Tensile Property Variation with Wall Thickness in Selective Laser Melted Parts

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Abstract

3D printed parts with complex geometries have different section thickness which leads to non-uniform mechanical properties due to microstructure and defect distributions. Hence, it is essential to characterise the localised mechanical properties to obtain a better understanding of the variability. The tensile property variability is captured by testing miniature sized tensile coupons that are extracted from different part locations which is more representative, when compared to testing printed tensile coupons. In the current work a benchmark study was first carried out to correlate miniature tensile properties with ASTM standard tensile test for different wall thickness in SLM Maraging steels. Following this, tensile property variation at different locations in an AM fabricated impeller part was studied. It was observed the thin sections in the part exhibited large variability in the elongation values. The effect of heat treatment on the tensile properties in the impeller was also studied.

Introduction

Additive manufacturing can fabricate complex part designs with variable section thickness. The variability in section thickness can lead to variation in mechanical properties; hence it is essential to characterise the mechanical properties at different locations within the part to capture the variability. Previously, hardness measurements were routinely employed [1] to obtain location specific mechanical properties. However, hardness testing cannot completely capture the mechanical property since it is restricted to a point location. Defects formed such as porosity and inclusions affect bulk properties hence its influence can be captured in 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 [2], and has been compared with standard ASTM size specimens obtaining good correlation, [3]. Miniature samples become essential to determine the quality of 3D printed parts and to study the part quality variation from batch to batch or from platform to platform. Also many 3D printed parts have complex shapes with different wall thickness which can lead to non-uniform mechanical properties. Miniature samples can be an effective tool to obtain the non-uniformity in mechanical properties of the 3D printed part based on section thickness.

A benchmarking study carried out in previous research [4], demonstrated that the miniature samples correlated well with ASTM size samples for different wall thickness. The miniature samples also exhibited good repeatability for the tensile and yield strengths. The objective of the current study is to examine the mechanical properties in a SLM printed impeller, which is a functional part that has both thin and thick sections. The tensile property variations are captured in the impeller part in the as-built and for different heat-treatment cycles.

Methodology

Part geometry for the study

To study the mechanical property variation in a functional part, an impeller geometry was selected which contained many thin section veins as seen in Figure 1. The impeller parts were printed in a Concept Laser M2 Cusing machine using default parameters and maraging steel BÖHLER W722 grade powder. The thick sections in the impeller part are at the base and the center of the component, hence a geometry with different section thickness can be obtained from the impeller. A small extension to the veins were also added to the part as seen in

Figure 1 shown by the red arrow. The extensions were attached to veins with weak supports, which enables them to be easily removed after the fabrication of the part.

Four such impeller parts were printed in Concept Laser M2 Cusing, in order to study the mechanical properties in the as-print and three different heat treated conditions. In Table 1 the different conditions studied for location specific tensile properties in the part are given.

Table 1. Different post-processing conditions employed for the impeller part.

Post processing conditions of impeller part	
1	As built
2	HT1: Standard heat-treatment, Ageing 490°C/6hrs followed by cooling
3	HT2: Standard heat-treatment, Solution at 820°C/1hr and ageing at 490°C/3hrs
4	HT3: Recommended heat-treatment at 460°C/8hrs

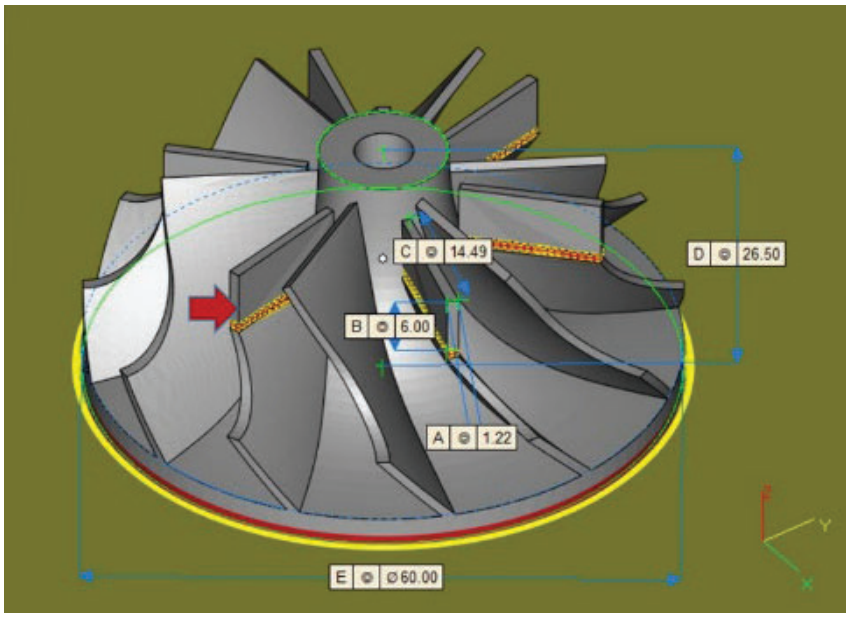

Figure 1. The design of the impeller part printed on the Concept Laser with the extensions attached by a support as shown by the red arrow. All the dimensions given are in mm

Miniature tensile samples

Miniature samples were machined from different locations in the impeller part from different section thickness (blade, centre and base regions). The dimensions of the miniature tensile sample is illustrated in Figure 2 as shown below.

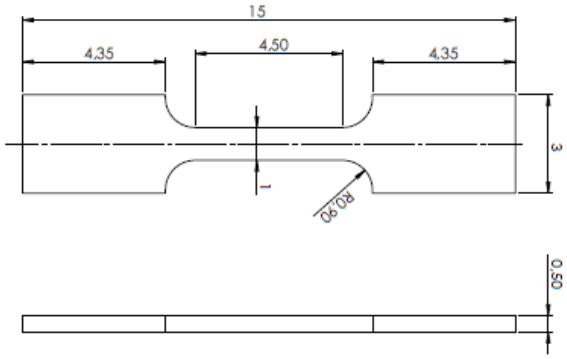

Figure 2. Tensile coupon dimensions for miniature samples. All dimensions in mm.

The miniature sample dimensions are 1.5cm long, 3mm wide and 0.5mm thick. Such small size specimens enabled a study of location specific tensile properties in a complex part. The samples were extracted from different locations in the impeller part, six samples from the thin section (veins), and two samples each from the centre and base region.

The machining procedure influences the surface of the sample, hence also affects the tensile properties. A detailed study was performed to study the influence of machining process on miniature tensile properties which is published elsewhere [5]. An optimal 3 step EDM cuts was undertaken to reduce the surface roughness to less than 4 μm. The miniature tensile samples were polished and etched to look at the presence of recast layer due to EDM wire cut as shown in Figure 3. The recast layer was very minimal with less than 2 μm thickness as seen in Figure 3, hence will not have any influence in the tensile test results.

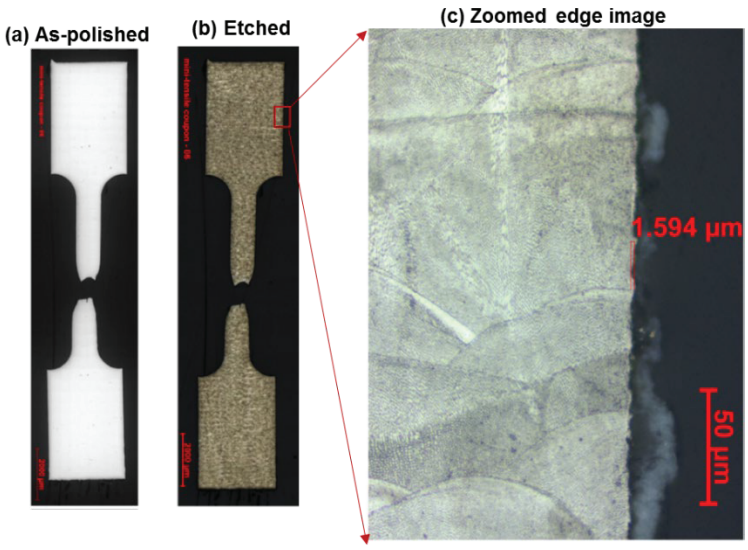

Figure 3. Miniature tensile coupons (a) as polished (b) etched and (c) zoomed edge image exhibiting recast layer less than 2 μm.

Tensile testing

The samples were tested at COMTES FHT (http://www.comtesfht.com/), 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 an optical extensometer based on digital image correlation. Figure 4 shows the setup used for miniature tensile sample testing.

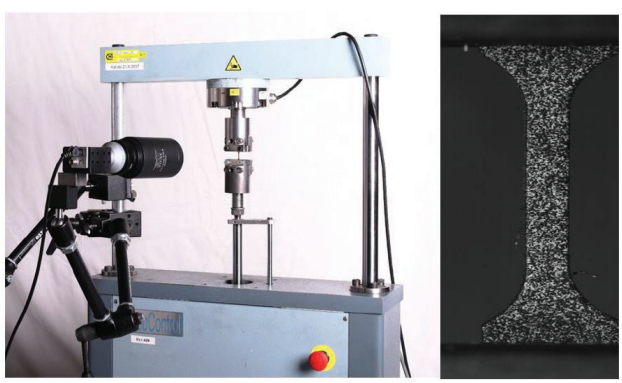

Figure 4. Tensile testing equipment for miniature samples with an optical extensometer

The fracture surface of the tensile tested samples were examined using SEM to identify defects and the cause of crack initiation. The samples were mounted in an epoxy resin and finely polished as shown in Figure 5.

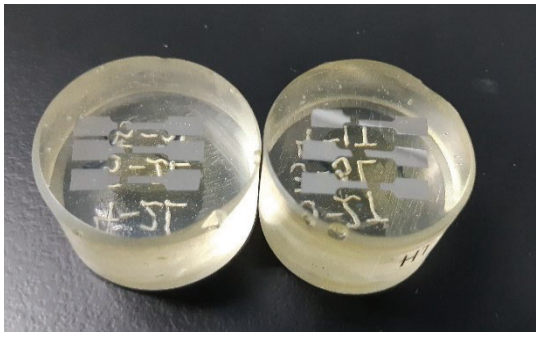

Figure 5. Tested miniature samples mounted in epoxy resin for microstructure and hardness analysis.

X-Ray CT scan of thin sections in the part were carried out using a Nikon X-Tek XT H 50 system. The machine has a maximum power rating of 450W and can move in four axes. The power rating is varied based on the sample thickness to achieve complete penetration of the part.

Results & Discussion

Mechanical property variation in a Selective Laser Melting (SLM) printed impeller

The four impeller parts were printed on Concept Laser M2 Cusing Machine as shown in Figure 6.

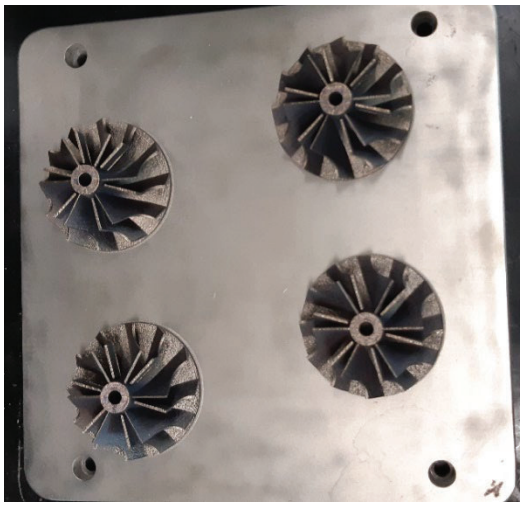

Figure 6. Impeller parts printed on the Concept Laser M2 Cusing machine.

The extension samples in the impeller parts were peeled off to enable X-Ray CT analysis of the samples. In Figure 7 is shown the as-built impeller part with the extensions peeled off from the veins.

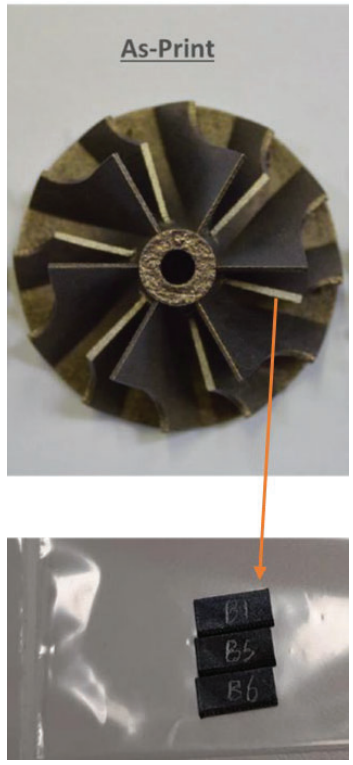

Figure 7. As-print impeller part fabricated with the extensions removed.

X-Ray CT study

The scan for the extensions samples was carried out using X-ray CT at lower power which enable penetration of the sample using a spot size of approximately 6μm. With the lower spot size, the defects in the thin coupons were clearly visible as shown in Figure 8. The thin extension samples from the impeller part showed numerous pores located at the edge and near the surface as show in Figure 8. These near surface pores were observed at all sections in the thin extension sample.

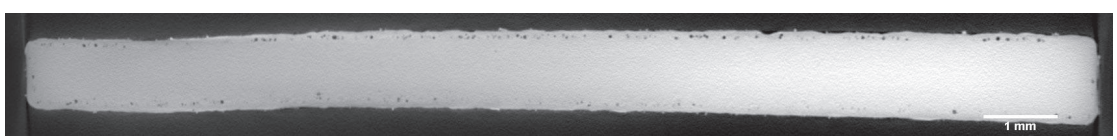

Figure 8. X-Ray CT scan of a thin extension exhibiting porosity near the surface of the sample.

Tensile test results from miniature samples from different sections in impeller part

Miniature tensile samples were extracted at different location in the impeller part. The different locations has different section thickness, for example the veins are approx. 1.2mm , the base is 5mm with the centre portion approx. 10mm in thickness. The tensile samples were extracted at these different locations, (blade, centre and base) as illustrated in Figure 9a, to capture the variability in mechanical property as function of section thickness. Figure 9b shows the extracted coupons locations from the blade, centre and the centre regions of the impeller.

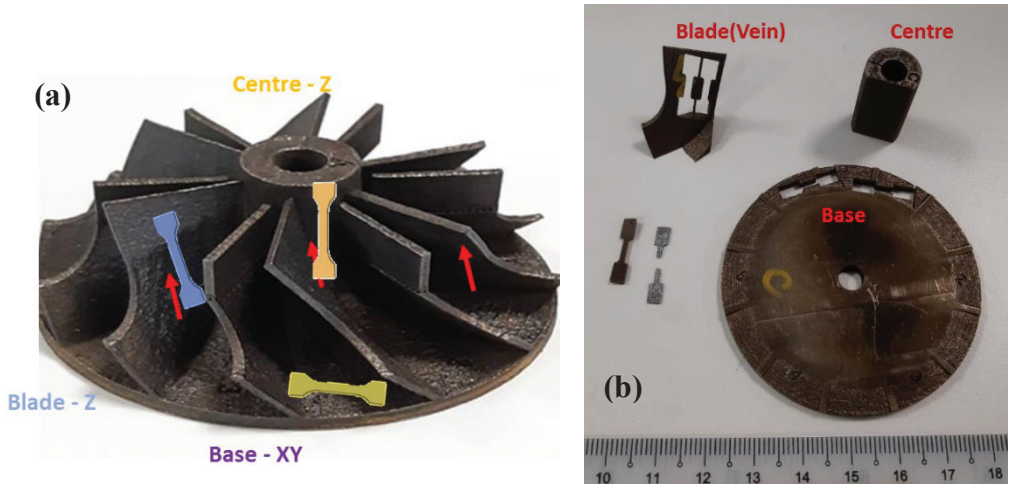

Figure 9. (a) Location of miniature tensile samples extracted in the impeller part. (b) Extracted samples from the blade, centre and base region.

The tensile curves for the miniature samples extracted from the as-printed impeller part is shown in Figure 10. The solid lines correspond to the base and centre regions and the dotted lines to the thin section blade. It is clear from Figure 10 that the tensile curves for the thin sections (dotted lines) show more variability in the elongation values as compared to the tensile curves for the thick sections.

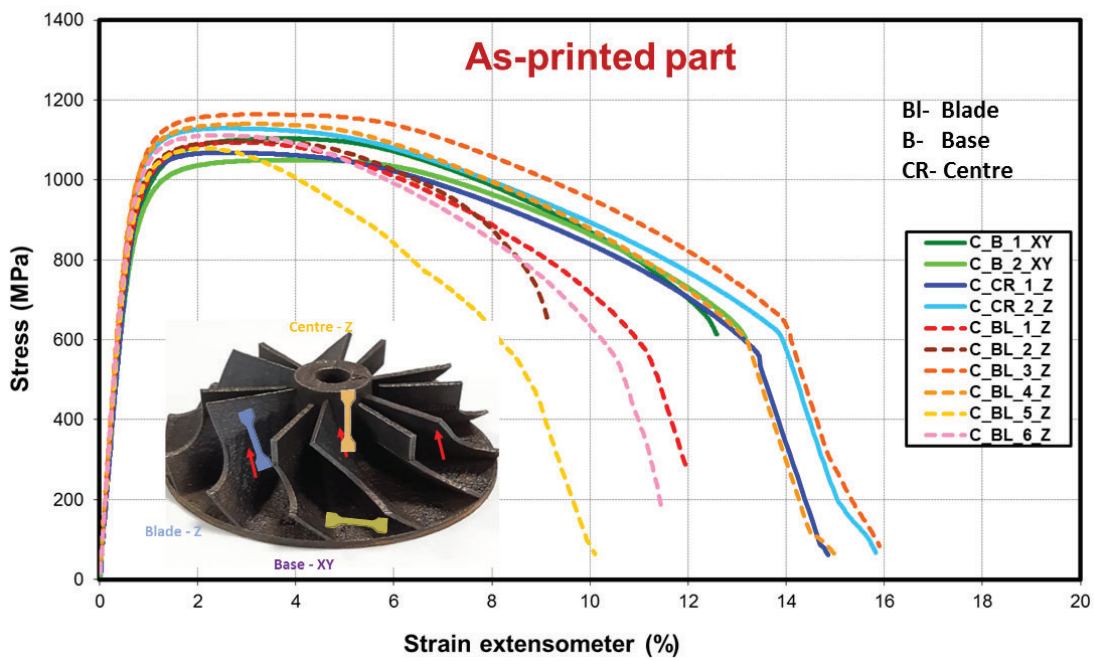

Figure 10. Tensile flow curves for miniature samples extracted from as-printed impeller.

In Figure 11(a, b, c) the tensile strength, yield strength and the elongation % values for the samples in the blade, centre and base regions were plotted respectively for the as-built part. It can be observed from Figure 11(a), the strength values for the thin sections (blade) were slightly higher as compared to the samples from the thick sections (i.e. base and centre). However, the elongation in the thin sections i.e. blade showed larger variation.

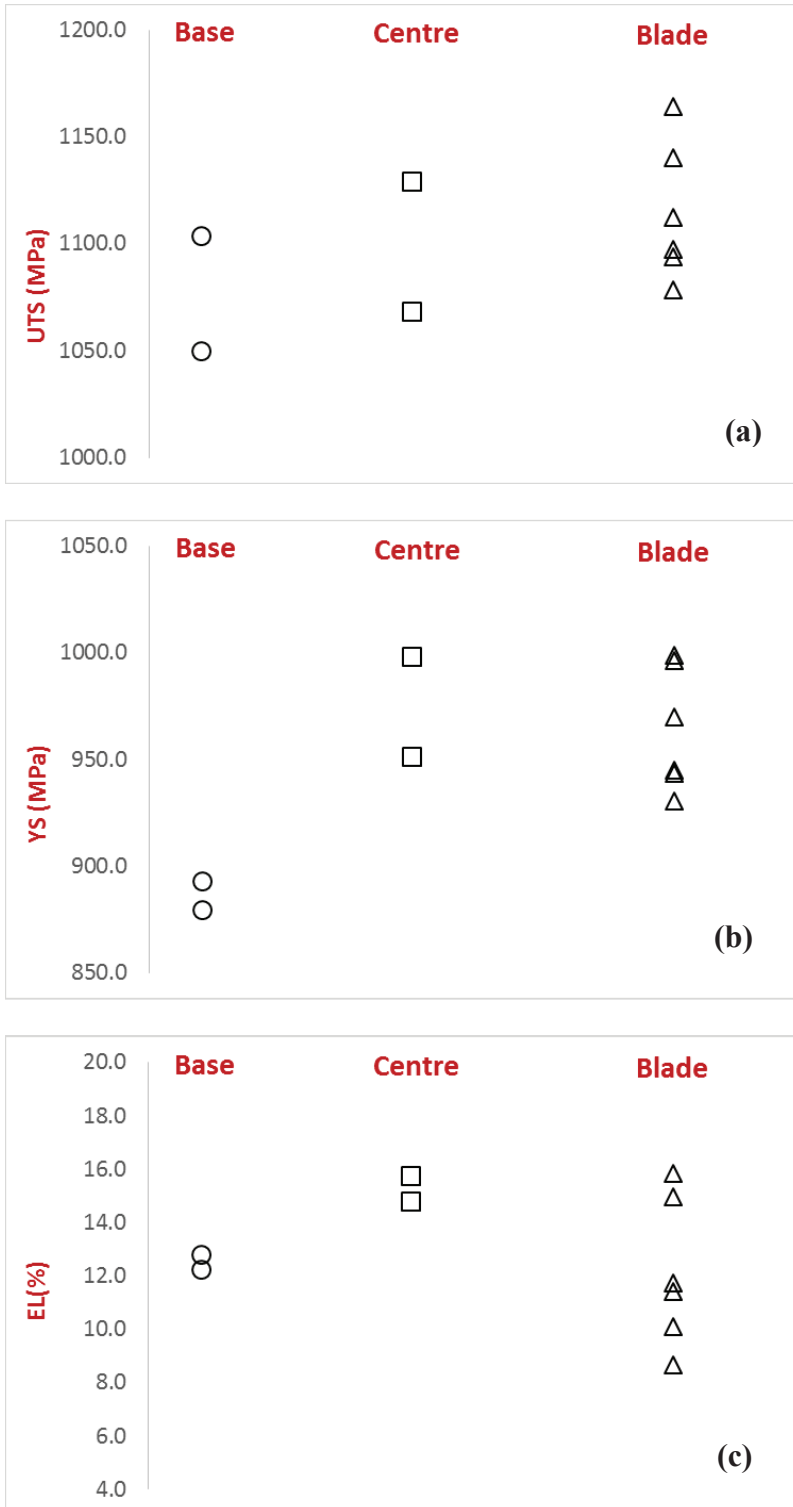

Figure 11. Ultimate Tensile Strength (UTS), Yield Strength (YS) and Elongation (%) for miniature samples extracted at the base, centre and blade regions of the impeller in the as-built condition.

The fracture surface of two miniature samples, that exhibited good and poor tensile properties were investigated from the standard heat-treated part. Figure 12(a) shows fracture surface image of a poor tensile sample from the blade C_Bl_5_Z with 10.1% elongation. Figure 12(b) shows the fracture surface image of a sample from the centre of the impeller, C_CR_2_Z which had an elongation of 15.8% and corresponds to a good tensile sample. It is clear from Figure 12(a) that the fracture surface of the poor tensile sample has pore defects as indicated by the red arrows and is a possible cause of early failure when compared to the good tensile sample (Figure 12(b)) that did not exhibit any obvious defects.

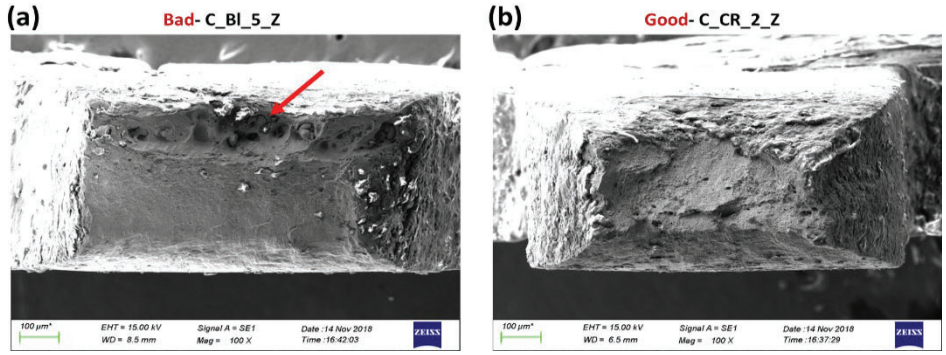

Figure 12. Fracture surface of the impeller part in the as-built condition. (a) Fracture surface of the sample showing poor elongation due to pore defects (red arrow) (b) Fracture surface of sample showing good elongation

In Figure 13 the tensile flow curves for the miniature samples extracted from the impeller part that has undergone HT1 standard heat-treatment. The solid lines correspond to the base and centre regions and the dotted lines correspond to the thin section blade.

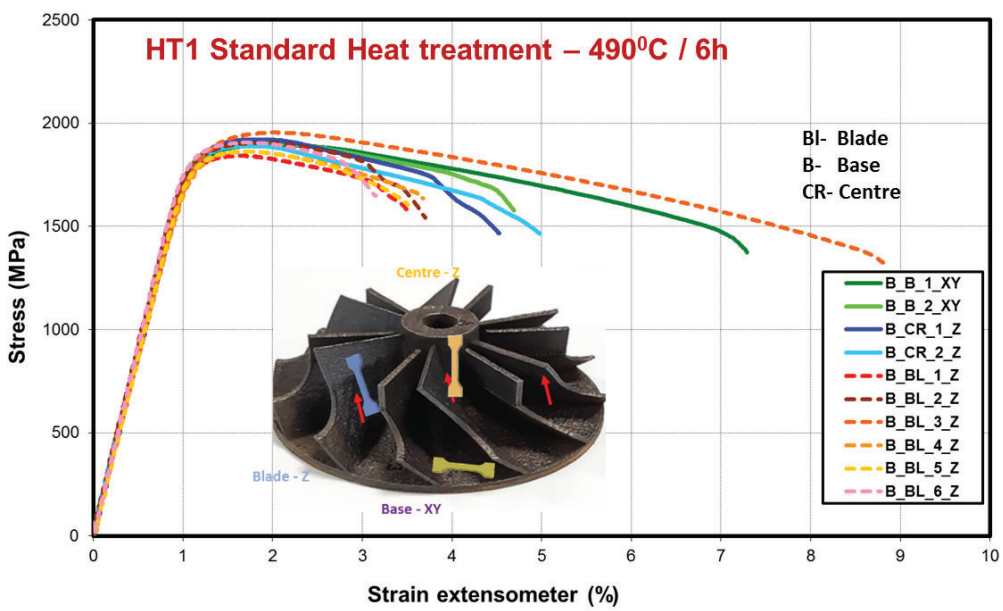

Figure 13. Tensile flow curves for miniature samples extracted from impeller part with HT1 standard heat treatment condition.

In Figure 14 (a, b, c) the tensile strength, yield strength and the elongation % values for the samples in the blade, centre and base regions are plotted respectively for the impeller part which has endured HT1 standard heat-treatment. After the age hardening heat-treatment, the strength of the samples has increased significantly due to precipitation hardening. The tensile properties of the samples from the thin sections are showing very low elongation and a large variability in strength as compared to the samples from the thick sections.

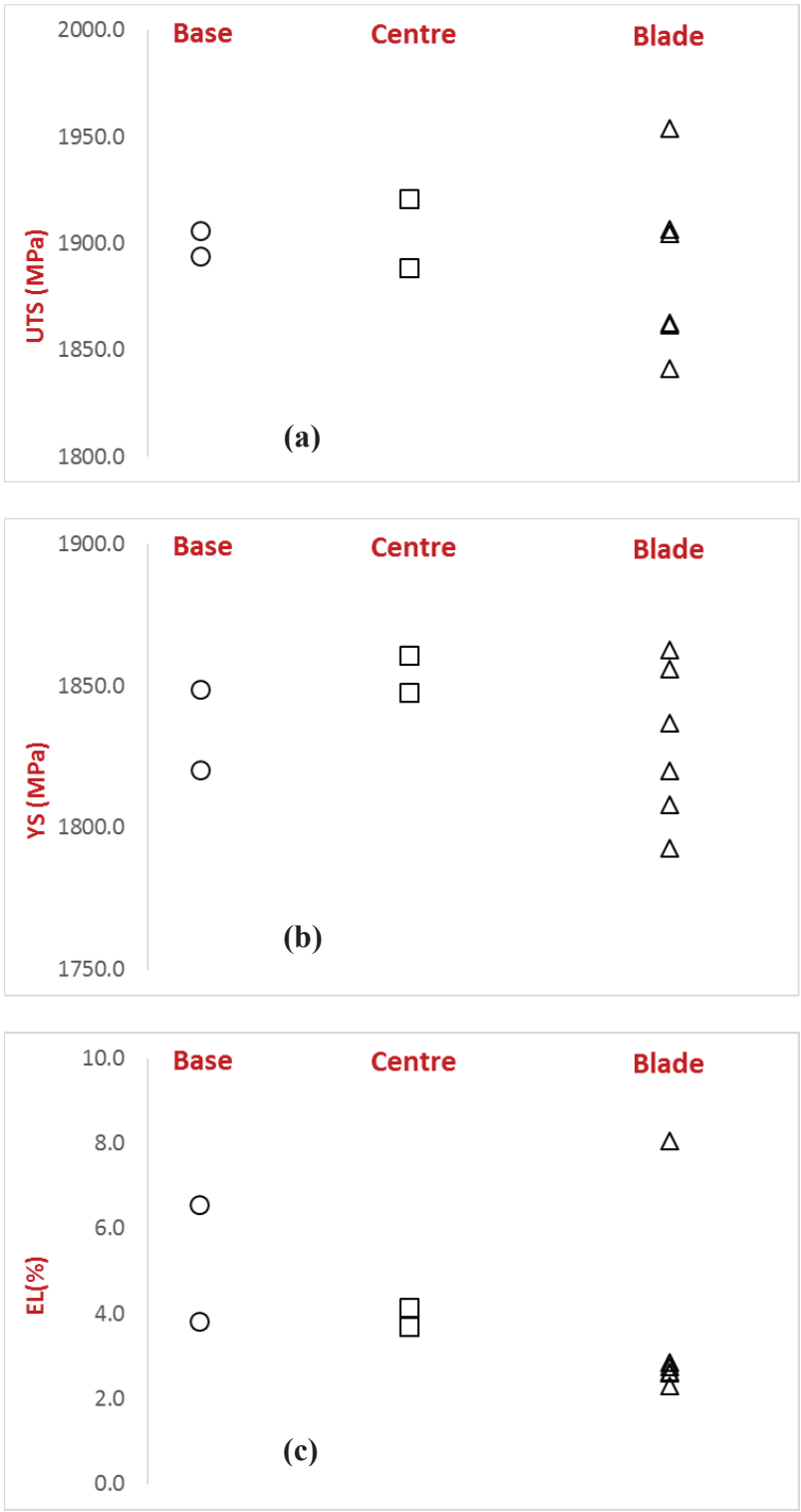

Figure 14. UTS, YS and Elongation (%) for miniature samples extracted at the base, centre and blade regions of the impeller which has endured HT1 standard heat-treatment.

The fracture surface of two miniature samples, that exhibited good and poor tensile properties were investigated from the standard heat-treated part. Figure 15(a) shows the fracture surface of a poor tensile sample from blade B_Bl_6_Z which has 2.3% elongation. Figure 15(b) shows the fracture surface image of a good tensile sample from blade B_Bl_2_Z which has an elongation of 8.1%. From Figure 15(a) it can be observed that the fracture surface has multiple pore defects as indicated by the red arrows and has caused early failure when compared to the good tensile sample with no obvious defects.

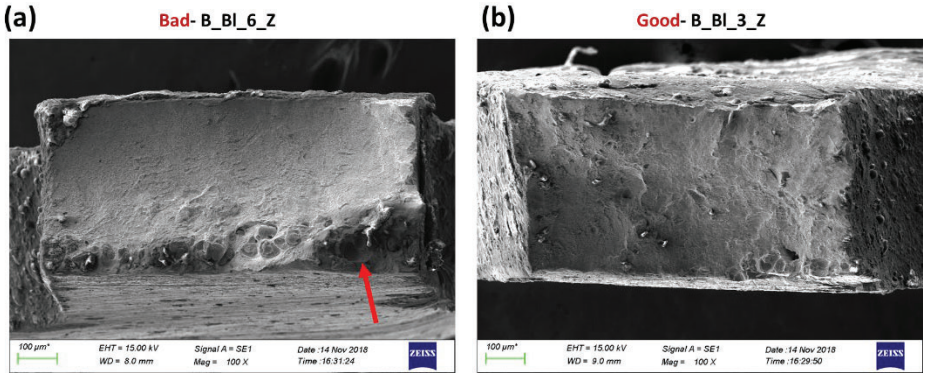

Figure 15. Fracture surface of the impeller that has undertaken HT1 standard heat treatment. (a) Fracture surface of the sample showing poor elongation due to pore defects (red arrow) (b) Fracture surface of sample showing good elongation.

In Figure 16 the tensile flow curves for the miniature samples extracted from the impeller part has endured the HT2 standard heat-treatment that included a solutionising treatment before age hardening. The solid lines correspond to the base and centre regions and the dotted lines correspond to the thin section blade.

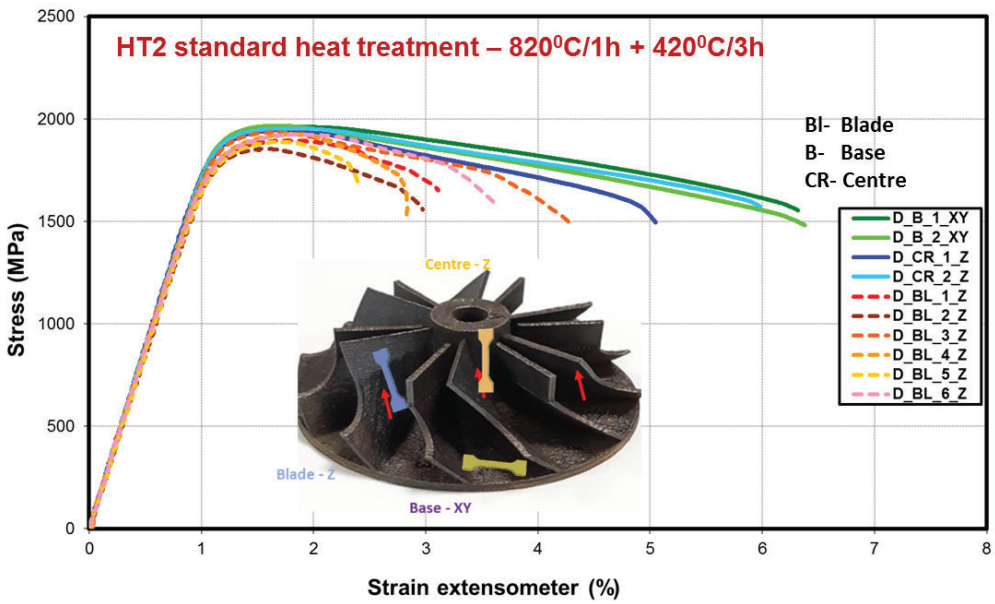

Figure 16. Tensile flow curves for miniature samples extracted from the impeller which has undertaken the HT2 standard heat-treatment.

In Figure 17(a, b, c) the tensile strength, yield strength and the elongation (%) values for the samples extracted from the blade, centre and base regions are plotted respectively for the impeller that has undergone HT2 standard heat-treatment. As observed previously the strength of the samples have increased significantly due to precipitation hardening after heat- treatment. The tensile properties of the samples for the thin sections are showing very low elongation as compared to the thicker sections. From Figure 17(a), it can also be observed that tensile strength of the samples from the thin sections are significantly lower as compared to the thicker sections after the HT2 standard heat-treatment procedure. Due to higher heat-treatment temperature of HT2, the thinner sections have undergone more softening as compared to thick sections, owing to lower thermal mass in these locations. When compared to tensile strength of samples using HT1 standard heat-treatment in Figure 14a, the ultimate tensile strength of the samples from the base region are higher using HT2 standard heat-treatment.

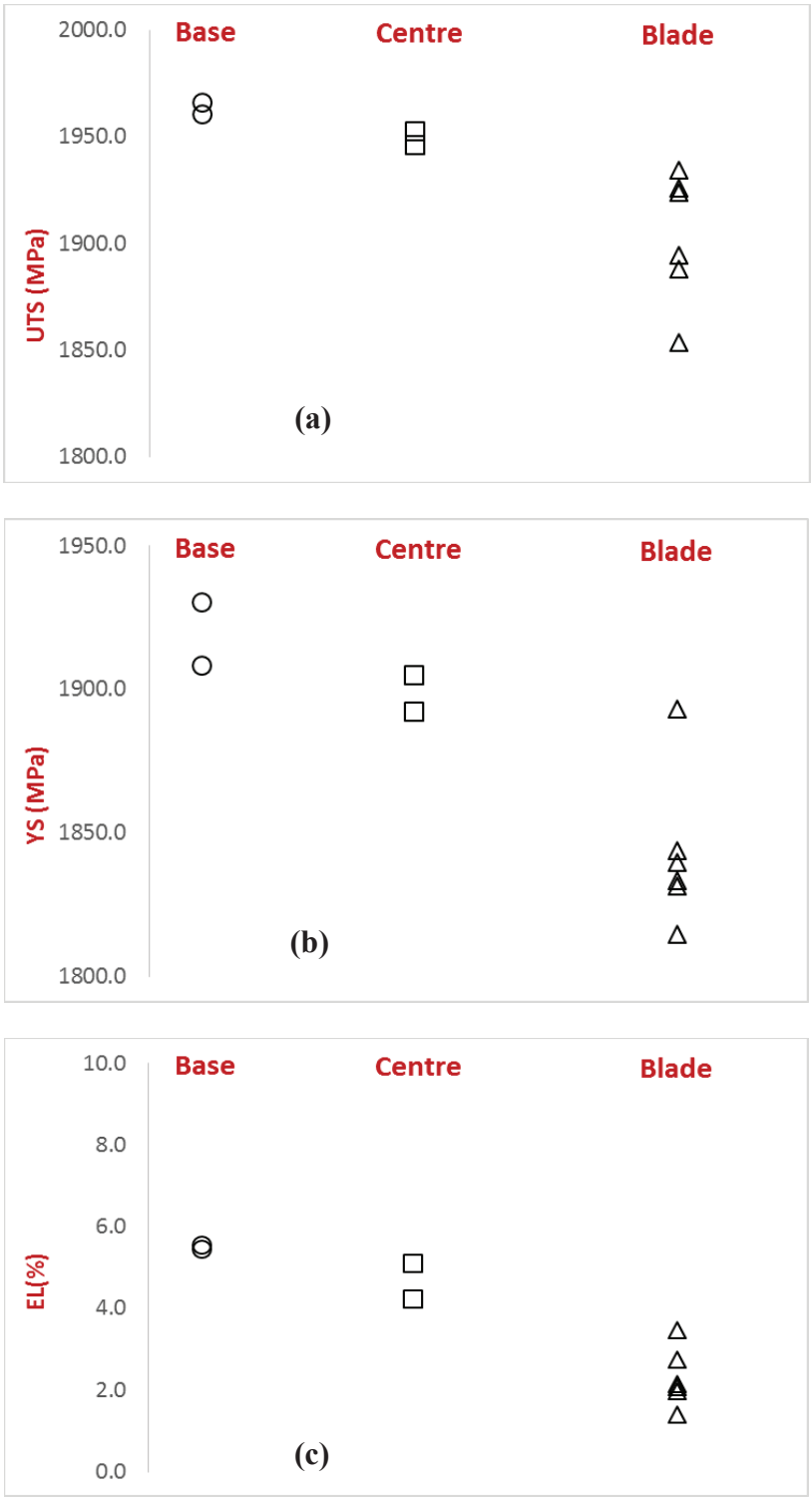

Figure 17. UTS, YS and Elongation (%) for miniature samples extracted at base, centre and blade regions in the impeller part that had undergone HT2 standard heat-treatment.

The fracture surface of two miniature samples, that exhibited good and poor tensile properties were investigated using HT2 standard heat-treated part. Figure 18(a) shows the fracture surface image of a poor tensile sample from the blade D_Bl_5_Z which had a 1.4 % elongation. Figure 18(b) shows the fracture surface image of a good tensile sample from the base of impeller, D_B_2_XY which had an elongation of 5.6%. From Figure 18(a), the fracture surface of the poor tensile sample has multiple pore defects as indicated by red arrow that resulted in early failure. The fracture surface of a good tensile sample in Figure 18(b) was observed to have no obvious defects.

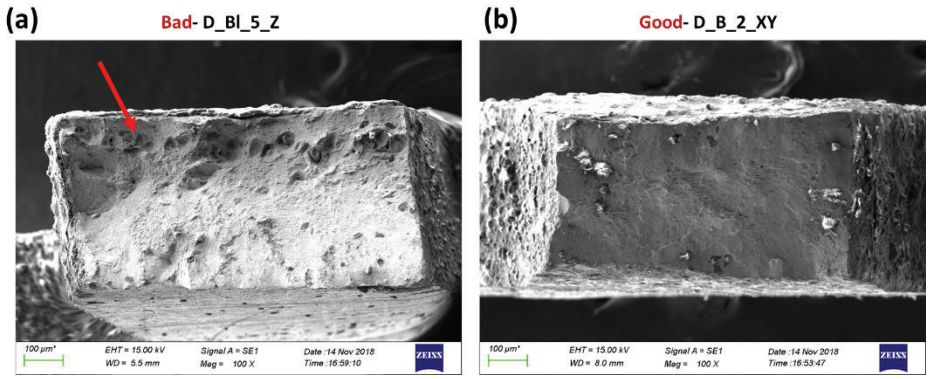

Figure 18. Fracture surface of the impeller part that had undergone HT2 standard heat treatment. (a) Fracture surface of the sample showing poor elongation due to pore defects (red arrow) (b) Fracture surface of sample showing good elongation.

The tensile samples extracted from the extensions that displayed high and low porosity from the X-ray CT scan were chosen for tensile testing. In Table 2, the tensile property values are tabulated with the corresponding porosity values from the samples at three different conditions (as-printed, HT1 standard heat-treatment and HT2 standard heat-treatment). From Table 2 we observe that there appears to be no direct correlation of the tensile property to the porosity values observed in the CT scan. The reason for this observation may be because, there is no large variation in porosity values between the samples and the tensile property, especially elongation %, is dependent on local pore initiating failure in the sample rather than the overall porosity.

Table 2. Tensile properties of selected samples extracted from the extensions of the impeller part. Also given is the porosity values in the samples obtained by X-Ray CT.

	HT1 Standard Heat Treatment			As-Printed part			HT2 Standard Heat Treatment		
Sample	1	2	3	1	2	3	1	2	3
UTS (MPa)	1955.0	1941.3	1919.5	1124.3	1128.0	1129.0	1912.1	1859.9	1911.5
YS(MPa)	1915.9	1874.6	1814.9	898.1	880.4	914.0	1755.3	1697.3	1730.3
El(%)	5.6	6.5	7.7	11.7	14.1	13.3	6.2	4.3	4.7
Porosity fraction from XRay CT	0.00081	0.00076	0.00054	0.00151	0.00173	0.00160	0.00165	0.00168	0.00111

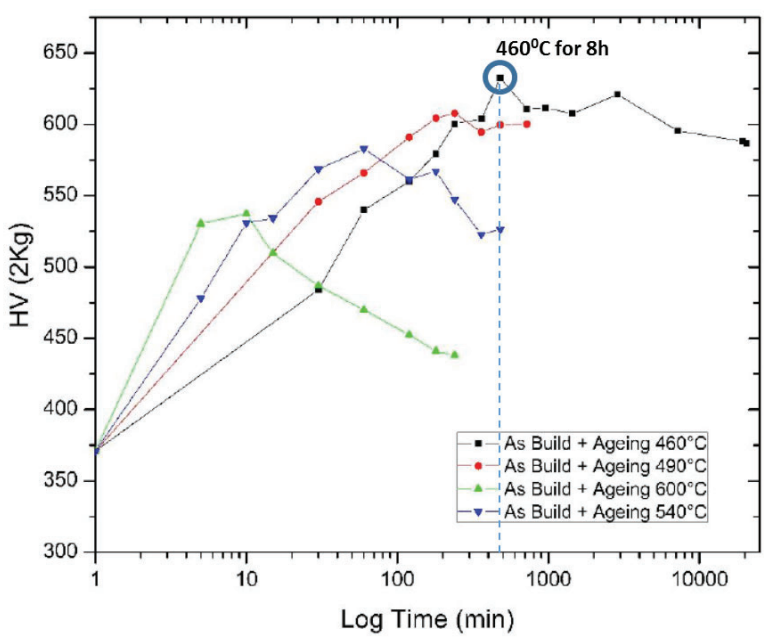

Figure 19. Vickers hardness variation in maraging steel as a function of different heat-treatment cycles [6]. The highest hardness corresponded to heat-treatment at 460°C/8hrs.

The heat-treatment cycle was identified from the literature Masneri[6] as shown in Figure 19. It can be inferred from Figure 19 that the peak hardness is achieved for soak temperature of 460°C and at longer soak times at about 8 hours. Hence the final impeller part was heat-treated at 460°C for 8hrs and the tensile properties of miniature samples at different locations were examined.

Tensile results from recommended heat-treatment

Tensile flow curves for different samples extracted from the impeller that has been post-processed with the in-house recommended heat-treatment of 8 hours at 460°C is shown in Figure 20. As previously conducted, miniature samples were extracted at different locations at the base, centre and blade sections of the part to examine the variation of tensile properties with section thickness.

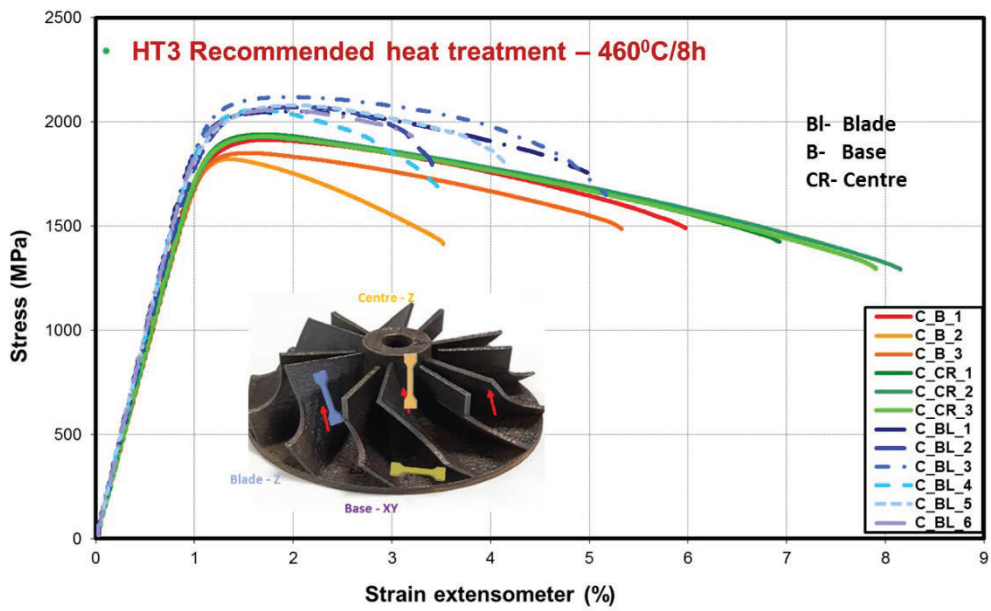

Figure 20. Tensile flow curves of miniature samples extracted from the impeller using in-house recommended heat-treatment.

The samples from the thin section (blade) are plotted as dotted lines and the samples extracted from the thick sections (centre, base) are plotted as solid lines. It is clear from Figure 21, that the tensile properties in the thin sections exhibited higher strength when compared to the tensile properties from the thick sections. The tensile properties (UTS, YS and El(%)) for the three different heat-treatments (HT1 standard, HT2 standard, recommended HT3) were plotted for different locations in the impeller as shown in Figure 21 a, b and c.

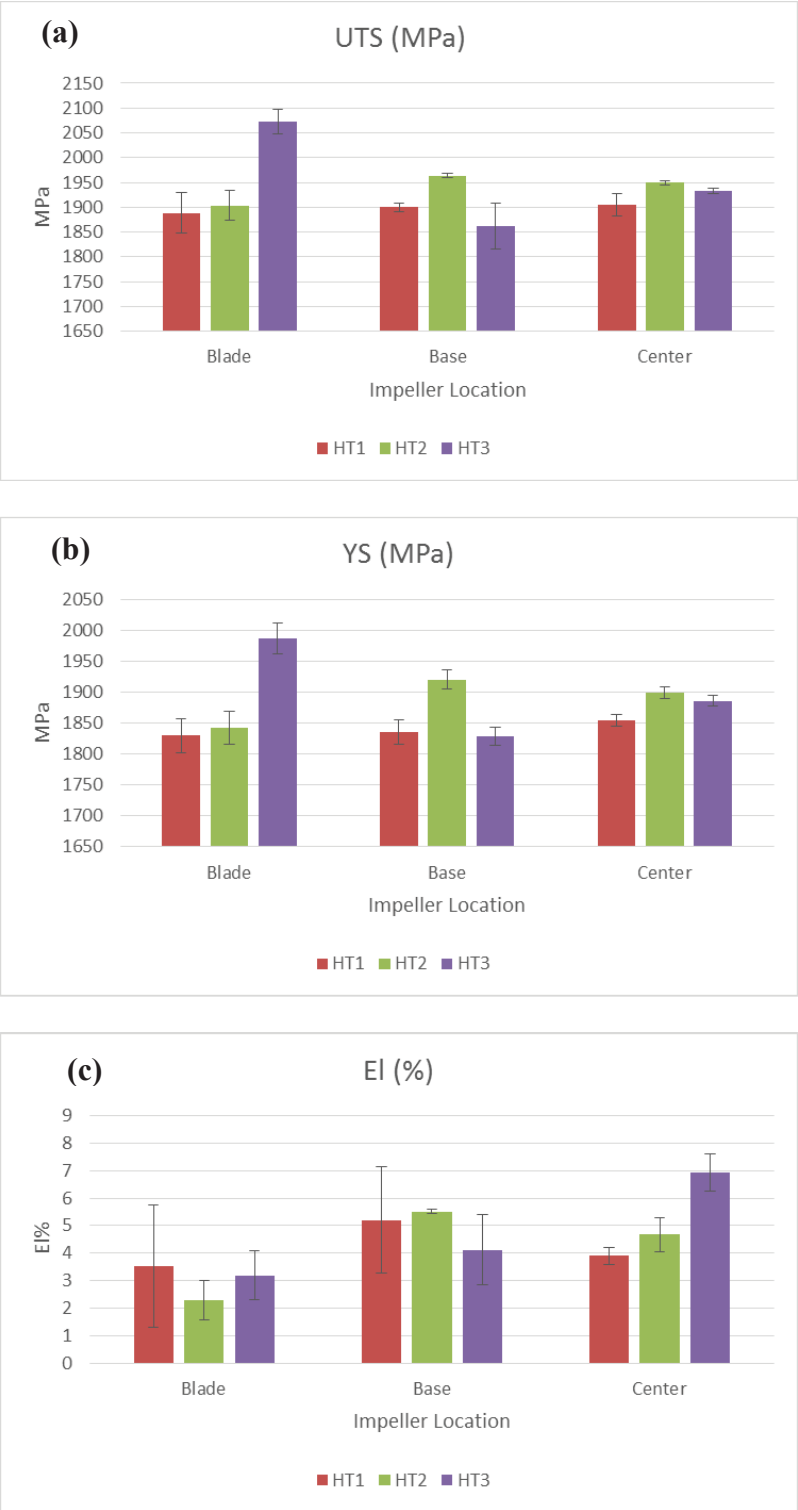

Figure 21. Tensile properties (a) UTS (b) YS (c) El(%) for the impeller which endured three different heat-treatments at three different locations.

From Figure 21 it can be observed that the recommended heat-treatment profile of 460°C for 8hrs, provided an improved strength for thin sections (blade region) as compared to the other two heat-treatment profiles. However, such a difference was not observed in the thick sections for the different heat-treatments. Thin sections have lower thermal mass which may have resulted in faster phase transformation kinetics when compared to thick sections for the prescribed heat-treatment. The difference in kinetics has resulted in different microstructure and properties within the sections. It may be possible to further optimise the heat-treatment profile by increasing the soak time to achieve better strength in the thicker sections. A detailed study is required to analyse the phase

composition differences between the samples at different locations and different heat-treatments to further optimise the soak time. As seen in Figure 20, the elongation values do not show any clear trends between the different heat-treatments.

Conclusion

The following points can be concluded from the current study.

1. For the tensile property variations in the impeller part, thin section (blade) regions exhibited more variability in elongation due to more defects observed in the thin sections.
2. X-Ray CT scan of thin extension samples reveal numerous pore defects on the edge and near the surface of the sample.
3. Fracture surface examination clearly indicates that the early failure in samples were caused due to pore defects in sample gauge area.
4. Between the three different heat treatments (HT1, HT2 and HT3), the HT3 heat treatment (460°C for 8hrs) gives significantly higher strength in the thin section (blade). The heat treatment HT2 (solutionzing and ageing) gave a slightly better strength in the thick sections (base and center). This demonstrates that part geometry has influence in heat treated properties.
5. Miniature tensile sample testing provides an effective way to measure localized mechanical behavior of the part that compares well with ASTM standard tests.
6. Some of the advantages of having miniature tests are; a) Cost saving achieved; a small extension in the part can be used to test tensile properties b) Location specific mechanical property information is generated for an AM database.

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