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Material Behaviour

# Residual stress measurement in Fused Deposition Modelling parts

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ABSTRACT

Fused Deposition Modelling (FDM) has become one of the most employed technologies to build complex 3D prototypes directly from a computerized solid model. In this process, the model is built as a layer-by-layer deposition of a feedstock wire. One of the most important issues in the FDM process is the distortion of the part during the printing. This issue is due to the rapid heating and cooling cycles of the feedstock material that could produce accumulation of residual stress during part building up. The aim of this work is to measure the residual stress in FDM parts made of ABS employing the hole-drilling method. In order to avoid the local reinforcement of the strain gage, an optical technique, i.e. ESPI (electronic speckle pattern interferometry), is employed to measure the displacement of the surface due to the stress relaxation. Furthermore, the effect of the stacking sequence and the residual stress distribution on each side of the specimen have been investigated.



## 1. Introduction

Fused Deposition Modelling (FDM), invented in the early 1990s by Stratasys, has become one of the most employed technologies to build complex 3D prototypes directly from a computerized solid model. Nowadays, this technology is used in many fields such as aerospace, medical, construction and cultural [1,2] but there are many other potential fields where it could be employed. Moreover, the diffusion of the low-cost desktop 3D printers such as RepRap, Maker-Bot, Cube, etc., has made this technology widely accessible even at home and office.

In this process, as for many others 3D printing technologies [3], the model is built as a layer-by-layer deposition of a feedstock material. Initially, this is in the form of filament that is, successively, partially melted, extruded and deposited by a numerically guided heated nozzle onto the previously built model [1]. After the deposition, the material cools, solidifies and sticks to the surrounding material. Once the entire model has been deposited, the FDM part shows orthotropic material properties with behaviour similar to a laminate orthotropic structure [4,5]. Nowadays, besides the traditional FDM materials such as PLA (polylactic acid) and ABS (acrilonitrile-butadiene-stirene), many others materials have been employed and developed, e.g., short fibre composites [6], metals [7], bioresorbable polymers (PCL) [8], ceramics [9] and metal/polymers mixture materials [10]. PLA has better thermo-mechanical characteristics than ABS, showing higher mechanical resistance and a lower coefficient of thermal expansion that improves the printability of PLA, reducing the warp effect during the printing phase. Indeed, the distortion of the part during the print is one of the most important issues in the FDM process. The rapid heating and cooling cycles of the feedstock material could produce accumulation of residual stress during part building up [11,12]. This residual stress could lead to distortion and de-layering problems [13], which seriously affect the shape and the final dimensions of the parts or it could prevent the finalization of the objects due to unsticking of the part from the bed. In order to reduce these issues, a common technique is to use a heated bed with some type of adhesive on the surface of the bed. Although, such procedures help to reduce distortions, they can increase the residual stresses in the final part.

Several techniques can be employed to measure the residual stress in plastic parts. One of the most well-known is the incremental hole-drilling method [14]. In this semi-destructive technique, the introduction of a hole into a stressed body causes localized stress relaxation and deformation around the hole. The strain distribution can be measured by a strain gage rosette or by an optical technique [15]. Until now, some works have dealt with experimental measurements to determine residual stress distribution in plastic parts [16–19] but, to the authors' knowledge, not in FDM parts. Turnbull et al. [16] carried out a comparison of several techniques in order to measure residual stresses in polymers such

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as polycarbonate, ABS and Nylon. They concluded that the hole drilling is in accordance with the other techniques and, even if it shows some problems due to the calculation procedures, it can be employed as a valid measurement method. Nau et al. [17] highlighted that the procedures and process parameters valid for stress analysis in metallic materials cannot be applied in plastic materials. They pointed out that the surface preparation of specimens, strain gauge bonding and drilling speed are critical issues in order to obtain a correct measure. However, both Turnbull et al. [16] and Nau et al. [17] did not consider the local reinforcement effect that the installation of a rosette produces in materials that have a low Young's modulus. Finally, Magnier et al. [15] carried out a deep investigation on the influence of material viscoelasticity, room temperature and local reinforcement of the strain gauge on the measure of deformation by HDM of plastic materials. They pointed out how these parameters can produce a difference of up to 30% between the results recorded by strain gauge and DIC.

Only one paper has tried to deal with the residual stress issues in FDM by numerical simulation. Zhang and Chou [20], using simplified material properties and boundary conditions, have simulated different deposition patterns and have demonstrated the feasibility of using the element activation function to reproduce the filament deposition. They found that residual stress is higher in the first deposited layer compared to the last layer, and that there was a modification of the residual stress distributions by changing the tool-path pattern. However, they did not validate their model using residual stress measurements but only by comparing the distortion of the printed part and the numerical prediction.

The aim of this work is to measure the residual stress in FDM parts made of ABS employing the hole-drilling method. In order to avoid the local reinforcement of the strain gage, an optical technique, i.e. ESPI (electronic speckle pattern interferometry), is employed to measure the displacement of the surface due to the stress relaxation. Furthermore, the effect of the stacking sequences on the residual stress distribution has been investigated. Four stacking sequences have been printed, i.e. $\pm 30^\circ$, $\pm 45^\circ$, $0^\circ/90^\circ$ and $0^\circ$ only. In addition, the residual stress distribution on each side of the specimen has been investigated; for this purpose the measurements have been carried out on the top, i.e. the last printed layer, and the bottom of the specimens, i.e. the first printed layer.

## 2. Materials and methods

In this work, the ESPI technique has been employed to measure the displacement around a hole drilled inside the material. Due to the orthotropic behaviour of FDM parts, the isotropic model usually implemented in commercial hole drilling software cannot be used. Thus, an orthotropic FEM model has been developed to calculate the displacements due to some known stress cases. The combination between the experimental displacement data and the FE model allows calculating the residual stress in the parts.

### 2.1. Experimental procedure

A RepRap Prusa i3 equipped with marlin firmware and a nozzle with a diameter of 0.4 mm has been employed to produce the specimens. These have a rectangular shape and the dimensions of 80 × 40 × 7 mm. Four stacking sequences have been studied, i.e., the raster angles are $\pm 30^\circ$, $\pm 45^\circ$, $0^\circ/90^\circ$ and $0^\circ$ only. A layer with a $0^\circ$ raster angle has the deposited beads parallel to the major side of the specimen. Moreover, the samples have been fabricated with the minimum dimension of the part perpendicular to the build platform. Fig. 1 shows the coordinate system for the deposition and for the residual stresses.

The parameters reported in Table 1, such as the layer thickness or the number of contour lines, have been kept constant for every specimen.

In Table 1, the air gap is the distance between two, adjacently deposited, beads of the same layer; the layer thickness and the bead width are, respectively, the height and the width of a deposited filament. The number of contours represents how many edges have been deposited before filling the inner part with inclined beads. The bed temperature has been set to 90 °C and some glue on the bed has been employed to reduce the warping effect. The solid model, created using a 3D CAD, has been sliced using the open source software Slic3r. In Table 2, a description of the material properties [4], i.e. Young's modulus and ultimate tensile strength (UTS), of a single layer at different raster orientations have been reported. Also, the properties of the raw material have been shown.

The measure of the residual stresses has been carried out on three different samples for each stacking sequence. Moreover, to obtain better knowledge of the residual stress in the top and the bottom of the samples, three holes have been drilled on the top of each specimen, i.e. starting from the last layer deposited, and three on the bottom, i.e. starting from the first layer deposited (Fig. 2). An average value for each side of the specimen has been calculated based on the data of these three holes.

The holes were drilled by means of a high-speed compressed air turbine which is mounted on a precision travel stage. Turbine rotation speed was set to 5000 rpm after some preliminary tests that indicated that this speed allows obtaining good quality holes [12]. The cutter is made of tungsten coated by TiN and has a

**Table 1**
Fixed printer parameters.

| Parameter | Value |
|---|---|
| Air gap [mm] | 0 |
| Layer thickness [mm] | 0.2 |
| Bead width [mm] | 0.67 |
| Number of contour lines | 3 |
| Bed temperature [°C] | 90 |
| Nozzle temperature [°C] | 215 |

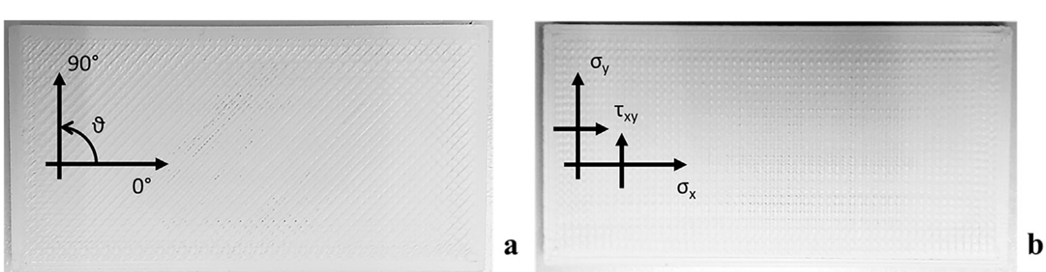


**Fig. 1.** Specimen examples with $\pm 45^\circ$ (a) and $0^\circ/90^\circ$ (b) stacking sequence.