

Mechanical property of thin walled selective laser melted parts and the effect of heat treatment

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Abstract. The variability in mechanical properties in selective laser melted (SLM) maraging steel parts was captured by testing miniature size tensile coupons that were extracted from different locations in the part. Tensile testing provides better mechanical response to defects such as pores and inclusions as compared to hardness testing. The effect of heat treatment on the tensile property variation with different section thickness was also studied. It was observed that tensile property of miniature samples was more sensitive to porosity defects in maraging steel samples. The elongation values in the tensile specimens exhibited more variability as the section thickness of the part was reduced. This was due to the presence of more pore defects in thin wall sections. Heat treatment did not influence the tensile properties with respect to the wall thickness except for an increase in the strength due to hardening.

1 Introduction

Additive manufactured parts have the potential to incorporate complex part designs with variable section thickness. This variability in section thickness can also lead to variation in mechanical properties; hence it is essential to characterize the mechanical properties at different locations within the part to capture any variability. Previously, hardness measurements were routinely employed [1] to capture the location specific mechanical properties. However, hardness testing does not completely capture the mechanical properties since, defects formed such as porosity and inclusions affect only the tensile properties. To obtain location specific tensile properties in the part, it may be necessary to machine out miniature samples and perform tensile testing. Tensile testing of miniature samples have been attempted by various researchers in the recent past and have been compared with standard specimen tensile results [2-5]. The important feature of miniature sample testing, is it can assess the quality of printed parts and be used as a part qualification procedure. Any variation in mechanical properties within part or batch to batch variability can be captured and reported.

In the current research an additive manufactured part of maraging steel, with different sectional thickness were fabricated in order to assess wall thickness effect on mechanical properties, as these may vary with deposition thickness [6]. Miniature samples were machined out to perform tensile testing in the as-built and heat treated condition. The variation in tensile properties as a function of part section thickness were analysed, and the tensile properties of miniature samples were compared and benchmarked with ASTM size tensile samples that were also extracted from the different wall thickness of the part.

2 Materials and Methods

Different wall thickness ranging from 1 mm to 10 mm was printed in a part using Concept Laser machine with maraging steel alloy from OEM supplied powders. The process parameters used were



also OEM recommended which was uniform for the whole part as given in Table 1. The part design with different wall thickness and the orientation with respect to build direction is shown in Figure 1. Miniature and ASTM size samples were extracted from different wall thickness in the part as shown in Figure 1. Both transverse and lateral oriented (along the build plane and perpendicular to build plane) miniature samples were machined out for tensile testing. For ASTM size samples only lateral oriented samples were tested for different wall thickness. The 1 mm thick wall ASTM sample was not tested due to slight distortion. The dimensions of the tensile samples are illustrated in Figure 2 as shown below. The larger sized samples were machined as per ASTM E8 specification.

Table 1. Process parameter setting for Surface and contour region

Layer thickness (μm)	Region	Laser Power (W)	Scan Speed (mm/s)	Spot Size (μm)	Trace distance (mm)
25	Surface	260	950	125	0.11
	Contour	90	150	50	-

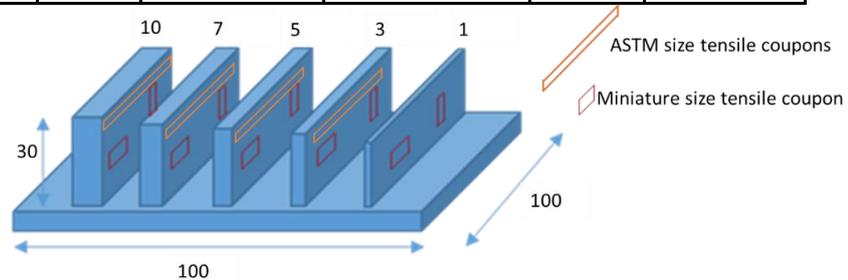


Figure 1. 3D printed part with different wall thickness. Also shown the sample orientations extracted for miniature and ASTM size samples. All dimensions in mm.

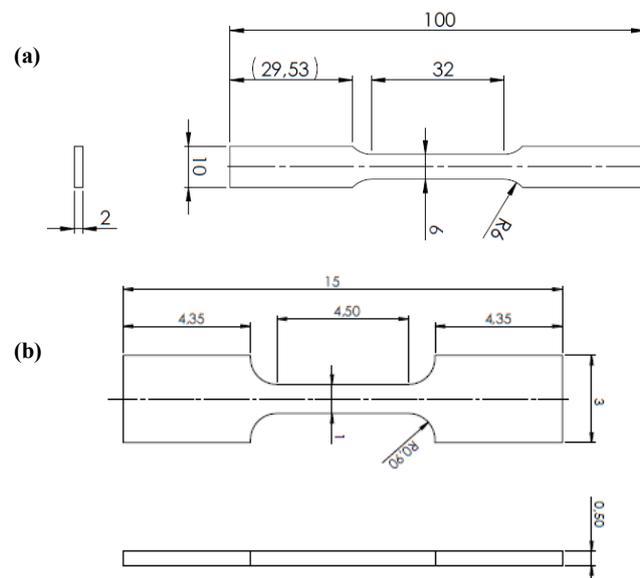


Figure 2. (a) Standard tensile coupon, dimensions as per ASTM E8 specifications (b) Tensile coupon dimensions of miniature samples. All dimensions in mm.

The miniature sample dimensions shown in Figure 2 (b) were 15 mm long, 3 mm wide and 0.5 mm thick. Such small size specimens enabled a study of location specific tensile properties in a complex part. Three samples for each orientation (lateral and transverse) were extracted for the miniature samples and one sample as per ASTM E8 specification, for the different wall thickness.

The samples were tested using a special testing apparatus for miniature tensile samples. The load cell has a capacity of 5kN and the deformation was measured by means of optical extensometer based on digital image correlation.

The fracture surface of the tensile tested samples were examined in a scanning electron microscope (SEM) to identify defects and the cause of crack initiation. The samples were then mounted in an epoxy resin and fine polished as shown in Figure 3, in order to measure the Vickers micro-hardness and examine the porosity near the fracture location.



Figure 3. Tested miniature samples mounted in epoxy resin for microstructure analysis

3 Results and Discussion

The printed part with the different wall thickness is shown in Figure 4. Dimensional measurements of the different wall thickness were observed to lie within 2% of the actual prescribed dimensions.



Figure 4. 3D printed part with different wall thickness.

The tensile strength (yield and ultimate tensile strength) for different samples in the as-printed and heat-treated samples were extracted from different wall thickness as shown in Figure 5. Also shown are the tensile properties of the ASTM standard samples extracted from different wall thickness.

From Figure 5 it can be observed that the yield strength of miniature samples were higher than that of standard ASTM samples, whereas such a difference was not observed in the tensile strength values for both as-printed and heat-treated conditions. No clear trends were observed for strength variation as a function of wall thickness in the as-printed condition, which would indicate there is minimal microstructural variation with different wall thickness for maraging steels. Figure 6, shows the microstructure observed using SEM for 1 mm and 10 mm wall thickness for the as-printed part. A cellular morphology was observed in both images for the two wall thickness indicating high cooling rates which is typical for selective laser melting process. The spacing between cells was calculated by counting number of cells in a given area (as highlighted in Figure 6 (a) and (b)), and the spacing (λ) is related to number of cells in an area (N_a) by the equation $\lambda = 1/(N_a)^{0.5}$ [7]. The cellular spacing (N_a) calculated from multiple images was found to be $1.24 \pm 0.73 \mu\text{m}$ for 1 mm wall thickness and $1.14 \pm 0.16 \mu\text{m}$ for 10 mm wall thickness, clearly indicating no difference in the scale of microstructure for maraging steel.

The tensile strength values for the miniature samples matches well with ASTM standard samples which indicates there is no change in strength due to size effect. It has been reported [7] that the tensile strength values remain stable for different thickness until a critical ratio of sample thickness to grain size (t/d) is reached, whereby the results starts to deviate. This critical (t/d) ratio is material dependent and for SS304 material, the strength and ductility reduces below a sample thickness of 0.147 mm [8]. For maraging steel miniature samples with the thickness of 0.5 mm, has not reached the critical limit and does not deviate from the ASTM samples.

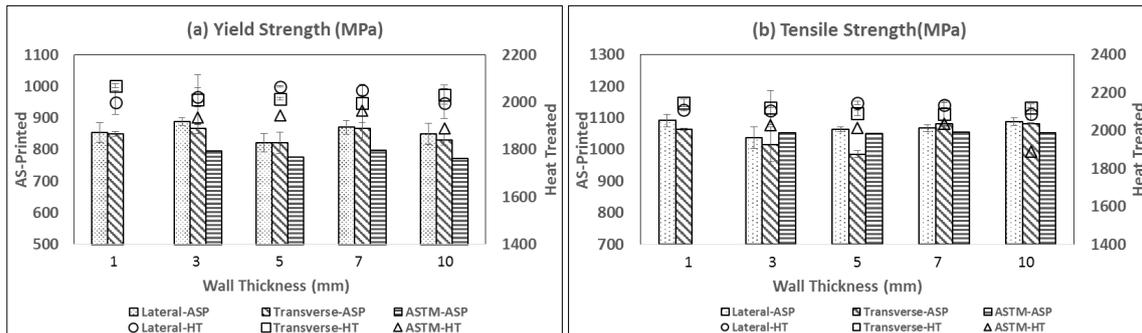


Figure 5. Tensile properties ((a) Yield and (b) Tensile strength) as a function wall thickness for miniature samples and ASTM standard samples extracted from the as-printed and heat treated part.

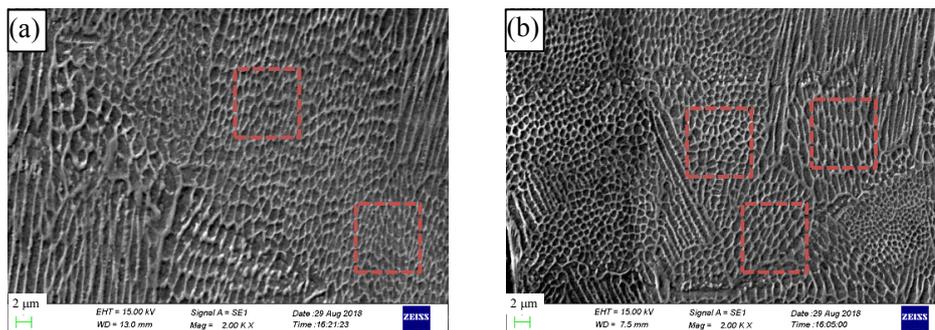


Figure 6. Cellular microstructure observed under SEM for (a) 1 mm wall thickness and (b) 10 mm wall thickness. Boxes highlighted to calculate cellular spacing.

Maraging steels are precipitation hardening steels, whereby the alloy is heat-treated to allow the precipitation of intermetallic phases which improves the strength significantly. A standard recommended heat treatment for maraging steels is 490°C, held for 6 hours followed by fast cooling was carried out in a vacuum furnace for the part. It is clear that the strength of the samples have increased by more than 100% after heat treatment when compared to the as-printed part. The increase in strength was offset by reduction in elongation from 12% for as-printed samples to 3% for heat-treated samples as seen in Figure 7.

From Figure 5, it was also observed that the lateral oriented samples showed slightly higher strength as compared to transverse oriented samples. This is due to the columnar grain texture developed during 3D printing which yields anisotropic behaviour in terms of strength. Such similar observations were also found by other researchers [9-10].

The elongation percent exhibited more variation especially for thin wall thickness samples as seen in Figure 7. The ductility of the samples were mainly influenced by the pore defects present in the part. The tensile properties of miniature samples are more sensitive to defects in the sample since the relative size of the defect to sample size is higher in miniature samples when compared to the larger ASTM sized samples. It is clear from Figure 7 that 3 mm, 5 mm and 1 mm samples exhibited

large variance in elongation. The biggest pores in the samples from different wall thickness were characterised as shown in Table 2. A trend was observed in the presence of large pores as a function of wall thickness as seen in Table 2. The samples from thin walls have larger sized pores as compared to samples from thick walls which possibly explains the larger variance in ductility values in thin section samples. The influence of pore size on ductility in relation to sample size is also reported by other researchers [11-12]. Boyce et al. [11] reported a maximum pore size in relation to tensile sample thickness that did not affect the ductility when compared to pore-free samples.

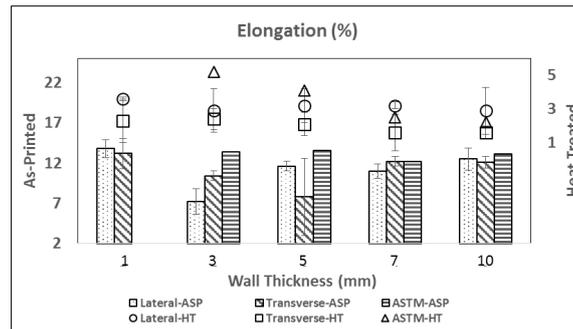


Figure 7. Elongation (%) as a function wall thickness for miniature and ASTM standard samples from the as-printed and heat-treated part.

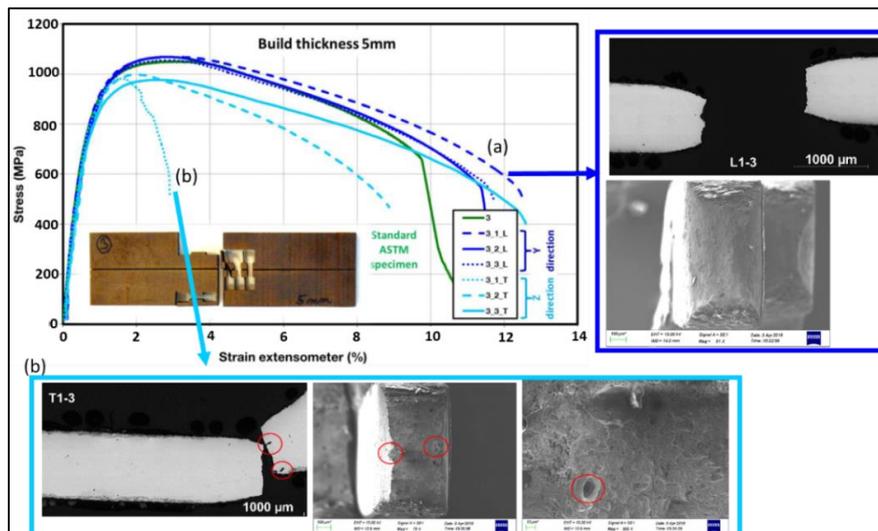


Figure 8. Tensile flow curves from 5 mm wall thickness as-printed part and fracture surface of samples that have failed with low elongation (b) and exhibited good elongation (a).

Table 2. Largest pore sizes observed in the as-printed miniature samples.

sample	Biggest pore size (µm)			
	1	2	3	average
1mm	40.56	34.06	27.77	34.13
3mm	31.91	20.32	20.3	24.18
5mm	21.61	16.89	13.37	17.29
7mm	22.29	17.07	15.73	18.36
10mm	18.25	14.1	13.67	15.34

The low elongation value observed in the tensile curve of the sample correlates well with the defects that were seen on the fracture surface. In Figure 8, the tensile curves of 5 mm samples from the as-printed part and the fracture surfaces were observed for two samples 3_1_L and 3_1_T, marked (a)

and (b) respectively. Sample (b) which was oriented transverse to build plane exhibited poor strength and elongation as seen in Figure 8. The fracture surface of the sample (b), revealed presence of numerous pore defects (highlighted by the red circles), that potentially caused early failure. The fracture surface of sample (a) which was oriented laterally to build plane, exhibited highest elongation, and did not have any obvious pore defects as seen in Figure 8(a).

4 Summary

The following points can be concluded from the current study:

1. The tensile values for the miniature samples of gauge length 4.5 mm correlates well with ASTM size samples which had a gauge length of 32mm. The miniature samples exhibited good repeatability in both tensile and yield strengths.
2. The samples tested from thin walls (1 mm, 3 mm and 5 mm) in the part exhibited more variability in elongation as compared with samples from thicker walls (7 mm and 10 mm). This was due to the thin walls having larger sized pore defects as compared to the thicker walls.
3. No trends were observed for strength values as a function of wall thickness. This was possibly due to the microstructure of maraging steel not varying with thickness of the part. However this variation is material dependent, and it has been observed that Ti6Al4V [1] exhibited a variation of approx. 15% in hardness between the section thickness.
4. Miniature tensile sample testing provides an effective way to measure localized mechanical behaviour of the part and compares well with ASTM standard tests.
5. Miniature tensile testing also achieves cost savings because a small extended portion in the part can be created and machined off to obtain tensile properties. This is more representative, than printing separate larger coupons and test for tensile properties.

References

- [1] Tan XP, Kok YH, Tan YJ, Vastola V, Pei QX, Zhang YW, Tor SB, Leong KF and Chua CK, 2015, *Journal of Alloys and Compounds*, **Vol. 646**, pp. 303-309.
- [2] Dzugan J, Procházka R, and Konopik P, 2015, *Small specimens Test Techniques: Vol 6* ASTM International, pp 12-30
- [3] Dzugan J, Sibr M, Konopik P, Procházka R and Rund M, 2017, *IOP Conference Series: Materials Science and Engineering*, **Volume 179**, conference 1
- [4] Rund M et al. , 2015, *Procedia Engineering Investigation of Sample-size Influence on Tensile Test Results at Different Strain Rates*, **Vol. 114** (Amsterdam: Elsevier science bv) pp 410-15
- [5] Procházka R, Džugan J and Kövér M, 2015, *Arch. of Mat. Sci. and Eng. Miniature specimen tensile testing of AZ31 alloy processed by ECAP*, Volume 76, Issue 2 (Gliwice: International OCSCO World Press) pp 134-9
- [6] Dzugan J, Prochazka R, Rund M, Podany P, Konopik P, Seifi M and Lewandowski J J 2018 Effects of thickness and orientation on the small scale fracture behaviour of additively manufactured Ti-6Al-4V *Mater. Charact.*
- [7] Andrew J. Elliott. "Directional solidification of large cross-section Ni-base superalloy castings via liquid-metal cooling". PhD Thesis, University of Michigan, Ann Arbor, MI, 2005
- [8] Kundan Kumar, Arun Pooleery , Madhusoodanan K , Singh RN, Arnomitra Chatterjee , Dutta BK, Sinha RK, 2016, *Materials Science and Engineering A*, **Vol 675**, pp 32-43
- [9] Mang Ni, Chao Chen, Xiaojun Wang, Pengwei Wang, Ruidi Li, Xiaoyong Zhang, Kechao Zhou, 2017, *Materials Science and Engineering A*, **Vol 710**, pp 344-351
- [10] Kok Y, Tan XP, Wang P, Nai MLS, Loh NH, Liu E, Tor SB, 2018, *Materials and Design*, **Vol 139**, pp 565-586
- [11] Boyce BL, Reu PL, Robino CV, 2006, *Metallurgical and Materials Transactions A*, **Vol 37A** , pp 2481-2492
- [12] Agnew SR, Elliott BR, Youngdahl CJ, Hemker KJ, Weertman JR, 2000, *Materials Science and Engineering A*, **Vol 285**, pp 391-396