3D printers – review of printing clothing, footwear and accessories

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Review

This article describes 3D printers which bring new possibilities to produce articles from different class of materials. 3D printing is applied to wide areas, like medicine, architecture, machines, art, clothing. Those are systems , which not only are used for modelling and prototyping, but also for production of unique parts for individual, regardless we are talking about artificial organs, bones or clothing and footwear. 3D printing is also used for production in small series/batches. With these techniques it is possible to produce items, wich can not be produced in any other way; this is one of the many reasons why there is so fast expansion of this technology. In this article, besides presenting how the technology works, used materials and applied areas, some more space is devoted to production of unique fashion clothing and footwear, as well asof other fashion items.
Key words: *3D printer, three dimensional printing, fast prototyping, clothing printing, footwear printing*

1. Introduction - what is 3D printing

Three dimensional printing is transformation of computer designed 3D model into physical object. This procedure is realized through usage of different forms of 3D printing technologies. Intent is rapid prototyping and rapid manufacturing. Prototypes are used to check shape, dimensions, interference to achieve functionality, ergonomical requirements, to produce samples for client, photo shooting for marketing needs, for different testing etc. Production of objects in small quantities is cost prohibitive when classical production is used [1]. Three dimensional printing is used more and more to produce the final product.

At the beginning the used materials were mostly termoplasts and that's why this period of 3D printing evolution is named "plastic era". Today there are different kinds of materials, like metals and organic materials. In usage are also combined materials where also their properties can be changed during printing process. There is no need to emphasize all possibilities for designers in different branches of human activities, from machine designers, architects, construction engineers, industrial designers, medics and many others, even to pastry makers to find new ways of producing prototypes or unique products for particular client; artificial biological organs, bones, skin, blood vessels ect. The possibilities are infinite,and this is, it could be said, only beginning. The most significant effort is directed toward development of new materials, speeding up the 3D machines, decreasing the surface roughness and price reduction. It is accepted opinion that 3D printers will be common household item and that people will print all kinds of needed objects.

2. 3D printing history

3D printing starts in 1982 with invention of stereolitography, where the objects are created based on digital data using laser and resin as material.

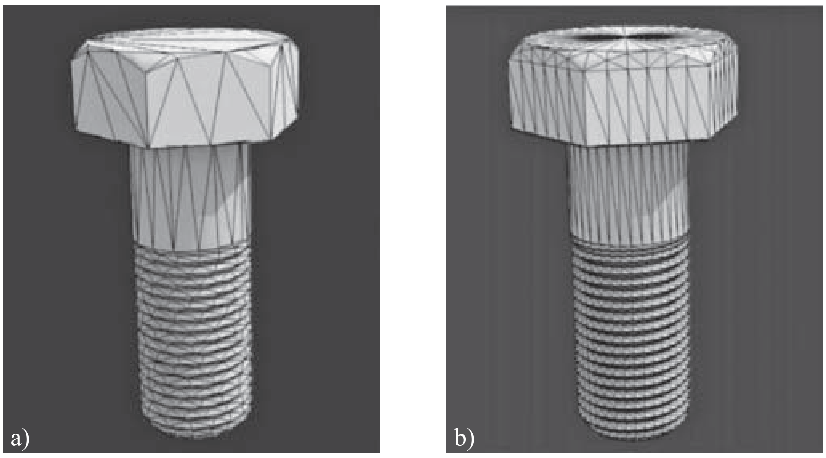

Fig.1 Screw in mesh form for 3D printing: a) mesh with low density, b) mesh with adequate density

First functional 3D printer was introduced in 1984, and worked similarly as ink-jet printer, but instead of ink, it used desirable material. Additional to X and Y axes the Z rotational axes was introduced. Besides high price, printer was too expensive and it had several deficiences. 3D printer history is young; first 3D printer for selective laser sintering (SLS) was invented in 1986., and two years later FDM (Fused deposition modelling) printer was introduced) which used termoplast. In 1995 *ZPrinting* was introduced from company ZCORP, 2005, 3D printer *RepRap* was developed at University of Belfast. Year 2009 is significant for medicine because 3D bioprinter was introduced where it was possible to print bio parts and replacement organs. Some of 3D printing patents expired in 2014. This, significantly contributed to faster expansion of technology, because many smaller companies joined this revolution where also we see many new applications of 3D printing [2, 3].

3. Different printing techniques

3.1. STL program

The object to be printed, first has to be designed with adequate programs for three dimensional creation. Object needs to be represented with set of closed surfaces, which define volume. (I-DEAS, CATIA, Pro/Engineer, Autocad, SolidWorks, Maya, Autodesk Inventor, 3D Studio Max and many others) are used for this purpose. They are selected depending mostly on usage, application domain and price. Another technique to get 3D models is with the usage of 3D scanners.

Standard and widely accepted format for data exchange is STL (*Standard Triangulation Language)* This format was introduced by 3D Systems company in 1989. This is the format, where three dimensional surfaces are approximated with triangles. Modelled object surface is subdivided into series of small planar triangles with orientation, and each of them is called *face*. Triangles are optimally placed to ensure complete coverage of the object surface. All of them create the *mesh.* Mesh needs to be satisfactorily dense to ensure acceptable quality of printed object f4]. Because of the planar quality of faces it is not possible to get ideally curved surfaces [1]. An example of screw is given in Fig.1 [5].

After creation of STL file, another program is used to create layers. All geometries of each layer are described with G-code language (standard to drive CNC machines).

3.2. 3D printers

There are many different kinds of 3D printers. The basic principle of 3D printing is layering where layer after layer is superimposed on each other. During the printing process aggregate state of material is changed from liquid or powder to firm state. Most frequently used techniques are SLS, FDM and SLA. The fundamental difference is in the way how the layers are created [6].

3.2.1. Selective laser sintering – SLS

Selective laser sintering by using laser liquates powder and after cooling produces rigid object. Process depends on material (powder) properties, mostly liquating (sintering) temperature and CO_2 laser power.

The printing starts with preheating near sintering temperature and than the final sintering is achieved with laser. (This method is named *Direct Metal Sintering).* Here are the steps: First layer of powder is established, laser sinters the material, the supporting plate is lowered by layer thickness, new layer of powder is applied and under control of computer the laser sinters the layer. Layers can be thin up to hundred microns. This process is repeated until all layers are sintered and whole object is printed. The movement of lasers ray is achieved with rotating mirror which directs the ray in X and Y plane. After sintering one layer, roller brings another powder layer, Fig.2. This technique has advantage because the powder also supports the complete model and no additional structures or material are not needed. The most frequently used materials are plastic, metal, ceramic and glass.

It is possible to change physical properties of sintered object by changing the density, creating alloy or prolonging the curing (baking) time [7].

Mechanical properties of printed objects with this technique are better than printed objects achieved by (SLA). Residual powder which is not sintered could be reused. Here are some of plastic materials: polyamid (DuraForm PA), polyamid mixed with glass particles (DuraForm GF), and polystyrene (CastForm PS) [1].

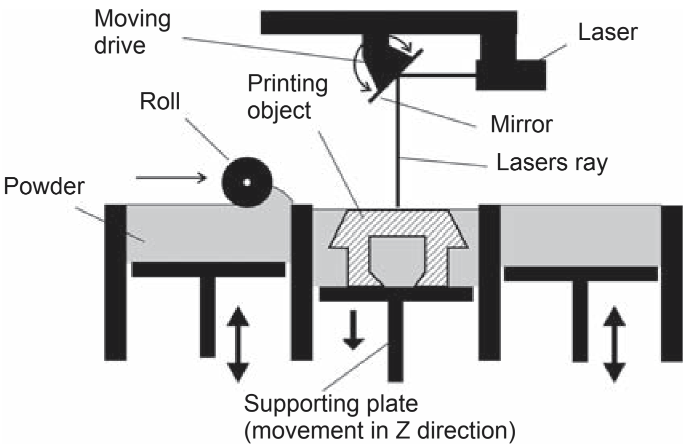

Fig.2 Principle of Selective laser sintering – SLS

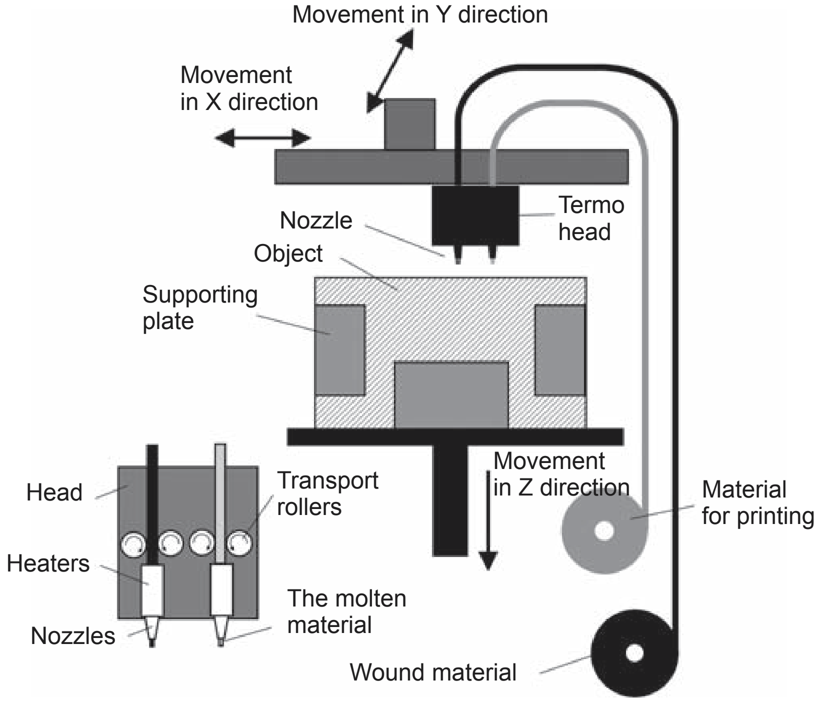

Fig.3 Principle of Fused Deposition Modelling – FDM

When working with metal, the laser power is much higher. Here are some Metal materials: titan, bronze, messing, copper, silver, gold, stainless steel etc.

Titan – is very light material. It is used as titan powder, which is sintered by laser. Stainless steel – in form of powder mixed with bronze powder coated with polymer bonding material (LaserForm ST-100 and 200). Stainless steel is least expensive material for products from metal. The products made by SLS are very strong [1, 8].

Available material is also ceramic, which looks great and it is temperature resistant.

3.2.2. FDM – Fused Deposition Modelling

Printing process starts with object 3D model conversion into STL format, than sliced into layers with slicing program. Material in form of termoplast filament passes through termo head, which melts the material. Melted material is extruded through nozzle which can be small as 100 microns. Melted material is deposited in layer based on the program which describes the object. The termohead is moved in x and Y direction and movement in Z direction is done after finishing one layer, Fig.3 [9].

To ensure support structures (for parts which are hanging in air), printers use two types of materials; one for object and other for support. This support material can be desolved in water or easily broken away after print is finished. The layer thickness can be from 25 microns to 200 microns, depending on machine precision what is for many printed objects satisfactorily relative to desirable surface smoothness. If not, than some conventional method of smoothing is applied.

For FDM process following materials are mostly used: ABS (Acrylonitril Butadiene Styrene), medical ABS, E20 (elastomer based on polyester), wax for precise casting etc [1]. For additional strength ABS can be reinforced with carbon. It is desirable that printing is done in an environment where temperature is lower than melting temperature of used material. Printed objects from ABS can be easily smoothed by treatment in acetone vapor.

For many products (design, home, decorative) coloring is important. Till now the printers could not use a wide pallet of color filaments but very soon there will be additional devices for automatic real time color mixing into any filament color [10].

What kind of material is going to be used, depends on the mechanical, chemical physical properties of final product, color, appearance and application. The most commonly used plastic materials are: ABS, PLA, Nylon, PC, PVA etc. For FDM technology filaments diameters are 1.75 and 3 mm.

Specification of some of used materials is shown in Tab.1 [11].

3.2.3. Stereolithography - SLA

Stereolitography - SLA (or SL) is production technology from liquid photosensitive polymers. Under the influence of UV laser ray, which passes over the photosensitive liquid material, the surface is hardened.

After one layer is finished, the vessel with polymer is lowered and process is repeated until complete object is finished, Fig.4. After the object is printed and taken out, rinsed from polymer residue and then is further dried in UV separate vessel. This technique is faster than others, but materials are more expensive. Because material is more viscosiv, the move in Z direction for layer thickness of 0.1 mm doesn't allow that resin comes fast enough. To speed up the process, the plate is moved deeper. This allows faster overflow of new material. After this the plate is risen to the level of next layer to remove excess of material.

During the printing, hanging parts of objects needs to be supported. These support structures slicing software creates automatically.

Because of layering principle, surface has stepwise surface. If needed, the surface is additionally smoothed. One way to this is additional curing in UV furnace [1].

SLA printers have three major parts: computer which has two tasks - first task is to process STL file and produce layers and second to control process of printing; movement mechanism with enclosure and other mechanical parts. UV spectrum laser device with wavelength of 349 to 355 nm.

Stereolithography is suitable for faster model creation to test shapes, cast production, but more and more finds application in medicine for manufacturing of personalized orthopedic implants. This method is also suitable for cloth production. Disadvantages come from photopolymer with weaker mechanical properties and by contraction / squizing can cause stresses and strains. Photopolymers are toxic in liquid state.

WaterShed is the most frequently used material based on epoxy which mimics many PBT (polybutylene terephthalate) materials, Somos 8100 and 9100, epoxy based on polypropylene photopolymers, ACCURA SI 40. This material mimics polyamide properties and finally ACUDUR photopolymer [1].

Tab.1 Some of matarials for 3D printing

Name	Abbreviation	Melting temperature	Colors	Description
Polylactic acid	PLA	180˚C -230˚C	Different colors	Biodegradable plastic derivate. Products are robust and rather breakable, not high temperature resistant.
Acrylonitrile butadiene styrene	ABS	210˚C - 260˚C	Different colors including fluoroscentne i thermal colors	During melting it releases ugly odours that can be harmful to health. The products are less robust, less delicate and breakable. They are high temperature resistant.
Polyamide	PA	oko 245˚C	Natural white color	Products are flexible, light and chemical resistantand have low surface tension. Application in medical products.
Polycarbonate	PC	270˚C - 300˚C	Different colors	Hard and resistant material. Wide application.
Polyvinyl alcohol	PVA	oko 170˚C	White color	Polymer soluble in hot water, used for retaining constructions and products made from PLA and ABS.

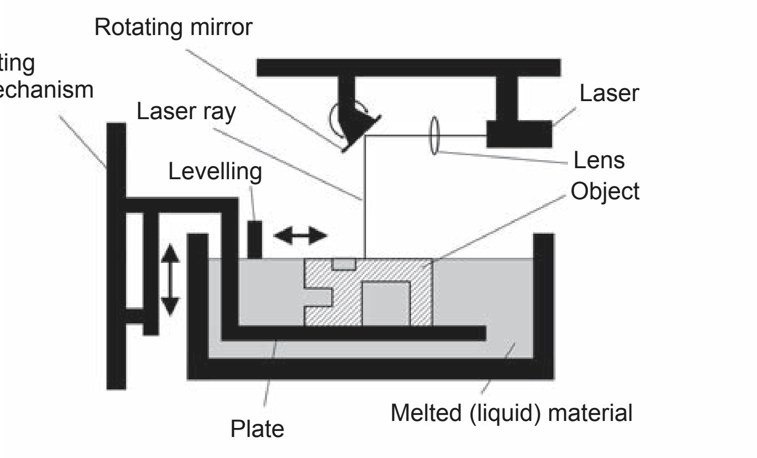

Fig.4 Principle of Stereolitography – SLA

DLP (*Direct Light Projecting*) is process similar to SLA, but instead of UV Laser ray uses digital projector with UV light.

3.2.4. Laminated object manufacturing – LOM

This is technology where cut out laminate material is superimposed on each other. Rollers have coiled tape of special laminate, it passes over the base plate which moves only in Z direction.

Foils can be from paper, polymer and composite. Laser ray is reflected by mirrors and cuts one layer, Fig.5. Similary to other techniques, mirror follows commands for particular layer. It is possible to use sharp cutting knifes instead laser as is the case in Solido [12].

The unused portion of foil is rolled on output roller. To stick together two adjacent layers, foil has on lower side polymer glue. After each layer is cut

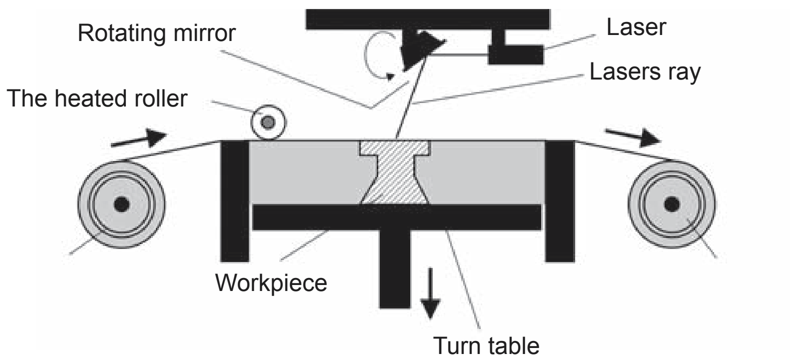

Fig.5 LOM working principle

Tab.2 Resolution and layer thickness of 3D technologies

3D technology	Resolution	Layer thickness
SLA -Stereolithography	±100 µm	50 µm
FDM - Fused Deposition Modelling	±127 µm	50 – 762 µm
LOM - Laminated object manufacturing	±127 µm	76 – 150 µm
SLS – Selective laser sintering – SLS	±51 µm	100 – 150 µm
3D jet printing	±127 µm	250 µm

out, the hot roller moves over foil and glues two layers together. After each roller pass, holding plate/moving table is lowered by foil thickness and rollers bring new foil over the printing object. Process is repeated until the whole object is printed. At the end of the process, printed object is protected with impregnation material. This technology is used for heavier objects. It is possible to print objects up to 50 kp weight (cca 490 N). One of the applications is cast production and automobile parts [12].

The most common material is paper. Advantage of this material is price and availability [13]. After printing some objects require additional processing to improve surface smoothness or mechanical properties. For this purpose materials like epoxy resins, polyuretanes, wax etc. are used.

3.2.5. 3D jet printing

This type of 3D printer uses *ink-jet* nozzles which spray the solidification agent on powder material. Used materials are plastomer powders, but also metal, ceramic or composite. Powder materials for this technology can be from gypsum with many different additives which improve visual and mechanical properties of final print. The powder is based on a mix of casting sand, gypsum and other additives. For some of the materials, after print follows the process of firming, e.g. thermal process to achieve sintering and injection of some metal which has lower melting point (e.g. copper) [1].

The technology of ink-jet printing is interesting because with similar 3D printers allows usage of bio materials, from wood powder to protein materials and live cells in medicine. Comparison of different 3D technologies is given in Tab.2 giving the resolution hand layer thickness.

4. Application in different areas

There is almost no human domain activity where the 3D printing is not applied for different purposes. Fig.6 shows the application in different areas [1]. Presented data are several years old and their purpose is orientation. There is continuous growth in all of these areas year by year, but the percentage of application is not significantly changing.

4.1. Medical applications

Medicine is one of the most fascinating areas of 3D printing. This relates to different areas, from dentistry, orthopedy, facial surgery to printing bio organs from patient cells.

Skin transplation is very complex. University of Toronto scientists developed the method for making "bio-ink" from skin cells. They are able to scan the wound and based on 3D model, they print the artificial skin directly over the wound [14]. Printed skin Is shown in Fig.7.

Production of biological samples opens new possibilities for testing new medicine. This will enable better

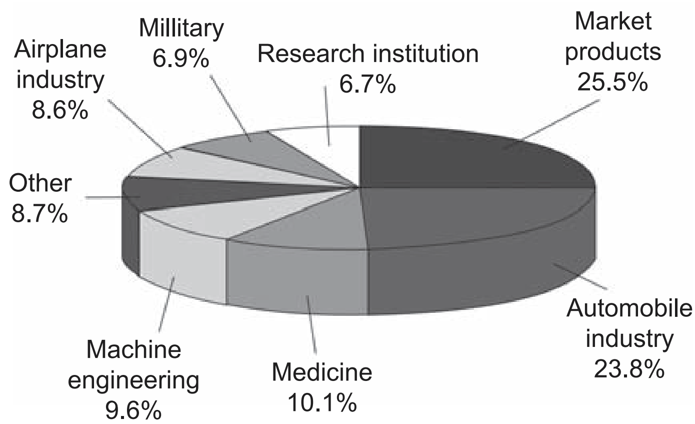

Fig.6 Application of 3D printers in different areas

Fig.7 Printed bio skin [17]

testing of medicaments and higher certainty for usage [14].
It is possible to print artificiall bones, Fig.8. As early as in 2013. doctors implanted vertebra to an older patient. Recently, the same has been done in Rijeka (Croatia). Damaged bones can be fixed by use of 3D print-

Fig.8 Printed model of jaw bones [14]

ing. With new technology 3D printer prints armature in shape of the bone and then fills the armature with stem cells. Stem cells have ability to self develop into different tissues. After implantation the tissue is dissolved within several months and replaced by completely new healthy bone grown from stem cells. In the year 2000, the biological kidney was printed. This was a small but functional kidney which was able in animals to filter the blood and extract the urine. According to some informations, the completely functional human kidney is printed, but not yet ready for implantation [15]. Already following body parts are implanted: bladder, ear, nose, blood vessels [14]. There are optimistic forecasts that in 5 to 10 years will be possible to print human organs based on stem cells and eliminated need for organ transplantation from donors [14].

Face reconstruction after difficult accidents are becoming standard procedure in facial surgery, Fig.9.
3D printing is suitable for production of prosthesis and orthotics customized for each patient Fig.10. Also the classical gypsum cast is replaced by "Cortex Cast" of mesh construction, which has reduced weight compared to classical method, Fig.11.

4.2. Application in machine engineering, car and airplane industry

As early as in the year 1992 first mechanical parts for different purposes were printed [2]. Those were plastic parts. Starting from the year 2000, industry started widely to print metal parts.
It is expected that 3D printing of rocket and airplane parts will significantly reduce amount of used material and reduce the production cost [17]. Already parts from tungsten alloys are printed. For this purpose tungsten powder is used. It is heated under pressure and on lower temperature bellow sintering it is transformed into compact elastic metal, which is able to withstand 3000 Celsius temperature. With this process parts from titan, tantalum and vanadium are replaced [17]. Fig.12 shows airbus 3D printed A320 hinges and changes to reduce the weight and material reduction, maintaining strength. First chassis prototype of ecologicly acceptable car was printed in Canada [18], and in 2013 in USA, Fig.13 [19].
In 2011. first drone under the name SULSA (Southampton Laser Sintered Aircraft), Fig.14 [20] was printed in Great Britain.
Soon it is expected satellite print from only one metal piece, what will reduce the cost by 50 %, e.g. several mil. euro [17].

Fig.9 Face reconstruction by 3D implanted part s[16]

Fig.10 3D printed prosthesis [16]

Fig.11 "Cortex Cast" printed mesh plastic cast [16]

Fig.12 3D printed A320 hinges [17]

Fig.13 Car printed in USA, year 2013 [19]

Fig.14 Drone printed in Great Britain, year 2011 [20]

Fig.15 Printed parts for prefabricated house (company Winsun New Materials) [21]

Fig.16 3D printing for furniture production - different kinds of materials (wood, plastic, metal) can be combined [22]

Before wider usage of metal printing the industry needs to solve several problems. The most significant is porosity, e.g. appearance of small air bubbles. The other is the surface smoothness of printed object. As with other new technologies, these problems will be solved [17].

4.3. Application in building construction and furniture production

We can observe very fast application of 3D printing in building construction. Architects are designing houses/buildings and based on their designs, they create models. Very soon based on their designs real houses are going to be printed. We can expect production of ecological and cheaper housing. There are already some promising results [21].

Using big 3D printer (6.6 m x 10 m x 6 m) Chinese company Winsun new materials printed 10 cheap houses in only 24 hours. Each house has 200 m^2. They used recycled construction material and industrial garbage reinforced with glass wool. Printing is done layer by layer (as in any other FDM printer) based on architectural 3D model. After printing all installations and isolation is added, Fig.15 [21].

Amsterdam will be one of the world first cities where the complete house will be printed. “Canal House” will have 13 rooms and will be located on one of the Amsterdam canals. The house will be assembled from 3D printed elements. Printing of elements already started and the forecast

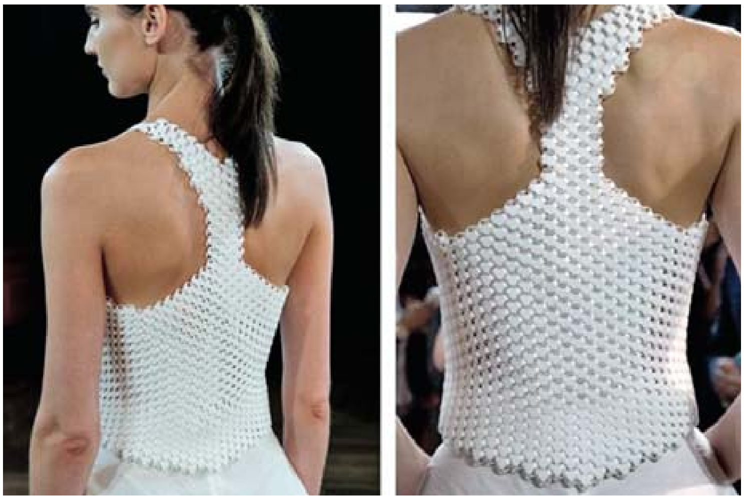

Fig.17 Upper printed part of dress, designer Bradley Rothenberg [23]

Fig.18 3D printed clothing, Iris van Herpen [24]

Fig.19 3D printed clothing, Iris van Herpen [26]

Fig.20 Design of footwear combines with clothing creations [26]

Fig.21 Footwear and clothing crations produced with 3D printing technology [26]

Fig.22 3D printed underwear [27]

is that it will take 3 years to finish the house [21].
There are already printed furniture. It is printed from plastic materials, but also from wood powder mixed with resin. Furniture elements (frames, backrests, footing, sides etc.) are not full, but inside there is an adequate mesh. By this technique it is possible to save lot of material, but maintaining structural strength. In furniture production different kinds of materials (wood, plastic, metal) can be combined, Fig.16.

4.4. Printing clothing and footwear

Already today we can see printed designers model clothing, fashion accessories, jewelry, bags and shooes. It is predicted that this is going to be one of the biggest applications of 3D printing. Printing enables unlimited creativity. In this moment they are unique samples and that they are not for each day usage yet, but it is not far away of that. The new materials are going to enable wide usage.
Already at NY Fashion Week in New York, which was organized By Katie Gallagher we could see collection "Fantasm" spring 2015. Fig.17 shows upper printed part of dress from designer Bradley Rothenberg. Dutch designer Iris van Herpen is very first one who presented 3D printed Clothing, Fig.18 and 19.. As was noted by A. Fisher [24], despite that clothing is flexible, and even can be washed in wash machine, still it looks too stiff. As she is saying: *" They are excellent for show, but are not practical to drive to school"*.
The cost of printing is very high, because it takes lot of time and still requires manual stiching of printed parts.
For her design reporter Jean Paul Cauvin says that she creates innova-

Fig.23 3D printed footwear [28]

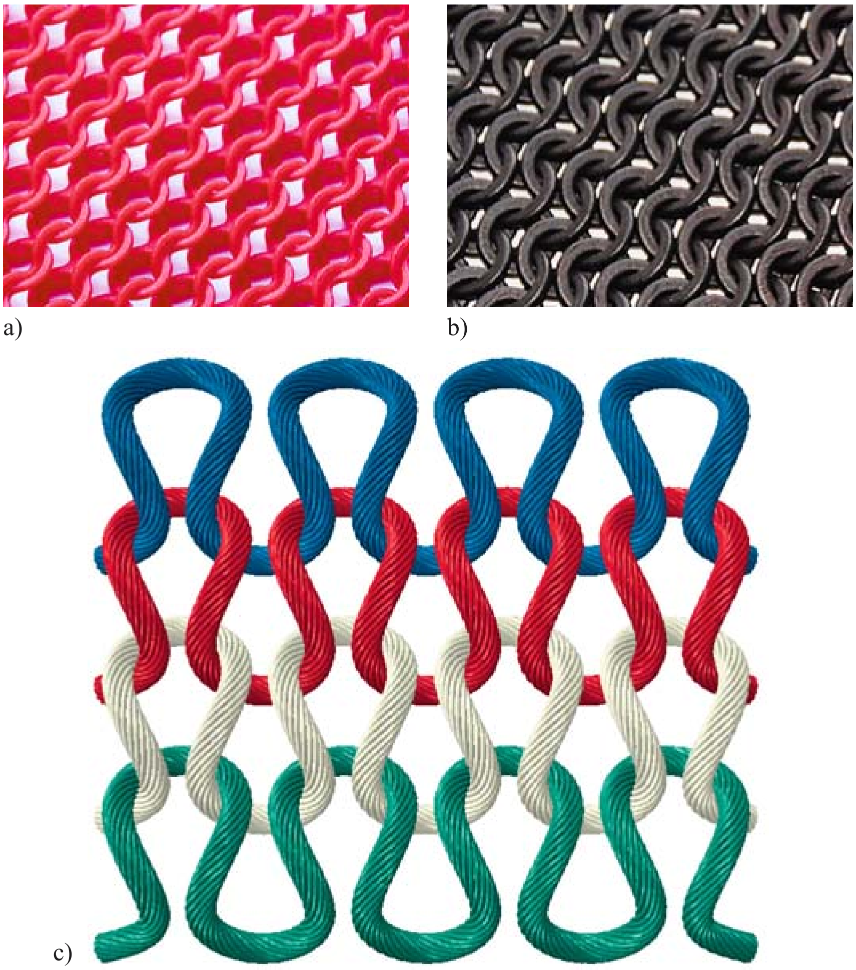

Fig.24 *Exhibition London College of Fashion* in London 2013 series of printed "textile structures" [28]

Fig.25 3D printed jewelry [16]

tions and experimental futuristic design. She is turnig all fashion on its head and this is escape from reality [25]. For printing she uses SLA - stereo lithography technique. She follows her path which she expresses with the words: "For me , fashion has always been about setting your own boundaries and making a statement." This talented designer started also to design footwear, which she combines with clothing creations, Fig.20 and 21 [26].

German clothing company Lascana, together with Russian designer Vitoria Anoka from Moscow printed intimate underwear, Fig.22 [27].

At *exhibition London College of Fashion* in London 2013. series of printed products were shown, Fig.23 [28]. For textile industry the most important is design and mesh patterning, as for instance in knitting, Fig.24. The possibilities are huge, because it is possible to realize any imagination.

There are already products which are finding day to day usage and these are jewelry, bags, bracelets, watch belts, belts, clothing decorations, Fig.25 and 26. These products can be produced very fast and weared at any occasion. The price of this products is determined not by cost of manufacturing but the price of design.

5. Conclusion

3D printing is a one of new technologies which will significantly change many domains of human activity and work processes. In some areas, specially in medicine, big changes and unsuspected possibilities are expected. Big changes are going to happen in automobile, airplane industry, ship vessels and space technology. It is definite that 3D printing will have significant impact on clothing design because in realization of design ideas almost there will be any limitation. We expect huge development of new materials, because they are of fundamental importance to printing technology. This is definetly technology of future, unlimited possibilities and currently is at very beginning.

Fig.26 3D printed jewelry, bags, bracelets, watch belts, belts, clothing decorations [16]

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