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EFFECT OF PROCESSING CONDITIONS ON THE BONDING QUALITY OF FDM POLYMER FILAMENTS

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ABSTRACT:

The purpose of this paper is to investigate the mechanisms controlling the bond formation among extruded polymer filaments in the fused deposition modeling (FDM) process. The bonding phenomenon is thermally driven and ultimately determines the integrity and mechanical properties of the resultant prototypes. The bond quality was assessed through measuring and analyzing changes in the mesostructure and the degree of healing achieved at the interfaces between the adjoining polymer filaments. Experimental measurements of the temperature profiles were carried out for specimens produced under different processing conditions, and the effects on mesostructures and mechanical properties were observed. Parallel to the experimental work, predictions of the degree of bonding achieved during the filament deposition process were made based on the thermal analysis of extruded polymer filaments. Quantitative predictions of the degree of bonding achieved during the filament deposition process were made. The model was used to estimate the effects of different manufacturing parameters in the FDM process. Results suggest that better control of the cooling conditions may have strong repercussions on the mechanical properties of the final part fabricated using the FDM process.

Keywords: 3D printing, Additive manufacturing, metal, polymer.

I. INTRODUCTION:

Recent advances in the fields of computer-aided design (CAD) and rapid prototyping (RP) have given designers the tools to rapidly generate an initial prototype from a concept. There are currently several different RP technologies available, each with its own unique set of competencies and limitations [1]. Using RP methods we are able to obtain real concept about a new product. RP meets the current needs in the industry to shorten design cycles and improve the design quality. The main advantage of layered manufacturing (LM) over conventional manufacturing is that complex shapes can be physically realized without elaborate tooling. However, there are some specific part shapes like thin, slightly curved shell-type structures (skull bones, turbine blades, etc.) where the application of LM is poorly suited and may result in lack of strength, stair-step effect (poor surface finish) or large number of layers, resulting in higher build time [2]. Each process has various process parameters (build direction, layer thickness, temperature, etc.) that affect the character of RP part. Among many process parameters, the components build direction and raster angle are quite important for the FDM process [3 ÷ 5]. Fused deposition modelling (FDM) is one RP system that produces prototypes from plastic materials such as ABS (Acrylonitrile-Butadiene-Styrene) by laying tracks of semi-molten plastic filament onto a platform in a layer wise manner from bottom to top. It is known that process parameters such as the air gap between adjacent tracks, raster angle, raster width and thickness of deposited layers influence the performance of parts produced on an FDM machine [6]. In the FDM hardware, the FDM head moves in two horizontal axes across a foundation and deposits a layer of material for each slice. The material filament is pulled into the FDM head by the drive wheels. It is heated inside the liquefier in the FDM head so it comes out in a semi-liquid state. The successive layers fuse together and solidify to build up an accurate, three-dimensional model of the design. A crucial feature of the FDM process is its potential to fabricate parts with locally controlled properties like mechanical properties, density and porosity [7]. It is even becoming possible to manufacture functional parts in addition to prototypes. In order to fully evolve the FDM into a manufacturing tool, a number of improvements are essential. The functional parts require the process improvements for greater dimensional control and better tolerances, improvements in surface finish, the variety of polymers available for use should increase and the mechanical properties of the prototyped parts should be enhanced to maintain their integrity during working. To improve this promising technology, recent years have seen a substantial amount of research in the area of FDM manufacturing process planning. Research work has included the consideration of processing parameters and their optimization [8 ÷ 12] and mechanical properties [4, 13 ÷ 16]. Some studies have been conducted to determine the optimum parameters of FDM, and performance criteria often used include build time, strength, toughness and surface integrity of the prototypes, normally for injection moulding and tooling applications [17-20]. Strength of parts made by FDM suffers from anisotropy and adhesive strength between layers (or across filaments) is appreciably less than the strength of continuous filaments - longitudinal strength.

II. RELATED STUDY:

Fused deposition modeling (FDM) is a rapid prototyping technology suited for producing parts with complex geometries. The FDM machine is basically a computer numerically controlled gantry machine, carrying two miniature extruder head nozzles, one for the modeling material and the other for the support material. In the FDM process, parts are fabricated by extruding a molten filament through a heated nozzle in a prescribed pattern onto a platform. As the material is deposited, it cools, solidifies and bonds with the adjoining material. When one whole layer is deposited, the base plate moves down by an increment equal to the height of the filament and the next layer is deposited. FDM prototypes can be viewed as composites structures composed of partially bonded filaments. The process requires minimal manpower and is increasingly used to fabricate customized products for engineering as well as medical applications.

One limit of using FDM for preparing prototypes of plastic parts is that these parts are typically thin walled and with the width of extruded fibre (0,511 mm) it is almost impossible to create walls thinner than 1 mm or these walls are very brittle (e.g. snap fit). Another issue with FDM prototypes is surface quality which is dependent on layer thickness (typically 0,254 mm) and build angle [21]. However, in a number of cases, proper choice of orientation of the part (build direction) in the FDM chamber may eliminate some of the abovementioned drawbacks [5, 22 ÷ 24]. Few mathematical models have been proposed [7, 25 ÷ 27] that show promise in terms of their predictive value. It is very difficult to evaluate the prototype interior structure. However, there is a very convenient method which allows scanning exterior shape, prototype dimensions as well as interior structure of prototypes. Computer tomography (CT) is the fusion of metrology and tomography. METROTOM is a well thought-out design with its 3D computed tomography with microfocus X-ray tubes and detectors. CT allows you to measure the interior of a work piece: all recorded data can be applied to all areas of quality assurance and be evaluated. CT technology allows non-destructive testing of damage and porosity analysis, material inspection, defect checks, etc. Abilities of this technology offer an excellent tool for evaluation of FDM prototypes structure. Therefore, this paper provides the results of experimental determination and analysis of the structure of some simple shapes fabricated using the FDM process in regard to different temperatures of the printing head, the envelope temperatures as well as location of parts built on the platform.

The modelling envelope temperature is regulated to aid in the bonding process. The FDM head deposits material as it follows the part geometry for each curve. It starts from the bottom curve and builds up the model to the top curve. Starting from an STL file, the geometry of a part can be read into Catalyst software and sliced at a pre-selected modelling resolution. Parameters of STL model (e.g. chord height and angle control) for RP process are very important for the accuracy of physical prototype.

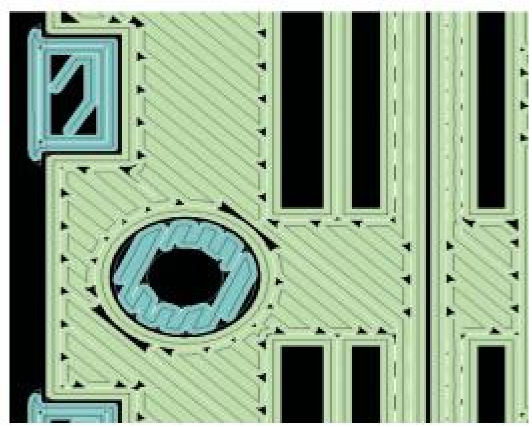

Fig.1. Structure in homogeneity in layer.

III. WORKING METHODOLOGY

The formation of bonds among polymer filaments in FDM parts is driven by the thermal energy of the extruded material. The temperature history of interfaces plays an important role in determining the bonding quality and therefore the mechanical properties of the final product. The bonding quality depends on the growth of the neck formed between the adjacent filaments and on the molecular diffusion and randomization of the polymer chains across the interface. In this work, the term healing refers to the molecular diffusion at the interface between filaments while sintering is used to describe the neck growth phenomenon driven by surface tension. Early studies on sintering dealt mostly with metals and ceramics and showed that the process is dominated by volume, surface and grain boundary diffusion. For polymeric materials, sintering is due mostly to the viscous flow mechanism. While the term is normally used to describe coalescence occurring below the melting point of the material, the expression has been carried on and accepted in the literature for the coalescence of polymers above their glass and melting transitions.

It was felt that there is a scarcity of data on the mechanism of bond formation between adjacent filaments making up FDM parts. Therefore, considerable research effort is still needed to fully understand the effects of material and processing parameters on the mechanical properties of the parts fabricated. In particular, there is next to no literature on the experimental determination of the thermal profiles of parts built using FDM. This data is especially important, as it is indicative of the bond formation between adjacent filaments and their influence on the mechanical properties. This paper provides the results of experimental determination of the thermal profiles of some simple shapes produced using the FDM process, their effects on the bond formation in terms of neck growth between adjacent filaments and the intermolecular diffusion at the interface and their evaluation in regards to the mechanical properties of the parts.

The temperature profiles obtained for both the 15- and 30-layer specimens show that the temperature of the filament located on the bottom layer periodically rises above the glass transition temperature with the deposition of each additional layer to the specimen. Each peak was followed by a rapid decrease in the temperature as the extrusion head moved away from the center position of the specimen. The minimum temperature (lower limit), increases with the number of layers deposited onto the platform. The profiles shown in Figure show that the filaments remain above the glass transition temperature during a significant portion of the fabrication process. This confirms the importance of heat transfer through conduction within the structure with the deposition of the filament, as suggested from the predictions obtained using the 2D analytical model proposed in Below Figure. Experiments and model predictions suggest that the heat transferred through conduction from the top layered filament affect the development of bonds between lower layers of filaments.

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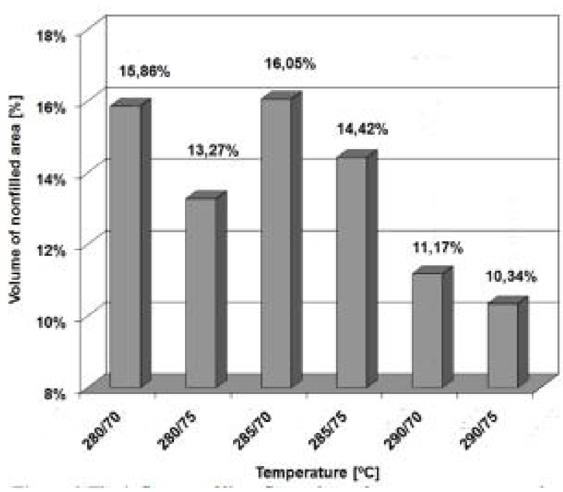

Fig.2. The influence of liquefier and envelope temperatures.

The influence of temperature change is not so significant, except for the highest temperatures combination used in this experiment, where the difference is about 3 %. As a result it is clear that not only the FDM printing condition, but also the shape of the fabricated part influences the structure homogeneity represented by the volume of nonfilled area in samples.

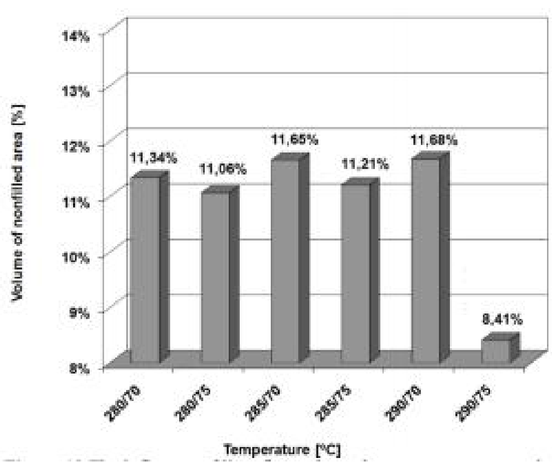

Fig.3. The influence of liquefier and envelope temperatures.

4. CONCLUSION:

The aim of experimental research was the FDM prototypes structure analysis and evaluation of processing conditions that influence the final structure of prototype. In order to research the influences of head and envelope temperatures on final structure of particular prototype layers, the specimens were printed with various temperatures of liquefier and envelope temperatures within device allowable temperatures. From obtained results it is obvious that material distribution is not uniform in the whole volume of scanned specimens, and higher density can be observed in the area of layer building start point. It was found out that the structure homogeneity represented by the volume of nonfilled area is affected by the shape of the fabricated part. The influence of processing temperatures on structure homogeneity was less significant in the parts with circular cross-section than in the part with rectangular cross section.

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