EVALUATION OF 3D PRINTED AEROFOIL MODELS FOR WIND TUNNEL TESTING

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1. INTRODUCTION

1.1. AIM OF THE STUDY AND MOTIVATION

3D printing, as an additive process, offers much more than traditional machining techniques in terms of achievable complexity of a model shape. That fact was a motivation to adapt discussed technology as a method for creating objects purposed for aerodynamic testing. The following paper provides an overview of various 3D printing techniques. Four models of a standard NACA0018 aerofoil were manufactured in different 3D printing methods: Multi-Jet Modelling (MJM), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). Various parameters of the models have been included in the analysis: surface roughness, dimension tolerance, strength, details quality, surface imperfections and irregularities as well as thermal properties.

1.2. 3D PRINTING AND AERODYNAMIC STUDY

Preparation of an appropriate model to conduct experiments is a crucial aspect of every science investigation. Usually, apart from the requirement to achieve a desired level of a model quality, it is also very important to keep in mind the costs and time of its manufacturing. Recently, development of technologies made the production of even very complicated objects simpler, cheaper and less time consuming. One of such techniques that can simplify life of every researcher seems to be a 3D printing (an example of additive manufacturing). This method of fabrication is a process of making

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a three-dimensional solid objects from a digital model. 3D printing is an additive process, where successive layers of material are laid down in controlled way in order to achieve desired shape. 3D printing is often put in opposition to traditional machining techniques, which mostly rely on the removal of material by methods such as drilling, turning, milling or cutting. The 3D printing has begun to exhibit great applications potential and advantages in the aerospace, construction, architecture, automotive, power engineering, dental and medical industries, biotech (human tissue replacement), education and many other fields providing a cost-effective and time-efficient way to produce low-volume, customized products with complicated geometries and advanced material properties.

In aerodynamic experiment a crucial factor is proper preparation of tested elements surface. Various 3D printing techniques provides different quality and surface finish which is not always acceptable for certain application [1]. The following paper attempts to review chosen properties of rough 3D printouts and analyse them.

2. MODELS MANUFACTURING

2.1. TECHNOLOGIES AND MATERIALS

Aim of the research carried out was to evaluate the utility of most common 3D printing techniques for aerodynamic study. Similar field has been already explored by various research centres (e.g. [2], [3]). In order to perform a reliable comparison of most common 3D printing methods, four models of standard NACA0018 aerofoil have been created in various materials and technologies: Multi-Jet Modelling (MJM), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). Each of them is described briefly in table 1. The most crucial factor defining the 3D printing technology and influencing the properties of final product manufactured is the type of bulk material used. Depending on the fact whether a solid filament is extruded (FDM), fine powder is laser-sintered (SLS) or liquid is solidified by means of UV light curing (MJM), models of various quality and properties are obtained.

Tab. 1. The overview of the most popular printing techniques and materials

Type	**Technology**	**Materials**
Extrusion	Fused deposition modeling (FDM)	Thermoplastics: PLA, ABS, nylon
Granular	Selective laser sintering (SLS)	Thermoplastics, metal powders, ceramic powders
Liquid	Multi Jet Modeling (MJM)	Acrylic Plastic

Materials used for printing models discussed in this paper were as follows: ABS – in FDM technology, nylon and alumide (blend of nylon and aluminium) – in SLS technology and UV curable acrylic plastic – in MJM technology.

Table 2 presents the most significant parameters of discussed materials and 3D printing techniques [4], [5], [6].

Tab. 2. 3D printing materials data

	Alumide	**PA 2200 (nylon)**	**UV curable acrylic plastic**	**ABS**
3D printing technology	SLS	SLS	MJM	FDM
accuracy	±0.15*mm*	±0.15*mm*	±0.025-0.05*mm*	- [a]
min. wall thickness	0.8mm	0.7*mm*	0.3*mm*	- [a]
density	1.36g/cm^3 [b] 0.67g/cm^3 [c]	0.93g/cm^3 [b] 0.45g/cm^3 [c]	1.02g/cm^3	1.05g/cm^3
tensile modulus	3800*MPa*	1700*MPa*	1108*MPa*	1627*MPa*
tensile Strength	48*MPa*	48*MPa*	26.2*MPa*	22*MPa*
flexural modulus	3600*MPa*	1500*MPa*	n/d	1834*MPa*
flexural strength	72*MPa*	58*MPa*	26.6*MPa*	41*MPa*
elongation at break	4%	24%	9%	6%
shore D - hardness	76	75	n/d	n/d
thermal properties	172-180°*C* (melting point) 177°*C* (heat deflection temp. at 0.45*MPa*)	172-180°*C* (melting point)	46°*C* (heat distortion temp. at 0.45*MPa*) 80°*C* (heat softening temp)	190-240°*C* (melting point) 90°C (heat deflection temp. at 0.45*MPa*)
recycling	non recyclable	recyclable	most recyclable	recyclable

[a] FDM accuracy depends on filament thickness and layer structure [8], [9], [b] laser-sintered part density, [c] bulk density

2.2 AEROFOIL DESIGN

Aerofoil with complex structure adapted for aerodynamic study has been designed and printed in 4 different materials described in previous section. Model dimensions are 100mm chord and 170mm span. Additionally two side segments have been manufactured with MJM technique. Segments assembled with the aerofoil extend its span to 300mm. As only central part of the assembly is used for measurements, side segments were printed in one technology (MJM with high definition in opposition to ultra-high definition option used for printing central element) and can be applied with all 4 testing models. Aerofoil wall thickness along its circumference is constant and equals 4mm. In the Figure 1 printed aerofoils are shown.

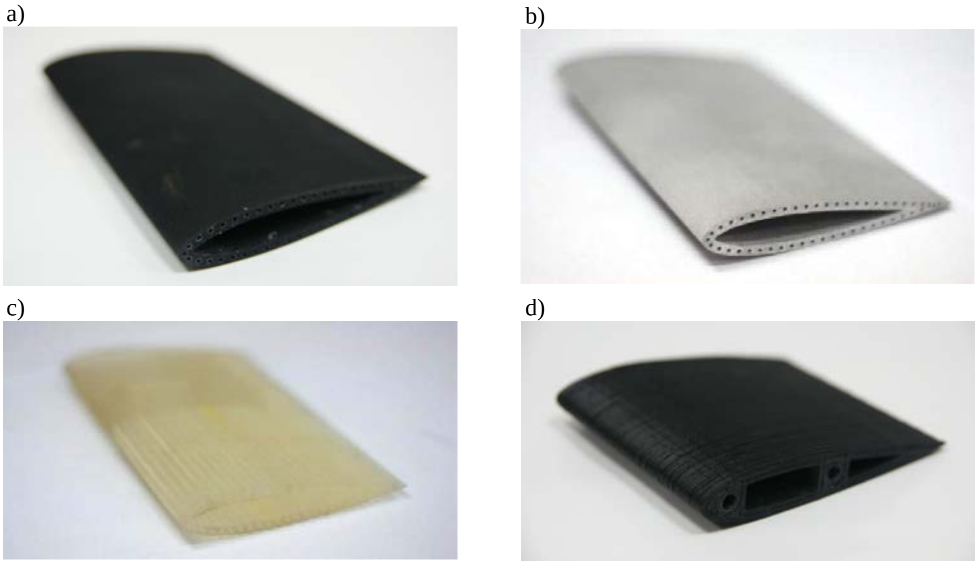

Fig. 1. Examples of 3D printed NACA0018 aerofoil models in (a) SLS (black PA2200), (b) SLS (alumide), (c) MJM, (d) FDM technology

3. MODELS EVALUATION

3.1. GENERAL OVERVIEW

Printed models differs visually from each other as it is shown in Figure 2. Preliminary evaluation of models quality has been performed. Most findings and observations are listed in Table 3.

Tab. 3. NACA0018 aerofoil models 3D printouts evaluation.

	MJM	**SLS**	**SLS (alumide)**	**FDM**
color/opacity	translucent	black	silver (shiny)	black
surface roughness	low	moderate	moderate	high
surface irregularities direction	chordwise	uniform	uniform	spanwise
ϕ 1.5mm holes quality	most open	blocked	most open	excluded from design
ϕ 0.4mm holes quality	most open	blocked	blocked	excluded from design

3.2. DIMENSIONS’ ACCURACY

In order to check quality of printed models and quantify level of fidelity with respect to design, measurements of models dimensions have been taken. 3 dimensions have been checked: chord length, aerofoil thickness and model shell thickness (in CAD design respectively equal to 100*mm*, 18*mm* and 4*mm*). Serial measurement with a standard calliper of accuracy 0,01*mm* has been taken. Average results of measurements with uncertainty and relative difference (with respect to design) are presented in Table 4. As it can be seen most of dimensions are well represented with deviation from original design no larger than 1%. An exceptionally worse result has been noted for Alumide printout regarding the shell thickness. It can be noticed as well that for FDM printout (even visually mostly inaccurate) the highest measurement uncertainty has been obtained. This is mostly caused by large irregularities of the surface influencing significantly serial measurement. The lowest deviation of results with respect to CAD design was achieved by means of SLS technique (black nylon printout).

Tab. 4. 3D printouts dimensions' accuracy.

	chord c			**thickness t**			**shell thickness s**		
	c_i [mm]	$U_c(c_i)$ [mm]	Δc_i [%]	t_i [mm]	$U_c(t_i)$ [mm]	Δt_i [%]	s_i [mm]	$U_c(s_i)$ [mm]	Δs_i [%]
MJM	99,59	0,03	-0,41%	18,12	0,04	0,67%	4,04	0,01	0,99%
SLS	99,52	0,03	-0,48%	18,01	0,02	0,06%	4,01	0,02	0,25%
SLS (Alumide)	99,78	0,02	-0,22%	17,86	0,02	-0,78%	3,86	0,02	-3,47%
FDM	100,0	0,1	0,00%	17,46	0,05	-3,00%	4,03	0,06	0,74%

3.1. SURFACE ROUGHNESS

During the evaluation procedure surface roughness of models has been also measured. Measurements were taken by means of Hommel T500 portable roughness tester. Each measurement was realised by taking approx. 300 samples at distance l_t=4,8*mm* and averaged in order to calculate Ra roughness value. Results are presented in Table 5. Due to manufacturing process (adding material layer by layer) various roughness value have been obtained depending on measurement direction. Two cases – chordwise and spanwise – have been investigated. Measurement was not possible in case of FDM printout for chordwise direction due to too excessive irregularities of the surface.

As it can be seen the smallest roughness was obtained for models printed in MJM technology. Ultra high definition MJM technique gives results comparable to roughness of aluminium aerofoil manufactured by means of electrical discharge machining. In case of MJM UHD technology direction-dependent nature of roughness is visible (spanwise roughness over 3 times smaller than chordwise one). SLS printouts Ra roughness vary within a range of 8,5–11*µm* which corresponds to surface quality achievable by rough subtractive machining. FDM printout is characterised by very high roughness value which is obvious due to manufacturing process nature (printing with a melted plastic wire of diameter in the range of 0,1–0,5*mm*).

Tab. 5. 3D printouts surface roughness

	Ra	
	chordwise	spanwise
MJM UHD	2,1	0,60
MJM HD	2,4	3,3
SLS	8,5	11
SLS (Alumide)	9,6	8,5
FDM	n/d	23
Aluminium*	0,84	1,5

4. SUMMARY AND CONCLUSIONS

Summarising presented study following observation and conclusions can be drawn:

- Roughness and dimension accuracy have been measured showing the level of quality of particular 3D printing technologies.
- As it was shown roughness of printed models depends on the direction due to nature of additive manufacturing (layer by layer model formation).
- A satisfactory level of dimension tolerance was achieved in case of all 3D printing technologies.
- A wide range of materials and technologies with various features and parameters are available.
- Thin-walled and tough models have been successfully manufactured.
- Certain 3D printed models are suitable for only limited temperature range. Otherwise they can soften, deflect, deform, etc.

LITERATURE

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