BENCHMARKNG OF FDM PRINTED REPLACEMENT PARTS FOR RURAL WHEELCHAIRS

W.A. Kinnear[1]*, J.G. van der Walt[1], V. Rossouw[2], G.J. Booysen[3]

[1]*Department of Mechanical and Mechatronic Engineering
Central University of Technology, South Africa
(Corresponding author: wakinnear@cut.ac.za)

[2]Department of Occupational Therapy
Free State Department of Health, South Africa

[3]Centre for Rapid Prototyping and Manufacturing
Central University of Technology, South Africa

ABSTRACT

Many disabled patients rely on wheelchairs for mobility to participate as equal citizens within society. Wheelchairs supplied through state healthcare are often not well suited to especially rural conditions and often break-down. This study investigates if entry level Fused Deposition Modelling (FDM) can be used to produce front caster wheels and seat post guides that commonly fail on wheelchairs. Results of the study has shown that these parts can be produced with good quality and at reasonable cost through FDM. The ability to manufacture custom made parts on request through FDM was shown to be a real advantage to supply hard to source wheelchair parts in the rural communities.

1. INTRODUCTION

A wheelchair is one of the most commonly used assistive devices, enabling many patients to become mobile. This creates opportunities for education and work and contributes to improved health and quality of life. The use of a wheel chair also makes patients more independent and frees up the time of their family members to pursue other productive activities. An estimated 1% of the world's population (65 million), need a wheelchair [1] while this number is roughly 2.3% (1.2 million) in South Africa [2].

Due to a lack of governmental funding and the large demand, occupational therapists in state hospitals are forced to prescribe cheaper less effective wheelchair designs. This problem is further highlighted in the rural areas where the basic folding frame wheelchair design is supplied to patients. These wheelchairs are for low activity, indoor environments and not rural settings often with dirt roads. These factors imply a high turnover of wheelchairs thus increasing the load on supply. Imported wheelchairs provided by governmental or donor organisations are not supplied with spare parts and local spares often do not fit them. Importing the missing or broken component sometimes costs more than purchasing a new locally produced wheelchair [3]. Presently wheelchairs in the governmental sector are maintained by therapists or local hospital maintenance personnel, depleting their already limited time and resources. A lack of repairs lead to many wheelchairs being discarded, leaving patients without wheelchairs.

Analysis of the wheelchair records of the Mangaung University Community Partnership Program (MUCCP) occupational therapy department show that a total of 43 wheelchair repairs were conducted in 2016. For the month of May 2017, 12 wheelchair repairs were reported, of which 7 caster wheels and 8 seat post guides needed to be replaced. The cost of a caster wheel and a seat post guide are R175 and R16 respectively. In an interview with the head occupational therapist it was highlighted that the caster wheels fail due to bearing failure resulting in the failure of the bearing housing or objects getting lodged between the caster wheel fork and the ribs of the caster wheel thereby breaking the ribs of the wheel. Figure 1 shows a typical broken wheelchair caster wheel while Figure 1 b shows a damaged seat post guide such as is mentioned here.

a b

Figure 1 Front caster wheel (a) and seat post guide (b).

This study aims to determine if Additive Manufacturing (AM) can be used to produce custom made durable parts to replace parts that commonly fail on wheelchairs. AM also referred to as 3D printing is defined by the American Society for Testing and Materials (ASTM) F2792 as “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” [4]. AM include a wide variety of processes that uses different materials and binding mechanisms but for the purpose of this research study, the focus will be on entry level Fused Deposition Modelling (FDM). FDM printers selectively extrude plastic filament in adjacent lines to form a layer. Once the layer is completed it extrudes the same plastic filament onto the previously extruded layer thus forming a 3D object as shown in Figure 2. These entry level FDM printers can now be purchased for as little as R6000 via the internet. There is also an extensive variety of polymer filaments available that can be processed through the printers with a typical cost of around R280/kg for Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA).

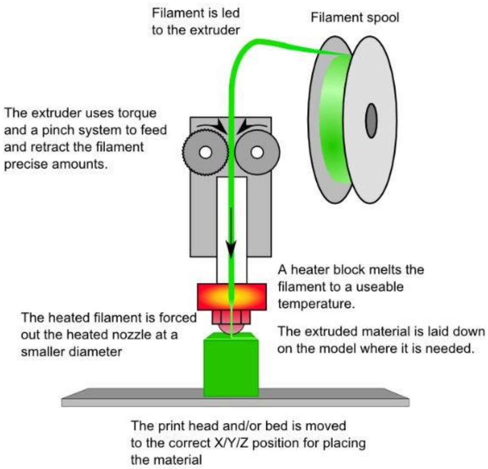


Figure 2. Working principals of a FDM machine [5].

FDM printing has been extensively use in recent years to manufacture "Do It Yourself" assistive devices and designs are freely available on websites such as Thingiverse and Instructables [6]. Effectiveness and reliability of these FDM produced devices is however debatable [7]. The quality of FDM produced part quality remain unpredictable compared to injection moulded parts. Dawoud et al. showed for example that the mechanical strength of injection moulded samples (37.7 MPa) was superior to that of the same samples produced through FDM (34.3 MPa) [8].

FDM process parameters (orientation, layer height, raster angle, print speed and air gap) has a major effect on the mechanical properties of parts produced [9]. Investigating print orientation, Bagsik et al. showed that the upright orientation exhibits poor mechanical properties, while on-edge and flat orientation showed better mechanical strength and stiffness [10]. Tymrak, 2014 showed that the average tensile strength of FDM printed parts are 28.5 MPa for ABS and 56.6 MPa for PLA. The average elastic moduli of ABS was found to be 1807 MPa while that of PLA was 3368 MPa [11]. Lužanin et al. studied the influence of layer thickness, deposition angle and fill density on flexural strength of PLA FDM samples and showed that these factors have a significant effect [12].

A study conducted by Es Said et al. examined tensile strength, modulus of rupture, and impact resistance for different layer orientations of ABS models. The 0° orientation samples displayed superior strength (20.6 MPa) and impact resistance (44.4 MPa) compared to all other orientations [13]. They concluded that anisotropic properties were caused by weak interlayer bonding and interlayer porosity. Anisotropy refers to the material properties being directional dependent.

Lee et al. employed the Taguchi method to find the optimal FDM process parameters for ABS, concluding that layer thickness, raster angle and air gap significantly affect the material's elastic performance [14].

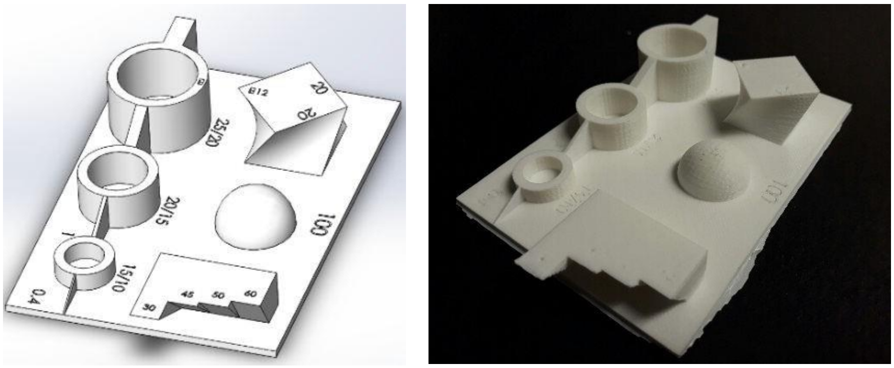
For FDM printing to be considered as process suitable for producing replacement parts for wheelchairs, the accuracy, strength and durability of parts produced need to be proven.

2. METHODOLOGY

The entry level Wanhao I3 plus was selected as the FDM machine to conduct this study. It can be readily purchased at low cost in South Africa, it is easy to setup and use and produces high quality parts for its price range. ABS and PLA was investigated as possible materials to print the wheelchair parts under consideration since these materials are also readily available at low cost. To design reliable FDM printed caster wheel hubs and seat post guides the mechanical properties and dimensional tolerances need to be determined for FDM printed ABS and PLA. The following experimental procedure was followed to qualify the printer and materials for the intended application.

2.1 Geometrical accuracy of parts produced

A test geometry with specific features that highlight the strengths and weaknesses of AM processes was designed to test printing accuracy as shown in Figure 3. The test geometry included features to measure accuracy in terms of printing height, internal diameter, external diameter and rib thickness.



a b

Figure 3. CAD design of dimensional accuracy test part (a) and FDM printed part (b).

The test geometry was printed in Wanhao supplied ABS and PLA material with a 0.4 mm diameter nozzle and at 0.1 mm layer thickness. Print speeds were 35 mm/s and 30 mm/s while nozzle temperatures were 220 ˚C and 195 ˚C respectively. Bed temperatures were 100 ˚C and 60 ˚C for the two materials. These printing parameters were as specified by the suppliers of the printer. The dimensional accuracy was determined for various fill densities (25, 50, 75, 100%) and shell thicknesses (0.8 and 1.2 mm). Three test parts were printed for each fill density and shell thickness. Six dimensional measurements were taken of each feature on the test part with a digital Vernier caliper and noted.

The feature on the lower right corner of the test part shown in Figure 3 was used to demonstrate the effect of overhang without support structures on printing accuracy. The feature had overhang angles at 30^0,45^0,50^0 and 60^0 as measured from the horizontal. The feature on each test part was scanned with a Kreon scanning arm with a Solano Blue laser scanning attachment to acquire a point cloud. The scan data was then compared to the Computer Aided Design (CAD) of the test part using Geomagic Control X software. A selection plane was used to determine the dimensional deviation of the overhang at each angle.

2.2 Mechanical properties of parts produced

In order to determine the part orientation and fill density best suited for printing wheelchair parts, a range of ASTM D638 Type IV tensile samples were printed in ABS and PLA. The yield strength, Ultimate Tensile Strength (UTS), elongation and Young's modulus were determined for various fill densities and shell thicknesses. Six samples were printed for each fill density and shell thickness, flat on the build platform in the y-direction as shown in Figure 4. Standard Cura slicing software build strategies were used to manufacture the samples.

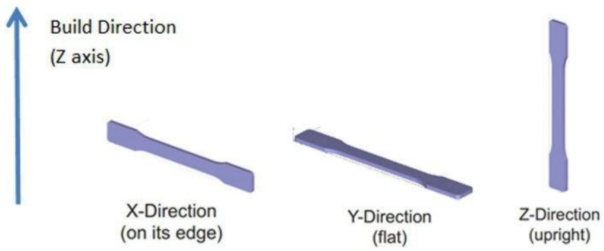


Figure 4. Schematic representation of tensile sample orientations [15].

In addition to this, ABS at 100% fill density samples were printed in the flat, on the edge and upright orientations to determine the anisotropic mechanical properties of the printed material. Different percentages of fill density (25, 50, 75, 100%) and shell thicknesses (0.8 and 1.2 mm) were applied to the samples.

2.3 Wheelchair component design and manufacturing

Caster wheel hubs and a seat post guide were designed to demonstrate the use of FDM printed wheelchair components in a real-world environment. The dimensions of an actual wheelchair caster hub was determined and designed in SolidWorks (Figure 5a). A standard wheelchair caster wheel is manufactured by injection moulding the hub and then over- moulding the soft tyre onto the hub. The tyre was removed from a broken wheelchair caster wheel and a new hub was printed on the Wanhao I3 plus (Figure 5b). The hub had to be printed in two halves to be able to assemble it onto the tyre with six bolts joining the halves (Figure 5c).

a b c

Figure 5 Design for wheel hub (a), printed hub halves (b) and assembled wheel (c).

A second design for a caster was also done (Figure 6a), this time utilizing the advantage that AM presents to produce internal structures.

a b

Figure 6 Revised designs for a wheelchair wheel hub (a) and printed hub halves (b).

The standard caster wheel has ribs to reduce the amount of plastic and cycle time of the injection moulding manufacturing process. These ribs are however easily damaged on a wheelchair. The revised design kept the ribs but has a 2 mm shell to cover the ribs (Figure 6b). A Finite Element Analysis (FEA) was performed on one half of the revised designed caster wheel using data from the mechanical properties of the ABS materials used. An impact force of 2 kN (200 kg (person with wheelchair) traveling at 10 km/hr) as an example was applied simulating a frontal impact. An FEA was also applied to the hub with the exposed ribs for comparison.

A seat post guide was designed according to the geometry of the original part and printed in ABS on the Wanhao I3 plus. Figure 7a shows a commercially available seat post guide while Figure 7b shows the printed guide and Figure 7c the printed guide as installed on a wheelchair.

a b c

Figure 7. Commercially available (a), printed (b) and installed seat post guide (c).

2.4 Cost comparison

A cost comparison was performed between FDM printed wheelchair parts and commercially available parts. Taken into consideration was the cost of the material used (R 280/kg), replacement cost of the FDM printer (life span of printer was estimated at 5000 hrs) and maintenance cost on the machine (estimated at R 500/1000 hrs). The time required to design the wheel hub was three hours while the design time for the seat post guide was one hour.

3. RESULTS

3.1 Geometrical accuracy of parts produced

With reference to Figure 8, PLA samples showed lower deviations in dimensions compared to that of the ABS samples for all features investigated on the dimensional accuracy test part. Height and inner diameter were undersize for both materials (PLA; 0.053 ± 0.012 mm and 0.0736 ± 0.035 mm, ABS; 0.097 ± 0.018 mm and 0.16 ± 0.067 mm). Outer diameter and rib thickness were oversize for both materials (PLA; 0.0812 ± 0.046 mm and 0.11 ± 0.055 mm, ABS; 0.11 ± 0.044 mm and 0.144 ± 0.053 mm).

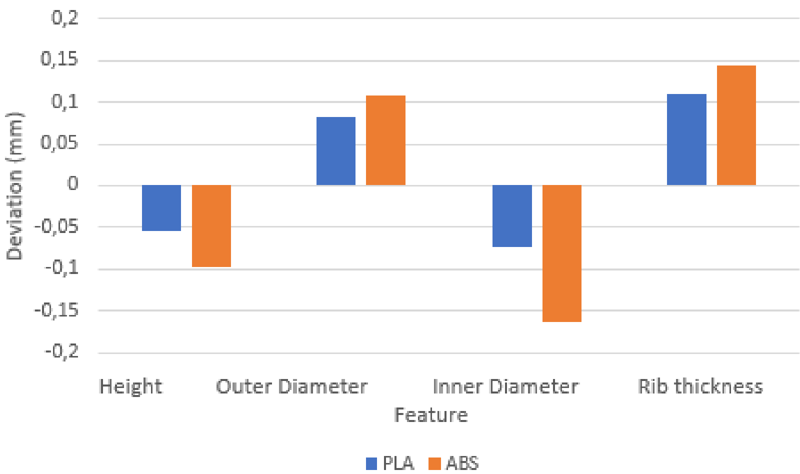


Figure 8. Dimensional deviation for different features on PLA and ABS test part.

Fill density and shell thickness did not have a significant effect on dimensional accuracy as indicated in Figure 9 - 12 (the 25/8, 25/1.2, 50/08, 75/0.8 and 100/0.8 as indicated on the graphs indicate fill densities and shell thicknesses that was applied respectively). For all features, an increase in feature size showed a decrease in dimensional accuracy.

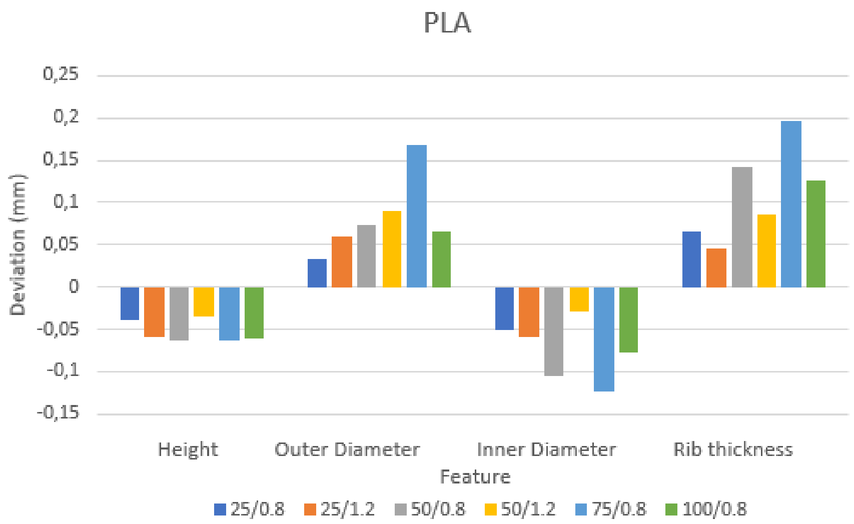


Figure 9. Dimensional deviation for different features on PLA test part in terms of fill density and shell thickness.

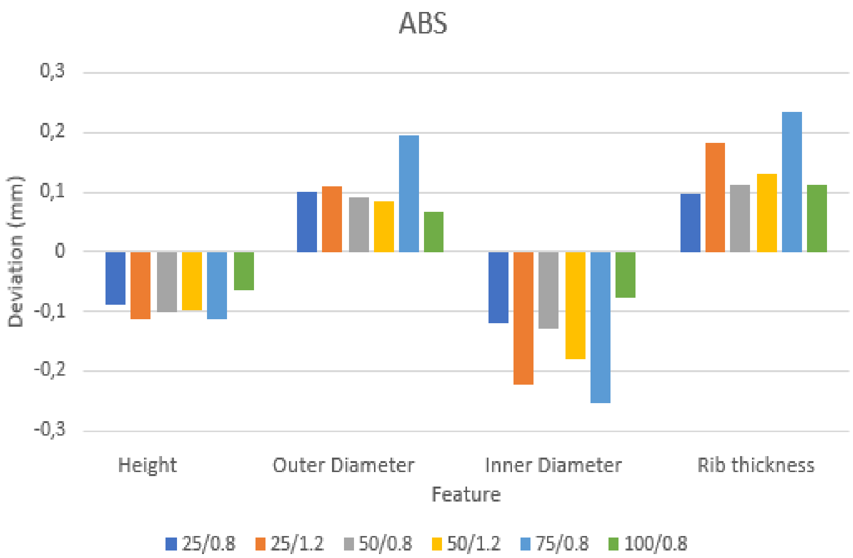


Figure 10. Dimensional deviation for different features on ABS test part in terms of fill density and shell thickness.

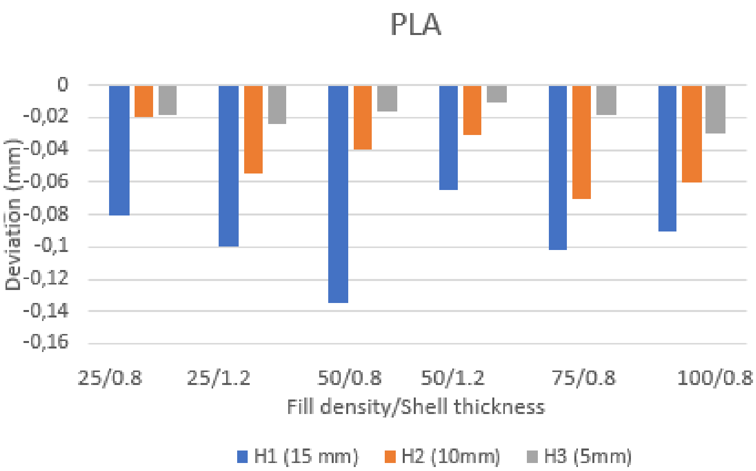


Figure 11. Dimensional deviation for height of features on PLA test part in terms of fill density and shell thickness.

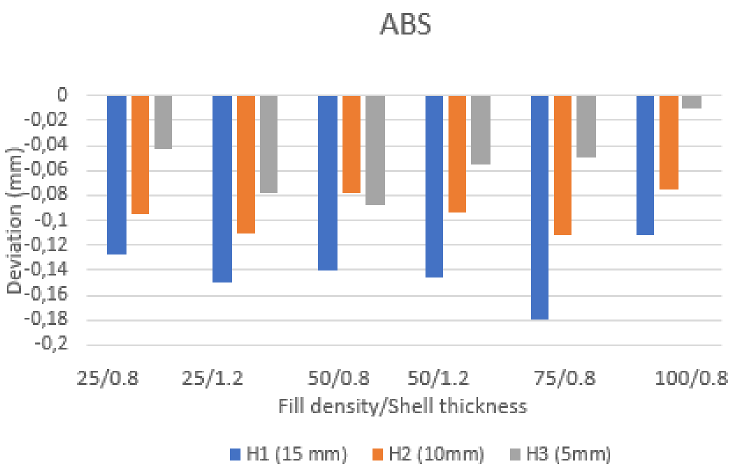


Figure 12. Dimensional deviation for height of features on ABS test part in terms of fill density and shell thickness.

In terms of the effect of overhang on accuracy as shown in Figure 13, ABS showed minimal deviation for angles of 60°, 50° and 45° (0.034 ± 0.019 mm, 0.041 ± 0.006 mm and 0.051 ± 0.046 mm). An angle of 30° however showed poor dimension accuracy (0.55 ± 0.08 mm).

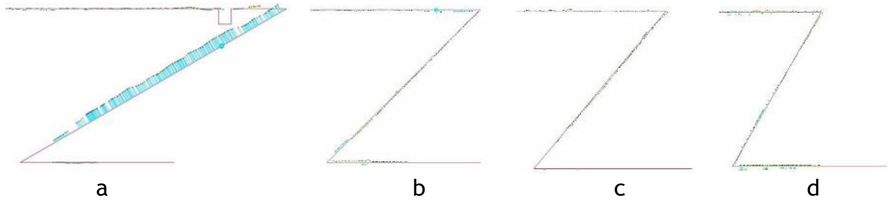


Figure 13. Dimensional accuracy comparison at overhang angles of (a) 30º, (b) 45º, (c) 50º and (d) 60º for ABS.

PLA remained largely dimensionally accurate for overhang angles of 60^0, 50^0, 45^0 and 30˚ (0.0885 ± 0.04 mm, 0.094 ± 0.08 mm, 0.13 ± 0.032 mm, 0.13 ± 0.09 mm).

3.2 Mechanical properties of parts produced

Table 1 indicate the mechanical properties of ABS and PLA printed on the Wahnao I3 plus printer at different fill densities. An increase in fill density and shell thickness improved the mechanical properties for both materials, however not significantly. The UTS of both 100% fill density ABS and PLA showed impressive results at 41.1 ± 1 MPA and 45.2 ± 1.6 MPa respectively. In general, the PLA samples showed better mechanical properties compared to that of the ABS samples.

Table 1 Mechanical properties of ABS and PLA test pieces at different fill densities (25, 50, 75, 100%) and shell thicknesses (0.8 and 1.2 mm)

	%Fill	Shell thickness(mm)	Yield strength(MPa)	UTS (MPa)	Elongation (%)	Young's modulus (GPa)
ABS	25	0.8	27.118±0.37	27.1±0.4	1.756±0.737	1.641±0.068
	25	1.2	28.875±0.75	28.9±0.7	1.883±1.139	1.632±0.033
	50	0.8	29.214±0.847	29.2±0.8	1.432±1.099	1.73±0.053
	50	1.2	29.52±1.083	29.5±1.1	2.210±0.749	1.866±0.052
	75	0.8	28.774±4.885	31.8±0.3	1.953±0.76	2.28±0.38
	100	0.8	30.54±4.68	41.1±1	2.7±1.6	2.6±0.29
PLA	25	0.8	33.597±0.561	33.6±0.6	1.834±0.454	2.12±0.436
	25	1.2	38.16±0.770	38.2±0.8	1.842±0.575	2.182±0.073
	50	0.8	36±1.431	36.3±1.5	2.15±0.727	2.089±0.147
	50	1.2	38.967±1.2	39±1.2	2.561±0.595	2.168±0.0618
	75	0.8	39.091±1.268	39.1±1.3	3.426±1.819	2.36±0.057
	100	0.8	45.162±1.559	45.2±1.6	2.956±0.685	3.095±0.258

An increase in shell thickness improved the elongation for both materials. The on the edge orientation (39.121 ± 0.69 MPa) showed better yield strength compared to the flat (30.54 ± 4.68 MPa) and upright (8.8±1.9 MPa) orientations. The on the edge (0.33 ± 0.25%) and upright (0.59 ± 0.319%) orientations showed poor elongation compared to the flat (2.7 ± 1.6%) orientation.

3.3 Wheelchair component design

Figure 14 shows results of the FEA as applied to the hub with the protective cover. A maximum stress of 27.19 MPa was determined for the 2 kN impact force that was applied.

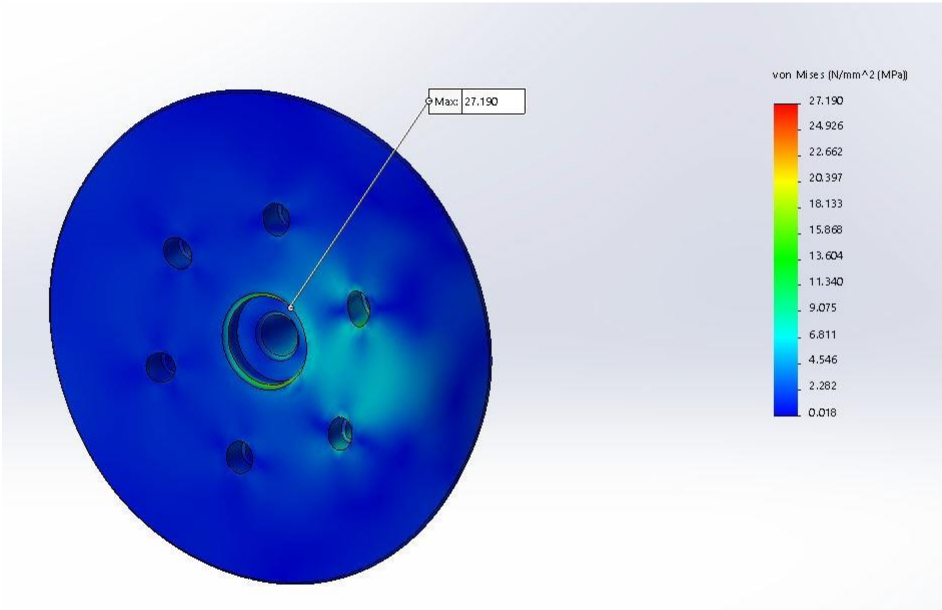


Figure 14. FEA of FDM printed hub with protective cover.

Applying the same 2 kN impact force to the hub with the exposed ribs (Figure 15) indicated a stress concentrations of 114.1 MPa at the tip of the rib which lines up with the direction from where the frontal impact force was applied.

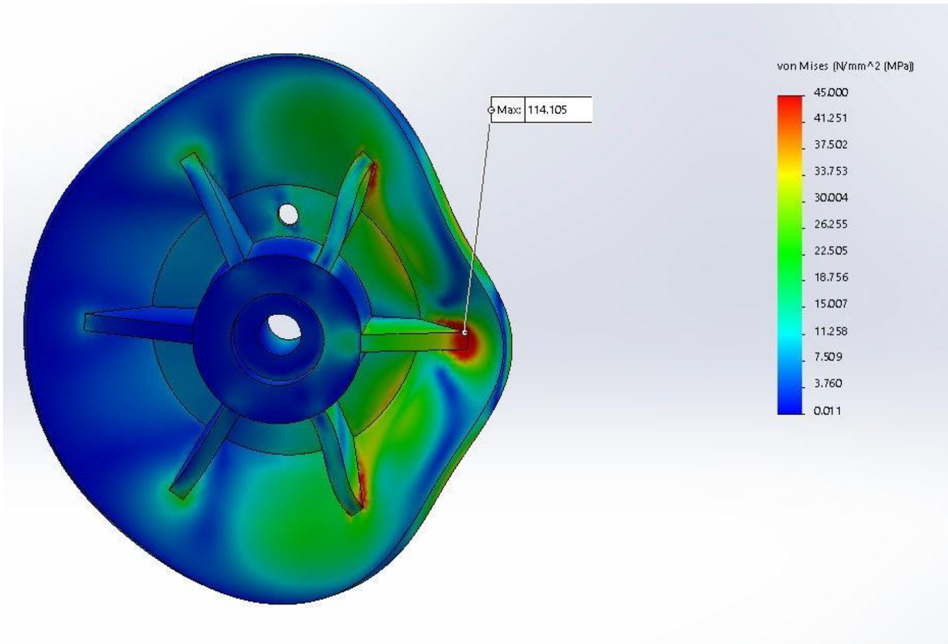


Figure 15. FEA of FDM printed hub with exposed ribs.

The FEA of the hub with the protective cover showed that the hub experienced a lower maximum stress compared to the hub with the exposed ribs when exposed to the same frontal impact force. This together with the benefit that the protective cover brings in terms of protecting the hub's internal structure from stones that may be caught between the caster fork and wheel shows this to be the better wheelchair caster design.

3.4 Cost comparison

The cost comparison for ABS and PLA for the different fill percentages and shell thicknesses against yield strength is shown in Figure 16. The yield strengths that are indicated is taken from Table 1 while the costs indicated were calculated with the cost of the material used, replacement cost of the FDM printer and maintenance on the machine taken into consideration (see section 2.4).

With an increase in fill density, the cost of production increased compared to the mechanical strength which only increased slightly. Increasing the shell thickness improved the elongation for both materials and only had a minimal effect on manufacturing cost. PLA samples cost more to produce compared to ABS samples, due to the slower printing speed needed to manufacture the samples.

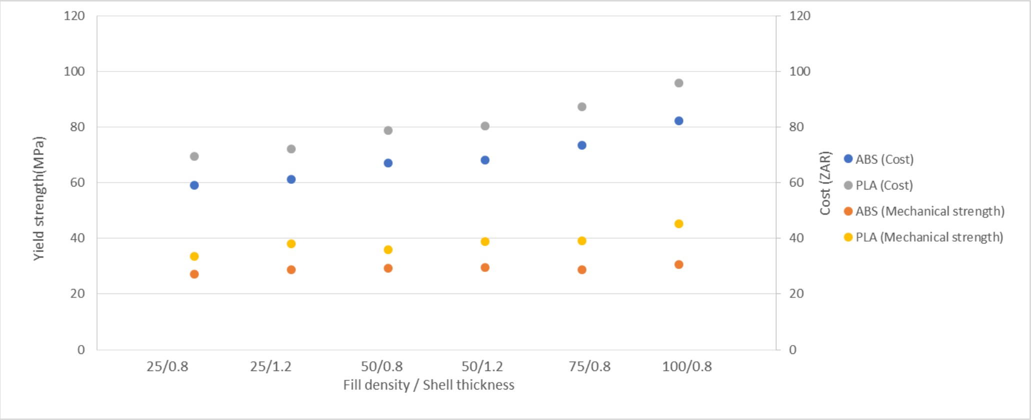


Figure 16. Cost - strength comparison of ABS and PLA at various fill densities and shell thicknesses.

A seat post guide and caster wheel hub with protective cover was printed in ABS and costs determined again taking the cost of the material used, replacement cost of the FDM printer and maintenance on the machine into consideration. The cost for design was not added to the cost of the parts since in this application, the parts are only designed once where after a number of the parts can be printed as required. According to Figure 14, a maximum stress of 27.19 MPa was calculated for the 2 kN impact force that was applied. Table 1 shows that this stress can be withstood by printing ABS at a shell thickness 0.8 mm and with a fill density of 25%. Printing the seat post guide at this settings took 2.43 hrs and the calculated cost was R 18.77. The caster wheel hub with protective cover took 26.38 hrs at a cost of R 113.01. The seat post guide was more expensive (R 16.00) to manufacture through FDM printing compared to its commercially available injection moulded counterpart. The caster wheels were however printed at lower cost (R 175.00) compared to a commercially available injection moulded caster wheel.

3.5 Case study

FDM printed caster wheels with open ribs as presented in Section 2.3 were installed on a wheelchair and tested in a real-world environment as a case study to demonstrate the durability of the parts. A patient has been using the wheelchair on a daily basis and travel an average of 6 km per day. After four months of use no signs of deterioration of the printed hubs are evident. As a follow up, the improved wheels with hubs that features protective covers will next be installed on the wheelchair and performance compared to the previous wheels over time.

4. CONCLUSION

This study has shown that low cost FDM printing can be used to print replacement caster wheel hubs and seat post guides for wheelchairs with quality comparable to commercially available replacement parts. Dimensional accuracy tests have proven that printed parts can be produced that is sufficiently accurate for this application. Mechanical testing of parts printed at different shell thicknesses and fill densities demonstrated the strength of parts that can be achieved. A simulated impacts on printed caster hubs indicated that the strength of the printed material as measured is adequate to handle the stress that it will be subjected to on a wheelchair. Testing a caster wheel with a printed hub by a patient as case study demonstrated the durability of the hub in a real-world environment. A cost comparison between commercially available caster wheels and wheels with a printed hub has shown that the latter can be produced at reduced cost. Printing seat post guides was shown to be slightly more expensive compared to the cost of commercially available replacement parts. Caster wheels and seat post guides are however difficult to source and the various wheelchairs available do not all make use of the same parts. The accessibility, availability and customization of AM to manufacture parts as needed makes it attractive as a solution to provide wheelchair spare parts in the rural communities.

5. ACKNOWLEDGEMENTS

This work was funded by the Technology Innovation Agency HEI seed funding programme entitled: Green sustainable assistive device manufacturing by additive manufacturing. The Research Chair in Medical Product Development through Additive Manufacturing at CUT as part of the South African Research Chair Initiative is acknowledged for their continued support as well as the South African Collaborative Programme in Additive Manufacturing. The Product Development Technology Station is also thanked for making time available for its staff members to conduct this research.

REFERENCES

[1] **World Health Organization,** 2008. Guidelines on the provision of manual wheelchairs in less resourced settings.

[2] **Lehola, P.** Census 2011: Profile of persons with disabilities in South Africa. Statistics South Africa, Report No.03-01-59

[3] **McIntyre, J.** 2010. Wheelchairs-A human rights issue or a mere mobility device? Personal reflections of an occupational therapist. *South African Journal of Occupational Therapy*, 40(1), pp.27-31.

[4] **Wohlers Associates**, What is Additive Manufacturing?. Available from https://wohlersassociates.com/additive-manufacturing.html. Accessed on 9 August 2017

[5] **RepRap**, File: FFF.png Available from http://reprap.org/wiki/File:FFF.png Accessed on 9 August 2017

[6] **Buehler, E., Branham, S., Ali, A., Chang, J.J., Hofmann, M.K., Hurst, A. and Kane, S.K.** 2015. Sharing is caring: Assistive technology designs on thingiverse. *In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 525-534). ACM.

[7] **Huang, S.H., Liu, P., Mokasdar, A. and Hou, L.** 2013. Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, pp.1-13.

[8] **Dawoud, M., Taha, I. and Ebeid, S.J.** 2016. Mechanical behaviour of ABS: An experimental study using FDM and injection moulding techniques. *Journal of Manufacturing Processes*, 21, pp.39-45.

[9] **Sood, A.K., Ohdar, R.K. and Mahapatra, S.S.** 2010. Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials & Design*, 31(1), pp.287-295.

[10] **Bagsik, A., Schöppner, V., Klemp, E.** 2010. FDM Part Quality Manufactured with Ultem*9085. *Direct Manufacturing Research Centre*.

[11] **Tymrak, B.M., Kreiger, M. and Pearce, J.M.** 2014. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials & Design*, 58, pp.242-246.

[12] **Lužanin, O., Movrin, D. and Plančak, M.** 2014. Effect of layer thickness, deposition angle, and infill on maximum flexural force in FDM-built specimens. *Journal for Technology of Plasticity*, 39(1), pp.49-58.

[13] **Es-Said, O.S., Foyos, J., Noorani, R., Mendelson, M., Marloth, R. and Pregger, B.A.** 2000. Effect of layer orientation on mechanical properties of rapid prototyped samples. *Materials and Manufacturing Processes*, 15(1), pp.107-122.

[14] **Lee, B.H., Abdullah, J. and Khan, Z.A.** 2005. Optimization of rapid prototyping parameters for production of flexible ABS object. *Journal of materials processing technology*, 169(1), pp.54-61.

[15] **Lambert P**, Tensile properties of materials: FDM printer & SLS printer. Available from https://www.sculpteo.com/blog/2014/05/14/material-considerations-choose-right-plastic-production-method-part-2/ Accessed on 9 August 2017