INFLUENCE OF 3D PRINTING PARAMETERS ON MECHANICAL BEHAVIOUR OF POLYLACTIC ACID (PLA) SPECIMEN UTILIZING FDM TECHNIQUE

SHATHISWARA RAO A/L SUBRAMANIAM

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

Universiti Malaysia PAHANG
Engineering • Technology • Creativity

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis, and, in our opinion, this project is adequate in terms of scope and quality for the award of the degree of Master of Science in Mechanical Engineering.

(Supervisor's Signature)

Full Name : DR. MAHENDRAN SAMYKANO
Position : SENIOR LECTURER
Date : 30TH JANUARY 2019

(Co-supervisor's Signature)

Full Name : DR. NGUI WAI KENG
Position : SENIOR LECTURER
Date : 30TH JANUARY 2019

STUDENT’S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at University Malaysia Pahang or any other institutions.

(Student’s Signature)

Full Name : Shathiswara Rao A/L Subramaniam

ID Number : MMM17018

Date : 30th January 2019

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ABSTRAK

Pencetakan 3D adalah teknologi yang mampu secara langsung menghasilkan model fizikal 3D bersama-sama dengan model matematik yang dimasukkan dalam sifat tambahan, di mana bahan-bahan tersebut ditambah untuk membentuk produk, tidak seperti kaedah pembuatan tradisional. Kemunculan pencetakan 3D telah memperoleh masa kitaran yang lebih pendek untuk mereka bentuk dan mengembangkan produk inovatif. Salah satu teknologi pencetakan 3D ialah pemodelan pemendapan (FDM). FDM telah digunakan secara meluas untuk pemodelan konsep dan visualisasi, bentuk, dan analisis fungsian. Walaubagaimanpun, potensi pencetak 3D murah masih kabur kerana menjejak kaki dalam perniagaan ini. Kajian ini bertujuan untuk melakukan penilaian eksperimen terhadap kesan parameter percetakan ke arah sifat mekanik Polylactic Acid (PLA) yang dicetak dengan menggunakan pemodelan pemendapan dengan menjalankan empat jenis ujian mekanikal iaitu ujian tegangan, mampatan, lenturan dan impak. Semua spesimen telah dicetak mengikut kehendak yang dinyatakan di dalam ASTM D638, ASTM D695, ASTM D690 dan ASTM D256 masing masing. Dua parameter yang dipilih untuk diubah dalam penyediaan spesimen dalam kajian ini adalah sudut raster dan ketumpatan bahan, dengan nilai 0°, 45°, 90° dan 10%, 50%, 99% masing-masing. Penilaian eksperimen mendedahkan bahawa semua ciri spesimen sangat dipengaruhi oleh peratusan infill, di mana semua tindak balas mekanikal meningkat dengan ketumpatan bahan, iaitu yang tertinggi berada pada 99% ketumpatan. Sudut raster menunjukkan kesan bervariasi berhubung dengan ujian mekanikal yang dijalankan. Untuk sifat tegangan, kekuatan tegangan muktamad dan ketegangan retak adalah tertinggi pada sudut 45° raster, manakala modulus elastik dan kekuatan hasil tinggi tertinggi pada sudut 0° raster. Sifat mampatan tidak terjejas dengan ketara dengan variasi sudut raster. Ciri fleksural dan kesan adalah tertinggi pada sudut 0° dan 45° raster masing masing. Untuk mengesahkan data eksperimen, analisis statistik dijalankan menggunakan pendekatan Design of Experiment (DOE) dengan metodologi permukaan respon. Kesalahan purata dikira membandingkan nilai eksperimen dan ramalan yang dijangkakan, di mana akauntabiliti data uji eksperimen telah disahkan dengan peratusan ralat di bawah 10%. Pengoptimasi tindak balas telah digunakan untuk memaksimumkan tindak balas mekanikal secara keseluruhan berkaitan dengan kombinasi parameter percetakan. Sifat tegangan optimum didapati pada gabungan parameter 99% infill dengan 36.36° raster angle. Sifat mampatan dan lentur menunjukkan tindak balas optimum pada peratus 99% infill dengan sudut 0° raster. Akhirnya, sifat impak didapati optimum pada peratus 99% infill dengan sudut 50° raster. Penilaian eksperimen dilakukan sekali lagi untuk mengesahkan akauntabiliti kombinasi parameter yang diperolehi. Ini akan menjadi panduan untuk pengguna pencetak 3D untuk menentukan kesesuaian pencetak 3D murah untuk mengarang produk yang diingini dengan tahap sifat mekanikal yang diperlukan untuk mematuhi faktor ekonomi. Seperti yang dicadangkan, kerja penyelidikan ini perlu diperluaskan dengan memasukkan parameter seperti kelajuan percetakan, suhu penyemperitan, jurang udara dan ketebalan lapisan supaya potensi pencetak 3D kos rendah dapat diterokai sepenuhnya bersamaan dengan pelbagai parameter percetakan.

ABSTRACT

Additive manufacturing is a technology capable to directly manufacture 3D physical model alongside with their inserted mathematical model in an additive nature, where the materials are fused together to form a product, unlike the traditional manufacturing method. The emergence of 3D printing has secured a shorter cycle time for designing and developing innovative products. One of the most common additive manufacturing technologies is Fused deposition modelling (FDM). FDM has been used widely for concept modelling and visualization, fit, form, and functional analysis and rapid manufacturing. The unavailability of extensive printer parameter information which directly reflects the mechanical properties of the 3D printed products has been a barrier for the low-cost 3D printer users to identify the connection between printing parameter, intended application and 3D printer used which becomes the key for reliability and economical factor. Moreover, the potential of a low-cost 3D printer remains blurry since high-end FDM machines are commonly used compared to low-cost FDM machines that just debuted into this business. This research work aims to perform an experimental evaluation on the effects of printing parameter towards the mechanical property of Polylactic Acid (PLA) printed using Fused Deposition Modelling Technique by conducting four types of mechanical tests namely tensile, compression, flexural and impact test. All the specimens were printed according to the requirement stated in ASTM D638, ASTM D695, ASTM D690, and ASTM D256 respectively. Two parameters chosen to be varied in specimen preparation in this research are raster angle and infill density, with value of 0°, 45°, 90°, and 10%, 50%, 99% respectively. Experimental evaluation revealed that all the specimen properties are highly influenced by infill percentage, whereby all the mechanical responses increases with the infill density, making the highest is at 99%. Raster angle showed varied effect with regards to the conducted mechanical test. For tensile properties, ultimate tensile strength and fracture strain were highest at 45° raster angle, while elastic modulus and yield strength were highest at 0° raster angle. Compression properties were not significantly affected by the variation of raster angle. Flexural and impact properties were highest at 0° and 45° raster angle respectively. To validate the experimental data, statistical analysis was carried out using Design of Experiment (DOE) approach with response surface methodology. The average error was calculated comparing experimental and predicted response value, whereby the accountability of obtained experimental data was confirmed with the percentage of error below 10%. Response optimizer was used to maximize the overall mechanical response with regards to the printing parameter combinations. It was determined that the optimum tensile properties were found at parameter combination of 99% infill percentage with 36.36° raster angle. Compression and flexural properties showed an optimum response at 99% infill percentage with 0° raster angle. Finally, impact properties were found to be optimum at 99% infill percentage with 50° raster angle. Experimental evaluation was carried out again to validate the accountability of obtained parameter combinations. This will serve as a guide for 3D printer users to decide on the suitability of low-cost 3D printer to fabricate intended products with needed mechanical property level to comply with the economic factor. As for recommendation, this research work should be extended by including parameters such as printing speed, extrusion temperature, air gap, and layer thickness so that the potential of the low-cost 3D printer can be fully explored.

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LIST OF SYMBOLS

W_c	Gauge width
W_o	Overall width
L_o	Overall length
a	Alpha value

LIST OF ABBREVIATIONS

3D	Three Dimensional
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
PEI	Polyetherimide
FDM	Fused Deposition Modelling
CAD	Computer-Aided Design
CAM	Computer Aided Manufacturing
ASTM	American Society for Testing and Materials
AM	Additive Manufacturing
STL	Stereolithography
USB	Universal Serial Bus
2D	Two Dimensional
UV	Ultra Violet
DOD	Drop On Demand
VP	Vat Photopolymerization
PBF	Powder Bed Fusion
SLA	Stereolithography
SLM	Selective Laser Melting
EBM	Electron Beam Melting
SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
DLP	Digital Light Processing
EBM	Electron Beam Melting
LOM	Laminated Object Manufacturing
DED	Direct Energy Deposition
LENS	Laser Engineered Net Shaping
EBW	Electron Beam Welding
SEM	Scanning Electron Microscope
UTS	Ultimate Tensile Strength
EM	Elastic Modulus
FS	Fracture Strain
YS	Yield Strength
CS	Compression Strength
CM	Compression Modulus

FS	Flexural Strength
FM	Flexural Modulus
EA	Energy Absorbed
IS	Impact Strength
T	Tensile
C	Compression
Fl	Flexural
Fa	Fatigue
I	Impact

REFERENCES

Abbas, T. F., Othman, F. M., & Ali, H. B. (2018). Influence of Layer Thickness on Impact Property of 3D-Printed PLA. *International Research Journal of Engineering and Technology (IRJET), 5*(2), 1-4.

Afrose, M. F. (2016). *Mechanical and viscoelastic properties of polylactic acid (PLA) materials processed through fused deposition modelling (FDM).* (Master's thesis), Swinburne University of Technology, Swinburne Research Bank.

Ahmed, A., & Susmel, L. (2017). Additively Manufactured PLA under static loading: strength/cracking behaviour vs. deposition angle. *Procedia Structural Integrity, 3,* 498-507.

Ahn, S.-H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal, 8*(4), 248-257.

Akande, S. O. (2015). Dimensional accuracy and surface finish optimization of fused deposition modelling parts using desirability function analysis. *International Journal of Engineering and Technical Research, 4*(4), 196-202.

Bagsik, A., Schöppner, V., & Klemp, E. (2010). FDM part quality manufactured with Ultem* 9085. *14th international scientific conference on polymeric materials, 15,* 307-315.

Bai, Y., & Williams, C. B. (2015). An exploration of binder jetting of copper. *Rapid Prototyping Journal, 21*(2), 177-185.

Bandyopadhyay, A., Krishna, B., Xue, W., & Bose, S. (2009). Application of laser engineered net shaping (LENS) to manufacture porous and functionally graded structures for load bearing implants. *Journal of Materials Science: Materials in Medicine, 20*(1), 29.

Banerjee, R., Collins, P., Genc, A., & Fraser, H. (2003). Direct laser deposition of in situ Ti–6Al–4V–TiB composites. *Materials Science and Engineering, 358*(1-2), 343-349.

Berman, B. (2012). 3-D printing: The new industrial revolution. *Business horizons, 55*(2), 155-162.

Bikas, H., Stavropoulos, P., & Chryssolouris, G. (2016). Additive manufacturing methods and modelling approaches: a critical review. *The International Journal of Advanced Manufacturing Technology, 83*(1-4), 389-405.

Bremen, S., Meiners, W., & Diatlov, A. (2012). Selective laser melting: a manufacturing technology for the future? *Laser Technik Journal, 9*(2), 33-38.

Brown, R. (2002). *Handbook of polymer testing: short-term mechanical tests*. Shrewsbury, UK: Rapra Technology Limited.

Calvert, P. (2001). Inkjet printing for materials and devices. *Chemistry of materials, 13*(10), 3299-3305.

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). *Could 3D printing change the world? Technologies, Potential, and Implications of Additive Manufacturing,* Washington, DC: Atlantic Council.

Chacón, J., Caminero, M., García-Plaza, E., & Núñez, P. (2017). Additive manufacturing of PLA structures using fused deposition modelling: effect of process parameters on mechanical properties and their optimal selection. *Materials & Design, 124*, 143-157.

Chen, L., He, Y., Yang, Y., Niu, S., & Ren, H. (2017). The research status and development trend of additive manufacturing technology. *The International Journal of Advanced Manufacturing Technology, 89*(9-12), 3651-3660.

Chockalingam, K., Jawahar, N., Ramanathan, K., & Banerjee, P. (2006). Optimization of stereolithography process parameters for part strength using design of experiments. *The International Journal of Advanced Manufacturing Technology, 29*(1-2), 79-88.

Chong, S., Pan, G.-T., Khalid, M., Yang, T. C.-K., Hung, S.-T., & Huang, C.-M. (2017). Physical characterization and pre-assessment of recycled high-density polyethylene as 3D printing material. *Journal of Polymers and the Environment, 25*(2), 136-145.

Christiyan, K. J., Chandrasekhar, U., Mathivanan, N. R., & Venkateswarlu, K. (2018). Influence of manufacturing parameters on the strength of PLA parts using Layered Manufacturing technique: A statistical approach. *IOP Conference Series: Materials Science and Engineering, 310*(1), 1-10.

Chu, C., Graf, G., & Rosen, D. W. (2008). Design for additive manufacturing of cellular structures. *Computer-Aided Design and Applications, 5*(5), 686-696.

Chua, C., Feng, C., Lee, C., & Ang, G. (2005). Rapid investment casting: direct and indirect approaches via model maker II. *The International Journal of Advanced Manufacturing Technology, 25*(1-2), 26-32.

Cormier, D., Harrysson, O., & West, H. (2004). Characterization of H13 steel produced via electron beam melting. *Rapid Prototyping Journal, 10*(1), 35-41.

Corney, J., Masood, S., & Song, W. (2005). Thermal characteristics of a new metal/polymer material for FDM rapid prototyping process. *Assembly Automation, 25*(4), 309-315.

Cui, X., Boland, T., D D'Lima, D., & K Lotz, M. (2012). Thermal inkjet printing in tissue engineering and regenerative medicine. *Recent patents on drug delivery & formulation, 6*(2), 149-155.

De Gans, B. J., Duineveld, P. C., & Schubert, U. S. (2004). Inkjet printing of polymers: state of the art and future developments. *Advanced materials, 16*(3), 203-213.

De Jong, J. P., & De Bruijn, E. (2013). Innovation lessons from 3-D printing. *MIT Sloan Management Review, 54*(2), 43.

Dodziuk, H. (2016). Applications of 3D printing in healthcare. *Kardiochirurgia i Torakochirurgia Polska, 13*(3), 283-293.

Farah, S., Anderson, D. G., & Langer, R. (2016). Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review. *Advanced drug delivery reviews, 107*, 367-392.

Feixiang, Z., Liyong, Z., & Xia, K. (2016). Study of impact of 3D printing technology and development on creative industry. *Journal of social science studies, 3*(2), 57.

Fernandes, J., Deus, A. M., Reis, L., Vaz, M. F., & Leite, M. (2018). Study of the influence of 3D printing parameters on the mechanical properties of PLA. *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018)*, 547-542.

Forster, A. M. (2015). *Materials testing standards for additive manufacturing of polymer materials* (Report No. 8059). Department of Commerce, US: National Institute of Standards and Technology.

Frazier, W. E. (2014). Metal additive manufacturing: a review. *Journal of Materials Engineering and Performance, 23*(6), 1917-1928.

Galantucci, L., Lavecchia, F., & Percoco, G. (2009). Experimental study aiming to enhance the surface finish of fused deposition modeled parts. *CIRP Annals-Manufacturing Technology, 58*(1), 189-192.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design, 69*, 65-89.

Getschmann, C. (2013). 3D Printing: Technology and Applications. *Proceedings of the 5th Seminar on Research Trends in Media Informatics*, 91-98.

Gibson, I., Rosen, D., & Stucker, B. (2015). Development of additive manufacturing technology. *Additive manufacturing technologies*, 19-42. New York, NY: Springer.

Gkartzou, E., Koumoulos, E. P., & Charitidis, C. A. (2017). Production and 3D printing processing of bio-based thermoplastic filament. *Manufacturing Review, 4*(1), 14.

Griffey, J. (2017). 3-D Printers for Libraries. *Library Technology Reports, 53*(5), 1-31.

Griffiths, Howarth, J., De Almeida-Rowbotham, G., & Rees, A. (2016). A design of experiments approach to optimise tensile and notched bending properties of fused deposition modelling parts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230*(8), 1502-1512.

Griffiths, C., Howarth, J., Rowbotham, G. d.-A., & Rees, A. (2016). Effect of build parameters on processing efficiency and material performance in fused deposition modelling. *Procedia CIRP, 49*, 28-32.

Gross, B. C., Erkal, J. L., Lockwood, S. Y., Chen, C., & Spence, D. M. (2014). Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. *Analytical Chemistry, 86,* 3240-3253.

Grünberger, T., & Domröse, R. (2015). Direct metal laser sintering. *Laser Technik Journal, 12*(1), 45-48.

Gunasekaran, A. (1999). Agile manufacturing: a framework for research and development. *International journal of production economics, 62*(1-2), 87-105.

Habeeb, H., Alkahari, M., Ramli, F., Hasan, R., & Maidin, S. (2016). Strength and porosity of additively manufactured PLA using a low cost 3D printing. *Proceedings of Mechanical Engineering Research Day 2016,* 69-70.

Hänninen, J. (2001). DMLS moves from rapid tooling to rapid manufacturing. *Metal Powder Report, 56*(9), 24-29.

Hofmeister, W., Wert, M., Smugeresky, J., Philliber, J. A., Griffith, M., & Ensz, M. (1999). Investigating solidification with the laser-engineered net shaping (LENSTM) process. *Jom, 51*(7), 1-6.

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology, 67*(5-8), 1191-1203.

International, A. (1997). *D-790-3, Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials*. West Conshohocken, PA: American National Standards Institute

International, A. (2005). *D256-04, Standard test method for determining the Izod pendulum impact resistance of plastics*. West Conshohocken, PA: American National Standards Institute

International, A. (2010a). *D638-14, Standard test method for tensile properties of plastics*. West Conshohocken, PA: American National Standards Institute.

International, A. (2010b). *D695-15: Standard Test Method for Compressive Properties of Rigid Plastics*. West Conshohocken, PA: American National Standards Institute.

Jamshidian, M., Tehrany, E. A., Imran, M., Jacquot, M., & Desobry, S. (2010). Poly-Lactic Acid: production, applications, nanocomposites, and release studies. *Comprehensive Reviews in Food Science and Food Safety, 9*(5), 552-571.

Junior, S. A. R., Ferracane, J. L., & Della Bona, A. (2008). Flexural strength and Weibull analysis of a microhybrid and a nanofill composite evaluated by 3-and 4-point bending tests. *Dental materials, 24*(3), 426-431.

Khaing, M., Fuh, J., & Lu, L. (2001). Direct metal laser sintering for rapid tooling: processing and characterisation of EOS parts. *Journal of Materials Processing Technology, 113*(1-3), 269-272.

Khan, S., Zakaria, H., Chong, Y., Saad, M., & Basaruddin, K. (2018). Effect of infill on tensile and flexural strength of 3D printed PLA parts. *IOP Conference Series: Materials Science and Engineering, 429*(1), 1-6.

Klosterman, D., Chartoff, R., Graves, G., Osborne, N., & Priore, B. (1998). Interfacial characteristics of composites fabricated by laminated object manufacturing. *Composites Part A: Applied Science and Manufacturing, 29*(9-10), 1165-1174.

Kruth, J.-P., Leu, M.-C., & Nakagawa, T. (1998). Progress in additive manufacturing and rapid prototyping. *Cirp Annals, 47*(2), 525-540.

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.

Laureto, J. J., & Pearce, J. M. (2018). Anisotropic mechanical property variance between ASTM D638-14 type i and type iv fused filament fabricated specimens. *Polymer Testing, 68*, 294-301.

Le, H. P. (1998). Progress and trends in ink-jet printing technology. *Journal of Imaging Science and Technology, 42*(1), 49-62.

Lee, Abdullah, J., & Khan, Z. A. (2005). Optimization of rapid prototyping parameters for production of flexible ABS object. *Journal of Materials Processing Technology, 169*(1), 54-61.

Lee, An, J., & Chua, C. K. (2017). Fundamentals and applications of 3D printing for novel materials. *Applied Materials Today, 7*, 120-133.

Letcher, T., & Waytashek, M. (2014). Material property testing of 3D-printed specimen in PLA on an entry-level 3D printer. *Advance Manufacturing, 2A*, 8.

Li, H., Wang, T., Sun, J., & Yu, Z. (2018). The effect of process parameters in fused deposition modelling on bonding degree and mechanical properties. *Rapid Prototyping Journal, 24*(1), 80-92.

Liao, Y., & Chiu, Y. (2001). Adaptive crosshatch approach for the laminated object manufacturing (LOM) process. *International Journal of Production Research, 39*(15), 3479-3490.

Lim, L.-T., Auras, R., & Rubino, M. (2008). Processing technologies for poly (lactic acid). *Progress in polymer science, 33*(8), 820-852.

Lužanin, O., Movrin, D., & 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), 49-58.

Mae, H., Omiya, M., & Kishimoto, K. (2008). Effects of strain rate and relaxation rate on elastic modulus of semi-crystalline polymer. *Transactions of JASCOME, 7*(2).

Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International journal of production economics, 149*, 194-201.

Mohamed, O. A., Masood, S. H., & Bhowmik, J. L. (2015). Optimization of fused deposition modeling process parameters: a review of current research and future prospects. *Advances in Manufacturing, 3*(1), 42-53.

Mpofu, T. P., Mawere, C., & Mukosera, M. (2014). The impact and application of 3D printing technology. *International Journal of Science and Research (IJSR), 3*(6), 2148-2152.

Mueller, B. (2012). Additive manufacturing technologies–Rapid prototyping to direct digital manufacturing. *Assembly Automation, 32*(2).

Murr, L. E., Gaytan, S. M., Ramirez, D. A., Martinez, E., Hernandez, J., Amato, K. N., & Wicker, R. B. (2012). Metal fabrication by additive manufacturing using laser and electron beam melting technologies. *Journal of Materials Science & Technology, 28*(1), 1-14.

Nugroho, A., Ardiansyah, R., Rusita, L., & Larasati, I. (2018). Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing. *Journal of Physics: Conference Series, 1130*(1),10.

Osakada, K., & Shiomi, M. (2006). Flexible manufacturing of metallic products by selective laser melting of powder. *International Journal of machine tools and manufacture, 46*(11), 1188-1193.

Othman, F. M., Abbas, T. F., & Basil, H. (2018). Influence of process parameters on mechanical properties and printing time of FDM PLA printed parts using design of experiment. *Journal of Engineering Research and Application, 8*(7), 65-69.

Park, J., Tari, M. J., & Hahn, H. T. (2000). Characterization of the laminated object manufacturing (LOM) process. *Rapid Prototyping Journal, 6*(1), 36-50.

Pham, D. T., & Gault, R. S. (1998). A comparison of rapid prototyping technologies. *International Journal of machine tools and manufacture, 38*(10-11), 1257-1287.

Pilipović, A., Raos, P., & Šercer, M. (2009). Experimental analysis of properties of materials for rapid prototyping. *The International Journal of Advanced Manufacturing Technology, 40*(1-2), 105-115.

Rabinskiy, L., Ripetsky, A., Sitnikov, S., Solyaev, Y., & Kahramanov, R. (2016). Fabrication of porous silicon nitride ceramics using binder jetting technology. I*OP Conference Series: Materials Science and Engineering, 140*(1),7.

Rajpurohit, S. R., & Dave, H. K. (2018a). Analysis of tensile strength of a fused filament fabricated PLA part using an open-source 3D printer. *The International Journal of Advanced Manufacturing Technology,* 1-12.

Rajpurohit, S. R., & Dave, H. K. (2018b). Tensile Properties of 3D Printed PLA under Unidirectional and Bidirectional Raster Angle: A Comparative Study. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, 12*(1), 6-11.

Roberson, D., Espalin, D., & Wicker, R. (2013). 3D printer selection: A decision-making evaluation and ranking model. *Virtual and Physical Prototyping, 8*(3), 201-212.

Saad, N., Al-Maamory, M., Mohammed, M., & Hashim, A. (2012). The effect of several service and weathering parameters on tensile properties of PVC pipe materials. *Materials Sciences and Applications, 3*(11), 784.

Savonen, B. L. (2015). *Criteria for Sustainable Product Design with 3D Printing in the Developing World*. (Master's thesis), Michigan Technological University, Michigan Tech.

Singh, R. (2011). Process capability study of polyjet printing for plastic components. *Journal of mechanical science and technology, 25*(4), 1011-1015.

Song, Y., Li, Y., Song, W., Yee, K., Lee, K.-Y., & Tagarielli, V. (2017). Measurements of the mechanical response of unidirectional 3D-printed PLA. *Materials & Design, 123*, 154-164.

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

Srivastava, V. (2017). A Reviev on Advances in Rapid Prototype 3D Printing of Multi-Functional Applications. *Science and Technology, 7*(1), 4-24.

Sun, & Karppi, R. (1996). The application of electron beam welding for the joining of dissimilar metals: an overview. *Journal of Materials Processing Technology, 59*(3), 257-267.

Sun, Rizvi, G., Bellehumeur, C., & Gu, P. (2008). Effect of processing conditions on the bonding quality of FDM polymer filaments. *Rapid Prototyping Journal, 14*(2), 72-80.

Thomas, D. S., & Gilbert, S. W. (2014). Costs and cost effectiveness of additive manufacturing. *NIST Special Publication, 1176*, 12.

Tian, X., Liu, T., Yang, C., Wang, Q., & Li, D. (2016). Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. *Composites Part A: Applied Science and Manufacturing, 88*, 198-205.

Torres, J., Cotelo, J., Karl, J., & Gordon, A. P. (2015). Mechanical property optimization of FDM PLA in shear with multiple objectives. *Jom, 67*(5), 1183-1193.

Tsouknidas, A., Pantazopoulos, M., Katsoulis, I., Fasnakis, D., Maropoulos, S., & Michailidis, N. (2016). Impact absorption capacity of 3D-printed components fabricated by fused deposition modelling. *Materials & Design, 102*, 41-44.

Turner, B. N., & Gold, S. A. (2015). A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyping Journal, 21*(3), 250-261.

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

Ventola, C. L. (2014). Medical applications for 3D printing: current and projected uses. *Pharmacy and Therapeutics, 39*(10), 704.

Wang, Gramlich, W. M., & Gardner, D. J. (2017). Improving the impact strength of Poly (lactic acid)(PLA) in fused layer modeling (FLM). *Polymer, 114*, 242-248.

Wang, Xi, J.-T., & Jin, Y. (2007). A model research for prototype warp deformation in the FDM process. *The International Journal of Advanced Manufacturing Technology, 33*(11-12), 1087-1096.

Wang, Zhou, Y., & Mallick, P. (2002). Effects of temperature and strain rate on the tensile behavior of short fiber reinforced polyamide-6. *Polymer composites, 23*(5), 858-871.

Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing. *ISRN Mechanical Engineering, 2012*, 10.

Wu, W., Geng, P., Li, G., Zhao, D., Zhang, H., & Zhao, J. (2015). Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS. *Materials, 8*(9), 5834-5846.

Xu, X., Meteyer, S., Perry, N., & Zhao, Y. F. (2015). Energy consumption model of Binder-jetting additive manufacturing processes. *International Journal of Production Research, 53*(23), 7005-7015.

Yu, D. M., Zhu, C. J., Su, J., & Wang, D. (2011). Process analysis and application for rapid prototyping based on fused deposition modeling. *Advanced Materials Research*, *179*, 875-880.

Zhong, W., Li, F., Zhang, Z., Song, L., & Li, Z. (2001). Short fiber reinforced composites for fused deposition modeling. *Materials Science and Engineering: A*, *301*(2), 125-130.

Zhou, X., Hsieh, S.-J., & Ting, C.-C. (2018). Modelling and estimation of tensile behaviour of polylactic acid parts manufactured by fused deposition modelling using finite element analysis and knowledge-based library. *Virtual and Physical Prototyping*, *13*(3), 177-190.

Ziemian, C., Sharma, M., & Ziemian, S. (2012). Anisotropic mechanical properties of ABS parts fabricated by fused deposition modelling. M. Gokcek (Ed.), *Mechanical engineering*, 159-180.