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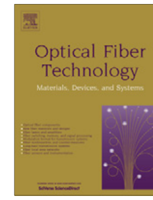

Ultrasonic embedding of nickel-coated fiber Bragg grating in aluminum and associated sensing characteristics

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A B S T R A C T

Fiber Bragg Gratings (FBGs) were embedded in metal foil using ultrasonic welding processes. Ultrasonic welding embedding processes, cross-sections of welded samples, the form change and wavelength shift of the Bragg peak during the processes, as well as the sensing characters of embedded FBGs were investigated. To understand the effects of metal foil properties on fiber embedding, optical fibers were embedded in similar and dissimilar metal foil samples. In order to study the effects of protective coating properties on the embedding processes, bare fibers, chemical nickel-plated fibers and chemical-electro nickel-plated fibers were compared in the ultrasonic welding process. Results indicate that only chemical-electro plated fibers and FBGs were successfully embedded in aluminum foils due to good protection and an appropriate matrix metal. Examination of the form change and wavelength shift shows that the FBGs are preserved well after the plating and ultrasonic welding processes. Thermal sensing results show that temperature sensitivity of the FBG was enhanced after chemical-electroplating and further enhanced after embedding in aluminum, which resulted from different thermal expansion coefficients of the SiO_2, aluminum and the nickel layer. Strain sensing results show (i) the embedded FBG remains in good condition when a cyclic tensile load (0–40 N) is applied; (ii) the relationship between wavelength and the applied load shows a linear trend.

1. Introduction

Fiber Bragg Grating (FBG) sensors have undergone a rapid development in recent years because of their features and advantages such as immunity to electromagnetic interference, remote sensing, ease in handling, low cost, small size and light weight [1–3]. A part or structure with embedded FBG sensors has the ability of real-time self-sensing of temperature and strain, which is of significant importance for assessing safety and integrity.

FBG sensor embedding has been studied intensively for composite structures in recent years [4,5]. However, only a few papers have reported embedding technologies for metal parts [6–10]. Lee et al. [6] and Lin et al. [7] respectively embedded optical fibers into aluminum and lead by a casting method. Seo et al. [8] described a metal coating method of optical fibers. In their work the fiber coating was applied by drawing the fiber through molten tin. Sandlin et al. [9] developed a plating method for metallization of the fiber, and embedded a FBG in the nickel based metal by high temperature brazing method. For all those metal cladding processes mentioned above, a large residue stress will be generated during the metal consolidation cooling process, and FBGs will be possibly damaged by the high temperature of the molten metal. Baldini et al. [10] placed single-mode fibers with gold coating into titanium matrix composites by arc spraying but the process is complicated and of high cost. Li et al. [11] developed a laser cladding method for embedding FBG in stainless steel. However, the FBG may be damaged by the high temperature associated with the laser in the steel sintering process.

Kong and his co-workers developed a metal–matrix composites and adaptive composites fabrication method using the ultrasonic consolidation (UC) process [12–14]. In their work, shape memory alloy (SMA), silicon carbide (SiC) and optical fibers were embedded in aluminum successfully. Moreover, Mou et al. and Yang et al. respectively succeeded in embedding FBG and fiber in aluminum foils using the same method [15,16]. Although the UC method has the potential to be used for embedding FBG in metals, it is of high expense due to the specially required equipments. In addition, embedding fibers with in-fiber Bragg gratings is of significant difficulty because the grating part has much lower bending

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strength than the normal part in the optical fiber. According to the process description of Chengbo, some of the FBGs were destroyed in the embedding process. Due to our experience, however, these problems can be easily solved by adding a protective metal coating on the FBG surface. In our previous work, a two-step method for metal coating of fiber Bragg grating was demonstrated, and a sensing model of metal coated FBG was also presented [17,18]. In this study, efforts were made to investigate the feasibility of embedding bare and nickel-coated fibers and FBGs in metals during ultrasonic spot welding of pure copper and aluminum. For that purpose, it is necessary to study the embedding process, as well as the thermal and strain sensing characters of the embedded FBG in a metal part.

2. Embedding FBG in metal using ultrasonic welding method

A series of experiments should be carried out for successful embedding of FBG in metal foils during the ultrasonic welding process. The process includes (i) protective method development for FBG, (ii) base metal selection for embedding, (iii) study on the effects of metal coating, (iv) light transmission and sensing characters examination of the embedded FBG.

2.1. Metallization of FBG

The single mode optical fiber with in fiber Bragg grating used in this work was made by Shanghai SynetOptics Technology Corporation. For embedding FBG in metals using ultrasonic welding method, the issue of most significant difficulty is that the optical fiber and FBG could be damaged due to the high temperature and stress. To solve the problem, a method with simplicity and low cost involving chemical plating and electroplating processes [17,18] was developed in our laboratory. By using this method, the FBG can be well protected and the length as well as the thickness of the metal coating can be easily controlled. The technique details have been described in the previous work [17,18]. In this paper, the fiber and fiber within fiber Bragg grating were chemical-electro nickel plated with the configuration shown in Fig.1. Optical fibers used in this study are coated with acrylate. The acrylate coat was removed by mechanical peeling with special scissors. After removing the organic coating, chemical-electro plating process was applied to the bare fibers and FBGs under the optimized processing conditions which were described in the previous work [17,18]. The chemical plating coating was about 3–5 μm in thickness, the chemical-electro plating coating has a thickness of about 180 μm and the length of all the metal coatings were controlled to be around 45 mm. Furthermore, the grating part was controlled to be in the middle of the metal coating.

2.2. Ultrasonic welding equipment and method

The welding equipment used in this paper is an ultrasonic spot welding machine, which is produced by Wuxi Neeke Corporation, China. Fig.2 shows the sketch of the setup of the welding equipment and the associated embedding procedures. For position-setting, the bare fiber or nickel coated fiber was carefully positioned on the top of a minute slot (the cross-sectional dimension of the slot is about 5 × 5 μm), which was cut by a mechanical slicer. When pressure and ultrasonic vibration are applied to the sandwich structure of metal foil/metal coated fiber/metal foil, friction breaks up the surface oxide, interlocking, diffusion and plastic deformation occurs within two metal foils [16]. Then the foils are bonded due to inter-diffusion and mechanical mixture and meanwhile the fiber is embedded in the metal during the welding process.

2.3. Embedding technique development

In order to embed FBG in metals by using the ultrasonic welding method, the base metals should be soft and have good plasticity for deformation. In this section the soft metals, i.e. pure copper and aluminum respectively with the thickness of 250 μm and 450 μm,

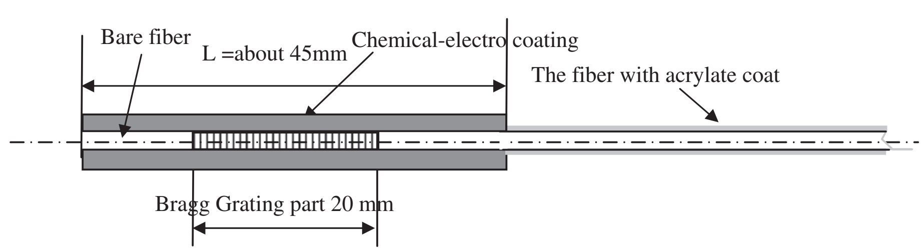

Fig. 1. Sketch of the chemical-electro plated FBG.

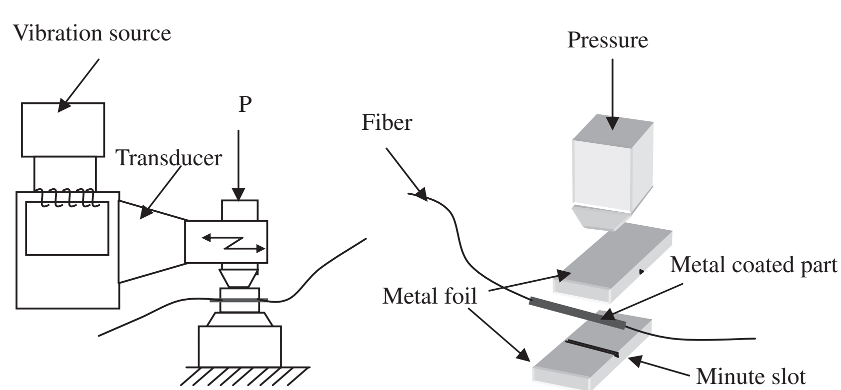

Fig. 2. Setup of the ultrasonic welding equipment and the embedding procedures.