JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES (JMES)
ISSN: 2289-4659 e-ISSN: 2231-8380
VOL. 14, ISSUE 4, 7416 – 7423
DOI: https://doi.org/10.15282/jmes.14.4.2020.10.0584

ORIGINAL ARTICLE

Effect of raster inclinations and part positions on mechanical properties, surface roughness and manufacturing price of printed parts produced by fused deposition method

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ABSTRACT – Additive manufacturing (AM) technology has the ability to produce parts or products using data from 3D CAD models based on adding material. Fused deposition modeling (FDM) is among the most popular AM technologies wherein the plastic materials like acrylonitrile-butadiene-styrene filaments get added in the form of semi-molten plastic layers from bottom to top to produce the final product. Besides, the merits of using the FDM process, it faces challenges related to strength, dimensional accuracy, surface finish, and so on. The mechanical, tribological, and surface finish of functional parts is an essential consideration in FDM. In this work, the role of process parameters such as the part positions and raster inclinations involved in the manufacturing of parts by FDM has been evaluated experimentally to obtain the desired properties for reducing production time, the quantity of supporting material, and overall cost including maintenance costs. The study revealed that part position is a more significant parameter than the raster inclinations on the surface roughness and mechanical properties of the FDM parts. It also concludes with the proper values of part positions and raster inclinations for achieving optimal mechanical properties, roughness, and manufacturing costs to withstand operating loading conditions.

ARTICLE HISTORY
Received: : 02nd Feb 2019
Revised: 12th Mar 2020
Accepted: 15th May 2020

KEYWORDS
Surface roughness;
FDM;
mechanical properties;
manufacturing cost;
rapid prototyping

INTRODUCTION

In recent years, rapid product development without compromising quality, cost, or material resources required to remain competitive in the global market of manufacturing industries. The bringing of a product to the market swiftly reduced the time and material in the various processes involved [1]. Vibrant manufacturing techniques show the improvements of parts produced through AM (additive manufacturing) without employing a shaping tool. One of these AM technologies is fused deposition modeling (FDM) to build prototypes and finished parts [2, 3]. The conventional design process starts with the recognition of the need and ends with a prototype model but with consideration of the fact that industries have changed from traditional product development methodology to rapid prototyping (RP) techniques. As RP shows high potential to reduce the cycling time and product manufacturing cost, various processes of RP to accommodate different materials varying from plastics to metals, which exhibit the potentiality of rapid prototyping, and FDM technology is popular among this [4, 5]. The FDM process adds a thin fabric of the plastic layer from a filament heated into a semi-liquid state one at a time to make a prototype part. Extrusion takes place through a tiny hole onto either the base support material or the preceding plastic layer. Various advantages such as diversity of available material, quick material change, thin parts manufacturing, less maintenance cost, attaining a higher tolerance up to 0.1 mm without supervision, free from toxic substances, yields very condensed mass, and carry out operations at low-temperature. The drawbacks include irregular surface, a time-consuming operation, and limited size or volume [6].

The literature discloses that most of the work carried out is on the improvement of surface finish through optimization rather than dimensional tolerance, mechanical and tribological properties, and the cost of the process. The optimal set of FDM parameters for the best surface finish is studied [7-9]. Achieving the surface finish rather than strength is very difficult as the rough finish affects the functionality of the part [9, 10]. The fact that the rough surface is mainly produced by a stair-stepping formation leads to the uneven surface has become a severe issue with all layer forming production methods. In such cases, the small value of layer thickness is likely to generate a higher surface finish but increases the production time [11, 12]. Experimental probes on the significances of FDM input factors (layer height, part and raster angles, air gap, raster thickness, etc.) and their interactions on the dimensional accuracy of the parts produced were analyzed using Grey Taguchi's parameter design. The part orientation is significant along the length and width direction of the part as these parameters affect the results in an extremely non-linear behaviour. The forecasting of total geometrical correctness is carried out on the basis of an artificial neural network [13]. The literature mentioned above indicates that the large portion of the studies on various techniques to the declining of surface roughness (SR), geometrical tolerances, and improvement of mechanical properties (MP). Part orientation and production costs are essential factors in determining

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the effect of FDM [14, 15]. Proper part orientation in an FDM process would decrease the production time and material consumption. The performance analysis of the FDM parts such as dimensional accuracy and SR was carried out by the control parameters (contour width, internal raster, and layer thickness) of its production process on six test models including various features (slots, cube, cylinders, ring, and so on). Measurements were conducted using a coordinate measuring machine and surface tester [16]. The study of essential process factors (as mentioned before) have been studied on the MP (such as tensile, bending, and impact strength) of FDM produced parts.

Orientation and raster angles are vital parameters that affected the responses. Variable FDM using an additive manufacturing system provides the different nozzle diameter for the polymer to improve the print resolution and lay-up time. The manufacturing cost optimization for the connecting rod prototype was fabricated using FDM at multiple orientations between 00 to 900 and studied the variation in some layers, lay-up time, and material and supporting material. The effect of five-layer orientations of parts of ABS with FDM machine on tensile strength, modulus of rupture, and impact resistance have shown that the 0° orientation displays superior strength and impact resistance compared to other angles. The study aims to probe the influence of the built-up orientation and raster angles on the MP and total production cost. The results considered in this study are the MP of FDM produced parts such as bending strength, elongation, modulus, shrinkage volume, tensile strength and SR. The specimens prepared through ASTM standard at seven different raster inclinations (00, 150, 300, 450, 600, 750, and 900) for three-part positions (horizontal or along the x-axis, vertical or along y-axis and perpendicular or along the z-axis) by the FDM method.

METHODS AND MATERIALS

Tensile specimens with seven raster angles and three different part orientations produced using Acrylonitrile-butadiene-styrene (ABS+P430) of carbon-chain-copolymer type of styrene-terpolymer-chemical family (refer Figure 1). ABS possesses advantages of higher mechanical strength, low cost, and convenient for fabrication.

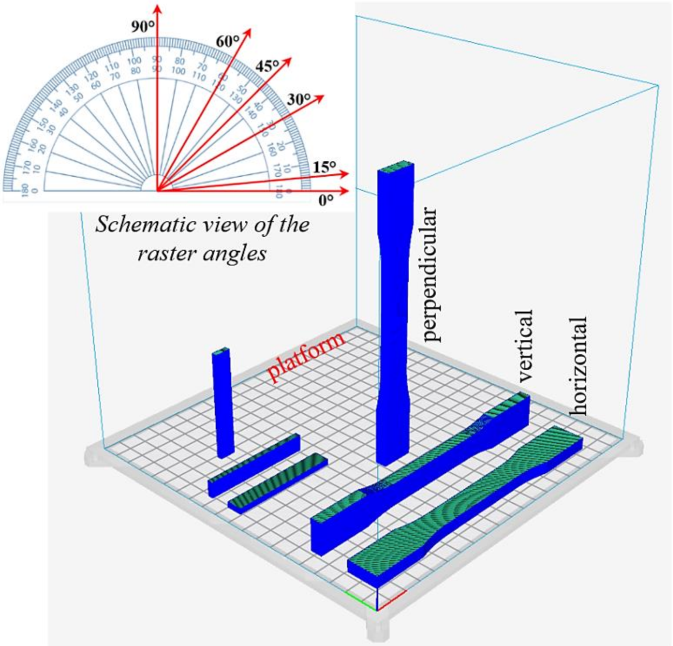

Figure 1. Printed part positions of a dog bone and 3-point bending and raster angles

The end-user FDM 3D printer used was a single-head Original Prusa I3 MK3 purchased from PRUSA RESEARCH, Prague, Czech Republic. Specimens built on substrates by adding ABS layers of 0.1 mm thick modeled in any CAD software exported as STL files with the part orientation and raster inclination shown in Figure 1. The synthetic thermoplastic polymer SR-30 is soluble support used as the base material. Mechanical properties namely, tensile strength, and three-point bending tests conducted according to ASTM D638 (having dimensions of 165 mm × 19 mm × 7 mm), and ASTM D790 (63 mm× 9.53 mm × 3.5 mm for three-point bending test), respectively as shown in Figures 2(a) and 2(b). The bending specimen supported at two-points 64 mm apart and centrally loaded with a spherical tool having a 5 mm nose radius at a constant crosshead speed of 2 mm/min. Figure 3 showed the printed parts of a dog bone (type I) and 3-point Bending, including the insight view of the infill density of 60% with a line infill pattern and crossed ±450 infill direction. The layer thickness was 0.1 mm, and the nozzle temperature was 2000C with a brass nozzle diameter of 0.6 mm with an aluminum oxide tip. All the experiments carried out using the Instron UTM machine (5900 Series) at room temperature. The SR was measured using a roughness tested in two directions of each tensile test sample (parallel and perpendicular to the drawing direction) on their top surface. In the tensile test, crosshead speed was at 1.0 mm/min. The ABS samples are comparatively weaker in strength in comparison to metals. Therefore, a more precise electromechanical UTM having a capacity of 100 KN with a load cell of 5 KN used for testing the samples [17].

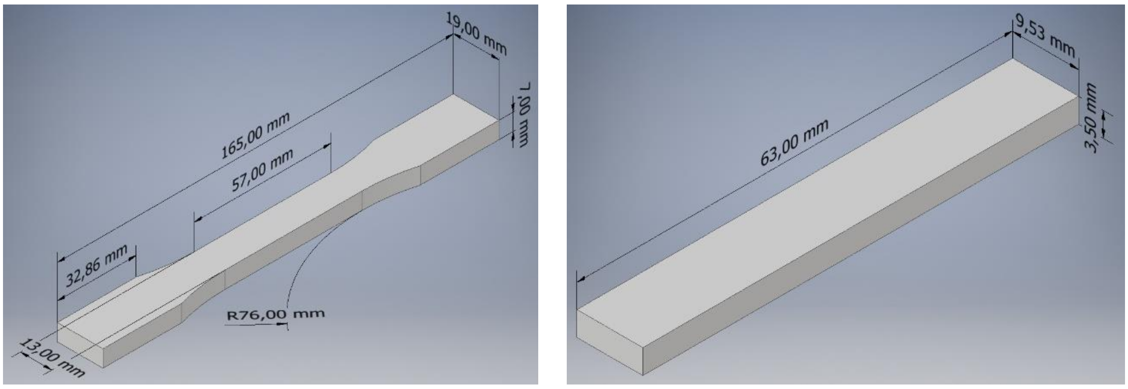

Figure 2. Test samples for the tensile test (left) and three-point bending test (right) produced by FDM 3D printer

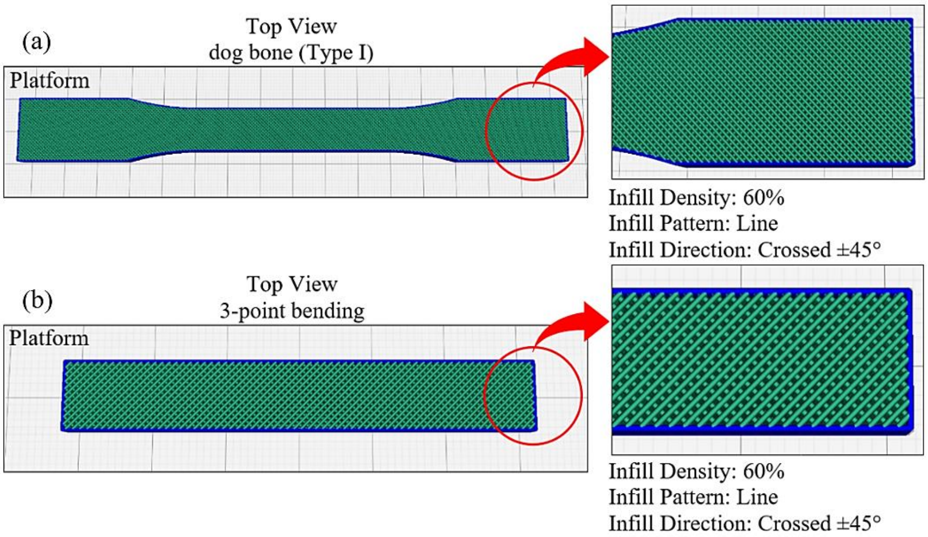

Figure 3. Process parameters like infill density, infill pattern and infill direction of: (a) dog bone (type I) and (b) 3-point bending

RESULTS AND DISCUSSION

The following results of the study present the effects of six raster angles and three-part orientations on the SR, flexural, and ultimate tensile strength and manufacturing cost.

Surface Roughness Evaluation

The surface roughness criterion helps in the assessment of the functionality of FDM parts, which are affected by the surface quality and are as important as the strength in the FDM parts. As regards the average values of surface roughness, R_a, the parameter was measured along and normal to the pull-out direction of a tensile test, as shown in Figures 4 and 5 drawn against the average value of the three-part position and six raster orientations of five test samples. The surface roughness, R_a, measurements in the normal direction were in contradiction of R_a measurements along the pull-out direction. The specimens built perpendicularly (placed along z-axis or normal to xy surface) position showing higher R_a value compared to all other specimens of R_a when measured along as well as normal to pull out the direction with the average R_a value of 19 µm. In the case of the x-axis or horizontal build specimens at 0° to 90° raster shows the almost same amount of R_a, whether it is measured along and normal to pull out directions. The Good surface was observed only in y-axis or vertical build specimens at 0^0 to 90^0 raster orientations when measured in the normal range to pull out the direction with an average R_a value of 2 µm. The effect of raster inclination on a given part position showed little changes in R_a value. With the increase in raster inclination (0^0 to 90^0 at a rate of 15^0), the surface roughness R_a value found to be decreasing as the fiber length with which the load gets distributed becomes smaller. If the part's surface shape is flat, then yields an excellent surface finish or otherwise it requires thorough investigation as regards the different surface shapes produced, such as stair-step to maintain the topology. Strength and surface quality are less dependent on each other for a given part position [18-19].

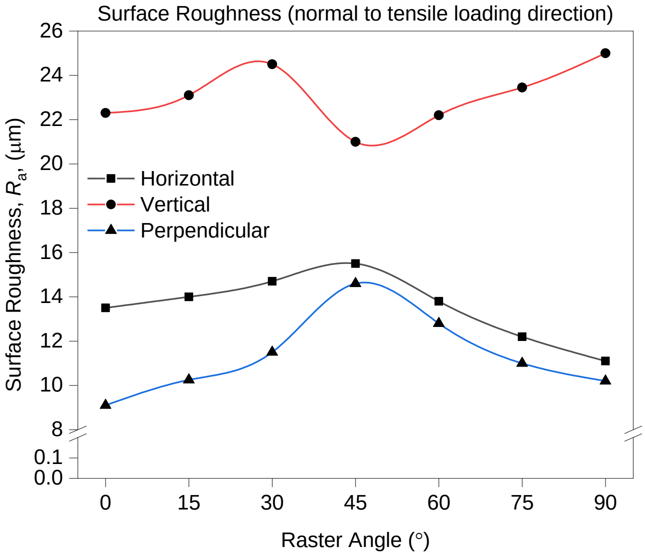

Figure 4. Surface roughness measured normal to the tensile loading direction

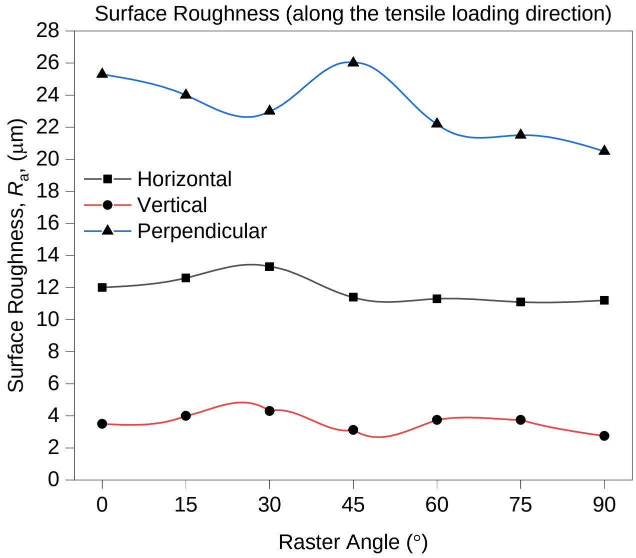

Figure 5. Surface roughness measured along the tensile loading direction

Tensile Test Evaluation

In this stage, ultimate tensile strength and elastic modulus of specimens prepared at different part position and raster inclinations are investigated and compared in Figure 6. There is a great deal of variation in the ultimate strength of specimens, and their limited variation is seen in elastic modulus concerning part positions [20]. The higher value of tensile strength and least elastic modulus are seen in part built with horizontal position compared to the other two-part positions of (vertical and perpendicular) built specimens. Figures 6, 7, and 8 also indicate that the build angular position appreciably influenced the tension properties of the FDM-processed parts. Superior ultimate strength was detected for specimen 00 raster inclination in horizontal and vertically built specimens offering low SR parameter R_a was measured along the pull-out direction. Both elastic modulus and ultimate strength found to increase significantly for the vertical part position at 00 raster angles. This is due to fibers being built densely following a line parallel to tensile strength, where a part exhibits flexibility as well as strong bonding when the load was applied. Therefore, different raster inclinations at which FDM parts produced demonstrate anisotropic strength properties depending on the part position. Especially, a perpendicular part positioned specimens exhibited very low mechanical properties. Results obtained are reliable because the raster angle decides the position of fibers along the cross-sectional area to determine the mechanical properties. The perpendicular part positioned built specimens shown a higher elastic modulus, but their tensile strength was significantly decreased by up to 35% and 45% from the vertical and horizontal part positioned built specimens, respectively. The highest elastic modulus and the ultimate tensile strength were obtained for a perpendicular part positioned at raster inclinations of 0^0 and 90^0, respectively.

Part position/orientation has a greater influence on the tensile strength as it allows the design to bear the tension loads axially along the fiber laid directions. In the above analysis, we have seen perpendicular part positioned samples that exhibited low strength with a higher risk of failure since the load was resisted by bonds between the fibers but not by the fibers themselves [21].

Flexural Strength Evaluation under 3-point Bending

The three-point bending test results were used for evaluating the flexural strength of the FDM samples by the application of loads that cause combined tensile and compressive stresses. The stress-induced in the specimen is more complicated to measure than that for the tensile test. For every raster orientation and part position, the flexural strength is found to be higher than the ultimate strengths especially, for the horizontal and vertical part positioned specimens compared to a perpendicular part position similar to the ultimate strength, as seen in Figure 6. Horizontal and vertical built specimens at 00 raster inclination exhibited high flexure strength as their fibers extruded in the direction along the bending plane. With the increase in raster inclination (00 to 900 at a rate of 150), the flexural strength was also found to be decreasing as the fiber length with which the load that could be distributed became smaller. For the normal to the plane (perpendicular) built specimens, the raster inclinations of 300 and 900 exhibited the highest flexural strength.

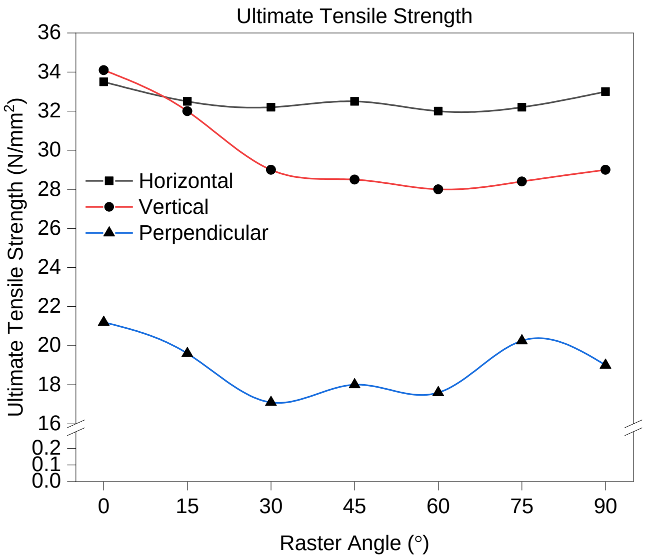

Figure 6. Ultimate tensile strength vs. raster orientations during the tensile test

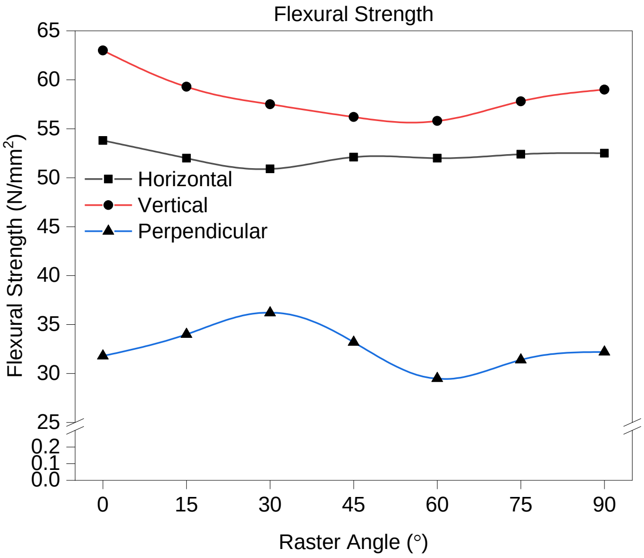

Figure 7. Flexural strength vs. raster orientations during the 3-point bending test

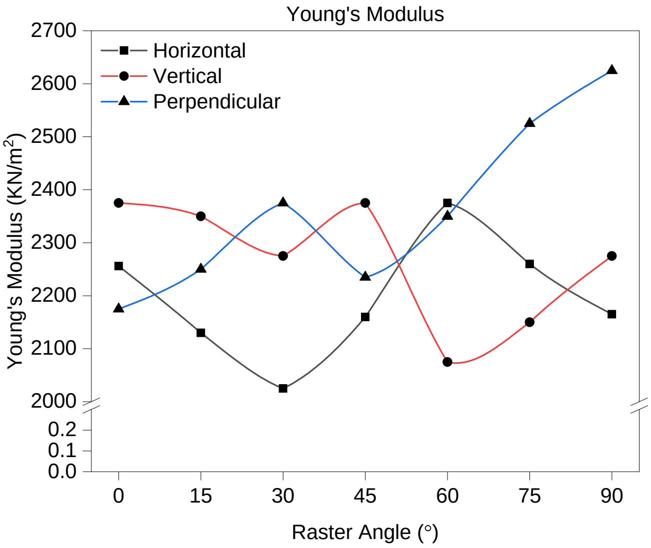

Figure 8. Modulus of elasticity vs. raster orientations during the tensile test

Production Cost

Based on the good mechanical properties of the specimen, support material, and build time, the production cost can be estimated because it varies extensively depending on the part position and height of the support. Many proposed techniques are available to reduce the production time either by depositing a less amount of material or by accelerating the part manufacturing method using internal and narrow-waisted structure to improve topology. Building time and quantity of supporting material are plotted in Figure 9, respectively. For the vertical part positioned specimens, it is seen that ultimate tensile strength decreased significantly as well as the quantity of support material. The highest ultimate strength is seen in the case of a vertical part positioned at 00 raster inclination taken at the highest quantity of support material and build time. The most favorable ultimate strength, build time, and quantity of support material was seen in the case of the horizontal part at raster inclination of 00 as shown in Figure 9(a). It is providing maximum strength, minimum time, and satisfactory support material, which had 3% less material compared to the vertical part at 00 and 90% support material higher than perpendicular part at 00 raster. Referring to Figure 9(b), the maximum flexural strength is seen at 00 raster of horizontal and vertical part positions and 300 rasters of perpendicular position-built parts. The horizontal built part at 00 raster showed 16% less than the vertical and 35% higher than the perpendicular part position. Taking production cost is more significant than the strength then the position of parts should be selected as to use minimum supported material in least production time. In this regard, the present study revealed that the specimens built in vertical position (for minimum support/ base material), and the specimen built in horizontal position (for least manufacturing time) as manufacturing time is closely associated to the number of layers [22].

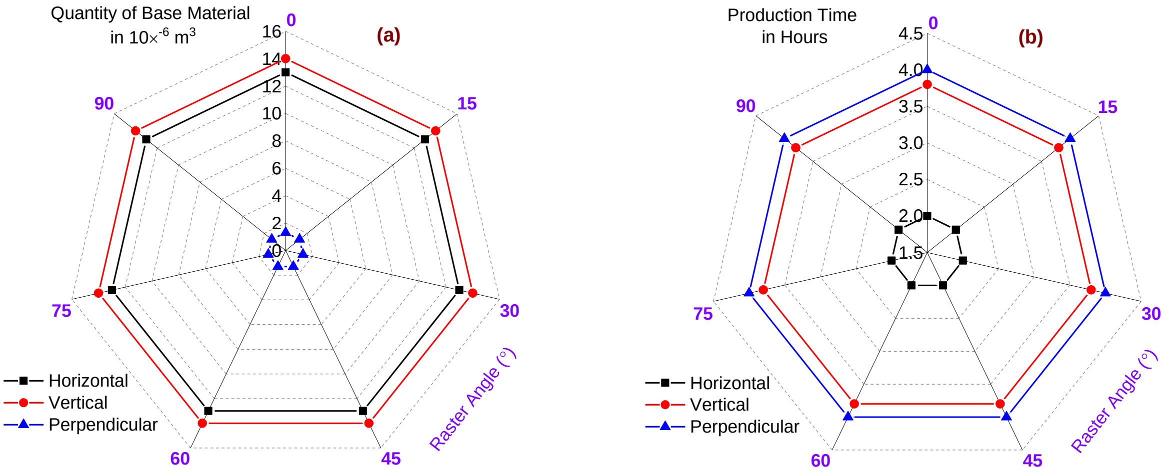

Figure 9. (a) Production time and (b) Amount of support material employed for FDM parts

CONCLUSIONS

Various mechanical properties such as strength (tensile and flexural) and SR of FDM parts studied experimentally under the influence of process parameters (raster angles and part orientations). Correspondingly manufacturing cost was evaluated regarding build time, support material quantity, and required mechanical property to build the relationship with process parameters of the FDM process. Both the process parameters influenced the mechanical properties and manufacturing costs to develop efficient products. Part position/inclination has shown a more considerable effect than the raster inclination on the SR and mechanical strengths of FDM parts. A well-established relationship exhibited between the SR and the mechanical strength (ultimate and flexural) for given process parameters followed the same pattern for roughness when measured along the pull-out direction of the tension test. In the case of part positions, perpendicular direction as regards the FDM parts positioned in the perpendicular direction did not perform well due to weak bonding between the fibers. The raster inclination of 00 had shown higher strength in every part position due to the availability of effective fiber lengths. To sum up, the parts build with a zero degree raster angle in the horizontal position produced an optimal MP and SR with an equivalent optimum manufacturing production time and cost.

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