APPLICATIONS OF THE ADDITIVE MANUFACTURING TECHNOLOGY TO MANUFACTURE THE HIP IMPLANTS

Aleksandar Rajic[1], Slobodan Stojadinovic[2], Dorian Nedelcu[3], Eleonora Desnica[2], Ljubica Lazic Vulicevic[1]
[1]Technical College of Applied Sciences, Zrenjanin, [2]University of Novi Sad, Technical Faculty ″Mihajlo Pupin″, Zrenjanin, [3]″Eftimie Murgu″ University of Resita, Romania
e-mail: aleksandar.rajic@vts-zr.edu.rs

Abstract: The paper presents an application of the Additive Manufacturing (AM) technology using a 3D Printer to manufacture hip implant patterns for investment casting process. The goal of the paper is to outline the manufacturing technology intended for prototype production with the use of PolyJet technology and investment casting technology for use in orhopaedics and the surgery of cemented hip joint replacement. At present the research is focused on the preparation of STL data and verification of the production technology of prototypes made using PolyJet technology. The procedure is defined within the work conducted in the international IPA Cross-border Cooperation Programme Romania - Republic of Serbia project where Rapid Prototyping (RP) technology were studied.
Key words: Additive Manufacturing, Rapid Prototyping, hip implant, investment casting, meltable wax model.

INTRODUCTION

The most recent approaches to technological innovations include technological innovations of products and processes as competition factors as well as the new information and flexible manufacturing technologies having new properties. Modern development and design of new products and technologies is based on CAD/CAM/CAE technology application.
Additive Manufacturing (AM) is a procedure of direct prototype production by means of the gradual addition of individual material layers. The procedure, based on 3D CAD file, is relatively known nowadays. Additive Manufacturing technologies is the most frequently used name for a technology family: Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacturing (RM) and Reverse Engineering (RE).
When the application of AM technology started in investment casting, the parts produced within the first AM systems were applied as meltable wax models in order to shorten the time and costs of casting. Economic benefit which the AM meltable models provide is reduced to individual and small series production due to high AM material costs.
The latest researches in technology of development of AM meltable models are redirected to development and application of Rapid Tooling technology which ensures fast development of tools/ molds for meltable wax models development in investment casting. The name Rapid Investment Casting (RIC) is RP and RT techniques application in investment casting. Additive Manufacturing technology is optimal for the process of custom implants. These are the reasons why AM technologies have such an important role in medicine.

1. INVESTMENT CASTING OF METAL IMPLANTS

The main feature of technological process of producing cast products by investment casting is to inject under pressure an easily melted model mass in tools made of metal or other material: after solidifying in the tool the mass assumes the shape of a cast piece. The injecting system is made in other tool. The model of cast piece is joined to the injecting system model after it has been removed from the model tool. Since the models are of small dimensions, more models are joined for one injecting system which makes a wax sprue. Several layers of suspension are applied on the prepared wax sprue, which form a solid shell after drying. The shell is made by melting the model assembly and is then put into special boxes and sprinkled with sand or grains, [9].

The box containing the shell is heated in a furnace to a relatively high temperature and then is cast. After cooling down the cast pieces are removed from the shell and then detached from the injecting system and cleaned. If necessary, thermal treatment of cast pieces is performed. Investment casting is used for making cast pieces of ferrous, non-ferrous and light metals. Investment casting produces high quality and geometricaly complex near net shaped metal parts with tight tolerances economically in case off mass production. The economic benefits of investment casting are limited to mass production.
Limitations of traditional investment casting, [7]:

- traditional investment casting requires the production of metal tooling for the injection of wax material to produce sacrificial patterns which leads to cost justification problems for prototyping, pre-series, customized and single casting and small and medium quantity production.
- major part of the total lead time is consumed in production of metal tooling required for wax pattern generation.
- before committing to manufacturing, numbers of design iterations are performed by tool makers by evaluating different mould design which further incorporate an additional cost and lead time.

Metal orthopedic implants made of meltable models are hip prosthesis stem for cemented implantation and Fig. 1 shows tool for meltable-wax model and finished hip implant metal cast piece. The material of metal implants is CoCrMo alloy.

Figure 1. Tool for meltable implant model (left) and finished hip implant metal cast piece (right) (Courtesy of investment casting foundry – Livnica preciznih odlivaka Ada)

There are several companies producing medical implants using stainless steel alloys in the Serbian market. This production is mainly carried out by machining or forging. Cobalt-based alloys are used more in the area of hip joint replacements production in the foundry industry at present.
CoCr alloys have been utilised for many decades in making artificial joints. They are generally known for their excellent wear resistance. Especially the wrought CoNiCrMo alloy has been used for making heavily loaded joints such as ankle implants. A very strict certification regarding the material quality causes problems to foundries. Hip implants are produced in different sizes, for the left and right hip separately. Producers are trying to satisfy each inividual patient's needs at a surgery.
The term RIC represents the employment of AM techniques in investment casting. The cost involved in designing and fabrication of metal tooling for wax injection process can be overcome by using AM techniques to fabricate sacrificial patterns for investment casting. Additive manufacturing also facilitates to reduce the overall lead time involved in production of prototype casting with excellent quality. By employing AM-fabricated patterns to produce the prototypes, there is no need to commit to production tooling for single part or small quantity production, [1].
Additive Manufacturing techniques provide various cost effective solutions by which preseries casting can be produced very economically. Presently, almost all commercialised AM techniques have been employed to produce IC patterns with varying success and many AM solutions in investment casting are being used by various industries and researchers. The use of Additive Manufacturing in investment casting is in three basic forms. Fig. 2 shows the three basic approaches used as RC solutions in RIC.

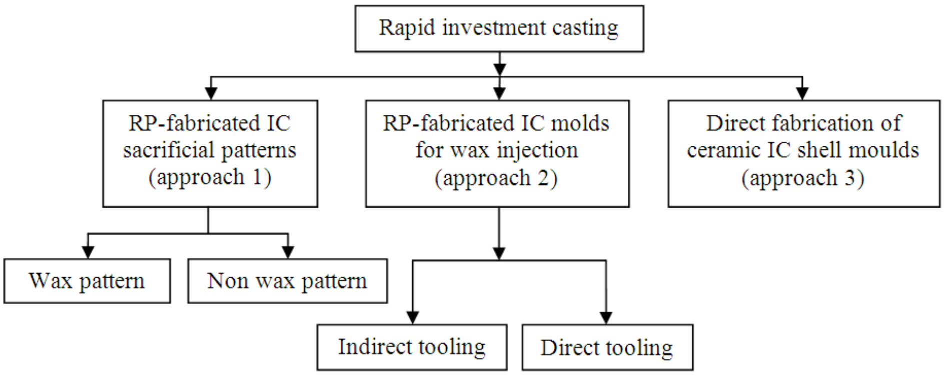

Figure 2. Rapid investment casting approaches [2]

2. THE DESCRIPTION OF THE 3D PRINTER

Objet Geometries machines build parts layer by layer combining inkjet technology with photo-polymerisation (UV curing) process, as shown in Fig. 3.

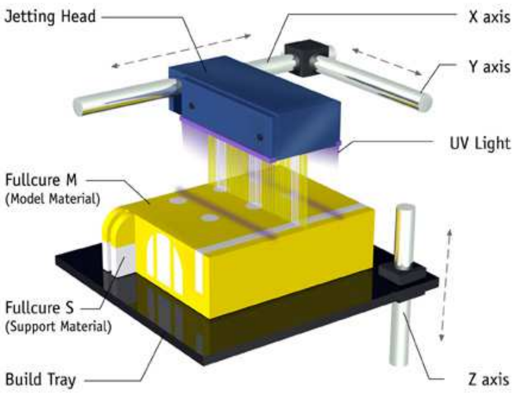

Figure 3. Polymer jetting printing process

Objet 3D Printer Multifunctional Desktop 30, Fig. 4, used in this study has maximum print size defined by the parallelepiped 294 mm x 192.7 mm x 148.6 mm, with a resolution of 600 dpi in the X, Y axis respectively 900 dpi in Z axis. The layer thickness on Z-axis direction is 28 microns. Accuracy can vary depending on the geometry, orientation and size of the object, up to 0.1 - 0.2 mm. The models do not require further finishing, but can still be processed by drilling, soldering, metal coating, painting. The wall thickness is 0.6 mm and minimum diameter of the holes is 1 mm.

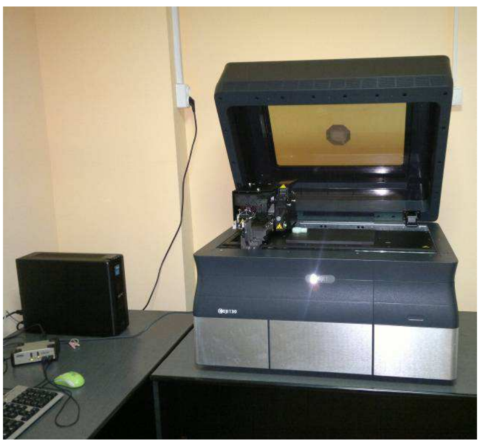

Figure 4. Objet 3D Printer Multifunctional Desktop 30
(Courtesy of Center for Numerical Simulation and Digital/Rapid Prototyping,
University "Eftimie Murgu" Resita, Romania

The range of material model (material used to print the full part of a model) available include Objet FullCure materials: VeroWhite, VeroBlue, VeroBlack, VeroGray, DurusWhite, TangoPlus, TangoBlack and FullCure®720. In this research was applied VeroBlack – FullCure870 material, and its properties are shown in Table 1.

Table 1. Material properties VeroBlack - FullCure870

Property	**ASTM**	**Units**	**Metric**
Tensile Strenght	D638-03	MPa	51
Elongation at Break	D638-05	%	18
Modulus of Elasticity	D638-04	MPa	2192
Flexural Strenght	D790-03	MPa	80
Flexural Modulus	D790-04	MPa	2276
HDT, °C @ 0.45MPa	D648-06	°C	47
HDT, °C @ 1.82MPa	D648-07	°C	43
Izod Notched Impact	D256-06	J/m	24
Water Absorption	D570-98 24 hr	%	1
Tg	DMA, E″	°C	63
Shore Hardness (D)	Scale D	Scale D	83
Rockwell Hardness	Scale M	Scale M	81
Polymerization density	ASTM D792	g/cm^3	1.17
Ash content	USP281	%	0.005

As support material (material used to print a model empty space) were used FullCure®705 Support a non-toxic gel-type photopolymer, that can be easily removed by Objet Waterjet System, Fig. 5, the equipment being included in the printer configuration. Waterjet use pressure water jet to remove material support.

Figure 5. Objet Waterjet System

3. THE CAD MODEL OF THE HIP IMPLANT

A total hip replacement (THR) is a surgical procedure whereby the diseased connective tissue (cartilage) and bone of the hip joint are surgically replaced with artificial materials. The hip joint is a ball and socket joint. The ball is the head of the thigh bone (femur). The socket (acetabulum) is a cup-shaped indentation in the pelvis. During hip replacement surgery, the head of the femur is removed and replaced with a metal ball set on a stem. The stem is inserted into the canal of the femur, as shown in Fig. 6 (right). It may be fixed in place with cement, or the stem may be designed for placement without bone cement. The socket is sanded down to healthy bone, and a plastic cup or socket is held in place with screws and/or bone cement, [9].

Figure 6. Hip prosthesis stem for cemented implantation

The 3D CAD model of the hip prosthesis stem was created using the SolidWorks software. The geometry of the hip implant is presented in Fig. 7. The maximal dimensions of hip implant are 150.13 mm x 103.18 mm x 26.65 mm.

Figure 7. The CAD model of the hip prosthesis stem

The CAD geometry of the hip implant was exported on an STL file, resulting in 19190 triangles, as shown in Fig. 8.

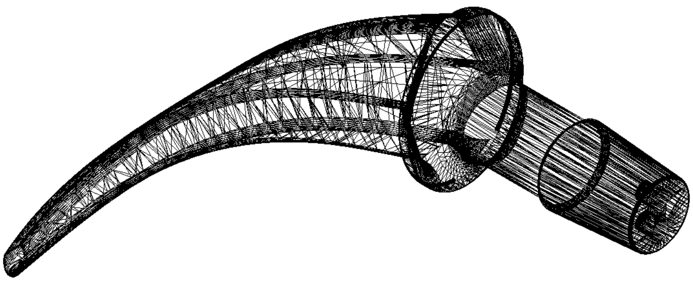

Figure 8. The STL format of the hip prosthesis stem (19190 triangles)

4. THE PRINTING PROCESS

Models that are saved in a CAD program as STL files may be inserted into the Objet Studio tray. Fig. 9 and Fig. 10 shows the STL files loaded in Objet Studio software. The orientation of models on the build tray affects how quickly and efficiently they will be produced by the 3D printer, where and how much support material is used, and whether or not model parts will have a gloss finish. To minimize printing time, [6]:

- the longest dimension of a model must be placed along the X-axis;
- the smallest dimension of a model must be placed along the Z-axis;
- the tallest model must be placed on the left of the tray.

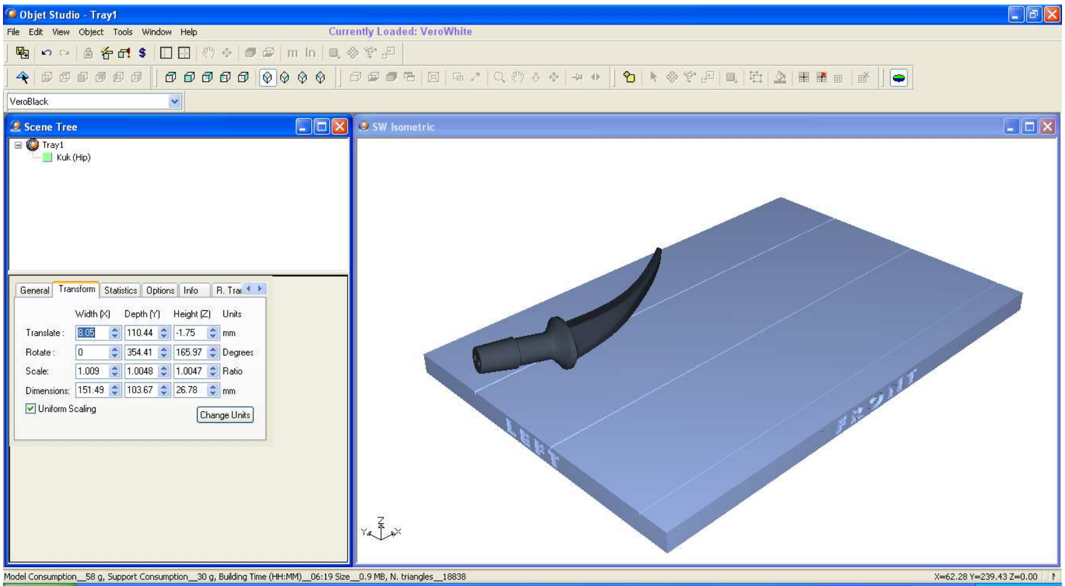

Figure 9. The STL file of the hip implant loaded in Objet Studio software and placed on printer tray

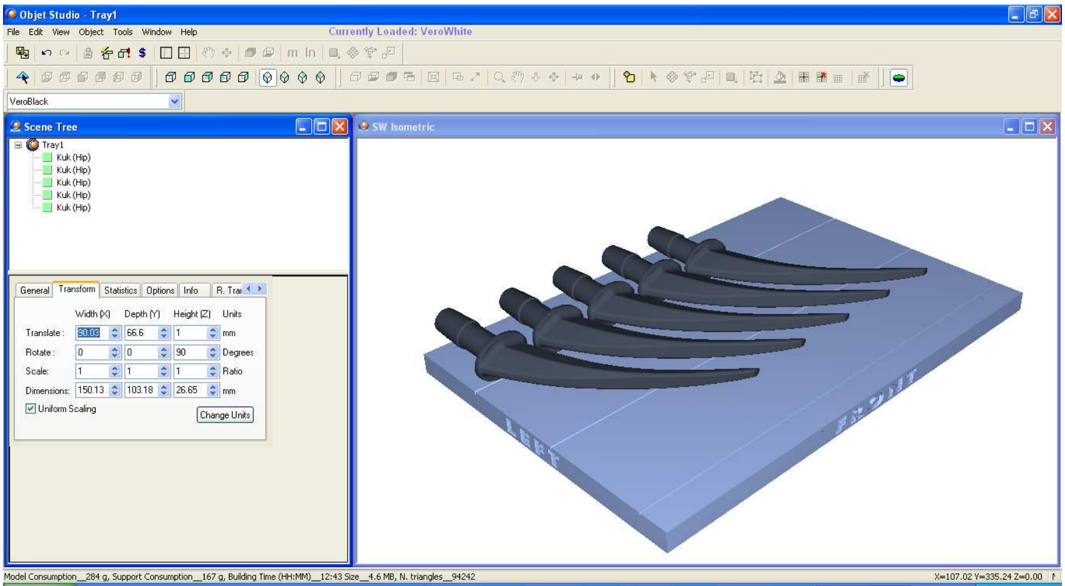

Figure 10. The 5 STL files of the hip implants loaded in Objet Studio software and placed on printer tray

When a tray is ready to be printed, it is sent to Job Manager, where it is placed in the print queue. When the job reaches the head of the queue, Job Manager preprocesses the tray file to create slices, and feeds them to the 3D printer. The printing parameters for the two case study are shown in Table 2.

Table 2. Printing parameters for the hip implant

Parameter	**UM**	**Hip implant 1 piece**	**Hip implant 5 pieces**
Material	-	VeroBlack	VeroBlack
Model Material	g	58	284
Suport Material	g	30	167
Printing Time	h/min	06 h 19 min	12 h 43 min
Layer Thickness (Z-axis)	μm	28	28
Layer's number	-	956	951
Triangles number	-	18838	94242

Objet Studio software offer the following additional features, [6]:

- dividing objects - to produce objects larger than the build tray by dividing the model into separate parts. With this feature, it is possible to print only a specific section of a model.
- choosing the support strength - when producing models, support material fills some hollow and empty sections. Objet Studio allows to adjust the strength of the structure formed with the support material. This adjustment is useful when producing either large / massive models or small / delicate models.
- smartcast - filling models with support material - many objects placed on the build tray from STL files are "solid"; this means that, when printed, the model will be completely filled with model material. Often, especially with large objects, this is unnecessary. Instead, the model can be filled with support material, which is less costly. It is also advisable to fill models with support material when preparing them for investment casting, since this material burns off more quickly during the process of making the cast. Objet Studio enables to print objects on the build tray with an outer shell of model material and a center filled with support material. This feature of Objet Studio is called "Smartcast/Hollow". It is possible to set the thickness of the shell between 0.015 and 3.825 mm.

For optimal efficiency, the two hip implants were decreased in the ratio 1:0.6 and manufactured along with a number of other parts. Fig. 11 shows the different stages in the printing of the hip implants. Fig. 12 shows the removal of the support material with Objet Waterjet System for the hip implant. Fig. 13 shows the final shape of the two hip implants.

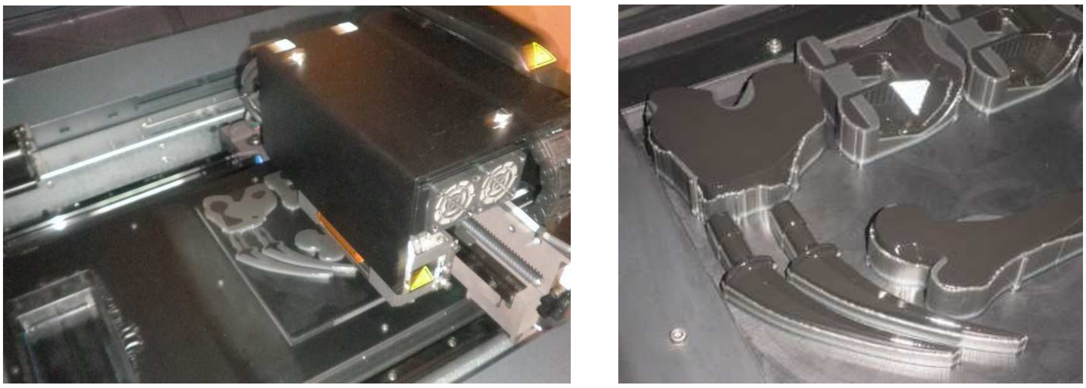

Figure 11. The different stages of the hip implants printing

Figure 12. The support material removal with Objet Waterjet System

Figure 13. The final shape of the two hip implants

Additive Manufacturing technology is used to produce the pattern for investment casting. The acuracy of the produced patterns is compatible with the accuracy of used in medical field especially for orthopedic surgery. The use of this semi-finished product is double. Firstly, it is possible to use this pattern as non wax pattern for investment casting. Secondly, by using the PolyJet patterns it is possible to make a silicon mould and with it cast the wax patterns in the vacuum chamber. Investment casting technology is applied hereafter.
Additive Manufacturing is also used to test the pattern against a replica of the patients' model. In the example shown in Fig. 14 the pattern of a hip implant design is tested against a replica of the patient femur produced from MRI data.

FIgure 14. The designed pattern can be tested against a patient organ replica

5. CONCLUSION

The application of Additive Manufacturing technology in the medical field, is an invaluable contribution of engineering technology to orthopedic surgery field. The PolyJet technology can be used to create complex objects, like hip implants and to use these objects for investment casting process as non wax pattern or for AM-fabricated molds for wax injection (indirect tooling). The following advantages are important: surface quality, smoothness details, great level of accuracy and reduced manufacturing time. Advances in Additive Manufacturing material will undobtedly producing ″clean″ parts that can be used directly as implants.
The paper ends with a hope that in future, Rapid Investment Casting solutions will emerge with the capability to provide dimensionaly more accurate and better surface finish medical implant castings of any size, shape and material with more speed and low cost.

6. REFERENCES

[1] Cheah, C.M., Chua, C.K., Lee, C.W., Feng, C., Totong, K., Rapid Prototyping and Tooling techniques: A review of applications for rapid investment casting, Springer-Verlag London Limited, 2004.
[2] Chhabra, M., Singh, R., Rapid casting solutions: A review, Rapid Prototyping Journal, Vol. 17, No. 5, pp. 328 – 350, 2011.
[3] Gibson, I., Advanced Manufacturing Technology for Medical Applications, Reverse Engineering, Software Conversion and Rapid Prototyping, John Wiley & Sons Ltd, 2005.
[4] Horacek, M., Charvat, O., Pavelka, T., Sedlak, J., Madaj, M., Nejedly, J., Dvoracek, J., Medical implants by using RP and investment casting technologies, China Foundry, Vol.8, No.1, pp.107 – 111, ISSN 1672 – 6421, 2011.
[5] Manuelde, A.M., Simoes, J.A., CAD-CAM-RTV – lost-wax casting technology for medical implants, Rapid Prototyping Journal, Vol. 15, No. 3, pp. 211 – 215, 2009.
[6] Nedelcu, D., Raoul, A., Danu, F., Rajic, A.: Applications of the Rapid Prototyping Technology to manufacture the Pelton runners, Analele Universitatii "Eftimie Murgu" Resita Anul XX, Nr. 1, 2013, ISSN 1453 – 7397, Article in press.
[7] Rajic, A., Manic, M., Rapid Prototyping technologies in investment casting of metal implants, Journal "IMK-14 - Research and Development", Krusevac, Year 16, Vol. 2, pp. 39 – 44, 2010.
[8] Rajic, A., Stojadinović, S., Desnica, E., Nedelcu, D., Reverse Engineering application in creation of 3D CAD model for investment casting of knee implant, II International Conference – Industrial engineering and Environmental Protection (IIZS 2012), Zrenjanin, pp. 306 – 312, 2012.
[9] Medical Disability Advisor, Hip Replacement Total, World Wide Web: <http://www.mdguidelines.com/hip-replacement-total> (cit. September, 24.2013).