Celebrating three decades of stereolithography

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It was the early 1980's, a time in which industrial manufacturing processes became more and more computer-controlled and optimised towards speed, accuracy and cost-efficiency. The design and product development process however was still mainly a manual undertaking, employing traditional tooling, mould making and casting techniques for producing prototypes. It could take up to two months before a design was converted into a physical prototype, and after evaluation the design would be altered and this cycle would be iterated several times. This led Charles (Chuck) Hull of Ultra Violet Products to come up with stereolithography, a new technique that employs computer-controlled laser curing of a resin to automatically fabricate plastic prototypes from computer-aided design (CAD) files, bringing the time to produce a physical prototype down from several weeks to a few hours. He filed a patent application for the technique in 1984, and after granting of the patent (Charles W. Hull, 1986) brought the first stereolithography apparatus to the market in 1986 under a new company called 3D Systems. With this he did not only invent a new technique, but initiated a whole new approach to product development, a revolution which is still happening today. We are therefore proud to have the inventor of stereolithography technique describe his experience in a foreword to this special issue. We are also obliged to Terry Wohlers, the world leading market analyst in the area of Rapid Prototyping/Additive Manufacturing, who puts the role of stereolithography in industry in past, present and future in perspective in his foreword.

Let us shortly introduce stereolithography (SL) to those readers unfamiliar with the technique. One starts with a CAD file, which can be drawn from scratch or can be based on digital imaging results, such as applied in reverse engineering or patient-specific medical applications. The 3D structure is (virtually) sliced into layers of a specific thickness that is used in the fabrication process (usually in the range of 25-100 μm). These data are then uploaded to the stereolithography apparatus (SLA) and the structure is fabricated in a layer-by-layer manner. The manufacturing of 3D objects by SL is based on the spatially controlled solidification of a liquid resin by photo-initiated polymerisation. Using a computer-controlled laser beam or a digital light projector with a computer-driven build stage, a pattern is illuminated on the surface of a resin. As a result of this, the resin in the pattern is solidified to a defined depth, until it adheres to the preceding layer. Then, the platform with attached structure is moved away from the surface with a distance equalling one layer thickness, after which the built layer is recoated with liquid resin. This cycle is repeated many times until a solid, three-dimensional object is obtained from which the excess resin is drained and washed off. For the interested reader, an excellent book on the fundamentals and practical application of SL was published already in 1992 by Paul Jacobs and still is an indispensable source for anyone working with the technique (Jacobs, 1992).

The introduction of SL opened up a whole new technological field which has been filled up with other new techniques among which laser sintering, fused deposition modelling, 3D printing and electron beam modelling. These techniques were (and often still are) termed Rapid Prototyping techniques, as initially they were mainly used to produce physical prototypes. As these technologies are continuously evolving, more and more materials are becoming available, fabrication costs are decreasing and the properties of manufactured parts are becoming better, these techniques are increasingly being used for the rapid manufacturing of fully functional products in small series. The time gain in product development, freedom of design and tool-free fabrication can outweigh the increased fabrication costs per item (Wendel, et al., 2008). As we are moving away from prototyping as the only application of such techniques, the term

Rapid Prototyping techniques is gradually being replaced by Additive Manufacturing (AM), as defined by the latest ASTM standard (ASTM-International, 2010). Regarding accuracy and resolution, stereolithography is superior to most other AM techniques. While in most fabrication techniques the smallest details are 50-200 μm in size, many commercially available stereolithography setups can build objects that measure several cubic centimetres at an accuracy of 20 μm. Stereolithography setups have been developed that make use of two-photon initiation of the polymerisation reaction, and in the laboratory, millimetre-sized structures with sub-micron resolution have been fabricated using these setups (Maruo & Ikuta, 2002). Such accuracy has not been achieved with any other AM technique.

Since its introduction, SL has attracted the attention of many researchers in industry as well as in the academic world. Where some focus on the further improvement of the technique or the development of new materials, others have adopted SL as a useful tool to find answers to their research questions in a variety of fields. The figure below shows the number of published journal articles on SL per year over the past 25 years, as indexed by Thomson Reuters Web of Science. All publications with stereolithography in their title are shown, as well as those with stereolithography in one or more of the topic fields (*i.e.* title, abstract or keywords). In the early years, when most research using stereolithography was on establishment of the technique itself, almost all papers on SL also had stereolithography in their title. Since 1995 the number of new publications with stereolithography in the title appearing each year has been stable at around 35, indicating continuous research activity with an important focus on the technique itself. The number of papers with stereolithography in the topic however has been gradually growing up to 142 papers published in 2011, indicating an increase in the application of SL without the research necessarily being on the technique itself.

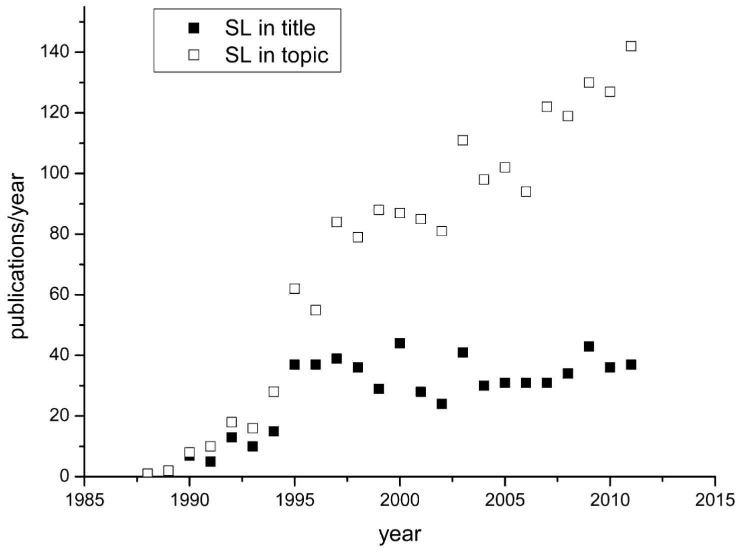

Figure 1. Papers published per year with either stereolithography in the title or in one of the topic fields (*i.e.* title, abstract or keywords)

This special issue on stereolithography gives a sample of the SL-based research activity anno 2012, with a mixture of papers on development, and on application in various fields. A feature article in this issue covers a decade of research to tackle the challenge of including multiple materials in one construct. This is still one of the major limitations of the SL technique. Another paper on technique development highlights ceramic stereolithography. It has been known since late last century (Chu, Szczepkowski, Wagner, & Halloran, 1996) that polymeric stereolithography resins can be loaded with ceramic powder to create composite parts with surprisingly high accuracy, taking into consideration that these particles scatter the incident light beam. With high volume fractions of ceramic particles, it is even possible to convert the green composite to purely ceramic parts by a simultaneous pyrolysis and sintering process. The included paper on this topic describes a systematic study into the influence of fabrication and post-processing parameters on the accuracy of SL-built ceramic parts.

Another paper describes the use of stereolithography-fabricated micro reactors to study the photolytic degradation of salicylic acid as a model water pollutant. The freedom of design and accuracy make SL a suitable technique for this purpose. A clinical dental application is also presented in this issue, describing a case study of the use of a stereolithography-fabricated model donor tooth and several guides to facilitate pre-operative planning as well as surgery in the case of tooth auto transplantation in a 10-year old child. Our fifth paper is a different example of a biomedical application; a study on the influence of fibronectin patterns on shape and direction of cells seeded on SL- fabricated patterned PEG-based hydrogels.

From being the only rapid prototyping technique around, SL has now become one of many. Each technique has its specific pros and cons. Particular disadvantages of SL are the limited range of available materials (one needs a photo-curable resin) and high costs. The last few years have seen the introduction of many low-cost additive manufacturing setups, mainly based on fused deposition modelling. With this evolution, a large audience of non-professional users and developers has become involved. It is now possible to order a kit for 1 to 2 thousand US dollars and build your own 'Fabber' at home. This 'democratisation of manufacturing' is said to cause a revolution similar to the introduction of the personal computer (Harouni, 2011). Stereolithography is perhaps too costly and complex to be part of this development, although attempts are made to miniaturise and simplify the setups for this technique as well (Stadlmann, 2011). For high-end applications in industry and research, the relative importance of SL in the field of AM is decreasing as more techniques become available. However, in comparison to other techniques, SL is still particularly versatile with respect to the freedom of designing structures, and the scales and resolutions at which these can be built: sub-micron sized structures as well as decimetre-sized objects have been fabricated. For this reason it can be expected that SL will remain on the AM scene for decades to come, and will remain indispensable to many designers, product developers, surgeons, dentists and of course researchers from whom we are expecting many more papers on further development and application of this wonderful technique.

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