EFFECT OF CUTTING STRATEGY ON MACHINING OF THIN WALLED POLYMER

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Abstract

This paper presents the effect of tool path on machining of thin walled thermoplastic polymer, ABS. The effects of cutting speed, feed rate and tool path are studied to evaluate surface quality on thin walled parts. Four different cutting pattern (“zig”, “zig-zag”, “follow periphery” and “trochoidal”) with uncoated WC tool were investigated in the cutting tests. The quality of grooves was examined by their surface roughness, dimensional accuracy and burr structure. Experiments show that the down-milling and “follow periphery” creates dimensionally more accurate grooves. Average 4 µm surface roughness and discontinuous chip formation is obtained in up-milling process. According to the study, the better surface quality and dimensional accuracy can be achieved by down milling in “zig-zag” pattern in terms of surface roughness.

Keywords: Polymer machining, tool path, thin wall

1 Introduction

Machining of polymers starts to play important role in industry in order to meet the demand of manufacturing of prototype parts. 3D printing is a popular rapid prototyping way to produce complex prototype parts. However, 3D printing process is more expensive than machining and also the material used in 3D printers is mostly not exactly same as the original material. By the help of the data taken from Arçelik AŞ, comparison between CNC and additive manufacturing is shown in Table 1. According to table, the products that machined at CNC show isotropic properties while additive manufacturing products show anisotropic properties. Most of the additive manufacturing techniques use materials like real but not the real ones. CNC machining is the most economical way of production when it is compared to additive manufacturing. After treatments can be easily applied for the CNC parts but they can be applied some of the additive manufacturing techniques. On the other hand, manufacturing of complex parts is easier with additive manufacturing. Most of the prototypes in house appliance have complex geometrical features and thin walls like detergent drawer. Because of the low elastic modulus and melting point, it is very difficult to maintain dimensional accuracy of machined parts. Machining parameters like cutting speed, feed, depth of cut, tool geometry and tool path are the main factors that affect the surface finish and dimensional accuracy. However, there are little information and investigation of polymer machining in literature. Alauddin et al investigated the general review of plastic machining [1].

	SLS	SLA	OBJET	FDM	CNC
Anisotropy	Isotropic	Isotropic	Isotropic	Isotropic	Anisotropic
Layer thickness / Surface roughness	100 µm	150 µm	33 µm	254 µm	-
Material	PA12	ABS like	PC like	ABS like	ABS and PC
After treatment capacity	Threading	-	-	Threading	Threading
Material Cost	25 X	60 X	90 X	60 X	1 X
Investment Cost	8 X	5 X	6 X	8 X	1 X
Dye capacity	Low	Medium	Good	Low	Good
Coating capacity	Low	Low	Low	Good	Good
Density	Medium	Low	Low	Medium	Good
Sealing	Low	Good	Good	Low	Good

Table 1: Comparison between CNC and additive manufacturing

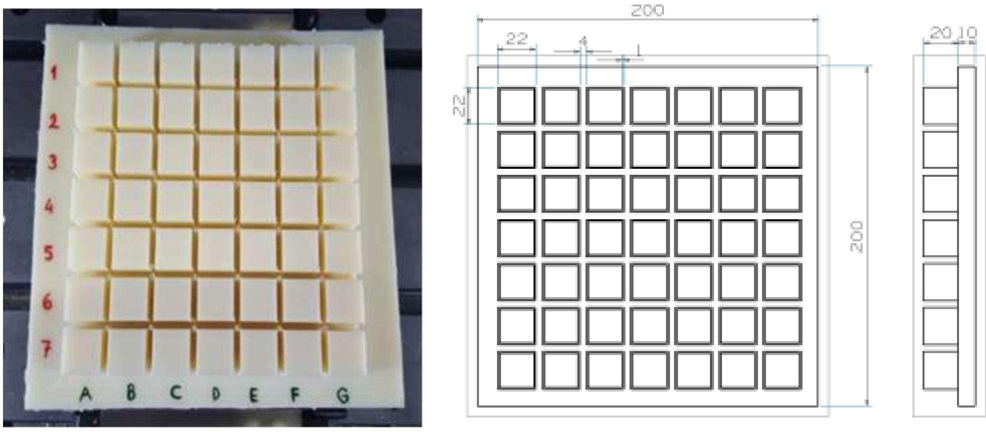
Tool geometry and cutting parameters are important factors on the machining of polymers. The effect of tool geometry is investigated by Izamshah [2]. The effect of cutting parameters in turning operation of polyethylene (PE) is investigated by Lazarević and the feed come out as the most important parameter [3]. Salles and Gonçalves studied the same topic on the ultra high molecular weight polyethylene and got the same results as Lazarević [4]. Arifin et al investigated the effects of CNC milling parameters on surface roughness on POM material [5]. Increase in cutting speed does not affect the surface roughness for polycarbonate (PC) material [6]. According to researches done by Ervine high cutting speed and feed results in blocking of chips go away [7]. Cooling strategies on polymers are so important and investigated by Aldwell), surface roughness results at the cryogenic conditions are better than the traditional ones [8]. Adiabatic shear bands will not occur under the glass transition temperature (Tg) theoretically [9]. Shih et al. researched improvement of surface roughness with the cryogenic cooling strategy [10].

Tool path is an another important factor on the surface roughness, according to Shamsuddin best tool path to obtain good surface roughness is parallel spiral and the worst tool path is true spiral [11]. According to Jabbaripour transversal inward tool path creates the best surface roughness and longitudinal outward creates the worst surface roughness on thin walled aluminum parts [12]. Corner machining in pocket milling is investigated by Choy and Chan, single loop strategy or double loop strategy should be applied to corners because it reduces the cutting forces according to their research [13]. Furthermore, radial path from floor to top of the surface gives the best surface quality on the form surfaces [14].

In this paper, effect of tool path and cutting parameters are studied. Experimental setup for workpiece, machine and tool paths are introduced. Then experimental results for surface roughness, wall thickness and burr formation are presented.

2 Experimental Setup and Design

In this study, acrylonitrile butadiene styrene (ABS) polymer was used as a workpiece material. The ABS has in the range of 25-65 MPa tensile strength, 1208-1939 MPa elastic modulus [15]. ABS test plate, 200 mm in length, 200 mm in width and 30 mm in thickness, were used for milling tests as shown in Figure 1, Grooving was applied to get 22x22x20 mmxmmxmm square blocks on the specimen. Pocket milling was performed to 20x20 mmxmm area in order to obtain square blocks which has 1 mm wall thickness. There are 49 square blocks on the ABS plate and the clearance between each block is made as 4 mm.



(a) (b)

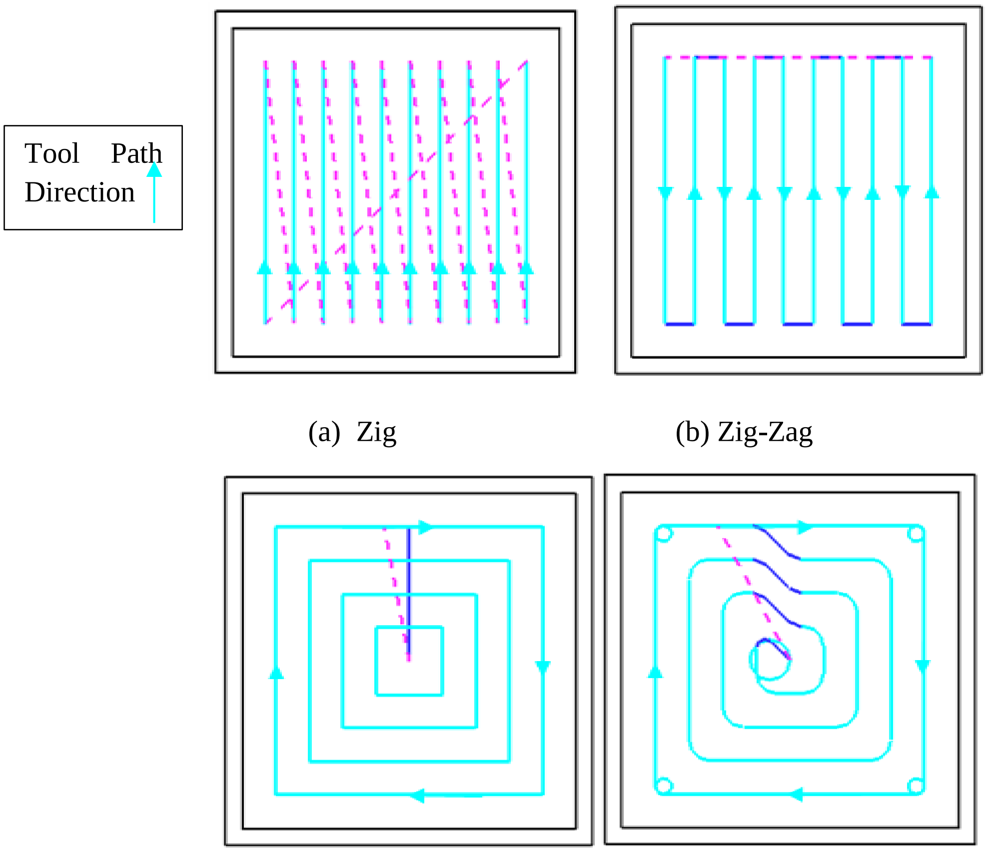
Figure 1: (a) Optical image of the test specimen, (b) Test specimen dimensions.

A 4 mm diameter, two flutes uncoated tungsten carbide end mill, as shown in Figure 2, is used in the milling tests (SECO – 99040-F). Maximum cutting depth is 8 mm and full length of end mill is 50 mm.

Figure 2: End milling cutter.

Cutting tests were conducted on 3 axes Mikron VCE 1000Pro CNC vertical machining center that has 16000 rpm spindle speed. Air was used to cool workpiece and take the chip away from cutting zone.

Surface roughness and dimensional accuracy in thin walled ABS polymer machining were examined in this paper. Cutting speed, feed and tool path were chosen as parameter that effect the surface roughness and dimensional accuracy. The level of chosen parameters is summarized in Table 2. All tests were repeated three times and total 48 tests were run. Four tool paths, “Zig”, “Zig-Zag”, “Follow Periphery” and “Trochoidal”, were chosen which are shown in Figure 3. Cutting speeds of these experiments are set as 100 m/min and 200 m/min. Feed per revolutions per tooth are chosen as the suggested value from tool manufacturer’s table 0.05 mm/rev/tooth and 0.3 mm/rev/tooth. Radial and axial depth of cut are kept constant as 2 mm. Each square boxes were investigated in terms of wall thickness, surface roughness and burr formation.



(a) Zig (b) Zig-Zag

(c) Follow periphery (d) Trochoidal

Figure 3: Four different tool paths in this experiment.

Cutting Strategies	Zig, Zig-Zag, Follow Periphery, Trochoidal
Vc (m/min)	100, 200
f (mm/rev)	0.1, 0.6
ap (mm), ae (mm)	2

Table 2: Cutting parameters.

The machined surface morphology was examined by using optical profilometer that is shown in Figure 4a (Bruker ContourGT). Surface roughness of parts and 3D scan of the surface images were obtained for 8x8 mm square. In order to control dimensional accuracy of wall thickness, GOM Atos 3D scanner was used which is shown in Figure 4b. Dimensional accuracy of wall thickness was investigated with respect to DIN ISO 2768-1 Standard (given in Table 3).

(a) (b)

Figure 4. (a) Bruker ContourGT optical profilometer, (b) GOM Atos 3D Scanning Technology

	Tolerance Limits (mm)							
Tolerance Range	0,5-3	3-6	6-30	30-120	120-400	400-1000	1000-2000	2000-4000
Tolerance	± 0,1	± 0,1	± 0,2	± 0,3	± 0,5	± 0,8	± 1,2	± 2

Table 3: Tolerance Limits according to the DIN ISO 2768-1 Standard.

3 Results

3.1 Surface Roughness

In order to measure surface roughness by optical profilometer, all walls were cut 1 mm above the bottom surface of machined wall. Surface roughness was measured in 8 mm^2 area on wall surface. Measured average surface roughness values are summarized in Figure 5. First part of the X axes shows the cutting speed (m/min) and the second part shows feed value (mm/rev) in Figure 5.

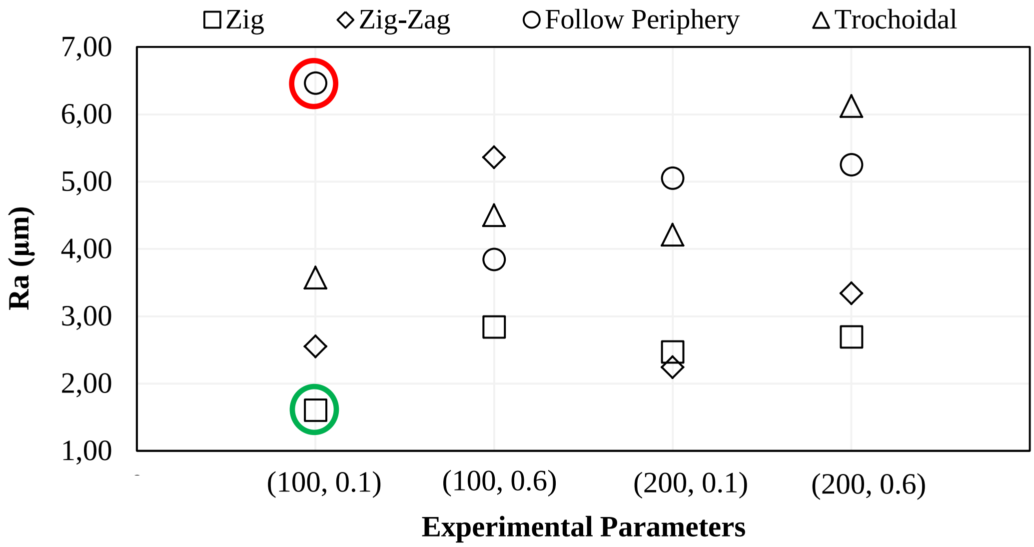


Figure 5: Comparison of surface roughness of different tool paths.

According to their surface roughness value, best tool path that created best surface roughness was “zig” cutting strategy. On the other hand, “follow periphery” tool path created the worst surface roughness result. While best surface was achieved with 100 m/min cutting speed and 0.1 mm/rev feed cutting parameters, worst surface was obtained with the same cutting parameters. This shows that tool path has an important effect on surface roughness.

Best surface roughness value which is 1.6 µm is obtained in “zig” tool path with 100 m/min cutting speed and 0.1 mm/rev feed. The worst surface roughness value (2.84 µm) in “zig” tool path is obtained with 100 m/min cutting speed and 0.6 mm/rev. The value of surface roughness was increased by 77% due to 6 times increase in feed values. In “zig” tool path, increase in cutting speed with low feed value causes rise in surface roughness. Also increase in feed value causes higher surface roughness results. Furthermore, high feed with same cutting speed creates higher surface roughness. This effect can be seen on the Figure 5.

In “zig-zag” tool path while best surface roughness (2.24 µm) is achieved by 200 m/min cutting speed and 0.1 mm/rev feed, the worst result of surface roughness (5.63 µm) is obtained with 100 m/min cutting speed and 0.6 mm/rev feed. In “zig-zag” tool path, best result was achieved at high cutting speed and low feed. Increase in cutting speed causes lower surface roughness, however increase in feed value results with higher surface roughness. To achieve better surface finish with “zig-zag” cutting strategy, cutting speed should be high.

By using “follow periphery” cutting strategy, the best surface roughness value (3,84 µm) is achieved with 100 m/min cutting speed and 0.6 mm/rev feed. Whereas the worst surface roughness result (6.46 µm) is obtained with 100 m/min cutting speed and 0.1 mm/rev feed in “follow periphery” tool path. But this result is outliner and will be neglected. Best surface roughness result was achieved at low cutting speed and high feed in “follow periphery” tool path. Increase in feed should cause increase in surface roughness at low cutting speed but it does not effect on high cutting speed.

In “trochoidal” tool path, the best result of surface roughness (3,57 µm) is achieved with 100 m/min cutting speed and 0.1 mm/rev feed; on the other hand, the worst result of surface roughness (6.12 µm) is obtained with 200 m/min cutting speed and 0.6 mm/rev feed. In “trochoidal” cutting strategy, best surface was obtained with low cutting speed and feed values. Increase in cutting speed causes increase in surface roughness at both high and low feeds. Also increase in feed creates higher surface roughness value with both high and low cutting speeds.

Machining time of tool paths with the same rapid feed rate are given in Table 4. Although “zig” tool path has the lowest Ra value, “zig-zag” should be chosen as the tool path for surface roughness criteria. Because “zig” machining time was almost twice as the “zig-zag” machining time. The reason why “zig” machining time is bigger than the others is non-cutting moves. Importance of machining time in production is very high, so “zig-zag” cutting tool is more convenient for production.

	Zig	Zig-Zag	Follow Periphery	Trochoidal
Machining Time (min)	28:08	18:03	18:43	18:22

Table 4: Machining time of different tool path.

Whereas the best result of surface roughness (1.6 µm) is obtained while cutting 100 m/min cutting speed and 0.1 mm/rev feed and “zig” cutting pattern, the worst surface roughness (6.46 µm) was measured at same cutting parameters pair and “follow periphery” cutting pattern. When the comparison of average surface roughness is done, “zig” tool path stands out as having lowest surface roughness; on the other hand, “follow periphery” has the highest average surface roughness.

The surface roughness micrographs were taken which are given in the Figure 6. Partially homogenous tool path (75 %) was formed in “zig” tool path because of the different surface roughness value at the crossing of each pass. More homogeneous tool path which is around 85 % of all area was formed in “zig-zag” except at the walls just like the “zig” cutting strategy. Follow periphery was the least homogenous tool path which is 50 % because it formed different surface roughness results at the corners. “Trochoidal” cutting strategy did not provide homogenous tool path due to its trochoidal movements.

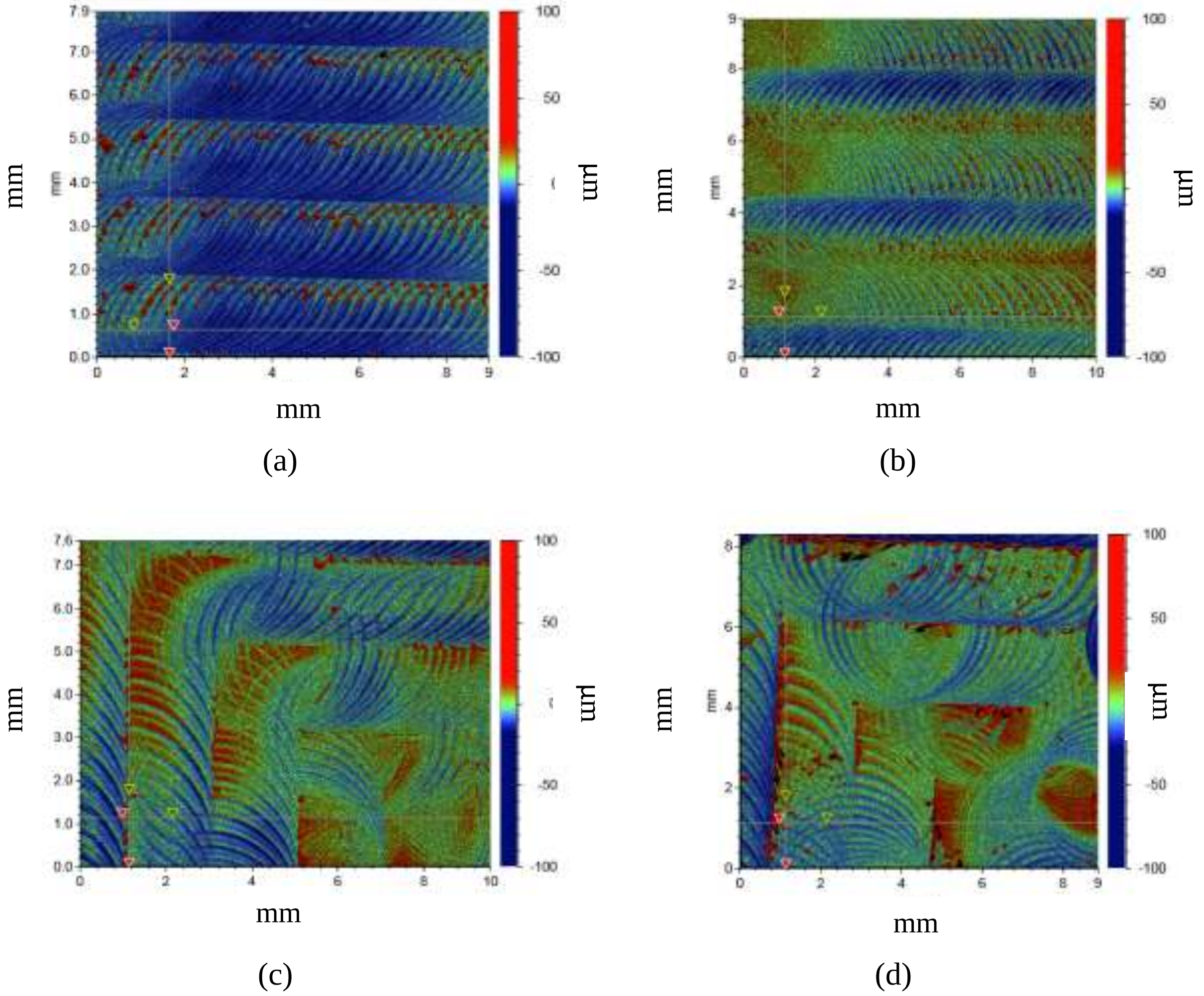


Figure 6: (a) Zig tool path, (b) Zig-Zag tool path, (c) Follow periphery tool path, (d) Trochoidal tool path.

3.2 Dimensional Accuracy

Dimensional accuracy was investigated by measuring wall thickness using 3D scanner. Each 22x22x30 mm machined boxes were removed from the workpiece in order to let the 3D scanner can measure all four walls. Measurements of wall thickness of each test are shown in Figure 7. In “zig” and “zig-zag” cutting, two walls were investigated because of the uncut regions on the entry and the exit surfaces. On the other hand, all four wall thickness were investigated for “follow periphery” and “trochoidal” tool path because they cut all of the walls smoothly.

Green zones in Figure 7 shows the wall thickness between acceptable ISO tolerance values which is ±0.1 mm. Red zones indicate the wall thickness over acceptable tolerance values (>0.1 mm), while blue zones show the wall thickness under acceptable tolerance values (<0.1 mm).

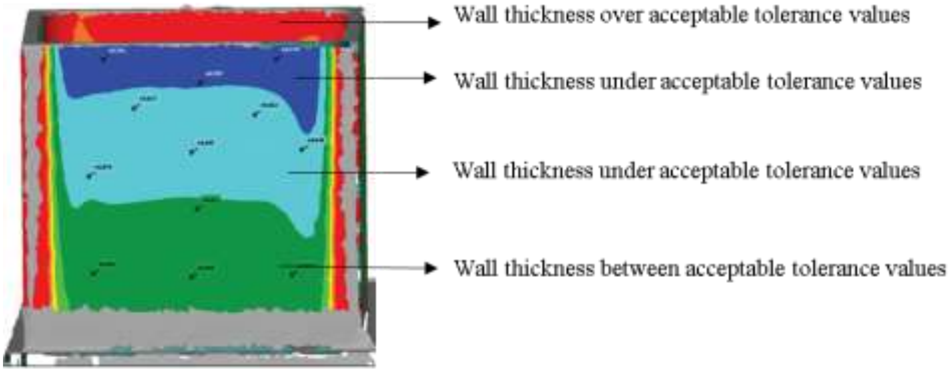


Figure 7: Designation of wall thickness image colors

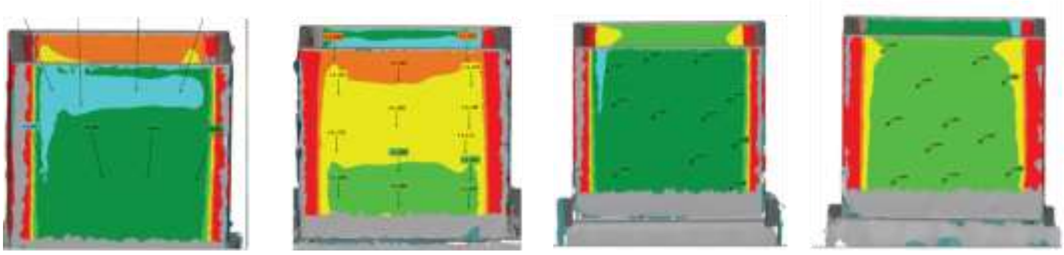
It can be seen that in Figure 8a, tight tolerances were achieved under 100 m/min cutting speed and 0.6 mm/rev feed in “zig” tool path. On the other hand, the worst results of wall thickness were obtained under 100 m/min cutting speed and 0.1 mm/rev feed. In “zig” tool path, best wall thickness values were achieved with low cutting speed high feed, while worst wall thickness values were obtained with low cutting speed and low feed. Increase in feed results with better dimensional accuracy, while increase in cutting speed result in less dimensional accuracy.

In “zig-zag” tool path (Figure 8b), At 200 m/min cutting speed and 0.1 mm/rev feed, less wall thickness deviation around 1 mm expected wall thickness; while the worst results were obtained under cutting parameters like 100 m/min cutting speed and 0.6 mm/rev feed. The best wall thickness results were achieved with high cutting speed low feed in “zig-zag” tool path. The worst wall thickness results were obtained with low cutting speed high feed value. Increasing the cutting speed in “zig-zag” tool path causes more uniform wall thickness, while increasing the feed results with decrease in dimensional accuracy.

In “follow periphery” cutting strategy (Figure 8c), surprisingly the best wall thickness results were obtained at highest level of feed (0,6 mm/rev) and 100 m/min cutting speed, however the worst results of wall thickness were obtained with 200 m/min cutting speed and 0.1 mm/rev feed cutting parameters. In “follow periphery”, low cutting speed and high feed resulted in the best wall thickness values. But high cutting speed and low feed resulted in the worst wall thickness values. While effect of feed was very minor at the low cutting speed, it created more dimensionally accurate walls at the high cutting speed with “follow periphery”. Increase in the cutting speed causes irregular wall thickness.

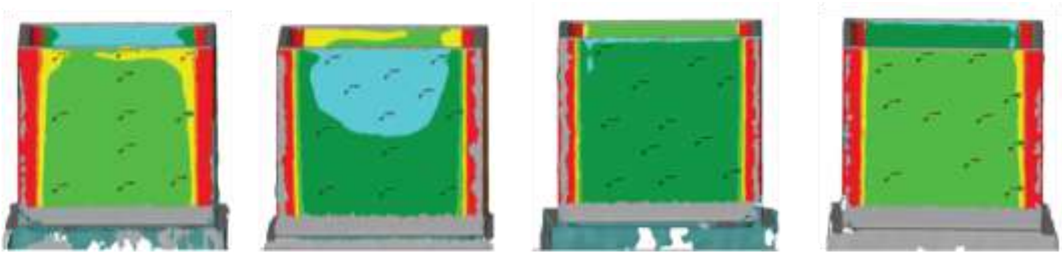
In Figure 8d, it can be seen that with “trochoidal” tool path, the steadiest wall thickness was achieved with cutting parameters like 100 m/min cutting speed and 0.1 mm/rev feed like “zig” cutting pattern; on the other hand, the worst result of wall thickness was obtained with 200 m/min cutting speed and 0.6 mm/rev feed. Cutting parameters like low cutting speed and low feed helped to achieve best wall thickness results in “trochoidal” tool path. On the other hand, high cutting speed and feed caused the worst wall thickness results. Increase in cutting speed causes decrease in dimensional accuracy. Also increase in feed results with worst wall thickness results.

When the dimensional accuracy is compared, best wall thickness values was achieved with “follow periphery” tool path, also the worst wall thickness value was obtained with “follow periphery” tool path. This shows that selection of cutting parameters are important in terms of dimensional accuracy.



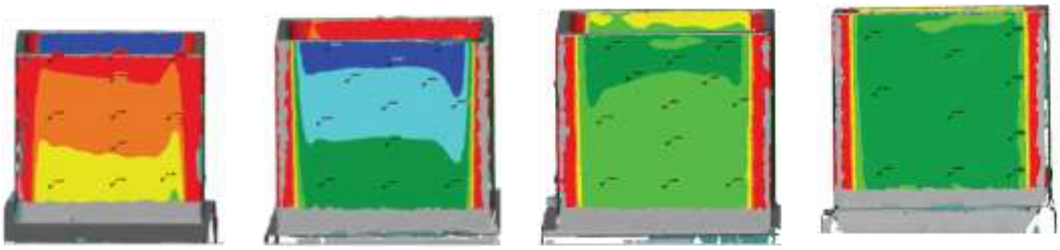
Zig 100 m/min 0.1 mm/rev   Zig 100 m/min 0.6 mm/rev

(a)



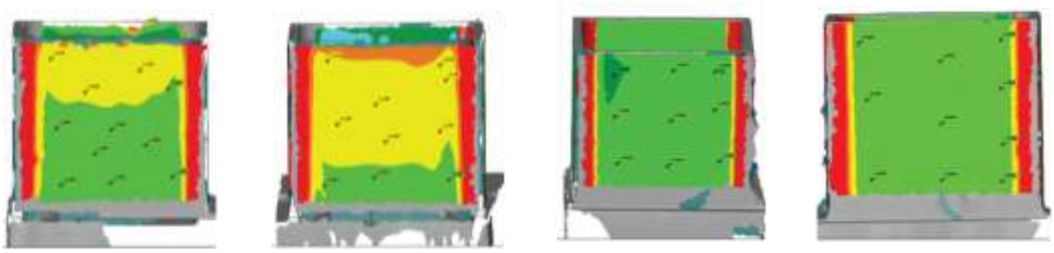
Zig-Zag 100 m/min 0.6 mm/rev   Zig-Zag 200 m/min 0.1 mm/rev

(b)



Follow Periphery 200 m/min 0.1 mm/rev   Follow Periphery 100 m/min 0.1 mm/rev

(c)



Trochoidal 200 m/min 0.6 mm/rev   Trochoidal 100 m/min 0.1 mm/rev

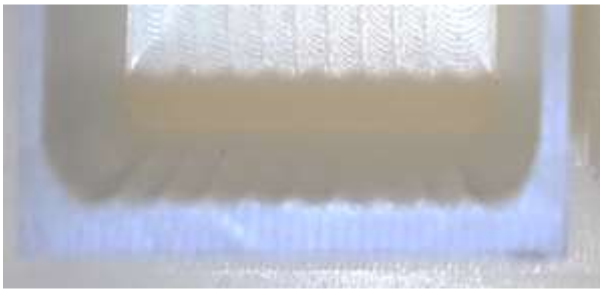
(d)

Figure 8: (a) wall thickness results of zig tool path, (b) wall thickness results of zig-zag tool path, (c) wall thickness results of follow periphery tool path and (d) wall thickness results of trochoidal tool path.

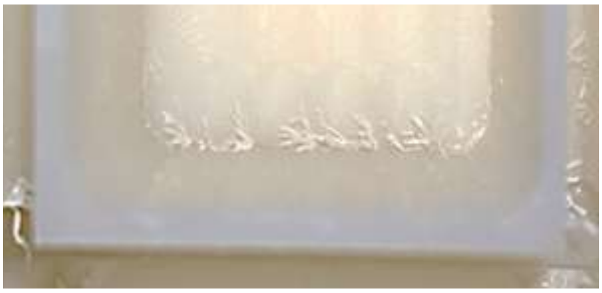
3.3 Burr Formation

Burr formation in all tool path is investigated visually. According to Figure 9, "zig" and "zig-zag" tool path left uncut areas at the walls. In "zig-zag" tool path, both up and down milling is occurred. Burr is formed through up milling direction. Because in up milling, tool pushes chip away from the workpiece. Because of the elastic properties of ABS chips do not cut off. However, in down milling, tool pushes chip to the workpiece that cause easily break the chips off (Figure 9b). Best result of burr formation is achieved by "follow periphery" tool path. Besides, there are no uncut areas in Figure 9c in contrast to "zig" and "zig-zag" tool path. "Trochoidal" (Figure 9d) tool path creates good burr formation on the walls; however, there are ruined regions on the bottom surface of the specimen because of the stuck chip on the tool surface.

Although "zig" and "zig-zag" tool paths created less surface roughness values, they left uncut areas on the walls. Furthermore, "zig-zag" tool path applies both up and down milling which result in burr structures on the up milling sides. "Follow periphery" is the best tool path for burr formation because it leaves no burrs on the surface. "Trochoidal" tool path is good for the wall machining, but it leaves burrs on the surface of the specimens.



(a) Zig tool path



(b) Zig-Zag tool path

(c) Follow Periphery tool path

(d) Trochoidal tool path

Figure 9: Burr formation of tool paths

4 Conclusions

Pocket milling of ABS materials with 4 different tool path such as "zig", "zig-zag", "follow periphery" and "trochoidal" are investigated in this paper. In terms of surface roughness, "zig" tool path creates the best surface roughness results, but "zig" tool path has the most machining time, it is so high with respect to other cutting strategies. On the other hand, "follow periphery" is the best tool path for achieving the best wall thickness results. Also "follow periphery" leaves no burr on the cutting surfaces. To achieve the best outcome, first "zig-zag" tool path can be applied to get best surface roughness, then "follow periphery" tool path can be applied to clean-up for the uncut areas of walls. Future works will focus on the tool path parameters above and to find optimum cutting parameters with those tool path. Furthermore, temperature and force analysis will be completed in the future works.

5 Acknowledgments

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6 References

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