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A novel selective laser melting process for glass fiber-reinforced metal matrix composites

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ABSTRACT

A novel selective laser melting (SLM) process is presented for fabrication of glass fiber-reinforced metal (GFRM) matrix composite material. The SLM experiments are conducted using aluminum powders as matrix material and S-2 glass fibers as reinforcement. Laser heating turns the aluminum powders into a molten viscous flow which encapsulates the S-2 glass fibers. The glass fibers are not melted during the SLM process as the glass transition temperature is significantly higher than the melting point of aluminum powder. After the process, a mechanically enhanced glass fiber-reinforced metal matrix composite is produced with intact glass fibers embedded in the aluminum matrix.

1. Introduction

The high technology materials for next generation to be used for aerospace and aircraft require high thermal resistance and mechanical strength. Metal matrix composites have the potential to meet these requirements. Existing efforts have produced metal matrix composites with long continuous reinforced fibrous materials, e.g., carbon fiber in the aluminum (Al) matrix [1–5]. However, these fiber-reinforced metal matrix composites are expensive due to the high cost of fiber materials. To make fiber-reinforced metal matrix materials more widely accessible for various applications, a more cost-effective fiber material should be used. Therefore, glass fiber with relatively low cost is proposed in this work as the fiber reinforcement [6]. The authors' group has developed a selective laser melting (SLM) process to fabricate glass fiber-reinforced glass (GRFG) composite [7]. This process demonstrated the effectiveness of glass fiber as the reinforcement and thus can be potentially transformed into metal matrix composites. Meanwhile, aluminum is considered as the most suitable matrix material since fiber damage and generation of brittle crystals will not occur when aluminum is used as metal matrix material [8]. An infiltration method has been reported to fabricate glass fiber-reinforced metal (GFRM) composite [8], which produced metal matrix infiltrated glass fiber bundle by passing the glass fibers into a molten aluminum bath near an ultrasonic waveguide. However, this method is very slow and costly.

In this work, a novel SLM process is developed to produce a new type of glass fiber-reinforced metal (GFRM) matrix composite. Suitable glass fiber and metal powder are selected for this new SLM process to ensure the integrity of the fiber reinforcement. The microstructure of the built specimens and chemical composition, particularly at the fiber-metal matrix interface, are investigated using various characterization tools. The hardness of the resultant composite is measured to evaluate the mechanical strength.

2. Experiments

A continuous wave fiber laser with a wavelength of 1070 nm was used to scan an Al powder bed with glass fibers embedded. S-2 type glass fibers and 99.5% purity Al powder were selected as fiber reinforcement and metal matrix materials, respectively. The S-2 glass fiber with a mean fiber diameter of 10 μm and glass transition temperature (T_g) of 1056 °C was used as fiber reinforcement due to its low cost and high thermal resistance [6]. During the process, Al powders absorb most of the laser energy, while the glass fibers behave as a transparent medium to fiber laser. Fine Al powders turn into a molten viscous liquid induced by laser energy, and flow through the glass fibers and enclose the solid fibers, which are not melted due to their high glass transition temperature. The working temperature during the SLM process has to be controlled

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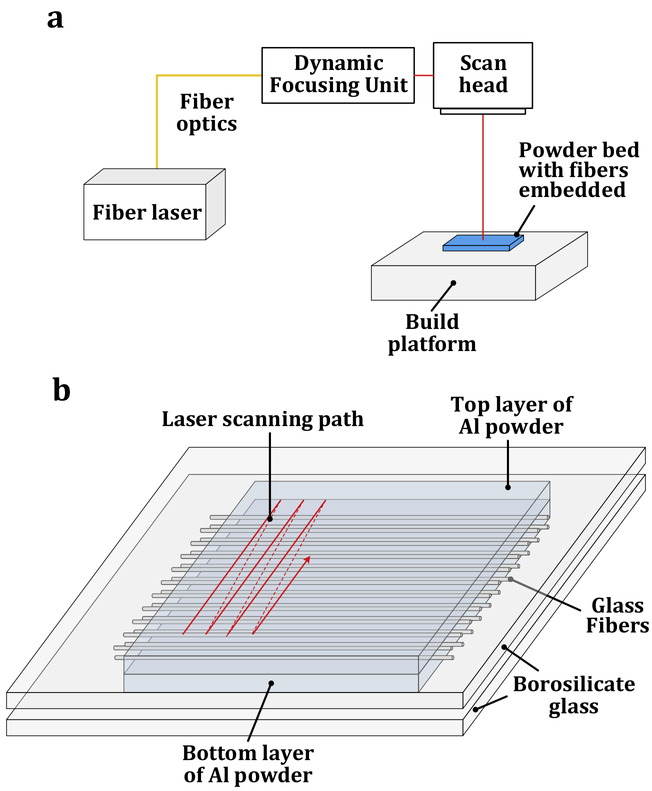

Fig. 1. SLM experiments: (a) experimental setup; (b) process schematic.

between 660 °C and 1056 °C to keep the fibers intact. A compacted GFRM composite with well-embedded glass fibers is thus formed upon cooling.

An experimental setup was developed for the new SLM process of GFRM composites employing a multi-mode 500 W continuous waveform Ytterbium fiber laser (IPG YLR-500-MM-AC-Y11, λ = 1,070 nm). As illustrated in Fig. 1a, the process used a raster scan scheme enabled by a laser scan head (SCANLAB intelliSCAN 20) combined with a dynamic focusing unit (SCANLAB varioSCAN 40i) in the depth direction. The glass fabrics procured from Fibre Glast have uniformly distributed fibers. Before the SLM experiments, the S-2 fibers were uniformly stacked on the bottom layer of Al powder. On top of the fiber layer, another layer of Al powder was leveled to make sure the uniformity was maintained. The Al powder layers had a layer thickness of about 1 mm spread and leveled on the build platform, as shown schematically in Fig. 1b. To avoid any balling effect during SLM, transparent borosilicate glass slides were employed on both sides of the powder bed [9–11]. During the SLM experiments, the following optimal set of laser processing parameters was used to achieve the best bonding quality: a laser power of 83.6 W, a scanning speed of 1.25 mm/s and a pitch of 2.5 mm between two laser scanning lines. The laser spot size was set to be 5 mm during the experiments. The rectangular specimens with a dimension of 20 mm $\times$ 20 mm $\times$ 2 mm were built using this SLM process. Two different distribution of glass fibers were used in this study, i.e., sparsely distributed fibers and fiber bundles.

The fabricated GFRM composite specimens were sectioned using a diamond saw, polished using an Allied high-tech polisher and sputter coated using Emitech Sputter Coater K550. Scanning electron microscope (SEM) analysis was performed using the Hitachi S-4800 SEM to investigate microstructure. Energy-dispersive X-ray spectroscopy (EDS) was conducted using the IXRF EDS unit equipped with the Hitachi S-4800 SEM to study any chemical composition change. The Vickers microhardness of the GFRM composite specimens was examined using a commercial digital microindentation tester (LECO 300 M) equipped with a diamond indenter using a load of 200 gf.

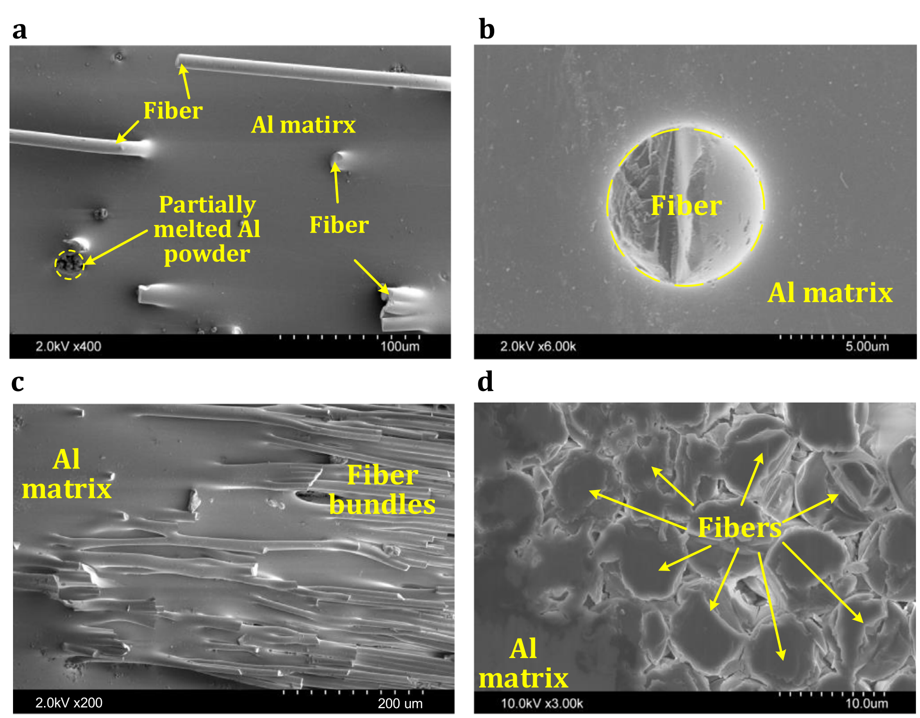

Fig. 2. GFRM composites with sparsely distributed glass fibers: (a) Longitudinal view along the fiber placement direction; (b) Cross-sectional view around a fiber; (c) GFRM composites with glass fiber bundles in the longitudinal view; (d) Cross-sectional view around fiber bundle.

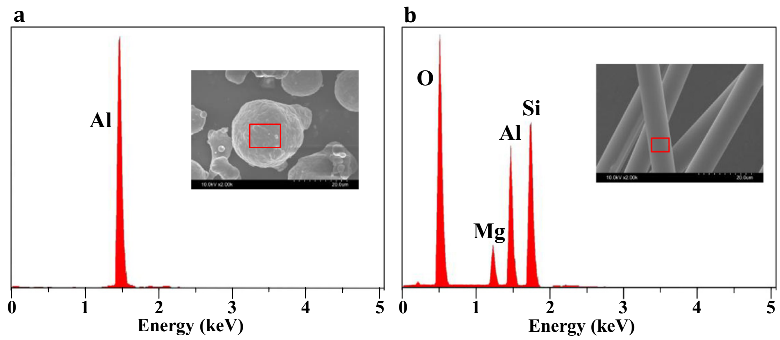

Fig. 3. EDS spectra of (a) pure Al powder; (b) S-2 glass fiber.

3. Results and discussions

Fused joining between glass fiber and Al matrix was first studied with fibers sparsely distributed between the metal powder layers. As shown in Fig. 2a, Al powders were entirely melted to form the solid Al matrix while the glass fibers were undamaged and well-enclosed by the Al matrix. Almost no defects could be found in the Al matrix at the fiber-matrix interface except some tiny locations with un-melted powder. The fiber-matrix interface was examined using a cross-sectional view of the microstructure as shown in Fig. 2b. The fiber-glass interface appears to be indistinguishable, indicating that the glass fiber was well fused with Al matrix. Through accurate control of the laser processing parameters, the glass fiber would remain intact while the Al powder can be fully melted to form metal matrix.

The process was further investigated with a large bundle of fibers stacked inside the metal powder layers. Longitudinal SEM image (Fig. 2c) was taken near the edge of the produced GFRM composite. It is found that the melted Al powder has covered the fiber bundles uniformly. In the cross-sectional view, as shown in Fig. 2d, fibers are well enclosed by the Al matrix without distinct defects. A maximum of 40% fiber to matrix weight ratio was achieved in the current study. The transport of material during the process is controlled by molten metal flow and re-solidification. Compared with other metals, aluminum has relatively low viscosity [13–17], and viscosity of aluminum [18] decreases as temperature increases. Thus the molten aluminum flow should exhibit smooth Newtonian flow behavior. The good bonding between the fiber and Al matrix also indicates that the temperature during the process was well controlled between the melting temperature of aluminum and the fiber glass transition temperature. Therefore, it can be inferred that the Al powder has been fully melted and flowed into the fiber bundle.

EDS analysis was firstly conducted on the pure Al powders and S-2 glass fibers prior to the SLM experiments. Al powder consists of almost 100% Al element as evidenced in Fig. 3a, and raw S-2 glass fiber consists of Al, Si, Mg and O elements (Fig. 3b), which indicates that the chemical composition of S-2 glass fiber is a combination of SiO_2, Al_2O_3 and MgO [12].

EDS analysis was performed on the cross-section of the GFRM specimens to observe the change of chemical composition during the SLM process. The locations of the EDS analysis is shown in Fig. 4a. The EDS spectrum at Location 1 indicates the presence of Al, Si, Mg and O elements (Fig. 4b). It is similar to the EDS spectrum of S2 glass fiber before the process. This indicates that almost no damage happened to the S-2 glass fiber during the process. In the meantime, EDS spectrum of Location 2 shows the existence of only Al and O elements (Fig. 4c) which proves that molten Al powder does not damage the glass fiber and no part of fiber mixed with the metal matrix. It also indicates that a small portion of the Al matrix gets oxidized during the process [19,20]. The EDS results

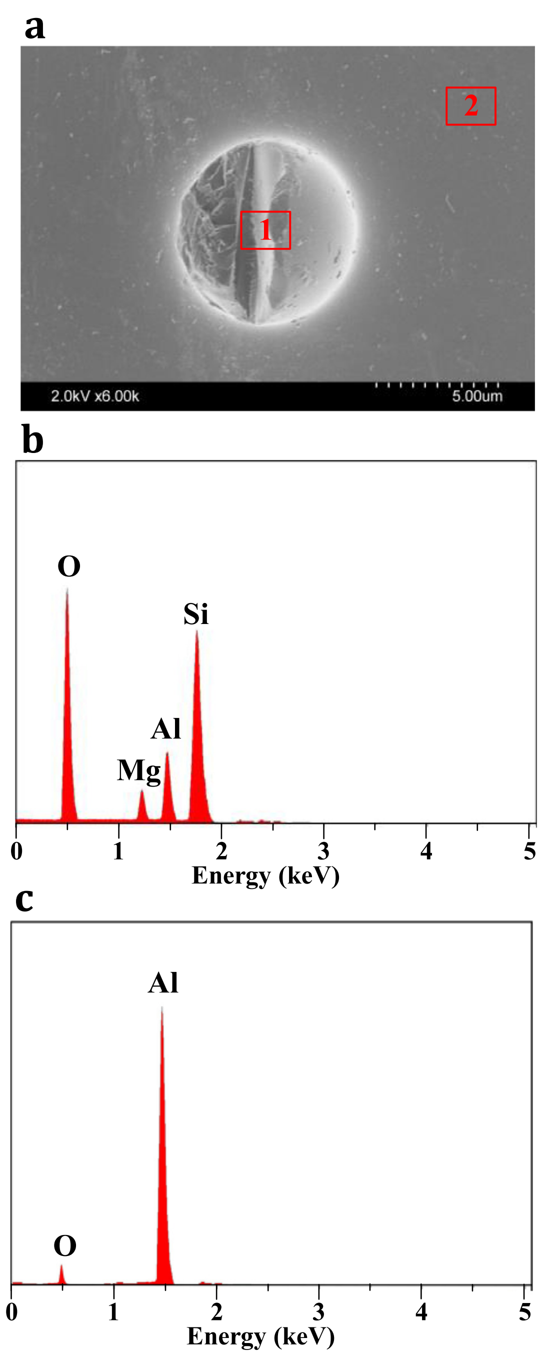

Fig. 4. (a) Cross-sectional view of a GFRM composite specimen with one fiber embedded in the Al matrix; (b) EDS spectra of S-2 glass fiber and (c) EDS spectra of Al matrix after SLM experiments.

further verify that a good bonding has formed between the glass fiber and Al matrix without any damage to the fibers during the process.

The microhardness of pure bulk aluminum was 26.0 ± 1.3 HV [21,22]. Through the SLM process, the microhardness of the fiber-reinforced Al matrix composite was enhanced up to 56.2 ± 5.0 HV. The microhardness measurement result indicates that this novel SLM process can fabricate metal matrix composite materials with significantly improved mechanical strength. The high bonding quality and enhanced mechanical strength of the fabricated GFRM composite has demonstrated the feasibility of the developed process in this work.

4. Conclusions

This work demonstrated a novel SLM technique for fabrication of fiber-reinforced metal matrix composites using S-2 glass fibers and aluminum as reinforcement and metal matrix, respectively. During SLM experiments, the molten metal material viscously flowed into glass fibers, and the glass fibers were well encapsulated inside the Al matrix without any damage due to the accurate temperature control during the process. A maximum of 40% fiber to matrix weight ratio was achieved in the current study. Using this novel SLM process, mechanically enhanced glass fiber-reinforced metal matrix composites were successfully manufactured.

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