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Workpiece and Machine Design in Additive Manufacturing for Multi-Axis Fused Deposition Modeling

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Abstract

Additive Manufacturing (AM) technologies require innovative design paradigms and guidelines that exhaust the offered freedoms in geometry and material. The aim of the Design for Additive Manufacturing is to provide design opportunities and to enhance workpiece properties taking into account constraints of the process, e.g. kinematics and limitations of print technology. Most AM applications are constrained to three-axis movements limiting the fabrication of workpieces layer by layer to one fixed building direction only. This causes limitations of strength properties, surface quality and the need of supporting structures. Multi-axis AM enables completely new design possibilities going beyond current optimization and design strategies of conventional AM workpieces. This innovation requires multiple design and manufacturing changes in the internal and external geometry of the workpiece as well as in machine and printing head technology. This paper identifies the requirements and capabilities of multi-axis AM and presents possible solutions to overcome the identified challenges. Preliminary results for multi-axis AM are described on an exemplary workpiece.

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1. Introduction

Additive Manufacturing (AM) has become an ambitious technology of the production industry, in recent years. The reasons for this unique rise are diverse potentials of AM, like free forming of individual parts in an economic process, integration of functions, multi-material workpiece fabrication and topology optimization. This manufacturing method enlarges the possible variety of workpieces by overcoming limitations of conventional subtractive manufacturing and forming technologies. Therefore, AM allows new freedom in the design of products. To merge the practice of designing and optimizing of workpieces beneficially, DfAM was developed recently [1]. Although DfAM is widely spread in literature, it is not completely defined yet. The aim of DfAM is to enable designers to synthesize the shapes, sizes, structures and materials of their constructions with the AM process capabilities in order to reduce manufacturing difficulties. To achieve this aim, still a wide range of new methods, approaches and tools are necessary [2]. Furthermore, the design of new workpieces requires knowledge about the limitations and possibilities of AM processes [3].

The development of AM started with the objective of rapid prototyping in the early 1980s, where stereolithography was the first commercial process. Up to now, there is a great range of technologies that are powder-, liquid- or solid-based. Most of them are layer-based processes with slicing of the workpieces in horizontal layers and one fixed vertical building direction. Today, one of the most common AM technologies is Fused Deposition Modelling (FDM) that was invented by the US-American enterprise *Stratasys* in 1991 [1]. Typical materials used in FDM are high polymers, such as acrylonitrile butadiene styrene (ABS) [4], polylactides (PLA) and other bioplastics [5].

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This paper focuses on the FDM process since it is a freeform process that allows the extension to more than three axes by adaptation of the kinematics, printing head and trajectory planning. Commercial FDM printers consist usually of three axes that limit the process to 2,5 dimensions [6, 7]. First five-axis FDM prototypes were built at lab scale for preliminary testing [8].

This paper describes the potential of multi-axis FDM and the challenges that have to be overcome. As a case study, an application from the medical sector is chosen due to its high importance in the society, the need for individual workpieces and low batch sizes. The workpiece under investigation is a handle of a walking frame for elderly people. First, the limitations induced by three axes are described in Section 2. Then, new design possibilities of multi-axis FDM workpieces are discussed in section 3. Afterwards, a concept of a multi-axis machine is presented in section 4. Section 5 shows preliminary experimental results and the benefits of this technology. The last section provides a short summary and an outlook towards possible research topics in the future.

2. Limitations of current FDM processes

State-of-the-art FDM printers are limited to three-axis movements with a fixed building direction in Z. Consequently, the slicing software splits the workpiece description (usually STL format) into single slices with a constant layer thickness that is limited by the nozzle diameter. For each horizontal slice, a path is calculated based on the nozzle diameter in 2D while focusing on the outer geometry. This results in G-code that can be interpreted by the machine control.

The main drawback of this approach is the limitation to one fixed building direction, causing a possible lack of strength, the stair-step effect and the need of support structures. Another drawback is the use of STL files, which only represent the outer geometry of the workpiece, while the user selects one filling method for the complete internal workpiece structure (e.g. diagonal infill) [3]. Consequently, structural optimization regarding load stresses or thermal effects is not carried out. Finally, the position and orientation of the part on the printing bed is chosen manually, although it affects the properties of the final workpiece. In the following, the effects of those drawbacks are discussed in detail.

2.1. Filament orientation

Since three-axis FDM is a layer-based technology, where semi-molten material is extruded in planes, no homogeneous material is printed. Anisotropic workpiece properties are generated [3] because the strength between layers is much lower than in filament direction [9, 10].

Preliminary experiments show the effect of different printing strategies on the workpiece properties (Fig.1). For these investigations, tensile specimens were produced with different tool paths for filament orientations. The parts consisting of PLA were printed with a nozzle diameter of 0.25 mm and tested according to DIN EN ISO 527-2 standard. For obtaining a uniform surface, all specimens contained three perimeters. The results of the tensile tests show not only different maximum peaks of tensile strength (lengthwise specimens have approx. 1,5 times higher peaks than 45°-135°-laying) but also different young`s moduli. Obviously, slicing in Z-axis generates crosswise filament orientation tensile properties in this direction that cannot be prevented in three-axis FDM process and result in lower strength properties. Variation of density and infill patterns has also a huge impact on the workpiece strength [9, 11]. Since the three-axis FDM process consists of layering with one constant building direction, matching load-capable optimization of mechanical properties cannot be carried out in most workpieces.

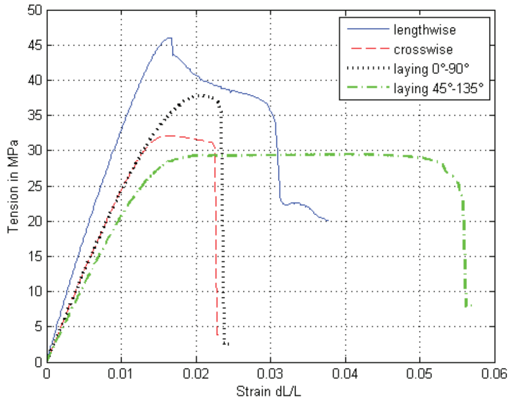

Fig. 1: Tensile tests of PLA specimens with different filament orientations. Lengthwise = filament orientation in tensile direction, crosswise lateral for all layers. Laying = changes filament orientation in every layer

2.2. Stair-step effect

The resolution and stair-step effect are significant surface issues of the components produced by FDM. Due to filament layer slicing in Z-direction, the surface is not smooth and stairs are visible [12]. The stair-step effect increases with thicker layers and smaller gradients in building direction, as can be seen in Fig. 2. These surface problems have an impact on the possible application domains of AM parts. Above all, in the field of ergonomic design of human-machine interfaces (HMI) like actuators and handles, the staircase effect is a major problem. The variable product parameters of the haptic interface design comprise the structure, shape and surface [13]. However, the surface quality is mainly influenced by the AM process.

Fig. 2: Stair-step effect on a handle of a walking frame