Tensile properties evaluation of additively manufactured AISI 316L thin wall and bulk material using various miniaturized specimen geometries

S Rzepa¹, D Melzer¹, M Koukoliková¹, P Konopík¹, M Brázda¹, J Vavřík¹
¹COMTES FHT a.s., Průmyslová 995, Dobřany, 334 41, Czech Republic

E-mail: sylwia.rzepa@comtesfht.cz

Abstract. Additive Manufacturing is an innovative technology, which allows creating structures of complex and unique geometries layer by layer. The mechanical properties of deposited objects can vary depending on their length, thickness and deposition orientation due to different cooling rates and various thermal conductivity. Austenitic steel AISI 316L, deposited using direct energy deposition technology, was an experimental material. The technology employs a high-power laser beam as an energy source for the powder melting. During the process, a powder is blown through the nozzle by protective gas into the processing area and subsequently molten. The aim of the study was to compare basic mechanical properties of the specimens extracted from a thin wall and a bulk material. The specimens were tested in horizontal and vertical orientations in relation to the build orientation in machined and as-deposited states. The tensile characteristics of proportional and non-proportional specimens were investigated within the study. The miniaturized tensile test specimens were employed in order to examine the strength and elongation of the experimental material. The mechanical testing results were complemented by microstructural analysis using a light microscopy (LM). Based on the obtained results, it can be concluded that the specimen proportionality affects not only the specimen elongation, but also the strength values of investigated material.

1 Introduction

Additive manufacturing (AM) is a novel technology allowing creation of unique, three-dimensional objects of complicated geometries that found an application in automotive, medical and aerospace industries. In this technology, a process planning is not required since a model created by means of Computer Aided Design (CAD) can be manufactured directly, layer-by-layer.

The influence of the deposition parameters and scanning strategy on the material microstructure, mechanical properties, defects content and residual stresses for both, direct energy deposition (DED) and powder bed fusion (PBF) technologies is a topic that focuses an attention of many researchers [1],[2]. During the manufacturing process, a microstructure that varies over one deposited object can be created due to different heating and cooling conditions, which are influenced by an object dimensions, geometry and contact with supporting structures. This phenomenon significantly affects the mechanical properties of created part.

In the study, a direct energy deposition (DED) technology was employed for the deposition of experimental material, in which the powder is blown through a nozzle with inert gas, deposited in spot and melted using a laser beam as an energy source. The DED systems can be applied for
repairing of remanufacturing of already existing parts as well as creation of functionally graded materials that are advantages specific only for this technology [3],[4]. A single additively manufactured structure of complex geometry (such as turbine or propeller) is characterized by various wall thicknesses within the whole part. In many cases, it is impossible to manufacture a testing specimen with the dimensions defined by standard due to insufficient available material. In addition, the extraction of proportional specimens of minimal size results in modification of the surface conditions that is disadvantageous when the AM-ed part is intended to be used in as-deposited state and the in-service conditions have to be reproduced during mechanical testing. Džugan et al. [5] studied the effect of surface grinding on the miniaturized tensile test results. They concluded that the surface condition and defects play a great role in material behaviour. It is also worth noting that the mechanical properties of parts manufactured by different AM technologies were characterized by various sensitivity on the amount of removed by machining material. The specimen proportionality effect was also studied by Moura et al. [6]. They stated that the proportionality coefficient \( k \) (according to ISO 6892-1) can significantly influence the tensile test results. According to their research, with increasing \( k \) coefficient, the elongation and tensile toughness decrease. The trend can be extrapolated by a logarithmic function.

The aim of the study was to investigate the mechanical properties of AM-ed 316L thin wall and bulk material as well as the effect of a specimen size and proportionality on obtained tensile characteristics. The specimens were tested in machined and as-deposited states in vertical and horizontal orientations. The mechanical behaviour of the material was studied based on the results of miniaturized tensile test (MTT). The microstructure was examined by means of a light microscopy (LM).

2 Materials and methods
The experimental material was 316L stainless steel (SS 316L), which can be distinguished by relatively high strength and ductility as well as great corrosion resistance. The material is widely used in petrochemical industry, pharmaceutical and medical equipment or marine applications and others. The experimental material was deposited by InssTek MX600 Powder Blown DED machine equipped with a 2 kW fibre-guided Ytterbium laser. The deposition was conducted under protective atmosphere of argon. The particle size of the powder used for the deposition ranged from 45 to 105 \( \mu m \). The laser power was set up as 400 W and 800 W for the thin wall with dimensions of 40 × 30 × 2.9 mm and the bulk material with dimensions 35 × 35 × 35 mm, respectively. The microstructural investigation was conducted my means of a light microscope NIKON ECLIPSE MA200 cooperating with NIS Elements 5.2 software. The metallographic samples were subjected to the standard metallographic preparation.

The mechanical properties of the AM-ed 316L experimental materials were examined based on the miniaturized tensile test (MTT) results. The method was widely used in other studies and documented as reliable way of material characterization [7]-[9]. The specimens were manufactured by a wire electric discharge machine (WEDM) according to the cutting schema presented in Figure 1. The experiment was carried out under quasi-static conditions at room temperature according to the methodology described in the standard ISO 6892-1 using a universal testing machine TiraTest with a load capacity of 10 kN. The deformation was recorded by a DIC system Mercury RT calibrated in 2D mode. Prior to testing, the specimens were polished, cleaned and measured in three different locations (thickness and width). Subsequently, the specimens were covered with a stochastic black and white pattern that allowed non-contact deformation measurement. After testing, the specimen dimensions were measured again using a stereomicroscope and the tensile parameters were evaluated (yield and ultimate tensile strength, uniform and total plastic elongation designated as YS, UTS, UE and EL, respectively). The machined specimen geometries were proportional and non-proportional according to the standard ISO 6892-1. The specimen designation system followed the document ASTM WK4922 [10].
3 Results and discussion

The results of microstructural analysis are presented in Figure 2 and Figure 3. The maximal depth of cratered melt pools of 600 µm and 600-1000 µm were observed for the thin wall and the bulk material, respectively. The elongated grains growing epitaxial across many deposited layers were noticed for both microstructures. In addition, many fine grains were found in close proximity of the dendritic ones. At high magnification, a cellular structure was identified for the thin wall. The porosity measurement revealed globular pores evenly distributed. The total porosity was evaluated as 0.015% and 0.183% with a maximal pore size of 40 µm and 85 µm for the thin wall and bulk material, respectively.

Figure 1. Additively manufactured bulk material and thin wall – cutting schema.

Figure 2. Results of microstructural analysis of the thin wall: a) melt pool detail, b) microstructure detail.
The results of MTT are presented in Figure 4 - 6. Three different specimen geometries were used for a thin wall mechanical properties investigation: machined (thickness of 0.5 mm, L0 = 4 mm), as-deposited non-proportional (original wall thickness of 2.9 mm, L0 = 4 mm) and as-deposited proportional (original wall thickness of 2.9 mm and L0 = 13 mm). An anisotropy of the tensile properties was observed as the XZY-oriented specimens yielded about 50 MPa higher values of both, yield and ultimate tensile strength, in comparison to ZXY-oriented specimens. Furthermore, the elongation of XZY-oriented specimens was about 4 and 10 % lower in comparison to ZXY-oriented specimens for both, as-deposited and machined states, respectively. In addition, the non-proportional (NP_AD) MTT specimens yielded systematically higher values of all evaluated tensile parameters compared to the machined proportional specimens. In the case of non-machined specimens, the reduction of the tensile parameters could be expected since very rough and defected surface of AM-ed objects can act as a stress concentrator and cause earlier material failure. Nevertheless, the results of as-deposited proportional (P_AM) specimens correspond to those for the machined proportional (P_M) specimens. This phenomenon demonstrates that the different values obtained for NP_AD and P_M batches are a result of various proportionality coefficient $k$. This observation is in a good agreement with the results published by Fotovvati et al. [11]. They presented the results for Ti-6Al-4V, which revealed that the YS and UTS decrease with the increasing proportional coefficient.

Figure 4. Engineering stress-strain curves for representative specimens extracted from additively manufactured 316L thin wall (P – proportional, NP – non-proportional, AD – as-deposited, M – machined).
Four different specimen geometries were tested in order to investigate the influence of the specimen thickness on the tensile test results for bulk material. The specimens with thicknesses of 2, 1, 0.5 mm (width of 2 mm) as well as the specimens 0.5 mm thick (width 1 mm) were machined. All specimen geometries were designed to be proportional according to $k = 5.65$. The evolution of YS, UTS and UE is presented in Figure 5 for ZXY and XYZ orientation, respectively. The observed trends show continual increase of YS and UTS values with increasing gauge length for both ZXY- and XYZ-oriented specimens. For the greatest gauge length of 11 mm, the UTS and YS values significantly decrease. This tendency does not apply to UTS value of XYZ-oriented specimens. In the case of UE, the trend is the same for XYZ-oriented specimens and for ZXY-oriented is opposite.

![Figure 5](image_url)

**Figure 5.** Summary of the strength values and uniform elongation in dependence on specimen cross-section (and resulting gauge length) for additively manufactured 316L bulk material in ZXY and XYZ orientations.

The results of MTT for proportional machined specimens were compared between thin wall and bulk material. The tensile stress–strain curves are presented in Figure 6. The specimens extracted from bulk material yielded slightly higher YS and UTS values but also slightly lower UE. Nevertheless, the results are in good agreement with small deviation regarding the fact that the thin wall and bulk material were deposited applying different deposition parameters.

![Figure 6](image_url)

**Figure 6.** Engineering stress-strain curves for representative MTT ($L_0 = 4$ mm) specimens – comparison of the tensile characteristics between bulk material and thin wall.

4 Conclusions
The aim of the study was to investigate the effect of the different tensile specimen geometries on the mechanical properties of the additively processed bulk and thin walled 316L material. The conclusion points are as follows:

- The results of the tensile test of the thin wall showed that the as deposited non-proportional tensile specimens yielded higher strength and elongation values compared to the machined-proportional ones. Furthermore, the as deposited proportional specimens yielded very similar values to the proportional machined ones. It demonstrates that the proportionality of the specimen has significant influence not only on the measured elongation but also on the strength parameters. Furthermore, the effect of the original as deposited surface is negligible for the measured tensile parameters.

- The results for proportional specimens extracted from the bulk material with different thicknesses showed a trend of increasing YS and UTS values with increasing gauge length (specimen cross-section) regardless of the orientation to the point of the gauge length of 11 mm where a sudden drop of the tensile parameters was observed. The same trend was observed for UE of the XYZ-oriented specimens. In the case of ZXY-oriented specimens UE systematically decreased with gauge length increase.

- The comparison of the MTT results between bulk and thin wall additively processed 316L showed that the results are in good agreement. Thus, the different additive manufacturing parameters applied for the bulk and thin wall manufacturing has negligible effect on the material performance.

Acknowledgement

This paper was developed thanks to the project of Pre-Application Research of Functionally Graduated Materials by Additive Technologies, No.: CZ.02.1.01/0.0/0.0/17_048/0007350, financed by the Ministry of Education of the Czech Republic.

References

[1] Saboori A, Piscopo G, Lai M, Salmi A, Biamino S 2020 *Materials Science and Engineering A* **780** 139179
[2] Shipley H, McDonnell D, Cullen M, Coull R, Lupoi R, O'Donnell G and Trimble D 2018 *International Journal of Machine Tools and Manufacture* **128** pp. 1-20
[3] Mathhoob I, Akinlabib E T, Arthura N and Tiotiengab M 2020 *CIRP Journal of Manufacturing Science and Technology* available online
[4] Dzugan J, Melzer D, Koukolikova M, Vavrik J and Seifi M, *Structural Integrity of Additive Manufactured Materials & Parts STP1631* pp. 247-256
[5] Dzugan J, Seifi M, Prochazka R, Rund M, Podany P, Konopik P and Lewandowski J J 2018 *Materials Characterization* **143** pp. 94-109
[6] Moura L, Vittoria G, Guimarães G A, Bertoni da Fonseca E, Pellizzer G L, Webster T, Najar L and Eder S 2020 *Journal of Materials Science* **55(22)** pp. 9578-9596
[7] Dzugan J, Sibr, M Konopík, P, Procházka R and Rund M 2017 Mechanical properties of AM components. IOP Conference Series: Materials Science and Engineering 179 012019
[8] Gussev M N, Busby J T, Field K G, Sokolov M A and Gray S E 2015 Small Specimen Test Techniques *6* pp. 31-49
[9] Gotterbarm M, Seifi M, Melzer D, Dzugan J, Salem A, Liu Z and Körner C 2020 *Additive Manufacturing* **36** 101449
[10] ASTM WK49229. Standard Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing – work in progress (2017)
[11] Fotovvati B, Alireza S and Asadi E E 2019 *Materials Science and Engineering: A* **760** pp. 431-447