Cost Evaluation of Shell and Compact Models in 3D Printing

Zhodnotenie nákladov pri 3D tlači škrupinových a kompaktných modelov

Tomislav Galeta, Milan Kljajin, Mirko Karakašić

Abstract

Compact models printed on 3D printer capture a significant amount of passive building powder. This can be avoided if models are designed as shells in cases where it is acceptable. In this paper performed is a cost evaluation of compact versus shell models in 3D printing process. The evaluation revealed that the shell models are less expensive only if models are infiltrated by wax. For other infiltrants, there is no significant cost difference between shell and compact models. Shell models are even more expensive than the compact models, especially as the base size is increasing.

Keywords: 3D printing, cost calculation, rapid prototyping

Abstrakt

Kompaktné modely tlačené na 3D tlačiarňach spotrebúvajú enormné množstvo pasívneho stavebného prášku. Tomu sa dá predísť ak sú modely, v prípustných prípadoch , navrhované ako škrupiny. Príspevok sa zaoberá ekonomickým zhodnotení kompaktných a škrupinových modelov v procese 3D tlače. Hodnotenie odhalilo, že škrupinové modely sú lacnejšie iba v prípadoch, ak obsahujú voskom. Pre ostatné infiltranty nie je medzi kompaktným a škrupinovým modelom výrazná cenová úspora. Dokonca škrupinové modely sú drahšie oproti kompaktným, obzvlášť pri rastúcej veľkosti základne.

Kľúčové slová: 3D tlač, kalkulácia nákladov, rýchle prototypovanie

1 Introduction

Three-Dimensional Printing (3DP) is the one of Rapid Prototyping (RP) technologies. It combines a layered approach from RP technologies and a conventional ink-jet printing. A 3D printer prints a binder fluid through the conventional ink-jet print head into a powder, one layer onto another, from the lowest model's cross-section to the highest.

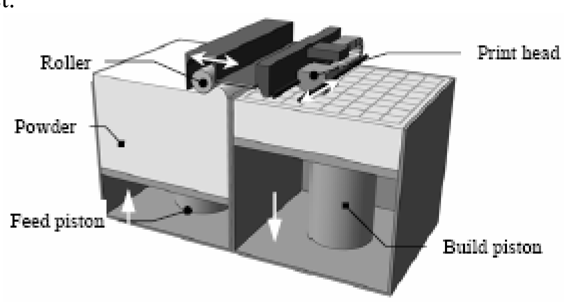

Fig. 1 *3D printing*
Fig. 2 *3D tlač*

Inside the printer, there are two pistons: feed and build piston (*Fig. 1*). To begin the 3D printing process, the printer spreads a layer of powder of the same thickness as the crosssection to be printed.

The print head then applies a binder solution to the powder, causing the powder particles to bind to one another and to the printed cross-section one level below. The feed piston comes up and the build piston drops one layer of the thickness. The printer then spreads a new layer of powder and repeats the process, and in a short time, the entire part is printed [1]. After printing, the part is removed from the powder bed, depowdered and dried.

When compact or solid model is printed on the 3D printer, the printer does not distribute the binder uniformly in powder. Binder is printed in a higher concentration at the edges of the part, creating a shell around the exterior of the part. Inside the part, the printer builds an infrastructure by printing strong skeleton within part walls with a higher binder concentration. The rest of interior is printed with lower binder saturation.

Printed model could be infiltrated with cyanoacrylate, epoxy resin or wax to achieve better mechanical properties. Cyanoacrylate gives good mechanical properties in the shortest time, but is most expensive. Epoxy resin also gives good mechanical properties, somewhat slower but nevertheless cheaper then the cyanoacrylate. Cyanoacrylate and epoxy resin do not penetrate through the entire model, but only 2 to 8 mm deep. Wax gives the weakest models but it is fast, convenient and several times cheaper then cyanoacrylate. It penetrates through the entire model.

Therefore, if cyanoacrylate or epoxy resin are used, model could be considered as a strong shell filled with a weak mixture of powder and binder. In such circumstances, powder captured inside the model could be considered as passive powder and shell model might be a rational way to avoid passive powder and thus reduce printing cost [2, 3]. For this reason, we set up a hypothesis that shell models reduce printing cost in the 3D printing. In this paper, we performed a cost evaluation of compact versus shell models in 3D printing process. Evaluation was performed for the 3D printer model 310 from Z Corporation, powder zp130, binder zb56 and infiltrants: cyanoacrylate Loctite 406, epoxy resin Loctite 9483 and usual wax Cera Alba.

2 Models

Two sets of models are being considered: compact models and shell models (*Fig. 3*). The compact model set contains four cube-models with four different base dimensions: 50, 100, 150 and 200 mm. For convenience, compact models are labelled with C before base size number, e.g. C50.

The shell model set contains similar four cube-models, but with opened bottom faces. Top and side faces are designed as thin walls with 4 mm wall thickness. Internal ribs are added to models in orther to increase their strength. Internal ribs' thickness is equal to outer walls' thickness. The wall thickness is determined according to a minimum expected infiltrant penetration [4]. Shell models are labelled with S before base size number, e.g. S50.

Prior to the cost calculation, basic model properties are calculated in the printer software [4]. Properties are presented in tables separately for compact models (Tab. 1) and for shell models (Tab. 3). For shell models, the last dimension (4 mm) is the wall thickness. It is interesting to notice that printing times are same for compact and equivalent shell models. The printing time mostly depends on the number of printed layers per model.

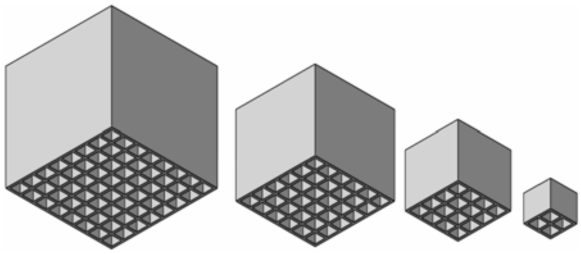

Fig. 3 *Shell models*
Obr. 4 *Škrupinové modely*

Tab. 1 *Properties of compact models*
Tab. 2 *Vlastnosti kompaktných modelov*

Model	Dimensions [mm]	Volume [cm^3]	Surface [cm^2]	Printing Time [hh:mm]
C50	50×50×50	125	150	1:16
C100	100×100×100	1000	600	3:11
C150	150×150×150	3375	1350	5:55
C200	200×200×200	8000	2400	9:52

Tab. 3 *Properties of shell models*
Tab. 4 *Vlastnosti škrupinových modelov*

Model	Dimensions [mm]	Volume [cm^3]	Surface [cm^2]	Printing Time [hh:mm]
S50	50×50×50×4	59	290	1:16
S100	100×100×100×4	386	1829	3:11
S150	150×150×150×4	1202	5625	5:55
S200	200×200×200×4	2728	12686	9:52

3 Cost calculation

3D printing cost consists of powder cost (C_p), binder cost (C_b), infiltrant cost (C_i), machine cost (C_m) and operator cost (C_o). Total printing cost is a sum of these costs:

$$C = C_p + C_b + C_i + C_m + C_o \qquad (1)$$

Powder cost is a product of the printed model volume and the powder price. Binder cost is product of the used binder volume and the binder price.

Infiltrant cost depends on the type of infiltrant used. For cyanoacrylate and epoxy resin, it is calculated by formula:

$$C_{ice} = \frac{0{,}2 \cdot S \cdot P_i}{5} \qquad (2)$$

Where S is the model surface; P_i is the infiltrant price; multiplier 0,2 designates a minimum expected infiltrant penetration into the model; and divisor 5 designates porosity i.e. available space for infiltration inside the model. For wax, since it penetrates through the entire model, the infiltrant cost is calculated by formula:

$$C_{iw} = \frac{S \cdot P_i}{5} \qquad (3)$$

Machine cost is a product of printing time and a printer's amortization price per hour. Operator cost is a product of the operator time and operator's wage per hour. The operator's time includes time used for machine preparation and time for machine cleaning as well as time used for a model post processing.

4 Results

Cost calculation for all considered models is presented in diagram (*Fig. 5*). Please note that in order to preserve confidentiality, relative total cost is used. Total cost for a particular model is related to compact model C50 infiltrated with cyanoacrylate (labelled C50C), i.e. total printing cost of a particular model is divided by total printing cost of reference model:

$$RC_n = \frac{C_n}{C_{C50C}} \qquad (4)$$

In diagram, models are grouped by base size, then by model type and eventually by infiltrant type. Consequently, next to the bar that represents relative total cost of the compact model infiltrated with cyanoacrylate is a bar of shell model with the same infiltrant.

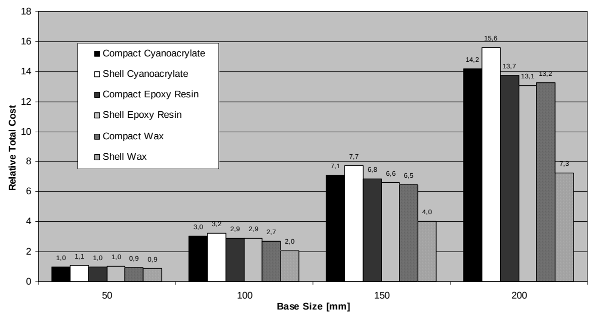

Fig. 5 *Total costs related to compact model C50 infiltrated with cyanoacrylate*
Obr. 6 *Celkové náklady kompaktného modelu C50 obsahujúceho kyanoakrylát*

From the diagram of total cost, it can be seen that differences in total costs among models and infiltrant types are increasing as the base size of the model is increasing, but not proportionally regarding base size nor regarding particular infiltrant. To reveal the cause of the different increase, a cost structure should be considered. Therefore, costs structure regarding particular infiltrant is presented in following figures: *Fig. 7* – cyanoacrylate; *Fig. 9* – epoxy resin and *Fig. 11* – wax.

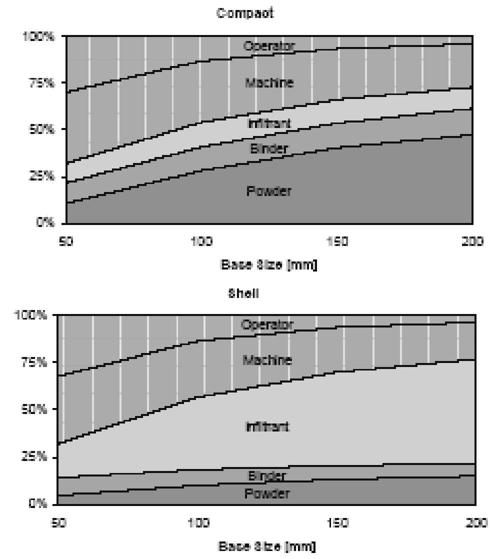

Fig. 7 *Costs share of models infiltrated with cyanoacrylate*
Obr. 8 *Rozdelenie nákladov modelov obsahujúcich kyanoakrylátom*

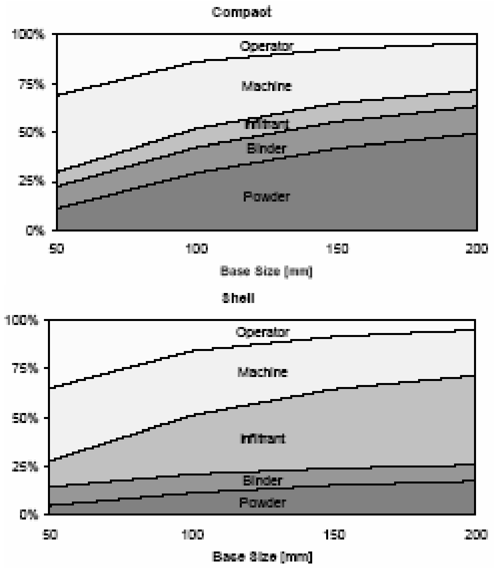

Fig. 9 *Costs share of models infiltrated with epoxy resin*
Obr. 10 *Rozdelenie nákladov modelov obsahujúcich epoxy resin*

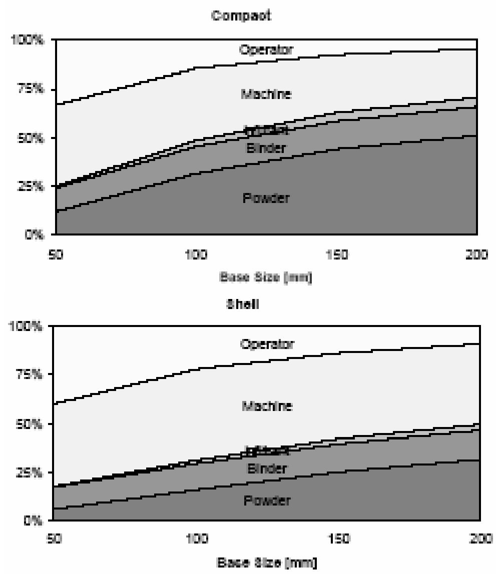

Fig. 11 *Costs share of models infiltrated with wax*
Obr. 12 *Rozdelenie nákladov modelov obsahujúcich vosk*

5 Analysis of results

Results of total costs show that there are no significant cost differences for small models, whether compact or shell type or infiltrants are considered. From all cost share diagrams, it is clear that infiltrant and powder costs have small shares in total printing costs for small models. Operator and infiltrant costs have major shares for small models.

As the base size of the model is increasing, infiltrant and powder shares in total printing costs are increasing extensively for almost all model types and infiltrants. Exceptions are shell models infiltrated by wax that have a lesser increase of shares then other models. The reasons for this are a low price of wax and a low powder share in shell models. The price of wax is more than 40 times lower than the price of cyanoacrylate.

Cost differences are the highest for the biggest models. The biggest waxed shell model is more than twice cheaper than the biggest cyanoacrylated shell model and almost twice than the biggest cyanoacrylated compact model.

If the focus is set on cost differences among compact and shell models, then it could be noticed that there is no significant differences neither among cyanoacrylated models nor among models infiltrated with epoxy resin. This is valid for all considered base sizes.

However, differences among waxed compact and waxed shell models are considerable starting from the base size of 100 mm and increase with the size.

6 Conclusions

In primary hypothesis, we assumed that shell models instead of compact models could lower the costs of 3D printing. After the cost calculation and the analysis of results, it is clear that shell models lower the printing costs only if models are infiltrated by wax. For all other infiltrants, there is no significant difference between shell and compact models. Furthermore, shell models are somewhat costlier than the compact models, especially as the base size is increasing.

Therefore, if the printing cost is more important than model strength and a specific application of model allows it, shell models infiltrated by wax should be used. For the fastest fabrication and the best strength, the compact model infiltrated with cyanoacrylate is the first choice. If a fabrication speed is not crucial, the compact model infiltrated with epoxy resin could be considered.

Although it is possible that some of presented conclusions could be valid for similar machines or rapid prototyping techniques like [5], all conclusions should be considered only for selected 3D printer and selected materials. We should also keep in mind that new powder-; binder- and infiltrant-materials for 3D printing technique are produced every year. New materials demand new cost calculations and new analysis.

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Tomislav Galeta, PhD ME
Superior Assistant
Mechanical Engineering Faculty
Gunduliceva 20A, Slavonski Brod, Croatia
Telephone: +385 35 493439 Telefax: +385 35 446446
tgaleta@sfsb.hr, www.sfsb.hr

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