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Extruder path generation for Curved Layer Fused Deposition Modeling

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Abstract

Extruder path generation for a new rapid prototyping technique named "Curved Layer Fused Deposition Modeling" (CLFDM) has been presented. The prototyping technique employs deposition of material in curved layers in contrast to flat layers as in Fused Deposition Modeling (FDM). The proposed method would be particularly advantageous over FDM in the manufacturing of thin, curved parts (shells) by reduction of stair-step effect, increase in strength and reduction in the number of layers. The criteria for the generation of tool paths for CLFDM are proper orientation of filaments and appropriate bonding between adjacent filaments in same layer and in successive layers.

Keywords: Fused Deposition Modeling; Rapid prototyping; Skull bone; Layered manufacturing

1. Introduction

Rapid prototyping (RP) refers to a group of solid freeform fabrication (SFF) processes that are capable of developing complex shapes without part-specific tooling in a short span of time. Newer RP processes are being developed and commercialized every year [1]. Layered Manufacturing (LM) technology is employed for most of the RP processes wherein a part is produced by employing layer-by-layer deposition of material. Fused Deposition Modeling (FDM) is one of the commercially exploited LM processes where a filament of heated (fused/semi-solid) thermoplastic material is extruded through a deposition nozzle (which would henceforth be referred to as the 'extruder' in this article) and applied over a flat surface to form a layer (Fig. 1). The main advantage of 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 (higher build time) [2]. The reason behind such low part quality is the discontinuous nature of the filaments in building up the part by LM (Fig. 2).

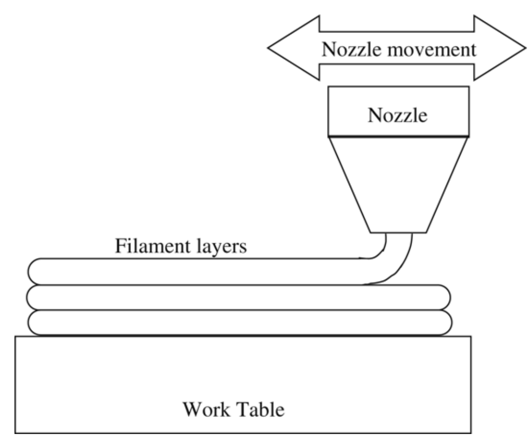

Fig. 1. Schematic diagram of FDM.

Strength of parts made by FDM suffers from anisotropy [3] and adhesive strength between layers (or across filaments) is appreciably less than the strength of continuous filaments (longitudinal strength). Zhong et al. [4] studied the mechanical properties of short fiber-reinforced ABS polymers for use as a FDM feedstock material. On comparison of the longitudinal strength with the adhesive strength, it was observed that the former was substantially higher than the latter. Hence, discontinuity of filaments on the part shown in Fig. 2 produced by FDM would tend to reduce its strength. Apart from this, there is pronounced stair-step effect in the sample of Fig. 2 and it is obvious that layer thickness would have to be appreciably

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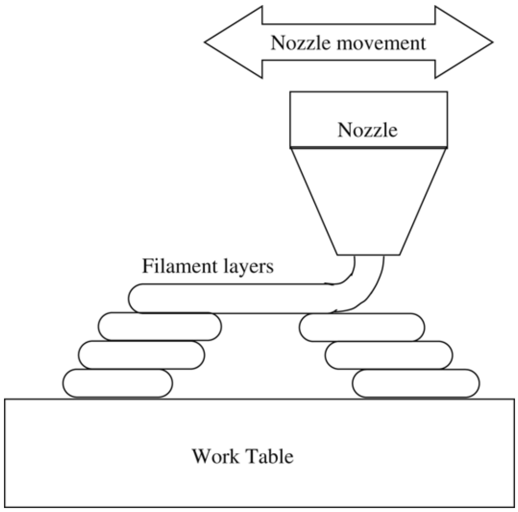

Fig. 2. Prototyping of a thin curved part in FDM.

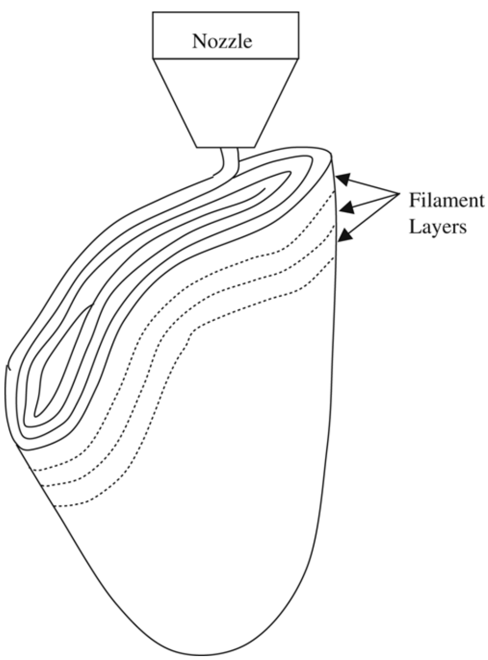

Fig. 3. Choice of build direction to achieve continuous filaments in thin sections.

reduced in order to achieve better surface finish. This in turn would increase the build time, as mentioned earlier.

However, in a number of cases, proper choice of orientation of the part (build direction [5–8]) in the FDM chamber may eliminate some of the above-mentioned drawbacks. For example, in the case of a typical curved thin part under consideration, continuity of filaments can be obtained in the concerned section of the part if it is held upright (Fig. 3) in the deposition chamber and the deposition carried out as shown (contour fill). However, discontinuity of filaments would still exist across these sections shown by dotted lines. In fact, there would not be any continuous fibers across these sections. Further, if the part has bi-directional curvature (Fig. 4) the selected build orientation would not serve the purpose.

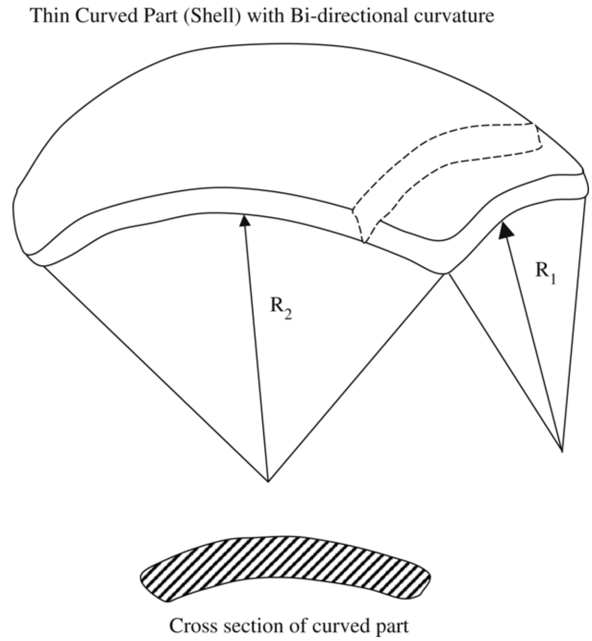

Fig. 4. Typical example of a thin curved part with bi-directional curvature.

Adaptive slicing is perhaps the main strategic response of FDM to solve these problems. Thinner layers in regions of low (near-horizontal) surface slope and high curvature would certainly reduce the surface roughness. At the same time, build time is not expected to increase substantially as higher layer thickness would be retained in places of high (vertical or near-vertical) surface slope and low curvature. However, the improvement in strength of the part due to thinner layers would be marginal. Further, if thinner layers are applied only at selected regions (the very idea of adaptive slicing), the part would remain as weak as the thick-layered regions. In the available literature, one may find a number of attempts for adaptive slicing of parts [9–15], which include both direct slicing and slicing of faceted surfaces in the form of STL files.

"Curved layer FDM" or CLFDM — as proposed in this work, may offer solutions to most of these issues for thin curved shell-type parts as discussed above. In this process, which proposes an entirely new building paradigm for FDM, the filaments would be deposited along curved (essentially non-horizontal) paths instead of planar (horizontal) paths.

If the literature is considered on RPT (Rapid Prototyping Technology) in general, the idea of curvilinear (non-horizontal) material deposition is not entirely new in other spheres of additive manufacturing. Klosterman et al. [16] have developed curved layer LOM (Laminated Object Manufacturing) process for monolithic ceramics and ceramic matrix composites (CMC). The advantages of this curved layer process are elimination of stair-step effect and improved surface quality, increased build speed, reduced waste, and easier decubing. Researchers from CREDO Laboratory, Clemson University [17] had started an endeavor on variable slice orientation in SLA process. Significant improvement in surface quality due to deposition at variable slice orientation had been envisaged. Kerschbaumer et al. [18] presented an algorithm for generating tool path for 5-axis laser cladding using adaptive slicing