

APPLIED SCIENCES AND ENGINEERING

Continuous fiberizing by laser melting (Cofiblas): Production of highly flexible glass nanofibers with effectively unlimited length

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The development of nanofibers is expected to foster the creation of outstanding lightweight nanocomposites and flexible and transparent composites for applications such as optoelectronics. However, the reduced length of existing nanofibers and nanotubes limits mechanical strengthening and effective manufacturing. Here, we present an innovative method that produces glass nanofibers with lengths that are, effectively, unlimited by the process. The method uses a combination of a high-power laser with a supersonic gas jet. We describe the experimental setup and the physical processes involved, and, with the aid of a mathematical simulation, identify and discuss the key parameters which determine its distinctive features and feasibility. This method enabled the production of virtually unlimited long, solid, and nonporous glass nanofibers that display outstanding flexibility and could be separately arranged and weaved.

INTRODUCTION

Generating materials with improved structural and physicochemical features and operational performance represents an important and long-standing technological challenge. Synthetic and analytical studies have highlighted potential applications of nanofibers and nanowires in numerous fields, such as lightweight composite materials, energy generation, filtration, chemical sensing, biomedicine, and electronics (1–4). Early work by Griffith (5) has shown that the strength and flexibility of fibers increase significantly with decreasing diameter. The increase in strength is attributed to a reduction in the number of defects, such as vacancies, impurities, and surface scratches, per unit length as the diameter decreases. Furthermore, the gain in flexibility has triggered the design of innovative fiber-based high-performance materials, such as bendable composites and new fabrics. Extensive efforts have been deployed to develop advanced continuous nanofibers, but conventional spinning methods cannot robustly produce fibers thinner than approximately 2 μm (4).

The use of nanoscale reinforcements in composites is controversial because it increases the strength of composite materials but not to the extent expected (6, 7). These poor results, which typically occur when using short discontinuous reinforcements, such as carbon nanotubes (6) or silica nanoparticles (7), may arise from aggregation and inadequate alignment of the reinforcements, as well as insufficient bonding and load transfer at the interfaces. In addition, the quest for improved structural materials should also consider appropriate fracture resistance. In this sense, long macroscopic fibers have proven useful in conventional extrinsic toughening strategies, such as crack deflection and bridging, where they can increase the toughness of brittle materials by composite reinforcing (8). However, from the perspective of toughening, the use of short discontinuous reinforcements are not effective to improve the performance of the nanocomposites, as the extrinsic toughening mechanisms are promoted by increasing, not by decreasing, the reinforcement dimensions (9). Thanks to their

made-to-measure lengths, continuous nanofibers can combine the benefits of macroscopic reinforcements with the assumed advantages of nanoreinforcements, which might lessen all these disadvantages. They would also be simple to manipulate and align during the manufacturing of advanced composites in addition to reducing fabrication cost and health risks (4).

Several methods have been developed to generate nanofibers. Electrospinning (ES) is the chosen method to produce polymer nanofibers (2). This simple and cost-effective technique can generate ordered and aligned nanofibers that can be collected as yarns or mats (2, 10). Therefore, while polymer microfibers are mainly mass produced by melt spinning, ES is the method of choice to produce polymer fibers of nanometer-size diameters (2). Ceramic nanofibers can also be electrospun using a sol-gel precursor, but their fabrication presents some additional limitations. Calcination of the electrospun sol-gel can cause the nanofibers to clump up and form a mat, which cannot be separated, ordered, or woven. Furthermore, their mechanical strength is usually markedly reduced by the residues and porosity induced during calcination (11).

Continuous silica fibers are typically drawn from a solid preform, which is melted at its tip. These fibers present superior chemical, photochemical, and heat resistance because they retain useful strength characteristics at temperatures up to 1090°C (12). Moreover, because of their low density (2.2 g/cm³), they exhibit the highest specific strength of any pristine glass fiber on record (12). High-temperature taper drawing has led to glass nanowires displaying diameters as small as 50 nm and lengths reaching tens of millimeters (13). Laser spinning has provided solid, nonporous, and well-defined glass nanofibers with lengths up to several centimeters (14) and tailored compositions even from low viscous melts (15). However, this process was not continuous; consequently, the nanofibers exhibited substantial but noncustomizable lengths.

Here, we report a laser-based method that produces practically endless, continuous, solid, and separated glass nanofibers from the melt of a solid preform without requiring a crucible. The continuous fiberizing by laser melting and supersonic dragging (Cofiblas) method leads to glass fibers with controlled and uniform diameter, which can be selected in a range of 30 μm down to 300 nm. Unlike laser

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