Drilling of Additive Manufactured Poly Lactic Acid Modified by Drilling of Additive Manufactured Poly Lactic Acid Modified by Ultrasonic Vibration Ultrasonic Vibration

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Drilling of Additive Manufactured Poly Lactic Acid Modified by Ultrasonic Vibration

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Abstract

Complex geometries can be produced by using additively manufacturing method (AM). As usual, the AM parts have rough surfaces in which post processing operations are needed. One of the useful operations is ultrasonic drilling process. In this process, an additional movement is added to the cutting tool to improve the machinability factors. In this study, poly lactic acid(+) was selected as workpiece where the quality of the holes generated by ultrasonic drilling, were investigated. The examination parameters were delamination, circularity, and cylindricity. As a result, it was shown that UD process could properly improve the examination parameters. It was explained that harmonic movement of drill bit in UD improved the stability of the process by a decrease in cutting forces and chip adhesion. Moreover, a significant reduction was observed in delamination factor by using ultrasonic vibrations.

Keywords: Additive manufacturing; ultrasonic; PLA; delamination, circularity, cylindricity.

1. Introduction

Additive manufacturing (AM) refers to one of the manufacturing methods in which the final product is fabricated by adding a source of material based on the desired digital geometry [1, 2]. The AM approach is different from the reducing methods such as machining in which the material is removed from the original size. The fundamental difference between the decremental and incremental manufacturing methods has given rise to a number of new techniques and business opportunities that result in the possibility of profound change in the manufacturing of biomedical and aerospace components. Production of more complicated components could be achieved by using AM method [3]. Poly Lactic Acid (PLA) is one of

materials produced by AM process. This material is also called plant-based thermoplastic. PLA is a strong and light material, simultaneously. One more important thing is that PLA is a biodegradable and a recyclable material which is prepared from renewable raw materials. Its applications is as follows: packing, covering, industrial clothing with optimal UV resistance, good resistance to staining, medical usage such as PLA screws in orthopedic surgery [4]. Fused deposition modeling (FDM) is one of the AM methods could be used to manufacture PLA specimens. A schematic of this process is illustrated in Fig. 1.

Fig. 1. FDM process.

Apart from the AM process, the post processing activities of AM parts are another important issue. As an example, drilling of these parts is a common operation to generate the holes in them. In latter studies, Ming et al. [5] investigated chip formation and hole quality in drilling of additively manufactured Ti6Al4V alloy in which chip morphology was evaluated in dry drilling. In another work, drilling of this alloy was carried out by Rysava et al. [6]. It was reported that the best quality of the hole was attained when the cutting speed and feed rate were at the lowest value. Dang et al. [7] evaluated the effect of microstructure on tool wear when drilling of additively manufactured Ti6Al4V was applied. They expressed that heat treatment of AM part increased the chip adhesion on the drill bit that resulted by an increase in flow plasticity and a decrease in the brittleness of the material. Khaliq khan et al. [8] machined an additive manufactured Ti-6Al-4V material. The process was done under dry and minimum quantity lubrication (MQL) cutting conditions. In their work, surface quality, tool wear, and residual stresses have been examined. It was mentioned that machining of AM parts in MQL conditions caused an improvement in the results. These works were implemented in conventional drilling (CD), while utilizing ultrasonic drilling (UD) method could improve the results to some extent. In UD approach, a high frequency vibration with small amplitude is

superimposed on the drill bit [9-12]. Fig. 2 shows a schematic of UD process. With respect to the previous studies [13, 14], it can be observed that ultrasonic drilling could improve some machinability factors where non-AM materials were as a case study. It is seen that the drilling tool has a coupled rotary-vibratory movement during the operation. UD process was applied for different materials by some researchers. Debnath et al. [15] exerted the ultrasonic vibration in drilling of glass fiber reinforced epoxy laminates where hole circumferential quality has been improved compared to CD. Feng et al. [16] examined UD process when the workpiece material was carbon reinforced polymers. They concluded that lower tool wear has been obtained by adding ultrasonic vibration to the drilling tool. Tabatabaeian et al. [17] showed that the presence of delamination could be effective on the mechanical properties of glass fiber composites during the drilling process. It has been claimed that the delamination phenomenon was to be more considerable in higher rotary speeds. Wei and Wang [18] used ultrasonic vibration in drilling of a layered material. In that study, Ti-6Al-4V/Al2024-T351 laminated material has been used where thrust force, burr size, and surface quality of drilled holes were studied. They used a twist drill bit for this process. Finally, it was reported that thrust force, temperature, and burr height of the materials were reduced 28.6%, 13.2%, and 54.5%, respectively. Wu et al. [19] analyzed the drilling process of carbon fiber–reinforced plastics (CFRP) when ultrasonic vibration was applied on the cutting process. They focused on the delamination factor which is one of the problems occurred in drilling of layered materials by considering the effect of cutting parameters on this factor. As a result, it was indicated that by an increase in feed value, more delamination was generated. However, the result of UD process was better than CD one.

Fig. 2. A schematic of vibratory drilling. (U is displacement, a is amplitude, ω is the angular frequency, and t is time).

Therefore, as the AM-PLA is a widely used material and the UD process is a useful method, the aim of this study is to investigate the different aspects of hole quality (such as the size of delamination, circularity, and the cylindricity) when ultrasonic drilling of AM-PLA is carried out.

2. Experimental procedures

The experimental examinations were conducted on a three-axis milling machine. An additively manufactured PLA+ (Poly Lactic Acid plus) was selected as workpiece material which was produced by Prusa i3 device related to eSUN company. The workpiece dimension is as follows: 100×50×5 mm (Table 1). Owing to the sharp edges producing better surface quality, a standard HSS tool was chosen as a drill bit in which its diameter was 6 mm. A 4-flutes drill bit has been used. The drilling parameters are listed in Table 2 which are selected based on the recommendation of the manufacturer and also the workpiece material. Three Levels were defined for each particular cutting parameters during CD and UD.

Table 1. The printing parameters of PLA.

Parameter	Unit	Value
Extrusion temperature	°C	220
Bed temperature	°C	60
Infill density	%	100
Number of layers	-	12
Raster angle	°	90

Table 2. The experimental drilling parameters.

Parameters	Unit	Values
Rotational speed	<i>rpm</i>	565, 955, 1500
Feed rate	<i>mm/rev</i>	0.08, 0.15, 0.25
Ultrasonic vibration	-	on, off

Fig. 3 shows the experimental setup where an ultrasonic drilling tool was used (the frequency has been 19.5 kHz). Furthermore, other equipment are illustrated in Fig. 4. In this study, the equipment are as follows:

- A Visual measurement machine (VMM) was used to take the images from the machined holes.
- A Kistler 9257B dynamometer was used to measure cutting force during drilling operation.
- A 3 kW ultrasonic generator (MPI Company from Switzerland) was used to generate ultrasonic vibrations.
- A Coordinate measurement machine (CMM) (Sky 8 from Italy) was used to measure the diameter, circularity, and the cylindricity of the machined holes.

Fig. 3. The experimental setup.

Fig. 4. a) The dynamometer, b) VMM, and c) related to the force measurement.

3. Results and Discussions

In this work, two types of drilling process have been implemented: CD and UD. Cutting forces were measured during the process. After machining, the specimens were evaluated by considering the delamination, circularity, and the cylindricity of the machined holes. Besides, the effect of chip adhesion on the quality of drilled holes were also considered.

3.1. Thrust force

The thrust force, which is in feed direction, was measured during the tests b using a dynamometer. The average of measurement results are compared in Fig. 5. In general, thrust forces decreased by an increase in cutting velocity and increased by an increase in feed value in both CD and UD. It could be due to thinner and thicker chip formation resulted by high velocity and high feed rate, respectively [20]. Besides, it is ascertained from this figure that the force values obtained in UD are almost lower than CD ones in all cutting conditions. Two reasons caused this outcome to be extracted: engagement time and the positive tool rake angle. In CD, the thrust force is stabilized after running the operation, while it is oscillated harmonically in UD. In other words, in the engagement time, the thrust force goes to the peak value and in the disengagement time, it goes back to the zero value. Note that, the peak value in UD was lower than that of CD. Therefore, the average values in UD are lower compared to CD.

Fig. 5. Thrust force results at different cutting conditions.

The second reason of force reduction might be more positive tool rake angle generated in UD. In CD, the rake angle (α) is not constant and it changes along the drill lip-length [21]. It is attained from Eq. (1).

$$\tan \alpha = \frac{r_x}{R} \times \frac{\tan \omega}{\sin \varphi}$$

(1)

In this equation, r_x , R , ω , and φ are the selected radius at each particular point along the lip-length, the radius of drill bit, the helix angle, and the half angle of the drill point. Furthermore, the rake angle has some differences by the cutting rake angle generated during the operation (α_w). The cutting rake angle is calculated based on Eq. (2) where β is the helical angle. It is generated by feed motion (f) which is also calculated with respect to Eq. (3). In this equation, D is the drill diameter [22].

$$\alpha_w = \alpha + \beta$$

(2)

$$\tan \beta = \frac{f}{\pi D}$$

(10)

In accordance with above equations, more positive rake angle is generated in UD. In fact, there are two harmonic steps (downward and upward) in UD. As the vibratory drill bit goes down, the momentary feed value (f) increases resulting more positive rake angle. It was proved that an increase in tool rake angle causes a decrease in the length of tool-chip contact which results in the lower friction and heat in this zone [22]. As a result, the thrust force is reduced. Although in the upward motion the momentary feed value (f) decreases, it could not negatively effect on the thrust force when the engagement of tool and chip is insignificant.

3.2. Delamination

Delamination is one of the phenomena which can be occurred during the post processing of additively manufactured parts considering the fact that these kinds of parts are produced layer by layer [23]. Accordingly, a variety of layered materials can be failed if delamination is happened. Some materials like concrete, laminate composites, and AM ones are classified in this category. With respect to that, the conventional machining of these materials are usually faced with some difficulties. Therefore, it is very important that efficient machining methods such as hybrid ones (e.g. UD) to be used to improve the conditions. The focus of this study is to reach this desire. Fig. 6 shows a schematic of delamination existed in drilling process. Accordingly, the delamination factor (F_d) is calculated based on Eq. (4) [24, 25].

$$F_d = \frac{D_2}{D_1} \quad (4)$$

In this equation, D_1 and D_2 are the drilled hole diameter and the maximum hole damage diameter, respectively. D_1 is obtained by using a CMM device and D_2 is obtained by using a VMM device. The VMM results of the delamination are given in Fig. 7 where they are at different cutting velocities when the feed value is at its high level (0.25 mm/rev). It is clearly seen that delamination was remarkably eliminated when ultrasonic vibration has been added to drilling process, while it was severely happened during CD process. For better understanding, the total results of delamination factor are collected in Fig. 8.

Fig. 6. A schematic of delamination.

The figure shows that an increment in feed value causes the delamination factor to be increased. In general, higher feed value results in more volume of uncut chip thickness causing more cutting force requirement. Consequently, an increase in cutting forces increases the delamination factor when the workpiece material is layered. On the other hand, the effect of cutting velocities is not in a specific trend and in some levels it reduces the delamination factor and in some others vice versa [26]. One more parameter which could be effective on the delamination is the temperature. In fact, higher cutting forces cause tool-chip contact to be increased resulting higher temperature in the cutting zone. As a result, the softening is happened for PLA+ where the chip sticks on the drill bit. In such a condition, the workpiece is dominant to be faced with more delamination [27].

In comparison, it is ascertained from the Fig. 8 that the delamination values in UD have lower variations compared to CD. It can be explained by more stability of UD process resulted by lower cutting forces [28-30]. It means that the UD process could reduce the effect of cutting parameters on the surface quality by a decrease in cutting forces, temperature, and tool-chip contact length.

Fig. 7. The VMM results of delamination during CD and UD at different velocities (rpm) (feed rate = 0.25 mm/rev).

Fig. 8. Delamination results.

3.3. Circularity and Cylindricity

Two other parameters, which are taken into account in drilling process, are circularity and cylindricity. The desirability of these parameters are very effective on the quality of drilled hole. To evaluate them, a CMM device is used. The probe is moved in the circumference and in the height of the hole to investigate the circularity and cylindricity of drilled holes, respectively. Accordingly, Fig. 9 depicts a schematic of examination tests carried out by CMM device, in this study.

Fig. 9. A schematic of measuring the circularity and cylindricity by CMM.

The final evaluation results are listed in two graphs in Fig. 10. In both CD and UD, the effect of feed variations has been more than cutting velocity. It is seen that an increase in feed value caused both circularity and cylindricity were worsen. However, this effect was reduced in high level of cutting velocity for cylindricity. In general, increase of feed value makes the cutting process more difficult. It means that higher cutting forces are needed to cut the material. In this condition, the temperature increases in the cutting zone and the chip tends to stick on the drill bit [31]. This event results in the reduction of surface quality parameters such as dimensional accuracy (e.g. circularity and cylindricity). Apart from the feed value, the graphs show that the quality of these parameters were improved by an increase in cutting velocity where the velocity could somehow decrease the negative effect of feed value.

Fig. 10. a) Circularity and b) cylindricity.

As the UD result is compared to CD, it is revealed that the vibratory motion improved the cutting process. Almost, all holes in UD were produced with more precise circularity and cylindricity. It can be explained by lower cutting forces in UD. Moreover, the intermittent movement of drill bit in UD caused the temperature on the cutting tool to be reduced and lower adhesion of chip to drill to be happened [32]. To clarify above explanations, Fig. 11 is prepared. This figure illustrates the drill bits after running a test during CD and UD. It is clearly seen that lower adhesion was occurred in UD compared to CD. As the PLA+ is a soft material, each particular variation can significantly effect on the dimensional accuracy of drilled hole. In particular, it is predictable that as long as the chip sticks on the body of the drill bit or stick as a built-up edge in CD, the drilled holes not to be generated, precisely. That being the case, the vibro-impacts, which are harmonically generated in UD, causes less adhesion of chip to the body of the drill bit [33].

Fig. 11. Chip adhesion on the drill bit.

4. Conclusions

In the present study, the surface quality of the generated holes during ultrasonic drilling of poly lactic acid plus, was evaluated. The examinations were carried out on the thrust force, delamination, circularity, cylindricity, and chip adhesion. The main results can be summarized as follows:

1- The thrust force results showed that the obtained values in UD were almost lower than CD ones in all cutting conditions. Drill-chip disengagement time and more positive tool rake angle have been introduced as two main reasons.

2- An increment in feed value caused the delamination factor to be increased. In general, higher feed value results in the more volume of uncut chip thickness. Accordingly, more cutting force requirement caused more delamination to be generated. The effect of cutting velocities has not been in a specific trend and in some levels it had negative effect and some others vice versa.

3- It was reported that delamination was remarkably reduced when ultrasonic vibration was added to drilling process. This event has been explained by lower softening phenomenon and lower cutting forces generated during UD compared to CD.

4- It was seen that an increase in feed value caused both circularity and cylindricity were worsen. Because, higher cutting forces were generated in high level of feed rates. In comparison, all holes in UD were produced with more precise circularity and cylindricity. It has been clarified by lower adhesion of chip to drill which improved the surface quality and surface accuracy.

Consequently, it could be recommended that for drilling of the parts that are produced in layered form (like AM parts), is better to utilize the nonconventional methods like ultrasonic drilling where it works significantly better than conventional ones, as seen in this paper.

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