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Utilization of fused deposition method 3D printing for evaluation of discrete element method simulations

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Abstract. FDM 3D printing is used for designing prototype assessment in engineering production. It is usually used to verify the functionality of kinematics mechanisms. It can also be used for innovation in agricultural production, eg. the development of new mechanisms for agriculture tools. Such a mechanism as well as the entire components is printed using FDM and they are made of plastics. This whole can be experimentally verified in a laboratory trough. The article deals with the verification of the possibilities of using FDM technology for the design of agricultural tools. The material properties, namely stress-strain, of the plastics after printing are entered into the Ansys mechanical library, and the DEM results are also imported into Ansys mechanical. Material properties of plastics for FDM technology such as PLA, PETG show that its mechanical properties limited their using for validation.

Key words: FEM, DEM, design of tools, mechanical, manufacturing, industry 4.0.

INTRODUCTION

The development of manufacturing sectoral lines is increasingly showing its latest innovations with each line by continuous improvement, taking various best steps. All improvements in existing processes are according to the kaizen principle has already been made by previous founder and researcher in Mechanical Engineering (Shahrubudin et al., 2019). An industry concept 4.0 is synonymous with the transformation of manufacturing activities into smart manufacturing, designed to meet and exceed current challenges (Cahyati, 2019). The application is carried out with a shorter product manufacturing cycle, an adjustment to the manufacturing of the product through competitive measures, one of the applications being to eliminate borderless and boundaries.

Fused Deposition Modelling (FDM) is currently become a popular fabrication process and commonly used for modelling, prototyping, and production application. This process favour the ease of fabricating three-dimensional objects of almost any form and less waste than traditional subtractive production method. As one of methods in additive manufacturing process, fused deposition modelling utilizes extrusion of material formed in filament to build structural 3D model by layering from bottom to the top. The filament is melted according to the melting temperature of certain material and extrusion occurs through the nozzle, subsequently. Materials are subjected to phase changes under relatively high temperature. The material is soon after being deposited and it cools down and solidifies right after deposition. The movement of the nozzle is based on the process parameters resulting the path generation. A desired structure, such as accurate dimension and splendid mechanical performance, may be achieved accurately and precisely by configuring each component of parameters. Wide range materials, from polymers, ceramics, to metals, has been developed into 3D printing filaments. These materials have two main roles, which could be as the build material and support material. The common material combination is PolylacticAcid (PLA) and Polyvinyl Alcohol (PVA) (Yang et al., 2015; Ziemian et al., 2015; Wulle et al., 2017; Alief et al., 2019).

Present research are focused on material innovation, inside structure printed geometry and mechanical properties (Hao et al., 2011; Alief et al., 2019), commonly using of 3D printing for geometry and kinematic testing of design (Guerrero-Villar et al., 2015) or how to influence the mechanical properties with changing technological parameters by printing (Hossain et al., 2014; Lanzotti et al., 2015; Ning, Cong, Hu, & Wang, 2017; Khan et al., 2018; Poudel et al., 2018). In the existing literature, many studies were reported on the strength of the FDM 3D printed parts and their anisotropic behaviour using the traditional layer-based 3D printing (Poudel et al., 2018).

These technologies and with the use of various printing materials are also suitable for designing and testing parts of agricultural machines or testing a new shape of agricultural tools such as chisels, discs, etc. or full frames with them. It is necessary to verify the computational tasks, either in a field test or as in the case of tool shape innovation, first is under laboratory conditions using 3D printing technologies. Due to the load and shape of the agricultural tools, it is possible that the 3D printing technology used using conventional printing materials may cause deformations in the test that affect, for example, the drought force and thus it is not possible to correctly evaluate the simulation results (Fig. 1).

Figure 1. Detail of model soil trough.

The aim of this work is determined condition for testing of chisel with using DEM and FEM analysis for 3D printed prototypes.

MATERIALS AND METHODS

The BCN 3D printer was used to print samples to determine mechanical properties. The setting of the printing properties is shown in Table 1, 3D printer type is BCN3D sigma R19.

The mechanical properties of the printed sample (Fig. 3) were determined by a tensile test on a Labortech MPtest 5.050 universal tester (Fig. 2) with a maximum load of 5 kN.

The dependencies of force and elongation was measured. These dependencies were recalculated to stress-strain diagram (Fig. 2, b). Young modulus was determined from stress-strain diagram, and relationship between stress and strain was given to Ansys material library like multilinear.

Table 1. Table of parameters settings 3D printer, print laxer 0.3 mm, perimetrs 0.4 mm, print speed 50 mm s^{-1}, object infill 100%, orientation 45° and 90°

Print parameters	Place	Nozzle temperature (°C)	Bed temperature (°C)
PETG	close	225	70
PLA	open	215	60
ABS (90°)	close	245	90
ABS (45°)	close	250	100

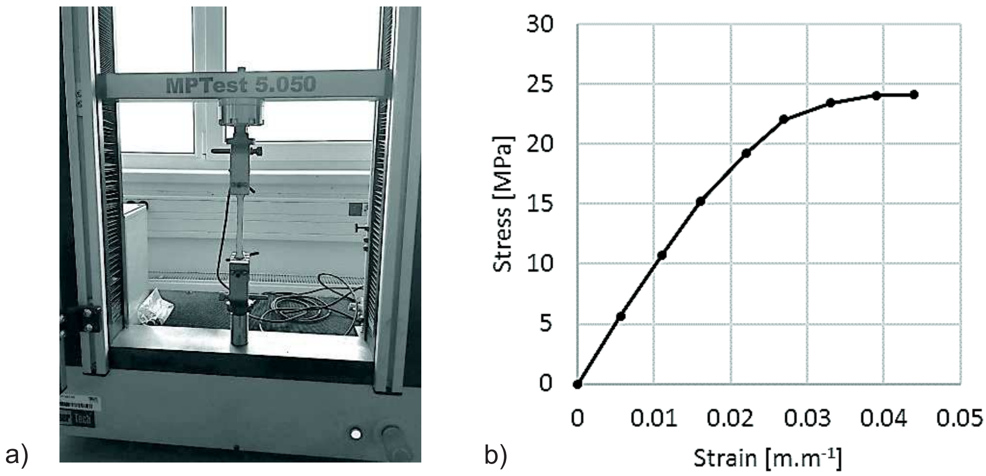

Figure 2. Sample testing in universal testing machine and data for plastic model in ANSYS.

SpaceClaim software was used for drawing of small agriculture tools. For the deformation analysis and future use in the laboratory soil trough, the tools were created in 1 : 2 scale. Specifically, it was a chisel with a chisel and wings, it is used in agriculture for loosening with no-tillage technology. RockyDEM software was used to simulate chisels in a bulk matter environment. Material properties of bulk matter were determined by shear test, pressing test and angle of repose. These tests are described in (Kadau et al., 2006; Sadek et al., 2011; Kotrocz et al., 2016).

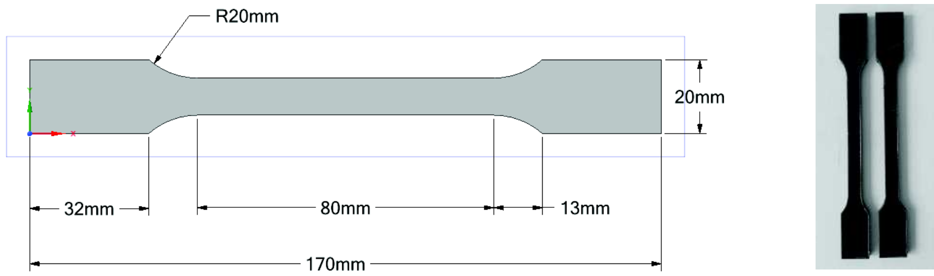

Figure 3. Test sample, Samples from PLA material, 3D printing technology and laser cutting.

The material model settings are shown in Table 2. The chisel body was simulated at a constant speed of 1 m s^{-1} and a depth of 100, 150 and 200 mm, which would correspond to twice the depth under field conditions.

Table 2. Table of parameters ANSYS settings, Poisson's Ratio 0.35 (-)

Materials	Young modulus (MPa)	Maximal Stress (MPa)	Stress 0.02 (MPa)	Elongation (-)
PETG	1,048 ± 23.8	32.0 ± 1.4	20.0 ± 0.4	4.66 ± 1.2
PLA	1,313 ± 19.2	42.7 ± 1.3	25.2 ± 3.1	5.05 ± 1.0
ABS (45°)	914 ± 10.5	23.6 ± 0.7	17.4 ± 0.3	5.92 ± 0.4

The chisel body pressure results were exported for each node, averaged, and imported into Ansys mechanical. The mesh deformation shape result was exported from Ansys mechanical as a *.stl file and then inserted into the RockyDEM simulation using the same material model (Table 3). The maximum stress, and strain at points of interest were also analysed. These points of interest on the geometry mesh can represent the deformation state of the tool for easy understanding of the process. The procedure is shown schematically in Fig. 4. The result of the tensile force of the simulation was compared for the deformed and deformed part. Only simulations results give us information about invisible processes into laboratory trough during experiment.

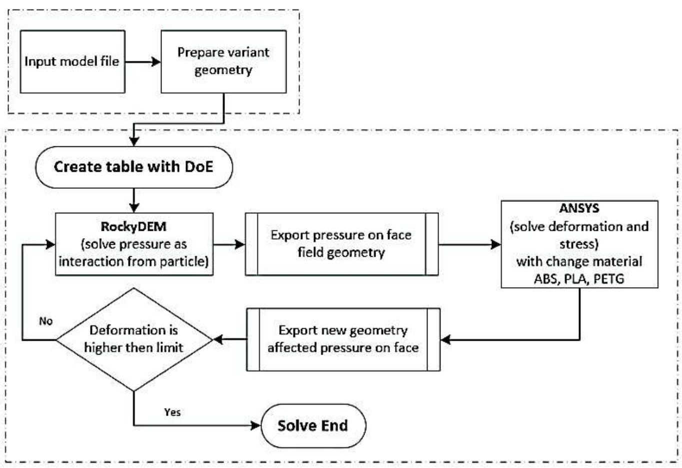

Figure 4. System analyses diagram.

Table 3. Table of parameters for RockyDEM

Parameters	Detail of Parameters		Data Source
Normal force	Hysteretic linear spring		(ESSS Rocky, 2018)
Adhesive force	Linear		(ESSS Rocky, 2018)
Tangential force	Linear spring coulomb limit		(ESSS Rocky, 2018)
Numerical softening factor	1		Selected
Gravity	9.81 m s^{-2}		Selected
Material properties	Dry sand /dry dredged sand/wet dredged sand	Material of Chisel	–
Bulk density (density), kg·m^{-3}	1560/1533/1620	7850	(Ucgul et al., 2015)
Young's modulus, MPa	40/35/32	Table 5	(Budynas & Nisbett, 2015; Ucgul et al., 2015)
Poisson's ratio	0.3	0.3	Selected
Particle size, mm	10	–	Selected
Number of particles	0.383 million	–	Selected
Material interaction properties	Particle–particle	Particle–tine	–
Static friction	0.6/0.33/0.33	0.5	Selected
Dynamic friction	0.3/0.83/0.83	0.5	Selected
Tangential stiffness ratio	1/1/1	1	Selected
Adhesive distance, m	0/0/0.0001	0.0001	Selected
Stiffness fractiona	0/0/0.05	0	Selected
Restitution coefficient	0.2/0.3/0.3	0.3	Selected

RESULTS AND DISCUSSION

The results of the tensile tests show that the highest Young's modulus has PLA and subsequently PETG. The same order is for maximum strength and deformation strength of 0.2%. At the same time, the stress specified for the deformation of 0.2% is the maximum design stress that must not be overcome. Otherwise, the printed sample will be permanently deformed and degraded for further use in the experimental laboratory soil trough. The values of deformations at the points of interest of the mesh and the maximum stress of the chisel model are given in Table 4 and Fig. 5 (schematically indicates A, B, C spot).

The results of deformations and stresses show that materials usable for prototype production and their use for experiments in the laboratory soil trough will be problematic in the case of high area loads due to the interaction of the particulate matter and the tool body. While it is possible to replace 3D printing with the production of prototypes made of metals on CNC machines or conventional technologies, we clearly lose simplicity, speed and cheapness.

The load simulation results imported as a result of the RockyDEM simulation show that the ABS material, which is toughness, has very large deformations and it been only applicable to dry sand experiments conditions at shallow depths. This is due to his small Young modulus. PLA and PETG may be more suitable, but these are more brittle materials. According to the analyses, they are also suitable for dredged sand and wet dredged sand up to 150 mm depth. At a greater depth, the tool is deformed completely.

Table 4. Data of sand materials – ABS/PLA/PETG (Stress limit is 20 MPa/38MPa/28 MPa – bold highlight)

Stress (MPa) ABS/PLA/PETG	Type 5	type 10	type 15	type 20
Dry sand				
A		3.31/3.25/3.28	6.83/6.53/6.68	14.16/12.55/13.48
B		12.63/12.43/15.53	14.56/14.60/14.67	**35.40**/35.90/35.29
C		4.72/3.20/3.22	7.60/4.83/4.86	12.54/8.61/9.13
Dry dredged sand				
A		1.17/1.15/1.16	11.46/10.44/11.04	4.78/4.60/4.71
B		8.49/8.49/8.49	17.40/17.32/17.38	**23.43**/22.81/23.20
C		3.35/2.40/2.41	10.63/6.29/6.58	9.27/6.41/6.71
Wet dredged sand				
A	8.88/8.50/8.72	29.25/21.02/25.63	13.71/12.84/13.35	**32.72**/25.45/**29.73**
B	13.23/12.85/13.13	**32.12**/32.27/.32.21	**32.27**/32.51/**32.42**	**73.96**/**81.82**/**77.18**
C	3.41/3.38/3.40	16.59/14.68/15.84	16.13/14.68/15.60	**32.79**/30.24/**31.86**

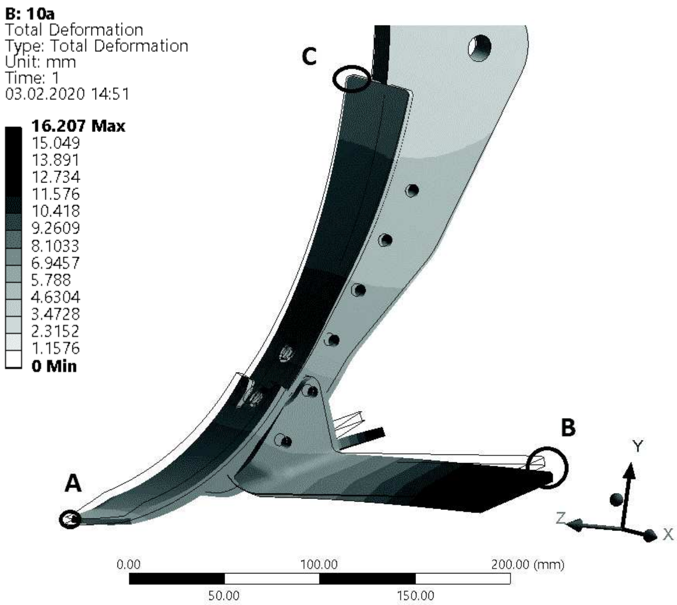

Figure 5. Total deformation agricultural tool in ANSYS, load is from RockyDEM.

The results of the deformed meshes, which were imported into RockyDEM from Ansys mechanical, show that PLA and PETG material in the prototype tool construction has enough stiffness to avoid affecting the draught forces that can be measured in the experimental soil trough. The Fig. 6 shows an example of vertical export (Fy – original shape and Fy_A – deformed as a result of Ansys mechanical simulation) and tensile force (Fz – original shape and Fz_A – deformed as a result of Ansys mechanical simulation) acting on chisel body, lateral force Fx is neglected because of the symmetry of the body. This result is valid for dry sand and a depth of 150 mm. The results of the mean values of the individual forces are given for comparison in Table 5.

The results of the draught force that was simulated on the deformed chisel body with the deformed wings as a result of the simulation in Ansys mechanical are shown in Fig. 6 for dry dredged sand.

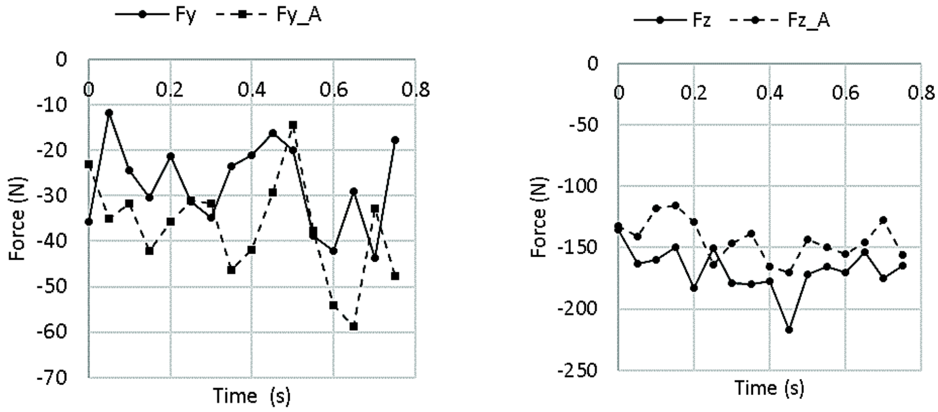

Figure 6. Results of simulation – vertical force Fy (A is deformed) and draught force Fz (A is deformed), ex. For dry sand at 150 mm depth.

Table 5. Sand, FxA (ansys deformed mesh), FxO – original shape

Dry sand	Fx_A (N)	Fy_A (N)	Fz_A (N)	Fx_O (N)	Fy_O (N)	Fz_O (N)
10 cm depth	5.07	-6.5	-94.3	6.76	-14.1	-90.2
15 cm depth	-3.32	-31.5	-165.9	-2.11	-37.0	-158.7
20 cm depth	-0.81	-60.0	-248.1	-0.41	-66.9	-245.0
Dry dredged sand	Fx_A (N)	Fy_A (N)	Fz_A (N)	Fx_O (N)	Fy_O (N)	Fz_O (N)
10 cm depth	-1.24	-12.9	-82.4	-1.44	-12.3	-84.6
15 cm depth	-0.05	-27.7	-177.1	-1.16	-35.8	-151.4
20 cm depth	-4.42	-48.9	-249.1	-7.30	-67.4	-240.5
Wet dredged sand	Fx_A (N)	Fy_A (N)	Fz_A (N)	Fx_O (N)	Fy_O (N)	Fz_O (N)
5 cm depth	-5.40	36.4	-151.3	-1.31	16.7	-149

Although it may appear that the deformation error is small to determine the draught and vertical forces, it appears to be a combination of deformations of the individual parts of the chisel body prototype with wings that deform due to the load so that the total force error is small. However, if we compare the individual body parts, i.e. the chisel, the wings, the mouldboard at points of interest that represent the deformation A, B and C of Fig. 7, we find that due to the deformation the chisel resistance increases, and the wing resistance decreases. The total force therefore appears to be like the undeformed body. ABS as a material is also not suitable from this point of view, since the total deformations at points of interest A and B are greater than 20 mm already at a depth of 150 mm in dry dredged sand. On the contrary, it seems to be a suitable material to produce the prototype PETG or PLA, which have a maximum deformation of about 20 mm, but at a depth of 200 mm or in shallow processing in wet dredged sand.

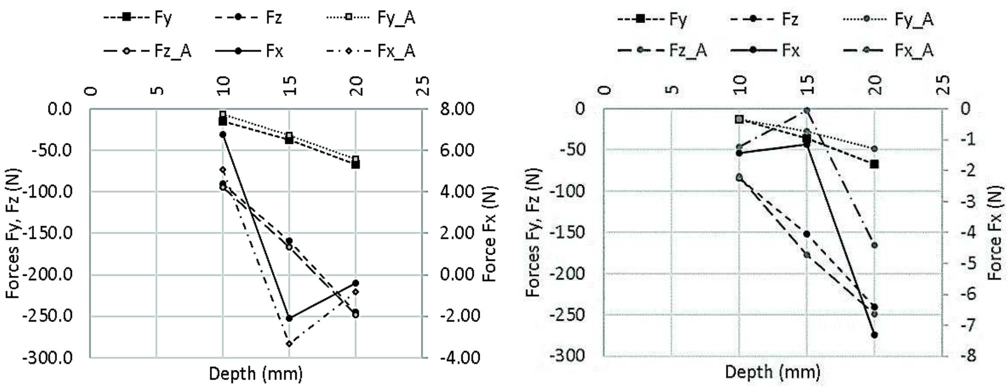

Figure 7. Left is original shape and right is shape after RockyDEM analyses.

At smaller depths, the deformations are smaller and do not affect the vertical or draught forces overall. Therefore, to set up the prototype of an agricultural tool, this material is used in less stressed prototype structures. For example, a mouldboard. For other parts, special consideration should be given to the deformation of the parts or the use of a metal part. This, however, completely loses the effect of flexibility, low time and low cost. Another possibility would be to create these stressed parts of composite material or metals (Kešner et al., 2019; Ucgul & Saunders, 2020), which we can expect longer time and higher price, but not in the complexity of the metal prototype. Therefore, although 3D printing of prototypes is widely used (Guerrero-Villar et al., 2015; Wulle et al., 2017; Alief et al., 2019), it will have limitations for model validation in agricultural tool experiments. Several publications (Lanzotti et al., 2015; Yang et al., 2015; Ziemian et al., 2015; Cahyati, 2019) mention usability for prototype production but are usually aimed at manufacturing mechanical systems to verify kinematics, stability, or deformation. Our results show that it is possible to use 3D printing from these materials to decrease the time of innovation in the field of agricultural machines, but with limitations, especially in experimental validation of simulation results.

CONCLUSIONS

Using 3D printing technology to produce prototype models of agricultural tools and structural parts is possible. However, it has the limitations of the relatively low Young modulus of elasticity and hence the stiffness of the printed models. The results of the simulations have shown that it will be possible to use this technology for validation in a laboratory soil trough, but in an environment that produces a relatively low draught resistance.

3D printing technology for the production of agricultural tool prototypes will be applicable, for example, to dry sand up to 150 mm deep or wet dredged sand up to 100 mm deep. Greater depths for validation of simulations in the laboratory soil trough lead to a large deformation of parts of the agricultural tool and hence to draught force. For this purpose, it will be necessary to use either material like metals or composite materials. However, it will decrease the advantage of using 3D printing technology for its variability, production speed and cost of prototype.

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REFERENCES

Alief, N.A., Utomo, M.S., Kartika, I. & Whulanza, Y. 2019. Geometrical and mechanical performance of multi-material fused deposition modelling. *IOP Conf. Series: Materials Science and Engineering* **557**. doi:10.1088/1757-899X/557/1/012022

Budynas, R. & Nisbett, K. 2015. *Shigley's mechanical engineering design (10th ed.)*.

Cahyati, S. 2019. Integrated CAD customization system for fused deposition models in additive manufacture with 3D printing machine. *IOP Conference Series Materials Science and Engineering* (**694**). doi:10.1088/1757-899X/694/1/012008

ESSS Rocky. 2018 *Rocky DEM technical manual*.

Guerrero-Villar, F., Torres-Jimenez, E., Dorado-Vicente, R. & Jiménez-González, J.I. 2015. Development of Vertical Wind Turbines via FDM Prototypes. In *Procedia Engineering,* Vol. **132**, pp. 78–85. Elsevier Ltd. doi:10.1016/j.proeng.2015.12.482

Hao, L., Raymont, D., Yan, C., Hussein, A. & Young, P. (2011). Design and additive manufacturing of cellular lattice structures. In *Innovative Developments in Virtual and Physical Prototyping* (pp. 249–254). CRC Press. doi:10.1201/b11341-40

Hossain, M.S., Espalin, D., Ramos, J., Perez, M. & Wicker, R. 2014. Improved Mechanical Properties of Fused Deposition Modeling-Manufactured Parts Through Build Parameter Modifications. *Journal of Manufacturing Science and Engineering, Transactions of the ASME* **136**(6). doi:10.1115/1.4028538

Kadau, D., Schwesig, D., Theuerkauf, J. & Wolf, D.E. 2006. Influence of particle elasticity in shear testers. *Granular Matter* **8**(1), 35–40. doi:10.1007/s10035-005-0217-y

Kešner, A., Chotěborský, R., Linda, M. & Hromasová, M. 2019. Methodology of the stress detemination in the tool module during the work of the agriculture machine. *Agronomy Research* **17**(2), 481–490. doi:10.15159/AR.19.103

Khan, S., Fayazbakhsh, K., Fawaz, Z. & Arian Nik, M. 2018. Curvilinear variable stiffness 3D printing technology for improved open-hole tensile strength. *Additive Manufacturing* **24**, 378–385. doi:10.1016/j.addma.2018.10.013

Kotrocz, K., Mouazen, A.M. & Kerényi, G. 2016. Numerical simulation of soil-cone penetrometer interaction using discrete element method. *Computers and Electronics in Agriculture* **125**, 63–73. doi:10.1016/j.compag.2016.04.023

Lanzotti, A., Grasso, M., Staiano, G. & Martorelli, M. 2015. The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. *Rapid Prototyping Journal* **21**(5), 604–617. doi:10.1108/RPJ-09-2014-0135

Ning, F., Cong, W., Hu, Y. & Wang, H. 2017. Additive manufacturing of carbon fiber-reinforced plastic composites using fused deposition modeling: Effects of process parameters on tensile properties. *Journal of Composite Materials* **51**(4), 451–462. https://doi.org/10.1177/0021998316646169

Poudel, L., Sha, Z. & Zhou, W. 2018. Mechanical strength of chunk-based printed parts for cooperative 3D printing. In *Procedia Manufacturing*, Vol. **26**, pp. 962–972. Elsevier B.V. doi:10.1016/j.promfg.2018.07.123

Sadek, M.A., Chen, Y. & Liu, J. 2011. Simulating shear behavior of a sandy soil under different soil conditions. *Journal of Terramechanics* **48**(6), 451–458. doi:10.1016/j.jterra.2011.09.006

Shahrubudin, N., Lee, T.C. & Ramlan, R. 2019. An overview on 3D printing technology: Technological, materials, and applications. In *Procedia Manufacturing*, Vol. **35**, pp. 1286–1296. Elsevier B.V. doi:10.1016/j.promfg.2019.06.089

Ucgul, M., Fielke, J.M. & Saunders, C. 2015. Three-dimensional discrete element modelling (DEM) of tillage: Accounting for soil cohesion and adhesion. *Biosystems Engineering* **129**, 298–306. doi:10.1016/j.biosystemseng.2014.11.006

Ucgul, M. & Saunders, C. 2020. Simulation of tillage forces and furrow profile during soil-mouldboard plough interaction using discrete element modelling. *Biosystems Engineering* **190**, 58–70. doi:10.1016/j.biosystemseng.2019.11.022

Wulle, F., Coupek, D., Schäffner, F., Verl, A., Oberhofer, F. & Maier, T. 2017. Workpiece and Machine Design in Additive Manufacturing for Multi-Axis Fused Deposition Modeling. In *Procedia CIRP,* Vol. **60**, pp. 229–234. Elsevier B.V. doi:10.1016/j.procir.2017.01.046

Yang, S., Tang, Y. & Zhao, Y. F. 2015. A new part consolidation method to embrace the design freedom of additive manufacturing. *Journal of Manufacturing Processes* **20**, 444–449. doi:10.1016/j.jmapro.2015.06.024

Ziemian, S., Okwara, M. & Ziemian, C.W. 2015. Tensile and fatigue behavior of layered acrylonitrile butadiene styrene. *Rapid Prototyping Journal* **21**(3), 270–278. doi:10.1108/RPJ-09-2013-0086