printed at the different pulling rate, (a) 1mm/s, (b)3mm/s , (c) 5mm/s and (d) 7mm/s, respectively.

In general, the properties of metal matrix composite are fundamentally linked to its interfacial reactions. To identify the interfacial reactions of the printed $C_f/Sn_{50}Pb_{50}$ composite, the microstructures of specimens printed at different pulling rates and the temperature of 235℃ were analyzed by the Gemini SEM 500 scanning electron microscope at Instrument Analysis Center of Xi'an Jiaotong University. The coating of Cu together with a part of Ni disappeared at the rate of 1mm/s, which formed an irregular edge (Fig. 3(a)). Improving the pulling rate to 3mm/s can keep the edge of Ni coating smooth and intact (Fig. 3(b)) and it is worth noting that the microstructural morphology of the two later prints show the existing of Cu coating at the rate of 5mm/s and 7mm/s (Fig. 3(c) and 3(d)). That is mainly because a fast dissolution of Cu/Ni and interfacial reactions occurred during the slow printing process.[18,19] It is worth nothing that interfacial reactions between Cu and Sn formed the intermetallic compounds, such as Cu_6Sn_5[18] and Cu_3Sn[19], which guarantee the reaction bonding in the interface. Hence FTP provides a powerful tool to tailor the interfacial bonding properties of composites by controlling interfacial reactions. Furthermore, a frame which is 10 layers (0.5mm height per layer) was printed by this approach (Fig. 4).

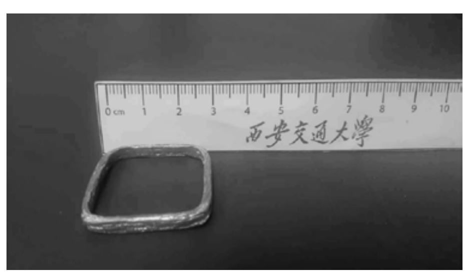

FIG. 4 The frame printed by FTP.

Conclusion

In summary, an alternative approach is introduced in this paper to realize the additive manufacturing of MMC. The specimen at 245℃ has larger tension strength and the coatings of carbon fiber are separated because of the better adhesion property. The level of interfacial reactions decreases with increasing of printing rate from 1mm/s to 7mm/s at 235℃. At the rate of 1mm/s and 3mm/s, the Cu coating is entirely consumed with the interfacial reactions.

The mechanisms of the FTP printed $C_f/Sn_{50}Pb_{50}$ prototype demonstrated in this study can be universally extended to a vast range of other continuous fiber reinforced metal matrix composite system that possess appropriate wetting behavior. FTP of more technically interested metal matrix composite systems such as SiC_f/Al, G_f/Mg and SiC_f/Ti will be a key subject of future work.

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