Extrusion-based additive manufacturing: trajectory design and material deposition optimisation

PhD Thesis

George Papazetis

Abstract

Additive Manufacturing (AM) constitutes a significant category of manufacturing processes, that has been available for over thirty years. Especially during the last decade, AM has attracted research attention, in an effort to upgrade its utilization from prototyping to end-use industrial applications. One of the most common techniques is extrusion-based AM, also referred as Material Extrusion (ME). Superior design flexibility, consolidation capability of complex assemblies and reduced lead-time are some of the main potentials that ME brings to industrial manufacturing. Currently, the offered competitive advantages, render ME suitable for the production of small batches or one-of-a-kind parts, with increased complexity and customization. However, certain issues still exist, hindering the process from unleashing its full strength. From the industry point of view, the reluctance to integrate ME is mainly attributed to the lack of process standardization that would guarantee predictable and repeatable production. In an attempt to contribute to the efforts towards ME process maturation, this thesis investigates timely issues from two aspects: trajectory design and optimisation of material deposition.

Manufacturing of complex parts consisting of numerous surfaces and possessing complex internal structure has become feasible by the layer-wise fabrication manner of ME. Nevertheless, 3D modeling of such structures induces significant processing difficulties for CAD software even on state-of-the-art computers. Apart from modeling, conversion of complex parts in Stereolithography (STL) file format is likely to induce errors, if not complete conversion inability. Although STL is still the standard intermediate step between design and process planning (slicing) for ME, it is widely accepted that this format is soon becoming obsolete. In this light, a CAD-direct process planning approach is investigated in the first part of this thesis. A representative case concerns lattice scaffolds, containing structured macro-pores which can be produced following the ME paradigm. A process planning algorithm is proposed, exploiting the macro-pore as a periodically repeated unit cell. The two latest versions of the implemented code are presented in this work, developed within Application Programming Interface (API) of Solidworks™ CAD software. The penultimate version deals with the representation of the lattice scaffold as a set of segmented files. The first set represents the unit cells lying on the outer boundary of the scaffold and being represented in their exact shape as separate STL files, pertaining to each layer. These consist mostly of incomplete unit cells due to their intersection with the layer boundary. The rest of the unit cells, lying totally inside the scaffold boundary, are represented in essence by a reference point and a reference direction. The last version of the code implements significant updates in order to directly export machine instructions, in the form of G-code commands, that are ready to drive the ME fabrication system. Each unit-cell is now handled as a separate object with individual properties, such as position ID, reference point and pore size. The on-boundary unit-cells are connected to unified and continuous (when possible) trajectory paths, according to their relative position. They are directly exported as G-code commands, totally by-passing segmented STL file representation of the initial version. Similarly, the reference points of internal unit-cells, from the initial version are utilized to populate G-code commands, thus composing the entire layer. Process parameters for slicing are provided by the user before code execution. The functionality of the exported G-code is verified for the fabrication of a lattice scaffold segment.

From the aspect of material deposition optimization, the open challenge for ME corresponds to the need for quality parts, fabricated with increased productivity. The free-form strategy of material extrusion and deposition is often accompanied by defects, resulting from non-optimal combination of process parameter settings. The large number of available parameters initiates the need to separate what is “allowable” from what is “feasible”, regarding determination of settings. In the second part of this thesis, a predictive process-planning tool to balance productivity and quality of ME parts according to user requirements is developed. Taguchi design of experiments (DoE) method is employed in order to determine the process parameters that impact shape fidelity over a wide range of parameter settings and in terms of material deposition stability that results in defect-free products. The development of four common fabrication defects is investigated on

simple specimens, which are reverse-engineered and quantified by CAD-to-part 3D comparison. The experimental analysis is based on robust statistical tools and methods, allowing for reliable conclusions. Interaction terms were identified as statistically significant, indicating the non-linear behavior of the process in contrast to what is often assumed in literature. Although, conservative material flow rate settings are typically advised for stable extrusion, the low limit, below which defects form, was identified. A highly reliable Artificial Neural Network (ANN) is configured in an optimum way, and trained on the previous experiments with the aim to predict shape fidelity across the entire parameter level range. Hence, material flow rate, which is a function of the investigated factors, is provided with direct feedback by the ANN regarding possible defects occurrence. The increased granularity of the trained ANN facilitated the detection of the maximum feasible flow-rate, which the Taguchi analysis of the experimental results alone was not able to trace.

The conditions under which material is extruded and deposited on the build platform are often associated with the resulting dimensions of the printed part. Phenomena of anisotropic shrinkage and non-uniform temperature gradients during solidification cause variation of dimensions along the different printing directions or according to the geometric feature that is fabricated. In order to further optimise ME process, a novel approach of adaptive settings during material deposition is proposed in the third part of the thesis. The well-established response surface methodology is applied on a specially designed specimen, containing holes and thin wall features along the three printing directions, in order to obtain separate models that predict dimensional accuracy. This scheme creates a problem with multiple responses and is typically tackled with multiple-objective optimisation routines in order to obtain optimal parameter settings that simultaneously satisfy contradicting requirements, thus carrying a degree of compromise. To improve this, the proposed approach separately optimises dimensional accuracy on every included feature and along the different printing directions, thus providing enhanced flexibility to the derived optimal solution. Optimal settings obtained from the prediction models are fed directly to the material extrusion system as modified machine instructions. Different parameter settings for different regions of the same layer or even varying material extrusion rate and feed rate along continuous trajectory are validated. The efficiency of the proposed approach is compared with multiple-objective optimisation based on the desirability method. The test specimen presented enhanced dimensional accuracy for four out of five features, exhibiting reduction regarding the average deviation from the designed part.

Limitations from the previous solution pertained to the maximum permitted degree of in-situ variations for flow-rate and printing speed, which sometimes caused deposition instability. In ME process, increased performance and part quality is achieved when the extruded strands are uniformly deposited according to the designed trajectory, without defects and with minimal deviation from the intended strand shape and dimension. In the last part of the thesis, the extrusion variation along a single linear trajectory path was experimentally evaluated according to its ability to maintain strand width uniformity and also mitigate start-stop errors, reflected by overfills and underfills at the extreme points of the deposited strand. The investigation was performed via a designed fraction factorial experiment and was enriched with other tested parameters that were expected to impact strand width stability, including priming/retraction length and speed, printing speed and melt temperature. This objective becomes more challenging when ME subsystems must be optimally synchronized, in order to perform material deposition at higher rates, given the timely need to improve ME process productivity. In particular, higher flow-rates are likely to trigger instant extrusion blockage, resulting in intermittent paths. Two separate metrics were determined to quantify deposition quality, namely material deposition discontinuity (MDD) and strand width deviation (SWD), as function of corresponding regression models. Image analysis methods are employed to evaluate factor contribution to the fabrication of simple linear segments, and to effectively measure the free form shape of the resulting strands. Frame analysis of video recording was also performed to capture the material extrusion profile during the deposition stages. Analysis of the experiments revealed the mechanisms that trigger material deposition discontinuity (MDD) during part fabrication. Instant nozzle blockage was successfully captured in the frame analysis and correlated with tested factors. Extrusion variation was found to have comparably lower impact than priming/retraction length, which is responsible for severe overfills and underfills when not optimised. Although increased melt temperature was found to facilitate continuous deposition at higher rates, it was constrained by the uncontrolled oozing that induced defects in the form of stringing. The models were utilized as roadmaps towards continuous and uniform deposition for two indicative case studies, namely at normal and increased melt flow rate. Compared to non-optimized runs at similar flow rates, continuous and more uniform deposition is achieved for both cases.