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In-situ monitoring of strain and temperature distributions during fused deposition modeling process

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ABSTRACT

The present work investigates the integration of fiber Bragg grating (FBG) sensors for continuous in-situ and in real-time monitoring of strain fields build up as well as of developed temperature profiles during the fabrication procedure of structures built via the Fused Deposition Modeling (FDM) technology. A methodology is presented for simultaneous monitoring of strain and temperature profiles from the recorded spectrum of an embedded optical sensor when the deposited material remains close to its glass transition temperature. The used FBG sensors were embedded either longitudinally or transversely to the test samples' long axis and within different layers of the structures. Analysis of the FBG recordings indicates that the generated residual strain values are significant during material consolidation of the deposited layers. It is also shown that the solidification induced strain levels and the developed temperature gradients are strongly influenced by the samples' position onto the building platform. The findings demonstrate that an embedded optical sensing system is proven to be a reliable choice for real-time monitoring of the FDM process and the printed part's quality.

1. Introduction

Fused Deposition Modeling (FDM) is one of the most promising methods included in the category of Additive Manufacturing (AM) technologies because of its high speed, inexpensive machinery and durable part materials. The major benefit provided by this technique arises from the potentiality of building functional components with complex design features and tailored mechanical properties (high strength, stiffness, lower weight, porosity, density, etc.) [1–2], without the requirement of any further tooling and human interface. Three-dimensional structures can be fabricated automatically from computer aided design (CAD) files via the FDM technology, which utilizes the idea of melting extrusion and resolidification of polymer materials. More specifically, the model material which is widely used is thermoplastic, such as the commercial Acrylonitrile Butadiene Styrene (ABS) [3–5] and the Polylactic Acid (PLA). The FDM parts are constructed by the sequential deposition of layers once upon the other. Initially, the used raw material is in the form of a flexible filament that is gradually softened and melted in the liquefier and subsequently extruded through a heated nozzle onto the building platform. The semi-molten material that is deposited, quickly cools, solidifies and bonds with the adjacent rasters, while at the same time change of phase is occurred. After the completion of a whole built layer, the worktable moves downwards in order to accept the extruded material of the next layer. This procedure is repeated until the final element is fabricated. In FDM parts, the formation of bonds among individual roads (rasters) of the same layer and neighboring layers is facilitated by the diffusion bonding mechanism driven by the thermal energy of the semi-molten material. Additionally, the quality of bonds depends on the neck growth which is formed between the adjoining rasters, as well as on the molecular diffusion and randomization of the polymer chains at the interface [6–8]. Once the building process is completed, the final FDM component can be considered as a laminate composite structure with vertically stacked layers, consisting of partially bonded rasters with interstitial voids (air gaps) which lead to varying mechanical properties [9–15].

Although the FDM process has presented enormous progress over the recent years, there are still some aspects of significant interest that should be investigated. This technique is characterized by the accumulation of internally induced residual stresses and strains during layer deposition of filament. The non-uniform stresses and strains which are generated due to the contraction of the material during the rapid transition from one physical condition to another (remelting and rapid cooling cycles) can affect the dimensional accuracy of the manufactured component and result to phenomena of distortion, inter or/and intra layer delamination, cracking or even failure of the overall structure. Out of these issues, temperature distribution and thermal gradients occurred during the fabrication process due to the subsequent deposition of heated material, which is rapidly cooled and then reheated, are of outmost importance. Such information concerning the temperature history of a FDM constructed element is significant since it plays an important role in determining the bond formation quality on the interface of adjacent filaments and thus, the final mechanical properties of the structure. The information provided by literature regarding the

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experimental determination of the developed temperature profiles for parts built via the FDM process is limited, as few researchers have conducted relative studies on this subject [8,16–17].

In present days not many non-invasive methods are available for real-time monitoring and quality control during the fabrication process of components built using advanced manufacturing technologies [18]. Quan et al. [19] has reported that the lack of reliable in-situ monitoring for purposes of controlling the building process and final product quality has impeded the development of AM technology. As a result, embedment of fiber Bragg grating (FBG) sensors within structures for real-time measurements of induced residual strains and temperature variations monitoring appears to be a highly innovative and promising method for detecting important process defects at an early stage. The reflected spectrum of a Bragg grating can provide information concerning the solidification shrinkage strains developed during the layerwise fabrication process. As stated above, these strains can induce large forces and thus inner stresses which when accumulated in the structure can give rise to delamination, warpage and cracks. Additionally, the recorded Bragg peak wavelength can be used for calculating temperature variations, generated during the printing process, which strongly influence the bond formation among extruded rasters and consequently the final quality, shape, as well as the strength of the laminate component. In general, various research works have been conducted concerning the incorporation of fiber optic sensors within polymeric and composite materials for in-situ curing monitoring [20–21]. Karalekas et al. [22] used a partially embedded long FBG into an epoxy cylindrical specimen to monitor the strain distribution evolution along its axis when subjected to subsequent cycles of thermal ageing at 70 °C and 110 °C. The results demonstrated the capability of FBG sensors in providing important information on the degree of cure and evolution of fabrication induced strains inside the epoxy. Montanini et al. [23] and Kang et al. [24] have used FBGs for real-time monitoring of cure kinetics and simultaneous monitoring of temperature and strain in epoxy based composites fabricated in an autoclave. In relation to the FDM process, a preliminary study has been reported by Kantaros et al. [25] in which an embedded FBG sensor was used to investigate the magnitude of the post-fabrication residual strains as a function of selected processing parameters (layer thickness and raster orientation).

This work demonstrates for the first time the applicability of optical fiber Bragg grating sensors for continuous in-situ real-time monitoring of strain and temperature variations which influence the parts' quality in AM processes. In the proposed methodology, short and single mode FBGs are embedded within different layers of test structures built using a high-end commercial FDM machine. It is presented that based on the recorded data and the conducted analysis the developed strain fields and temperature profiles are calculated effectively from the same sensor. Additionally, the effect on the developed strains as a result of the specimens' position onto the building platform is also investigated. Finally, the resulted strain magnitudes at the end of the fabrication process are characterized based on recordings taken from samples fully detached from the building platform.

2. Methods and materials

2.1. Fiber Bragg gratings

FBG sensors exhibit several advantages [26], such as fast response, high sensitivity, signal integrity, long-term stability, immunity against electromagnetic radiation, insensitivity to radio frequency interference and good corrosion resistance. In terms of performances, they present multifunctionality (allow measurement of parameters including strain, temperature, pressure, load, acceleration, vibration, etc.) and are easily multiplexed in a serial manner along a single optical fiber [27–28]. Bragg gratings are formed by modulating periodically and permanently the index of refraction in the core of a standard optical fiber. This modulation is occurred using an intense ultraviolet (UV) source such as UV laser [29]. The amount of the periodic change of the refractive index depends on the intensity and duration of the controlled exposure to UV radiation as well as the photosensitivity of the optical fiber. The operating principles of FBGs are based on the measurement and mathematical reconstruction of data derived from the propagation and reflection of light. Thus, it becomes possible to make an accurate characterization of the loading condition subjected to the structure and consequently to the fiber from the wavelength-encoded response of the sensor, which can be directly recorded and processed [30].

More specifically, the fundamental purpose of a Bragg grating is to selectively reflect only a narrow spectral element of a broadband light source, when light propagates through this modulated structure. For a single mode and uniform FBG, the reflected signal presents a peak centered on the Bragg wavelength λ_{B0}, which is directly related to the mean effective refractive index n_{eff} of the core and the grating period Λ, through the Bragg condition $\lambda_{B0} = 2n_{eff}\Lambda$ [31–33]. Only the wavelengths which satisfy the Bragg condition are affected and strongly back-reflected. All the other light signals of a broadband light source, which are at wavelengths other than the Bragg wavelength, are not phase matched and for that reason they are essentially unaltered transmitted. The n_{eff} and Λ parameters are strongly influenced by strain and temperature. Therefore, both of them are modified when uniform changes in strain and/or temperature are occurred along the FBG resulting in a shift of the Bragg wavelength without modification of its shape.

When the FBG is embedded into a host material and subjected to a homogeneous axial strain ε_x and/or a uniform temperature change ΔT, the difference between the Bragg wavelength λ_B and the reference one λ_{B0} obtained from the peak shift of the spectra, before and after loading, is given by the following equation:

$$(\lambda_B - \lambda_{B0})/\lambda_{B0} = \Delta\lambda_B/\lambda_{B0} = (1-p_e)\varepsilon_{\mathrm{res}} + (1-p_e)(\alpha_m - \alpha_f)\Delta T + (\alpha_f + \xi)\Delta \mathrm{T}. \quad (1)$$

In this equation is assumed that the two transverse strains ε_y, ε_z applied to the fiber are related to the axial one ε_x by $\varepsilon_y = \varepsilon_z = -\nu_f\,\varepsilon_x$ (where ν_f is the Poisson's ratio of the fiber). In Eq. (1), $\Delta\lambda_B = \lambda_B - \lambda_{B0}$ [22,34] is the wavelength difference before and after the loading, p_e is the strain-optic constant for the optical fiber which is measured experimentally (where $p_e \approx 0.215$ [35]), α_m is the coefficient of thermal expansion of the host material, α_f is the coefficient of thermal expansion of the glass fiber (where $\alpha_f \approx 8 \times 10^{-7}$ °C^{-1} [36]), ξ is the thermo-optic constant of the fiber (where $\xi \approx 8.3 \times 10^{-6}$ °C^{-1} [37]), ε_{res} accounts for the solidification induced residual strains and $(\alpha_m - \alpha_f)\,\Delta T$ for the strains ε_T due to thermal expansion mismatch [38].

2.2. Experimental procedure

The specimens considered in the present work were fabricated on a Stratasys (Dimension Elite) FDM 3D printer by using the commercial ABS P430 as the model material and the P400SR as the support material. Prismatic specimens of rectangular cross section were produced having dimensions of 20 mm × 40 mm (width × length) and consisting of 41 layers (10.414 mm height).

Eight different types of samples were constructed for investigating in-situ and in real-time the magnitude of solidification developed residual strains and the temperature profiles exhibited during the deposition of the model material. Two experimental runs per each type of test samples were carried out. In order to take measurements of the temperature variations and calculate the generated residual strains, thermocouples as well as FBG sensors were embedded simultaneously within the FDM fabricated blocks. The samples were built either horizontally or perpendicularly to the building platform for studying the dependence of the developed residual strain values to the specimen's position on the worktable. More specifically, each specimen contained a FBG sensor which was integrated centrally either longitudinally or transversely to the long axis of the sample and a thermocouple which was always