RECENT E-MANUFACTURING SOLUTIONS DEVELOPED BY EOS

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ABSTRACT

e-Manufacturing means the fast, flexible and cost-effective production of parts directly from electronic data, which can include rapid prototyping, rapid tooling, (spare) parts on demand etc. Especially interesting is the direct manufacture of end-use parts. In this paper, recent case studies will be presented showing commercial e-Manufacturing projects including small production batches and mass customized series production from various industrial branches. The paper also discusses the relevance of several recent technological innovations in laser-sintering for e-Manufacturing, especially how increasing the productivity of machines and process chains has increased the range of applications which are cost-effective using laser-sintering.

Case studies include:

- small series production (up to a few thousand p.a.) of products
- production of customized (one-off) products
- mass production of customer-specific (mass customized) products
- optimized tooling concepts for production of up to millions of products

Keywords: e-Manufacturing, rapid manufacturing, laser-sintering, DMLS, series production

1. INTRODUCTION

As previously reported [1, 2], laser-sintering technologies have developed from originally being applied principally to rapid prototyping (RP), to being methods for batch size adapted manufacturing in all phases of the product life cycle, i.e. including prototyping, production and even spare parts. Of course laser-sintering can also be used to create products which do not have a conventional life cycle, for example one-off parts such as a special fixture, a scientific apparatus or a unique work of art, which may not even have been through a prototyping stage. And the range of applications is also not limited to "products" in the conventional sense. Laser-sintering can also be used to produce parts which are neither prototypes nor intended to be sold, for example a visualization model from medical scan data of a skull to help a surgeon plan a complicated operation, or a model of a complex molecule to help scientists.

To cover the wide range of applications described above, a term should be used which is not limited to a particular kind of application, such as prototyping, or a particular reason for use, such as rapid. We favour the term e-Manufacturing, which we define as:

> *"Fast, flexible and cost-effective production of parts directly from electronic data".*

In 2002, Junior [1] summarized the state of the art in the various laser-sintering technologies with reference to real-life examples and including a detailed discussion of how to overcome barriers and exploit the opportunities of e-Manufacturing. Already in 2003, increasing numbers of reported case studies [2, 3, and 4] showed that e-Manufacturing was making inroads into various manufacturing sectors. A broadening of the use of e-Manufacturing for end-use products continues to be observed, with more examples being reported each year [5, 6]. This paper updates the publications mentioned above by adding some new examples of industrial use and also reporting the latest technological advances.

2. ECONOMIC SMALL SERIES PRODUCTION BY DIRECT PLASTIC LASER-SINTERING

Many products are required in relatively low production quantities, e.g. a few thousand, a few hundred or even less, right down to one-offs (see next section). However until now, this has almost always resulted in very high unit costs due to the lack of production methods which are economic for small quantities. Therefore such low-volume series production has normally been reserved for niche products where a very high price can be accepted or justified, and in many cases good product ideas have had to be abandoned because they were not economically viable due to the small expected sales volume. The arrival of e-Manufacturing is fundamentally changing the product planning paradigm by offering a means to produce such products in an economically viable way. A project performed recently by Tecnologia & Design in Italy illustrates well how e-Manufacturing with laser-sintering can be beneficially applied to producing such small production runs, in this case a limited edition of designer sunglasses (Fig. 1).

The main components of sunglasses are the frame and the lenses. Lenses are available as standard items in a wide range of styles, so the main determining factor for a new model is the frame. A high-value limited edition product demands high quality, e.g. should be robust, but also needs high aesthetic appeal to be commercially successful. By using laser-sintering in this project, it was not only possible to produce such a high-quality product economically at low volume, but also to integrate an unusual and appealing design which would have been difficult and costly to produce conventionally – the cut-outs at the sides of the main frame which would have required additional sliders if produced via tooling.


Figure 1: Limited edition sunglasses with frames manufactured by laser-sintering

The plastic parts were produced by direct laser-sintering on an EOSINT P 380 system with PA 2200 (nylon 12) as series material. After removing the parts from the powder bed (Fig. 2), they were polished by abrasive tumbling, a fully automatic process which resulted in very smooth surfaces while retaining the

Figure 2: A frame immediately after the laser-sintering process.

Figure 3: Example of quality control – mechanical testing.

required dimensional tolerances. The polished parts could then be coated using a water-transfer foil method, the same process as used for the conventional production, to create a designer-quality surface in a variety of colours and patterns. Standard optical-grade lenses were then added. The finished article (Fig. 1) is indistinguishable from products manufactured by conventional methods. The mechanical properties of the completed sunglasses were tested using conventional test equipment and routines, including a tensile testing (Fig. 3), to confirm that they fulfilled all the requirements of a series product.

Tecnologia & Design also analysed the production economics and compared them to the conventional route via injection moulding. The economic analysis showed that the break-even point in terms of costs was a quantity of 1000 in this case, i.e. for smaller quantities laser-sintering is cheaper and for higher quantities it would be cheaper to produce tooling for injection moulding. The cost for producing a batch of 500 via laser-sintering was €7,695, corresponding to a unit cost of approximately €15. A similar analysis of the time requirements showed that by using laser-sintering with a single EOSINT P 380 system, the limited edition of 500 sunglasses could be produced via laser-sintering in 31 days, whereas with injection moulding this would need 62 days, the vast majority of which is for tooling design and production. In terms of time to market, i.e. the time needed to complete the first sellable product, the advantage was even greater: just 16 days for e-

Figure 4: Ski boot buckles manufactured in polyamide by laser-sintering

Manufacturing compared to 47 days for conventional production. Of course if the e-Manufacturing route is chosen, then this also offers many other benefits such as production flexibility, possibility to modify the design without additional costs, etc. A detailed discussion is given in reference [4].

In another similar project, Tecnologia & Design produced a small production run of buckles for a new ski boot (Fig. 4). Such products are typically initially required as a production quantity of just a few hundred for the professional version, before deciding whether to introduce a large volume of a consumer version for the following season. In this project, the cost break-even point compared to injection moulding was about 600 sets, and the total production time for a batch of 600 buckles was 27 days for laser-sintering compared to 65 days for injection moulding.

3. PRODUCTION OF CUSTOMIZED (ONE-OFF) PRODUCTS BY PLASTIC LASER-SINTERING AND DIRECT METAL LASER-SINTERING (DMLS)

There are also many cases where extremely small production quantities, down to one-offs, are required. In these cases the arguments discussed above regarding the economics of low-volume production apply even more. Examples of products which have justified one-off production so far include tailor-made clothing for astronauts or Formula 1 drivers; equipment for surgeons which can save valuable hours or minutes of operating theatre time; specialised equipment for plants with high running costs such as power stations or oil platforms; and of course exclusive luxury goods targeted at wealthy purchasers.

The Belgian company Freedom of Creation is using EOSINT technology to create novel and individualized designer products including lighting, timepieces and fashion accessories [3]. Some examples are shown in Fig. 5. By using laser-sintering when creating lighting products, for example, it is possible to create effects that are impossible when using other techniques. These lamps have already been commercialized as high value, limited edition products, and could of course also be personalized. The ability to design fabrics from digital data means that clothing and similar products can be created fully automatically without any need for cutting, sewing etc. The fashion garment shown demonstrates the potential for creating exclusive designer clothing and accessories, but there could also be many other areas of application. Such fabrics can also be built in metal using direct metal laser-

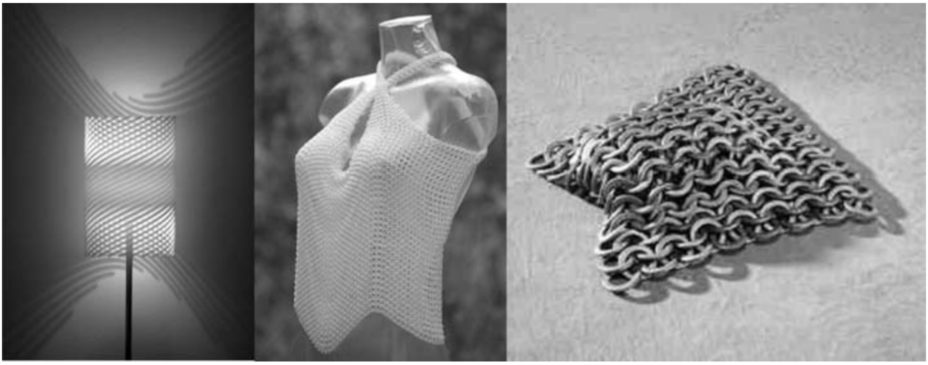

Figure 5: Examples of laser-sintered products from Freedom of Creation: (left) lampshade, (middle) clothing, (right) close-up of metal fabric produced by DMLS

sintering (DMLS), as shown, which opens up possibilities for protective clothing such as gloves, or perhaps for other industrial requirements such as electro-magnetic shielding.

Figure 6: Housing for a dental camera: (left) the product in use, (middle) the original production parts made from sheet metal, (right) the e-Manufacturing version made by direct metal laser-sintering (DMLS).

Potential applications areas for manufacturing final products with DMLS have also been investigated in a European project. One application investigated for the Finnish manufacturer of dental products, Planmeca, was the feasibility of producing housings for a dental camera (Fig. 6). The original motivation for this particular investigation was that the tooling for the conventional stamped and welded sheet-metal housings was wearing out, but that the product was nearing the end of its life cycle. The idea was therefore to investigate e-Manufacturing as a way to produce a relatively small quantity of series parts to avoid the costs of new tooling, which would be difficult to recover from the low remaining sales volume. To test the technical feasibility, the two parts of the housing were built by DMLS using an EOSINT M 250 Xtended system and were post-processed by polishing (upper right picture) and matt nickel coating (lower right picture). This worked well, and the product name was incorporated directly in the housing to demonstrate an additional advantage. The only technical disadvantage was that the wall thickness had to be higher, resulting in a heavier product. However with recent improvements in DMLS technology it is now possible to build thinner walls [7]. Although the costs could not be analysed in this project due to missing data, it is unlikely that DMLS would be an economically viable production method for e.g. hundreds of such parts. However it does offer significant potential for customized products. To demonstrate this, a second "ergonomic" housing was designed and built with the external geometry modified to include indentations for where the camera is gripped (see left picture). In the case of very specialized products, e.g. equipment for surgery, it may well be worth paying an additional price for a device which was tailored to the hand of the surgeon, in order to improve the speed or quality of his work. It was also noted that the internal electronics in products such as this are often changed during the product lifetime, typically requiring modifications to the internal fixture elements, and that such design changes could be made with minimal cost and effort using e-Manufacturing. Also, the internal fixtures can be integrated in the laser-sintered parts, whereas they conventionally require additional manufacturing steps.

Due to the higher process costs, DMLS is today generally only economically suitable for manufacturing relatively small quantities of small parts. However parts up to 250 mm in size have successfully been built and tested in several applications such as complex housings and turbo machinery [5]. Also, commercial projects with economic production batches of up to 900 metal parts have been reported [4].

4. MASS PRODUCTION OF CUSTOMER-SPECIFIC PRODUCTS

Phonak Hearing Systems is one of the top three developers and manufacturers of hearing systems worldwide. In 2000, Phonak started a collaborative project with Siemens to develop improved ways of manufacturing in-the-ear (ITE) hearing aids. These devices contain highly sophisticated digital sound processing electronics, yet are small enough to fit inside the ear and be hardly noticeable. The electronics are contained within a plastic shell, which has to fulfil very demanding requirements, e.g.

- high accuracy and feature detail to sit well in the ear
- thin walls to leave space for the electronics
- bio-compatibility, i.e. safe for contact with human skin
- has to survive the harsh environment of the human body (grease, sweat etc.) for many years without degradation.

Conventionally these shells are manufactured by taking a wax impression of the patient's inner ear, forming a flexible mould around it and casting UV-curable acrylic resin into the mould. This is time-consuming manual work with many potential sources of error, and if anything goes wrong so that the shell does not fit perfectly, then the whole process has to be started again. Therefore there was a high potential and need for improvement. Phonak identified the possibility to optimize this process by directly laser-sintering the shells, and has developed a corresponding process chain [3]. Today the wax impressions are optically scanned, the digitized data are converted into a virtual shell to fit both the patient and the electronics, and the shells are then laser-sintered on an EOSINT P 380 system using specially pigmented (skin-coloured) PA 2200 material (Fig. 7). The resulting product is called e-Shell™.

In order to implement this process chain for commercial production, the laser-sintered shells had to undergo an intensive material qualification including biological testing, mechanical properties, accelerated life testing (humidity, temperature cycling, sweat exposure, UV light exposure etc.) and field trials. All these tests were passed so the process chain could be implemented, but Phonak has also done a lot more work to optimize the process. They now build up to three levels of shells per job, each level containing 60-120 shells ranging in size from 10 x 10 x 15 mm to 30 x 30 x 25 mm. The powder layer thickness is 100 µm and the shell wall thickness 0.6 mm. To monitor and ensure process reliability, five specially designed control parts are

Figure 7: Optimized manufacture of in-the-ear hearing aids: (a) digitized virtual shell, (b) laser-sintering on EOSINT P 380, (c) laser-sintered shell, (d) final product in ear

included in the centre and corners of each shell level and are evaluated for statistical process control. The results show that the 6 sigma spread of the most critical dimension (10mm) is within ± 0.1mm and that the whole part platform area can be used without restriction.

In addition to the expected advantages of producing the e-Shells by e-Manufacturing, the optimized process chain has produced a number of further benefits. First, results of market surveys showed that users preferred the laser-sintered shells to the earlier version. It was found that the satin-like textured surface held better in the ear and produced fewer problems with sweat than a shiny surface. In fact, the e-Shells scored at least as well as a comparison group of satisfied customers of UV-cured shells in all categories, and scored significantly better regarding security in ear, long-term comfort, lack of acoustical feedback and general satisfaction. In other words, changing to laser-sintering improved the quality and perceived value of the product from a customer's point of view. Together with the improved accuracy and mechanical properties, this meant that the level of returns was significantly lower. And even in cases of loss or damage, a replacement shell can be made very quickly and easily because all the necessary data are already stored in a database.

5. ECONOMIC SERIES PRODUCTION VIA TOOLING

Beyond the examples described above, there are of course still very many cases where direct series production by laser-sintering is not acceptable, for example due to part size, economies of scale or material requirements. In most of these cases, a tooling-based production route remains the best option at present. Many of these situations however can benefit from the application of e-Manufacturing with laser-sintering. A good example of such a case was performed recently by the service provider FIT GmbH of Parsberg, Germany, for their customer Hamm in Tirschenreuth [5]. Hamm required the production of an innovative new joystick steering system for use in construction vehicles (Fig. 8). The required production quantity for this niche application is typically a few thousand parts, and in this case it was 5,000. The joystick was an assembly comprising 15 plastic parts plus various other electronic, mechanical and switching components, so had high accuracy requirement due to the assembly tolerances, and also had to provide highest reliability for up to 20 years of utilization under demanding construction site conditions. In addition, there was high time pressure as the new product was intended to be launched at a trade show in just six weeks time. FIT GmbH won the production order by being the only supplier who was able to guarantee the

Figure 8: The "HI-Drive" joystick and an example of a vehicle in which it is used

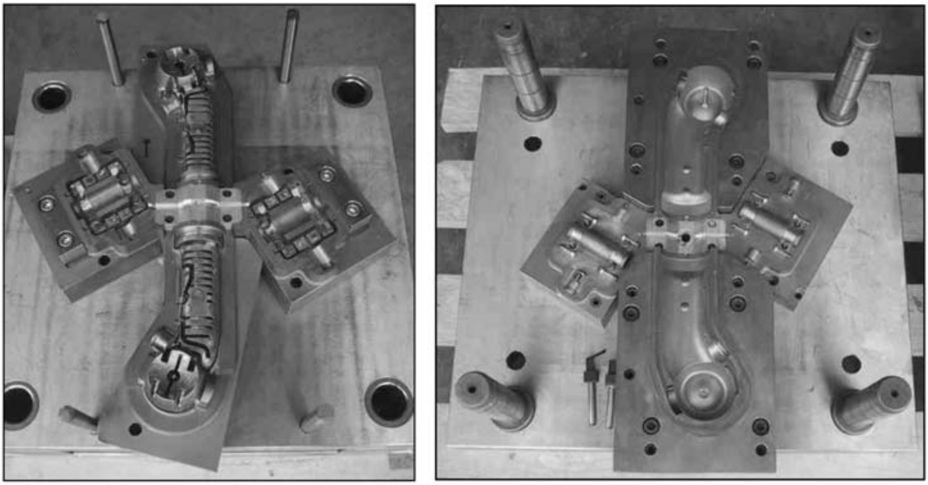

Figure 9: One of the injection moulds containing eight laser-sintered tool "onserts"

production run of 5,000 injection moulded parts, in some cases 10,000 for doubled components, within the six weeks demanded (the next best offer was 16 weeks), and also at a price approximately 50% lower than that of the cheapest competitor, who offered conventional tooling. This was only possible by the optimized application of e-Manufacturing technologies.

For the production of one of the plastic parts, FIT used a direct production via EOSINT P with polyamide material, similar to the projects described above. For the other 14 components, injection moulding in PA 6.6 GF30 was required. For these cases, FIT built the tooling using DMLS on an EOSINT M 250 Xtended system. To be able to produce the complete tooling for 14 parts within just a few weeks, it was necessary to optimize both the tooling concept and the workflow. The concept used is illustrated by the injection mould shown in Fig. 9. It is a four-cavity mould containing the left- and right-hand cavities for two of the parts. Each cavity has been designed so that a minimum volume of material had to be laser-sintered; indeed the total volume for all tools in the project was just 3.1 litres. To minimize geometric restrictions, work steps and tooling components, the cavities have been mounted directly onto the tooling plates instead of inserting them into machined pockets – FIT calls these "onserts" as opposed to "inserts". Two potential risks of this approach have been compensated by other measures: (i) simple steel blocks have been screwed on as reinforcement in critical areas where thin laser-sintered walls would otherwise have to hold the full injection pressure, and (ii) the four cavities have been arranged in a symmetrical cross-formation to avoid the mould opening due to uneven forces. Using this approach, the entire tooling could be produced on a single EOSINT M 250 Xtended machine in just 290 hours total build time. Machining was only needed for the reinforcing blocks and for some small pins etc. with regular geometries which were inserted into the laser-sintered tooling.

In fact, the customer made several changes to the part designs after the project had started, which caused 3 weeks delay in the project, but with the help of their rapid prototyping technologies FIT was still able to provide Hamm with all the parts necessary for the product launch at the trade show. And the entire production batch was still provided in record time and without any quality problems.

6. THE EFFECT OF IMPROVEMENTS IN LASER-SINTERING TECHNOLOGY

The case studies described above clearly show that there has been a trend in recent years from prototyping towards end-use parts and batch production. This trend has been enabled and supported by continuous innovation to improve the performance of laser-sintering technologies in several key areas.

An important success factor for producing end-use parts directly with laser-sintering is the material properties. Over the years both the plastic and metal materials have been significantly improved so that, for example, parts built in today's PA 2200 polyamide material have mechanical properties comparable to and in some cases better than injection moulded PA12 or ABS. Metal parts in DirectSteel H20 can have a tensile strength of up to 1,100 MPa and a hardness of more than 40 Rockwell C. At the same time the accuracy and surface finish of the parts has been greatly improved. The introduction in 1999 of fine metal powders for building DMLS parts in 20 micron layer thickness represented a real breakthrough for this application [8].

There has also been a trend towards larger build envelopes. This started already in 1995 with the twin-laser EOSINT S 700, which was designed with a process chamber large enough to build moulds and cores for 4- and 6-cylinder engine components. In the meantime a twin-laser system for plastic laser-sintering was also introduced: the EOSINT P 700, which has a build volume diagonal of one metre. Larger build envelope means not only the possibility to build larger parts, but also that more parts can be built in one job. In a full load, an EOSINT P 700 can manufacture about 150 pieces with a size of about 100 mm x 100 mm x 100 mm. The same load can hold almost 20,000 pieces with a size of 20 mm x 20 mm x 20 mm, or more than 150,000 pieces with a size of 10 mm x 10 mm x 10 mm.

Especially when considering larger parts or batch production, the system productivity is a critical factor, and this has been improved in various ways. The EOSINT S 750 system achieves typically 80% higher productivity than its predecessor by using higher power (100W) lasers and a dual focus technology. The EOSINT P 380 system also achieves 100% or more productivity improvement compared to the original EOSINT P 350 by using optimized thermal management and laser exposure strategies. The new EOSINT M 270 system uses a shorter wavelength laser beam with dual focus and faster mechanics to accelerate the building process [7]. Productivity can also be increased by fitting more parts into each build job, and EOS has introduced a software package called EOSPACE to optimize the packing density of parts in an automated way.

The time and cost of producing parts depends not only on the build speed in the machine, but also on the efficiency of the other steps in the process chain. EOS has developed Integrated Process Chain Management (IPCM) systems for EOSINT P and S systems which include peripheral devices for removing laser-sintered parts from the powder bed, recycling unused powder back into the machine and other handling steps. Both these systems also build the parts in an exchangeable frame to enable fast turnaround time between jobs, which also increases total productivity.

7. SUMMARY AND DISCUSSION

The examples given in this paper show that e-Manufacturing is already being used successfully for production of end-use parts in a variety of applications. It is to be expected that the number and range of suitable applications will continue to expand.

An important driving force for this trend is the factor "cost per part". There are general market trends towards increased numbers of product variants and also shorter product lifetimes, which result in smaller numbers of pieces required per variant, i.e. lower production quantities. e-Manufacturing has a natural advantage in this situation, and the ongoing improvement in the productivity of laser-sintering systems and process chains means that the break-even points are continuously improving, i.e. the quantities are increasing for which e-Manufacturing of a given geometry is more economical than conventional production.

Material properties continue to be a limiting factor for the spread of e-Manufacturing, but the range and the properties of available laser-sintering materials is continuously improving. In future there will be new and improved plastic and metal materials, for example with higher strength, elasticity and/or toughness. Also there will be more and automated post-processing methods, for example for smoothing or coating laser-sintered parts, so that specific textures and patterns can be achieved.

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