Journal of Materials Processing Technology 219 (2015) 181–192

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Roughness prediction in coupled operations of fused deposition modeling and barrel finishing

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ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form 7 December 2014
Accepted 13 December 2014
Available online 3 January 2015

Keywords:
Fused deposition modeling
Barrel finishing
Roughness prediction
Finishing operation
Material removal estimation
Surface improvement

ABSTRACT

Fused deposition modeling is one of the most used additive manufacturing technologies to produce prototypes and final parts without geometrical complexity limitations. One of the most limiting aspects of this technology is the obtainable roughness. Frequently, to comply with the component requirements, it is necessary to improve surface quality by finishing operations. Barrel finishing is typically employed in industry to finish fused deposition modeling components due to the advantage that the part does not need to be clamped and the process parameters are marginally affected by the part shape. The aim of this work is to develop a geometrical model of the deposited filament in order to predict the surface roughness of part after barrel finishing operation. The model depends upon the fused deposition modeling process parameters, namely the layer thickness and the deposition angle, and the material removed during barrel finishing operation. The estimation of this quantity is measured as function of working time by a profilometer procedure showing an inverse square relationship, as confirmed by the statistical analysis. The proposed formulation is not restricted to average roughness: several parameters are provided. The theoretical models are validated by an experimental campaign. The comparison between modeled and experimental data shows a significant reliability by means of statistical analysis. This formulation is a useful tool in computer aided manufacturing step to choose the optimum combination of process parameters in order to obtain the desired results provided by barrel finishing operation.

1. Introduction

The term Additive Manufacturing (AM) has been defined by ASTM International Committee F42 in (ASTM F2792-12a, 2012) as “process of joining materials to make objects from 3D model data, usually layer-upon-layer, as opposed to subtractive manufacturing methodologies, such as traditional machining”. This standard for terminology established a classification of AM processes into seven categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, vat polymerization. The category material extrusion refers to process in which material is selectively dispensed through a nozzle or orifice: this group is based on the technology first developed by Stratasys known as Fused Deposition Modeling (FDM) (Chua et al., 2010). It fabricates, layer by layer, components by depositing molten material in filament form. A temperature-controlled extrusion head is fed with material which is then heated to a semiliquid state. The head loads material from a cartridge or a spool and extrudes the filament in thin layers onto a fixtureless base. The surrounding air, maintained at a temperature below the material melting point, makes the exiting material quickly solidify. A Computer Numerical Control (CNC) system moves the head following the *x*–*y* toolpath of the desired layer. When a layer is completed, the table lowers and a new layer starts over the previous one. Overhanging parts need to be supported by particular structures made by another material, namely the support. This structure is eliminated in a post-processing stage by hand operation or dissolution. At present, the materials employed to produce part are thermoplastics such as ABS, Nylon, polyethylene, polypropylene, polycarbonate, a variety of blends (Gibson et al., 2009).

FDM involves a number of stages that move from the virtual model to the finished parts. The first step is related to the 3D model generation, typically in CAD environment or by reverse engineering techniques. The second step is the conversion to the interchange file: Standard Triangulation Language (STL) file format encloses tessellated surfaces and it has become the standard de facto for AM. In the third step the file is transferred to the prototyping system and process parameters are chosen in a Computer Aided Manufacturing (CAM) environment. The geometry is then sliced into layers and the generated curves are verified. The fifth step regards the

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http://dx.doi.org/10.1016/j.jmatprotec.2014.12.021
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Nomenclature

R_a	average roughness
MR	material removal
r	profile radius
f	profile spacing
x	FDM generic profile length
$y(x)$	FDM generic profile height
$y_M(x)$	machined profile height
x_m	flattened profile abscissa
y_m	flattened profile height
ξ	roughness reference line
$y_c(x)$	roughness profile height
λ	auxiliary variable
α	deposition angle
L	layer thickness
R_q	root mean square roughness
R_t	total roughness
R_{sk}	skewness
R_{ku}	kurtosis
Δ_a	mean profile slope
Δ_q	root mean square of profile slope
MRR	material removal rate
t	working time
R^2	R-squared statistic
R^2_{adj}	adjusted R-squared statistic

support creation. Then the toolpaths of the model, the support and the transition moves are generated and saved. The system is ready for an automatic fabrication of the physical part. The last stage is the post processing operation, which consists in the detachment of the part from the table and the support removal.

The above descripted process steps highlight the advantages of this technology. It does not need elaborate analysis of part geometry to determine the sequence of the operations (Boschetto and Bottini, 2014); hence only part specifications are necessary and process parameters do not depend upon geometrical complexity. It can fabricate functional parts, it is a clean process and material waste are kept to a minimum (Chua et al., 2010). These aspects explain the wide diffusion in the industry: 44% of the prototyping systems in the world are FDM based (Wohlers, 2012). In the last two decades it has become an increasingly important tool ranging from the prototyping in the design stage (Gebhardt, 2003) to the fabrication of molds or mold inserts (rapid tooling) and fully functional end-use parts (Hopkinson et al., 2005).

Due to the simplicity, reliability, and affordability of the process, the FDM have been widely recognized and adopted by industry, academia, and consumers. It is used by research and development sectors to improve the process, develop new materials, and apply the FDM systems in a wide range of engineering applications like aerospace, automotive, biomedical, customer product industry, design and tooling (Masood, 2014). Ingole et al. (2009) highlight the cost-effective advantages as rapid tooling for sand casting, investment casting and plastic molding. FDM has been found as a good investment casting solution by Singh and Singh (2014). Gibson (2005) shows how FDM and its variations are suitable for plastic prosthetic socket, bone engineering, tissue engineering.

Despite of its diffusion this technology presents the limitation related to the surface quality. The staircase effect markedly affects FDM parts as it employs thick filament: 0.254 mm is the most used thickness and only for some material it is 0.127 mm (Chua et al., 2010). It is higher than the most of AM technologies such as stereolithography (0.05 mm), selective laser sintering (0.02 mm), 3D printing (0.05 mm), polyjet (0.016 mm). Other problems are related to thermal and mechanical aspects because the polymer is rapidly cooled introducing part distortion and stresses; in this condition the shrinkage is unpredictable. Kantaros and Karalekas (2013) investigated solidification induced residual stresses and strains which determine inaccuracies such as curl and distortions, and provokes defects such as delaminations. They found the magnitude mainly depends upon layer thickness and deposition orientation. Wang et al., 2007 developed a model to predict warp deformation due to temperature gradients: it provided a tool for controlling and tailoring the part distortion.

These problems limit the part surface finishing which is an important requirement to assure component functionality. A number of theoretical investigations focused on the surface roughness of FDM parts and mainly on the average roughness R_a (Boschetto and Bottini, 2014). Armillotta (2006) investigated the capability of FDM technique to reproduce fine details and texturing of parts. Several RP processes are considered by Campbell et al. (2002) highlighting the dependency of surface finish upon the part surface angles. Pandey et al. (2003a) developed a model of R_a considering layer thickness and build orientation as the main variables; in this work the layer profile is assumed to be a sequence of parabola arcs. Ahn et al. (2009a) proposed a model based on a geometry of part with sharpened staircase profile: experiments indicated FDM roughness distribution curve was properly reflected in predictions. An improvement of this model has been presented in Ahn et al. (2009b): the filament profile section has been approximated by an elliptical curve; the experiments showed that surface angle, layer thickness and overlap between adjacent layers are significant factors affecting the surface quality. Boschetto et al. (2012) assumed roughness profile as a sequence of circumference arcs: in this work the models of several roughness parameters have been developed as a function of process parameters; regression over experimental profile data validated model assumptions and predictions. A 3D model which takes into account the measurement direction has been introduced by Boschetto et al. (2013a). This allows to model other roughness parameters such as spacing and hybrid ones. The model is reliable in the range of deposition angle 25°–155° and for measurement direction with angle smaller than 80°. A refinement of this model has been proposed by using neural network approach, making it effective all over the range of the deposition angle (Boschetto et al., 2013b). In the same work experiments pointed out that the use of different materials, machines and filling strategies does not affect the proposed formulation. These models highlight that this technology is characterized by a lower limit of average roughness: for the most common layer thickness 0.254 mm it is 16.5 μm. This can lead to the need of secondary finishing operations when esthetic and functional requirements are not satisfied. Pandey et al. (2003b) employed CNC milling to improve surface roughness: this finishing operation is limited by tool size, time-consuming preliminary analysis for complex objects by means of machine setup and CNC code generation. The same problems are encountered in other machining operations such as abrasive flow machining (Williams and Melton, 1998) and abrasive jet deburring (Leong et al., 1998). Stratasys, the producer of FDM apparatus, has developed a semi-automated finishing system for ABS parts (Espalin et al., 2009): this method needs human intervention and a post curing phase. Galantucci et al. (2009) investigated a post treatment based on chemical reaction by a solution of dimethyl ketone: a design of experiments was performed to find optimal solution concentration and process time, depending on part shape and dimensions; experiments showed a marked improvement of surface roughness but a large scattering has been achieved. McCullough and Yadavalli (2013) employed a similar acetone-based method with the aim to seal surfaces and make FDM suitable for microdevices which need hydrophilicity