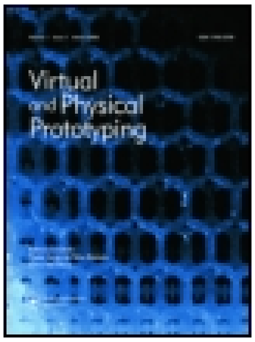

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Effect of support on printed properties in fused deposition modelling processes

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ABSTRACT
Additive manufacturing still suffers from redundant support material usage when printing parts with overhanging features. All the supports will be removed after fabrication, resulting in wasted materials. There are many works conducted for reducing support waste by improving support strategies. However, using different support strategies may lead to different printed qualities. In this paper, the effect of support strategy on printed qualities is investigated in fused deposition modelling processes. Three different support strategies are adopted for manufacturing the same 3D part. The finished surface roughness and flexural properties are compared for evaluating different support strategies, as well as the material waste and printing time. The results show that different support strategies may result in different printed surface roughness and flexural properties. To achieve the balance between support consumption and properties of printed parts, it becomes necessary to understand the effect of supports on printed qualities for choosing a best support strategy.

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Additive manufacturing; support strategy; printed quality; surface roughness; flexural properties

1. Introduction

Unlike conventional subtractive manufacturing processes, additive manufacturing (AM) fabricates parts in a 'layer-by-layer' manner, adding material into one part where necessary (Jin, He, and Du 2017; Weng et al. 2018; Weng et al. 2018). AM techniques manufacture three-dimensional (3D) parts by successively depositing material one layer after another such that the predesigned shape finally formed. Parts with intricate structures can be fabricated in one-step, thus getting rid of the limitations of traditional processing strategies or commercial shapes. Additionally, the elimination or reduction of the need to assemble multiple components in AM can lead to a significant reduction in fabrication time and human labour. Another advantage of AM is that objects can be manufactured on demand, thus there is no need for inventory of spare parts. Because of the above mentioned benefits, AM is becoming increasingly popular for producing high performance parts for medical, aerospace, automotive applications and even personalised products (Zheng et al. 2017; Lyons 2014; Staiano et al. 2018; Wang et al. 2018). The most common and widely used AM technology is the fused deposition modelling (FDM), due to its simplicity and low cost. However, one of the drawbacks of FDM is that this technique generally needs support structures for assisting overhang, hole or edge features, resulting in wasted materials and printing time (Liu and To 2017; Jiang, Xu, and Stringer 2018b; Jiang, Stringer, and Xu 2018; Jiang, Xu, and Stringer 2018a).

There are many research works conducted on reducing support usage or developing some new support strategies (Suntornnond, An, and Chua 2017). Strano et al. (2013) developed a novel optimisation algorithm by using pure mathematical 3D implicit functions for designing cellular support structures. The block-based inner support strategy for reducing material and fabrication time was proposed by Lee and Lee (2017). In addition, Vaidya and Anand (2016) adopted the shortest path algorithm proposed by Dijkstra (1959) for generating cellular support structures. Liu and To (2017) tried to integrate topology optimisation in AM processes for reducing material consumption. Currently, the authors also proposed a printable threshold overhang angle method for reducing supports (Jiang et al. 2018) and a benchmarking part for comparing different support strategies (Jiang et al. 2018). The effect of the infill on the mechanical properties in FDM has been investigated by Johnson and French (2018). Printing direction's effect on mechanical properties in AM was also investigated (Quan et al. 2018). Wang et al. (2018) studied the effects of certain process parameters on the mechanical properties of a filled polypropylene in FDM processes. Finding a compromise between various printing

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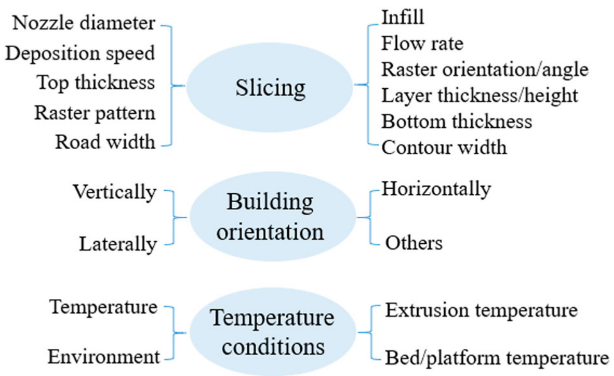


Figure 1. Process parameters that have been studied on their effects on printed mechanical properties (Popescu et al. 2018).

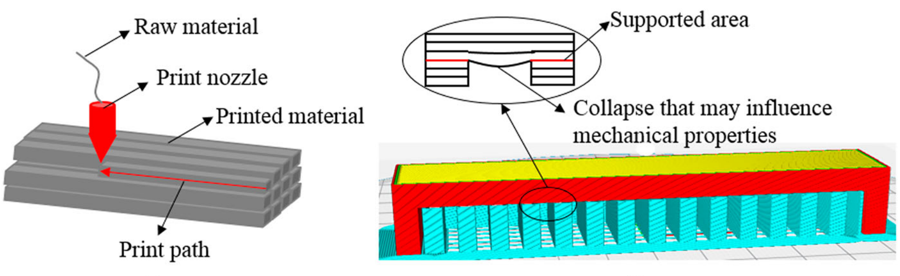
variables on each support strategy can be systematically and numerically exploited through multiple objective optimisation (Deng and Suresh 2015, 2016, 2017a, 2017b). In a very recent review paper of Popescu et al. (2018), all the process parameters' effects on printed mechanical properties have been reviewed (see Figure 1), except for the effect of support structure. Research of support structure's effect on printed qualities is still missing in FDM processes.

In this paper, the effect of support structures on printed surface roughness and flexural properties is investigated in a FDM machine, considering material waste and printing time at the same time. After knowing the influence of support on printed qualities, the best support strategy will be able to be found based on the final product's requirements. It is also necessary to investigate the effect of support on printed qualities for further improving the mechanical properties of additively manufactured products.

2. Theoretical analysis

Theoretically speaking, the reason why support structures have influence on printed mechanical properties can be explained as shown in Figure 2. As the process of AM is layer-based, from the bottom to the top (see Figure 2(a)), the connection status between each layer are determined by the printing parameters including the temperature, pressure, print speed and layer thickness etc. The effects of different parameters on printed mechanical qualities have been investigated by many researchers (Li et al. 2018; Quan et al. 2018; Ali, Ghadbeigi, and Mumtaz 2018; Yuan et al. 2018; Dizon et al. 2018; Wang et al. 2018). However, research on support structure's effect on the final printed mechanical properties which is also an important factor is still missing. As can be seen from Figure 2(b), the unsupported area will have some kind of sagging (no matter small or large). These unsupported layers will influence the layer printed upon them, as well as the connection status between them. Therefore, the support structure also plays as an important factor that can influence the final printed mechanical properties. As can be imagined from Figure 3, the final mechanical properties of the same part, but printed with different support methods, will be different. The final properties of fabricated parts will be influenced by the designed to-be-supported area, as well as support structures.

Thermal conditions between support structures and final part are also very important to the final fabricated mechanical properties. With different contact area and support regions, the thermal conduction is different in various support strategies during the printing process. Zhang et al. (2015) conducted some investigations on the effect of standard heat treatment on the mechanical properties of Inconel 718 super-alloy in the selective laser melting process. The effect of thermal treatment on mechanical properties of polypropylene/calcium carbonate nanocomposites was also investigated (Nascimento, Eiras, and Pessan 2016). The support structures can be regarded as a conduction structure which can help disseminate heat from the printed layer, thus influencing the final printed mechanical properties. As shown in Figure 3, these two support strategies will lead to different heat conduction situations due to different contact areas, thus resulting in different thermal conditions (Kakac 2018). For the support strategy as shown in Figure 3(a),



(a) (b)

Figure 2. (a) Layer-by-layer process of AM; (b) Example of support's effect on final printed qualities.

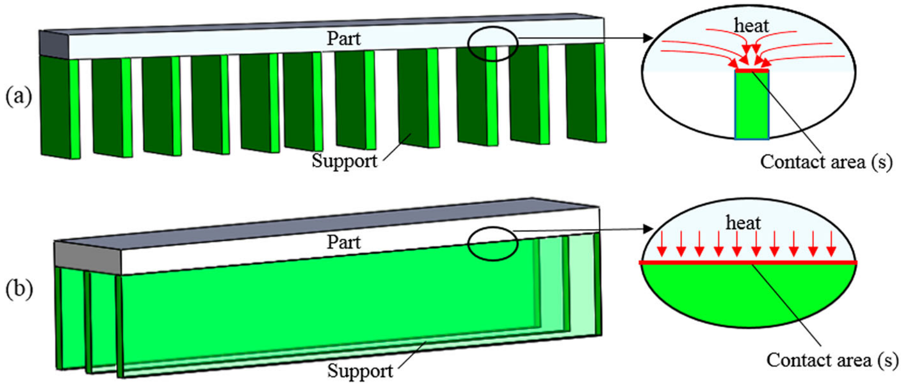


Figure 3. Two example support strategies with different contact areas and thus different thermal conditions.

the contact area is smaller than that of Figure 3(b), resulting in different thermal conditions and thus different final printed mechanical properties.

3. Methods

For investigating the effect of support structure on printed qualities, three different support strategies, specifically line, grid and zigzag support methods (see Figure 4) provided by Cura 3.2.1 were utilised for manufacturing these components. In Figure 4, the blue structures represent the supports; the yellow structures are the infill structures; while the red area is the wall of parts. The fabrications for the three different support strategies were conducted under the same conditions. Each of them has been reproduced three times, therefore, nine samples were obtained totally. The dimensions of this demo component are shown in Figure 4(d). The two raises are designed to make some space under the part, so the support can be generated under the part. The two raises will not have influence on the results as these two raises sit at the end which are not measured for its mechanical properties (as can be seen in Figure 5). A Kossel Delta 3D printer from Shenzhen Anycubic co., LTD was utilised as the equipment for performing the experiments. The shape of build area is circular in this printer, with a diameter of 180 mm. The maximum printable height is 300 mm. The diameter of the printing nozzle is 0.4 mm. PLA is a popular material used in AM and has successfully reached commercial-scale production in recent years. The main excellent properties of PLA are good mechanical properties (i.e. high modulus and strength), biocompatibility, high transparency and low toxicity (Chow, Teoh, and Karger-Kocsis 2018). It has been widely used in many fields such as medical applications (Hamad et al. 2015). Due to these advantages and its popularity, PLA is used for testing. The filament diameter of the used PLA material is 1.75 mm. Table 1 lists the parameters and printing settings used for fabrication.

For testing the flexural properties of the printed parts, Instron 5576 testing machine as shown in Figure 5 was used. The tests were performed under ASTM D790

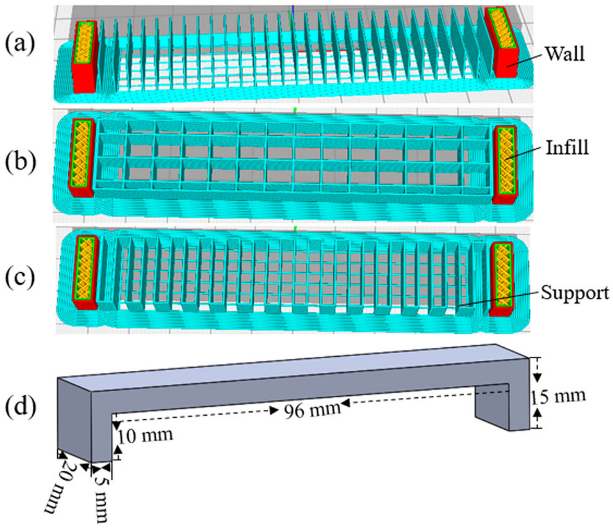


Figure 4. (a) Line support; (b) Grid support; (c) Zigzag Support; (d) Dimensions of the model part.

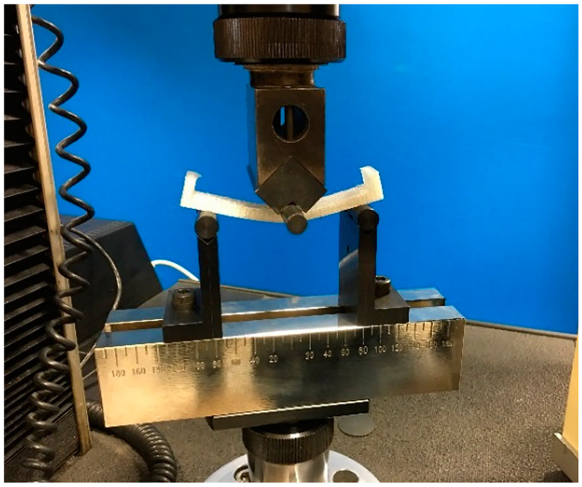


Figure 5. Three-point bend test.

Table 1. Parameters of printer settings.

Items	Value
Layer height (mm)	0.2
Wall thickness (mm)	0.8
Bottom/top thickness (mm)	0.8
Infill density (%)	30
Print temperature (°C)	210
Print speed (mm/s)	30

standard, at a span length of 82.3 mm and crosshead speed of 2.2 mm/min. The ambient temperature was 22.5 °C and the ambient humidity was 55% during testing. SURFTEST SJ-210, which is a surface roughness measuring tester from Mitutoyo Corporation (Surftest 2018), was used for measuring printed surface roughness (R_a) of the components fabricated with different support methods.

4. Results and discussion

To give a comprehensive evaluation of different support strategies, geometric accuracy, support usage, printing time, printed surface quality and flexural properties were recorded and compared. For each support strategy, the average values were obtained from the three repeated samples.

4.1. Geometric accuracy

Geometric accuracy is important in 3D printing. All the parts printed should be within the geometric tolerance after fabrication. For comparison, the original designed values and measured actual values are listed in Table 2. The corresponding original designed dimensional values can be found in Figure 4(d). As can be seen in this table, the geometric accuracies are almost the same in different support strategies. Therefore, the geometric accuracy will not be compared in the following sections.

4.2. Support usage

Support usages (wasted material) and the material used for fabricating the final part in different support strategies are listed in Table 3. As shown in this table, line support costs the least support material (only 2.93 g) i.e. saves more material, followed by Grid and Zigzag support methods. Line support is the best choice from the perspective of material consumption. Material usages of the final part (after removing supports) are almost the same in different support strategies.

Table 2. Original designed dimensional values and corresponding actual values after printing in different support strategies.

Original designed value (mm)	Measured average value in line support (mm)	Measured average value in grid support (mm)	Measured average value in zigzag support (mm)
5	5.12	5.11	5.12
10	10.09	10.10	10.08
15	15.08	15.07	15.08
20	20.06	20.07	20.07
96	96.05	96.04	96.05

Table 3. Average material consumptions in different support strategies.

	Material usage (g)	
Support strategy	Support	Final part
Line	2.93	8.52
Grid	4.69	8.49
Zigzag	4.79	8.51

4.3. Printing time

Table 4 shows the time consumption in fabricating a whole part (including support). It can be seen that the line support method costs the least time for finishing a whole part. This is mainly because of that line support method consumes the least support material, thus saving extra time for extruding more support materials. However, this is also determined by print paths and strategies. Zigzag support method consumes more material than Grid method, but costs less printing time than Grid method. This is because Zigzag structure may need longer path for nozzle travelling. For filling a layer during printing process, there are many different paths and nozzle travelling strategies. Taking filling the layer in Figure 6 as an example, both the two nozzle travelling paths can achieve the goal of printing this layer. However, time spent on finishing this layer may be different, depending on the value of *m, n, l, and s*. For the strategy shown in Figure 6(a), the printing time can be calculated as follows,

$$t_a = \frac{30m + 5l + 4n + 8s}{v} \tag{1}$$

where v is the speed of nozzle travelling, *m, l, n and s* are the dimensions shown in Figure 6. Also, time spent on the strategy as shown in Figure 6(b) is

$$t_b = \frac{12m + 5l + 38n + 76s}{v} \tag{2}$$

Therefore, consuming the same material does not mean costing the same time on fabrication. The printing

Table 4. Average printing time in different support strategies.

Support strategy	Time (s)
Line	5405
Grid	5820
Zigzag	5640

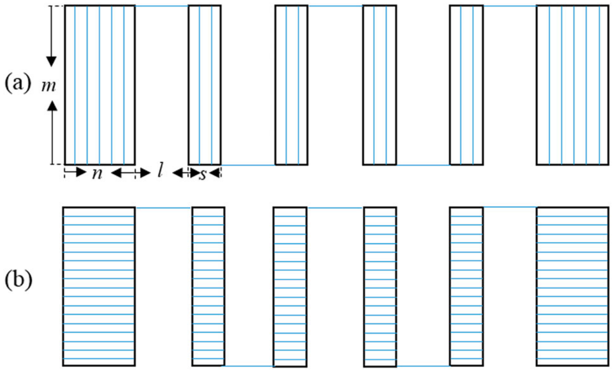


Figure 6. Two examples of nozzle travel path strategies.

time is also related to the nozzle travel path and strategy, as well as the dimensions of part (e.g. *m, l, n and s*). The team of Jin has conducted many trials in path planning optimisation for improving path strategies (Jin et al. 2017; Jin et al. 2017; Jin, He, and Du 2017; Jin et al. 2017; Jin, Du, and He 2017).

Among these three support strategies provided by Cura 3.2.1, Line support method is the best strategy from the perspective of printing time.

4.4. Printed surface quality

Surface roughness (R_a) of supported area (bottom face) after removing support structures in different support strategies were shown in Figure 7. As can be seen, Zigzag support has relatively the best surface quality, though no significant difference among the three support methods. Zigzag support strategy is the best choice from the perspective of finished surface quality.

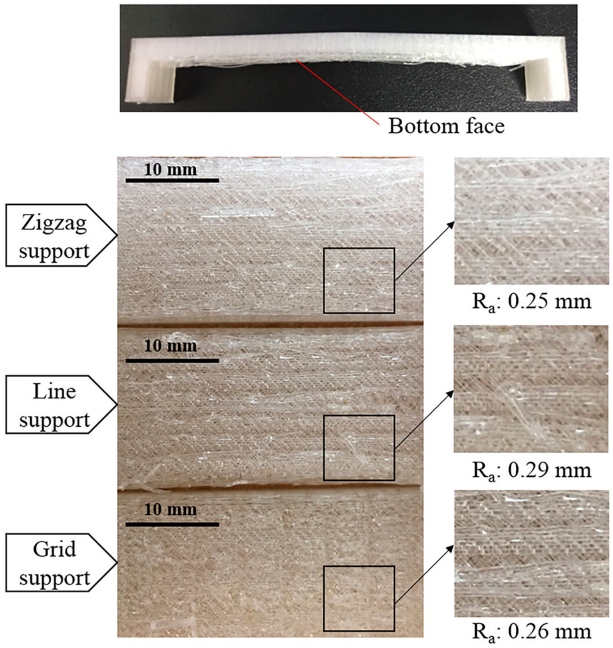


Figure 7. Printed surface quality after removing supports of different strategies.

Table 5. Results after flexural testing.

Support method	Load at break point (N)	Displacement at break point (mm)	Flexural stress (MPa)	Flexural modulus (MPa)	Flexural strain (%)
Grid	110.11	5.99	28.41	1383.63	2.59
Zigzag	176.71	6.56	39.52	1547.11	3.05
Line	135.29	7.77	29.49	1180.92	3.66

4.5. Flexural properties

Table 5 presents a comparison of experimental flexural tests between different parts printed in different support methods. As can be seen, Zigzag support method is the best choice if considering the largest load the printed part can stand, followed by Line and Grid support methods. Figure 8 shows the stress-strain curves obtained from flexural tests on parts fabricated in different support strategies.

Zigzag support strategy has the largest flexural modulus, followed by Grid and Line support strategies. One of the reasons is that, in Zigzag support strategy, the areas in the final part near the supports act as weak areas due to different cooling conditions. In another word, the zigzag has an isolation effect on the final part, resulting in higher flexural strength. However, the final part printed in Line support strategy shows a lower flexural strength, which is attributed to the limited isolation effect in the single direction. Under Grid support strategy, the isolation effect is neutralised to some extent due to the transition of the X-Y direction, dramatically reducing the isolation effect. The thermal transfer inside the parts and support structures are also quite different in different strategies. Moreover, surface roughness of the printed part also contributes a lot to the final mechanical properties (Jiang, Li, and

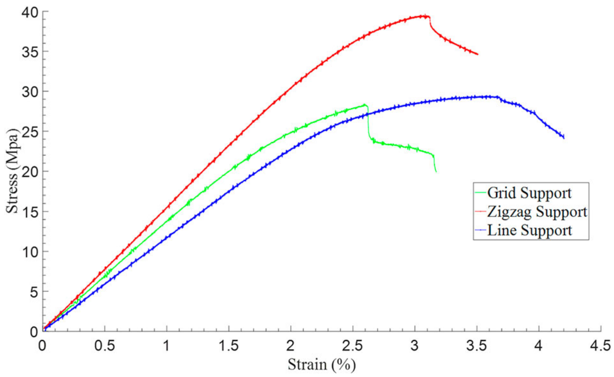


Figure 8. Stress-strain behaviour of parts printed in different support methods.

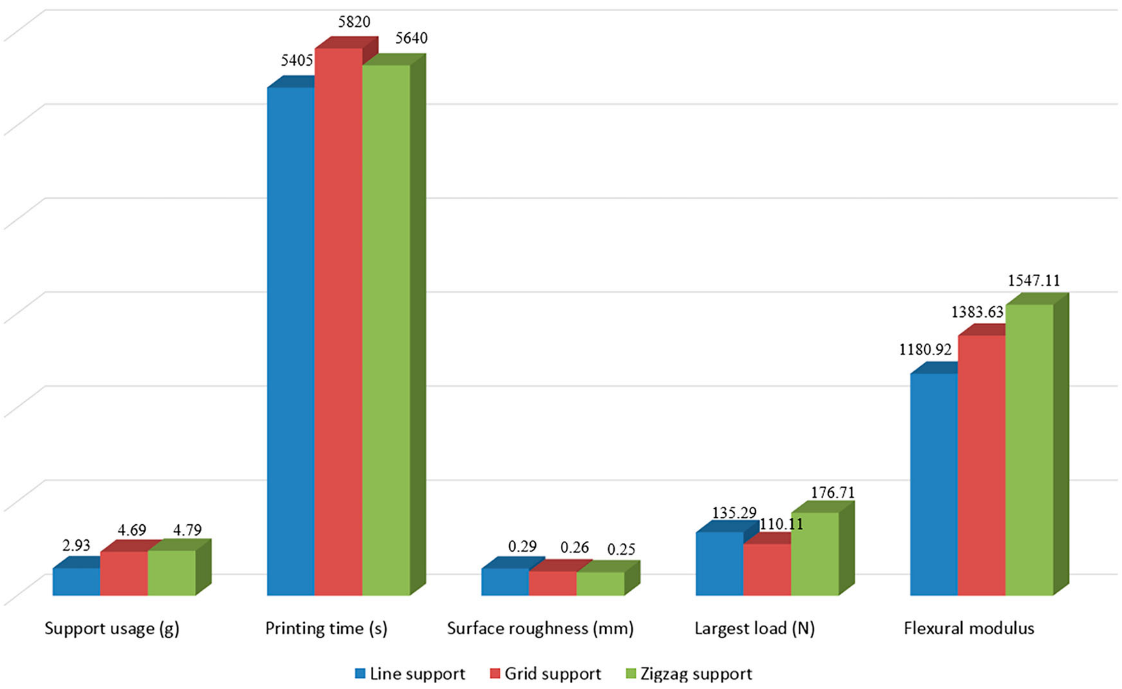


Figure 9. Test results for main properties of parts printed in different support strategies.

Tanabashi 2006). In the experiments conducted in this paper, better printed surface quality may lead to higher mechanical strength.

4.6. Balance between qualities and properties

Generally speaking, the objective is that the largest flexural strength can be obtained with the best printed surface quality, the least support material usage and printing time. However, this is not the case, different support strategies have their own advantages and disadvantages. How to achieve a balance among all these properties is also a significant problem. As can be seen from the test results, Line support strategy consumes the least support material and printing time. However, the flexural strength of parts printed in this support method is lower than Zigzag method. Though Grid support strategy costs more support material and printing time for finishing a part than Line support method, the load part of Grid method can stand is still lower than Line support method. Therefore, for achieving the largest load that the part can stand, Line support method is better than Grid support method.

Figure 9 collects all the property results together for comparison. As can be seen, in terms of support waste and printing time, Line support method is the best option. While in terms of other properties, Zigzag support is better than others. For obtaining a best support strategy, the choosing process should include the final properties you want. For example, when fabricating a part for demonstration (e.g. models for showing structures), the surface roughness is the most important factor and the mechanical properties are not the focus. Then, the best choice is Line support method. While if the final part is a function-based structure (e.g. for standing a load), then Zigzag support method is the best choice.

5. Conclusions

In this paper, the effects of support strategy on printed properties (e.g. surface roughness, flexural properties) was investigated, considering support waste and printing time at the same time. Three support strategies (Zigzag, Grid and Line) from Cura 3.2.1, which have been widely used in the additive manufacturing community, were tested with PLA material. The following conclusions can be obtained.

Different support strategies can influence the final printed mechanical properties in FDM processes. The reasons for these differences are mainly because of various thermal conditions, support designs and finished surface roughness in different support strategies.

According to the results, parts fabricated in Zigzag support method has the largest flexural modulus and can stand the largest load of all.

Line support strategy consumes the least support material and printing time, which is the most sustainable support method of all.

The rules for choosing a best support method should depend on the requirements of the final part (what properties the final part needs). The balance between different properties should be considered.

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References

Ali, Haider, Hassan Ghadbeigi, and Kamran Mumtaz. 2018. "Processing Parameter Effects on Residual Stress and Mechanical Properties of Selective Laser Melted Ti6Al4 V." *Journal of Materials Engineering and Performance* 27 (8). Springer US: 4059–4068. doi:10.1007/s11665-018-3477-5.

Chow, W. S., E. L. Teoh, and J. Karger-Kocsis. 2018. "Flame Retarded Poly(Lactic Acid): A Review." *Express Polymer Letters* 12 (5): 396–417. doi:10.3144/expresspolymlett.2018.34.

Deng, Shiguang, and Krishnan Suresh. 2015. "Multi-Constrained Topology Optimization via the Topological Sensitivity." *Structural and Multidisciplinary Optimization* 51(5): 987-1001.

Deng, Shiguang, and Krishnan Suresh. 2016. "Multi-constrained 3D Topology Optimization via Augmented Topological Level-Set." *Computers & Structures* 170: 1-12.

Deng, Shiguang, and Krishnan Suresh. 2017a. "Topology Optimization Under Thermo-Elastic Buckling." *Structural and Multidisciplinary Optimization* 55(5): 1759-1772.

Deng, Shiguang, and Krishnan Suresh. 2017b. "Stress Constrained Thermo-Elastic Topology Optimization with Varying Temperature Fields via Augmented Topological Sensitivity Based Level-Set." *Structural and Multidisciplinary Optimization* 56: 1413.

Dijkstra, E. W. 1959. "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik* 1 (1): 269–271. doi:10.1007/BF01386390.

Dizon, John Ryan C., Alejandro H. Espera, Qiyi Chen, and Rigoberto C. Advincula. 2018. "Mechanical Characterization of 3D-Printed Polymers." *Additive Manufacturing* 20 (March). Elsevier: 44–67. doi:10.1016/J.ADDMA.2017.12.002.

do Nascimento, Estêvão Mestres, Daniel Eiras, and Luiz Antonio Pessan. 2016. "Effect of Thermal Treatment on Impact Resistance and Mechanical Properties of Polypropylene/Calcium Carbonate Nanocomposites." *Composites Part B: Engineering* 91 (April). Elsevier: 228–234. doi:10.1016/J.COMPOSITESB.2015.12.040.

Hamad, K., M. Kaseem, H. W. Yang, F. Deri, and Y. G. Ko. 2015. "Properties and Medical Applications of Polylactic Acid: A Review." *Express Polymer Letters* 9 (5): 435–455. doi:10.3144/expresspolymlett.2015.42.

Jiang, Yujing, Bo Li, and Yosihiko Tanabashi. 2006. "Estimating the Relation Between Surface Roughness and Mechanical Properties of Rock Joints." *International Journal of Rock Mechanics and Mining Sciences* 43 (6). Pergamon: 837–846. doi:10.1016/J.IJRMMS.2005.11.013.

Jiang, Jngchao, Jonathan Stringer, and Xun Xu. 2018. "Support Optimization for Flat Features via Path Planning in Additive Manufacturing." *3D Printing and Additive Manufacturing*. doi:10.1089/3dp.2017.0124.

Jiang, Jingchao, Jonathan Stringer, Xun Xu, and Pai Zheng. 2018. "A Benchmarking Part for Evaluating and Comparing Support Structures of Additive Manufacturing." In 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018), 196–202. doi:10.25341/D42G6H.

Jiang, Jingchao, Jonathan Stringer, Xun Xu, and Ray Y. Zhong. 2018. "Investigation of Printable Threshold Overhang Angle in Extrusion-Based Additive Manufacturing for Reducing Support Waste." *International Journal of Computer Integrated Manufacturing* 31 (10). Taylor & Francis: 961–969. doi:10.1080/0951192X.2018.1466398.

Jiang, Jingchao, Xun Xu, and Jonathan Stringer. 2018a. "A New Support Strategy for Reducing Waste in Additive Manufacturing." In The 48th International Conference on Computers and Industrial Engineering (CIE 48), 1–7. Auckland.

Jiang, Jingchao, Xun Xu, and Jonathan Stringer. 2018b. "Support Structures for Additive Manufacturing: A Review." *Journal of Manufacturing and Materials Processing 2018, Vol. 2, Page 64* 2 (4). Multidisciplinary Digital Publishing Institute: 64. doi:10.3390/JMMP2040064.

Jin, Yuan, Jianke Du, and Yong He. 2017. "Optimization of Process Planning for Reducing Material Consumption in Additive Manufacturing." *Journal of Manufacturing Systems* 44 (July). Elsevier: 65–78. doi:10.1016/J.JMSY.2017.05.003.

Jin, Yuan, Jianke Du, Yong He, and Guoqiang Fu. 2017. "Modeling and Process Planning for Curved Layer Fused Deposition." *International Journal of Advanced Manufacturing Technology* 91 (1–4). The International Journal of Advanced Manufacturing Technology: 273–285. doi:10.1007/s00170-016-9743-5.

Jin, Yuan, Jianke Du, Zhiyong Ma, Anbang Liu, and Yong He. 2017. "An Optimization Approach for Path Planning of High-Quality and Uniform Additive Manufacturing." *International Journal of Advanced Manufacturing Technology* 92 (1–4). The International Journal of Advanced Manufacturing Technology: 651–662. doi:10.1007/s00170-017-0207-3.

Jin, Yuan, Yong He, and Jianke Du. 2017. "A Novel Path Planning Methodology for Extrusion-Based Additive Manufacturing of Thin-Walled Parts." *International Journal of Computer Integrated Manufacturing* 30 (12). Taylor & Francis: 1–15. doi:10.1080/0951192X.2017.1307526.

Jin, Yuan, Yong He, Guoqiang Fu, Aibing Zhang, and Jianke Du. 2017. "A Non-Retraction Path Planning Approach for Extrusion-Based Additive Manufacturing." *Robotics and Computer-Integrated Manufacturing* 48 (December 2016). Elsevier Ltd: 132–144. doi:10.1016/j.rcim.2017.03.008.

Johnson, Gabriel A, and Jesse J French. 2018. "Evaluation of Infill Effect on Mechanical Properties of Consumer 3D Printing Materials." *Advances in Technology Innovation* 3 (4): 179–184.

Kakac, Sadık. 2018. *Heat Conduction*. Fifth edition. Boca Raton: Taylor & Francis, CRC Press, [2018]: CRC Press. doi:10.1201/b22157.

Lee, Jusung, and Kunwoo Lee. 2017. "Block-Based Inner Support Structure Generation Algorithm for 3D Printing Using Fused Deposition Modeling." *The International Journal of Advanced Manufacturing Technology* 89 (5–8). Springer London: 2151–2163. doi:10.1007/s00170-016-9239-3.

Li, Kaikai, Linlin Liu, Jimei Wu, Meng Li, and Shenghui Yong. 2018. "Study on the Mechanical Performance Optimization of FDM Built Parts." In, 563–569. Springer, Singapore. doi:10.1007/978-981-10-7629-9_69.

Liu, Jikai, and Albert C. To. 2017. "Deposition Path Planning-Integrated Structural Topology Optimization for 3D Additive Manufacturing Subject to Self-Support Constraint." *Computer-Aided Design* 91 (October). Elsevier: 27–45. doi:10.1016/J.CAD.2017.05.003.

Lyons, Brett. 2014. *Additive Manufacturing in Aerospace: Examples and Research Outlook*. *The Bridge*. Vol. 44. National Academy of Engineering. https://trid.trb.org/view.aspx?id=1328197.

Nascimento, E. M., D. Eiras, L. A. Pessan. 2016. "Effect of Thermal Treatment on Impact Resistance and Mechanical Properties of Polypropylene/Calcium Carbonate Nanocomposites." *Composites Part B: Engineering* 91: 228–234. doi:10.1016/j.compositesb.2015.12.040.

Popescu, Diana, Aurelian Zapciu, Catalin Amza, Florin Baciu, and Rodica Marinescu. 2018. "FDM Process Parameters Influence over the Mechanical Properties of Polymer Specimens: A Review." *Polymer Testing* 69 (August). Elsevier: 157–166. doi:10.1016/J.POLYMERTESTING.2018.05.020.

Quan, Zhenzhen, Jonghwan Suhr, Jianyong Yu, Xiaohong Qin, Chase Cotton, Mark Mirotznik, and Tsu-Wei Chou. 2018. "Printing Direction Dependence of Mechanical Behavior of Additively Manufactured 3D Preforms and Composites." *Composite Structures* 184 (January). Elsevier: 917–923. doi:10.1016/J.COMPSTRUCT.2017.10.055.

Staiano, Gabriele, Antonio Gloria, Giovanni Ausanio, Antonio Lanzotti, Claudio Pensa, and Massimo Martorelli. 2018. "Experimental Study on Hydrodynamic Performances of Naval Propellers to Adopt New Additive Manufacturing Processes." *International Journal on Interactive Design and Manufacturing* 12 (1). doi:10.1007/s12008-016-0344-1.

Strano, G., L. Hao, R. M. Everson, and K. E. Evans. 2013. "A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing." *International Journal of Advanced Manufacturing Technology* 66 (9–12): 1247–1254. doi:10.1007/s00170-012-4403-x.

Suntornnond R, An J., and Chua C. K, 2017. "Roles of support materials in 3D bioprinting – present and future." *International Journal of Bioprinting*, 3(1): 83–86. doi:10.18063/IJB.2017.01.006.

Surftest SJ-210- Series 178-Portable Surface Roughness Tester. 2018. Accessed July 27. https://ecatalog.mitutoyo.com/Surftest-SJ-210-Series-178-Portable-Surface-Roughness-Tester-C1794.aspx.

Vaidya, Rohan, and Sam Anand. 2016. "Optimum Support Structure Generation for Additive Manufacturing Using Unit Cell Structures and Support Removal Constraint." *Procedia Manufacturing* 5: 1043–1059. doi:10.1016/j.promfg.2016.08.072.

Wang, Yuanbin, Robert Blache, Pai Zheng, and Xun Xu. 2018. "A Knowledge Management System to Support Design for Additive Manufacturing Using Bayesian Networks." *Journal of Mechanical Design* 140 (May). doi:10.1115/1.4039201.

Wang, Lu, J. Elliott Sanders, Douglas J. Gardner, and Yousoo Han. 2018. "Effect of Fused Deposition Modeling Process Parameters on the Mechanical Properties of a Filled Polypropylene." *Progress in Additive Manufacturing*, *May*. *Springer International Publishing*, 1–10. doi:10.1007/s40964-018-0053-3.

Weng, Yiwei, Mingyang Li, Zhixin Liu, Wenxin Lao, Bing Lu, Dong Zhang, and Ming Jen Tan. 2018. "Printability and Fire Performance of a Developed 3D Printable Fibre Reinforced Cementitious Composites under Elevated Temperatures." *Virtual and Physical Prototyping*, *December*. *Taylor & Francis*, 1–9. doi:10.1080/17452759.2018.1555046.

Weng, Yiwei, Mingyang Li, Ming Jen Tan, and Shunzhi Qian. 2018. "Design 3D Printing Cementitious Materials via Fuller Thompson Theory and Marson-Percy Model." *Construction and Building Materials* 163: 600–610. doi:10.1016/j.conbuildmat.2017.12.112.

Yuan, Kangbo, Weiguo Guo, Penghui Li, Jianjun Wang, Yu Su, Xin Lin, and Yanping Li. 2018. "Influence of Process Parameters and Heat Treatments on the Microstructures and Dynamic Mechanical Behaviors of Inconel 718 Superalloy Manufactured by Laser Metal Deposition." *Materials Science and Engineering: A* 721 (April). Elsevier: 215–225. doi:10.1016/J.MSEA.2018.02.014.

Zhang, Dongyun, Wen Niu, Xuanyang Cao, and Zhen Liu. 2015. "Effect of Standard Heat Treatment on the Microstructure and Mechanical Properties of Selective Laser Melting Manufactured Inconel 718 Superalloy." *Materials Science and Engineering: A* 644 (September). Elsevier: 32–40. doi:10.1016/J.MSEA.2015.06.021.

Zheng, Pai, Yuanbin Wang, Xun Xu, and Sheng Quan Xie. 2017. "A Weighted Rough Set Based Fuzzy Axiomatic Design Approach for the Selection of AM Processes." *The International Journal of Advanced Manufacturing Technology* 91 (5–8). Springer London: 1977–1990. doi:10.1007/s00170-016-9890-8.