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ECCOMAS
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Design Challenges And Opportunities Of 3D Printing

Abstract

In the future, the number and complexity of products made using additive manufacturing (AM) techniques will increase rapidly. The development of softwares and algorithms related to processes will eliminate extra intermediate steps between the product design and the end product, and will finally give us more intelligent way to manufacture these new products. More efficient 3D printing processes will enable the production of cheaper individual items and, furthermore, they will increase the demand for these high-quality tailored unrivalled solutions. The market potential is huge. However, at present the fundamentals of the area are only lightly studied and several key challenges concerning structural behavior and performance have to be solved before these techniques can be used in a widespread, cost-effective manner. Success in this task creates a basis for mathematical modeling and design, which will considerably accelerate the development time cycle of consumer products. With new computational methods becoming even more sophisticated and faster, the repeatability and reliability of the product design process will improve, enabling further production quality advances in the manufacturing industry. 3D printing assisted by Artificial Intelligence (AI) will become one of the major components of concept of ’Industry 4.0’ approaching independently operating and even self-contained systems.

1 Additive Manufacturing Change The World

Additive manufacturing also known as rapid prototyping or 3D printing is a rapidly evolving and expanding product manufacturing discipline, which will drastically change our understanding and thinking of industrial production in the future. 3D printing process can be applied for several materials, for example, plastics, metals, ceramics, graphite, graphene and concrete. The benefits of additive manufacturing are numerous: 3D printed objects can be easily produced wherever and whenever needed, and it is possible to make significant changes with respect to original blueprints during the process. Moreover, different materials will be more efficiently used and, for example, some of the traditional metal processing methods will be partly or wholly replaced by alternative additive manufacturing solutions. As methods and techniques evolve the production of tailored multi-material 3D printed objects will increase and new innovative structures will emerge. Additive manufacturing can also decrease the complexity of engineering solutions in final products because some of the traditionally required assembly constraints can be loosened, and optimally, the printed products are ready-to-use when the printing process is completed. One major game change when using 3D printing techniques is its possibility to tailor solutions uniquely and still produce products efficiently, a number of items in one run. One of the most significant challenges is the part quality. Available material combinations, inadequate dimensional tolerances, surface roughness, and other volumetric defects constrain the quality and eventually define the mechanical properties of the part, which are crucial for product functionality. The defects may be related to several stages at workflow: wrong product design, problems with deposition system, uneven cooling, poor parameter selection or scanning strategy etc. For example, the properties of parts produced by fused deposition modeling (FDM) method are often related to the

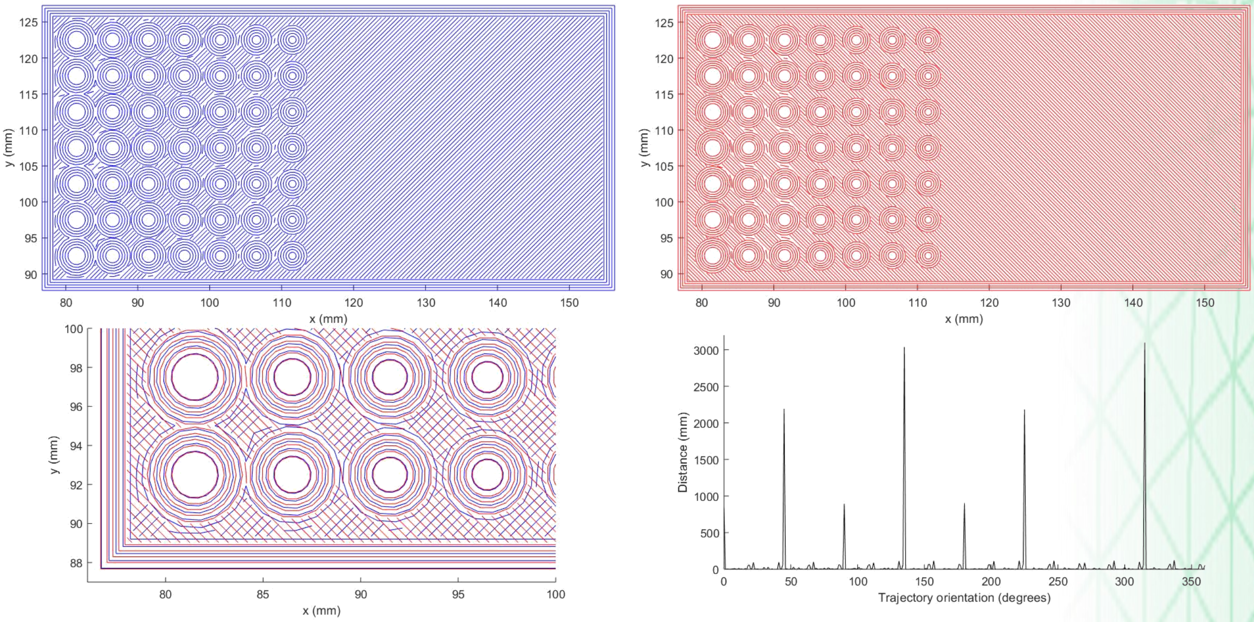

Figure 1: Trajectories of the bottom layer (top-left) and the top layer (top-right) of the two layer sample. Both layers were printed with 0.06 mm thickness. Magnification including both layers (bottom-left). The histogram of the total trajectory length printed in specific orientation (bottom-right). The sample was originally designed for the accuracy testing of the printer.

orientation of the printing trajectories (routes, see Fig. 1) defined in the slicing operation and the patterns chosen to infill objects.

The 3D technology itself is not new, but since the expiration of the key patents, low cost 3D printers have emerged in the daily use of small companies and individual hobbyists. Material extrusion based techniques are most commonly available and has become the most popular rapid prototyping techniques for plastic materials in the last decade. All 3D printing processes follow generally similar steps. Commonly, the object is designed with CAD (Computer Aided Design) software and imported to the slicer program in a stereo lithography (STL) format. The program cross-sections the model into individual thin layers of defined heights and converts all necessary information into the g-code that can be directly read by the 3D printer. Based on this control information the required tasks tailored to a specific 3D printing technique, machine and used material(s) are executed. As an example, in FDM process, the printer heats up a liquefier to the right temperature to melt the polymer filament, and begins extruding the material. Filaments are fed through the heated liquefier by two drive wheels and extruded through a nozzle onto the platform. After each layer is finished the build platform moves down (or nozzle moves up) by a specified layer height, and the process repeats for the next cross-sectioned layer until the object is completed, see Fig. 2. This article is a result of an ongoing cooperation between technology enterprises and Faculty of Information Technology, University of Jyväskylä. The projects ’Opti3D’ and ’Industry 4.0 - Additive Manufacturing Technologies’ are funded by Regional Council of Central Finland.

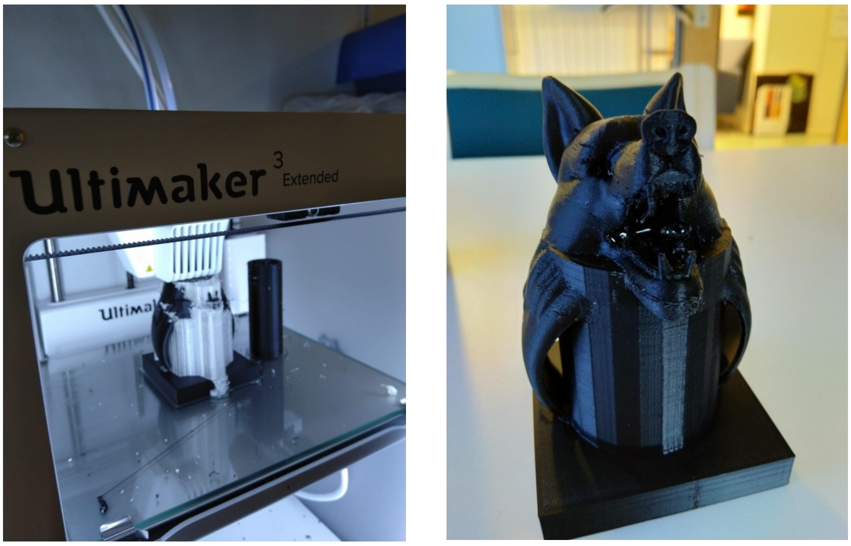

Figure 2: Ultimaker 3 Extended 3D printer producing statue (left). The statue is printed with black ABS (acrylonitrile butadiene styrene) and white water-soluble PVA (polyvinyl alcohol) is used as support material. Statue (original design grabcad.com/library/wolf-ring-1) after the support material has been dissolved (right).

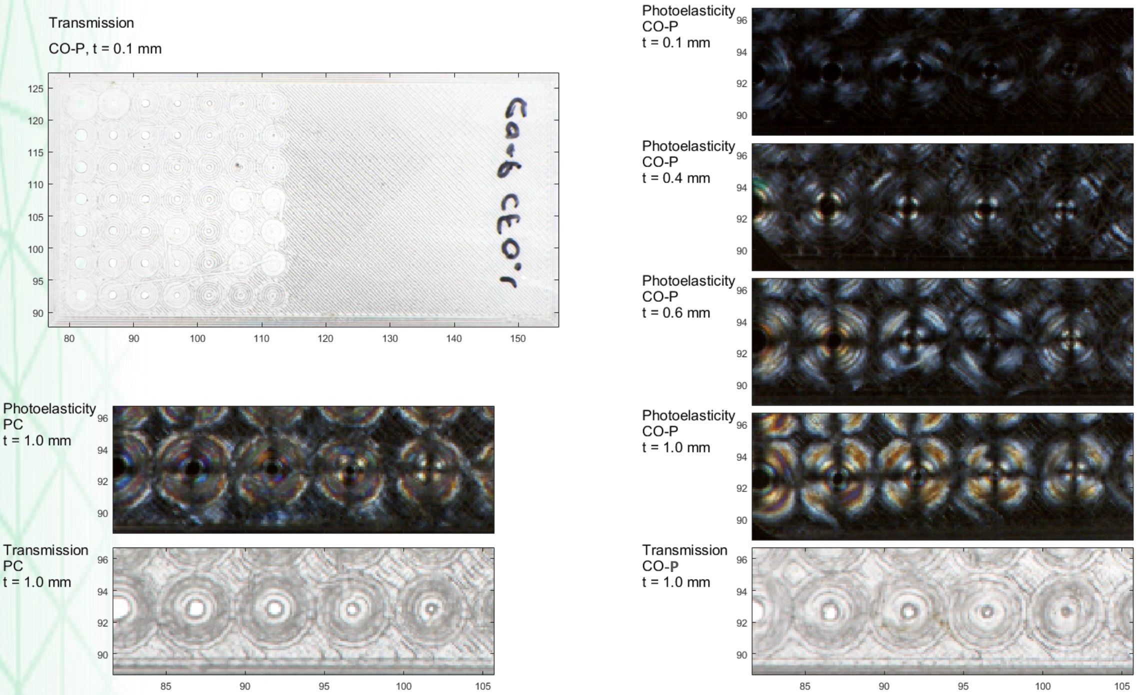

Figure 3: White light transmission and photoelasticity experiments using hyperspectral imaging. The crosspolarization is utilized in the visualization of photoelasticity. Objects are printed using FDM with polycarbonate (PC) and co-polyester (CO-P). Thickness (t) is the target thickness of the 3D printed strip. The strip having a thickness of 0.1 mm (CO-P) is printed using trajectories shown in Fig. 1.

2 STRUCTURAL PROPERTIES OF 3D PRINTED OBJECTS

The number of studies being conducted on additive manufacturing has increased progressively during last years. From reference [1], reader will find an excellent review of various themes related to these technologies. One major perspective has been the physical testing of tensile strength, fatigue and other characteristics of the final products. The effect of design of FDM build parameters on the properties of ABS filament parts was studied in [2] and [3]. The layer orientation was found to have significant effects on the tensile strength, modulus of rupture, and impact resistance in [2]. Congruent results were also achieved in [3] of the trajectory orientation effects on tensile and compressive strengths. The overlap of trajectories had also clear effect on tensile strength while bead width, model temperature, and color were insignificant factors. Anisotropic characteristics were observed and assumed to be caused by air gaps between trajectories and weak interlayer bonding and porosity in [2] and [3].

In [4], the tests and results along with statistical analyzes of the data clearly suggest that specimens with 0.2 mm layer thickness are stronger than specimens with 0.4 mm layer thickness, and that layer thickness and trajectory orientation both have a significant effect on the mechanical properties of material. In [5], FDM was used to produce PLA (polylactic acid) filament specimens for mechanical properties testing. Trajectory orientation had only small effect on tensile strength and bending stress, while in fatigue testing, the 90 degrees specimens were clearly the least resistant to fatigue loadings. The study was continued using ABS filament in [6] with a conclusion that 0 degree orientation yield the highest mechanical properties and that the mechanical properties improves when number of layers increase. However, after 12 layers the effect of increasing more layers on the increase of the elastic modulus and maximum stress is only minor. In the article [7], Wendt et al. proposed that, in order to establish AM as a group of controlled and competitive processes for the production of loaded parts, it is the necessity to establish a complete methodology for the extraction of relevant mechanical properties from simple mechanical tests like the tensile test. In reference [8], the authors have also taken into account the flexural creep modulus of three AM polymeric materials made by SLS (selective laser sintering) and FDM. From the experimental results they concluded that the mechanical properties decrease with increasing temperature. More tensile test are reported e.g. in [9] and [10].

Compression has been considered

for example by Guessasma et al. in the study [11], where they considered that the nature of the arrangement of porosity and its orientation play a central role in either enforcing rapid damage growth or slowing down its extension. In the article [12] the compression test data indicates that the 45 degrees trajectory specimens are significantly weaker in compression than other trajectory orientations, and they distort prior to failure as a result of shearing along the trajectory axes. Moreover, tension tests indicate that the ultimate and yield strengths are the largest for the 0 degrees trajectory orientation, followed by the +45/-45, 45, and 90 orientations in descending order. The Taguchi method was used in the case of experimental catapult design in order to achieve optimum elastic performance of a compliant ABS prototype in the article [13]. The measurements of compressive strength in [14] showed that parts created by three different techniques, FDM, 3D printer and NCDS (nano composite deposition system), have anisotropic characteristics. From the compression test, it was confirmed that the ”build” direction was an important process parameter that affects the mechanical properties. In addition, it was found that parts created with a 3D printer had low compressive strength compared to other processes, and that FDM parts had high compressive strength.

In the study [15], a functional relationship between the process parameters and strength (tensile, flexural and impact) were determined using response surface methodology. As a result authors found that if the number of layers is larger, it will result high temperature gradient towards the bottom of the part. Moreover, an increase in the number of layers also rises the number of heating and cooling cycles and thus residual stress accumulation increases. The authors continued their studies in the article [16] where they concluded that the reason for low strength is also due to anisotropy, caused by the polymer molecules aligning themselves with the direction of flow when they are extruded through the head nozzle. They used artificial neural networks (ANN) in this case and finally found the optimal parameter setting through Quantum-behaved Particle Swarm Optimization (QPSO).

In the study [17], the production cost was analyzed, and it was concluded that the cost depends on the production time and support material (see Fig. 2). The authors noticed that by selecting an optimal part orientation in FDM process, it is possible to shorten the production time and reduce material consumption. If strength is of primary concern and the demand is to manufacture stronger parts, then the position of the parts must be designed to carry tensile loads along trajectories.

Internal stresses arising during 3D printing process are closely related to the previously mentioned parameters and strength properties. During the last decade studies related to the internal stresses in 3D printed objects have been performed; see for example [18] and [19].

3 FULL POTENTIAL OF 3D PRINTING AVAILABLE BY COMPUTATIONAL METHODS

Recently more attention has been drawn to the mathematical modeling and computing of properties related to final products. In the study [20], a mathematical model for predicting the tensile elastic properties of fiber reinforced 3D printed components is presented. The procedure is straightforward. At first,

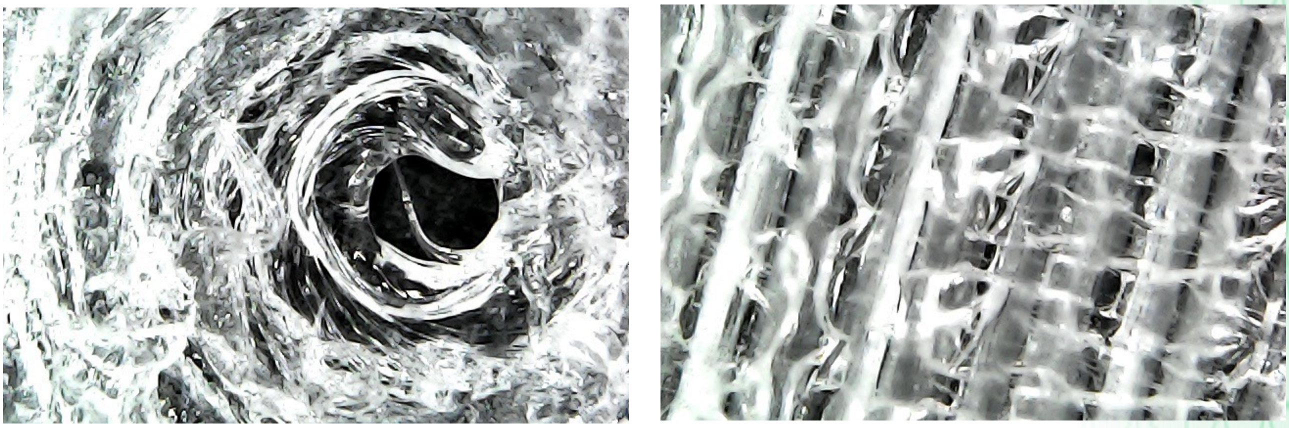

Figure 4: Magnifications (x1000) of the 3D print in Fig. 3: a single hole (left) and the oriented pattern (right) from the test plate. The black paper is used as background.

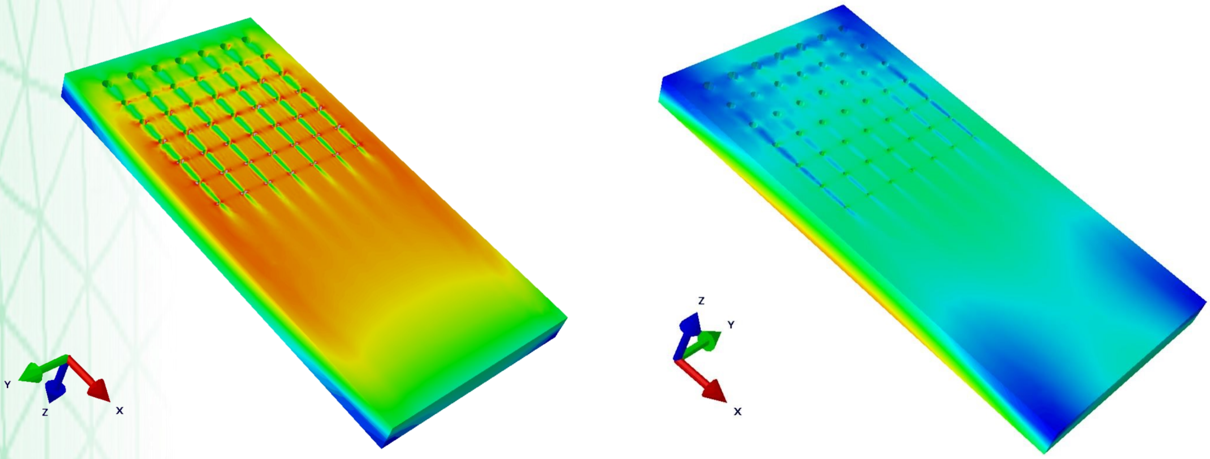

Figure 5: Schematically simulated stress field with layer-wise optimized trajectories.

micromechanical models are used to determine the effective properties of the FDM printed components. Second, a coordinate system transformation is applied to the solid and infill layers. Finally, volume averaging of the stiffness matrices of each of the crosssectional regions is performed. In [21] a finite element analysis related to the part distortions was performed. It was concluded that the printing speed and the layer thickness are the most important factors affecting the part distortion. Modeling of residual stresses in the case of laser assisted additive manufacturing was considered in [22]. It was shown that the residual stresses can be decreased by reducing the layer thickness. Residual stress build-up in metal based additive manufacturing was also considered in [23] via finite element modeling. It was concluded that the bed pre-heating temperature has the largest quantitative impact on the residual stress. Temperature gradients during selective laser melting (SLM) were simulated in [24]. It was found that the highest temperature gradients exist at the start of the first track scan. Simulations related to the residual stress in SLM was also performed in [25]. The effect of process parameters such as laser power, scan speed and scan strategy were investigated. The results suggested that the stress gradually increases during the SLM process due the heat accumulation effect.

Only few examples about modeling and simulation related to the additive manufacturing are given above; more information can be found, for example, from the reference [26]. During the last years the publication rate of these studies have increased enormously. Challenges are related, for example, to phase-changing and different scales and knowledge of material behaviour due to melting. The enlargement of the additive manufacturing and increased computing power will inevitably lead to expand the ’traditional’ modeling and simulation approaches to more sophisticated method including online measurements and optimization assisted by Artificial Intelligence. With these computational tools the real power of additive manufacturing can be obtained.

4 DEMONSTRATION OF FEW ADVANCED METHODS IN THE CONTEXT OF DESIGN SCIENCE

The additive manufacturing technology is at the intersection of mechanics, materials and computational science. A close interaction between different approaches is needed to produce high precision and performance products as well as intelligent systems without need of human intervention.

The imperfections arising during AM process can be studied by transmitting light when object is printed using material behaving as dielectric in the visible region. Fig. 3 presents the transmittance of printed samples produced using layout of Fig. 1 and co-polyester and polycarbonate as filament materials. Lowered transmission in some parts of the trajectory interfaces makes them visible. This is caused by light scattering at irregularities, such as air gaps between adjacent trajectories (see Fig. 4). By introducing polarizing elements on transmission measurement, the internal stress state is revealed based on photoelastic phenomenon (see Fig. 3) [27]. Many transparent noncrystalline materials become optically anisotropic when internal stresses exist. The components of the light wave that are parallel and perpendicular to the direction of the stress propagate through the plastic at different speeds inducing retardation between the two components. This retardation is proportional to internal principal stresses according to the stress-optic law

$$\Delta_{12} = tC_B(\sigma_1 - \sigma_2) \qquad (1)$$

where Δ_{12} is the retardation, t is the thickness, C_B is the stress-optical constant of material in Brewsters and σ_1 and σ_2 are the stresses in the principal directions. When monochromatic light is used, the dark and light fringes appears, whereas with white light illumination colored fringes are observed. The qualitative analysis of white light experiment can be done using The Michel-Levy chart. The Stokes or Jones calculus are used for quantitative modeling. The spectral imaging improves the possibilities to extent the photoelastic techniques to stress analysis of 3D printed objects. A schematically simulated stress field with layer-wise optimized trajectories with in-plane topology of sample (Fig. 3) is presented in Fig. 5. Localized stress concentrations caused e.g. by mechanical loading, non-uniform temperature, inadequate or non-uniform annealing and sharp corners or protrusions can be analyzed by simulations and measurements and they can be used also for quality control during production.

5 CONCLUSION

Despite the fact that additive manufacturing is a recent production method, a great amount of experimental and modeling work has been already performed. However, as an immature technology there are substantial challenges to be overcome; only few important questions are studied more closely. A more extensive view is required to optimize both the printing process and properties of the printed object. Moreover, as a component of 'Industry 4.0' the 3D printing should be able to operate as a solid part with cyber-physical systems, internet of things, smart factory and internet of services. It is clear that many advances can be achieved in a near future with Artificial Intelligence. Nevertheless, the development of 3D printing requires a great amount of computational tools before chancing the world once and for all.

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