ORIGINAL ARTICLE

Investigation of Optimum Milling Parameters in Micro Dimples Machining

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ABSTRACT – This research used a carbide ball nose end mill cutting tool to fabricate a micro dimple on the aluminium block. The problem is that the micro dimple should be fabricated with a better surface finish which is related to surface integrity and form accuracy of the dimple. The objective is to study the optimum CNC milling parameters for the micro dimple fabrication and analyse the surface integrity and form accuracy of the dimple. Based on three different parameters which is depth of cut, feed rate, and spindle speed, the better surface roughness and the diameter, depth of micro dimple are experimented using the carbide cutting tools to fabricate micro dimple and analyse the data using 3D confocal microscope. The better surface roughness, high form accuracy and surface integrity of micro dimple structure were achieved with the optimum CNC milling parameters. The high spindle speed, low depth of cut and low feed rate showed the best results for the surface roughness and form accuracy. The proposed parameters were high spindle speed of 3600 RPM, low depth of cut 0.25mm and low feed rate of 50mm/min.

INTRODUCTION

Nowadays, the demand for micro-component is increasing due to miniature components or equipment such as micro cameras, microdevice, microscopes and many more. Due to these high demands, manufacturers are seeking for the best fabrication process to produce micro components or parts. The micromachining can be used to fabricate micro features such as a micro dimple. With the high demand for micro-components, the manufacturers are seeking the best fabrication process to get the best end products for these components.

Micro dimple is a microfeature that was used in fabricating the lens. It can be used as a mold for lens forming. It can also be used in reducing the friction between two metals. The application of micro dimples is usually be used to improve oil lubrication, especially in automotive engines. The micro dimples usually are fabricated using EDM die sinking, electrochemical micromachining and grinding.However, there are constraints in fabricating micro dimples using electrochemical micromachining and EDM die sinking. One of the constraints in EDM is the accuracy and repeatability of positioning. Because multiple dressed electrodes may be required to machine a micro-hole at a specific location (Xpos, Ypos), the precision of the machine positioning will have the greatest impact on the hole's position, while the repeatability will have the greatest impact on the hole's size and shape [1]

A micro dimple is a microfeature that is widely used, for example in an application such as sensors and lenses (imaging). A mold with micro dimple features will be pressed on a specimen such as polymer, and the micro dimples will be copied onto the sample. To confirm the accuracy of the micro dimple of the samples during the process, the micro dimple insert should be accurately fabricated. A process such as electrochemical micromachining, EDM die sinking and grinding was reported as one promising technique to fabricate the micro dimple, however, the complicated process and high cost caused it not suitable for mass fabrication. At the same time, milling was also reported as one of the techniques to fabricate a micro dimple. Milling used a tool such as an end mill and ball nose to fabricate a feature at lower cost and less time [2].

However, some defects and problems may occur during this process such as the surface roughness, accuracy dimension burr. These constraints can be overcome by controlling the milling parameters such as spindle speed, rpm of the machine, depth of cut and the method of the milling whether dry or wet milling. In this research, different milling parameters will be carried out to obtain the accuracy of the micro dimples final form. Within this research, the accuracy of milling parameters can lead to a good micro dimples condition at the end. The aims of the research are as the following:

- To study the optimum milling parameters of micro dimples cutting.
- To analyse the surface integrity of the micro dimples.

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- To determine the form accuracy of the micro dimples.

In this project, the optimum milling parameters in fabricating the micro dimples will be investigated. The scopes of this project are as the following:

- Micro dimples fabrication using milling and equipment preparation.
- Form analysis of the suitable milling parameters.
- Analyse the results.

RELATED WORK

In our "smaller, lighter, faster, and cheaper" world, the demand for miniaturised goods and devices is growing and this has driven further miniaturisation of materials, devices, systems and processes. A micro dimple is a micro function that is typically used in applications such as sensors and lenses, for instance (imaging). On a sample such as silicone, a mould with a micro dimple mechanism will be pressed, and the micro dimples will be copied onto the sample. The micro dimple insert should be correctly produced to confirm the precision of the micro dimple of the samples during the process. Besides, micro dimples also have been used in the lubrication system in the engine mechanism as shown in Figure 1. This is because the dimple structure on a moving engine part functions as an oil reservoir. Earlier research showed that the dimple structure in the engine components could minimise erosion by about 30% - 50%. The dimple structure machining and the surface integrity are very important in order to determine the quality of the dimple. A quality dimple can be defined through its capability to reduce or increase the tribological characteristics of the rubbing or sliding surfaces. This dimple will be functioned as a reservoir and as a trap or filter in the lubricant. This will help the lubrication flow during the lubricating process.

The dimples structure and surface integrity are being defined through the different parameters during the process. There are two techniques in the development of the dimple structure through milling machining, vibration-assisted and traditional milling machining activities. Different micro-manufacturing techniques, such as wire electrical discharge machining (WEDM), pulsed laser ablation (PLA), and concentrated ion beam (FIB), have been developed, but they are difficult to tune and precisely monitor and may only apply to specific material groups. One of the processes to fabricate this dimple is through the milling process.

Milling Process

Based on the previous research, some of them used the ball end mill with an inclined system as one of the techniques for producing efficient and reliable micro dimple pattern manufacturing. As shown in Figure 1 the milling process of the micro dimple is used and this is because the ball end mill technique is an easy and less costly method of machining that can be used to create micro dimple patterns. A ball end mill is also popular for producing three-dimensional contour form on moulds and dies products that can be found [3]. The characteristics of the ball end mill are the same as the slot bit but the shape of the end is hemispherical. On the other hand, milling process is also known as a flexible process since it uses a combination of different cutting techniques and geometry of cutting tools that can create different dimple structures on the workpiece. This method was used since it was not a costly machining method and a simple method for fabricating micro dimples. Next, several issues should be considered such as to avoid tool breakage and vibration, the material removal volume should be decreased. Then, the instrument's edge radius as shown in Figures 2 and Figure 3 has an effect on the process of removal. When the uncut chip thickness is of the same order or less than the instrument's edge radius, the effective rake angle becomes highly negative, causing ploughing and related elastic-plastic deformation of the workpiece material to become much more dominant factors in the process. Then, as each tooth passes, a chip will not be produced. The cutting mechanism shift from ploughing-dominated to shearing-dominated and back to ploughing-dominated again within a single excursion of a tooth through the cut when the uncut chip thickness differs during a single engagement of a tooth in the cut. Next, the miniaturising of the end mills are required in order to process the micro-milling. A few characteristics need to be fulfilled in manufacturing the micro end mill such as grinding, coating, and calculations should take into account not only the precision of the edge shape but also the edge roughness.
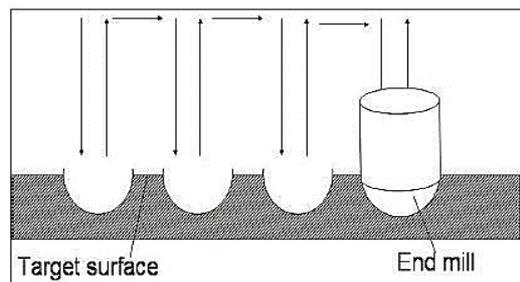
Figure 1: Milling process of micro dimples. (Source: Hassan et al., 2017)

Milling Parameters

Milling parameters such as depth of cut, spindle speed, feed rate, and machining condition, whether used wet or dry methods, are critical for obtaining high form accuracy and surface integrity of micro dimples. It is important to avoid vibration in the milling process and in the research, the researcher used three different cutting speeds, feed per tooth and depth of cut. It showed that vibration deteriorates the consistency of the machined surface, produces a larger burr, and decreases the life of the instrument. Following that, when using tungsten carbide tools, the cutting tool/workpiece material pair and the cutting edge radius had a combined impact on the chips produced during the subsequent revolutions, whereas the chips created with diamond tools were intact and separate [4]. Furthermore, the cutting force and thrust force were of the same order as a result of the cutting edge radius, and this cannot be overlooked. In the previous experiment, it would give a clear vision of how chip formation during the milling process. In micro milling homogeneous aluminium material, the chip forming process is very different from that in the traditional process of milling. Figure 3 shows the actual tooth path and chip thickness in the milling process. The size effect, which is understood as the increase of the particular cutting force with decreases in cutting thickness, is the most common phenomenon.
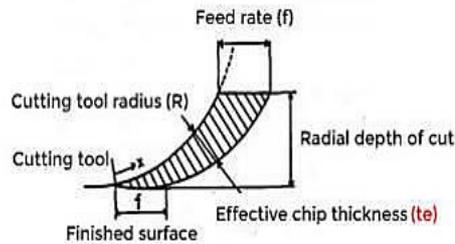
Figure 2: Actual tool path and chip thickness in micro-milling (Source: Niu et al., 2018)
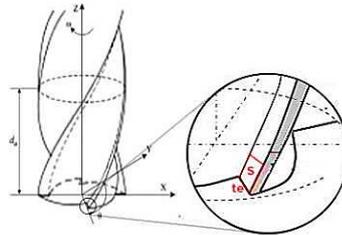
Figure 3: Cross-section of the chip generated in micro-milling (Source: Niu et al., 2018)

Besides, the parameters involved in this experiment were cutting speed and resulting the high-speed demonstration method provides the potential for better dimple shapes than the lower speed [5,6]. Once the elliptical vibration texturing (EVT) was used in the milling process, the vibration frequencies should be considered as the parameter in order to validate the texturing process, the precision of the micro-dimples was calculated and compared to an empirical model.

Electro Discharge Machining

One of the well-known techniques in micro mould manufacturing is electro-discharge machining (EDM). EDM wire cutting and its working theory is about applying some impulse voltage between electrode wire and workpiece through a servo structure-controlled voltage impulse source to get a certain gap when realising impulse discharge between electrode wire in the working liquid and workpiece. Sinker EDM and EDM wire cutting are EDM devices commonly used to produce moulding. With cavity style EDM, volume EDM, and also sinking EDM dies, hence Sinker EDM was named. The responsible technic of this EDM sinker is to use the planned cathode tools and erode the anode workpiece using the sparking phase of electrical discharge. EDMs are popular for making moulds, keyways, hex-shaped metal objects, and taped moulds with smooth finishes and can cut intricate sinker shapes. Sinker EDM is capable of machining new classes of high strength, heat resistance and hardness materials such as molybdenum, tungsten, columbium, and alloys [6]. Due to the sparking, anode and cathode need to have a spark gap to ensure the workpiece will not be affected due to the small particles of erosion.

METHODOLOGY

Work flowchart
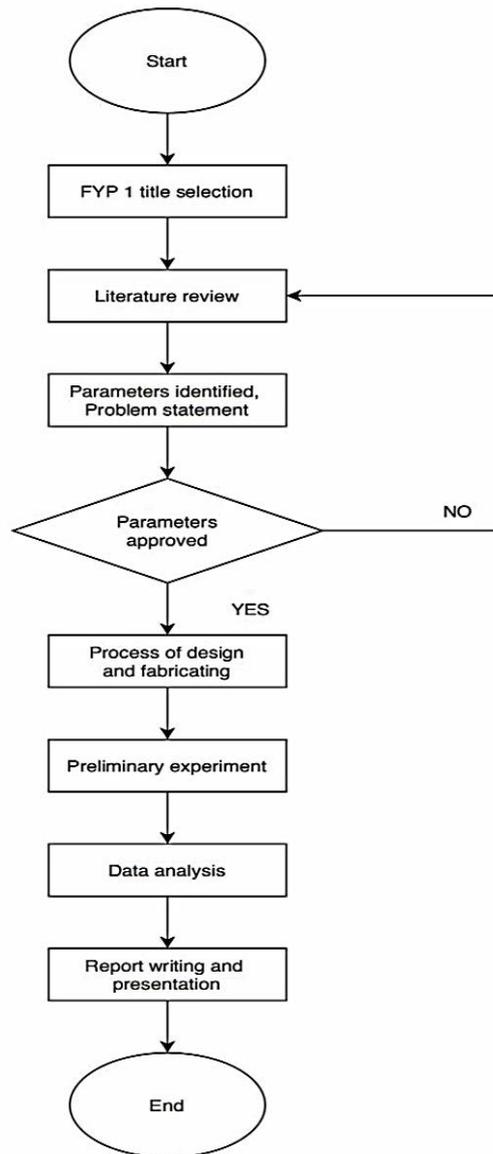
Figure 4: Flowchart for the workflow

Chosen Parameters

Firstly, to fabricate a micro dimple with good surface integrity and high form accuracy of the micro dimples a few parameters need to be selected to carry out this research. The parameters that will be used are depth of cut(mm), feed rate (mm/min) and spindle speed (RPM).

Tools

Tools that will be used to fabricate this micro dimple are a ball end mill as shown in Figure 5 and the milling machine that will be used is the NC Milling machine (MAKINO KE55) as shown in Figure 6 below. The tool size diameter that will be used is 5 mm with a round tip radius of 2.5 mm and the tools are usually made up of carbide and consists of two flutes. This tools' finishing is coated with Titanium Nitride (TiN) to provide high lubricity and increase chip flow in softer material. In comparison to uncoated tools, the tool's heat and hardness resistance allow it to work at 25% to 30% faster speeds in machining. These tools have a round tip that is used to machine curved details. They are used for milling slopes, rounded slots and others with a smooth finish. These tools can be used in milling into wood, plastic, metals and, etc. NC MAKINO KE55 can be used for the vertical milling process with a power of 5.6 kW and a maximum speed of 4000 RPM. This machine weight 300 kg and is controlled by CNC type Professional-JN.

Figure 5: Ball End Mill

Figure 6: NC milling machine (MAKINO KE55)

Workpiece material

The Aluminium Alloy block was chosen to be used for the micro dimple fabrication onto its surface. Aluminium Alloy and its alloys are used in most modern manufacturing processes because they possess high strength, corrosion resistance, conductivity, and durability properties. Table 1 below shows the mechanical properties of Aluminium Alloy 6061.

Table 1: Mechanical Properties for Aluminium Alloy 6061

Mechanical Properties	Metric
Young's Modulus	5GPa
Poisson's Ratio	0.33
Density (kg/m^3)	2700
Ultimate Tensile Strength	296.4 MPa
Strength Coefficient	562.5 MPa
Strain Hardness	0.5487
Yield Strength	45.8

The size of the workpiece is 50mm × 50mm × 29 mm as illustrated in Figure 3.4 below. During the milling process, the workpiece will be shaped in a micro dimple with a hexagonal shape. The Aluminium block needs to be squared and flattened the surface at first. Face milling will be carried out to ensure the surface is flat and smooth. A micro dimple with the shape of a moth's eyes has been designed as shown in Figure 7 below. The micro dimple is designed in a hexagon pattern by overlapping the circles and the radius of the dimple is 2.8mm with the depth of the dimples is 0.5mm.
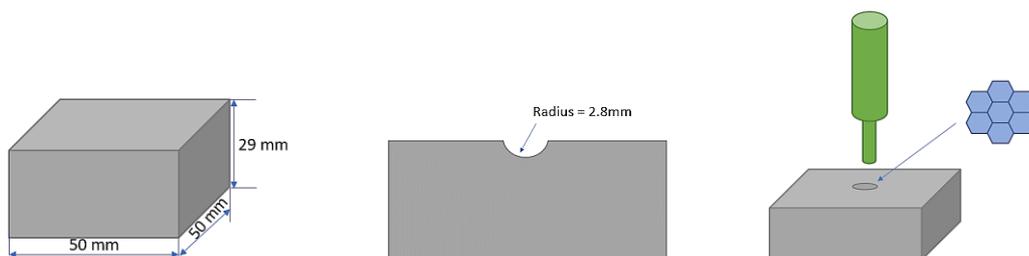
Figure 7: Aluminium block, dimple radius and dimple design

Milling Process

The milling process will be carried out using three different parameters and a dry-cutting method. The process begins with a 0.25 mm depth of cut and uses the feed rate of 50mm/min, 100mm/min, and 150mm/min. For each of the feed rates, different spindle speeds were used at 2200, 2900 and 3600 Revolution Per Minutes (RPM). Next, the process continued with 0.5mm for the depth of cut and the steps were repeated. The value for the RPM was calculated as shown:

$$RPM = \frac{1000 \times M/M}{\pi \times D} \tag{1}$$

where, RPM is revolution per minute, *M/M* is meters per minutes and *D* is diameter of the tool. In this research, aluminium is been chosen, so the value of M/M is 45 and the tool diameter is 5mm.

$$RPM = \frac{1000 \times 45}{\pi \times 5}$$
$$= 2864.79 = 2900 \text{ RPM}$$
$$25\% \times 2900 = 725$$

$$\text{Increase for 25\%}: 2900 + 725 = 3625$$
$$= 3600 \text{ RPM}$$
$$\text{Decrease for 25\%}: 2900 - 725 = 2175$$
$$= 2200 \text{ RPM}$$

Table 2: Design of Experiment

Depth of Cut (mm)	Feed Rate (mm/min)	Spindle Speed (RPM)
0.25	50	2200
		2900
		3600
	100	2200
		2900
		36000
	150	2200
		2900
		3600
0.5	50	2200
		2900
		3600
	100	2200
		2900
		3600
	150	2200
		2900
		3600

Measurements

A 3D Confocal Microscope was used to measure the micro dimples from the test specimen. The measurement of the micro dimple was carried out as it's able to verify and inspect the defects of the specimen and also its form accuracy and surface integrity.

The formation of burr, the diameter of micro dimples and the surface roughness of the microdimples were analysed by performing the microstructure analysis on the preparation sample specimen after the milling process. The difference in parameters was compared to each other to identify which parameters were the most suitable for fabricating micro dimples. Figure 7 shows the 3D Confocal Microscope machine used to conduct this analysis experiment. The OLS5100 laser microscope, designed for failure analysis and material engineering testing, blends outstanding measurement precision and optical performance with smart tools that make the microscope simple to use. This microscope can quickly and accurately calculate shape and surface roughness at the submicron level to simplify the workflow with reliable data. It also has Smart Lens Advisor to help the users choose the right objective lens for the roughness measurements.

Analysis

Analysis of Variance (ANOVA) is a statistical technique that separates observed variance data into different components to use for additional tests. ANOVA is used to analyse the mean differences of parameters between the groups of feed rate and spindle speed on the fabrication of micro dimple effect. In order to analyse the data collected from the experiment, the Analysis of Variance -(ANOVA) approach is implemented by using Microsoft Excel. In this study, two-way ANOVA was used to carry out the analysis. The effect of the independent variables on the predicted outcome, as well as their relationship to the outcome, was investigated using a two-way ANOVA test. The dimension of the micro dimple, depth of cut 0.25mm and 0.5mm will be determined for all three sets of experiments, then ANOVA will be applied by using the data average value. The alpha value was assumed to be 0.05. Before carrying out the AVOVA analysis, the null hypothesis will be assumed, stated as the following:

H0: The means of the observations by factor one are the same.
H1: The means of the observations by factor two are the same.
H2: There is no interaction between factor one and factor two.

After that, compare the F-value and F-critical value (Fcrit) on the ANOVA description; if the F-value is smaller than Fcrit, the null hypothesis is accepted; if the F-value is larger than Fcrit, the null hypothesis is rejected. It may also compare the P-value to the alpha value, which is 0.05; the null hypothesis is rejected if the P-value is less than 0.05; if the P-value is greater than 0.05, the null hypothesis is accepted. The inference that can be drawn from this study is whether the parameters interact to contribute to the development of micro dimples. The graphical method also can be used to analyse the data. The data collected is tabulated and converted into a graphical form in the graphical method to classify the parameters that had the greatest impact on the development of micro dimples.

RESULTS AND DISCUSSION

The measurement of the geometrical of the dimples was taken at the area of the dimple's centre. This measurement was measured using the 3D laser microscope. To begin with, the diameter of the dimples was measured from the shape of the hexagon of the dimples. In addition, the depth of the dimples were measured at the centre for each dimples and lastly, the surface roughness also measured in the machined area to investigate which parameters will have the lowest surface roughness. Figure 8 below shows the actual dimple on aluminum, while Figure 9 shows the magnified view of dimples under the 3D laser microscope.
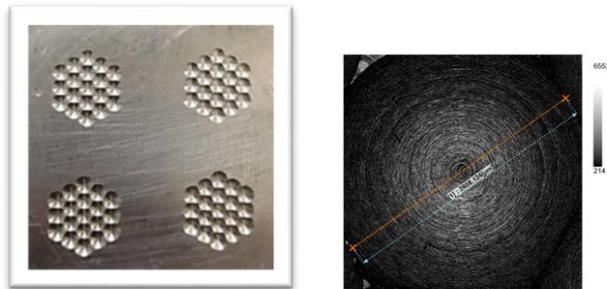
Figure 8: Actual dimple onto aluminium and the magnified view of dimples under a 3D laser microscope

(a)   (b)
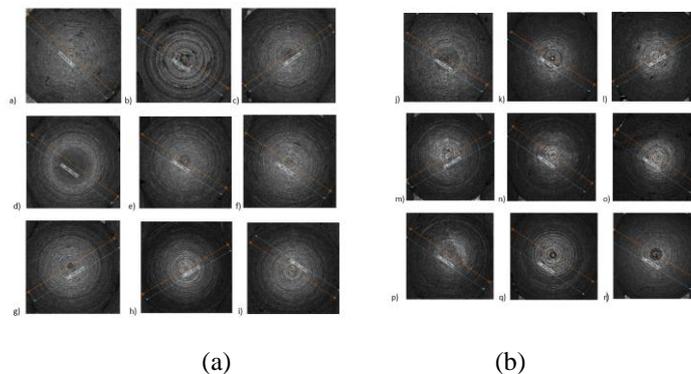
Figure 9: The diameter of the dimples by using (a) 0.5mm, and (b) 0.25mm depth of cut

Figure 9 above shows the intensity views for a single dimple representing the different parameters. To begin with, Figure 9 (a) using the depth of cut 0.5mm with different parameters setting were observed using a 3D Laser Microscope:

(a) the feed rate of 50 mm/min with spindle speed of 2200 RPM, b) feed rate of 50 mm/min with spindle speed of 2900 RPM, (c) feed rate of 50 mm/min with spindle speed of 3600 RPM, (d) feed rate of 100 mm/min with spindle speed of 2200 RPM, (e) feed rate 100 of mm/min with spindle speed of 2900 RPM, (f) feed rate of 100 mm/min with spindle speed 3600 of RPM, (g) feed rate of 150 mm/min with spindle speed of 2200 RPM, (h) feed rate of 150 mm/min with spindle speed of 2900 RPM, and (i) feed rate of 150 mm/min with spindle speed of 3600 RPM.

Figure 9 (b) shows the diameter of the dimples by using 0.25mm depth of cut with different parameter setting: Starting with (j) feed rate of 50 mm/min with spindle speed of 2200 RPM, k) feed rate of 50 mm/min with spindle speed of 2900 RPM, (l) feed rate of 50 mm/min with spindle speed of 3600 RPM, (m) feed rate of 100 mm/min with spindle speed of 2200 RPM, (n) feed rate of 100 mm/min with spindle speed of 2900 RPM, (o) feed rate of 100 mm/min with spindle speed of 3600 RPM, (p) feed rate of 150 mm/min with spindle speed of 2200 RPM, (q) feed rate of 150 mm/min with spindle speed of 2900 RPM, and (r) feed rate of 150 mm/min with spindle speed of 3600 RPM. The summary on the dimple measurement and the ANOVA for both cases 1 and 2 are shown in Tables 3 and 4, respectively.

Table 3: Dimple Measurement

Depth of Cut (mm)	Feed Rate (mm/min)	Spindle Speed (RPM)	Dimple Measurement (μm)		
			Diameter	Depth	Surface Roughness (Ra)
0.25	50	2200	2728.483	29.495	6.344
		2900	2802.000	21.161	5.223
		3600	2802.202	38.995	4.089
	100	2200	2781.318	28.771	4.886
		2900	2800.704	38.213	15.680
		3600	2799.053	43.895	8.396
	150	2200	2778.706	28.638	9.721
		2900	2809.848	32.610	9.802
		3600	2854.584	29.010	3.235
0.5	50	2200	2992.557	32.825	9.459
		2900	2804.354	23.262	6.301
		3600	2804.082	28.082	7.497
	100	2200	2892.195	44.3	11.139
		2900	2774.136	35.194	14.936
		3600	2810.754	33.055	12.704
	150	2200	2766.301	34.801	14.163
		2900	2757.282	25.105	4.360
		3600	2801.375	25.676	9.259

Table 4: Summary of the ANOVA for both Case 1 and Case 2

Null Hypotheses	Comparison of F-value to F-crit value	Comparison of P-value to 0.05	Status
Case(i): Micro Dimple Analysis by using Brass Electrode			
H_0	$F < F_{crit}$	Bigger	Do not reject
H_1	$F > F_{crit}$	Smaller	Reject
H_2	$F < F_{crit}$	Bigger	Do not reject
Case (ii): Micro Dimple Analysis by using Copper Electrode			
H_0	$F > F_{crit}$	Smaller	Reject
H_1	$F > F_{crit}$	Smaller	Reject
H_2	$F > F_{crit}$	Bigger	Do not Reject

CONCLUSION

The three cutting parameters, such as depth of cut, spindle speed, and feed rate, have a significant impact on the surface integrity and form accuracy of micro dimples. In this study, the machinability of micro dimples was studied through the milling machine by using a carbide ball nose cutting tool. Furthermore, the surface integrity can be analysed through the surface roughness. This is due to the fact that the lower the surface roughness, the better the surface integrity. Next, the form accuracy of the micro dimple can be measured by the diameter of the dimple. This means that the nearest the value to the target diameter, the higher the form accuracy of the micro dimple. Then, the spindle speeds affect both diameter accuracy and surface roughness but the feed rates only affect the roughness. Finally, the findings of this study demonstrated that a lower depth of cut, a lower feed rate, and a higher spindle speed can result in better surface roughness.

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