Materials Letters 222 (2018) 70–73

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/mlblue

# A novel magnetic-field-driving method for fabricating Ni/epoxy resin functionally graded materials

Jing Li [a], Xiaoling Peng [a,b,*], Yanting Yang [a], Jiangcai Xu [a], Panfeng Wang [a], Bo Hong [a], Dingfeng Jin [a], Hongxiao Jin [a], Xinqing Wang [a], Hongliang Ge [a]

[a] *College of Material Sciences and Engineering, China Jiliang University, Hangzhou 310018, China*
[b] *State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China*

ARTICLE INFO

*Article history:*
Received 25 February 2018
Received in revised form 23 March 2018
Accepted 28 March 2018
Available online 29 March 2018

*Keywords:*
Composite materials
Magnetic materials
Functionally graded materials (FGM)
Magnetic-field-driving method
Anisotropic property

ABSTRACT

A uniform magnetic field was applied to prepare Ni-epoxy resin functionally graded material (FGM) with gradient and anisotropy both in microstructures and resulting properties. By moving a magnetic field imposed on the green sample perpendicular to the field direction from one end to the other, Ni particles were driven by the field and distributed gradually in epoxy resin matrix. The gradient of light transmittance and electrical resistivity reflected the graded structures in Ni-epoxy resin composite. Furthermore, Ni particles aggregated to form chain clusters along the field direction, which produced anisotropic electrical properties in direction along and perpendicular to the chains. It has been clearly proved that the magnetic-field-driving method is a facile and effective attempt to prepare FGMs.


## 1. Introduction

Functionally graded materials (FGMs) are a class of engineered materials characterized by a spatial variation of composition and microstructure aiming at controlling corresponding functional (i.e. optical, electrical, magnetic, *etc.*) properties. These materials can be designed for specific functions and applications with a broad range of outlets in aerospace [1], (bio)mechanical [2] or energy engineering [3], as well as sensor technology [4], tribology, optics [5], electronics or magnetics [6].

The preparation of FGM has always been the focus of research. Various practicable processing techniques have been developed for the fabrication of FGMs, e.g., centrifugal casting [7], layer-by-layer method [8], electrophoretic deposition [9], *etc.* Unfortunately, these processes are either complex to operate or difficult to obtain a continuously changing composition. Recently, another approach has been developed in our group to prepare FGMs in a static gradient magnetic field via slip casting [10,11]. Similarly, Wang et al. fabricated MnSb/Sb–MnSb FGMs by a semi-solid forming process under static magnetic field gradients [12,13]. The key aspects of the both methods are a distinct difference in magnetic susceptibility of the components and a sufficiently steep field gradient, which allows the magnetic components to be pushed to the strong field regions by magnetic force. The utilization of the external magnetic fields provides a promising direction to fabricate FGMs comprising magnetic particles with nonmagnetic matrix. Currently, almost all the preparation research utilizing magnetic fields is restricted to static fields, and the resultant structure depends primarily on the field gradient. However, it is hard to achieve large field gradient in a large area under static fields, except in some extreme conditions such as superconducting magnetic field which is usually accompanied by complicated equipment and high energy consumption.

Based on previous work, a novel magnetic-field-driving method was explored to fabricate FGM. Ni and epoxy resin were selected due to their remarkable advantages, such as easy processing, good mechanical properties as well as chemical stability. During the process, Ni particles, the magnetic component, moved from one side to the other of the sample to form composition gradient driven by the magnetic field. Therefore, the graded properties were investigated in this paper.

## 2. Experiments

Ni powders with an average diameter of 1.2 μm and epoxy resin (E-51, brand in China) were used as raw materials. Diethylenetriamine was selected as the hardener for curing the epoxy resin. Ni powders (10 wt%) were mixed with epoxy resin and well stirred

* Corresponding author at: College of Material Sciences and Engineering, China Jiliang University, Hangzhou 310018, China.
*E-mail address:* pxlqingliu@cjlu.edu.cn (X. Peng).

https://doi.org/10.1016/j.matlet.2018.03.180
0167-577X/

for a uniform dispersion. The slurry was poured into a cuboid mold with the size of 30 × 10 × 2 $mm^3$, which was placed on the horizontal centerline of a magnetic field, as illustrated in Fig. 1a. The magnetic field was generated by an magnetic circuit comprising a couple of NdFeB sintered magnets and electrical iron. The air gap was 3 × 50 × 10 $mm^3$, and magnetic flux density was 200 ± 1 mT in the center area. The magnetic field was moved horizontally over the sample with a velocity of 1 mm/s. 5 cycles was repeated. Then the magnetic Ni particle will be moved from place 1 to place 2, as illustrated in Fig. 1b. The sample was solidified for 2 h at 20 °C, followed by 0.5 h at 100 °C.

The microstructures of the sample (parallel to the moving direction and field direction) were observed every 10 mm by the optical microscopy (MeF-3, Reichert, Austria). The sample was cut to 6 pieces (5 × 10 × 2 $mm^3$) to conduct the light transmittance by a spectrophotometer (U-4100, Japan) with the wavelength of 600 nm, and the electrical conductivity by a high resistance meter (ZC90, China).

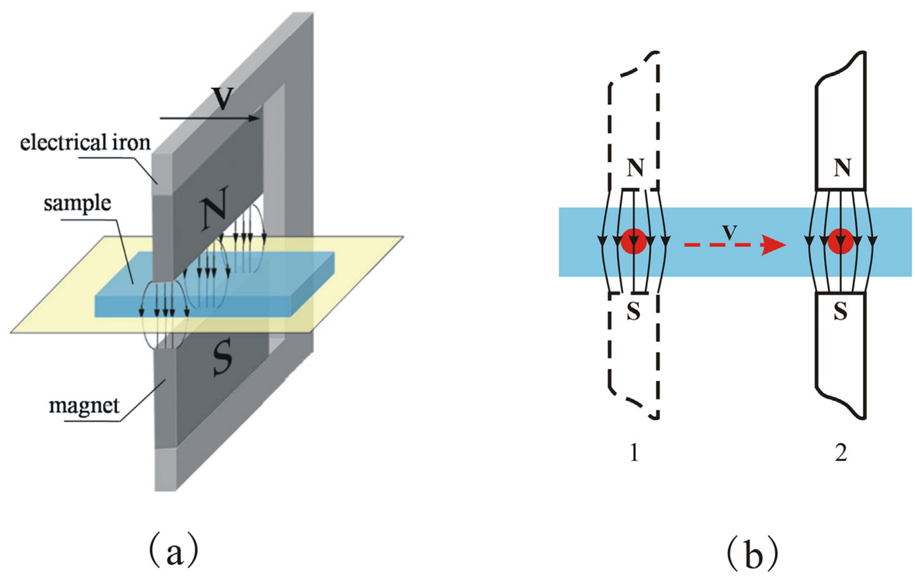


**Fig. 1.** (a) Schematic illustration of sample preparation by a magnetic-field-driving method; (b) Schematic illustration of magnetic Ni particle motion in a magnetic field.

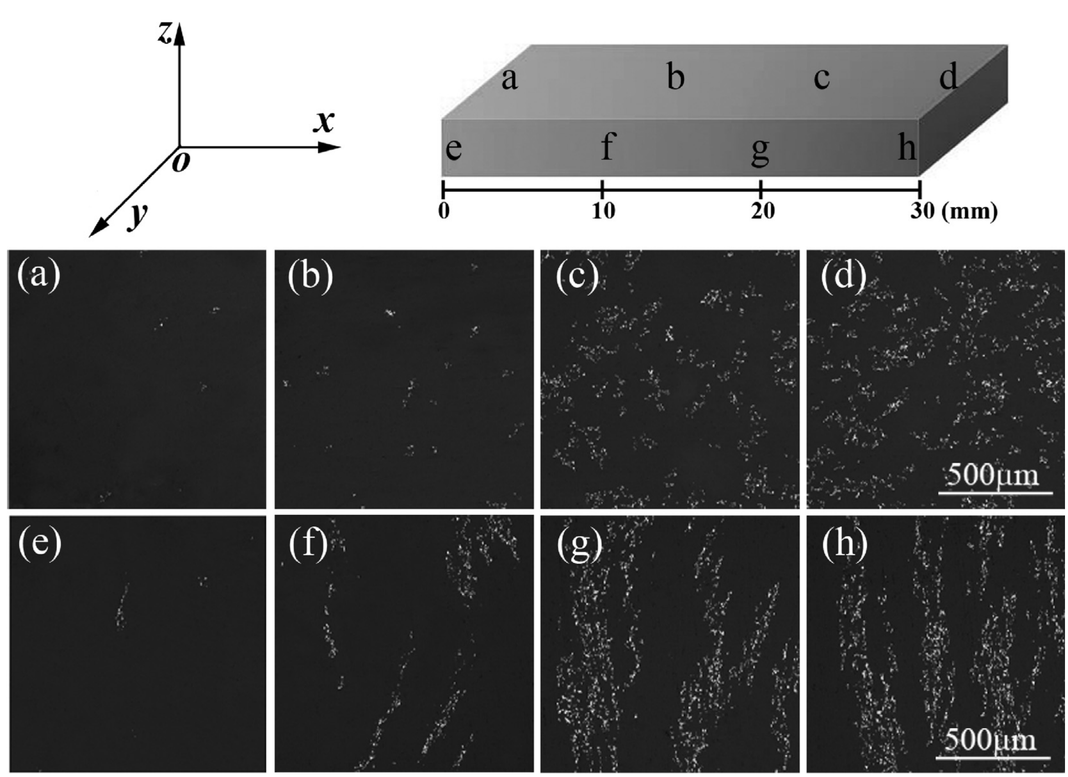


**Fig. 2.** Microstructures of Ni-epoxy resin sample in the upper plane xoy (a–d) and the frontal plane xoz (e–h). The inset shows the corresponding regions of each figure, and the dimensional orientation of experiment: ox is the field moving direction, oy is the transverse direction and oz is the magnetic field direction.