Tensile strength and dimensional variances in parts manufactured by sla 3D printing

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Abstract: *With the rise of additive manufacturing (AM) technologies, a numerous limitations in conventional manufacturing have been circumvented. Additive manufacturing uses layer-by-layer fabrication of three-dimensional physical models directly from a computer-aided design (CAD) model. The CAD design is transformed into horizontal cross-section layers that are stacked together in physical space until the physical model is completed. This process can be used to directly manufacture tools for injection molding or for any other technology that requires a specific cavity shape to produce a part. This is referred to as Rapid Tooling (RT) and one of the up and coming AM technologies is the resin based stereolithography (SLA).*

An increasing number of companies are starting to develop desktop machines that utilize this technology and their low cost and high speed changes the design workflow. As a printing technology, SLA creates parts with a smooth surface finish which is ideal for applications such as investment casting for developing jewelry or rapid tooling for injection molding.

The development of rapid tools using SLA usually requires more rigid materials which can withstand higher temperatures and stresses and part models that need to have more accurate dimensions in order for a precise part to be produced from that specific tool. Even though models created by SLA have more isotropic characteristics compared to other 3D printing technologies, there are still some variations linked to the process parameters. This paper covers how orientation of the model on the build plate impacts the part accuracy and the tensile strength of the models. The effects of different post-processing procedures after SLA printing are also taken into consideration, since most resins need to be UV cured after 3D printing in order to achieve maximum mechanical strength.

This paper gives designers and engineers better understanding on the final properties of the models and the tolerances that have to be taken into consideration when designing parts intended to be manufactured via SLA 3D printing.

KEYWORDS*: ADDITIVE MANUFACTURING, 3D PRINTING, TENSILE STRENGTH, STEREOLITHOGRAPHY, SLA*

1. Introduction

In regard to prototyping and small series production, the advancements in additive manufacturing have made great strides and have changed the way we approach new products development. The limitations of industrial machines like purchase costs, maintenance fees and technical expertise are more or less circumvented by the introduction of desktop 3D printing mainly based on the FDM (Fused Deposition Modelling) and SLA (stereolithography) technologies.

SLA 3D printing in particular has created major opportunities for designers and engineers to evaluate more options and iterations of their designs since the print resolution of that technology can be up to 25 µm thus offering more precision and finer details on the models.

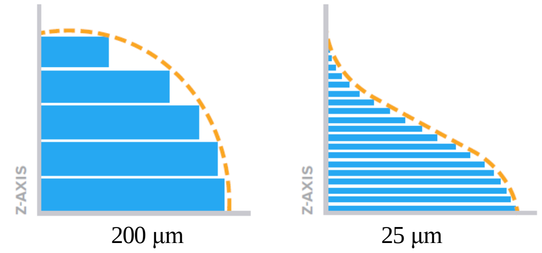


Fig. 1.1 *Layer thickness on surface finish– schematic representation (Source: [5])*

The surface finish on SLA compared to FDM while printing is also different and this is due to the way the layers are built.

In FDM, the build material is a prefabricated filament that is wound up and stored in a cartridge from which it is continuously fed to the extrusion head. In the head, the material it is partly molten by an electric heating system and extruded through a nozzle that defines the string diameter that nearly equals the layer thickness. Usually, string diameters range from 0.1 mm to 0.4 mm. The platform moves in z- direction and defines the layer thickness, as the material is squeezed on the top of the partly finished part [7]. This mainly limits the possible surface quality that is possible to be achieved using this manufacturing technology.

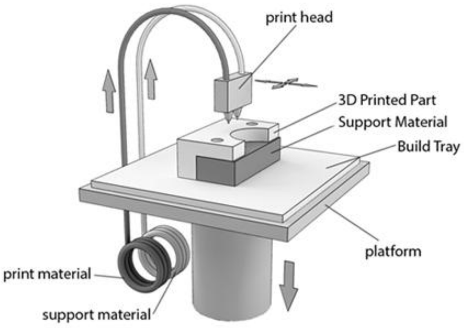


Fig. 1.2 *Fused Deposition Modeling (FDM) – Schematic (Source: https://www.dddrop.com)*

SLA on the other hand, is not only the oldest but also still one of the most detailed additive manufacturing process and delivers parts with very good surfaces and fine details. The parts are created by local polymerization of the initially liquid monomers. Initiated by a UV-laser beam, the polymerization turns the liquid into a solid, leaving a scaled solid layer. The laser beam is directed by a galvo-type scanning device that is controlled according to the contour of each layer. A typical machine can be seen in Fig. 2.3, left. After the build, the part is cleaned and finally fully post-cured in a UV chamber (postcuring oven). [7]

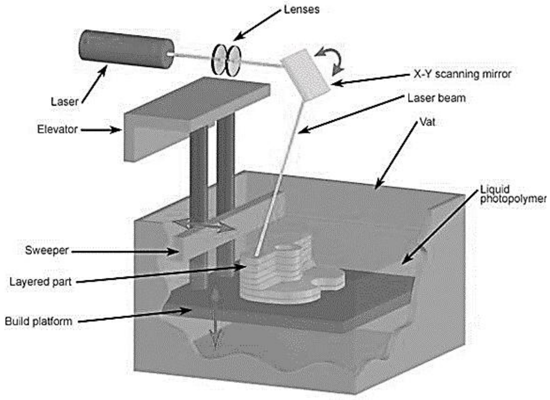


Fig.1.3. *Stereolithography (SLA) – Schematic (Source:http://www.custompartnet.com)*

Even though, SLA is the older technology, the affordability of FDM 3D printers, mostly due to their simpler design and cheaper parts has made them more widespread so most research on the influence of part orientation on strength is done on that technology. The need to post-process the SLA parts with UV curing also adds another level of complexity. The UV curing and furthermore any additional thermal post-processing causes some shrinkage on the part that needs to be taken into consideration when designing parts for assembly.

The surface quality of the printed parts is also mainly dependent on the part orientation during printing. The surface quality doesn't only affect the visual properties but also the roughness of the finish which is important in certain application of 3D printed parts.

For example, one of the most common sources of failure in molding inserts produced with SLA 3D printing has been described as the result of the molded parts features contacting the core inserts, thus causing these features to break during ejection [1]. This is due to the friction forces between the molded plastic and the inserts. Low tool strength especially at elevated temperatures has been cited as a contributory factor to failure and an FEA model on proper draft selection has been covered in the research of Harris et.al [2]. This means that the proper orientation of the models during printing not only influences appearances but has other implications depending on the application in question.

Furthermore, the process by which a layer is created has a dramatic impact on the quality and physical properties of the final part. A part printed at 100 micron layers on an FDM printer looks different from a part printed at 100 micron layers on an SLA printer, because of the way the layers are built.

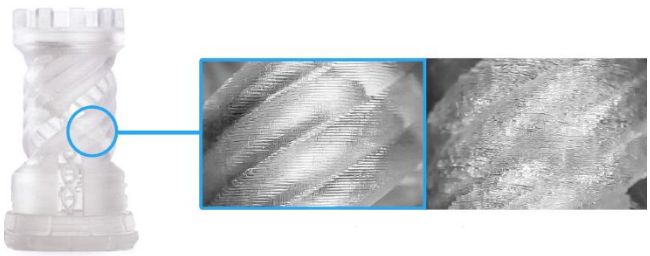


Fig. 1.4. *100 µm resolution print; SLA parts (left) have a better surface finish than FDM prints (right). (Source: [4])*

The aim of this article is to provide engineers and designers with some information about the influence of various part orientations and their influence on the strength properties of parts printed using the SLA technology. Since the experiment is done on multiple specimens

2. Mechanical strength depending on the 3D printing technology

There are a lot of different factors that need to be taken into consideration when preparing a part for 3D printing, especially if that part is supposed to withstand higher stresses. Among them is the orientation of the model on the build plate and minimizing overhangs that require supports. The orientation of the parts on the build plate is extremely important for the mechanical properties because they tend to vary with respect to direction. When building a part using any additive manufacturing technology the main parameter that determines the final physical properties is the way layer adhesion is achieved which differs from technology to technology. This anisotropic behavior is already pretty researched when it comes to FDM 3D printing but when it comes to SLA, the mechanical properties are more uniform.

2.1. Anisotropy in FDM parts

Since FDM 3D printing is based on building with extruded plastics, layer adhesion is achieved by mechanical bonds. The final part is produced from multiple linear layers and will have anisotropic properties regardless of its orientation on the build plate.

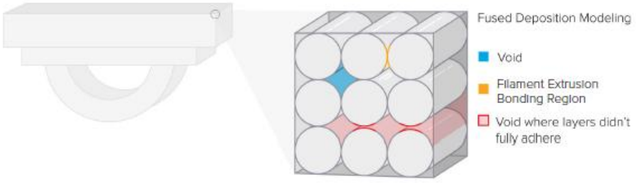


Fig. 2.1. *Composite matrix of a FDM part – Schematic (Source: [4])*

FDM 3D printers form layers by depositing lines of PLA or ABS. This process means that layers are not bonded together as strongly as the lines (filament extrusion) themselves; there are voids in between the rounded lines and it's possible that layers may not fully adhere to one another. [4]

On figure 2.1 it's shown that the surfaces of each layer are not completely adhering to one another. Even when the previous layer is still heated, the new layers only have partial adhesion and as a result the final part is anisotropic and has a smaller density compared to the parts produced with other polymer processing technologies like injection molding.

For this reason it is extremely difficult to obtain a completely enclosed and waterproof part with FDM 3D printing because there are always microscopic gaps in the porous matrix of the part. When bonds are considered at the molecular level, clear differences appear between the intermolecular forces in each extruded line and the bonding forces that bind the individual layers together. Each individual polymer extrusion line is composed of fairly rigid and intertwined high-strength polymer chains. As additional lines are extruded to or above the previous extrusion, it is almost impossible to establish equal contact between the previously applied plastic and therefore locations with lower strength and stiffness appear.

This means that if the direction of extrusion of the filament is taken into account, the final printed part will have the highest strength in the direction of the extruded lines, and its mechanical properties will be lower in the directions in which the interface regions of the part are oriented. Namely, these are the two axes normal to the direction of the extruded line.

The conclusion from this phenomenon is that the parts obtained with FDM technology of additive manufacturing are anisotropic, have different mechanical characteristics in different directions and their build plate orientation has a great importance on their functionality, especially in cases when they are to be used as functional parts and should withstand some load.

2.2. Anisotropy in SLA parts

In the SLA additive manufacturing technologies where the material is a liquid photopolymer resin there are almost no differences between the chemical bonds between the molecules of each separate layer and the neighboring layers.

While the model is being built, the monomer of the resin form covalent bonds between each other forming each layer. Because the polymerization process is not fully finished and the part is kept in a so called “green state”

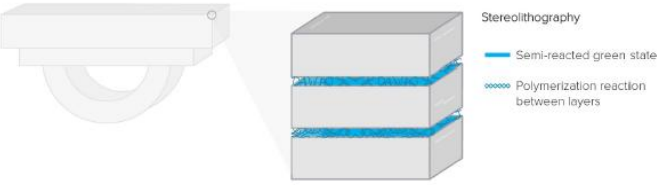


Fig. 2.2. *Continuous polymer matrix of a SLA part – Schematic (Source: [4])*

In this “green state”, the material still has free molecular strains that can be bonded to the next layer during printing. While forming each subsequent layer the polymerization reaction includes strains from the previous layers and this way covalent chemical bonds are formed in both the axial and transversal directions.

This means that on a molecular level, practically there shouldn’t be any difference between the Z axis and the XY plane due to the chemical bonds and each part produced with this technology can be seen as a singular molecule.

Despite the pronounced isotropy in the theoretical consideration of the SLA 3D printing process, some previous research has shown that there are still some mechanical differences depending on the orientation of the models. These differences, although insignificant, are mostly caused by small deviations in the movements of the printer along the X, Y and Z axes.

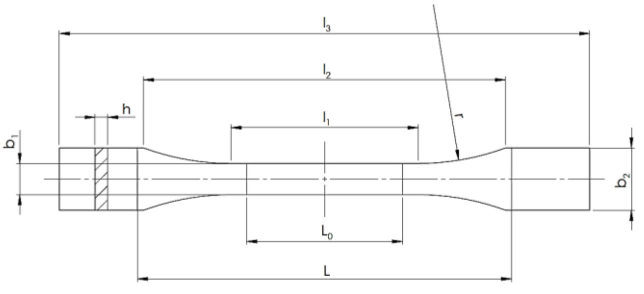
The influence of model orientation on the mechanical strength of printed parts has been examined in the research of Barclift and Williams [10], Cazon et. al [9] and in the Formlabs internal study [4]. [9] and [10] used the Stratasys PolyJet technology, while [19] used a Form2 SLA printer.

3. Methods

3.1. Tensile test

A tensile test is the most fundamental type of mechanical test where a testing sample is subjected to uniaxial tension until failure.

The tensile test of each specimen was done according to the guidelines in the standard EN ISO 527-2:1996. The 1BA test specimen used and its dimensions are shown in Figure 3.1.



Type of specimen [mm]		**1BA**
l_3	overall length	≥75
l_1	length of narrow parallel-sided portion	30 ± 0,5
r	radius	≥30
l_2	distance between broad parallel-sided portions	58 ± 2
b_2	width at ends	10 ± 0,5
b_1	width of narrow portion	5 ± 0,5
h	thickness	≥2
L_0	gauge length	25 ± 0,5
L	initial distance between grips	l_2^{+2}

Fig. 3.1 *1BA tensile testing specimen (Source: [9])*

Each specimen was printed on a Formlabs Form2 SLA 3D printer using the HighTemp resin. Each specimen was later washed for 6 min in an isopropyl alcohol bath and then UV cured for 120 minutes at a temperature of 80°C, as per the recommendation found in the Formlabs datasheet.

There were 8 different orientation tested (as shown in Fig 3.2 and 3.3) with 3 specimens in each group (24 total):

1. Horizontal orientation (flat) (x-y)
2. Horizontal orientation (flat) (y-x)
3. Horizontal orientation (on the side) (x-y)
4. Horizontal orientation (on the side) (y-x)
5. Vertical orientation (flat) (x-y)
6. Vertical orientation (flat) (y-x)
7. 45° inclination (x-flat)
8. 45° inclination (x-side)

The test was one on a Shimatzu Autograph AGS-X series machine with a load cell capacity of 10 kN with a crosshead speed of 1 mm/min.

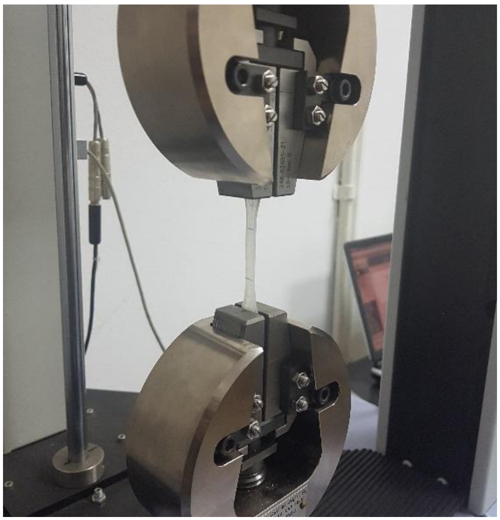


Fig. 3.2 *Test specimen placed inside the grips of the Shimatzu Autograph AGS-10kN*

From each of the test pieces the ultimate tensile stress was calculated as:

$$\sigma_m = \frac{F}{A_0}$$

where F is the force and A_0 is the starting cross-section area ($b \ x \ h$) of 10 mm^2.

From each of the test pieces the relative strain was calculated as:

$$\varepsilon = \frac{L - L_0}{L_0}$$

where L_0 is the initial gauge length of 25 mm and L is the length that corresponds with σ_m.

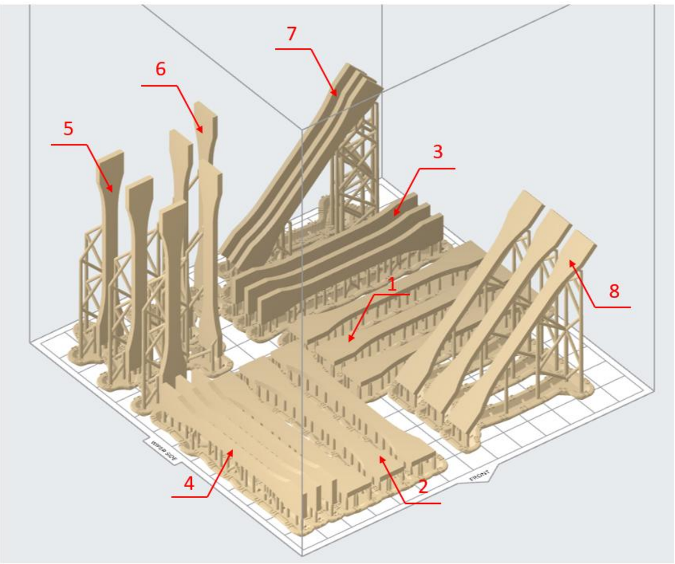


Fig. 3.3 *Different orientation of the test pieces in the Formlabs PreForm slicing software*

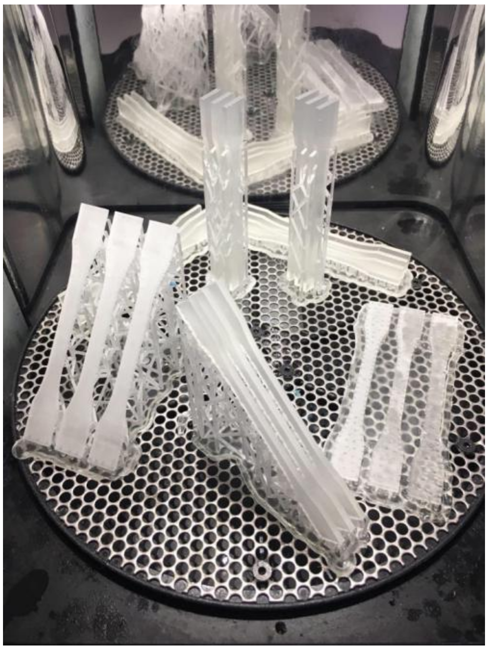


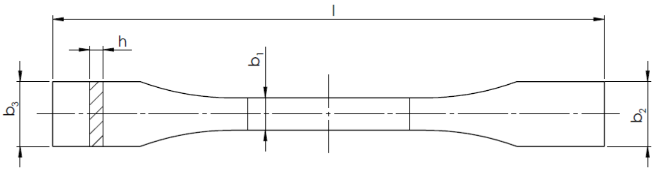
Fig. 3.4 *Different orientation of the test pieces during curing*

All experimental results from the tensile testing are shown in table 4.1 and are plotted on the histograms in figures 3.5 and 3.6 together with the standard error that is within 92% confidence interval. The results show a slight anisotropy in the mechanical strength with the highest UTS being measured in the specimens from group G that are oriented with a 45 degrees inclination on their flat side.

As far as the elongation at break, the High Temp resin is fairly brittle so only a small elongation and strain was measured with almost no plastic deformation on the parts.

3.2. Dimensional variations

Since the mechanical test is done on 24 different speciments, the 5 linear dimensions shown in Fig. 3.5 of each of the specimens were measured. This totals 120 measurements of different linear dimensions. Each measurement was taken 3 times at 3 different points and an average of the 3 measurements is presented for each dimensional control in table 3.2.



Measurements for dimensional control	
l	overall length
h	thickness
b_1	width of narrow portion
b_2	width at end 1
b_3	width at end 2

Fig. 3.5 *Measurements for dimensional control*

The standard deviation for all controlled dimensions is around 0,1 except the one for the largest measurement (overall length *l*) that is 0,270. However the % error for all measurement is below 1% as shown in Fig. 3.7

4. Conclusion and further research

Using SLA 3D printing technologies it is possible to produce extremely fine detail in the parts. The detail of these prints is in part determined by the models orientation during printing. The orientation also influences the surface finish that is important in certain applications like 3D printing molds for casting or injection molding.

This is especially important when the application involves printing with photopolymeric resins that need additional thermal postprocesing aside from the standard UV curing like the HighTemp Formlabs resin. Specifically with the HighTemp resin, the heat treatment raises the maximal heat deflection temperature of the material but it influences the mechanical characteristics like the strength and max elongation as well. If the resin is used for production of injection molding inserts, this has to be taken into account during the design process.

Despite the relative isotropic nature of the layer binding during SLA there are still some variances in strength (up to 10 %) in different print orientations.

Further research into the topic can be done by using different materials and test the strength according to different level of curing. As for the dimensional testing of the tolerances, the reaserch can be expanded to cylindrical surfaces, holes and interaxial dimensions.

Table 3.1: *Tensile testing results for the 24 specimens depending on the printing orientation*

	Ultimate tensile stress [MPa]	Ultimate tensile stress - Mean	Standard deviation	Relative strain [%]	Relative strain Mean	Standard deviation
A: Horizontal orientation (flat) (x-y)	39,00	**39,19**	**0,33**	4,56	**4,56**	**0,00**
	39,57			4,56		
	39,00			4,56		
B: Horizontal orientation (on the side) (x-y)	47,92	**44,04**	**7,62**	8,68	**7,53**	**2,67**
	35,27			4,48		
	48,95			9,44		
C: Horizontal orientation (on the side) (x-y)	36,09	**39,67**	**3,15**	4,48	**5,15**	**0,86**
	40,96			4,84		
	41,97			6,12		
D: Horizontal orientation (on the side) (y-x)	46,17	**42,24**	**3,43**	7,68	**6,03**	**1,49**
	40,60			5,60		
	39,94			4,80		
E: Vertical orientation (flat) (x-y)	49,45	**50,22**	**1,00**	8,44	**8,53**	**0,35**
	51,35			8,92		
	49,87			8,53		
F: Vertical orientation (flat) (y-x)	34,30	**39,70**	**4,67**	5,96	**7,11**	**1,14**
	42,31			8,24		
	42,47			7,12		
G: 45° inclination (x-flat)	58,95	**56,90**	**1,84**	8,80	**8,67**	**0,14**
	55,39			8,52		
	56,37			8,68		
H: 45° inclination (x-side)	33,60	**39,09**	**8,68**	4,24	**5,17**	**1,41**
	34,57			4,48		
	49,09			6,80		

Table 3.2: *Dimensional variances results for the 24 specimens depending on the printing orientation*

	l overall length [mm]	h thickness [mm]	b_1 width of narrow portion [mm]	b_2 width at end 1 [mm]	b_3 width at end 2 [mm]
A: Horizontal orientation (flat) (x-y)	74,49	2,15	4,98	9,91	9,95
	74,44	2,15	4,92	9,78	9,81
	74,39	2,18	4,87	9,87	9,87
B: Horizontal orientation (on the side) (x-y)	74,53	2,15	4,88	9,86	9,91
	74,5	2,14	4,92	9,83	9,89
	74,57	2,14	4,91	9,83	9,87
C: Horizontal orientation (on the side) (x-y)	74,5	1,95	5,05	10,08	10,07
	74,45	2,03	5,1	10,12	10,1
	74,45	1,99	5,05	10,16	10,12
D: Horizontal orientation (on the side) (y-x)	74,55	1,87	5,13	10,06	10,03
	74,51	1,87	5,08	10,02	10,06
	74,61	1,86	5,1	10,06	10,05
E: Vertical orientation (flat) (x-y)	74,61	2,02	5,11	10,05	10,11
	75,22	2,07	5,01	10,09	10,3
	75,22	2,07	5,01	10,09	10,3
F: Vertical orientation (flat) (y-x)	74,62	2,13	4,88	9,84	9,86
	74,61	2,1	4,86	9,87	9,87
	74,6	2,03	4,87	9,91	9,93
G: 45° inclination (x-flat)	74,95	2,02	4,82	9,88	9,86
	75,02	1,98	4,87	9,86	9,88
	75,04	1,95	4,88	9,89	9,86
H: 45° inclination (x-side)	74,98	1,85	4,84	9,85	9,83
	75,02	1,84	4,89	9,86	9,85
	75,07	1,86	4,87	9,86	9,91
Standard deviation	**0,272**	**0,114**	**0,100**	**0,115**	**0,141**

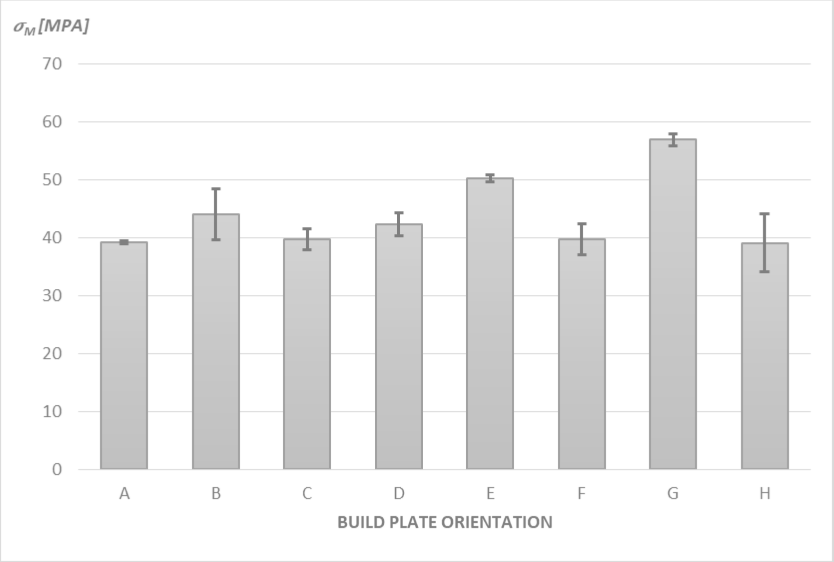


Fig. 3.5 *Mean ultimate tensile stress*

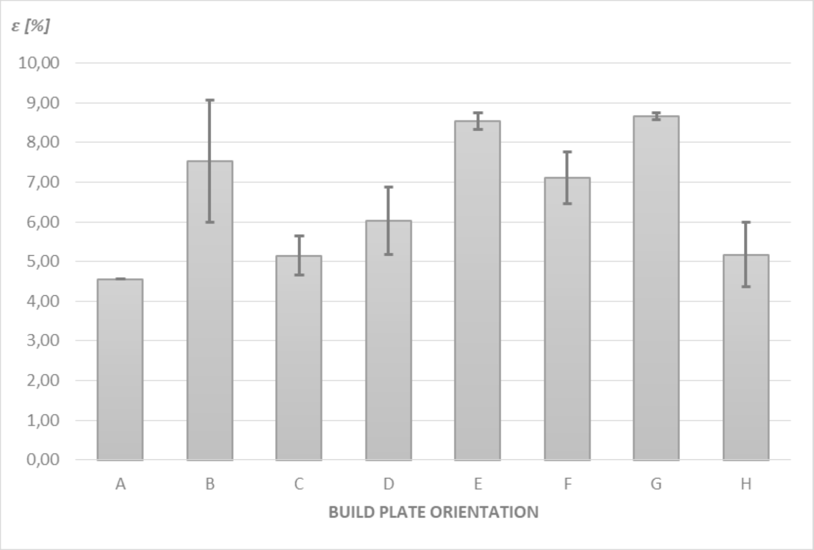


Fig. 3.6 *Mean relative strain*

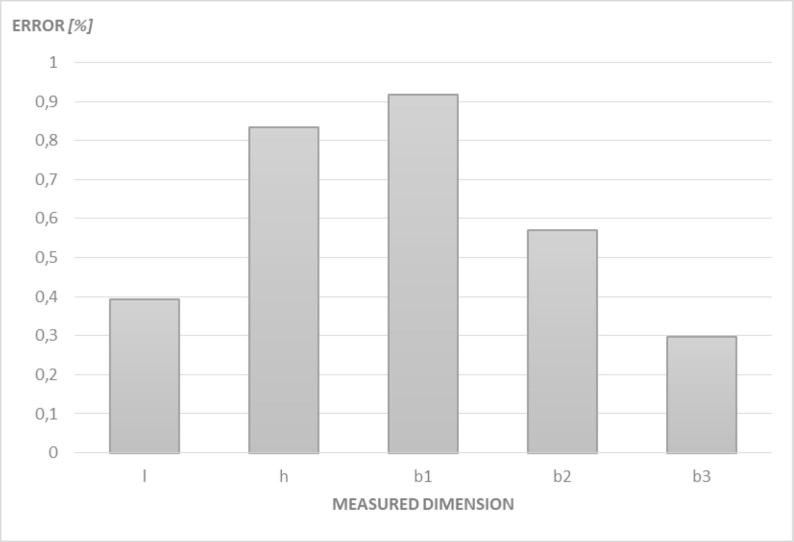


Fig. 3.7 *Measured dimensional error*

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