UDK 621.7:004.89
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 46(6)589(2012)

# DEVELOPMENT OF A 3D PRINTER FOR THERMOPLASTIC MODELLING

## RAZVOJ 3D-TISKALNIKA ZA TERMOPLASTIČNO MODELIRANJE

**Bogdan Valentan[1], Dušan Pogačar[1], Tomaž Brajlih[2], Tjaša Zupančič Hartner[2], Ana Pilipović[3], Igor Drstvenšek[2,1]**

[1]Ortotip, d. o. o., Ulica škofa Maksimilijana Držečnika 6, 2000 Maribor, Slovenia
[2]Univerza v Mariboru, Fakulteta za strojništvo, Smetanova ulica 17, 2000 Maribor, Slovenia
[3]Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia
bogdan@ortotip.com

*Prejem rokopisa – received: 2012-04-03; sprejem za objavo – accepted for publication: 2012-04-12*

Additive technologies are entering the market in all price segments and the development of new machines and materials is rapidly growing. Machines under 2000 € are more and more interesting for home and educational use. This paper presents the development of a 3D printer that shapes the parts layer by layer by depositing the material on a predefined position. The development is presented from the engineering point of view. The construction steps, the control and the actuator solutions are presented. The ABS plastic was analysed for its material properties. The 3D printer evolved from a prototype to the pre-production phase.

Keywords: polymers, rapid prototyping, FDM, additive technology, education

Dodajalne tehnologije vstopajo na trg v vseh cenovnih segmentih, razvoj novih naprav in materialov pa je v konstantnem teku. Naprave s ceno pod 2000 € so vse bolj zanimive za uporabo doma in v izobraževalne namene. Članek prikazuje razvoj 3D-tiskalnika, ki izdela izdelek s ciljnim nalaganjem materiala na določena mesta posameznega sloja. Prikazan je inženirski pogled na razvoj. Predstavljeni so konstrukcijski koraki in rešitev vodenja. Analizirane so bile lastnosti materiala ABS. Izdelek je prešel prototipno fazo in je sedaj v predproizvodni fazi.

Ključne besede: polimer, hitra izdelava, FDM, dodajalne tehnologije, izobraževanje

## 1 INTRODUCTION

The beginnings of layered technologies go back to 1985 when the first 3D printer based on the stereo lithography[1] was introduced. FDM (Fused Deposition Modelling)[2–4] was developed by S. Scott Crump in the late 1980s and was commercialized in 1990 by founding the company Stratasys. Today the company Stratasys[5] is the biggest producer of the FDM machines. Recently the patent for FDM has expired and today several new companies try to get a share of this market. Because of the simplicity of their procedure, the FDM machines can be sold, in comparison with the other additive technologies, at very low prices as the machines for homes or for undemanding industrial use.

## 2 BASIC PRINCIPLES OF FDM

The FDM procedure starts with a 3D CAD model that is usually exported as an STL file. The STL file is then sliced by the computer software into horizontal layers that are of the same height as the height of the layer in the FDM machine. A rod-shaped filament (in our case a polymer, but it can also be wax) is supplied to the machine through a nozzle. The nozzle is computer controlled in the XY plane and in one layer it forms the raster of the item in the respective layer. The material is liquefied in the nozzle and it hardens quickly when applied to the layer at a low temperature. To get a better performance, the entire system can be in a heated environment. After the first layer is finished, the working bed in the Z direction is lowered by the thickness of one layer and a new layer is now extruded[6,7]. When the geometry of a part is more complex having overhangs, a support structure must be added. This support can be made from the same material, using the same nozzle, but, in more professional machines, the second head is used and the support material is different (degradable in solvent). The thickness of the layer depends on the nozzle opening, the material dosage and the feed rate and it usually ranges from 0.05 mm to 0.5 mm. With the FDM procedure, practically all the thermoplastic materials can be used including the biocompatible and biodegradable materials and some elastomers, and it is possible to simultaneously produce several prototypes at the same platform. The mechanical properties depend on the position of the prototype on the working space and are usually lower in the direction of the z-axis.

The advantages of the FDM procedure are the amounts of materials that can be used, the machine size that is compact in comparison with some others, and decent mechanical properties of the finished parts.

The disadvantages are the need for a support structure, the unpredictable material shrinkage (especially at lower ambient temperatures), visible lines between the layers, roughness, and lower mechanical properties in the Z direction.

## 3 EXPERIMENTAL PART – PROJECT SOUSTVARJALEC

The project called SOUstvarjalec started in November 2010. Its goal was to develop the first Slovenian 3D printing machine with a modular design that can be easily upgraded for a special usage (regarding dimensions, used materials or production technology). SOUstvarjalec is a 3D printer that operates on the Fused-Deposition-Modelling principle. The nozzle is controlled with G code produced with an open-source G-code creator called Skeinforge. The machine allows the production of complex parts in one piece with minimum human interaction.

The start of the project was the selection of the optimum basic mechanical design. Several options were discussed, and simulations and optimizations were done (**Figure 1**).

The design was done from scratch using the SolidWorks CAD program aiming at its simplicity and low price (**Figure 2**). At that time some decisions regarding the basic properties were also made, like the working space (200 mm in the *X*, *Y* and *Z* directions), the maximum speeds and the accuracy (the choice of the motor design – NEMA 17 stepper motors), the material shape (a 3-mm rod – the standard one that allows the use of the other materials for the standard shape of the 3-mm rod), the nozzle diameter (a 0.5-mm diameter was chosen to get the best speed/part quality-performance ratio based on the other similar machine designs). For a good weight-to-mass ratio most of the support parts were made of aluminium (Al 6060) and the basic numerical analyses[8] were made during the construction. Most of the connecting parts were made of PA 2200 using a selective laser-sintering (EOS P100) machine.

**Figure 1:** Various forms of the basic design
**Slika 1:** Različne oblike osnovne zasnove naprave

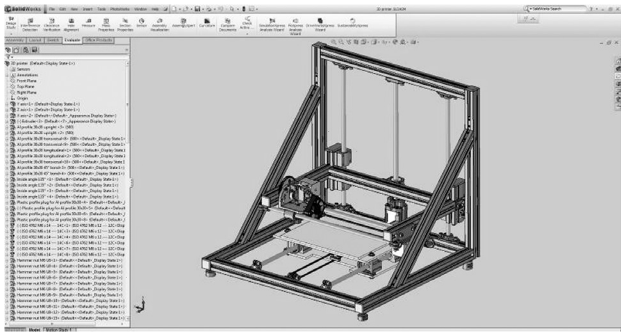

**Figure 2:** Partly finished 3D printer in the SolidWorks CAD program
**Slika 2:** Delno dokončan 3D-tiskalnik v CAD programu SolidWorks

The control electronics for the first prototypes were the open-source RepRap[9] generation-6 electronics that were designed especially for the simple 3D printers, but all the future machines will be equipped with the custom-made electronics that are currently in the test phase.

## 4 KEY-COMPONENT IMPROVEMENTS

At the end of the first stage several tests were made on the first prototype and some components needed to be redesigned. The major problem was with the thrust-screw design. To ensure good thrust of the material to the nozzle different screw designs were tested (**Figure 3**). The tests were done by weighing the machine that was placed in the fixed printing plate and measuring the force applied with the rod. However, the best design was unfortunately also the most expensive one to produce. To


**Figure 3:** Different thrust screws. With small diameters we gain a compact design and with large diameters we gain more force. The design of a groove is crucial.
**Slika 3:** Različne oblike pogonskih vijakov. Manjši premer vijaka omogoča kompaktnejšo izvedbo, večji premer pa večjo potisno silo. Oblika pogonske odprtine je ključna.

**Figure 4:** Different hot-end designs. Basically a hot end is assembled of a heater (a resistor), a nozzle, connection tubes and a thermal barrier (Teflon can be used, but PEEK is better).
**Slika 4:** Različne oblike vroče šobe. V osnovi vročo šobo sestavljajo grelnik (uporovni), šoba, povezovalne cevke in termalna bariera (ki je lahko iz teflona, vendar je PEEK boljša izbira).

ensure a long-time functioning without any jams, different hot-end designs were tested (**Figure 4**) by measuring the current consumption of the extruder motor so that comparable results were gained and the design was optimised. The thermal barrier was originally made of a Teflon block, but was, due to its softness at higher temperatures, later replaced by a PEEK part; however, it can also be made of ceramic or a composite[10,11].

## 5 RESULTS AND DISCUSSION – TESTING THE MACHINE'S CAPABILITIES

The machine was activated with some basic movements in all directions (and a fine tuning to ensure good accuracy and repeatability) and the test extrusions of the material through the nozzle to find some basic temperature settings that enable a smooth extrusion. The next step was the production of some basic shapes (a cylinder and a cube) so that the accuracy of the machine could be tested and the extrusion parameters corrected. Then the first free-form objects were printed (**Figure 5**). There were some findings in the relation between the environment temperature and the maximum dimension of the printed parts in the XY plane. We found that, due to internal stress caused by the cooling of the material and its consequent shrinkage, bigger parts start to warp, delaminate and depart from the working plate being, consequently, destroyed by the extrusion head. This phenomenon is less intense in the summer, when the temperatures are above 28 °C and they are completely unnoticeable at the temperatures of above 60 °C (a sealed enclosure with an additional heater and temperature regulation), when FDM can be used for producing parts of any dimensions made of an ABS material. Different materials need different environment temperatures to avoid delaminating and warping.

**Figure 5:** Some parts produced with SOUstvarjalec, most of them can be found on the internet in an STL format
**Slika 5:** Nekaj izdelkov, narejenih na SOUstvarjalcu, večina oblik je brezplačno na voljo na internetu v obliki STL-datotek

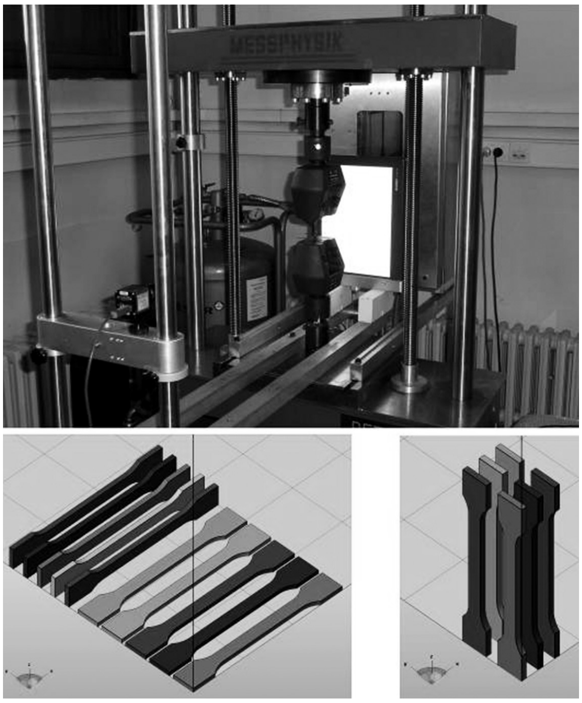


**Figure 6:** Test specimens on a universal measuring machine Messphysik Beta 50 – 5 and their shapes (the ones on the bottom left-hand side are made in the Z direction intended for testing the dependence of the nozzle temperature on the tensile strength, and the ones on the bottom right-hand side are made in the XY plane intended for a comparison with a professional FDM machine)
**Slika 6:** Preizkusni vzorec na univerzalni merilni napravi Messphysik Beta 50 – 5 in oblika preizkusnih vzorcev (spodaj levo narejeni v Z-smeri za analizo odvisnosti med temperaturo talilne šobe in natezno trdnostjo, spodaj desno pa narejeni v XY-ravnini za primerjalni preizkus s profesionalno FDM-napravo)

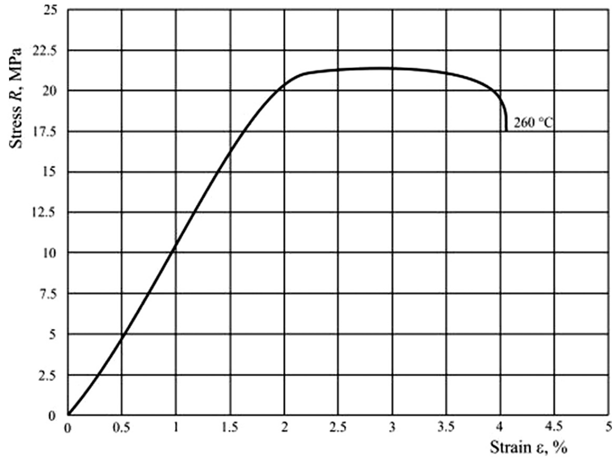


**Figure 7:** Typical response of a test sample
**Slika 7:** Tipičen odziv trganja preizkusnega vzorca

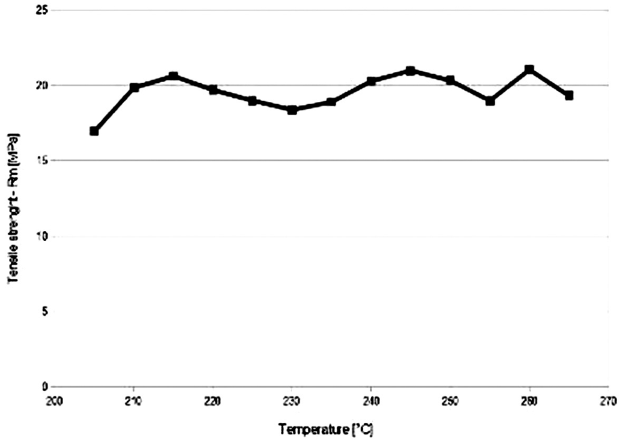


**Figure 9:** Reliance between tensile strength and the extrusion temperature. All test specimens were built in the Z direction (Z direction is critical since there can come to delimination between layers) at room temperature.

**Slika 9:** Odvisnost natezne trdnosti epruvet od temperature ekstruzije. Epruvete so bile izdelane v Z smeri (Z smer je kritična zaradi pojava deliminacije med posameznimi sloji) pri sobni temperaturi okolice.

To ensure the best possible visual and mechanical results of the printed parts, several tests according to ISO 527:1993 and ISO 178:2001 standards were made on a universal measuring machine (**Figure 6**).[12] The test probes were produced at different nozzle temperatures (different melting temperatures) and at the room temperature of 23 °C (±1 °C). The results (**Figures 7** to **10**) show that the temperature in the chosen area has a small impact on the tensile strength and the maximum load, but a large impact on the E-modulus.

At the higher melting temperatures a product loses its flexibility, so the logical decision would be to decrease the extrusion temperature to get the best possible results.

The results (**Figures 9** and **10**) show that there are some threshold temperatures for the ABS extrusion. At the temperatures below 210 °C the tensile strength starts to drop and at the temperatures exceeding 250 °C the E-modulus drops rapidly.

Unfortunately, a decrease in the extrusion temperature also triggers the effect of the growing force needed to push the material through the extrusion nozzle and, consequently, leads to more print failures caused by an extrusion jam. So, in the end, some compromise was needed and, on the basis of the results, the manufacturing parameters were adjusted to obtain the best mechanical properties and ensure a reliability of the machine.

At the end a comparison was made between a product made by a professional machine Stratasys Dimension (with a heating chamber and a price well over

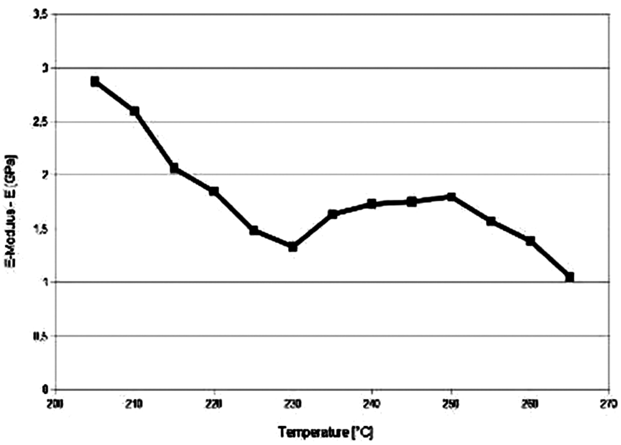


**Figure 8:** E-modulus of the test specimens built in the Z direction with respect to the temperature of the extrusion nozzle made at room temperature. The results show that at the higher melting temperatures the bonds in the material start to yield and the products lose their flexibility.

**Slika 8:** E-modul preizkusnih epruvet, izdelanih pokončno v Z-smeri v odvisnosti od temperature vroče ekstruzijske šobe, izdelani pri sobni temperaturi okolice. Rezultati so pokazali, da pri višjih temperaturah taljenja vezi začnejo popuščati in material izgublja fleksibilnost.

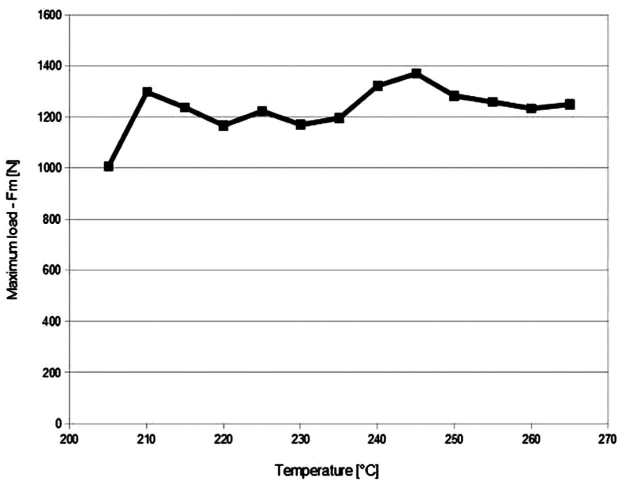


**Figure 10:** Maximum load of the test specimens in reliance to extrusion temperature. All test specimens were built in the Z direction at room temperature.

**Slika 10:** Največja obremenitev preizkusnih epruvet v odvisnosti od temperature ekstrudiranja. Epruvete so bile izdelane v Z smeri pri sobni temperaturi okolice.

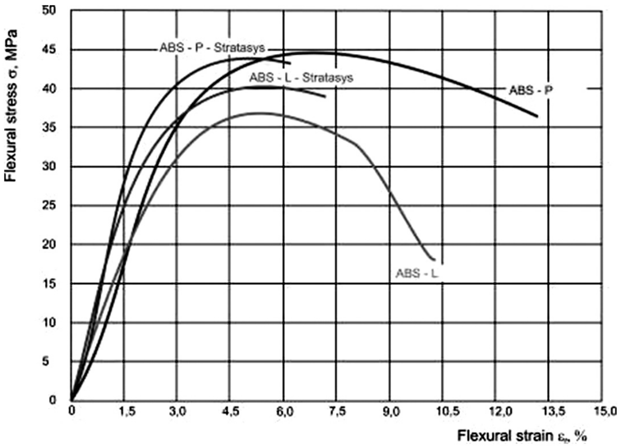


**Figure 11:** Comparison between a professional machine Stratasys Dimension SST 768 and SOUstvarjalec
**Slika 11:** Primerjava med rezultati trganja vzorcev, izdelanih na profesionalni napravi Stratasys Dimension SST 768, in vzorcev iz SOUstvarjalca

10,000 €) and a product made by SOUstvarjalec. Both machines made probes from ABS in the horizontal position (not as in the case of different temperature tests, when the probes were built in the Z direction) as, due to a larger delamination of the products built at room temperature, the conditions in the XY plane were better (because of the absence of a heating chamber). Test probes were made in the lying and upright positions in the *XY* plane. It can be seen that the results are pretty close one to another, especially when taking the price into consideration (**Figure 11**).

## 6 FUTURE DEVELOPMENT

The focus in the future development will be on the portable version of the SOUstvarjalec printer for the educational use and on the development of a closed version that enables a production of the parts at higher environment temperatures, with better mechanical properties and the possibilities to produce bigger parts (**Figure 12**). Several new materials were tested, like PLA (Polylactic acid) that is derived from renewable resources and is biodegradable, and even some biocompatible materials like PMMA (Poly(methyl methacrylate)) that is today used for the standard products in medicine (the bone cement) as well as PEEK (Polyether ether ketone), a thermoplastic with excellent mechanical and chemical resistance properties that are retained at high temperatures[13].

## 7 CONCLUSIONS

The presented development is only a part of the development done in the field of additive manufacturing by the company Ortotip. SOUstvarjalec is placed in the lower price segment (with the starting disassembled-KIT price of 1,600 €), but with the quality, the speed and, especially, the mechanical properties of the finished parts that provide a good alternative to the more expensive machines.

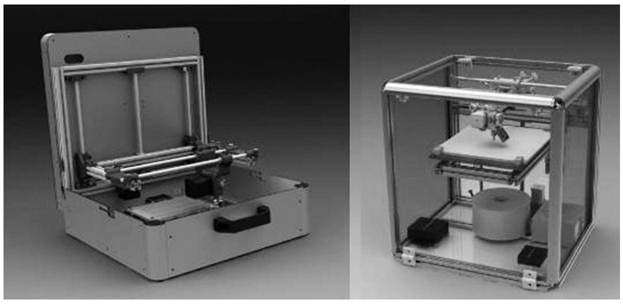

**Figure 12:** Development trend for the SOUstvarjalec line
**Slika 12:** Smer razvoja linije izdelkov SOUstvarjalca

When preparing for the print, the geometrical complexity of the product has to be analysed and the decisions made about its orientation, position and also about the reduction of the mechanical properties in the Z direction; in addition, the problems of removing the support material in a partly closed space should be taken into consideration.

The performed tests showed that the tensile properties are lower than in the cases of the products made by injection moulding or the products made with the professional FDM machines. The difference between our results and the injection moulding is normal since the material pressed at high pressures and velocities is much more homogeneous. The advantage of our printer over the professional machine is the production at lower environment temperatures that has an impact on the homogenisation of the product and the use of the special ABS material developed for the FDM procedure.

FDM machines heave a bright future because of their simplicity, the variety of different materials they can use (in addition to plastic there are experiments with silicone and even chocolate), the price of these materials and a growing community of enthusiasts that can afford to buy these machines and share the innovations.

**Acknowledgement**

The project was partly financed by the European Union – the European Social Funds.

## 8 REFERENCES

[1] Stereolithography – the first commercialized additive manufacturing process [cited 2012-2-22] Available from World Wide Web: http://en.wikipedia.org/wiki/Stereolithography
[2] FDM – introduction to FDM process [cited 2012-2-22] Available from World Wide Web: http://rpworld.net/cms/index.php/additive-manufacturing/rp-rapid-prototyping/fdm-fused-deposition-modeling.html
[3] K. Lokesh, P. K. Jain, Selection of rapid prototyping technology, Advances in Production Engineering & Management, 5 (**2010**) 2, 75–84

[4] T. Brajlih, B. Valentan, J. Balič, I. Drstvenšek, Speed and accuracy evaluation of additive manufacturing machines, Rapid prototyping J., 17 (**2010**) 1, 64–75

[5] Stratasys – web page of the biggest producer of FDM machines [cited 2012-2-22] Available from World Wide Web: http://www.stratasys.com/

[6] I. Pahole, I. Drstvenšek, M. Ficko, J. Balič, Rapid prototyping processes give new possibilities to numerical copying techniques, Journal of Materials Processing Technology, 164–165 (**2005**), 1416–1422

[7] I. L. Gibson, D. W. Rosen, B. Stucker, Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, Springer, New York 2010

[8] B. Berginc, M. Brezočnik, Z. Kampuš, B. Šuštaršič, A numerical simulation of metal injection moulding, Mater. Tehnol., 43 (**2009**) 1, 43–48

[9] Generation 6 Electronics – web page with resources for GEN 6 electronics [cited 2012-2-22] Available from World Wide Web: http://reprap.org/wiki/Generation_6_Electronics

[10] A. Maglica, K. Krnel, M. Ambrožič, Ceramic composites based on silicon nitride, Mater. Tehnol., 43 (**2009**) 3, 165–169

[11] T. Kroupa, R. Zemčík, J. Klepáček, The temperature dependence of the parameters of non-linear stress-strain relations for carbon-epoxy composites, Mater. Tehnol., 43 (**2009**) 2, 69–72

[12] A. Pilipovic, P. Raos, M. Sercer, Experimental analysis of properties of materials for rapid prototyping, Int J Adv Manuf Technol, 40 (**2009**) 1–2, 105–115

[13] PEEK – Polyether ether ketone, biocompatible thermoplastic [cited 2012-2-22] Available from World Wide Web: http://en.wikipedia.org/wiki/PEEK