Influence of Build Orientation on Tensile and Flexural Strength of FDM Fabricated ABS Component

Anubhav, Rakesh Kumar, Shubhra Kamal Nandi,
and Anupam Agrawal

1 Introduction

Additive manufacturing is a rapidly growing manufacturing process having the enormous capability to make state-of-the-art products. It was developed in the 1980s, when Japan (Murutani), France (Andre et al.), and the USA (Masters and Hull) filed different patents on a similar concept describing fabrication of a 3D object by addition of material in a layer-by-layer manner. Further, different concepts of layer addition were developed and patented with time, which shows the potential and prospect of AM processes [1]. Initially, it was primarily used for prototyping because of the high initial cost of machinery and devices. FDM process is used to fabricate thermoplastic polymer parts through depositing heated molten material using extrusion process [2]. ABS is a lightweight thermoplastic with many applications in automotive hardware parts [3, 4], appliances, piping, etc. ABS is the most commonly used thermoplastic because of its high dimensional stability and low glass transition temperature [5]. Its peculiar property of having good adhesion to metal coating makes ABS a suitable candidate for various impact loading components [6].

Much research has already been carried out to investigate the FDM-printed polymer and plastic materials for different applications. Kristiawan et al. [7] have reviewed filament processing and printing parameters to fabricate PLA, ABS, and PP using the FDM process. The effect of different raster angles and infill density on strength and quality of FDM-printed ABS was studied [8] and concludes that the part fabricated at 55° raster angle with maximum infill density gives better mechanical strength. Hossain et al. [9] performed experimentation with different raster scan strategies to improve the mechanical properties of 3D-printed parts. Attempts to

---

Anubhav · R. Kumar · S. K. Nandi · A. Agrawal (✉)
Indian Institute of Technology Ropar, Rupnagar, Punjab 140001, India
e-mail: anupam@iitrpr.ac.in

R. Kumar
e-mail: 2017mez0023@iitrpr.ac.in

N. Ramesh Babu et al. (eds.), *Advances in Additive Manufacturing and Metal Joining*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-19-7612-4_15

determine the anisotropic material properties with the effect of FDM build parameters for ABS show that the strength in a local area depends on the scanning direction [9]. Hatch orientation and hatch area also have an appreciable effect on 3D-printed plastics [11]. FDM-printed ABS and HIPS specimens were tested for tensile impact test and compression test to study the effect of layer thickness on fracture morphology [12, 13]. The presence of voids and bonds between deposited filaments has a more significant influence on the FDM-fabricated parts [14, 15].

Based upon the literature, it has been observed that it is very critical to correctly estimate the mechanical properties of FDM printed parts to make them suitable for various applications. Hence, the present work has been aimed to test 3D-printed ABS material with different orientations along with the horizontal and vertical directions. The FDM-fabricated ABS specimens have been tested for tensile and flexural (3-point bend test) to study its modulus, yield strength, and strain-energy absorption of ABS for its suitability in aerospace and automotive industries. Microscopic images have been used to study the type of failure in the fabricated parts and compared with the stress–strain behavior.

2 Materials and Methodology

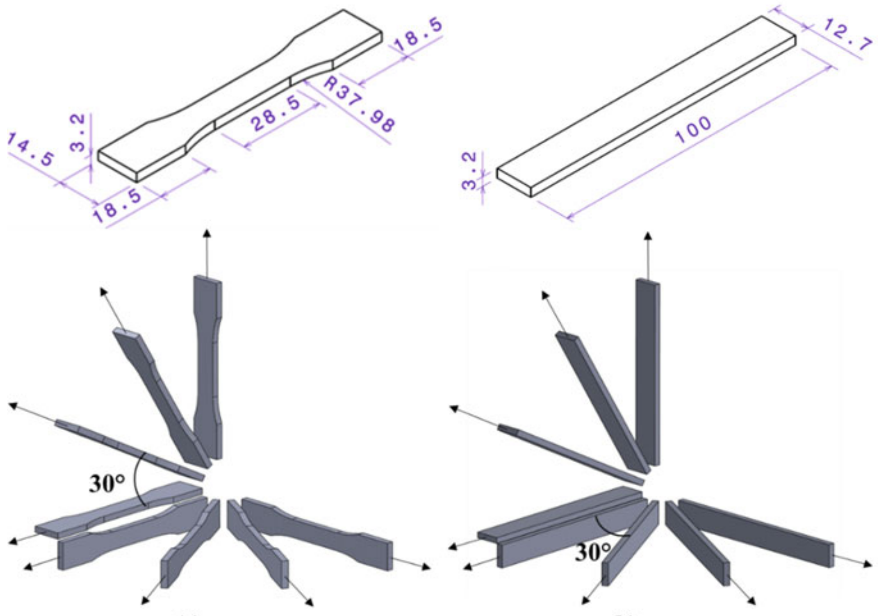
2.1 Materials and Part Fabrication

Acrylonitrile butadiene styrene (ABS), a thermoplastic, has a lot of real-life applications. Natural color ABSplus- P430 with SR-30 as support material is used to fabricate the required specimens using FDM-based Stratasys makes Mojo 3D printer. The 3D printer used specimen fabrication has a built volume of 127*127*127 mm^3. The process parameters used for the fabrication of the test specimen are as shown in Table 1.

The specimens used for tensile testing and flexural test (3-point bend Test) are fabricated as per Type-III, confirming ASTM D638-14 and ASTM D790 standard, respectively. The specimens were modeled using SOLIDWORKS® with specified dimensions, as shown in Fig. 1. The CAD model is then converted to STL format

Table 1 FDM material's property and process parameters used for the fabrication of specimen

Properties	Values
Density of ABS	1.05 g/cm^3
Melting point of ABS	230 °C
Nozzle temperature	200 °C
Platform temperature	70 °C
Infill density	100%
Layer thickness	0.17 mm
Filament diameter	1.75 mm



(a) (b)

Fig. 1 Specimen with dimensions and CAD model of 0–90° at a step of 30° oriented specimen in the horizontal and vertical direction **a** Tensile testing, **b** Flexural test (3-point bend) (All dimensions are in mm)

and then sliced using open-source slicing software CURA with a minimum layer thickness of 0.178 mm (minimum layer thickness printed by Mojo 3D printer) with 100% infill density. The specimens were fabricated at different orientation angles to understand the mechanical behavior and bonding of material during the deposition in FDM process. The study of FDM-fabricated specimens with different orientations will enable the understanding of the characteristics of layer deposition, which will be helpful to analyze and optimize the design of any part with inclined features. Hence, in this work, tensile and flexural specimens were fabricated at varying angles ranging from 0–90 degrees with a step of 30 degrees (Fig. 1).

2.2 Mechanical Characterization

The specimens fabricated at different orientation angles were tested to study the tensile and flexural behavior. Universal testing machine (Make-Tinius Olsen, Model-H50KS) was used for the testing with 50kN load cell. A deformation rate of 1 mm/min was maintained for the tensile and flexural tests until fracture, which was then analyzed under the optical microscope. The fracture behavior was observed with the help of optical microscopic image analysis. The required stress–strain values for FDM-fabricated ABS specimens were calculated for both the tests using the obtained force and displacement data from the UTM test by using respective formulae (Fig. 2);

$$\text{Tensile Stress }(\sigma_t) = \frac{\text{Force}(N)}{\text{Cross} - \text{Sectional Area}\left(\text{mm}^2\right)} \tag{1}$$

$$\text{Strain }(\varepsilon) = \frac{\delta l}{L} \tag{2}$$

$$\text{Flexural Stress}(\sigma_b) = \frac{3FL}{2bt^2} \tag{3}$$

$$\text{Flexural Strain }\left(\varepsilon_f\right) = \frac{6t\delta}{L^2} \tag{4}$$

$$\text{Modulus} = \frac{\text{Stress}}{\text{Strain}} \tag{5}$$

$$\text{Strain Energy Density }(u) = \int_0^{\varepsilon} \sigma_t d\varepsilon \tag{6}$$

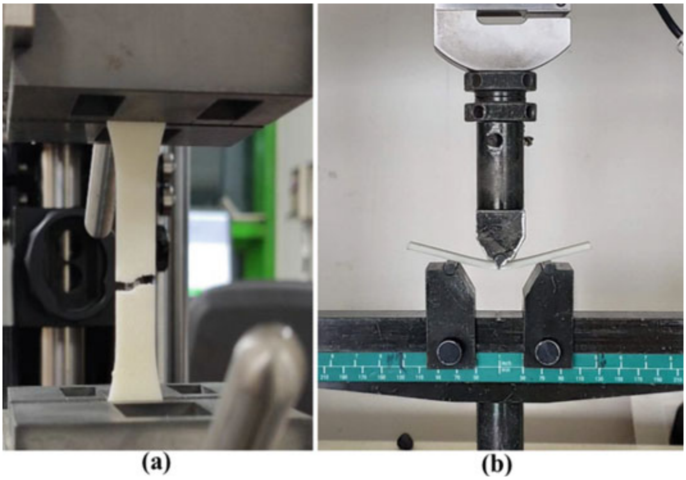


Fig. 2 Testing of FDM-fabricated specimen under different conditions **a** Uniaxial tensile test, **b** 3-point bend test

3 Results and Discussion

3.1 *Uniaxial Testing*

In total, three sets of ASTM standard tensile specimens of each category were 3D printed and tested to determine the mechanical properties. Deformation rate has a considerable effect in determining the stress–strain behavior; hence, a moderate rate of 1 mm/min was used to perform the tensile test experiment. Figure 3a shows the stress–strain plot for the vertically oriented specimens. The results indicate that the vertically printed parts have less plastic flow and are prone to brittle failure. The horizontally oriented specimens show better plastic flow as compared to vertically oriented specimens with the exception of H_30° (Fig. 3b). The horizontal specimens undergo 20–22% elongation before fracture, whereas the vertically aligned specimen is strained about 12–16% only. Hence, the horizontal specimen can withstand more stress as compared to vertically printed specimens.

Figure 4 represents the young's modulus and yield strength of the tested specimens, respectively. The young's modulus values were plotted and fitted with a second-order polynomial to correlate with the orientation angle (Fig. 4a). The modulus values increase with orientation angle for vertical specimens, whereas the horizontal specimen shows the highest modulus for 60° specimen. The yield strengths were calculated using 0.2% offset method for all the specimens. The yield strength of the vertical specimen represents a decreasing trend with an increase in orientation angle, while for horizontal specimen, it is maximum for a 90° oriented specimen (Fig. 4b). It indicates that the horizontally oriented specimens have better bond strength as well as they undergo more plastic deformation (more ductility) as compared to vertical specimens. As the deposition pattern for vertical and horizontal specimens are different hence the orientation of deposited filament has a more significant influence on part strength. In a horizontal specimen, the load is acting along the direction of deposited filament, whereas it is in the transverse direction for the vertical specimens (Fig. 5).

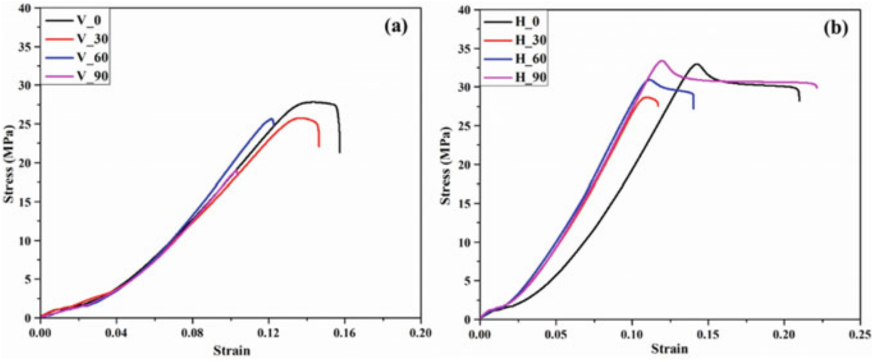


Fig. 3 Tensile stress versus strain plot for horizontal and vertical oriented FDM printed specimen

As the angle increases in the case of the vertical direction, the area of deposition for an instant also keeps on decreasing, which ceases the flow of material during UTM tensile testing. Hence, vertical oriented has less strength under tensile loading compared to horizontal specimens.

In Fig. 6, strain energy is computed and plotted against the respective strains up to the fracture using Eq. 6. When compared between vertical and horizontal results, the horizontal specimens are found to have more energy storage capacity than the vertical ones under the same loading conditions. The strain energy stored by horizontal specimens is more (almost twice) than that of vertically built specimens. Strain-energy absorbed till the yield point has been represented (in the inset image of Fig. 6) to understand the behavior of specimens in the elastic range.

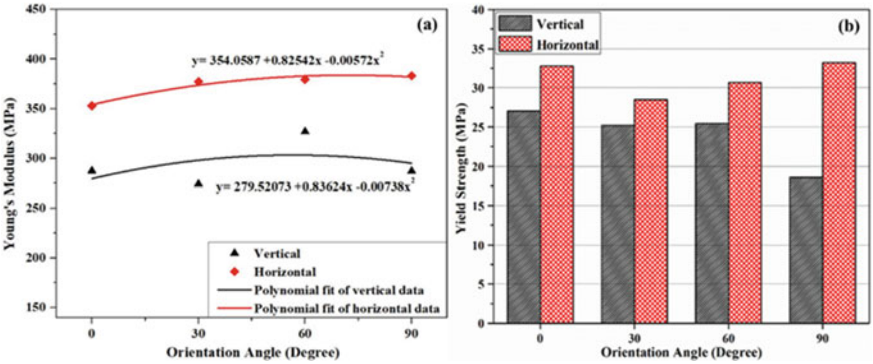


Fig. 4 Obtained results from stress–strain data for **a** Young's Modulus, **b** Yield Strength

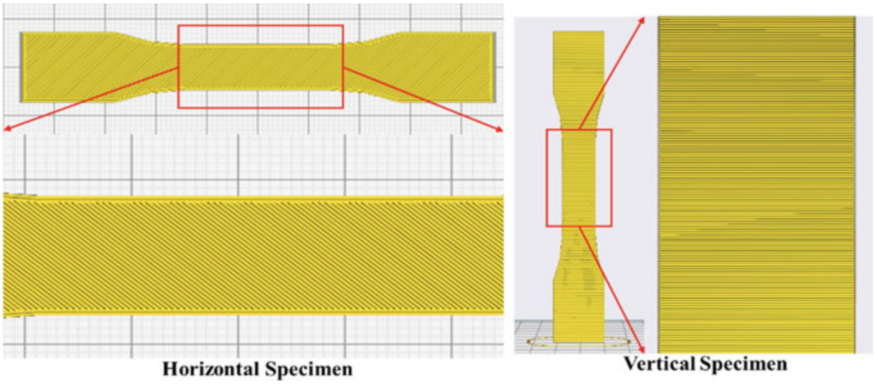


Fig. 5 Pattern of filament deposition in horizontal and vertical part printing

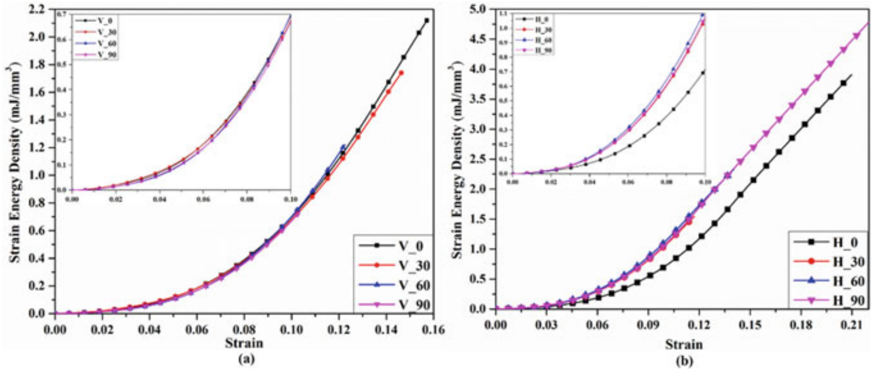


Fig. 6 Strain energy density obtained from tensile stress–strain data **a** Vertically oriented specimen, **b** Horizontally-oriented specimen

3.2 Flexural Testing

The 3-point bend test is the best method to measure the flexural properties under applied loading conditions. A set of 3-point bend test specimens were designed as per the ASTM D790 and 3D printed for further testing using ABS material. Like tensile test specimens, these specimens were fabricated in vertical and horizontal directions with a step of 30° angle. The specimens were tested at a velocity of 1 mm/min under 3-point load, and flexural modulus and flexural yield strength were calculated and compared (Fig. 8). The vertical specimen shows significantly less strain and flexural strength with increasing orientation angle (Fig. 7a), whereas in the horizontal specimen, the 0° and 90° specimen show approximately similar behavior.

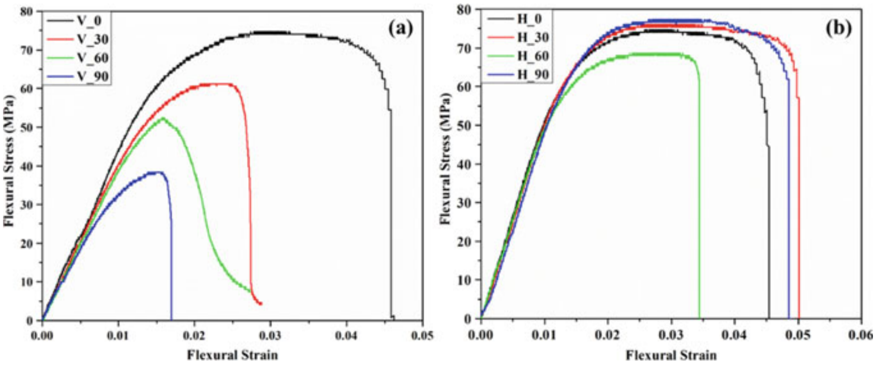


Fig. 7 Flexural stress–strain curve of vertically and horizontally oriented specimen

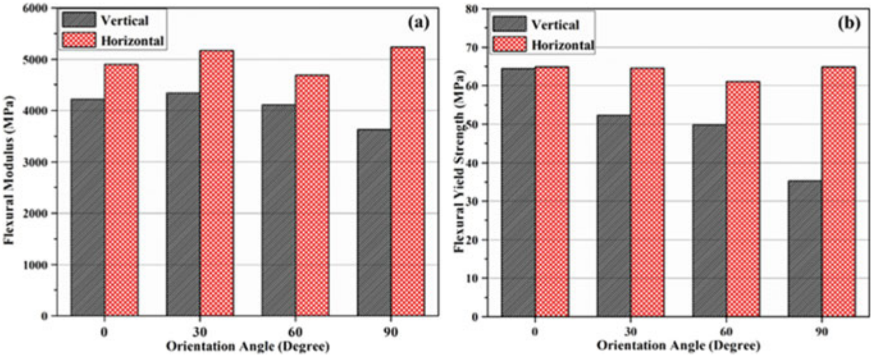


Fig. 8 Obtained results from Flexural stress–strain data for **a** Flexural Modulus, **b** Flexural Yield Strength

3.3 *Fractography*

Figure 9 represents the optical images of the fractured tensile specimens (for both vertical and horizontal orientations) to illustrate the type of failure that occurred in the specimen as it is clear that the outer peripheral layer for each specimen is fractured and tore off differently than the inner material. It happens due to the inherent fabrication constraint of the FDM process by printing the outer layer before filling the inner part in a defined scanning pattern. Fractographs of specimens of angle 0° and 30° with vertical show abrupt delamination of deposited filaments representing brittle failure. The 30° oriented horizontal specimen also shows a similar trend. Whereas in the case of 0°, 60° and 90° oriented horizontal specimens show material accumulation at the fractured zone, indicating ductile fracture. In a few cases (like V_60, H_0, H_60, and H_90), the accumulation of voids and crack formation is also visible, which explains the ductile fracture of the designed specimens.

4 Conclusion

The FDM process is the most versatile 3D printing process because of its ease to fabricate any customized part using thermoplastics for different applications. In the present work, it has been observed that the part orientation during printing plays a crucial role in its strength and behavior under different loading conditions. The obtained results show that the part orientation directly relates to material deposition and layering to bond the deposited material cohesively. Horizontally printed parts show qualitatively better tensile and flexural properties than the vertically printed specimens. For the horizontal specimens young's modulus and flexural modulus are about 350–385 MPa and 4.8–5.3 GPa, respectively, whereas for vertical specimen, it lies in the range of 275–325 MPa and 3.6–4.4 GPa, respectively. The obtained

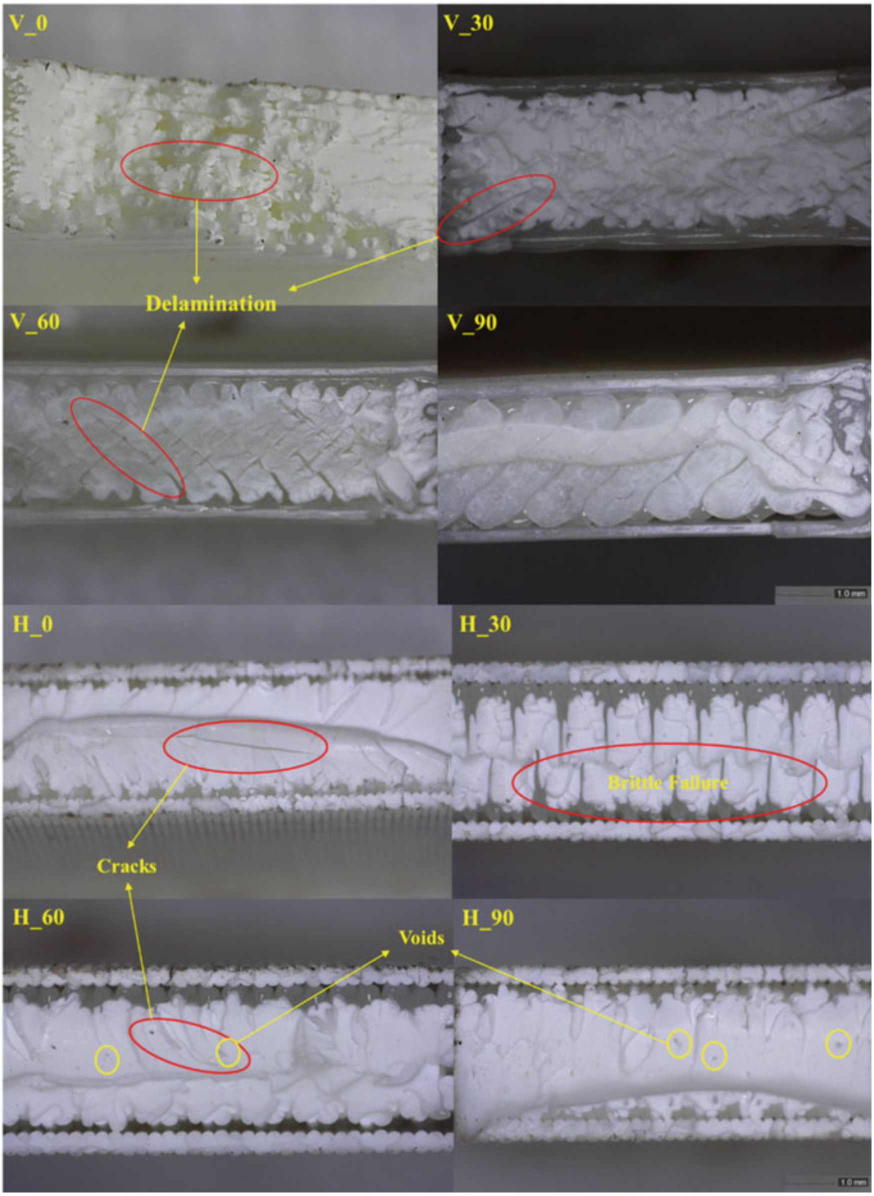


Fig. 9 Magnified optical images of the fractured surface of tensile specimens (scale bar −1.0 mm)

fractography indicates the modes of failure that occurred during tensile testing. This work will pave for future studies of complex geometries, metamaterial designing and optimal printing orientations.

References

1. Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D.: Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos. Part B Eng. **143**, 172–196 (2018). https://doi.org/10.1016/j.compositesb.2018.02.012
2. Singh, J., Chawla, K., Singh, R.: Applications of thermoplastic polymers in 3D printing. In: Reference Module Materials Science Materials Engineering, Elsevier, (2020). https://doi.org/10.1016/b978-0-12-820352-1.00010-9
3. Moore, J.D.: Acrylonitrile-butadiene-styrene (ABS)—a review. Composites **4**, 118–130 (1973). https://doi.org/10.1016/0010-4361(73)90585-5
4. Yadav, D.K., Srivastava, R., Dev, S.: Design and fabrication of ABS part by FDM for automobile application. Mater. In: Today Proceedings, vol. 26, pp. 2089–93. Elsevier, (2019). https://doi.org/10.1016/j.matpr.2020.02.451
5. Weng, Z., Wang, J., Senthil, T., Wu, L.: Mechanical and thermal properties of ABS/montmorillonite nanocomposites for fused deposition modeling 3D printing. Mater. Des. **102**, 276–283 (2016). https://doi.org/10.1016/J.MATDES.2016.04.045
6. Olivera, S., Muralidhara, H.B., Venkatesh, K., Gopalakrishna, K., Vivek, C.S.: Plating on acrylonitrile–butadiene–styrene (ABS) plastic: a review. J. Mater. Sci. **51**, 3657–3674 (2016). https://doi.org/10.1007/s10853-015-9668-7
7. Kristiawan, R.B., Imaduddin, F., Ariawan, D., Ubaidillah, Arifin, Z.: A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. Open Eng. **11**,639–49 (2021). https://doi.org/10.1515/eng-2021-0063
8. Selvamani, S.K., Samykano, M., Subramaniam, S.R., Ngui, W.K., Kadirgama, K., Sudhakar, K., et al.: Preliminary investigation of acrylonitrile butadiene styrene (ABS) properties. In: AIP Conference Proceedings, pp. 2059. (2019). https://doi.org/10.1063/1.5085983
9. Hossain, M.S., Espalin, D., Ramos, J., Perez, M., Wicker, R.: Improved mechanical properties of fused deposition modeling-manufactured parts through build parameter modifications. J. Manuf. Sci. Eng. Trans. ASME **136**, (2014). https://doi.org/10.1115/1.4028538
10. Ahn, S.H., Montero, M., Odell, D., Roundy, S., Wright, P.K.: Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyp J. **8**, 248–257 (2002). https://doi.org/10.1108/13552540210441166
11. Koch, C., Van Hulle, L., Rudolph, N.: Investigation of mechanical anisotropy of the fused filament fabrication process via customized tool path generation. Addit. Manuf. **16**, 138–145 (2017). https://doi.org/10.1016/j.addma.2017.06.003
12. Uddin, M.S., Sidek, M.F.R., Faizal, M.A., Ghomashchi, R., Pramanik, A.: Evaluating mechanical properties and failure mechanisms of fused deposition modeling acrylonitrile butadiene styrene parts. J. Manuf. Sci. Eng. Trans. ASME **139**, (2017). https://doi.org/10.1115/1.4036713
13. Mizera, A., Bednarik, M., Mizera, M., Tomanova, K., Mohorko, M.: Tensile impact behaviour of 3D printed parts on FFF/FDM printer Zortrax M200. In: MATEC Web Conference 2018, vol. 210, pp. 2–6. (2018).https://doi.org/10.1051/matecconf/201821004049

14. Gurrala, P.K., Regalla, S.P.: Part strength evolution with bonding between filaments in fused deposition modelling: This paper studies how coalescence of filaments contributes to the strength of final FDM part. Virtual Phys. Prototyp. **9**, 141–149 (2014). https://doi.org/10.1080/17452759.2014.913400
15. Rodriguez, J.F., Thomas, J.P., Renaud, J.E.: Characterization of the mesostructure of fused-deposition acrylonitrile-butadiene-styrene materials. Rapid Prototyp J. **6**, 175–185 (2000). https://doi.org/10.1108/13552540010337056