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Mechanical Testing of 3D Metal Printed Stainless Steel Specimens

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Abstract. Additive manufacturing (AM) is a cutting-edge production method, which has come a long way since its first introduction in the '80s. Back in the days its usage was very limited to stereolithography, and was only able to make weak structures, so it only worked for visualization. Four decades later it is one of the leading research fields in production areas, because of its flexibility and its ability to make almost any complex geometry. However, no matter how powerful it is, it is not omnipotent, there are certain size and shape restrictions even this method must apply to.

Keywords: Additive manufacturing, 3D metal printing, tensile testing, selective laser melting, powder bed fusion

Introduction

Technological advances throughout the years led to various kinds of 3D printing processes. Some of them use wire or fibre as a base material, while some of them use powder, which can be polymer, ceramic, or even metallic based, or simply liquid. Some of the processes are the following [1]:

- VAT polymerisation – liquid based
- Material extrusion – fibre (or filament) based
- Material jetting – powder based
- Binder jetting – powder (and binder liquid) based
- Powder bed fusion – powder based
- Directed energy deposition – powder or wire based

Selecting the right 3D printing process is important and may depend on our needs. If our desired product is only for visualisation or prototyping, we should choose a method which works faster, but having poor mechanical properties. If the product must withstand a certain amount of force, in a working condition, we may choose a slower, but more solid-building method. Each additive manufacturing method has its own unique characteristics, but in their essence all of them are similar and that similarity lies within the layer-by-layer addition, which the process builds up the part from the building plate.

There are a lot of studies, which focused on the printing properties of different AM methods. They usually conduct measurements towards layer thickness and building orientation [2][3][4]. The overall assessment is, that if we reduce the angle of the manufactured part, making it horizontally oriented [5], we can achieve ideal result, at least with thin-walled specimens. Round shapes are a bit trickier, but they share some of this beforementioned quality [6]. Round shapes however tend to build up less residual stress during their printing process, thus have better shape retention, while flat 3D printed pieces tend to warp, or in some extreme cases break, after or even during the process [7]. We wanted to experiment on these properties, while optimising our printing job for mechanical strength, printing time and warpage as well.

1. Materials and methods

To conclude our investigations, we selected Selective Laser Melting (SLM) as a manufacturing method. SLM technology uses a powder bed and either a laser or electron beam as the source of energy [8]. The schematic diagram is shown on Fig.: 1.

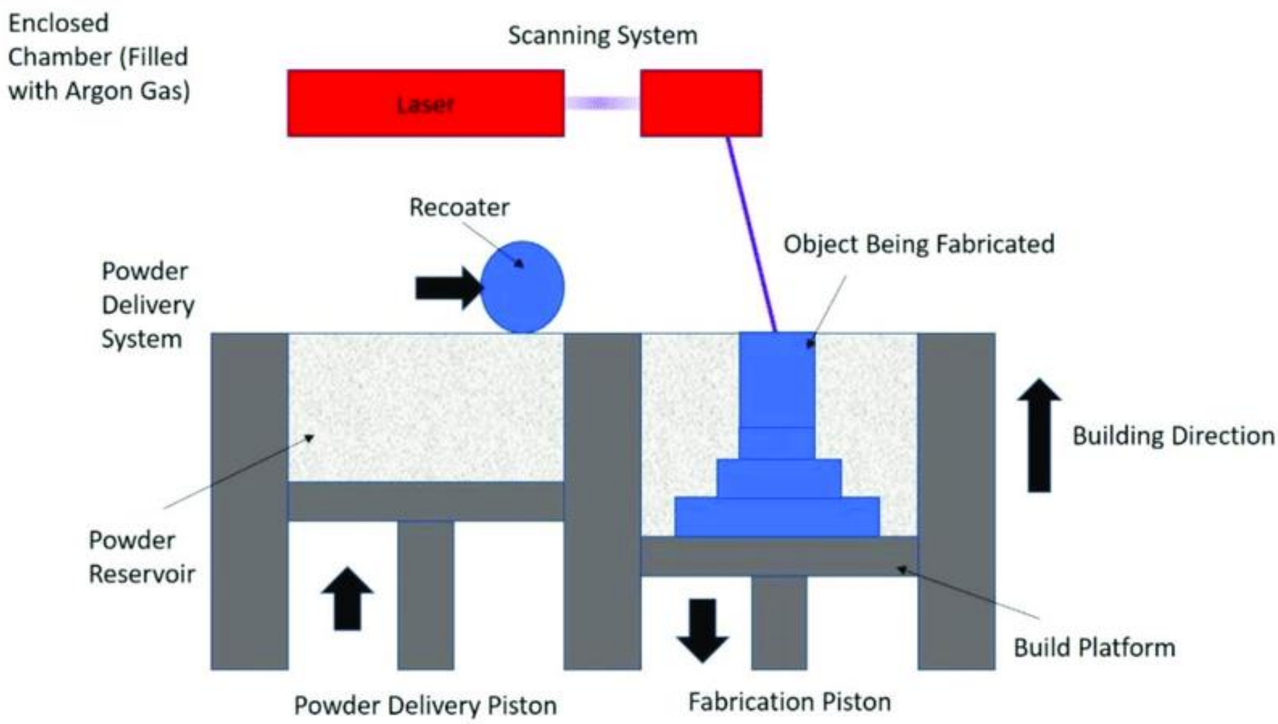

Fig.: 1. Conceptual view of SLM process

Image taken from: https://www.researchgate.net/figure/Schematic-diagram-of-the-selective-laser-melting-SLM-process_fig1_326891428 [9]

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The base material was a 17-4ph stainless steel powder bed, because of its excellent 3D printability and mechanical properties. The chemical composition is shown on Table I.

Composition	Weight percent (w/w%)
Fe	balance
C	< 0,07
Cu	4,00
Nb + Ta	0,03
Cr	17,00
Ni	4,5
Other	< 1,0

Table I. Chemical composition of 17-4ph stainless steel powder

The powder was made using gas atomization technique, to ensure the spherical morphology, which is optimal for 3D printing. The reason for this, that the powder particles should "roll over" each other, when the feeding mechanism spreads the new layer. If there is an imperfect or checkered particle, it may stick on the feeder and create a drag line. On this drag line will be void, thus an imperfect layer will be introduced to the process.

1.1. Process parameters

The printing machine used was an Orlas Creator, SLM machine, with nitrogen shield gas. The process parameters are shown in Table II.

Printing property:	Value:
Energy source	Yb: fiber, 250 W
Laser wavelength	1070 nm
Platform size	100 mm diameter, 110 mm height
Detail	x=80 µm, y=80 µm, z=20µm
Average accuracy	40 µm
Feeding mechanism	rubber coater, 200% feed rate
Shield gas	N

Table II. Printing parameters

Higher feed rate results in a more stable powder bed surface, thus ensuring better layer additions. The total time of the printing job was three and a half hours.

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2. Mechanical testing

The most efficient and cost-effective way to test 3D metal printed specimens, is to make tensile specimens. Its relatively fast to print, easily reproduceable, and the testing process is simple and fast, although require expensive hardware. The first batch of test specimens was made according to the ASTM E8 standard, however due to limited size, we had to differ from the given values. The results from a similar printing job are shown on Fig.: 2.

Fig.: 2. 3D metal printed tensile test specimens

The specimens were printed in a semi-vertical / semi-horizontal position, as Fig.:2 shows. In this way, the tensile testing was done in a parallel direction to the layers, thus granting us the most favourable results, while having an optimized printing job for printing time and warpage. If the one-dimensional pull force from tensile testing acts towards perpendicular to the layer setup, we will get weaker results [9].

During our experiments, we wanted to compare different thicknesses, thus altered the base tensile test specimens. 2 mm was set as basic, and there were 1 mm and 3 mm thick ones as well. Our goal here was to demonstrate, how these geometrical changes will affect the finished product in a simple testing environment. The tensile test results can be shown from Fig.: 3 to 5.

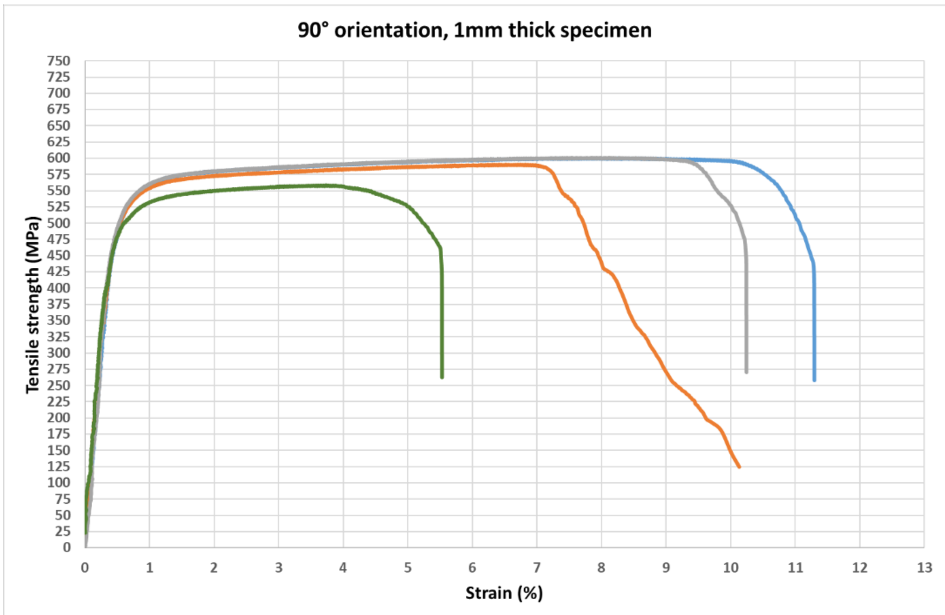

Fig.:3.Results from the 1 mm thick specimens

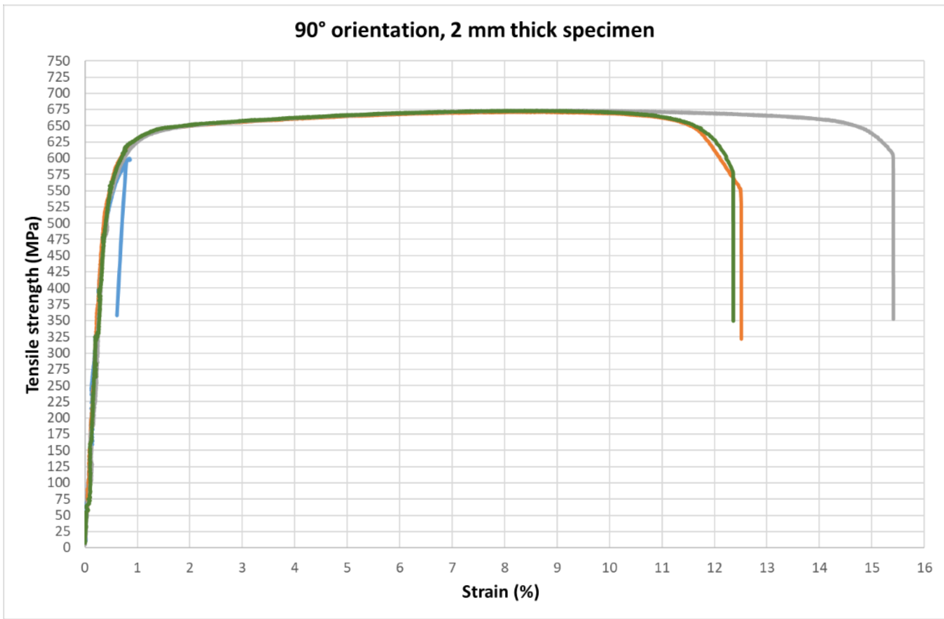

Fig.: 4. Results from the 2 mm thick specimens

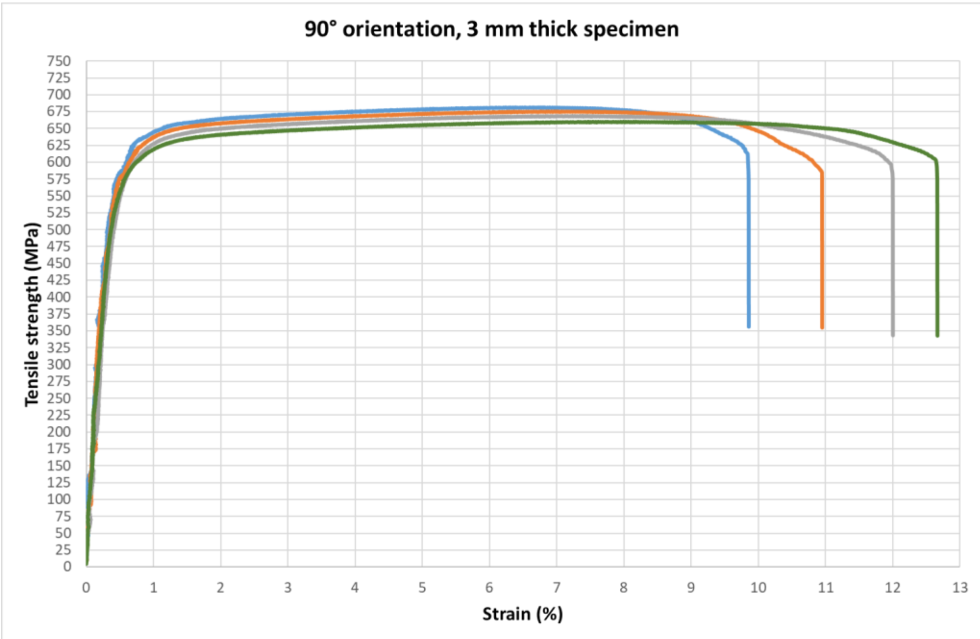

Fig.: 5. Results from the 3 mm thick specimens

The results, show that various thicknesses will produce different mechanical properties. The weakest values came out from the 1 mm thick specimens, mainly because these thin layers tend to build up huge amounts of residual stresses. This is another issue which occurs during 3D printing of metals, but it is for another study.

2 mm thick specimens had the most strain percentage values, while increasing the thickness to 3 mm lead to almost the same height in tensile strength, but with a more rigid breaking. According to this, we can assume that there is a lower and higher limit, where we can vary these values freely, without sacrificing much of mechanical strengths.

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2.1. Horizontally modified tensile test specimens

The next step in our study was to make further modifications on the specimens. As we could see, printing 1 mm thick specimens yields in mostly poor results, we only carried on with 2 and 3 mm-s. The concept of this measurement is shown on Fig.: 6.

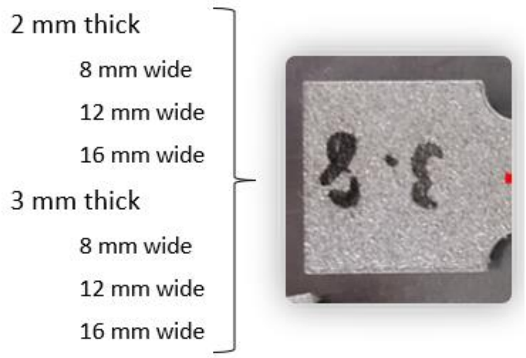

Fig.: 6. Modified 2 and 3 mm thick tensile specimens

The measurement in this case was also done in parallel way to the layer setup, however the specimens lied flat on the printing platform, thus had 0° orientations. The results can be seen on Fig.: 7.

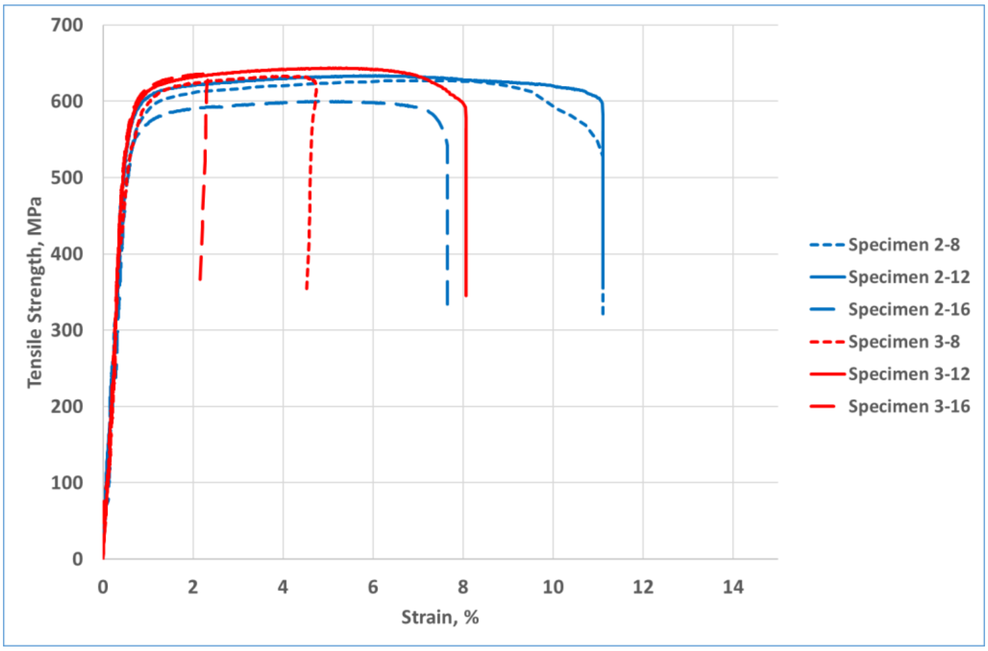

Fig.: 7. Results, from further modified specimens

As the results show, in 0° orientation still 2 mm thick specimens give us the best tensile strength to strain values, however the tensile strength values have dropped with the change of orientation. What we also see, is that changing the specimens' layers total surface area, we will have significant changes in these properties. This way we can also assume that on these dimensions there must be a lower and higher limit, which we can change the values freely.

Summary

During our measurements, we can state that tensile testing of 3D metal printed parts is highly dependent on orientation and size, while there is a certain value in geometrical ratio which we do not go below or exceed to get the desired mechanical properties. This value is also depending on the residual stresses, which the process must deal with. Different types of specimens, however, require different handling, thus we need to be careful when comparing different printing orientations.

References

[1] Davide Sher, *3D Hubs Publishes Complete 3D Printing Technologies Infographic » 3D Printing Media Network - The Pulse of the AM Industry*, https://www.3dprintingmedia.network/

[2] Yadollahi, A., Shamsaei, N., Thompson, S. M., Elwany, A., & Bian, L. (2017). Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel. International Journal of Fatigue, 94, 218–235. doi:10.1016/j.ijfatigue.2016.03.014

[3] Alsalla, H. H., Smith, C., & Hao, L. (2018). Effect of build orientation on the surface quality, microstructure and mechanical properties of selective laser melting 316L stainless steel. Rapid Prototyping Journal, 24(1), 9–17. doi:10.1108/rpj-04-2016-0068

[4] Pal, S., Gubeljak, N., Hudak, R., Lojen, G., Rajtukova, V., Predan, J., … Drstvensek, I. (2018). Tensile properties of selective laser melting products affected by building orientation and energy density. Materials Science and Engineering: A. doi:10.1016/j.msea.2018.11.130

[5] Tridello, A., Fiocchi, J., Biffi, C. A., Chiandussi, G., Rossetto, M., Tuissi, A., & Paolino, D. S. (2020). Effect of microstructure, residual stresses and building orientation on the fatigue response up to 109 cycles of an SLM AlSi10Mg alloy. International Journal of Fatigue, 105659. doi:10.1016/j.ijfatigue.2020.105659

[6] Zhao, J., Easton, M., Qian, M., Leary, M., & Brandt, M. (2018). Effect of building direction on porosity and fatigue life of selective laser melted AlSi12Mg alloy. Materials Science and Engineering: A, 729, 76–85. doi:10.1016/j.msea.2018.05.040

[7] Lu, X.; Chiumenti, M.; Cervera, M.; Tan, H.; Lin, X.; Wang, S. – Warpage Analysis and Control of Thin-Walled Structures Manufactured by Laser Powder Bed Fusion. – *Metals,* **2021**, 11, 686 https://doi.org/10.3390/met11050686

[8] William E. Fraizer, *Metal Additive Manufacturing: A review*, ASM International 2014

[9] Tawaddod Alkindi, Mozah Alyammahi, Rahmat Agung Susantyoko, Saleh Atatreh, *The effect of varying specimens' printing angles to the bed surface on the tensile strength of 3D-printed 17-4PH stainless-steels via FFF additive manufacturing,* Springer 2021