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Ellis, A., Brown, R. [orcid.org/0000-0001-6671-3239](https://orcid.org/0000-0001-6671-3239) and Hopkinson, N. (2015) The effect of build orientation and surface modification on mechanical properties of high speed sintered parts. *Surface Topography: Metrology and Properties*, 3 (3). 034005. ISSN 2051-672X

<https://doi.org/10.1088/2051-672X/3/3/034005>

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# The Effect of Build Orientation and Surface Modification on Mechanical Properties of High Speed Sintered Parts

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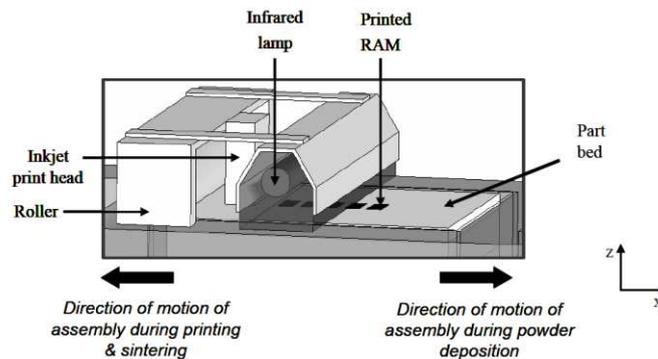
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## Abstract

High Speed Sintering is a novel Additive Manufacturing technology that uses Inkjet printing and infra-red energy to selectively sinter polymeric powder. The research presented here investigates the effect of build orientation on dimensional accuracy, density, mechanical properties and surface roughness of High Speed Sintered parts. Tensile specimens were built through 7 different angles between and including the XY (horizontal) and ZY (vertical) planes and analysed. The effect of the PUSH<sup>TM</sup> Process was also investigated across this range of build orientations. The results show that build orientation does influence the properties of the parts. A number of mechanical properties showed a relationship with build orientation. Density was seen to decrease as the angle increased from XY towards ZY. This increase in angle was shown to increase surface roughness while ultimate tensile strength and elongation at break decreased. At all build orientations, the PUSH<sup>TM</sup> process significantly reduces surface roughness, mildly increases part density and had a small effect on ultimate tensile strength whilst showing a small but consistent increase in elongation at break.

## Introduction

High Speed Sintering (HSS) is a novel polymer based Additive Manufacturing (AM) process. Rather than the use of a high powered laser as the energy source as in Laser Sintering (LS) HSS utilises Inkjet printing and IR lamps. To cause sintering, an Inkjet printhead deposits a radiation absorbing material (RAM) directly on to the powder bed.



**Figure 1: Schematic of High Speed Sintering**

The entire bed is then exposed to IR radiation using a lamp, the deposited RAM absorbs sufficient energy to rise the temperature of the underlying powder to sinter, with unprinted areas remaining unsintered. This process then repeats layer by layer until the build is complete. [1, 2]

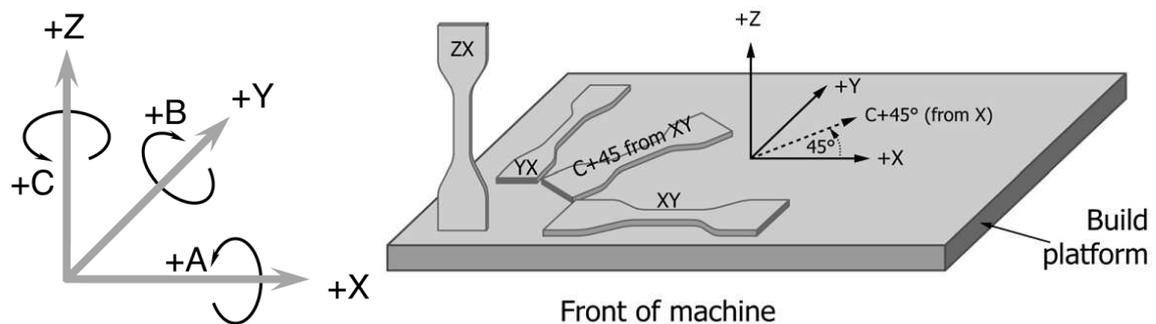
It has been reported how mechanical performance is effected by build orientation and processing conditions. [3-6] Previous work has suggested ultimate tensile strength, elongation at break and Young's Modulus of Laser Sintered parts built in ZY are lower than XY. Density was also found to be greater in XY than ZY, caused by greater shrinkage in XY than Z as proposed by Majewski *et al.* Properties from other tests, including compressive strength, compressive modulus, flexural strength and flexural modulus showed less sensitivity to orientation. [7-11] In addition to differences in mechanical properties, fracture surface also varies with orientation. It has been shown that ZY orientated parts exhibited straight line fractures between layers, while XY parts featured jagged fractures resulting from failure of individual layers at defect locations. [12]

Due to the novelty of the HSS process, most research to date has focused on parameter optimisation and enhancing mechanical properties of parts. [13-15] However, no research

has yet been performed on how build orientation influences mechanical performance and surface roughness. Thus, the research presented here was intended to address this unexplored area. Alongside the influence of build orientation on part properties, the effect of post processing will also be presented. The PUSH™ process is a proprietary polymer finishing process being licensed by the University of Sheffield. This is chemical surface treatment which acts to reduce surface roughness and improve aesthetic appeal leaving no chemical residue on the part.

## Experimental Procedure

The principle axes directions used in this work conform to ASTM 52921-13 for generic upward building AM systems and applies the right hand rule when describing intermediate orientations (**Figure 2** - left). [16, 17]



**Figure 2: Principle axes directions & right hand thumb rule (left) and Symmetry-simplified orthogonal orientation notation (right)**

Symmetry-simplified orthogonal orientation notation is used to identify part orientation, the first letter denoting the axis parallel to the longest dimension and the second letter denoting the axis parallel to the second longest dimension (**Figure 2** - right).[18] To optimise use of the build volume, a Type V tensile test specimen was modelled according to ASTM D638, shown below in **Figure 3**.

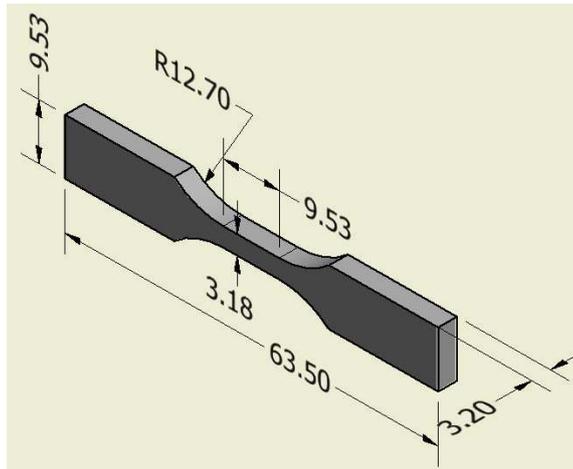


Figure 3: Type V tensile test specimen CAD model, dimensions in mm

This small test specimen enabled an even distribution of 7 build angles within the limits of the build volume; XY, B-15, B-30, B-45, B-60, B-75 and ZY as displayed below in **Figure 4** and **Figure 5**.

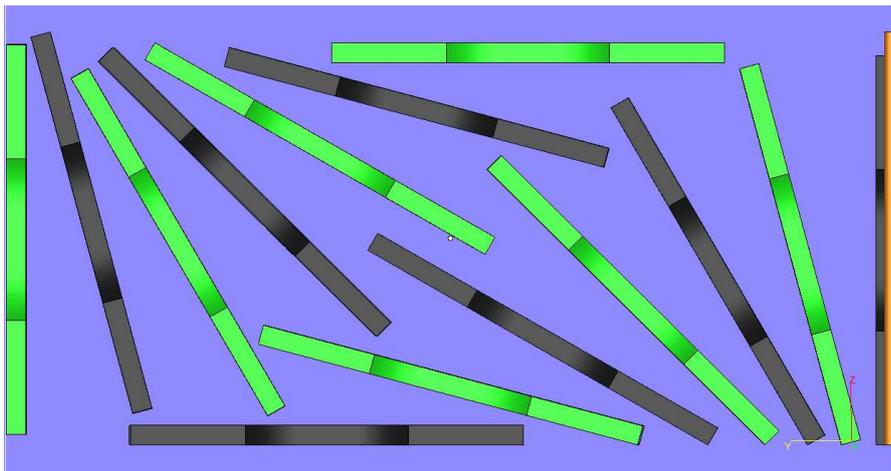
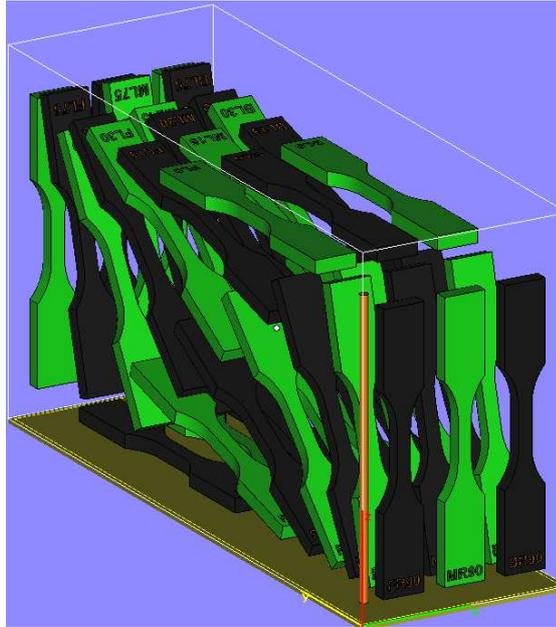


Figure 4: Side view of double fan array



**Figure 5: Distribution of dogbones in the build**

**Figure 5** is colour coded, the black specimens were left unfinished, while green specimens were subjected treated by the PUSH™ Process. Identifiers were designed into each specimen, the alphanumeric string served to identify the side (L=left, R=right) and depth (F=front, M=middle, B=back) of the specimen's origin, in addition to orientation (0=XY, 15=15° etc.). This fan array of tensile test specimens allowed maximum use of the available build volume. However, this arrangement allowed 6 specimens for each build angle, as such, mechanical testing the data presented represents the average from 3 tensile test specimens.

100% used Nylon 11 (DuraForm® EX-Natural) was used to manufacture the tensile test specimens with a 4% global shrinkage compensation applied using the machine parameters displayed below in **Table 1**.

**Table 1: Processing parameters used for Nylon 11**

Build Bed Overhead (°C)	Build Bed Jacket (°C)	Feed Bed Overhead (°C)	Feed Bed Jacket (°C)	Preheat (% at mm/s)	Sintering (% at mm/s)	Grey scale
180	170	150	135	80 at 150	100 at 100	0

A number of key dimensions for each specimen were measured using Senator SEN-331-2230K digital callipers. For each dimension, 3 equidistant measurements were taken across the whole specimen which were then averaged.

To calculate density, the mass of each specimen was measured using Ohaus Pioneer PA64C scales  $\pm 0.0001\text{g}$ . The volume was obtained using the original CAD model of the specimen and measured external dimensions to estimate the volume using the following equation:

$$V_{specimen} = V_{CAD} \left( \frac{WO_{specimen}}{WO_{CAD}} \times \frac{LO_{specimen}}{LO_{CAD}} \times \frac{T_{specimen}}{T_{CAD}} \right)$$

**Equation 1**

where  $V$  is the volume,  $WO$  the overall width,  $LO$  the overall length and  $T$  the thickness. Using this, an estimate of the density was found using the below equation:

$$Density, \rho = \frac{Mass, m}{Volume, v}$$

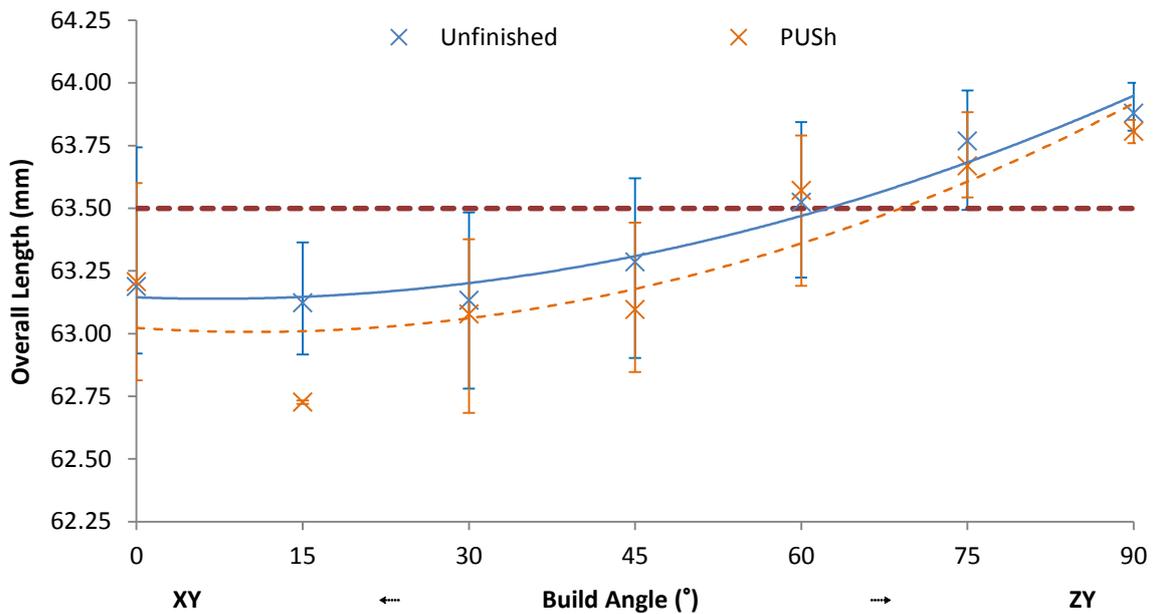
**Equation 2**

Tensile testing was conducted using a H500L laser extensometer, mounted on a Tinius Olsen H5KS Tensometer with a 5kN load cell and HW10 grips. To ensure failure between 30 seconds and 5 minutes, an extension rate of  $1\text{mm min}^{-1}$  was used.

$R_a$  was identified as the preferred surface roughness parameter. An 8mm evaluation was selected with 2mm pre and post travel lengths to eliminate transient errors. A Gaussian filter of wavelength 8mm was used to filter out waviness effects from a travel speed of  $2\text{mm s}^{-1}$ . 3 measurements were taken on the top and bottom faces of each specimen at the centre of the 2 grip areas and along the narrow section.

## Results & Discussion

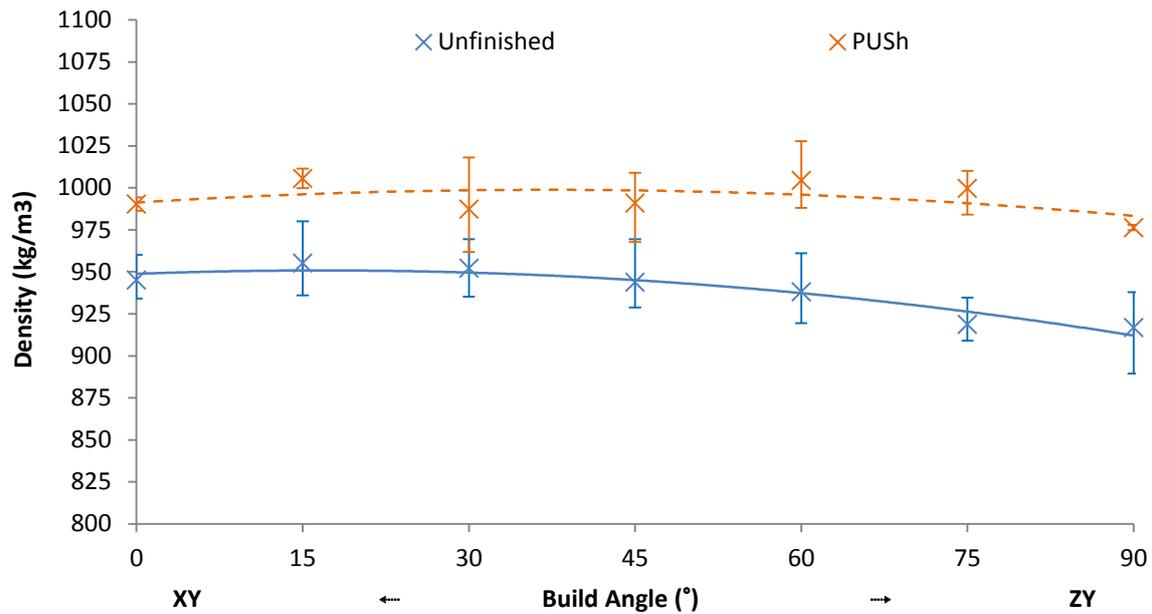
To assess dimensional accuracy, 3 tensile test specimens of each orientation were measured, treated by the PUSH™ Process and then remeasured. The results are shown below in **Figure 6** with the CAD nominal dimension plotted for reference.



**Figure 6: Effect of build orientation on specimen length on unfinished and PUSH™ parts**

It is clear that both unfinished and PUSH™ samples are both slightly undersized when built in XY, both approximately 0.25mm of the CAD dimension of 63.50mm. Both samples gradually increase accuracy until a build angle of 60° at which they are very close to the nominal dimension. The two orientations at steeper angles, 75° and 90° (ZY), showing increasing lengths respectively when compared to the input dimension. This behaviour was not unexpected and may be accounted for differential shrinkage across the range of build orientations. **Figure 6** shows that for all samples less shrinkage occurs as build angle increases. Therefore, as Z character of the specimen increases with build angle shrinkage becomes less prominent in the Z axis than X or Y[10]. Across the data range, parts subjected to the PUSH™ process possess a small but consistent reduction in length. This small reduction is attributed to the consolidation or removal of fine particles weakly adhered to the part surface.

Subsequent to dimensional analysis, density measurements were calculated. Analogous to the dimensional measurements, 3 samples of each orientation were weighed, treated by the PUSH™ process and then reweighed. **Figure 7** shows the effect of build orientation on part density.



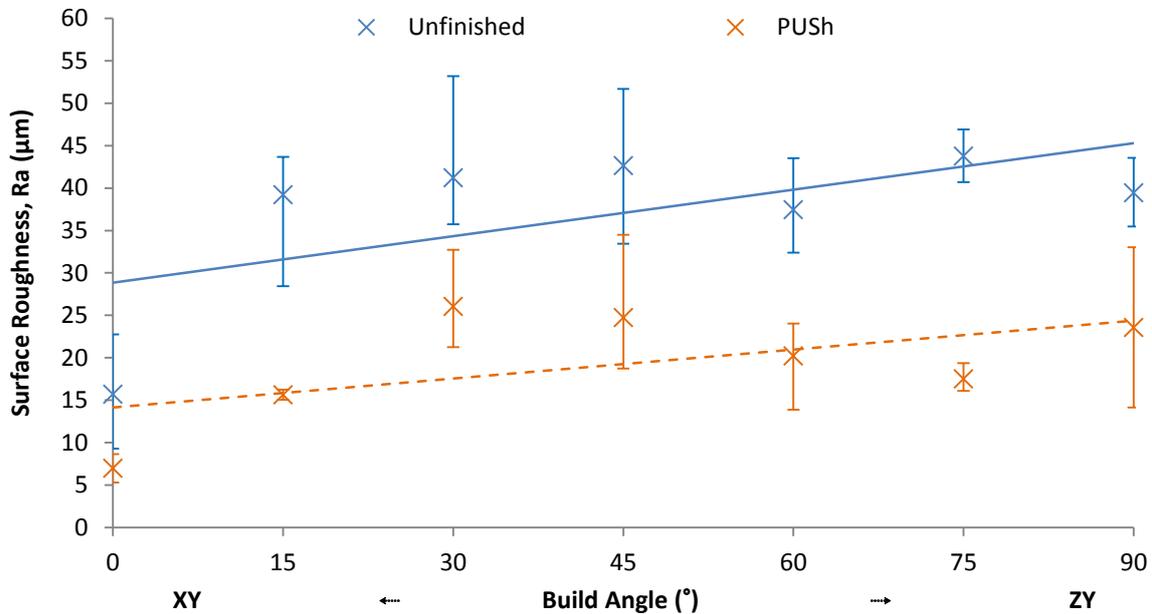
**Figure 7: Effect of build angle on density**

**Figure 7** shows density of unfinished parts exhibit a dependence on build angle, with density slowly decreasing from a maximum of 955kg/m<sup>3</sup> at 15° to a minimum of 917kg/m<sup>3</sup> at the maximum build angle of 90°. This trend follows the expected pattern from the dimensional measurements above, as the Z character of parts increases, shrinkage is reduced resulting in parts which are less dense. Although a trend is observed, it is important to reiterate the volumes used to calculate density were not measured, but rather are an estimation based on the extrapolation of CAD data.

The data indicates the specimens experience consolidation during the finishing process, acting to slightly reduce part length while maintaining the mass of the part resulting in an apparent increased density. However, this is a calculated effect, as the bulk density of the part would not be affected by a reduction in surface roughness. **Figure 7** also shows PUSH™ samples do not become apparently less dense with build angle but that density remains consistent across the range of build orientations explored thus eliminating the influence of build angle on part density.

To begin the assessment of the relationship between build angle and surface roughness, the top and bottom face of each test specimen was analysed by surface profilometry. The top surface of a specimen is identified as the face on which the specimen identifier was located. This is particularly important when considering build angles approaching 90°, at

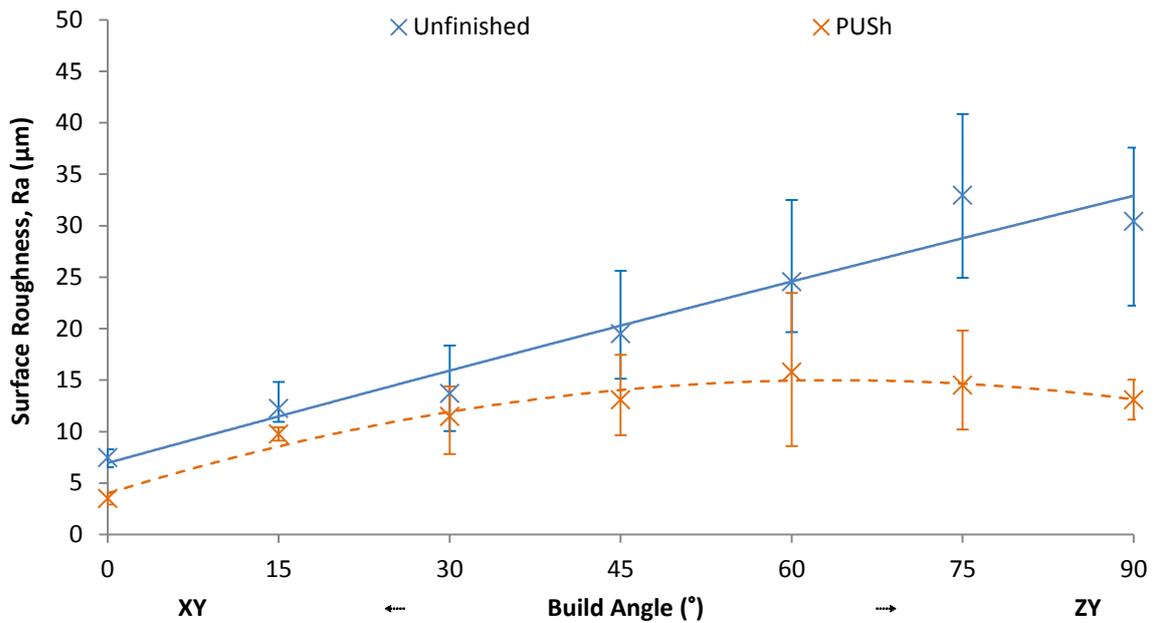
this point the 'top' surface is actually facing the right hand side of the build. Surface profilometry results obtained from the top surface of test specimens are shown below in **Figure 8**.



**Figure 8: Effect of build orientation on top face surface roughness**

Results show an increase in surface roughness for both sets of samples as the build angle increases. This may be rationalised by considering the number of layers contained on the measured surface, for the samples built in XY this is simply the surface roughness across one layer. However, as the build angle increases the number of layers increases and introduces the well-known stair stepping effect. The unfinished and PUSH<sup>TM</sup> specimens show a similar trend with the PUSH<sup>TM</sup> samples showing a significant reduction in surface roughness across the range of build angles.

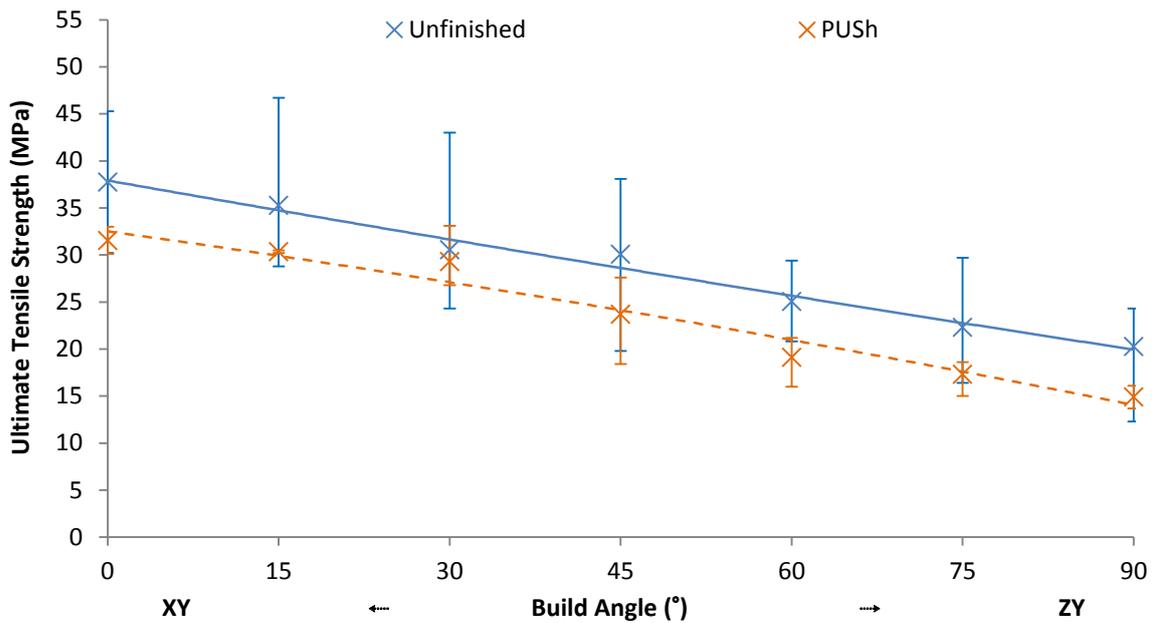
**Figure 9** shows the relationship between build angle and surface roughness for the bottom face of the specimens.



**Figure 9: Effect of build orientation on bottom face surface roughness**

It is important to note that although the trend line for unfinished specimens appears as linear, this is in fact a second order polynomial curve as used for all figures in this work. **Figure 9** shows the bottom face is consistently smoother than the top face across all build angles including ZY. This behaviour has been observed before and is not unknown to High Speed Sintered parts. A reason for this could be due to RAM being deposited on top of a layer or by the meniscus formed during liquid phase sintering causing the bottom surface to be less rough. Despite this, it would be expected that the top and bottom faces of the ZY specimen would be more similar as this orientation renders both the faces vertical in relation to the build direction. It is unclear why this is the case, it is possible the position of the face relative to the direction of motion has an effect, that is, powder is not deposited on both faces at the same time, one is deposited before the other.

**Figure 10** below plots ultimate tensile strength against build angle for unfinished and parts finished by the PUSH™ Process.



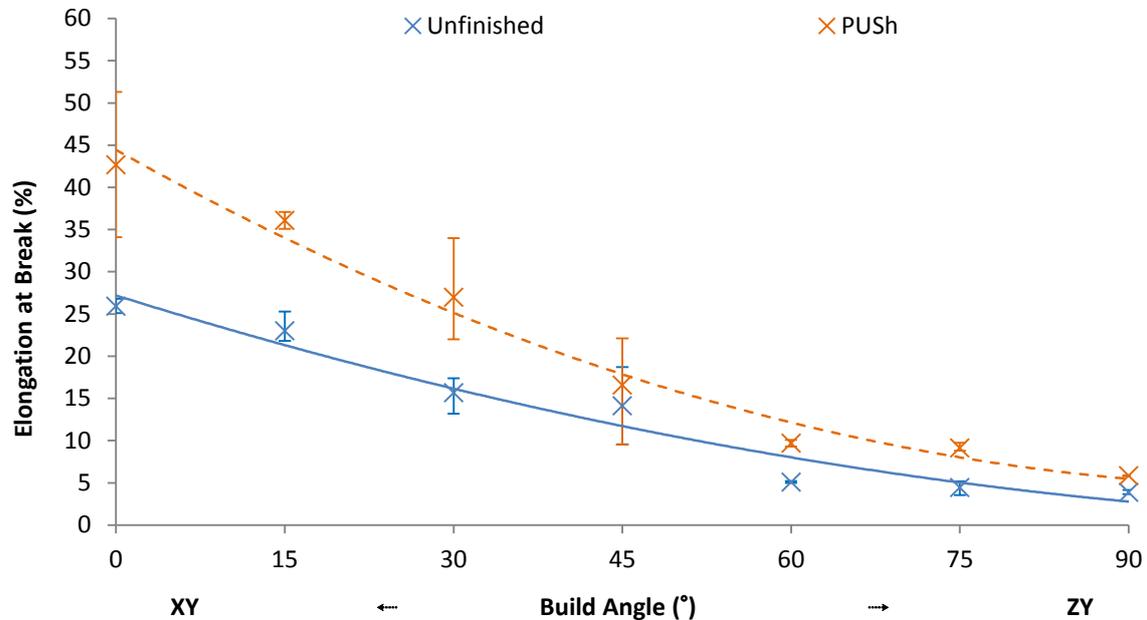
**Figure 10: Effect of orientation angle on Ultimate Tensile Strength**

UTS exhibits an almost linear relationship with build angle as shown above in **Figure 10** with a high of 38 MPa for unfinished samples reducing to 20 MPa at ZY. Majewski *et al.* have shown that build orientation for laser sintering had little effect on tensile strength. [19] This suggests that at the chosen parameters Laser Sintering was able to achieve greater consolidation in the Z direction and eliminate the influence of build orientation. The results shown here suggest that at these build parameters the Z consolidation of the parts is reduced compared to the consolidation in XY. Despite this, previous work on High Speed Sintering has shown that the amount of RAM deposited influences the mechanical properties of tensile test specimens.[20] In this work, the maximum of RAM possible was deposited, however this may not be optimum and in fact an excess of RAM may inhibit layer to layer consolidation. As such, it is possible that the amount of RAM deposited in this case was not ideal for Z penetration rendering the samples weaker along this axis.

The data appears to show slight reduction in ultimate tensile strength of PUSH™ samples across the range with a maximum of 32 MPa at XY and a lowest value of 15 MPa at ZY. This was somewhat unexpected given the evidence that the PUSH™ Process acts to make the samples appear more dense. Despite this decrease in the average value, the range is reduced across all build angles. It is suggested this is due to elimination of surface defects and acting as an equaliser making the surface of all samples more alike and yielding a more

repeatable range of values evidenced by the reduction in range bars for the PUSH samples across the data range.

**Figure 11** shows the relationship between build orientation and elongation at break.



**Figure 11: Effect of build orientation on elongation at break**

Elongation at break was found to decrease with increasing build angle. This was not unexpected and has been reported before by Gibson *et al* and Majewski *et al*. [3, 19] However, unlike UTS, EaB could not be well represented by a linear trend line and instead presented a more complex behaviour. This would suggest that inter-layer contact areas could play a role in intermediate build angles, although further work would be required to confirm this. From **Figure 11**, a clear increase in EaB can be seen due to the PUSH™ process. This may be the virtue of the samples possessing a smoother surface, reducing the number of crack initiation points and resulting in increased ductility. Fracture areas of specimens were also investigated. It was found that all specimens exhibited either a straight line or jagged fracture area, as described by Caulfield. [12] A transition from very brittle behaviour at high build angles to ductile behaviour at low build angles was found. This suggests that build orientation influences crack propagation, however, further work is required to investigate this effect more thoroughly.

## Conclusions & Future Work

It is clear that results obtained in the XY and ZY orientations matched trends reported in the literature. At build angles in between, the majority of properties investigated showed a dependence on build angle. Density was shown to gradually decrease as the angle increased whereas surface roughness was seen to increase. The observed behaviours were not unexpected some of which have been observed before in Laser Sintering. The PUSH™ Process was shown to yield parts with more consistent density across the build, reduce the influence of build angle on surface roughness whilst increasing elongation at break. Alongside the majority of anticipated results, the decrease in UTS for PUSH™ samples was not expected particularly as these parts were denser. This could be the interest for further work to discover an explanation. Moreover, further investigation of build angles between 15° and 30° may aid in a deeper understanding of the underlying principles governing the behaviour of elongation at break.

The work presented here demonstrates the importance of considering part orientation for the design and build of HSS parts. However, it is quite possible that changes in build parameters and greyscale would eliminate the influence of build orientation and provide a greater degree of design freedom. The trends observed in the work presented here exemplify the importance of users to identify the critical properties for their required application of maximum performance is to be achieved.

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