DETERMINING THE EFFECT OF THREE- DIMENSIONAL PRINTING ORIENTATION ON THE BENDING STRENGTH OF SAND MOULDS AND CORES WHEN USING A VOXELJET ADDITIVE MANUFACTURING MACHINE

JJ La Grange[1] K. Nyembwe[2] PJM van Tonder[3] DJ de Beer[4] & T van Wyk[5]

[1]Department of Industrial Engineering
Vaal University of Technology, South Africa
jacol@vut.ac.za

[2]Department of Metallurgy
University of Johannesburg, South Africa
dnyembwe@uj.ac.za

[3]Technology Transfer & Innovation
Vaal University of Technology, South Africa
malanvt@vut.ac.za

[1]Department of Industrial Engineering
North West University, South Africa
ddebeer@iclix.co.za

[1]Department of Industrial Engineering
Vaal University of Technology, South Africa
theresevw@vut.ac.za

ABSTRACT

Advances made in Additive Manufacturing (AM) or 3D printing led to the 3D printing of sand moulds and cores used in the foundry industry. Ideally, the mechanical properties of the 3D printed moulds and cores should be uniform throughout the 3D printed part. This will ensure that the casting produced from the 3D printed mould has uniform properties throughout the mould. The following study investigated the effect of the printing location and part orientation in the AM machine used to produce the 3D Printed mould on the bending strength property of sand parts. Several printing orientations and angles were considered in the investigation. Descriptive statistics was used to assess and interpret the results.

[1] The author was enrolled for an M Tech (Industrial) degree in the Department of Industrial Engineering, Vaal University of Technology

1. INTRODUCTION:

Additive manufacturing (AM) processes in the form of three-dimensional sand printing, offers an alternative to conventional mould manufacturing methods used for metal casting applications. This process presents several advantages, which includes: reduction of weight due to better design, increased geometric complexity and the saving of lead time compared to traditional mould making technologies.[2] Several commercial three-dimensional printing systems are available on the market. The most popular platforms include: Exone and Voxeljet.[4,5]

The Furan process is the most predominant chemical process used in three-dimensional sand printing technologies.[6] The later process is a no-bake process, consisting of a sulphonic acid coated sand bonded with a furfuryl resin. The furfuryl is selectively deposited on to the sand using a printing head. Silica sand is very popular in the printing process due to its availability and good properties (strength, permeability, thermal stability, collapsibility and reusability).[9]

Traditional mould and core making processes rely on a sand compaction process where the three-dimensional printing process uses a layer by layer adhesion process. A study by Nyembwe et al, compared the mechanical properties of three-dimensional printed parts to parts produced using traditional hand ramming.[1] The investigation revealed that the post processing of printed part, by baking, made their mechanical properties comparable to that of conventional produced parts.

AM processes can be applied as a substitution for or in combination with conventional processes. In the foundry industry the strength of sand moulds and cores needs to be homogeneous to ensure good casting results.[9] The cost of printing sand moulds and cores was identified as a possible technology uptake inhibitor, as decision makers in foundries, do not necessarily have discrete criteria to evaluate the economic feasibility of using printed sand moulds and cores, especially with complex geometry castings.[3]

Previous research showed that the mechanical properties of sand samples, printed in the same build on a Voxeljet VX1000 three dimensional sand printer, were not consistent when analysed.[1] In addition, literature showed that the printing orientation in AM produced parts had an effect on the part's mechanical properties. This study was therefore aimed at determining the effect of the build orientation and position on the mechanical strength of Voxeljet VX1000 printed parts.

The bending strength is the property used for the assessment and control of resin bonded sand moulds. This mechanical property provides a reliable indication of the resistance of sand moulds to casting defects related to the metallostatic pressure of the molten mould and sand erosion during the pouring of the molten metal in the mould cavity.

Only the bend strength was considered in the paper, as the following pilot study will be used as motivation for the comprehensive research study. The results of this study will be used to determine the bend strength variance of parts printed at different positions and orientations within the VX1000 building envelope, and whether if conforms to the bending strength specifications specified by Voxeljet[5].

2. DESIGN OF EXPERIMENT

The methodology adopted in this study could be broken down into three consecutive steps namely: Printing of sand test specimens, testing and data analysis.

2.1 Printing of sand test specimens

A Voxeljet VX1000 three-dimensional printer was used for the following study. Standard operating conditions were maintained including a printing layer thickness of 300µm. The printing material was limited to imported silica sand recommended by the original equipment manufacturer (OEM). The sand was pre-coated with 0.3% wt sulphonic acid activator.

The building envelope of the Voxeljet VX1000 is 600mm (X-axis) x 1080mm (Y axis) x 500mm (Z-axis). The full building envelope of the Voxeljet VX1000 was considered in the following study to investigate the possible variation of bending strength of parts printed within a single build process. Test specimens were placed at different orientations and angles throughout the building envelope.

The printed sand specimens conformed to the recommendations of the American Foundry Society (AFS) for bend strength samples (25.4mm x 25.5mm x 203.3mm).[7] All the samples were numbered with an alphabetic and numeric digit for identification purposes. The alphabetic digit indicated position in the built and the number indicated orientation.

Five print orientations and angles were considered in the following study (X, Y, Z and a 45°offset in the X & Y direction). All five of these orientations were placed at six different locations within the building envelope, as shown in Figure 1. Alphabetic digits were assigned to each position and selected as not to be misleading when printed into the grainy sand specimens.

From an operator perspective position C & I will be the closest to the operator, H & B in the middle of the build and G & A the furthest away from the operator. Direction X will be from position C to I as depicted in Figure 2. Direction Y will be from position C to A as depicted in Figure 2. The print head will first print in the primary movement direction after which it will adjust in the secondary movement direction where the process will repeat itself. The re-coater will recoat in the opposite direction as the primary movement direction. The re-coater will recoat the full bed with one layer immediately after the print head is finished printing that particular layer.

The position of the sand test specimens and the direction of sand printing can be seen in figure 2.

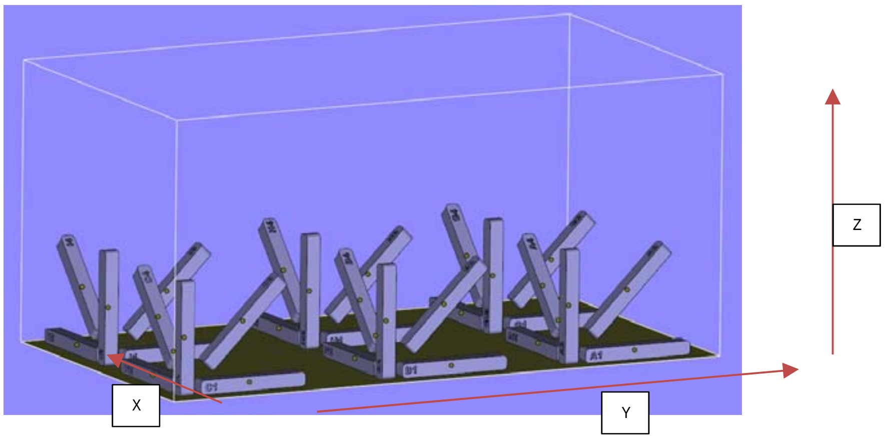

Figure 1: Building orientation of samples in the building volume

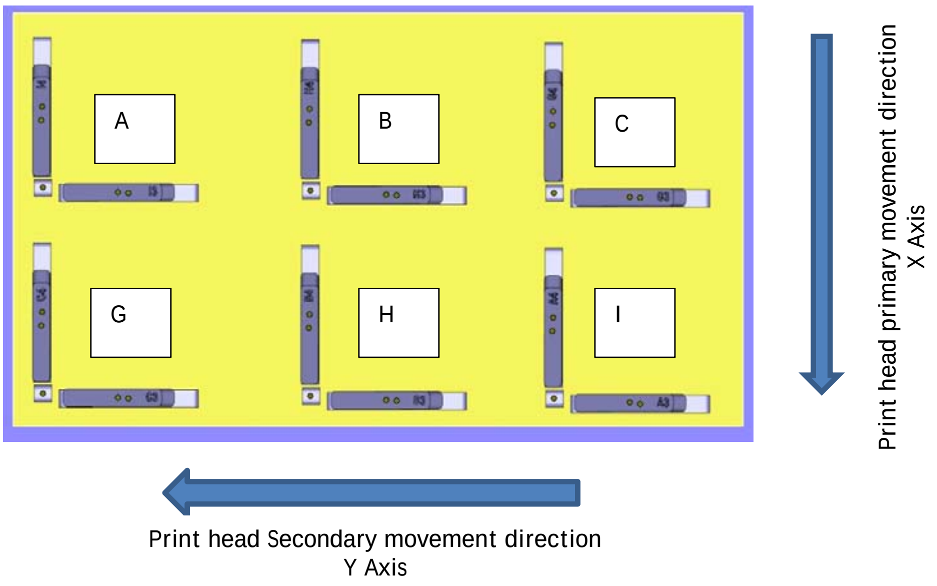

Figure 2: Building envelope with test sample layout

2.2 Curing and testing of specimens

The specimens were cured at 110ºC for 2 hours to ensure maximum part strength. The curing took place immediately after the parts were removed from the Voxeljet sand printer. The bend tests were done the following day, within 24 hours of curing as specified by AFS procedures. The tests were performed on a Ridsdale and Dietert Universal machine as shown in Figure 3.[8]

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Figure 3: Ridsdale and Dietert Universal machine

2.3 Analysis of results

The test results were analysed using both IBM SPSS statistical analysis and Microsoft Excel software, which included the central tendency, standard deviation and the normal distribution of the different print orientations and angles. The results were compared to the minimum required bend strength of 220 N/cm2 (0.22 kPa), as specified by Voxeljet.[5]

3. EXPERIMENTAL RESULTS

The bend test results of the different test samples are shown in Table 1, indicating the different orientations and angles within the building envelope. The results indicated that the bend strength of samples (I,Z) and (C,YZ) were lower than the minimum recommended OEM value. However, the bend strength of the remaining samples were more that the recommended 220 N/cm^2.

The position mean values, shown in Table 1, demonstrated that position I and C had lower values than position H, B, G & A. Orientation mean values show that the Z direction were lower than the other orientations.

The test results confirmed that the print orientation and position had an effect on the bend test results.

Table 1 Bend test results

	Y	Z	YZ	XZ	X	Mean (position)
I	269	188	288	250	294	258
C	269	238	188	281	306	256
H	275	231	319	300	375	300
B	256	238	306	306	269	275
G	319	244	313	294	363	306
A	338	281	294	300	338	310

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Mean (orientation)	288	236	284	289	324

Figure 4 shows a radar chart of the position mean bend test results.

It confirms that position I and C have lower bend strength in comparison with positions H, B, G and A. This chart indicates that location in the build has an influence on bending strength. The chart also shows that H, B, G and A has similar result and I & C also has similar results. Position I & C is located next to each other and are also the furthest point from the source of sand thus compaction or curing rates could have had an influence.

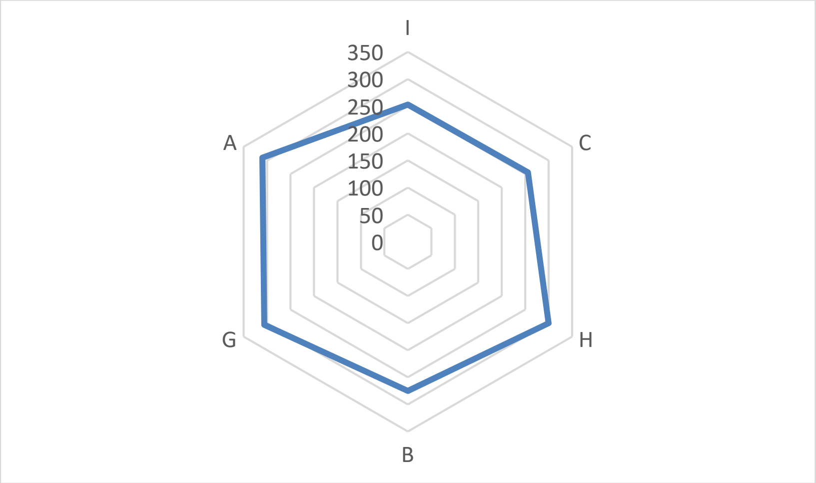

Figure 4: Radar chart in N/cm2

3.1 Central tendency

The mean values of the different print orientations can be seen in Table 2.

Table 2: Directional descriptive analysis

	N	Minimum	Maximum	Mean	Std. Deviation
Y	6	256.00	338.00	287.6667	32.78821
Z	6	188.00	281.00	236.6667	29.74335
YZ	6	188.00	319.00	284.6667	48.74286
XZ	6	250.00	306.00	288.5000	20.68574
X	6	269.00	375.00	324.1667	41.39283

The bend test results of specimens printed in the Y, YZ and XZ direction sre similar to previous studies, which are above the Voxeljet recommended bend strength of 220 N/cm^2.[5] It also became clear that the bend test results of the specimens printed in the X direction were greater than the results of previous studies and that of other orientations in this study.

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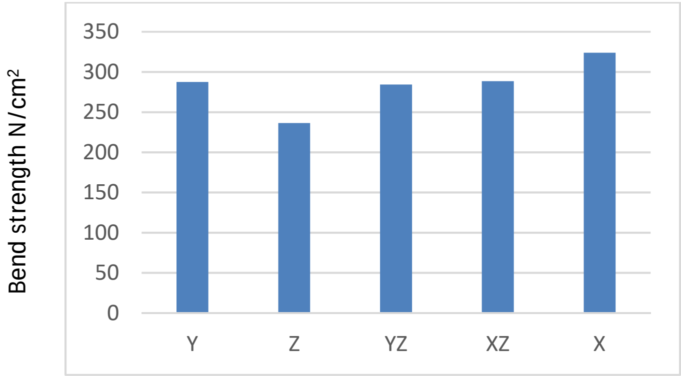

Figure 5: Bend test Mean values

The mean strength of test specimens printed in the Z direction was found to be the lowest of all the printed orientations as depicted in Figure 5. Z direction also produced the lowest bend strength in 5 of the 6 different origins. Therefore it may be an indication that parts printed with maximum Y or X or at 45 degrees will have a stronger bend strength compared to the same part positioned in the Z direction. The Z orientation represent the test samples with the smallest area amongst the different orientations that is covered by furan resin per layer by the print head.

3.2 Standard deviation

The standard deviation of the test results are shown in Figure 6. The figure shows that not all the directions provide the same variability of bend results. This variability ranges between 20 and 50 N/cm^2 which could be considered significant. The YZ orientation showed the largest variation. The lowest variation were obtained in the XZ orientation.

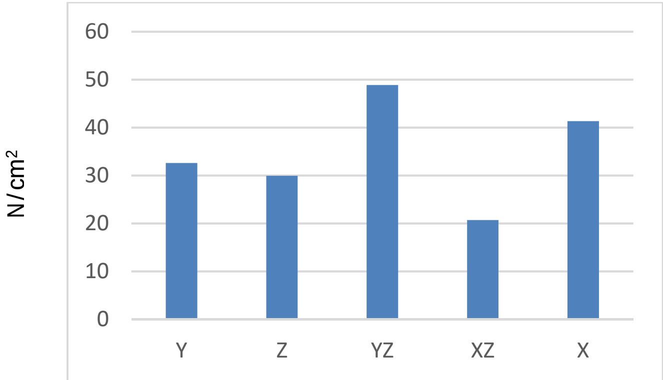

Figure 6: Bend test Standard deviation

The box plot in Figure 7, demonstrates that the highest bending strength were obtained in the X orientation. The lowest strength tested were in both the Z and YZ orientation. This figure also shows four outliers. An outlier indicates that the value is more than 1.5 times the interquartile range above or below the upper or lower quartile. An outlier may be the most important data depicted and in this study two outliers indicates bending strength below the Voxeljet reference value.

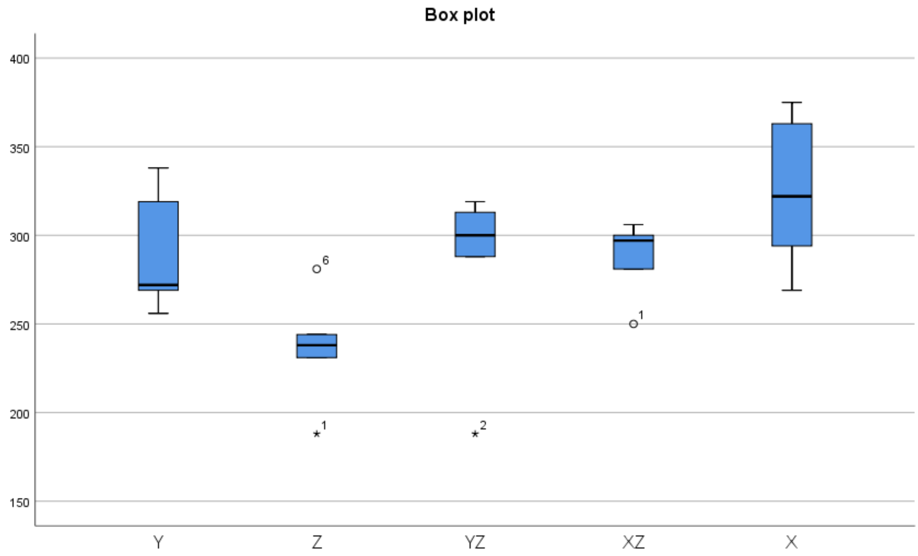

Figure 7: Whisker plot of bend test results

4. CONCLUSION

The following study investigated the variation of the bend strength of printed components at different print orientations and angles. The results showed that the majority mean value of parts printed in all the orientations are more than the reference supplied by Voxeljet. Although the mean values compare positively to Voxeljet's reference value, results showed that some individual test parts were below this value. Although this is statistical correct and acceptable it must be noted that the quality of a part may be impaired.

It was also determined that the build orientation has an influence on the part strength. Parts printed in the X direction yielded the best bend strength, whilst parts printed in the Z direction showed the lowest bend strength. A variation in the bend strength was found throughout the build volume as peak values were more prominent in certain printing locations. A possible explanation for this variation could include: Particle sizes and building temperature, which will influence the homogeneous bonds between the particles.

The results in the following pilot study will be used as motivation to a comprehensive study to investigate the effect of the building orientation and angle on the mechanical properties (bend, tensile and friability) of the printed parts. Future research will also identify the printing factors (sand distribution, sand temperature etc.) responsible for the variations in the part strength.

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