Evaluating the Hole Quality Produced by Vibratory Drilling: Additive Manufactured PLA+

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Research Article

Keywords: Additive manufactured PLA+, roughness, ultrasonic, force, delamination, circularity, cylindricality

Posted Date: March 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-161608/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on August 2nd, 2021. See the published version at https://doi.org/10.1007/s00170-021-07750-8.

Evaluating the Hole Quality Produced by Vibratory Drilling: Additive Manufactured PLA+

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Abstract

Improving the surface quality of additive manufactured parts like poly lactic acid (+) is an important study that is currently being carried out by researchers. To reach the high quality, different conventional and non-conventional methods are applied. In this study, the capability of ultrasonic vibration in drilling of an additive manufactured poly lactic acid (+)was examined. The process was implemented in two methods: conventional and vibratory drilling. Then, thrust force and chip type were analyzed and the effect of them on surface roughness, delamination, circularity, and cylindricality have been investigated. As a result, it was indicated that lower thrust force and broken chips, which were generated in ultrasonic drilling, caused the surface quality parameters to be improved compared to the conventional method.

Keywords: Additive manufactured PLA+; roughness, ultrasonic; force; delamination, circularity, cylindricality.

1. Introduction

Nowadays, non-conventional machining methods are being used more than before in which the machining of new materials with special qualities not to be properly responded by conventional methods. One of the non-conventional methods is ultrasonic machining (UM). In UM, vibratory movement in a small amplitude with high frequency is superimposed on the cutting tool, workpiece, or both of them [1-3]. The movement could be in one, two, and three directions [4, 5]. Drilling is a machining operation which can be modified by ultrasonic vibration. In common ultrasonic drilling (UD), the vibration is longitudinally added to the drill bit in feed direction [6]. Fig. 1 shows ultrasonic drilling process where the drill bit has a vibratory-rotary motion and the workpiece has a feed motion.

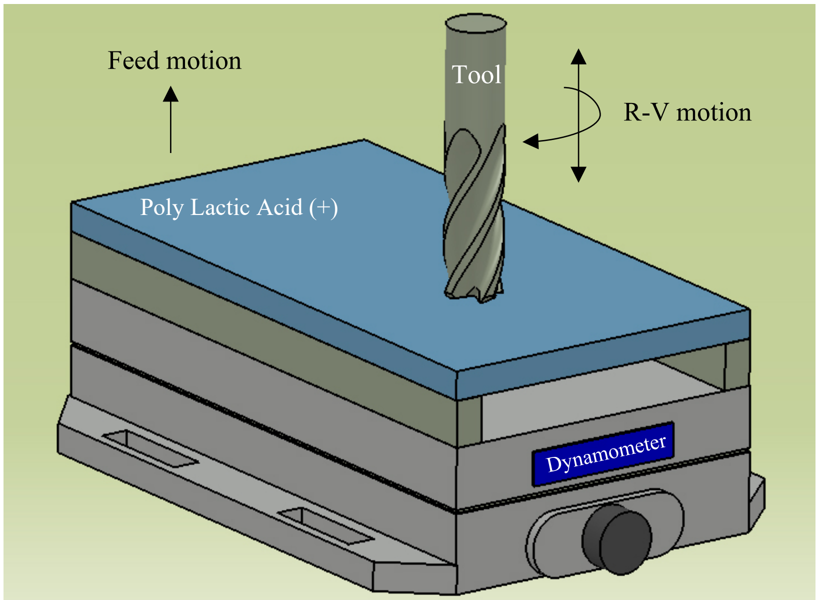


Fig. 1. A schematic of vibratory drilling.

Some papers with respect to UD process are briefly reviewed here. Accordingly, ultrasonic drilling of carbon reinforced polymers was carried out in which lower tool wear was reported compared to conventional drilling (CD) [7]. In another study, glass fiber reinforced epoxy laminates has been drilled by adding ultrasonic vibration. It was concluded that UD process caused better hole quality compared to CD [8]. Delamination is one of the factors which is investigated in drilling of layered materials. In one paper, it has been expressed that delamination affected the mechanical properties of glass fiber composites in drilling process which was more happened in higher velocities in both CD and UD. However, it was less in UD [9]. Thrust force, burr size, and surface quality of drilled holes were studied when ultrasonic drilling of a Ti-6Al-4V/Al2024-T351 laminated material was implemented. It has been mentioned that thrust force was reduced about 28.6% in UD compared to CD [10]. Ultrasonic drilling of a carbon fiber–reinforced plastics showed that better results about the delamination factor could be obtained by using ultrasonic vibration. Furthermore, it was reported that feed value was significantly effective on this factor [11].

Poly Lactic Acid Plus (PLA+) is a layered material which also needs to be drilled by non-conventional methods. The PLA+ is produced by renewable raw materials causing to be biodegradable and recyclable. One another name of PLA+ is plant-based thermoplastic. Owing to the simultaneous strong and light qualities, it is used in orthopedic surgery, packing, and covering [12]. This material is produced by using additive manufacturing (AM) approach, particularly, fused deposition modeling (FDM) method. In general, the AM process is used to incrementally manufacture the complicated parts which may not properly be manufactured by detrimental methods [13, 14]. However, the AM parts usually need post processing activities where their surface quality is not appropriate [15]. Drilling operation is one of post processing activities which is used to generate the hole in the AM parts. In the following, some of related papers are reviewed. Hole quality of an AM Ti6Al4V alloy has been investigated during the drilling process. It was clarified that low values of cutting velocity and feed rate result in the better surface quality [16, 17]. Moreover, the effect of microstructure on chip formation was also examined. It was reported that heat treated AM material increased chip adhesion on the drill bit compared to untreated one resulted by an increase in flow plasticity and a decrease in the brittleness of the material [18]. The use of minimum quantity lubrication in machining of an AM Ti–6Al–4V material showed that it caused the surface quality to be improved compared to the dry cutting conditions [19]. These works have been carried out in conventional drilling (CD). Therefore, the utilization of ultrasonic vibration in drilling of an AM PLA+ material is investigated, in the present study. Accordingly, cutting force, chip breakage, surface roughness, and hole quality factors such as delamination, circularity, and cylindricality are evaluated.

2. Experimental preparations

To conduct the experimental examinations, a milling machine has been used in which an ultrasonic head was mounted onto it. A 4-flute drill bit with 6 mm in diameter was selected to be used which was made of HSS. A PLA+ workpiece material with the size of 100×50×5 mm has been drilled. Its qualities related to the printing parameters, are listed in Table 1. Drilling process was implemented in two types: CD and UD. Furthermore, three levels were selected for cutting velocity and feed rate. Accordingly, 18 tests have been done, in total (seen in Table 2).

Fig. 2 illustrates the experimental set-up and the equipment. It is seen that a dynamometer (Kistler 9257B) has been used to measure cutting force during the operation. Besides, an ultrasonic generator (MPI Company from Switzerland (3 kW)) was utilized to generate ultrasonic vibrations with high frequency during the process. After running the experimental tests, a visual measurement machine (VMM) and a coordinate measurement machine (CMM) were applied to measure the delamination and the diameter, circularity, and the cylindricality of the drilled holes, respectively. Moreover, a Mahr roughness tester (Mar Surf PS1) has been used to measure the surface roughness.

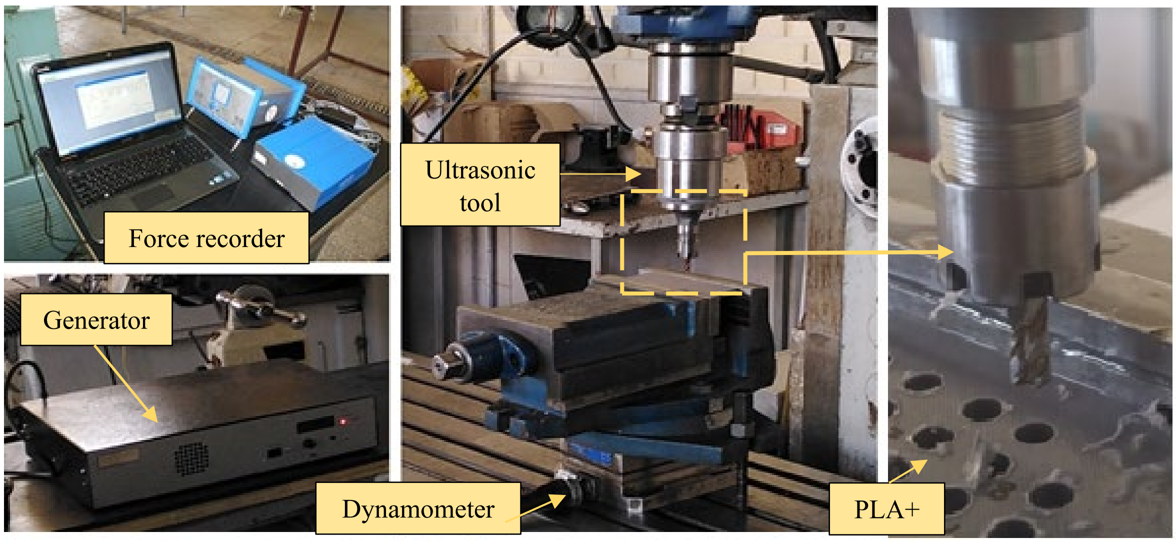


Fig. 2. Experimental setup and equipment.

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 used in CD and UD

Test number	Feed rate (mm/rev)	Velocity (rpm)
1	0.08	565
2	0.15	565
3	0.25	565
4	0.08	955
5	0.15	955
6	0.25	955

7	0.08	1500
8	0.15	1500
9	0.25	1500

3. Results and Discussions

The results and discussions section is divided into five sub-sections as follows: thrust force, chip breakage, surface roughness, delamination, and circularity and cylindricality. In these sub-sections, the parts which were drilled in two types of drilling (CD and UD) were analyzed.

3.1. Thrust force

In this sub-section, thrust force, which is in feed direction, is analyzed. In each particular test, the thrust force was measured by using dynamometer.

Fig. 3 depicts one of the recorded results with respect to the cutting time. It is ascertained from the schematic part of this figure that the more drill bit goes downward, the more thrust force increases in CD. It means that the depth of the drilling hole could effect on the CD process, while it was eliminated in UD. It is seen that ultrasonic vibration could control the process where the thrust force was in a same way during the time.

From the one side, it might be explained by harmonic intermittent of drill bit in UD. In fact, the drill bit goes down and goes back in UD, harmonically. This event causes working tool rake angle to be more positive in UD compared to CD. It should be noted that an increase in tool rake angle results in decrease in the length of tool-chip contact causing the lower friction and heat generation in the cutting zone [20, 21]. In another side, chip evacuation and the type of chip can be one more reason which is explained in the next sub-section, in details.

Apart from that, Fig. 3 shows that the thrust force in UD is lower than CD in all the cutting time. In UD, the harmonic movement of drill bit causes the cutting time is divided into two individual times: engagement and disengagement time. The thrust force increases during engagement time and it decreases during the disengagement time in UD where the repetition of this work causes the average value of thrust force to be reduced in UD compared to CD.

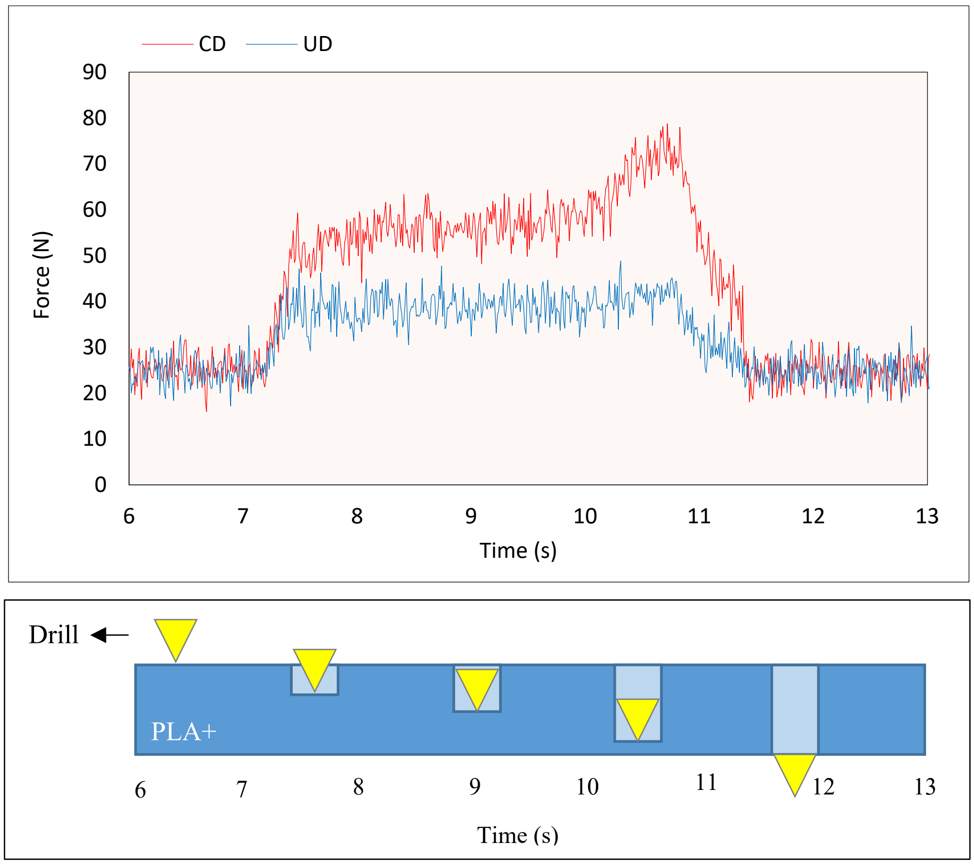


Fig. 3. Thrust forces recoded by dynamometer in the experimental works.

The total results of thrust forces are listed in Table 3. This table indicates that the force values obtained in UD are lower than CD ones in all cutting conditions. 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 [22].

Table 3. Thrust force results measured by dynamometer.

No.	Feed rate (mm/rev)	Velocity (rpm)	CD (N)	UD (N)
1	0.08	565	83	74
2	0.15	565	85	77
3	0.25	565	90	78
4	0.08	955	77	72

5	0.15	955	83	75
6	0.25	955	86	77
7	0.08	1500	59	53
8	0.15	1500	62	54
9	0.25	1500	65	56

3.2. Chip breakage

As mentioned in previous sub-section, chip type can be one of the reasons of force reduction. As usual, continuous helical coil or straight chip shapes are formed in CD. These types of chips fill the flutes in which the drilling process is faced with some problems such as chip evacuation. The chips generated in CD and UD are represented in Fig. 4. As it is seen, the continuous helical coil chip type was produced in CD, while it was changed to the segmented one when ultrasonic vibration was added to the operation. The reason of chip segmentation was vibro-impact mechanism commonly existed in UD process. This impact changed the natural curling of chip formation.

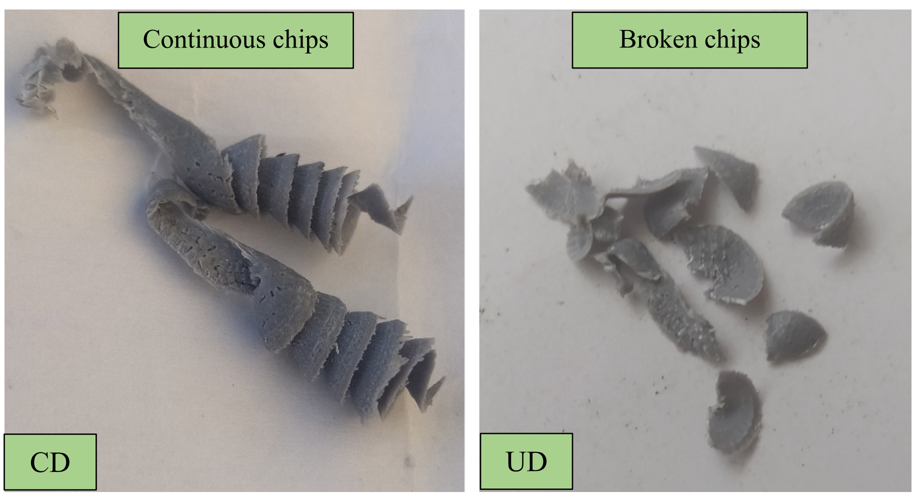


Fig. 4. Broken chips in CD and UD.

With respect to the Fig. 5, the drill bit is vibrated in feed direction. This figure shows the process in cross-section. It is cleared that the vibration results in the intensification of chip curling increasing more bending and more critical strain of chip breakage (ε_f). Therefore, chip breakage could be related with vibration amplitude (Eq. (1)) [23].

$$\varepsilon_f \propto Amplitude \tag{1}$$

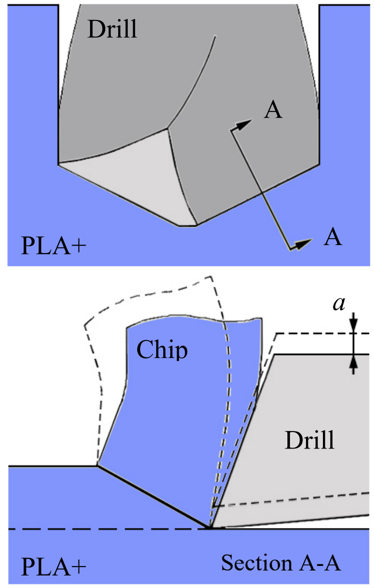


Fig. 5. Drill vibration in cross section.

As more bending of the chip is generated in UD, the chip radius is also reduced. Another relation can be introduced by Eq. (2). In this equation, r, r_f, t, and ε_{ch} are natural chip radius, fractured chip radius (r_f), chip thickness, and chip strain, respectively [24]. Accordingly, an increase in chip strain is occurred by a decrease in fractured chip radius resulting more chip fracture.

$$\varepsilon_{ch} = \frac{t}{2r}\left(1 - \frac{r}{r_f}\right) \tag{2}$$

3.3. Surface roughness

After investigation of thrust force and chip formation, effect of these results on the hole quality parameters is evaluated. The first parameter is surface roughness. For this analysis, the parts were cut and the surface roughness of inner wall of the drilled holes have been measured by using a roughness tester. To increase the repeatability of the measurement tests, three point of each particular hole were measured and the average values of them were compared by each other, as it is seen in Fig. 6. In general, an increase in feed value caused surface roughness to be worse, while better results were obtained by an increase in cutting velocity in both CD and UD. Apart from, it is ascertained from the figure that the average values are lower in UD compared to CD at all cutting conditions. In total, 15 to 20% reduction was observed when the drilling process modified by ultrasonic vibration. Based on the force results, it can be said that lower thrust force in UD shows that easier chip formation was done in UD causing better surface roughness. In other hands, less variation in force generation during UD (seen in Fig. 3) means that this process was more stable compared to CD. Therefore, more stability and easier chip shearing in UD caused the surface roughness to be lower compared to CD. To better understanding, Fig. 7 is also represented. Based on that, the feed marks generated in CD are somehow reduced in UD.

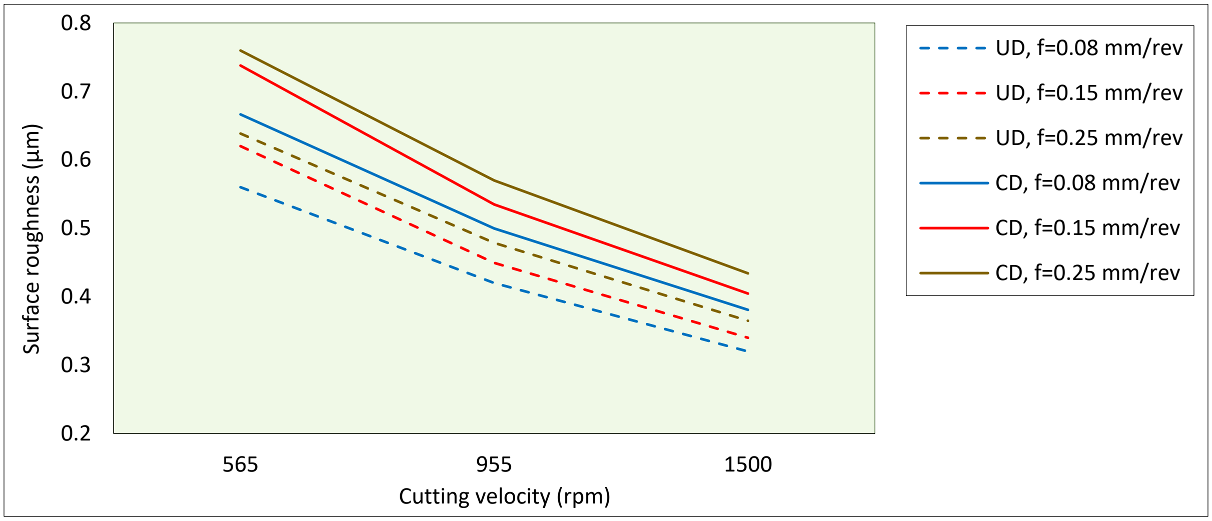


Fig. 6. Surface roughness results at different cutting conditions in CD and UD.

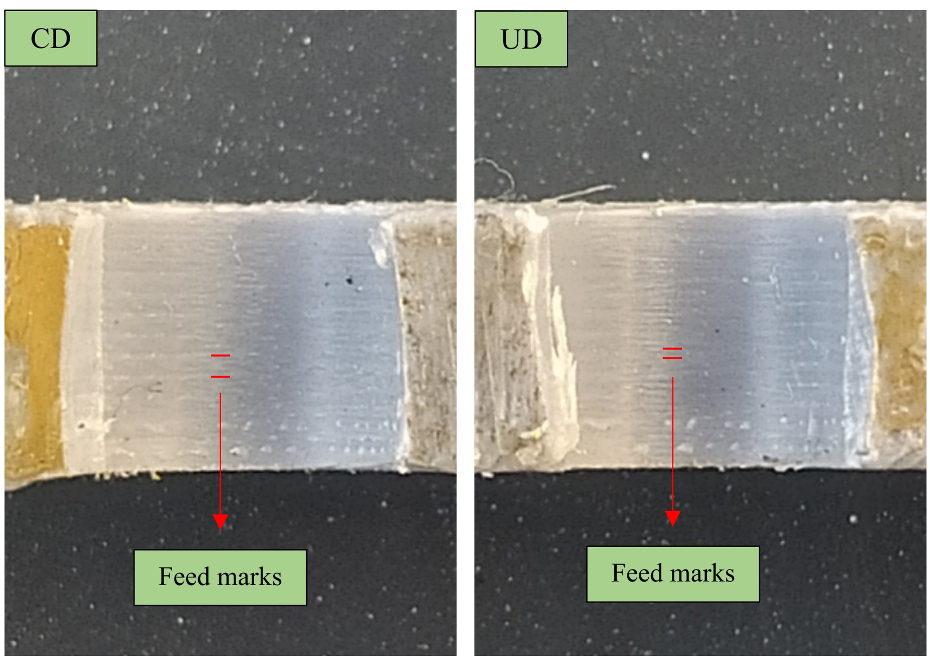


Fig. 7. The inner wall of drilled holes in CD and UD.

In addition to the above reasons, chip type also can be effective on the roughness results. Continuous helical coil chips in CD fill the drill flutes in which the evacuation of them are a problem. It could be worsen in high level of feed rates. In such a condition, drill-chip friction and cutting zone temperature increase. All these cause a decrease in surface quality [25]. Thus, chip breakage in drilling process could improve this condition which was seen in UD.

3.4. Delamination

To evaluate delamination parameter, a factor (F_d), which is based on two diameters, is used. Eq. (3) introduces this factor [26, 27]. D_1 is drilled hole diameter (measured by CMM device) and D_2 is the maximum hole damage diameter (measured by VMM device). Accordingly, Fig. 8 has been prepared to schematically show the hole conditions after drilling process. The left image expresses an ideal hole where there is no delamination when D_2 parameter is equal to zero. While, the right image depicts the hole with delamination when D_2 parameter is not equal to zero.

$$F_d = \frac{D_2}{D_1} \tag{3}$$

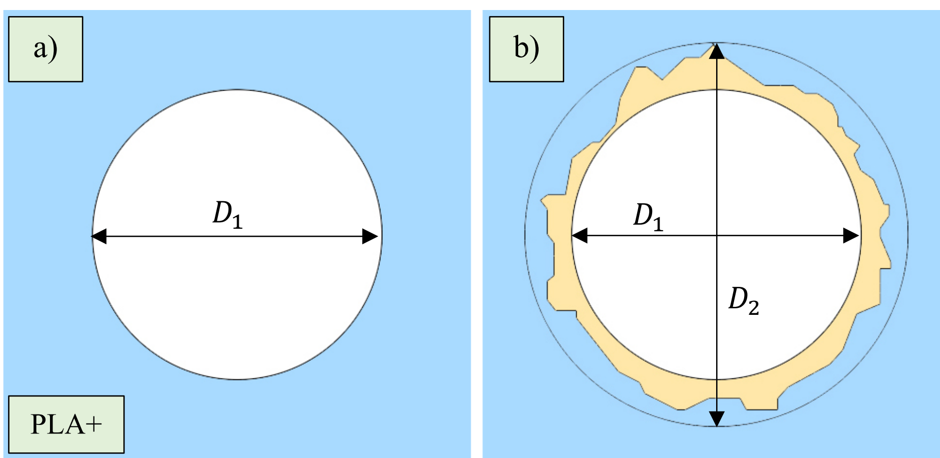


Fig. 8. Drilled holes: a) an ideal hole without delamination and b) a hole with delamination.

As usual, the right image in Fig. 8 is seen during the drilling of layered material like additive manufactured ones [28]. Thus, delamination in drilling of PLA+ material is not negligible, but it could be reduced to that much it is desired. That being the case, the ultrasonic drilling can respond to this issue. As it is given in Fig. 9, the workpieces have been drilled in CD and UD. Two holes of each of CD and UD were compared in this figure where a clear improvement in UD is observable. To better comparison, the complete results at different cutting velocities and feed values were listed in Table 4 including the VMM images and their values.

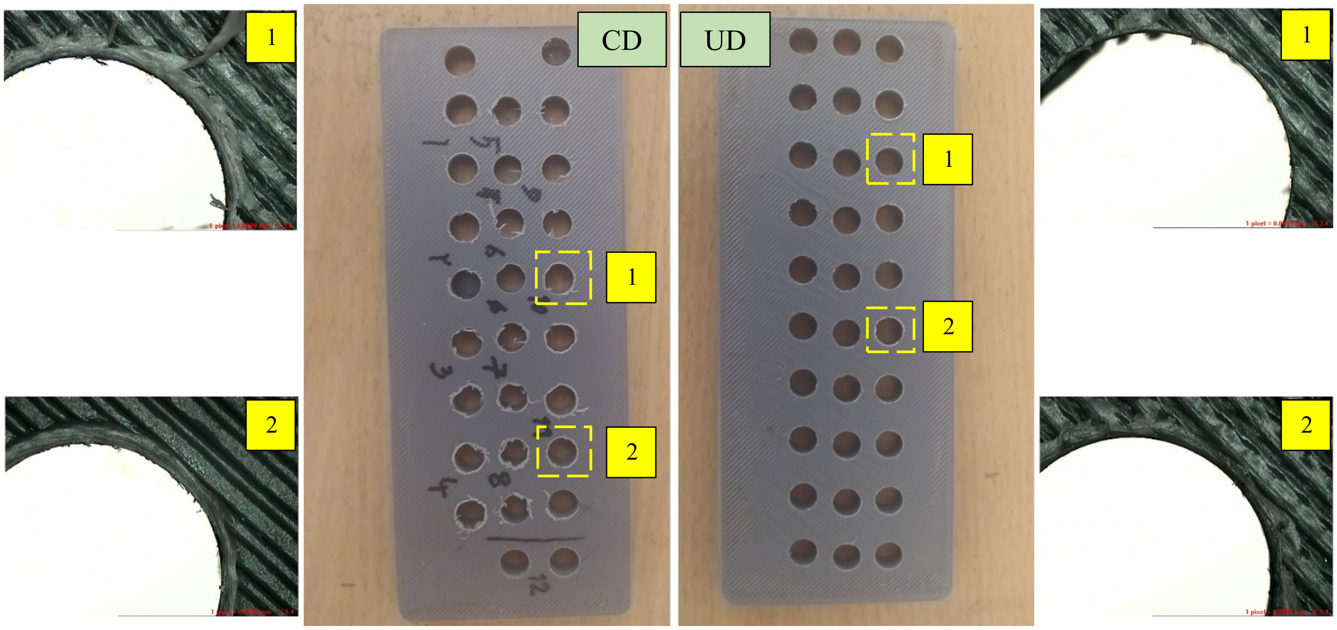


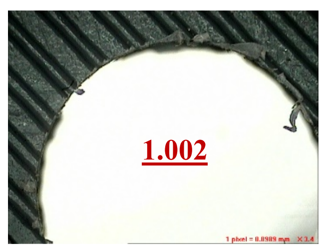
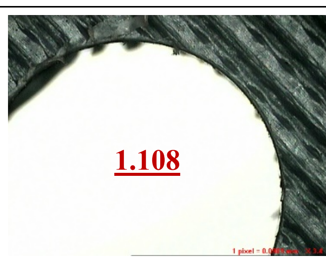
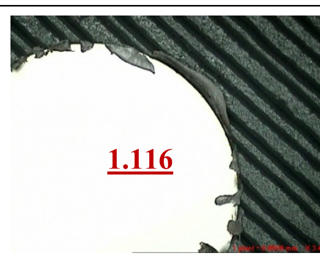
Fig. 9. Drilled PLA+ during CD and UD including VMM images.

It is ascertained from Table 4 that the delamination values in UD have been reduced about 18% compared to CD. If this results to be linked to the section of force results, it can be mentioned that lower thrust force in UD caused lower delamination and lower damage to be happened, however, it was not completely eliminated. This means that more stability in force generation leads to the formation of a more uniform chip shearing from the beginning to the end of drilling [29-31].

Apart from the comparison, the cutting parameters are also effective on the results. In both machining methods, feed value was more effective compared to cutting velocity where an increase in feed value increased the delamination factor, while the variation of cutting velocity was insignificant. However, in some cutting conditions, an increase in cutting velocity somehow decreased this factor. This trend was also seen in force analysis. In fact, the more volume of uncut chip thickness causes more cutting force requirement. Furthermore, an increase in cutting forces increases the delamination factor (particularly in layered materials) [32].

In total, the best results were obtained when the feed rate was at the lowest value and the cutting velocity was at the highest value for both CD and UD.

Table 4. The results of delamination prepared by VMM.

Type	Feed (mm/rev)	Velocity (rpm)		
		565	955	1500
CD	0.08			
	0.15			
	0.25			
UD	0.08			
	0.15			
	0.25			

3.5. Circularity and Cylindricality

With respect to Fig. 10 a CMM device has been used to investigate the parameters of circularity (the circumference of the hole) and cylindricality (the height of the hole). These parameters also define the hole quality the same as surface roughness. The all results of measurements are listed in Table 5.

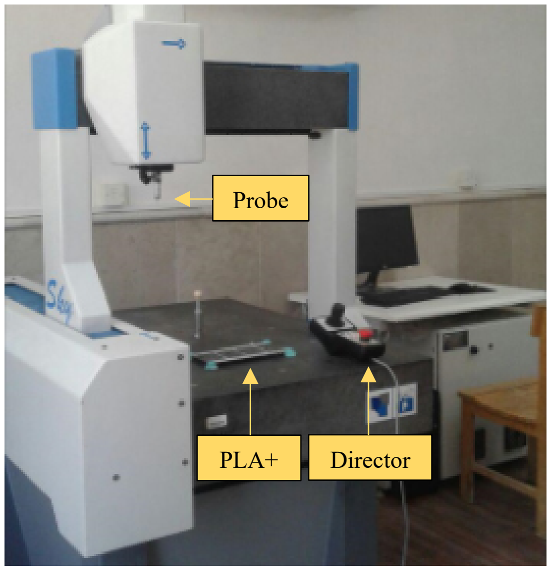


Fig. 10. The CMM device.

The table results reveal that feed increment was the most effective factor to reduce the desirability. In other words, an increase in feed value caused these parameters to be worsen as higher thrust forces were needed. This result could also be proved by surface roughness results. Actually, a decrement in the desirability of circularity and cylindricality caused the surface roughness to increase in a same trend, as well. It is also seen that the velocity increment improved the results.

In general, in the conditions that more cutting forces were needed to cut the material, the holes with less quality were generated, due to higher temperature existed in the cutting zone. Under these conditions, the temperature in the cutting area increases and the chip tends to stick to the drill [33]. This event leads to a decrease in surface quality parameters such as surface roughness, circularity, and cylindricality. Therefore, it is concluded that lower cutting forces can significantly improve the surface quality parameters which was achieved by using ultrasonic vibration. Based on the Table 5, more precise hole with respect to the circularity and cylindricality have been produced at all cutting conditions in UD compared to CD.

Table 5. The results of circularity and cylindricality measured by CMM.

No.	Feed rate (mm/rev)	Velocity (rpm)	Circularity		Cylindricality	
			CD	UD	CD	UD
1	0.08	565	0.0264	0.0204	0.0497	0.0415
2	0.15	565	0.0375	0.0324	0.0880	0.0572
3	0.25	565	0.0509	0.0423	0.1118	0.0626
4	0.08	955	0.0179	0.0199	0.0329	0.0275
5	0.15	955	0.0383	0.0242	0.0392	0.0368
6	0.25	955	0.0487	0.0302	0.0727	0.0607
7	0.08	1500	0.0189	0.0155	0.0327	0.0215
8	0.15	1500	0.0288	0.0263	0.0366	0.0272
9	0.25	1500	0.0408	0.0286	0.0405	0.0344

4. Conclusions

Thrust force, chip breakage, surface roughness, delamination, circularity, and cylindricality were the parameters that have been investigated during CD and UD, in this work. In accordance to the manuscript, following results can be represented:

1- The more drill bit went downward the more increment in thrust force was recorded in CD, while this variation was eliminated in UD. Ultrasonic vibration could control the process where the thrust force was in a same value during the cutting time. In general, thrust forces decreased by an increase in cutting velocity and increased by an increase in feed value in both CD and UD.

2- The continuous helical coil chip type in CD was changed to the segmented one in UD. The vibro-impact was introduced as a reason of chip segmentation. This impact intensified chip curling. It resulted in the more chip bending and more critical strain causing chip breakage.

3. 15 to 20% reduction in surface roughness was observed when ultrasonic vibration has been added. In one side, less variation in force generation (more stability) during UD was mentioned as a reason of roughness reduction. In another side, broken chips in UD caused the drill flutes to be filled less than CD which resulted in the better surface roughness.

4. The lowest results of delamination were obtained when the feed and cutting velocity were at the lowest and the highest values, respectively. The comparison results showed that the delamination values in UD have been reduced about 18% compared to CD. This means that more stability in force generation leads to the formation of a more uniform chip shearing in UD during the cutting time.

5. More precise hole with respect to the circularity and cylindricality were produced in UD compared to CD.

Eventually, it can be noted that ultrasonic vibration could reduce cutting forces and modify the chip formation in drilling of additive manufactured parts where these two outcomes cause the parameters of surface quality (surface roughness, delamination, circularity, and cylindricality) to be improved.

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Ethical approval: It is approved that the paper is original and has been written based on the authors' own finding. All the figures and tables are original and every expression from other published works were acknowledged and referenced.

Consent to participate: It is confirmed that all the authors are aware and satisfied with the authorship order and correspondence of the paper

Consent to Publish: All the authors are satisfied that the last revised version of the paper is published without any change

Authors Contributions: Mohammad Baraheni had 45% contribution in conducting the research and analyzing the results; Mohammad Reza Shabgard had 35% contribution in supervising the research and financial aid.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing Interests: It is declared that there is no conflict of interest in authorship and data provided.

Availability of data and materials: It is confirmed that the data and materials can be available after publication on the basis of springer nature rights and access.

Figures

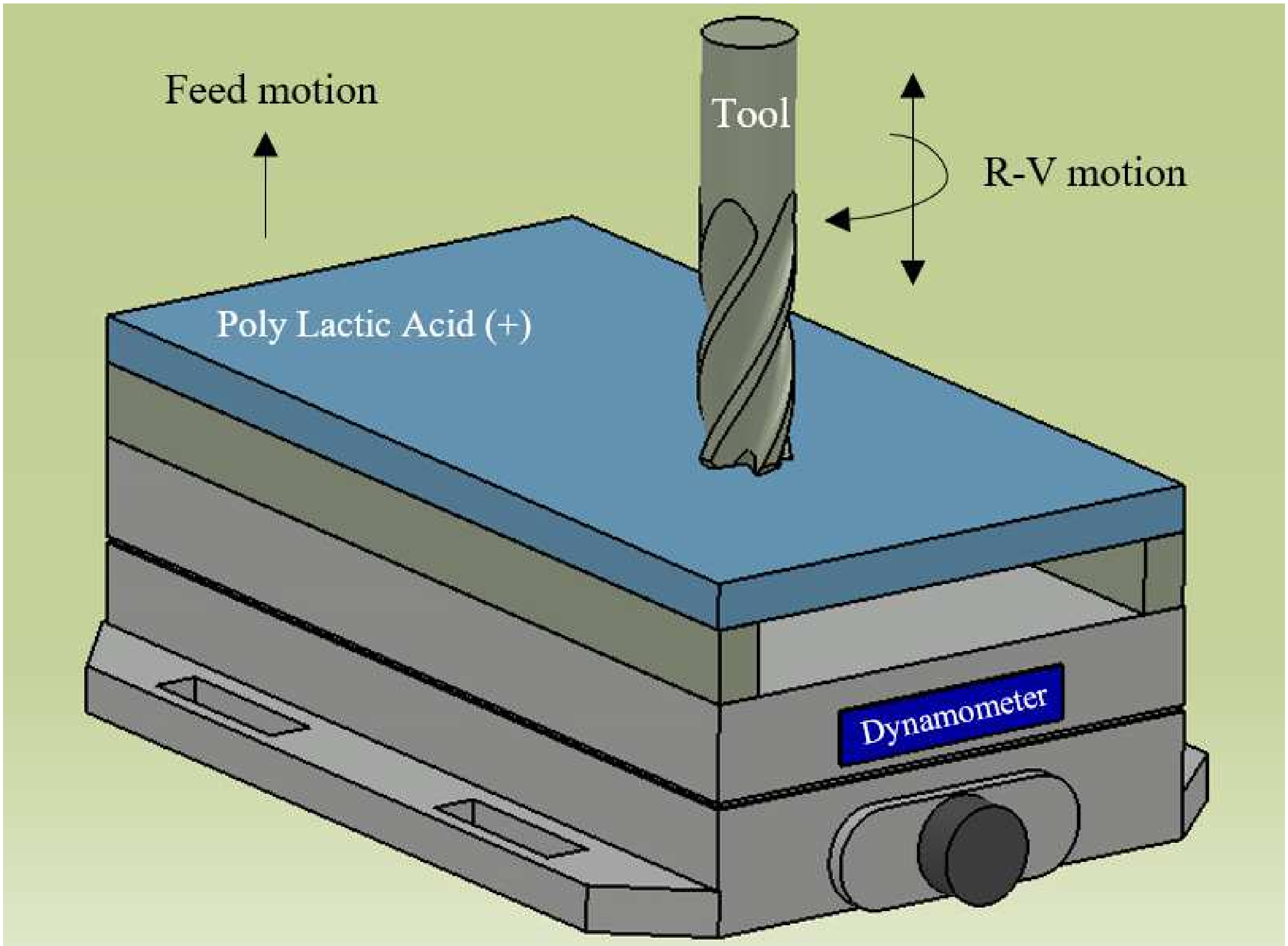

Figure 1

A schematic of vibratory drilling.

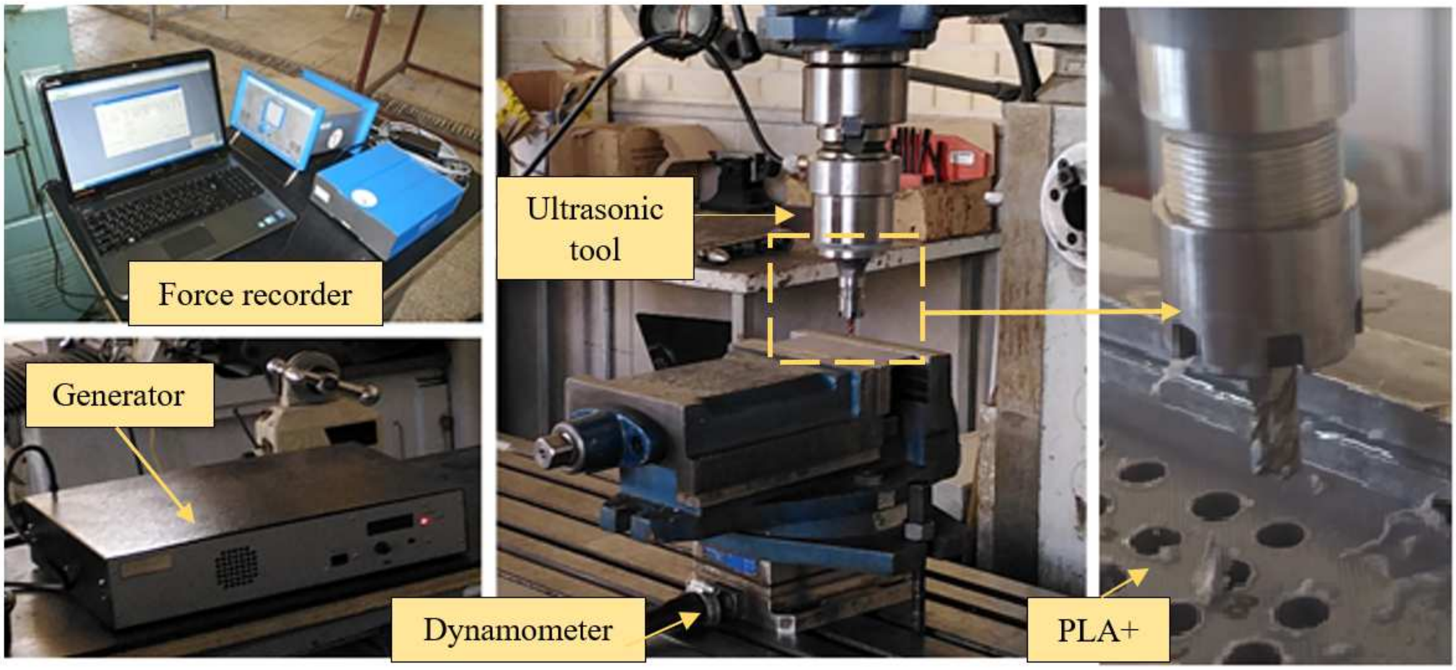

Figure 2

Experimental setup and equipment.

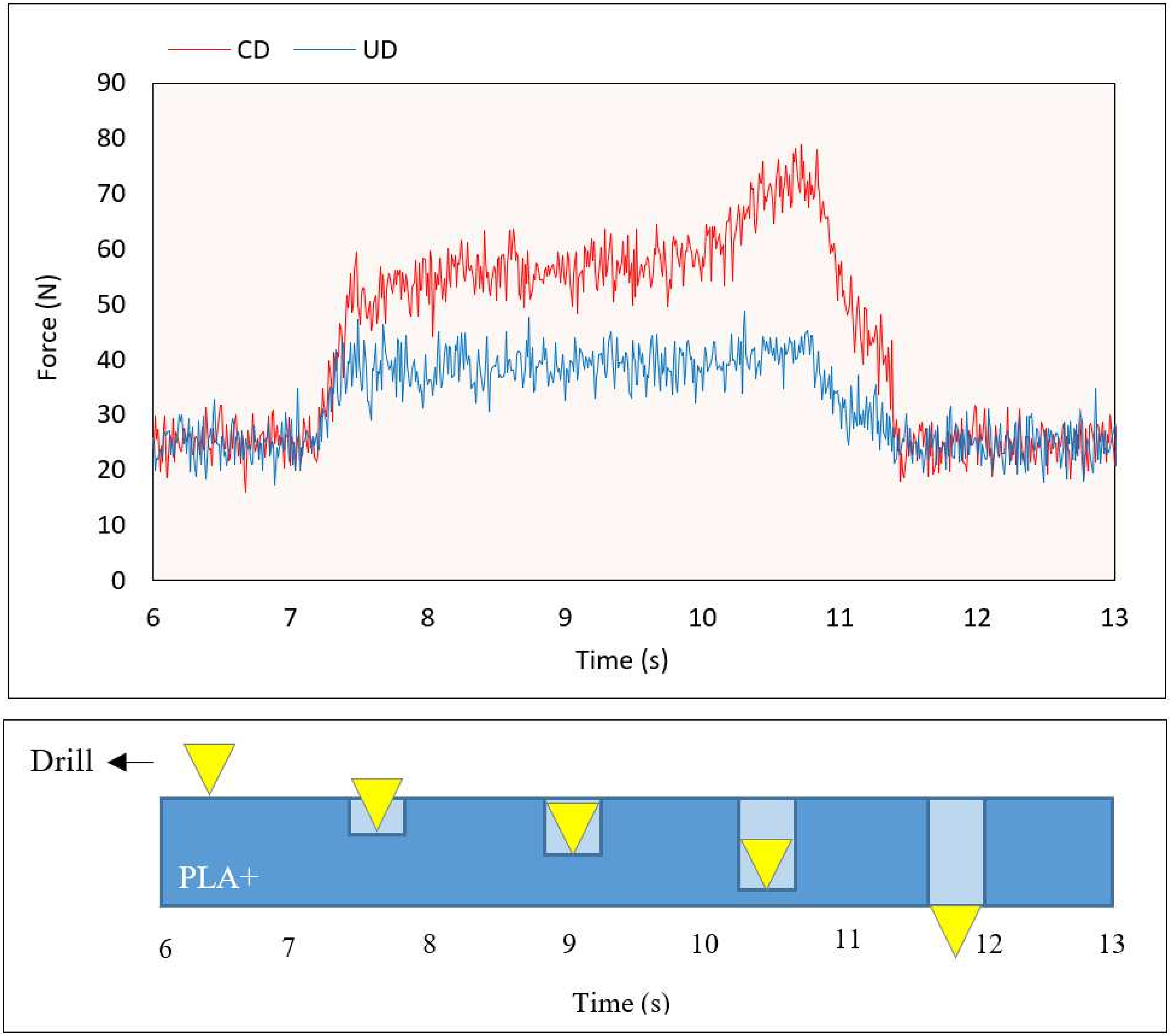

Figure 3

Thrust forces recoded by dynamometer in the experimental works.

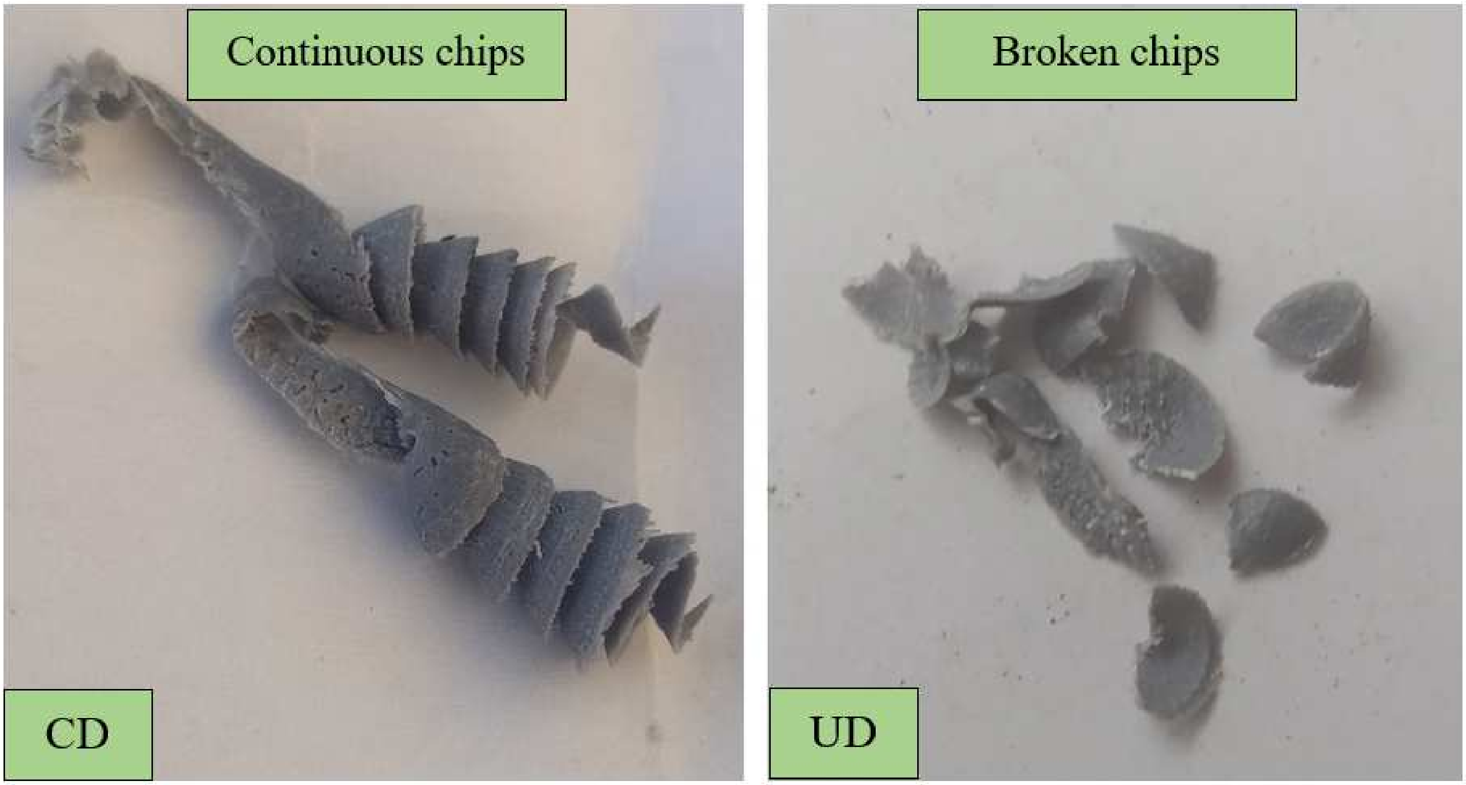

Figure 4

Broken chips in CD and UD.

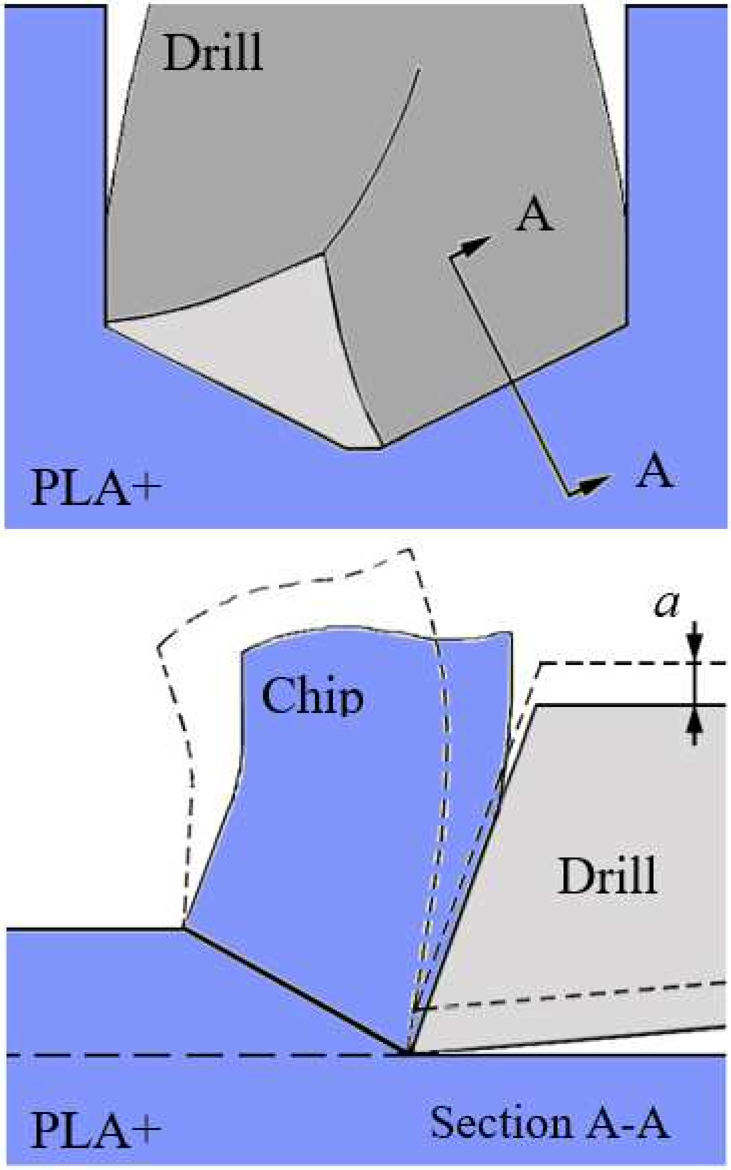

Figure 5

Drill vibration in cross section.

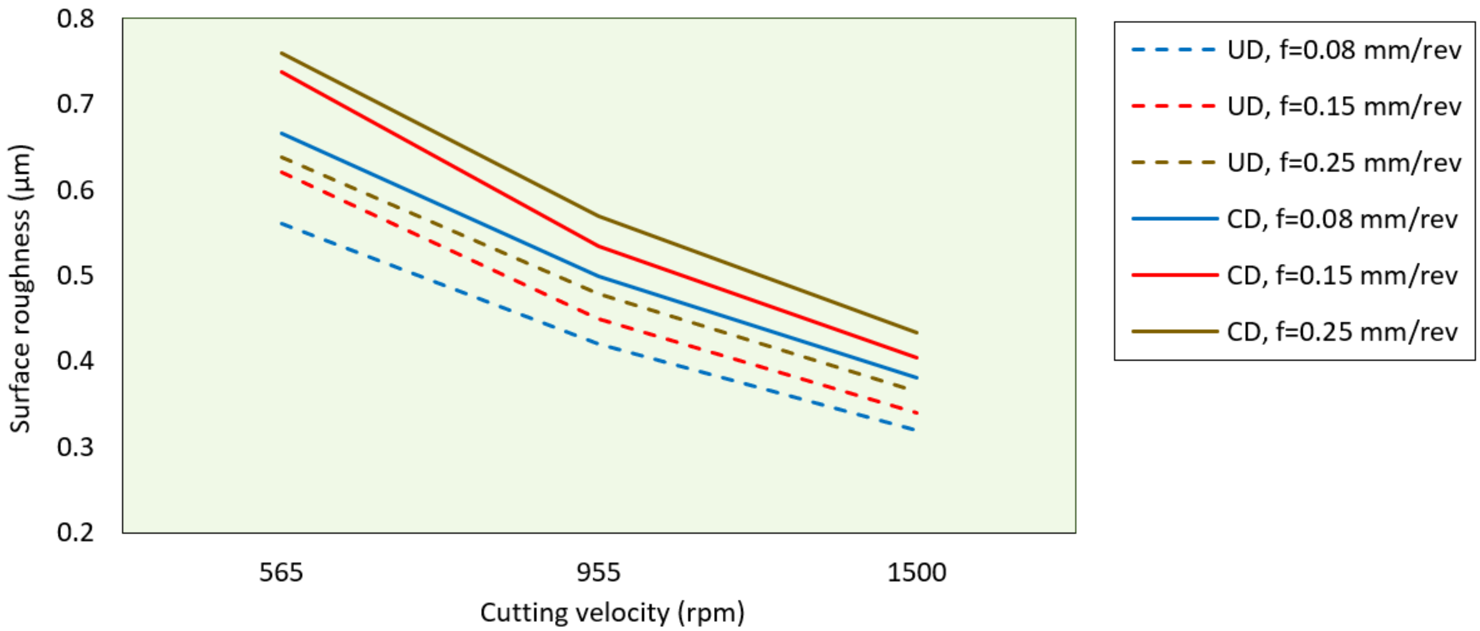

Figure 6

Surface roughness results at different cutting conditions in CD and UD.

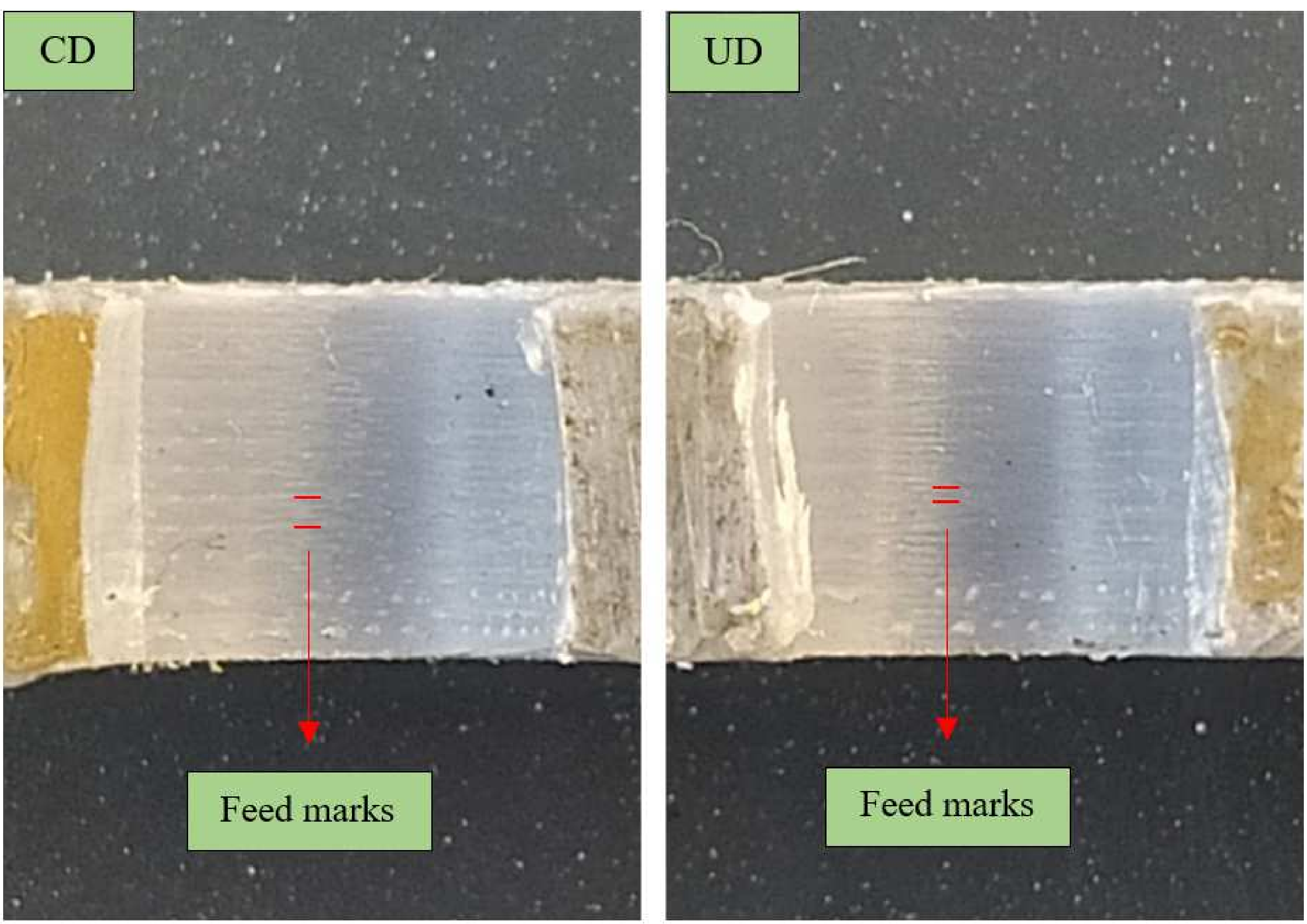

Figure 7

The inner wall of drilled holes in CD and UD.

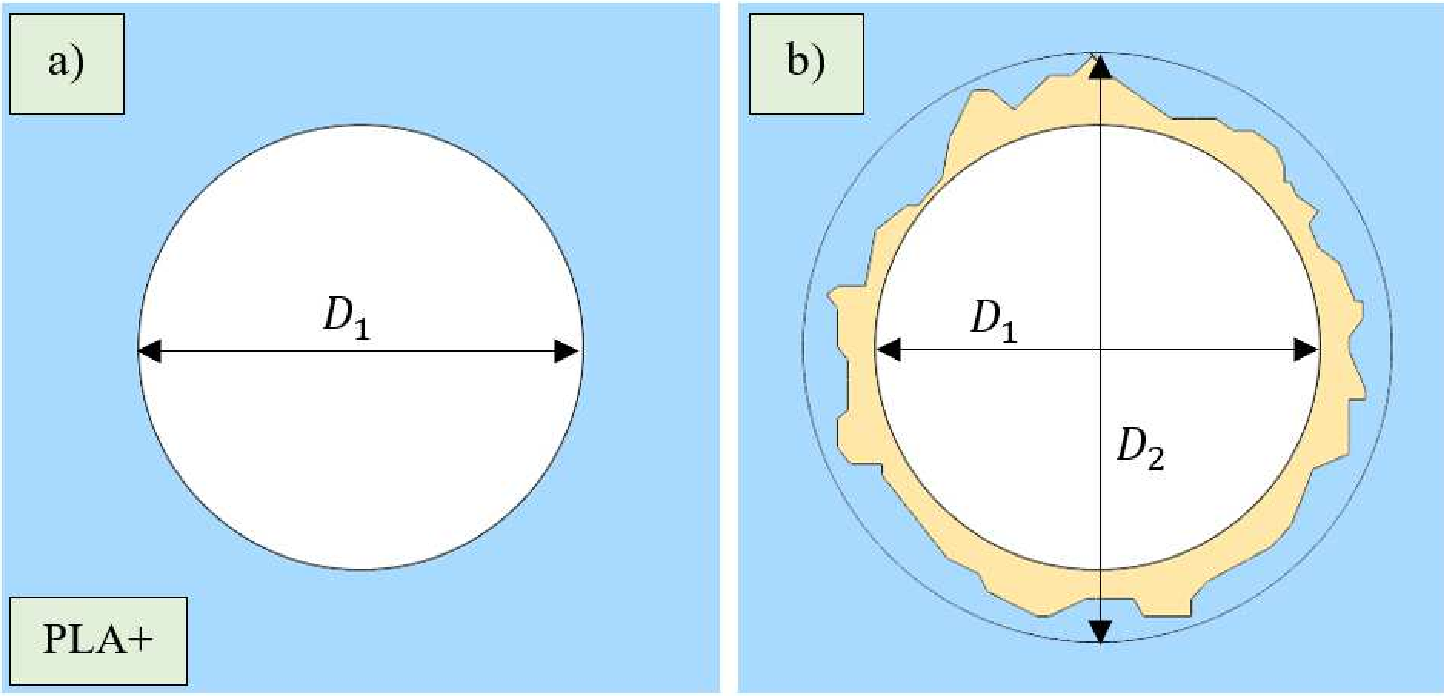

Figure 8

Drilled holes: a) an ideal hole without delamination and b) a hole with delamination.

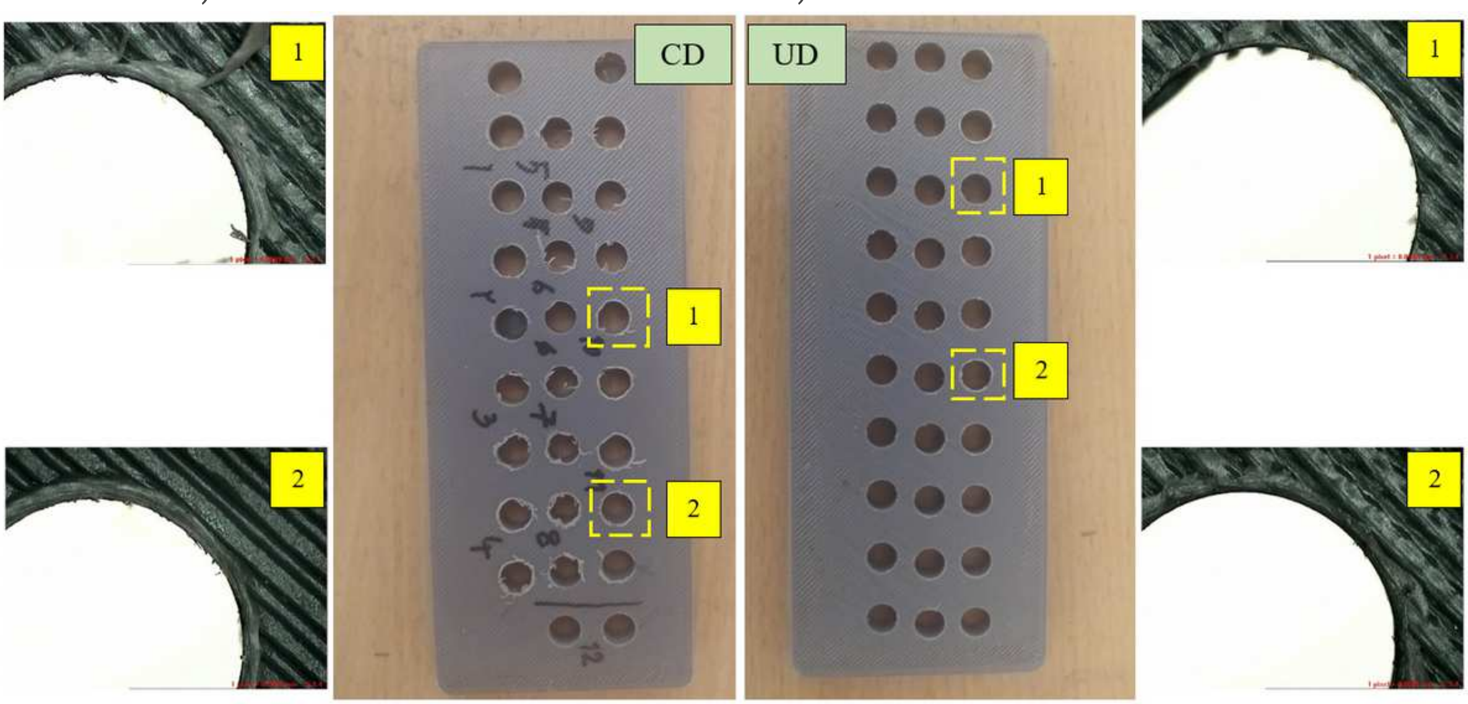

Figure 9

Drilled PLA+ during CD and UD including VMM images.

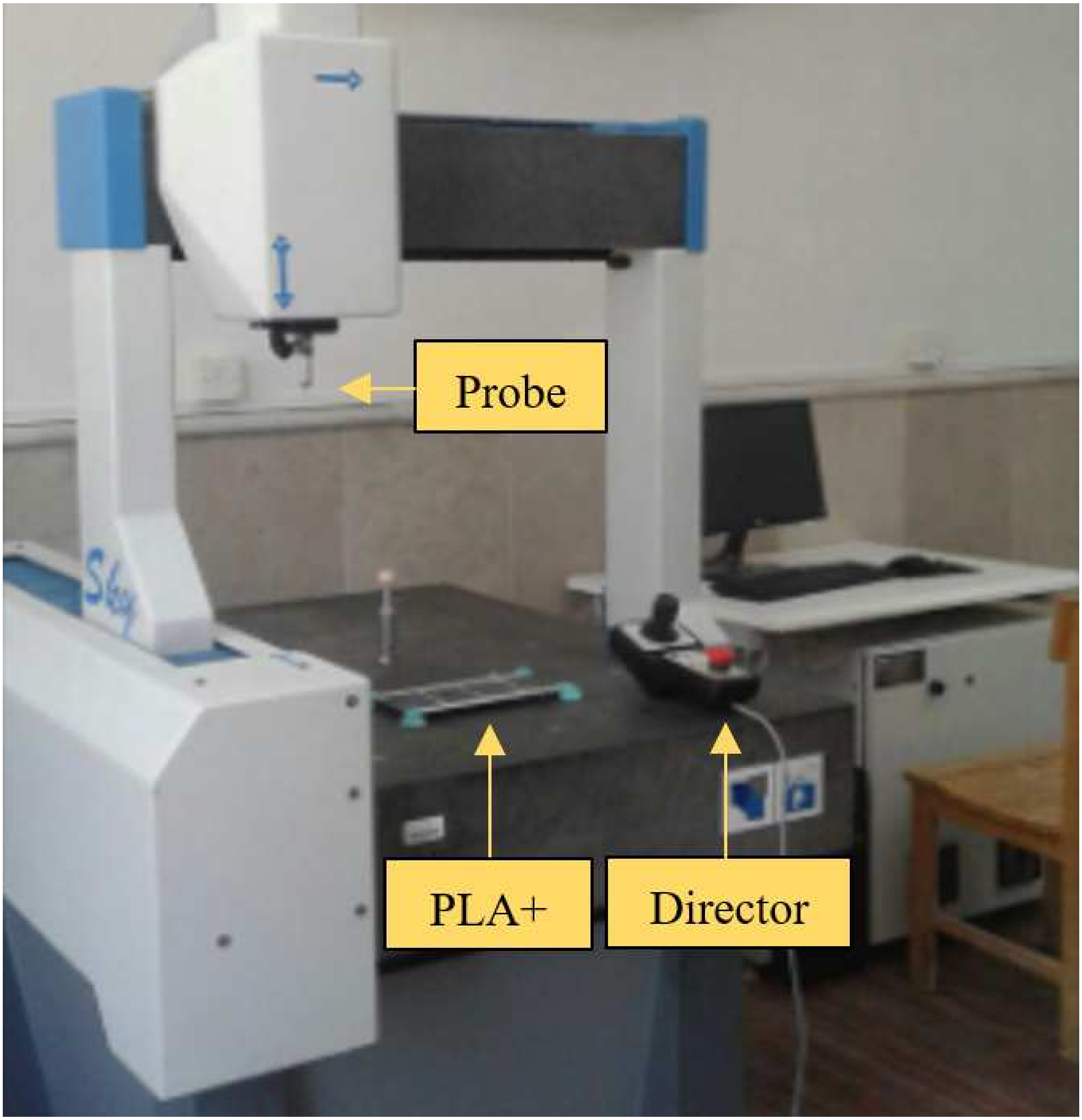

Figure 10

The CMM device.