ISSN 1330-3651
UDC/UDK 621.744.072:658.512.2

RAPID PROTOTYPING OF CASTING CORES

Ivan Štefanić, Pero Raos, Ivan Samardžić, Boris Tintor, Edo Musser

Subject review

There are many possibilities of rapid prototyping; however each technique has its own specificities and limitations. This paper presents an overview and brief analysis of different methods for rapid prototyping, with the aim to evaluate practical application of certain procedures in the casting industry and in the production of permanent casting cores. With regard to this, the three-dimensional printing (3D printing) exhibits the greatest potential because of its flexibility, speed and reasonable costs. The procedure of casting core production by 3D printing is presented on an example, and compared to conventional production process of casting core molding. The paper describes different approaches to the development of casting cores: direct, indirect, direct production of molds, and the main factors in deciding on the application of this technology.

Keywords: *casting cores, rapid prototyping, three-dimensional printing*

Brza izrada ljevačkih modela

Pregledni članak

Mogućnosti brze izrade prototipova su brojne, no svaka od tehnika ima svoje specifičnosti i ograničenja. U radu je dan pregled i kratka analiza različitih metoda brze izrade prototipova, s ciljem ocjene primjenjivosti pojedinih postupaka u ljevačkoj industriji, odnosno proizvodnji trajnih ljevačkih modela. Postupak trodimenzijskog (3D) tiskanja zbog svoje fleksibilnosti, brzine i prihvatljive cijene, pokazuje najveći potencijal u ovom smislu. Na konkretnom primjeru prikazan je tok proizvodnje ljevačkog modela postupkom 3D tiskanja, te provedena usporedba s konvencionalnim postupkom proizvodnje ljevačkog modela. U radu su opisani različiti pristupi izradi ljevačkog modela: neposredni, posredni, izravna proizvodnja kalupa, te glavni činitelji pri odlučivanju o primjeni ove tehnologije.

Ključne riječi: *brza izrada prototipova, ljevački modeli, trodimenzijsko tiskanje*

1 Introduction

Today's rapid product development and global market conditions set demands for entrepreneurs to adjust quickly to new conditions and to constantly adopt new technologies. Each company, irregardless of whether it develops its own final products, or acts as a supplier of components for larger companies, has to use the best available materials, processes and equipment in order to assure its quality and efficiency. This is especially true in casting industry, as strong competitiveness forces casters to constantly reduce production costs, to shorten timelines, and to increase productivity and quality. Additionally, great attention is directed towards environment protection. The aim of this paper is to present the possibilities of rapid prototyping technology, especially of 3D printing in development of casting cores, and to demonstrate the advantages of that technology on a practical example.

2 Rapid Prototyping

In the course of new product development, the tendency is to produce high quality products in the shortest time and at the lowest costs. In the past, there were mostly massive, identical products available on the market. Recently, companies have directed their marketing concepts towards requirements of end users.

In the area of new product development there are few noticeable trends, as follows: more attention is directed towards construction, mass production is losing on its importance, environment protection is highly respected, product life on the market is generally shortened, there are permanent product price discounts due to very strong competition, there is a requirement to comply with different regulations and standards in the course of product development, an interdisciplinary approach to product development is needed, the product development process involves many external experts (from multinational companies), which requires efficient communication. New products are more complex from functional and geometric point of view, and time needed for their production should be as short as possible. It should be emphasized that the construction phase of a new product development influences 80 % of product quality, and 70 % of development and manufacturing costs. It is possible to conclude that the maximum profit can be achieved by minimizing product development time, rather than development costs.

One of possible answers to such strict demands on product development is the use of methods covered by the concept of rapid product development (RPD). RPD approach seeks to accelerate the product development process by minimizing the time needed in the course of an idea development to product finalization and its market launch. When talking about the RPD approach, focus is put on computer-aided design and construction (CAD, CAM, CAE), fast production processes and reverse engineering. Rapid production can be achieved in three ways: rapid production of prototypes (Rapid Prototyping - RP), rapid production of tools (Rapid Tooling - RT) and rapid (direct) production (Rapid Manufacturing - RM). These processes allow quick production of very complicated shapes by direct application of computer data in mostly automated process [1÷4].

The basic steps of rapid prototyping are [5]:

1. Definition of three-dimensional CAD model by using standard software for computer modeling (AutoCAD, SolidWorks, Pro/Engineer, Catia, etc.).
2. Creation of the STL file: STL is the standard format used for rapid prototyping that presents three-dimensional surface as a set of planar triangles. Due to triangle planarity, it is impossible to obtain accurately curved surface, so this problem is solved by increasing the total number of triangles or by reducing their size.

1. "Cutting" of the STL file into layers: layer or model cuts by height are created by appropriate algorithms. Layers density, i.e. their distance depends on the desired accuracy, and can range from a few hundredths of a millimeter to several millimeters.
2. Physical creation of layers in an appropriate device: process is repeated for each layer, starting from the lowest one to the top one, until the final outcome.
3. Post-processing: after creating the model, residues of material are removed and, if necessary, the model is grinded, polished or varnished.

Rapid prototyping (RP) refers to a group of processes for producing three-dimensional pieces by means of special equipment and based on computer CAD models. The following section briefly describes important processes for rapid prototyping.

2.1 Stereolithography

Stereolithography (SL/SLA) is the oldest rapid prototyping process developed by the company 3D Systems in the United States. There are different types of liquid photopolymers used as material which hardens while exposed to the UV light of specific wavelength and intensity. Solidification of layers occurs under the influence of laser beams. Produced part is placed on the platform. After one layer becomes solid under the influence of laser beams, the platform moves down and the solidification of the next layer starts. As all layers become solid, the remaining liquid material is drained, the product is cleaned, and if necessary, additionally processed for obtaining adequate surface quality. This method is used for creation of conceptual, geometric and functional prototypes. It provides sufficient accuracy and surface quality, and there is no limit to shapes. Disadvantage of this method is relatively high costs and limitations to material selection (epoxy and acrylic resin) [1, 4, 5, 6].

2.2 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) is a procedure in which paper is spread on the working area by means of rollers. The paper is rolled over by a heated roller which melts polymer coating on the paper backside and sticks it with other layers. By means of an optical system, laser beam cuts the layer contour in the shape of a product cross-section. Platform with the model moves down and the whole process is repeated. After the model is created, material residues are removed, the model is ground and varnished to avoid moisture absorption and distortion of dimensional stability. Various polymeric and composite materials, as well as paper, can be applied. This method is applied in the conceptual design. Advantage of this method is a possibility to produce relatively large parts, with slightly lower costs, if compared to stereolithography. Disadvantage of this method is somewhat lower accuracy of produced model if compared to other methods, and limitations on the development of a model with thin walls. Hollow objects cannot be made by this method [1, 4, 5, 6].

2.3 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a technique for rapid prototyping of polymer materials, such as ABS (acrylonitrile butadiene styrene) or waxes (e.g. wax for precision casting). At the coil there is a thread of polymer material that enters the heated extrusion nozzle, in which the material is melted. The nozzle is attached to a mechanism that can move in all directions as based on data obtained from the CAD model. Applied layer quickly stiffens, upon which the platform that carries the model moves down to enable the next layer application. This method is used for production of functional prototypes and for precision casting technology, by using the appropriate wax. The main advantages of this method are its speed and safety. The equipment is cheaper than stereolithography and selective laser sintering. Disadvantages of the method are commercially unavailable materials, limited functionality by the choice of materials, and slightly worse dimensional stability. Furthermore, supporting structures are required in the course of melted material deposition, which have to be removed from the final model [1, 4, 5, 6].

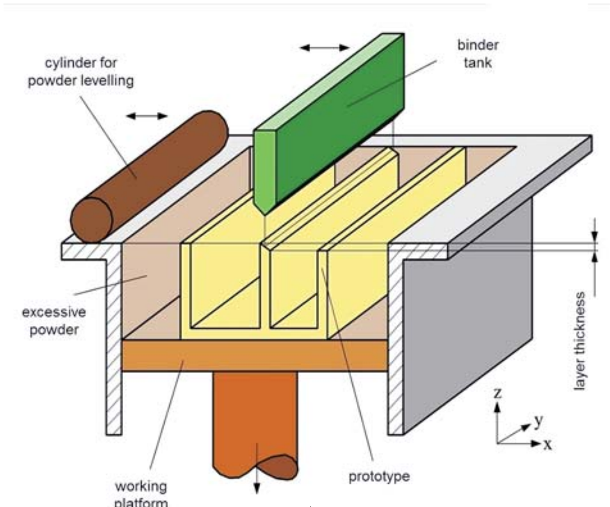
2.4 Selective Laser Sintering

Selective Laser Sintering (SLS) is a method which uses laser beam as concentrated heat source to selectively sinter various materials in powder state, for example, polyamide and other polymers, as well as various metals and their alloys. The process is preformed by a precise mechanism for rolling that distributes powder materials on the platform. Laser beam passes over a layer of powder and heats it to a temperature slightly beyond the melting point. This connects material particles and solidifies the layer. After that, the platform is lowered and a new layer of powder material is applied. The procedure is repeated until the whole model is done. The model is removed from the platform, cleaned and if necessary, additionally processed. This method is used to create visual and functional prototypes, tools for injection pressing, hard tools and EDM electrodes. One of the main advantages of this method is application of different materials, which makes it suitable for various industrial branches, and the ability to create components of great mechanical properties. Disadvantage of the method is the laser of higher power than in stereolithography, and very high investment costs. During the process, the chamber has to be constantly provided with nitrogen and toxic gases that appear during sintering need to be drained away [1, 4, 5, 6].

2.5 Three-dimensional printing

Three-dimensional printing (3D Printing, 3DP) is a process developed and patented by MIT (Massachusetts Institute of Technology) in the United States. Like all processes for rapid prototyping, this one also starts with the CAD model, which is divided into layers by a special algorithm. Various powder materials are used for making models by this method. Precise roller mechanism is used for application of powder materials in thin layers. After the layer of powder material is applied to the surface, the ink-jet head applies the binder, with the aim to selectively connect the powder particles. The platform is then lowered, and new layer of powder and binder is applied (Fig. 1) [1, 4, 5, 6].

Application of layers is repeated until the model is completed, which is followed by removal of material residues and surface finishing. In order to achieve adequate mechanical properties, the model can be infiltrated by other material (low viscosity epoxy and cyanoacrylate resins) [8, 9]. This method



a)

b)

Figure 1 Three-dimensional (3D) printing: a) procedure schema [1, 6]; b) device [7]

is characterized by speed, high precision and good dimensional stability. It is possible to successfully create prototypes and functional parts of complex shapes, at a price lower than of other methods. This procedure does not produce dangerous gases or vapors, as is the case with selective laser sintering or stereolithography. Due to these advantages, this method is widely applied in various fields, such as mechanical engineering, aeronautics and shipbuilding, where models produced by this technology are used for functional testing, for testing of navigability, for tests in air tunnels, or as presentation models [8, 9]. In architecture, this technique is applied in development of models to visualize architectural solutions and to communicate with clients. Furthermore, three-dimensional models can be produced by using results of computer tomography, which provides surgeons with possibility of detailed pre-operative planning, precise design of implants, selection of instruments and shortening the overall duration of surgery [10, 11].

2.6
Hybrid 3D printing and stereolithography (PolyJet)

Trying to overcome the shortcomings of the SLA process, the company Objet Geometries has developed a hybrid procedure that combines benefits of both SLA and 3D printing process, and called it PolyJet. During the PolyJet prototyping, the first step is 3D printing of a layer of photosensitive polymer material by means of nozzles (1536 nozzles). This procedure applies building material and supports that enable printing of complex geometrical shapes. After the printing, the layer solidifies under the UV light sources. In comparison to the SLA process, the basic advantage of the PolyJet is that all prototype layers harden at once, and not selectively. Before a new prototype layer starts, the platform is lowered for the thickness of the next layer. As one layer completely solidifies, it is possible to apply a new layer directly to the previous one without difficulties that arise in the SLA or SLS process. After the final layer is made, the support is removed. As the procedure is very accurate, there is less need for post-processing and for subsequent hardening of prototypes [1, 12].

3
Application of 3D Printing in Casting

The flexibility of this method opens the way for its wide usage in casting, especially in the development of permanent casting models designed for the molding sand, and for making of cores. Disposable models are made by powder materials based on cellulose and subsequently infiltrated by wax. These models replace the wax models in the process of precision casting. One of the features of this technique is the possibility for direct production of molds, which enables avoidance of the molding process itself. The basic idea behind the 3D printing in casting is to avoid designing, construction development, drawings, and modeling workshop with equipment and personnel, and to directly obtain casting models ready for molding or finished molds, as based on design concepts and technological solutions (Fig. 2).

Application of that technique in casting should be viewed as a new and powerful tool which will provide engineers with the possibility to significantly shorten the time needed for processing the order and reaching final models. When an engineer proposes a technological solution based on drawings or 3D CAD models, the time needed for molding the casting core by this technique can be divided into three parts, as follows: the time for preparation of printing, which can last from 0,25 to 0,5 hours; the time for printing, which can last from 0,5 to 16 hours, depending on the model size; and the time required for post-processing, lasting from 0,5 to 6 hours; core or mold by means of 3D printing is 1-2 days. Finally, the time required for development of a casting core or mold by means of 3D printing is 1-2 Example of a casting core for vertical railway switcher developed by the TERA TEHNOPOLIS Ltd. is presented in Fig. 3.

The model is designed for manual sand molding by the so-called CO2 process. Besides drawing, Fig. 3 presents the 3D CAD model, parts of 3D printed casting model, and finished mold. Besides obvious time savings, it should be emphasized that casting of models by 3D printing in this case significantly reduced human labor requirement. Preparation and post-processing phase of making casting cores by 3D printing requires only one worker, while conventional procedure requires mechanical technologist-CNC programmer, personnel responsible for supplies and preparation of materials, machine supervisor and modeler. Tab. 1 compares conventional procedure of casting core for vertical railway switcher with the model obtained by 3D printing.

With this technique it is possible to create permanent models that are optimized for molding, either by compacting of mold mixture (machine, manual molding), or by making molds within chemical processes of hardening [2, 13].

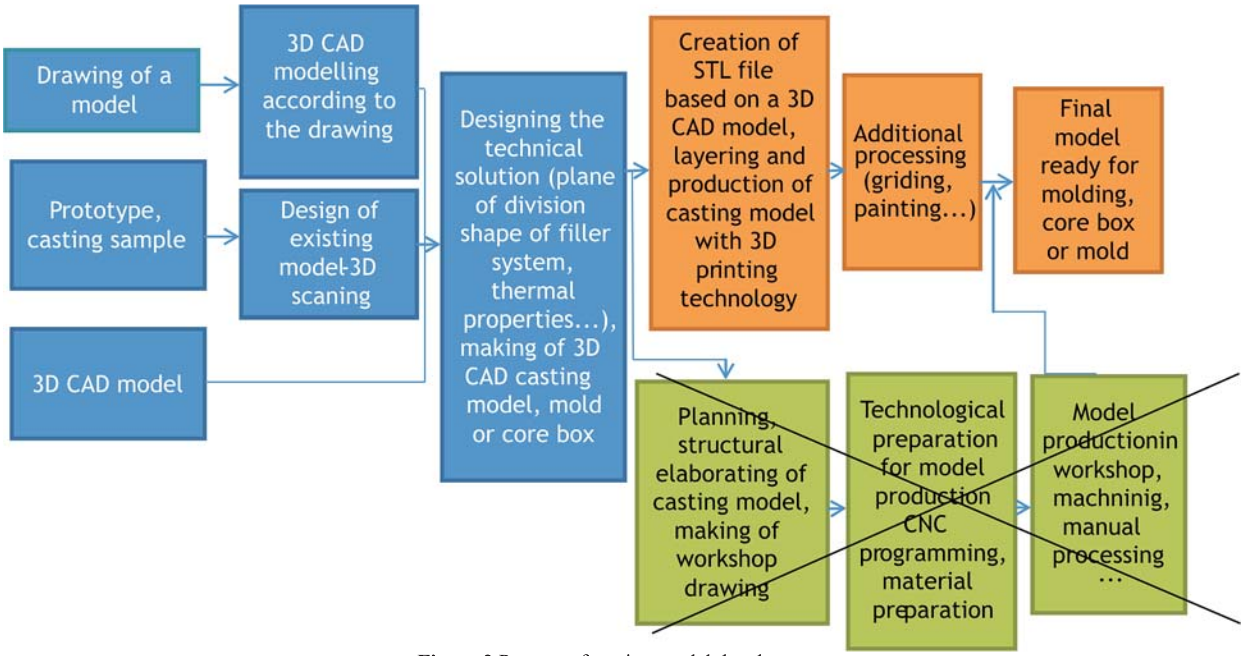


Figure 2 Process of casting model development

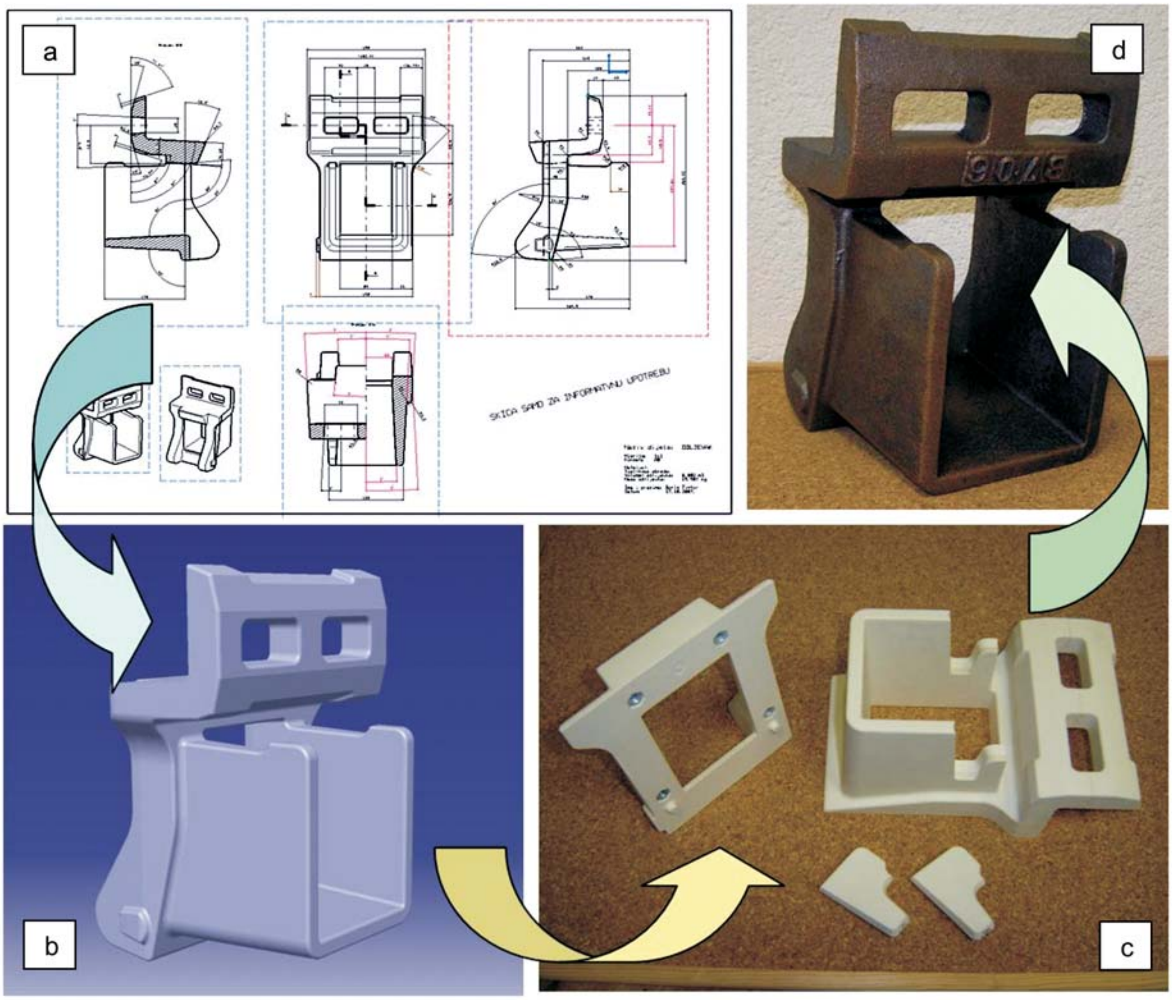


Figure 3 Vertical railway switcher: a) model drawing, b) CAD model, c) RP model, d) mold

Depending on the requirements, there are two basic ways of making permanent casting cores [2, 13]:

Direct method to create casting cores. This procedure is acceptable for making of permanent molds and cores for casting into a single mold, especially when referring to smaller batches, manual molding and parts of less height. Models are made directly by 3D printing, by using powder material of mineral origin which is strengthened and whose surface layer is additionally infiltrated by cyanoacrylate resin. High precision of the printed model and lack of restrictions in terms of shapes, can also simplify technological solutions for model construction.

Table 1 Comparison of different methods for casting core of vertical railway switcher

Conventional procedure*		3D printing**	
Phase	Time /h	Phase	Time /h
Technological planning	2,00	Creation of STL file	0,25
Programming tool path	6,00	Machine preparation	0,50
Creation of APT file	0,25	Making of a model	6,25
Postprocessing	0,25	Cleaning of a model	0,25
Material preparation	1,50	Additional processing	2,50
Machinery preparation	1,25		
Making of a model by milling	9,50		
Additional manual processing	7,50		
TOTAL	28,25	TOTAL	9,75

*Reference: OLT d.d.; ** Reference: TERA TEHNOPOLIS Ltd.

Indirect method to create casting cores. Machine molding for greater series of models requires permanent cores of great strength and durable form. By this method casting cores of the most complex shapes can be created in a quick and inexpensive way. Within 3D printing process, a mold (negative) is created first, and this mold is then filled by eg. epoxy resin. After solidification, the epoxy core, cast as measured, is removed from the mold and, if necessary, further treated by grinding, polishing and painting. This procedure enables complete avoidance of conventional technology for model creation by expensive machinery and with large portion of modeler's manual work.

As previously stated, the process of 3D printing enables direct production of disposable molds. This procedure is applicable for casting of nonferrous metals, such as alloys based on aluminum, zinc, magnesium, as well as for brass and bronze. Parts of mold, core and necessary accessories (Fig. 4) can be produced directly by 3D printing from special ceramic powder, which resists the temperature of up to 1200 °C.

Figure 4 Examples of molds for direct casting of aluminum produced by 3D printing [13]

All printed mold parts are put together, which is followed by direct casting of metals, cooling, and the cast release by mold breakage. By this procedure, time needed for creation of casts is reduced to a minimum. It is sure that the application of this procedure is not convenient for large-scale or mass production, but it is an optimal choice for creation of smaller number of pieces, or for creation of testing samples [13].

The main factors for deciding on the application of 3D printing for casting cores are:

- **Complexity of casting core:** the more complex a model is, the better the feasibility of this technique gets. Application of conventional methods for making models of complex shape presupposes demanding technical and technological preparation, application of many often expensive machine tools, and requires a significant portion of manual work. The final result largely depends on the skills of an individual modeler, and sometimes it is not even possible to make a model because of its complexity, so the order is returned to a client with requests for changes in model structure or form. 3D printing has no limits in terms of shape complexity, all model shapes can be made by 3D printing.
- **Size of casting core:** cores of maximum dimensions of 200 × 250 × 200 mm can be made from one piece, larger cores can be created by putting together of several parts. It is clear that this technique is not appropriate for creation of cores of large dimensions and volume.
- **Time needed for creation of casting core:** creation of permanent casting core by 3D model printing is an acceptable solution when there is a need to make very complex shapes in short time. By using this technique, certain mistakes that lead to delays in production can be avoided, thus increasing efficiency and providing possibility to meet strict demands of short deadlines.
- **Costs of casting core production:** within this technique, costs depend on the size or volume of a core and its eventual post-processing. Unlike conventional methods, the complexity of core shape does not affect its price. If compared to conventional methods, the greater the complexity of shapes is, the lower costs of production will be.

4 Conclusion

Overview of rapid prototyping process indicates the possibility of its application in various fields. It can be concluded that 3D printing technology was the most interesting for casting, especially in the development of permanent casting cores. In this paper, it was proved that this technology could significantly save up money and time needed for casting core development. By using this technology, some costly phases in the process of making casting cores could be avoided, such as construction analysis, drawing for modeling workshops, expensive machinery processing by particle separation, and a large portion of manual work. It is possible to print cores of very complex shape, production of which was limited until this technology emerged. There is a global trend of constant increase in application of this technology in many industry branches. However, in the Republic of Croatia, application of this technology in casting and in other areas is still in the beginnings.

5
References

[1] Šercer, M.; Raos, P.; Barić, G.; Godec, D. Napredni postupci proizvodnje polimernih tvorevina. // Bilten Razreda za tehničke znanosti, 10, 2(2009), pp. 33-57.
[2] Godec, D.; Šercer, M. Brza proizvodnja kalupa. // Polimeri. 28, 1(2007), pp. 32-39.
[3] Raos, P.; Grizelj, B.; Cumin, J. Rapid prototyping – 3D Printing // Manufacturing engineering, 140, 2(2008), pp. 40-42.
[4] Raos, P.; Stojšić, J.; Somolanji, M. Izbor optimalnog postupka brze izradbe prototipova. // Proceedings of the 2nd International Conference "Vallis Aurea" / uredio Branko Katalinić. Požega : Polytechnic of Pozega & DAAAM International Vienna, 2010., pp. 1229-1235.
[5] Šercer, M.; Jerbić, B.; Filetin, T. Brza izrada prototipova i alata. // Zbornik radova savjetovanja "Suvremene proizvodne tehnologije i materijali". Zagreb : HAZU, 2007., pp. 6-24.
[6] Godec, D. Utjecaj hibridnog kalupa na svojstva injekcijski prešanog plastomernog otpreska / doktorska disertacija. Zagreb : Fakultet strojarstva i brodogradnje, 2005.
[7] ZPrinter 310 User Manual. Burlington : Z Corporation, 2007. Str. 56-59.
[8] Galeta, T.; Kljajin, M.; Karakašić, M. Cost Evaluation of Shell and Compact Models in 3D Printing. // Výrobné Inžinierstvo - Manufacturing Engineering. 7, 3(2008), str. 27-29.
[9] Galeta, T.; Kljajin, M.; Karakašić, M. Geometric Accuracy by 2-D Printing Model. // Strojniški vestnik - Journal of Mechanical Engineering, 54, 10(2008), pp. 725-733.
[10] Raos, P.; Stoić, A.; Kopač, J. Manufacturing of customized medical implants // Proceedings of the 8th International Research/Expert Conference TMT 2004 / uredili S. Ekinović, S. Brdarević, J. Vivancos, F. Puerta. Zenica : Faculty of ME Zenica, Escola Tacnica Superior D'Enginyeria Industrial de Barcelona, 2004., pp. 99-102.
[11] Raos, P.; Stoić, A. An Approach in Manufacturing of Medical Implants // Proceedings of The 8th ESAFORM Conference on Material Forming / uredio Dorel Banabic. Cluj-Napoca : The Romanian Academy Publishing House, 2005., pp. 683-687
[12] Pilipović, A.; Raos, P.; Šercer, M. Experimental analysis of properties of materials for rapid prototyping. // International Journal of Advanced Manufacturing Technology, 40, 1-2(2009), pp. 105-115.
[13] Godec, D.; Šercer, M.; Pilipović, A. Direct Rapid Tool Production // Proceedings CIM 2009 Computer Integrated Manufacturing and High Speed Machining / uredili Eberhard Abele, Toma Uiljak, Damir Ciglar. Zagreb: Hrvatska udruga proizvodnog strojarstva, 2009., pp. 69-74.
[14] ZCast Direct Metal Casting Design Guide. Burlington : Z Corporation, 2007., pp. 7-23.

Authors' addresses

Štefanić Ivan, prof. dr. sc.
TERA TEHNOPOLIS d.o.o.
Gajev trg 6
HR-31000 Osijek, Croatia
e-mail: stefanic@tera.hr

Raos Pero, prof. dr. sc.
J. J. Strossmayer University of Osijek
Mechanical Engineering Faculty in Slavonski Brod
Trg I. Brlić-Mažuranić 2
HR-35000 Slavonski Brod, Croatia
e-mail: praos@sfsb.hr

Ivan Samardžić, prof. dr. sc.
J. J. Strossmayer University of Osijek
Mechanical Engineering Faculty in Slavonski Brod
Trg I. Brlić-Mažuranić 2
HR-35000 Slavonski Brod, Croatia
e-mail: isamar@sfsb.hr

Boris Tintor, dipl. ing.
TERA TEHNOPOLIS d.o.o.
Gajev trg 6
HR-31000 Osijek, Croatia
e-mail: tintor@tera.hr

Edo Musser, dipl. ing.
TERA TEHNOPOLIS d.o.o.
Gajev trg 6
HR-31000 Osijek, Croatia
e-mail: musser@tera.hr