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Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30

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ABSTRACT

The Fused Deposition Modelling process is a highly efficient Rapid Prototyping approach that makes it possible to rapidly generate even much complicated parts. Unfortunately, the Fused Deposition Modelling is affected by several parameters, whose setting may have a strong impact on the components strength. This paper is devoted to the study of the effects generated by the Fused Deposition Modelling production parameters on the tensile strength and on the stiffness of the generated components, tackling the question from both the experimental and the numerical points of view. For this purpose, an analytical model was developed, which is able to predict the strength and the stiffness properties, based on the number of contours deposited around the component edge and on the setting of the other main parameters of the deposition process. The fundamental result of the paper consists in the possibility of predicting the mechanical behaviour of the Fused Deposition modelled parts, once the raster pattern (dimensions, number of contours, raster angle) has been stated. The effectiveness of the theoretical model has been verified by comparison to a significant number of experimental results, with mean errors of about 4%.

1. Introduction

The Rapid Prototyping (*RP*) process experienced great advances in the last few years. Nowadays, it is possible to build parts, having even very complicated geometries in a short time and at low costs, when their requested mechanical proprieties are not too high. The main advantages consist in the easy generation of a 3D prototype from a concept and in the possibility of making the manufacturing and the assembly tasks less complicated. For this purpose, it is often possible to consolidate sub assemblies into single units, thus reducing the number of parts, the handling time, and the number of mating surfaces, which helps simplifying the mounting task. Moreover, the *RP* process is highly flexible since it is easy and economic to rearrange the process, when design changes must be taken into account. Unfortunately the strength and the stiffness of components built by this technology are not particularly high and, furthermore, they are difficult to be defined due to their strong anisotropy.

The Fused Deposition Modelling (FDM) from Stratasys is a typical example of a *RP* process, leading to the aforementioned characteristics [1–3]. The *FDM* is able to produce prototypes from plastic materials, such as Acrylonitrile Butadiene Styrene (*ABS*) or Polyetherimide (*ULTEM*), and the process consists in the deposition of filaments of the material at the semi-molten state. The filament is fed through a nozzle, located at the output of a heating device, and is deposited onto the partially constructed part. Since the material is extruded and laid in tracks at a semi-molten state, the newly deposited material fuses with adjacent material that has already been deposited. Afterwards, other material tracks are deposited, upon the completion of the current layer, and then the deposition of a new layer is started.

The final mechanical properties of parts obtained by means of the *FDM* process, are, often, uncertain, since they are influenced by a large amount of production parameters, which are, really, difficult to combine, in order to increase the strength and the stiffness of the built parts. As a consequence, the practical application of components processed by the *FDM* (and in general by *RP* techniques), is limited to low-loaded products and to those whose failures do not lead to severe effects. Regarding this issue, Lee et al. [3] and Howell [4] suggested that *FDM* processed parts may have some potentials for use in fields of mechanics, where compliant members or mechanisms are used. Possible applications are in the manufacturing of electro-mechanical actuators or in that of children's toys, for instance bows and arrows or small catapults as presented by Lee et al. [3]. In these cases, the not high strength is well compensated by the lower cost, by an easier mounting process and, especially, by good elastic properties. It is therefore

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important to predict not only the strength, but also the stiffness, and how they relate to process parameters.

1.1. Build parameters

The main production parameters affecting the mechanical behaviour of *FDM* processed components, in particular strength and stiffness, can be so summarized as follows:

- Part Building Direction: it is the direction along which a specimen is grown up, while it is being generated. It is perpendicular to the surface of each deposited layer and therefore strictly related to the part orientation in the build platform.
- Bead width: it is the width of the filament deposited by the *FDM* nozzle: its most common value ranges from 0.3 mm to 1 mm [1].
- Raster Angle: inclination of the deposited beads with respect to a reference direction (usually, load direction). A typical setting consists in +45°/−45° alternate layers.
- Air gap: distance between two adjacent deposited filaments of the same layer. The default value is usually zero, meaning that the beads touch each other [1]. A possible alternative is a positive gap, meaning that a gap is present between adjacent rasters, or a negative gap, implying that the bead tracks are overlapped.
- Layer thickness: thickness of the deposited bead and therefore of any single layer. It is usually one half of the bead width.
- Number of contours: the building procedure is usually arranged, so that the filament is initially deposited along the component edge. Upon the completion of the full edge, another filament is deposited at the inner side of the previously deposited contour. This procedure is followed until the stated number of contours has been deposited. The inner part of the component is finally filled by inclined rasters upon the completion of the first layer. The same manufacturing procedure is repeated for the generation of all the other layers.

1.2. State of the art and subject

Several papers deal with the influence of these parameters: the issue is mainly tackled by running experimental campaigns, assisted by techniques of Design of Experiment (*DOE*). The experimental task presented by Ahn et al. [1] involved flat specimens tested under axial load, in agreement with the Standards for tensile tests on plastics. The results emphasize the effect of the raster orientation and of the air gap, while the bead width does not seem to have a great effect. The strength is magnified, when the direction of the beads is parallel to that of load, while is very low when the rasters are perpendicular to the applied force. The air gap influences the production time of the components and their strength. A positive gap implies a rapid generation of the part, but has the negative outcome of resulting in a loosely packed part which exhibits a bad surface finishing and unsatisfactory mechanical properties. Conversely, a negative gap leads to more dense components, with higher strength, but their building time is usually too much incremented. The influence of these parameters is confirmed also by Lee et al. [3], with reference to *FDM* processed sling shot toys. Anitha et al. [5] also studied the effect of the layer thickness, which proved to increase the performance when the thickness decreases. On the other hand, the raster width confirms to be of a low significance. The *FDM* processed parts exhibit anisotropic properties not only regarding the raster orientation, but also with reference to the build orientation. The related effect is shown by Lee et al. [2] with reference to specimens, which are differently manufactured to be loaded under compression. The choice of the plane on which the part is sitting during its generation has strong effects both on the cost and on the time of the process, as discussed by Xu et al. [6] and Thrimurthulu et al. [7]. The previously cited parameters are considered by Sood et al. [8], where the authors perform an extensive experimentation on specimens under axial and flexural loads. Techniques of *DOE* are applied for the campaign planning and for the processing of the results. The surface response approach is successfully used for the development of empirical models relating the tensile strength to the levels of the process inputs.

What can be remarked is that no paper in literature deals with the effect of contouring. Just Ahn et al. [1] briefly pointed out the effect of contouring on the tensile strength, emphasizing its important role at limiting stress concentration at the notches, for instance at fillets. The adoption of offset contours around a discontinuity is able to prevent crack initiation, which may be enhanced by material anisotropy, even despite large fillets. However, no quantitative results are presented regarding the relationship between the strength or the stiffness and the number of contours. In addition to the remarks by Ahn et al. [1], it can be pointed out that in practical applications the deposition of at least one offset contour per layer has indeed a positive effect on the surface finishing of the part. As the part shape is well followed by the external beads, the external surface is made smoother, with a strong decrease of roughness and a positive outcome even from the aesthetic point of view. For this reason, contouring is nowadays a common practice among *FDM* manufacturers. However, an important point concerns the choice of the proper number of contours to be applied, considering also geometric constraints. The deposition of a suitable number of contours may potentially have an effect on strength and stiffness, depending on contour main orientation with respect to load direction.

The issue regarding the choice of contour number is related to the availability of *predictive models*, i.e. models that, taking the aforementioned build parameters into account, are able to predict the mechanical behaviour of the part, in particular its strength and stiffness. As previously remarked an interesting empirical model was developed by Sood et al. [8], but it does not take the contouring effect into account, moreover the part stiffness is not studied.

The present paper investigates the effect of contouring by running an experimental campaign, with specimens having different numbers of contours, and by developing an analytical model that is able to match the experimental results. The analytical model provides a full comprehension of the structural response of *FDM* processed parts, by interpreting it in the light of the principle of mechanics. This model considers the effects of part dimension, build orientation, bead width, raster angle, layer thickness and of course contouring. It is therefore able to predict the load acting on the sample, the strength and the stiffness.

The proposed analytical model can be a useful tool for the *FDM* designer or manufacturer. In particular, it can provide assistance for the determination of the achievable strength or stiffness by just increasing the number of contours, consistently with the geometrical constraints. Good mechanical properties can be, thus, obtained without modifying other process settings, such as the air gap or the raster angle, often maintained at default values by manufacturers.

2. Materials and methods

The experimental campaign involved specimens made of *ABS-M30*, a widely used material for *FDM* processed parts. Its mechanical properties are the following: Ultimate Strength of a single bead, $US_b = 33$ MPa, Elastic Modulus of a single bead, $E_b = 2400$ MPa, Tensile Elongation to failure $EF_b = 4\%$. The material characterization was performed on samples manufactured by injection moulding supplied by the material producer. Injection