Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-31 (2016) 36–41

Investigating Surface Finish for Material Extrusion Process using Graphical Programming Tools

R. Jill Urbanic*, L. DiCecco**

** Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, Windsor, Ontario, N9B 3P4, Canada (519-253-3000; e-mail:jurbanic@uwindsor.ca).*

*** Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, Windsor, Ontario, N9B 3P4, Canada (519-253-3000; e-mail:diceccol@uwindsor.ca).*

Abstract: The additive manufacturing material extrusion surface finish is periodic in nature, which has been explored by researchers employing either rectangular or elliptical bead models. The shallow inclination angle configurations exhibit the greatest 'staircase impact', but in addition to this, the assumed bead geometry influences physical distribution of undercuts and voids. Depending on the initial assumptions, the predictive model may not reflect a valid build configuration. Consequently, graphical programming tools are employed to develop rectangular, obround, and elliptical bead sets, which allows the bead shape and inclination angle to be altered dynamically for a wide range of configurations. The surface finish is predicted for selected bead geometry while considering the critical angle (multiple beads on the base layer) impact.

Keywords: Bead-Based Deposition Processes, Additive Manufacturing, Surface Finish, Graphical Programming Tools, Virtual Simulation.

1. INTRODUCTION

The Additive Manufacturing (AM) process family introduces a fabrication strategy in which incremental slices are stacked layer by layer to make products directly from Computer Aided Design (CAD) model data (ASTM-F42, 2016). In 2010, the American Society for Testing and Materials (ASTM) group formulated a set of standards that classify the range of Additive Manufacturing processes into 7 categories (ASTM) (Figure 1). Each process has unique machine-material-process planning elements. Typically, the user interface limits the interactions and process fabrication decisions. This simplified approach to process planning and fabrication is one of the reasons '3D printing' is used to describe the process family. Along with the limited user-interactions is a narrow material selection set, as well as limited control of the tool paths and process. For a given size, the build time is controlled by the part volume, the slice thickness, the number of layers, and the build orientation. For many commercial solutions, the fabrication process requires little human intervention; hence, the part volume-build material is the main influence for the fabrication costs. Although the process planning interactions are limited when interacting with AM systems, process dependent post processing (curing, removing support material, infusing a resin, surface smoothing, etc.) is required for several process families. As surface smoothing is a typical issue, alternative solutions to this issue have been developed. The surface finish characteristics relate to the layering manufacturing strategy, and the layer thickness. Some processes have been developed which deposit very thin layers (i.e. stereolithography can achieve 0.05 mm layer thicknesses). However, this influences the build time significantly.

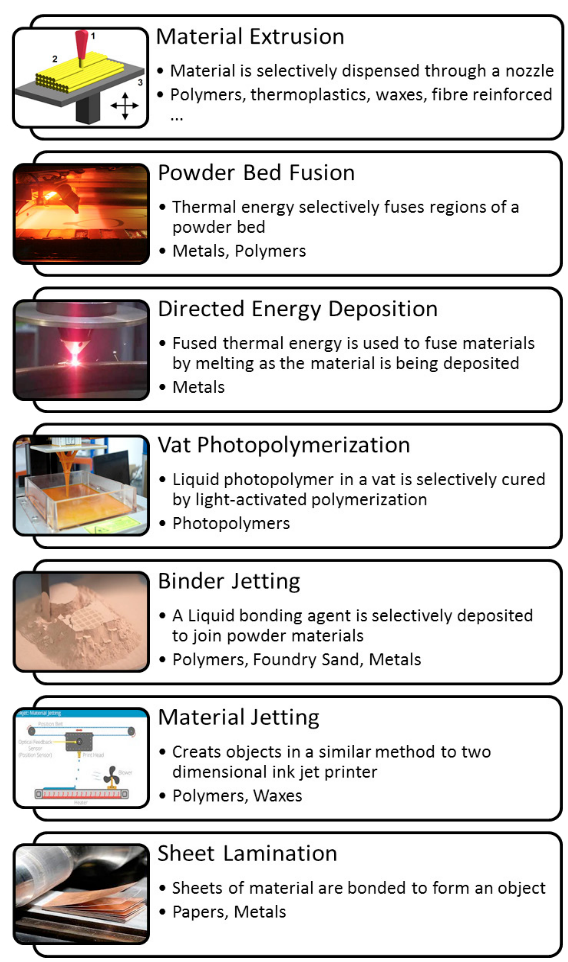


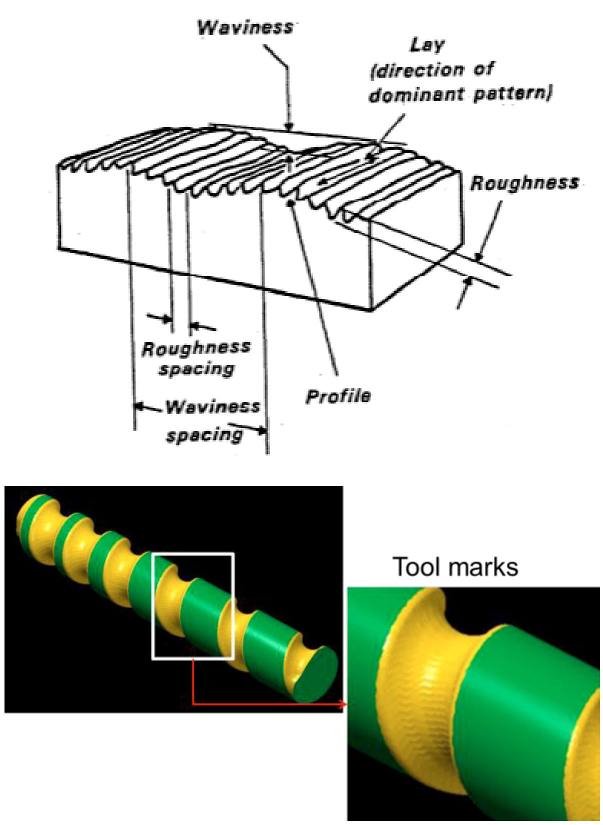
Fig. 1. AM process families.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.12.158

Consequently, many researchers have investigated the optimization challenge related to balancing the build time, layer thickness, and build orientation (Byun and Lee, 2005, Masood et *al*., 2003, Ma et *al.,* 2004, Pandey et *al*., 2003, Thrimurthulu et *al.,* 2004, Xu et *al,* 1999), and have introduced concepts such as adaptive slicing to address build time and surface finish issues simultaneously (Thrimurthulu et *al.,* 2004, Pandey et *al*., 2006). The goal of this research is to highlight the surface finish modelling challenges for the material extrusion process, and to develop representative surface finish curves and data.

1.1 Classic surface finish evaluation

The surface topology or surface finish typically has two structures associated with it: waviness and roughness (Vorburger and Raja, 1990). The roughness is characterized by closely spaced 'waves' and is directly related to the fabrication process (i.e. cutting tool marks); whereas, the waviness element occurs at a lower frequency, and the causes may be related to structural elements within the system (i.e., clearances and vibrations within a machine) (Figure 2 (a)).



(a)

(b)

Fig. 2. (a) Surface characteristics and terminology – note the 'Lay" or the dominant pattern [NIST], (b) simulated machining surface finish, illustrating tool mark patterns

Two standard formulations for surface finish are: *Ra* and *Rq*, where *Ra* is the average deviation from the profile, and *Rq* is the root mean square deviation. In this work, *Ra* is used (eq, 1) to represent the surface finish.

$$Ra = \frac{1}{l}\int_0^l |y(x)|dx \quad (1)$$

$$Ra = \frac{Area_{\_calculated}}{l_{\_calculated}} \quad (2)$$

A profilometer is used to measure the surface finish. The end stylus radii can have either a 60° or 90° included angle, with the radius of the tip being: 2 µm, 5 µm, and 10 µm. There is a relationship between the cutoff values and the stylus tip radii, which is defined in the DIN EN ISO 4288:1998 standards.

For the AM surface finish, a set of analytical models have been derived as there are repetitive patterns related to this process family, which is not typical for other manufacturing processes. This is discussed in the next section.

1.2 Surface finish models for AM

The surface finish for AM processes has been studied both theoretically and experimentally (Ippolito et *al.,* 2005, Perez, 2002, Anitha et *al.,* 2001, Galantucci et *al*., 2009) by several researchers, and as aforementioned, adaptive slicing and other optimization approaches have been proposed. The layering strategy introduces periodicity or a cyclic pattern dictated by a representative bead shape, and the inclination angle. From basic bead geometry primitives, the area and measuring length can be derived. Sreedhar et al. (2012), Xu et al. (1999), Thrimurthulu et al. (2004), and Zhou et al. (2004) employ a rectangular bead model for their research analyses. Sreedhar et *al*. (2012) investigated the impact of the planar surface angles on the surface finish, comparing the actual measured R_a and their periodic-rectangle model predictions. Xu et *al.* (1999) develop an optimization model considering the part geometry, build time, and 'build errors' or surface finish for a variety of AM processes. Thrimurthulu et al. (2004) expanded the general 'optimal orientation model. They developed an optimization model for the part orientation considering the build time and average part roughness, while simultaneously introducing adaptive slicing. They also considered the support material requirements for the fused deposition modelling process. Zhou et al. (2004) developed an adaptive slicing model independent of the CAD system using the STEP format, and a user defined tolerance. The general rectangular slice model is shown in Figure 3.

Byun and Lee (2005) developed an optimal orientation model using a variant of the rectangle model: they introduced filleted corner geometry. Other researchers (Ahn et al. (2009), Pandey et al. (2003), Boschetto et al. (2012, 2015)) considered the bead as an ellipse for their models. Pandey et al. introduce a (2003 a, 2003b) parabolic curve model. The ellipse and parabolic models are utilized as these shapes are more realistic.

Although differing shapes have been proposed, the periodic cycling is consistent, and the opportunities for an algorithmic solution have been recognized for years.