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BASIC CONCEPTS, APPLICATIONS AND POSSIBILITIES OF ADDITIVE MANUFACTURING TECHNOLOGIES

(Introductory article)

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Abstract: *This paper presents an introduction to additive manufacturing technologies. It describes concepts, principles, technologies, limitations and application of additive manufacturing. Classic manufacturing technologies, based on subtraction or deformation of material are already completely defined from the point of view of concepts and applications. Further development of the classic manufacturing technologies is focused on research of principles and technologies. On the other hand, additive manufacturing technologies represent new and exciting field of manufacturing which is still defining its concepts and finding new applications. High level of automation of the additive manufacturing process and lack of need for hardware tools enable manufacturing without form limits and customization of each individual product, with potential for revolution in design process. They have ability to change basic design paradigms and to lead to evolution of new breed of designers which will unite skills, knowledge and functions of industrial and mechanical designers. As it was the case with major developments of production concepts in past, it may eventually have deep social impact, changing organization of product development cycle, marketing, education and other aspects of human life.*

Besides the general discussion about additive manufacturing technologies, the paper also presents concept, organization and resources of Laboratory for reverse engineering and rapid prototyping/manufacturing of Faculty of Mechanical Engineering Kraljevo. It is established during the project "IMPuls", realized within EU funded "Regional Socio Economic Development Programme", as a research and development facility which should provide technical basis for enhancing innovation capacity and competitiveness of small and medium enterprises in the region. The laboratory enables manufacturing of prototypes and products by selective laser sintering, which is nowadays one of the most promising additive manufacturing technologies.

1. What is Additive Manufacturing – Definition/Concept

Additive manufacturing (AM) is common term for several technologies which are capable of translating virtual solid model data into physical model in quick and easy process.

These manufacturing technologies are directly the opposite of what classical methods such as milling, grinding, or drilling, where objects are formed by mechanically removing material. Modern AM concepts are based on automation of the process of material addition, controlled by a computer. These technologies produce three–dimensional objects in an automatic process directly from digital model by the successive addition of materials, without use of specialized tools. 3D object, described by a computer file, is fabricated by a machine which calculates a series of 2D cross sections and joins together hundreds of very thin layers of material, as it is illustrated in the Figure 1. The geometry of the parts is therefore completely reproduced in AM machine without having to adjust for peculiarities of manufacturing processes, like paying attention to tooling, restrictions of undercuts, drafts angles or other features. It can be said that the AM technologies are “What you see is what you built” (WYSIWYB) processes that are particularly valuable for manufacturing objects with complex geometry (Fig. 2). Other names are also used to designate the same set of technologies, like "Solid Freeform Fabrication" (SFF) and "Layered Manufacturing".

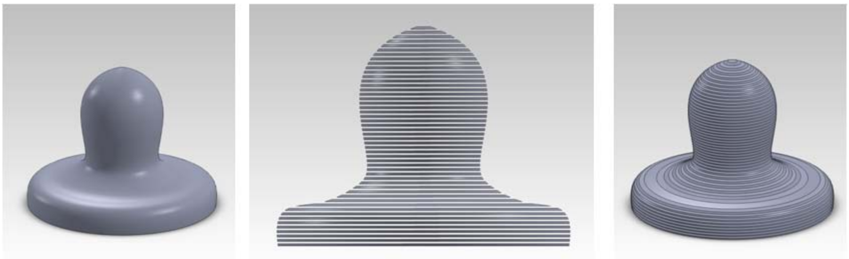


Fig. 1. An object, its layered representation and its layered 3D model

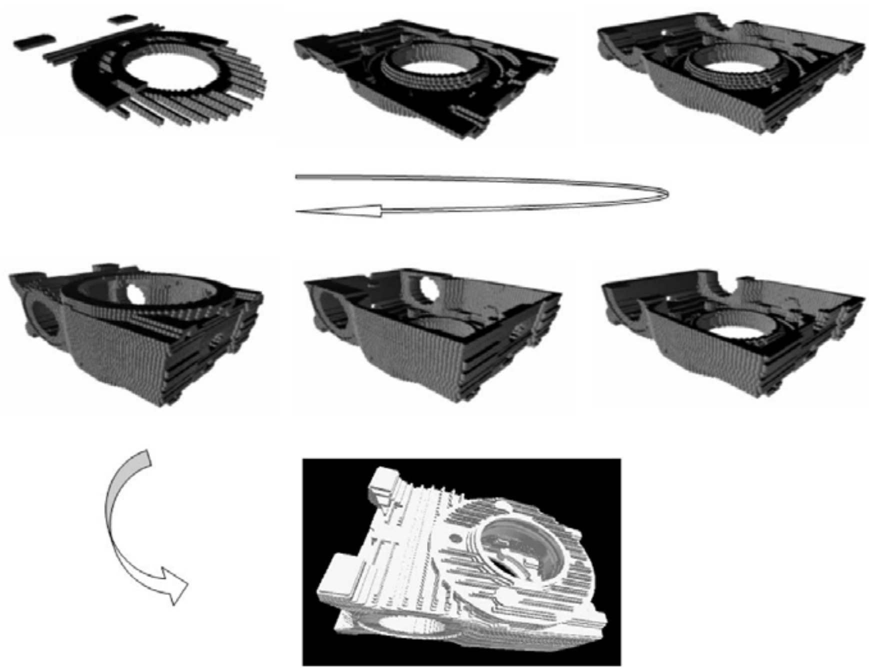


Fig. 2. Typical build process of a gearbox housing [1]

There are several different types of processes, but with a number of common traits:

- All require 3D CAD geometric models;
- Geometries are mostly communicated in STL format (Fig. 3-1);
- The building is carried out layer by layer (Fig. 3-2);

- Dependent on the process, there is usually needed for some finishing operation (Fig. 3-3)

The basic principle drives nearly all AM machines, with variations in each technology in terms of the techniques used for creation of individual layers and in bonding them together. Further variations include range and kind of materials, layer thickness, accuracy, speed and cost.

Fig. 3. Phases of a AM process

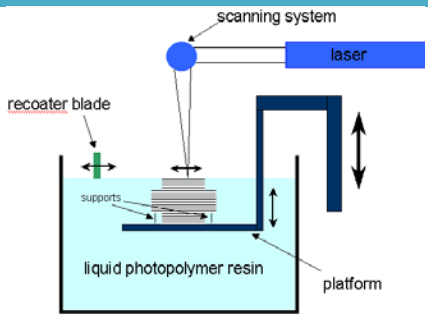
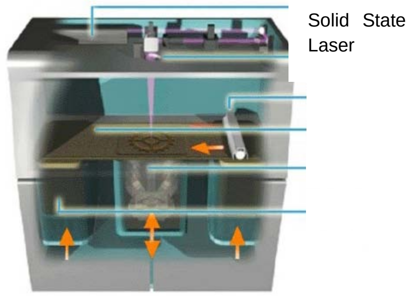
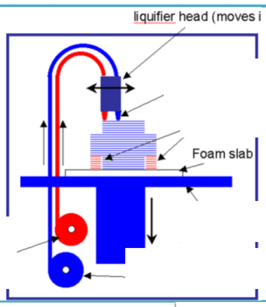
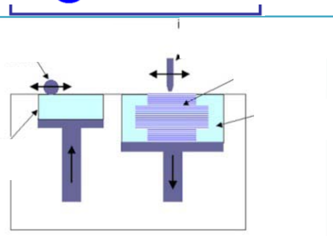
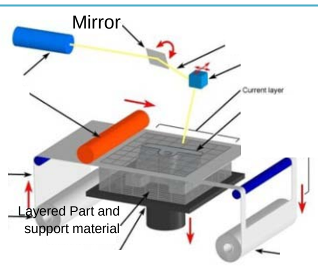
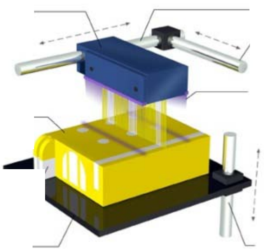
2. Additive manufacturing technologies

The layers may be manufactured by variety of methods (Table 1) from various materials that depend on the method that is used, and the most known are:

- stereolitography (SLA), based on selective curing of liquid polymer exposed to a light beam,
- fused deposition modelling (FDM), based on extrusion and fusion of polymer filaments,
- 3D printing, based on selective application of liquid binder to polymer powder
- laminated object manufacturing (LOM), based on joining of stacked paper cut-outs
- A special group of AM technologies represent technologies based on fusion of powder particles selectively melted by electron beam (Electron beam melting−EBM) or
- on selective sintering of powder particles by laser beam (SLS), which is going to be used in „3D Impuls“ laboratory of FME Kraljevo.

These new techniques allow to manufacture complex geometric objects (nested polyhedra, projections of polytopes) without the need of tedious final assemblage. These methods are generally similar to each other in that they add and bond materials in layerwise-fashion to form objects.

Table 1. Some basic AM technologies

PROCESS	PRINCIPLE	MATERIAL	BILDING PROCESS	COMMERCIALLY SYSTEMS
SLA		Liquid Polimer	Selective curing by exposure to light	3D Systems
SLS		Powder	Selective fusing by the heat of a laser	EOS, 3D Systems
FDM		Polymer Filament	Extrusion and fusion of filaments	Stratasys
3D Printing		Powder	Selective application of liquid binder	Z Corporation-3D Systems
LOM		Sheet Material	Sheet Material	Helisys (out of business since 1999)
Inkjet/ Polyjet		Photo-polymer	Layer-wise “Printing” of droplets	3D Systems, Object

3. Application areas

Additive manufacturing technologies are applied (as it is shown in Fig. 4) for production of concept models, functional prototypes, manufacturing tools and end-use parts. With respect to these primary applications, many of the technologies are frequently called by the names of specific applications such as rapid prototyping (RP), rapid tooling (RT) or rapid manufacturing (RM).

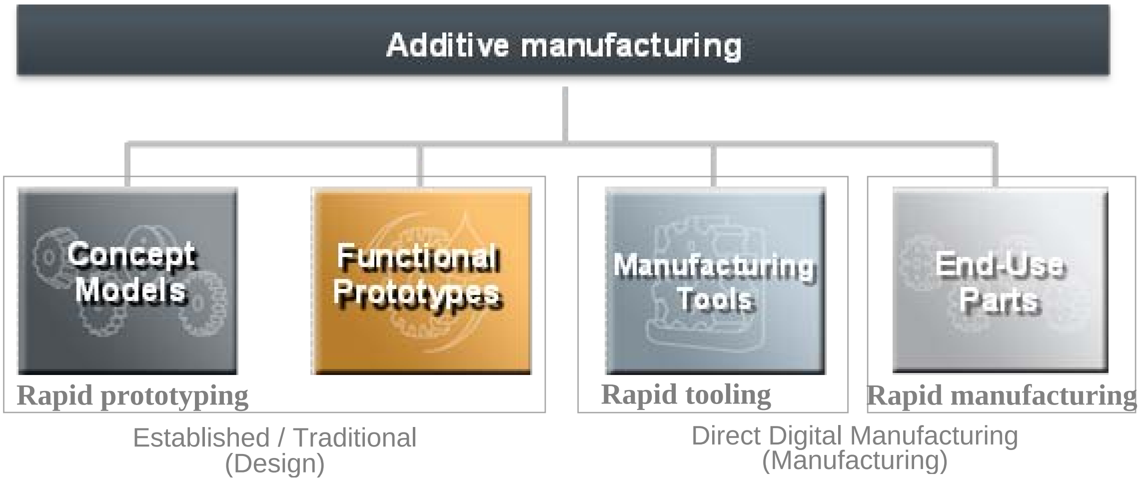


Fig. 4. Primary applications of AM technologies

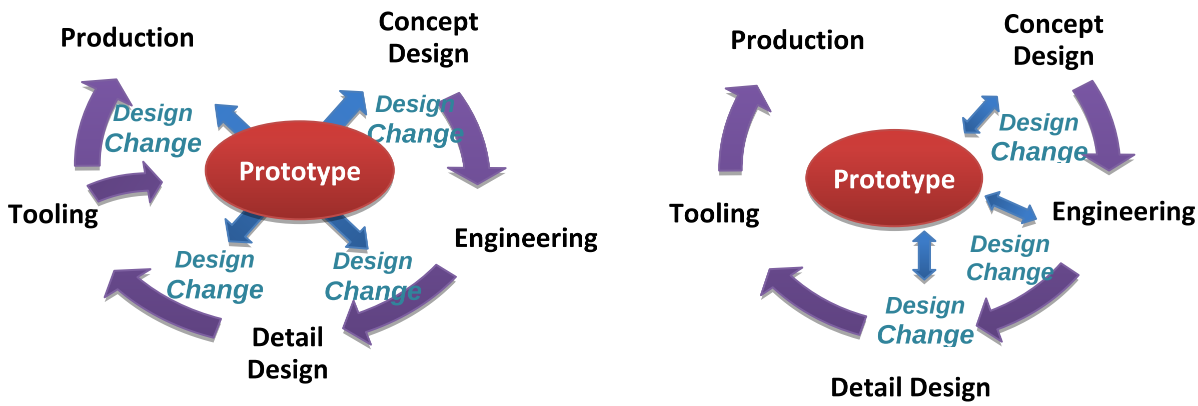


Fig. 5. Typical Design Cycle (left) and Ideal Design Cycle (right)

Possibility of application of these technologies directly changes design cycle of a new product (Fig. 5.). Additive manufacturing may be used in all phases of a product life cycle. In the phase of product development (design), AM is used for rapid prototyping, because it does not need any additional tool for production of a prototype. Implementation of rapid prototyping at the earliest stages of development of new products (RP) allows early detection of design errors and reduces late design changes without the need for expensive tool making. Furthermore, functional prototypes, which may be manufactured by some RP technologies, allow testing of parts. Due to the early availability of prototypes, application of RP enables that design changes take place only during the phases of concept design, engineering and detail design. On the other hand, without the application of RP, in the typical case, design changes occur during the whole design cycle, as it is shown in the Fig. 5. Therefore, application of RP substantially reduces time and costs of development of new and improved products.

In the phase of production, AM may be used as a tool for production of molds and complex tools (these application are known also as rapid casting−RC and rapid tooling−RT), because RT leads to cost and/or time saving during the complex tool production. Besides, AM does not put limitations on the shape of the manufactures objects, so tools manufactured by RT technologies may be optimized with the respect to their further application. For example, for large series production, any savings in the production of plastics parts can justify even increased costs in tool production; Direct metal laser sintering (DMLS) enables manufacturing of tools with highly complex external and internal geometries, with the cooling channels positioned along the complex surfaces of tools; the result is efficient cooling and increased productivity and reduction of costs per part. For example, with conventional machining, cooling channels are added into a tool by drilling, which restricts the cooling design to combinations of straight lines. With DMLS, both positions and shapes of cooling channels can be designed in a free-form way. Many studies and examples (Fig. 6) have demonstrated the benefits of optimized cooling. Theoretical and practical investigations by PEP [2] have shown reductions of mold temperature and reduction of cycle time. Cycle time can be reduced from 40-60 % by using Direct Tool (rapid tooling) with optimized cooling [3].

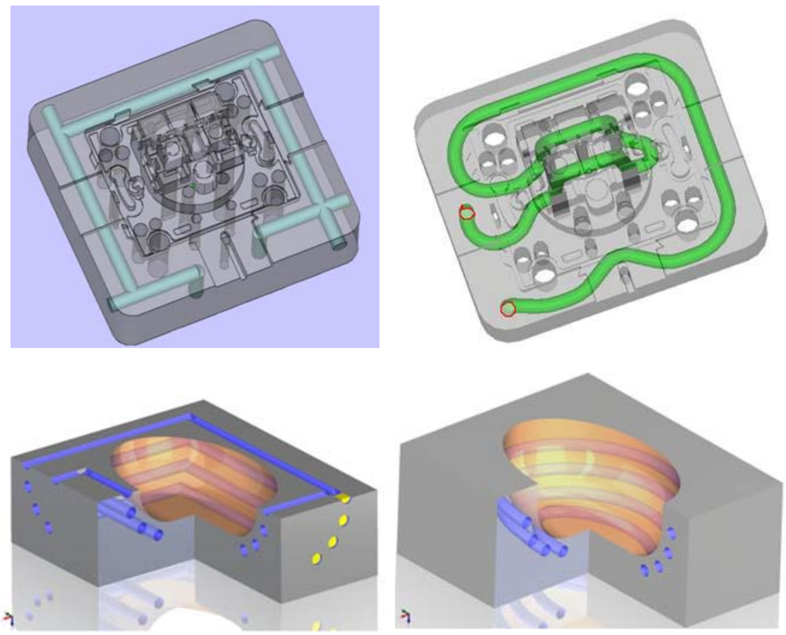


Fig. 6. Advanced tooling for improving tool performance: conventionally drilled cooling channels (left), optimized conformal cooling by DMLS (right) [6]

The most intriguing opportunity for application of AM lies in possibility of direct production of products by AM, so called rapid manufacturing–RM. RM is attractive because it offers:

- unlimited freedom in design of shape,
- unlimited possibilities for customized design,
- usage of the same equipment for large number of different products, that may be even manufactured on the same machine simultaneously.

Therefore, rapid manufacturing is an ideal choice for small series of products, highly customized products, representing powerful tool for innovative companies. Benefits of RM application are: decreased cycle time, decreased time to market, freedom of design, easy product redesign, and rapid response on market needs.

However, rapid manufacturing is still on the verge between development and application. The problems in application of RM depend on the considered technology, but six general problems of RM may be outlined:

1. reduced set of materials that may be processed by RM technologies
2. dimensions of parts are limited to comparatively small volumes
3. inverse dependence between surface quality and production speed of a component
4. lack of full set of design rules for optimizations of product design for RM
5. long time needed for design of 3D model of complex surfaces
6. high costs of the equipment

The first and the second problems are tackled by manufacturers of RM equipment and experts in RM technologies. The third problem is solved by combination of post-processing of products manufactured by RM and optimization of production parameters for desired production time and quality.

The solution of the fourth and fifth problems of RM requires multi-disciplinary approach because their solution requires collaboration of experts in industrial design, mechanical design, 3D scanning, reverse engineering, wide range of physical processes employed for formation of individual layers and their joining in course of RM, but also professionals with trans-disciplinary background, capable of understanding of both technological limitations and engineering requests and successfully mitigating their contradictions.

4. Wider social impact of additive manufacturing

Human society and human history are driven by their ability to manufacture. Either it was for introduction of new production materials in pre-history, or machines that replaced human work during industrial revolution or production concept such as assembly line, each significant change in manufacturing concepts reflected in history of human society. Rapid manufacturing has such a potential for change, because AM is not manufacturing concept for production volume. AM is manufacturing concept for variability of production.

Wider application of additive manufacturing technologies can substantially change concept of manufacturing. The AM concept, when equipped with rules for design by respective AM technologies as is the case with SLS technologies, for example, enables a new division of work, in which companies would specialize either in design or manufacturing, because AM manufacturing technologies do not depend on complexity of the manufactured product.

Machines for SLS are expensive in comparison with machines and tools for classical manufacturing processes, but the concept of their work, the ability to be used without limitation by design of the product, provides competitive advantage to innovative companies, that rely on new, improved and customized products in contests on their respective markets. Application of AM in general restores focus on product design and product properties, and not on the process of their manufacturing. AM provides possibility for development of culture of highly-customized products, that would revitalize values of individual mastery of designer, and not anymore of low average cost of mass production. On one side, such a culture would request large number of designers to respond to needs of market, opening the need for skilled and creative human work that vanished with culture of mass production, automation and robots. On the other hand, such a culture would favor values of talent, imagination and education, values that each modern society wishes to preserve and promote.

5. "3D IMPuls" -laboratory for Additive Manufacturing and Reverse Engineering of FME Kraljevo

Inspired by experiences and examples of good practice met during staff exchange with University in Bologna, teachers and researchers from Faculty of Mechanical Engineering Kraljevo established Laboratory for Additive Manufacturing and Reverse Engineering, which is also known by its trade name "3D IMPuls".

The Laboratory is established with four main goals:

- to provide services of RP, RT and RM to industry, to companies dealing with design, research and development, as well as to universities in surroundings of the Faculty;
- research work in the field of AM;
- promotion of AM technologies
- education of engineers and students for application of AM technologies.

The Laboratory also provides services and education in field of reverse engineering as a complementary knowledge to AM technologies. However, the Laboratory at present does not deal with promotion and research work in reverse engineering.

The Laboratory is established with the idea to become common research and development center of numerous small and medium companies dealing with metal and plastics. The companies do not have capacity to implement modern product design methodologies, which reduces their competitiveness. Therefore, there is interest for the modern design technologies, but its application is justified only if all of the companies use common facilities. University is natural choice for establishment of the common center because of availability of skilled personnel, unbiased market position and possibility to provide variety of funding sources for multitude of envisioned functions of the Laboratory. The chamber of commerce and industry unions, as well as the local governments, supported the concept and it is implemented through the Laboratory from the very beginning.

The equipment of the Laboratory consists at the moment of the machines for AM of metal and plastic parts by SLS technologies. The choice is performed because of the fact that SLS technology has capability to support all of the AM applications (RP, RT and RM). Besides, the SLS technology is capable for both metal and plastic processing. Variety of applications and materials was the request of the local industry, due to the fact that in this concept of the Laboratory, customer pool consists of large number of small and medium sized enterprises.

The machine for manufacturing of metal parts is EOS INT M280 (Fig. 7a). It is capable of manufacturing parts from steel, stainless steel, aluminum and titanium. The thickness of a layer depends on the material and varies between 20μm and 80μm, while the building speed, proportional to the material thickness varies between $2mm^3$/hour and $8mm^3$/hour. The dimensions of the building volume, which represent upper limits of the manufactured parts, are 250mm x 250mm x 325mm.

a) b)

Fig. 7. SLS machines in the “3D IMPuls” laboratory: a) EOS INT M280 b) EOS FORMIGA P 100

The machine for manufacturing of plastic parts is EOS FORMIGA P100 (Fig. 7b). It is capable of manufacturing parts from polyamide P2200, glass reinforced polyamide and, for RT purposes, polystyrene. The thickness of a layer is 0.1 mm, while the building speed varies between 1cm/hour and 2cm/hour. The dimensions of the building volume are 200mm x 250mm x 330mm.

For the purposes of reverse engineering the Laboratory has 3D scanner Atos Compact Scan 5M. The instrument enables digitalization, dimension measurement and inspection of objects. The working volumes vary between 40mm x 30mm x 20mm and 1200mm x 900mm x 900mm, with working distances varying between 450mm and 1200mm. Depending on the working volume, the 3D scanner has resolution 0.017 mm and 0.0481 mm.

The laboratory has separate premises for manufacturing of plastic parts, metal parts and for reverse engineering, but it also has advanced capabilities and whole range of modern presentation equipment for education and training, ranging from interactive work with small groups to promotion lectures for wide public.

The establishment of the Laboratory required substantial funding which was achieved by combining several international, national and local funds. The largest part of funding was provided by European Commission through the project “Innovative Management for New Products”, which was carried out within the framework of RSEDP2 programme by Faculty of Mechanical Engineering Kraljevo, DIEM department of University of Bologna, City of Kraljevo, Regional Chamber of Commerce Kraljevo and Center for Development of Small and Medium Enterprises from Kruševac. The budget of the project was around one million EUR and it provided the AM machines and 3D scanner, as well as support to training of personnel and promotion of the technology through development of 300 CAD models and manufacturing of 100 prototypes and products for SMEs in surroundings of Kraljevo. Education facilities and furniture were provided by non–government organizations "USAID Serbia" and "Initiative for Local Development" through the project “Procurement of the multimedia and other equipment serving IMC area of Kraljevo”. Additional funding was provided by local governments, City of Kraljevo and City of Čačak, while the laboratories are located within the room built with support of Ministry of Education and Science of Republic of Serbia.

The Laboratory started with work in July 2012, and the first experiences show wide interest from industry. More than three hundred companies from surroundings of Kraljevo showed interest for cooperation with the Laboratory, but the companies from Bosnia, as well universities from Italy expresses immediate interest for its services.

As it was the case during the phase of the establishment of the Laboratory, its further development will be guided by the needs of research and development market. At this moment, besides the SLS parts that have full functionality and high price, the market requests also products of cheaper AM technologies, for the purposes of RP and demonstrations. Therefore, the immediate plans of the Laboratory include provision and application of equipment for RP by 3D printing. Besides, it is noticed that designers do not use full potentials of AM technologies, so the proposals of research projects on development and promotion of design rules for AM technologies are being prepared.

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