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Investigation of Ultrasonic Assisted Drilling (UAD) Parameters for Hole Making of Ti-6Al-4V using Taguchi Method

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ABSTRACT

Ti-6Al-4V is widely used in high-tech industries due to its lightweight, high strength and corrosion resistance. Nevertheless, machining Ti-6Al-4V is very challenging given its low thermal conductivity. Ultrasonic Assisted Drilling (UAD) is one of the best machining techniques. In the manufacturing industry, hole-making is the final step before the end product is produced. The selection of parameters is crucial in obtaining accurate hole accuracy and a smooth surface finish. Cutting speed, feed rate, frequency, amplitude and tool material are important parameters in machining using UAD. Therefore, the optimisation of the combination of each of these parameters is pertinent in obtaining the best machining results. Screening parameters are widely used in optimising machining parameters. Taguchi is a statistical method that assists in optimising the experiments to be conducted. The expected findings from this study will facilitate the removal of insignificant parameters that could be used before proceeding to the actual runs. The impact of this study is to reduce costs, save time, as well as employ sustainable machining techniques.

Keywords:
Ti-6Al-4V, Ultrasonic Assisted Drilling (UAD), Hole Accuracy, Surface Roughness, Taguchi

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1. Introduction

The demand for titanium alloys in the industry is increasing, especially in aerospace. Ti-6Al-4V is a lightweight metal with a high strength-to-weight ratio, good heat transfer efficiency and strong corrosion resistance [1]. In airframes, titanium alloy is used for general structural material, bolts, and fasteners. However, Ti-6Al-4V is a difficult material to machine due to its low heat generation, high material hardness, and the creation of burrs during the machining process, which affects the surface smoothness [2-4].

The number of mechanical fasteners in a typical fighter aircraft might be in the range of 200 000 – 300 000, whereas a commercial airliner or transport aircraft can have as many as 1 500 000 to 3 000 000 fasteners, depending on the aircraft size. A hole has to be drilled for each of these fasteners and then the fastener has to be installed in each hole [5]. The joints are the weakest portion

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of any structure, its design is critical and performed under extreme precaution by drilling good-quality holes. Therefore, having hole quality is important. High rejection rates of aviation components, up to 60%, are a result of poor hole quality during final assembly, a complex problem that requires ongoing research to resolve. Hence, it is critical to keep the number of rejected parts due to poor hole quality under control [6]. While the joints are the weakest portion of any structure, its design is critical and performed under extreme precaution by drilling good-quality holes.

A drilling operation is the final process for manufacturing production and is also an important element that determines the quality of each material that can be effectively produced. The damage caused by the drilling process remains a drawback for the industry as it results in losses in terms of cost and production time. Among the damage that arises after the drilling process is completed is associated with the accuracy of the hole. The result of the drilling might be rejected and requires secondary machining operations to repair the holes, which leads to additional time and cost [7].

The challenge in machining Ti-6Al-4V material is producing an end product with good hole accuracy due to the material's difficulty in machining and low thermal conductivity [8]. In the industry, the main factor used to evaluate the accuracy and quality of the drill hole is the value of the deviation of the diameter of the hole. The diameter of the drilled hole is influenced by the feed rate and the cutting speed. The heat created during the drilling operation affects the size of the hole. This generated heat may cause the drill bit and workpiece to expand. Once the drilling is complete, the generated heat will be dissipated, resulting in the shrinking process. The diameter of the drill hole may increase as a result of heat expansion and contraction [9].

This experiment aims to investigate the effect of Ultrasonic Assisted Drilling (UAD) parameters, namely cutting speed, feed rate, frequency and amplitude on the machining performance (hole accuracy and surface roughness) for Ti-6Al-4V material under a dry condition. The significant parameters at the screening stage will be used for an experiment run at the optimisation stage. Additionally, this study aligns with Sustainable Development Goal (SDG) 9: Industry, Innovation and Infrastructure, which encourages scientific research to enhance the technological capabilities of the industrial sector toward Sustainable Industrial Development.

1.1 Overview of Titanium

The increasing application of titanium alloy may be seen in several industries, especially in aerospace [10]. Ti-6Al-4V is an extensively utilised material due to its lightweight, strength, uniqueness, and good weight-to-strength ratio. Given its high strength and low density, titanium has an outstanding weight-to-strength ratio, allowing it to be used to reduce aircraft weight without affecting structural strength [11-13]

Thermal expansion refers to the tendency of a material to change shape and volume in response to variations in temperature. As a result of its corrosion resistance and naturally low thermal expansion rate, Ti-6Al-4V is a durable material that is well suited for usage in the aerospace industry [14].

Ti-6Al-4V contains about 90% Titanium, 6% of aluminium, and 4% of vanadium [15]. The weight-to-strength ratio of metal is one of the elements considered when constructing an aerospace airframe. Aircraft engineers need to select metals with high specific strength in order to reduce fuel consumption and maintain high manufacturing standards [13]. Ti-6Al-4V has a high weight-to-strength ratio in comparison to other metals, with a density of 4400kg/m^3 and yield strength of 1000MPa, making it an excellent material for airframe construction.

The strength of a material can be assessed based on its yield strength, corresponding to the point at which the material begins to permanently deform when the maximum level of stress is applied.

Due to the difficulty of deforming Ti-6Al-4V, a stronger cutting tool is required. Titanium alloys do not react with other materials at room temperature. However, when the temperature of titanium alloys increases and exceeds 500°C, the reaction between titanium alloys and other metals such as cutting tools increases significantly, thereby posing a challenge during machining [16].

1.2 Ultrasonic Assisted Drilling (UAD)

State-of-the-art components of the aerospace and automotive industry go hand in hand with the use of high-performance materials. Like super alloys material. This material exhibits specific characteristics such as high strength at high temperatures, a good strength-to-weight ratio and others. These features are suitable in terms of technical requirements but come along with poor machinability.

For this reason, there is an increasing need for improved machining techniques. Ultrasonic Assisted Drilling (UAD) provide enhancement for different cutting process ranging from drilling, milling, turning and grinding [17-18]. Employing defined vibration, superimposed on the tool movement, improve chip breaking, increases tool life, minimize processing times and achieves higher part qualities.

The machining process in manufacturing that is commonly applied is the drilling process. The main challenge in the drilling process when it involves drilling materials that are difficult to machine to produce the final product according to quality with high production requirements. Approximately 40% to 60% of material is removed throughout the aerospace component drilling process [11].

Materials that are difficult to drill will present challenges in the form of surface roughness, tool wear and hole accuracy. Therefore, to overcome this problem ultrasonic-assisted drilling (UAD) was developed to overcome this problem. Ultrasonic-assisted drilling is a highly effective machining technique that can be used in place of conventional drilling. The quality of machining produced by UAD is better than CD [19].

The UAD mechanism is quite similar to that of the CD in that the workpiece is removed using a drill bit. The difference between the two drilling methods is that the UAD employs an impulsive motion trajectory [20].

During the UAD drilling process, the drill bit moves according to the rotation towards the workpieces with the assistance of ultrasonic frequency (16 - 40 kHz). A sinusoidal wave can be utilised to approximate the motion of the cutting edge [20].

When an alternate current (AC) is supplied to the ultrasonic processor control, the frequency of the input supply is amplified. The electromechanical transducer receives this high-frequency input signal and converts it to ultrasonic vibration. This enables the instrument to vibrate longitudinally. The vibration amplitude is increased by using an ultrasonic tool holder. Additionally, it directs and concentrates the vibration toward the tool tip holder [16].

1.3 Machining Parameter for UAD

Machining is a process that eliminates superfluous material through the efficient use of cutting tools. Since the dawn of machining, metalworking has been seen as a difficult activity, as improper parameter selection can have a detrimental effect on the cutting tool and the entire operation, resulting in lost time and material costs. Metal drilling is considered the most challenging machining operation since it involves the removal of material from a depth. High temperatures generated during this type of material removal might stymie drilling progress by producing tool wear and eventually tool failure. Often, in the case of difficult-to-cut metals, drilling operations are regarded as difficult jobs, as there is a risk of damaging cutting tools due to high temperatures, and tool wear is greater than in most machining processes. Additionally, if the tool is unable to subjugate the workpiece, it will fail catastrophically [21]

Five (5) important UAD parameters will be discussed in this study, namely, feed rate, cutting speed, amplitude, frequency and tool.

2. Methodology

The Taguchi technique is a tool for designing experiments in various fields. The strategy improves response quality with the least amount of experimentation, time, and money. Noise factors are production processes that cause the output performance of a product to diverge from its original design in quality engineering. Taguchi parameter design is a valuable method in the field of resilient engineering. Robust design engineering is a crucial tool for obtaining product and process conditions that are very sensitive to the different factors that influence the manufacturing and delivery of high-quality products at low costs. Robust design, according to the Taguchi technique, is the best way to reduce the impact of noise effects on slot cutting performance.

The signal-to-noise ratio (SNR) is the summary statistic, and it is used as the response variable in statistical analysis. The decision is based on the experiment's purpose. There are three specific goals in the response surface work as depicted in Table 1. The present study uses the SNR based on the smaller the better to minimise the response

Table 1
SNR-specific goals in the response surface

Type of SNR	Goal
The smaller the better	To minimize the response.
The larger the better	To maximize the response.
The target is the best	To achieves targeted value.

In the screening stage, the Taguchi design technique on Minitab Statistical Software was chosen due to its ability to reduce variation in the design stage. Cutting speed, feed rate, frequency, amplitude vibration and tools were all investigated for the selected variables. The L8 matrix was used to design a total of eight (8) runs. Surface roughness and hole accuracy (entrance and exit) will be measured as part of the machining process. Then, during UAD trials, all of the machining parameters affecting machining performance were screened. In order to proceed with the study, variables that were regarded as insignificant factors were discarded as the analysis would only focus on the most relevant variables affecting machining performance. These procedures entail the research flowchart and the experiment design process as shown in Figure 1 and Figure 2 respectively.

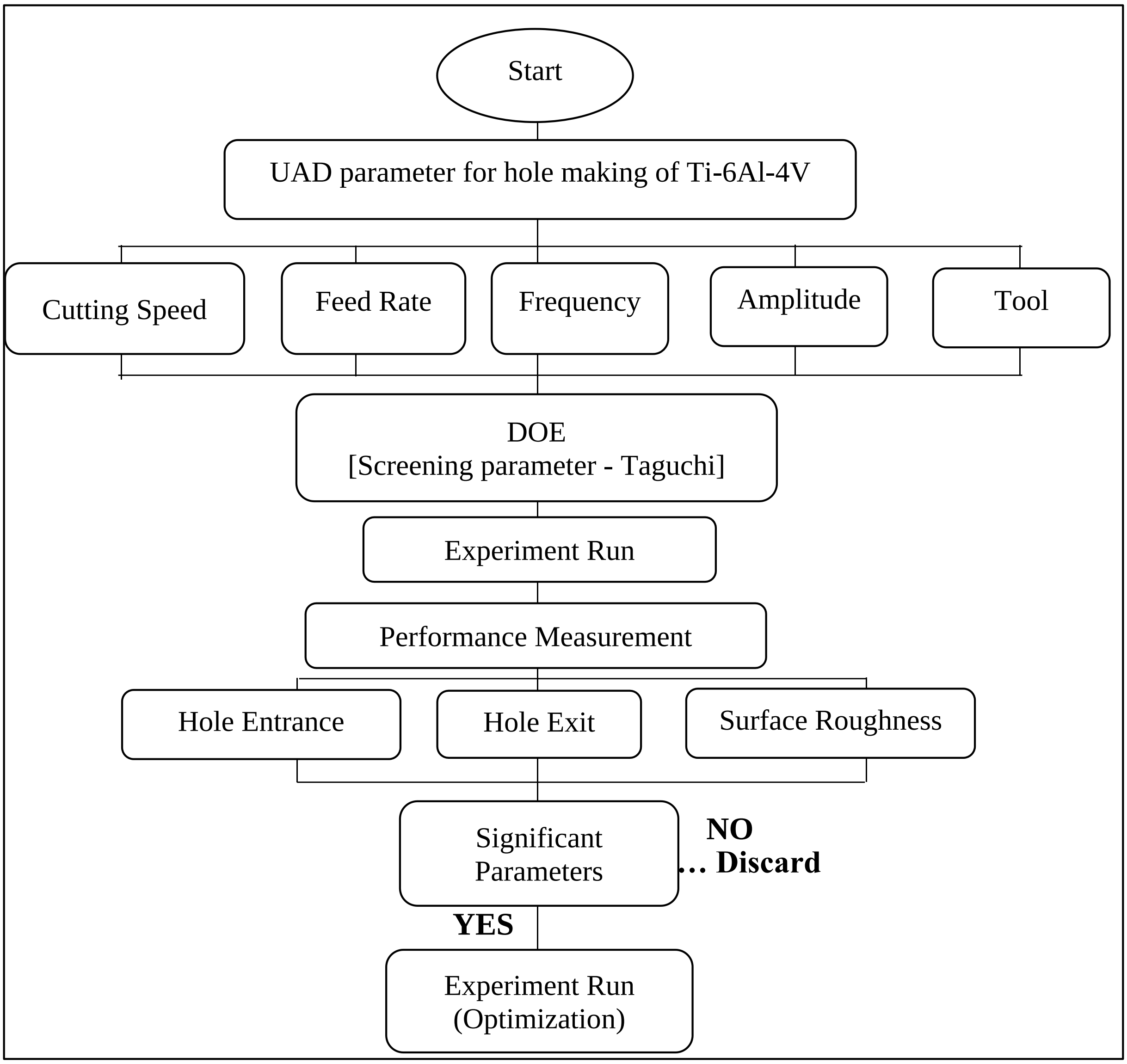


Fig. 1. Research flowchart

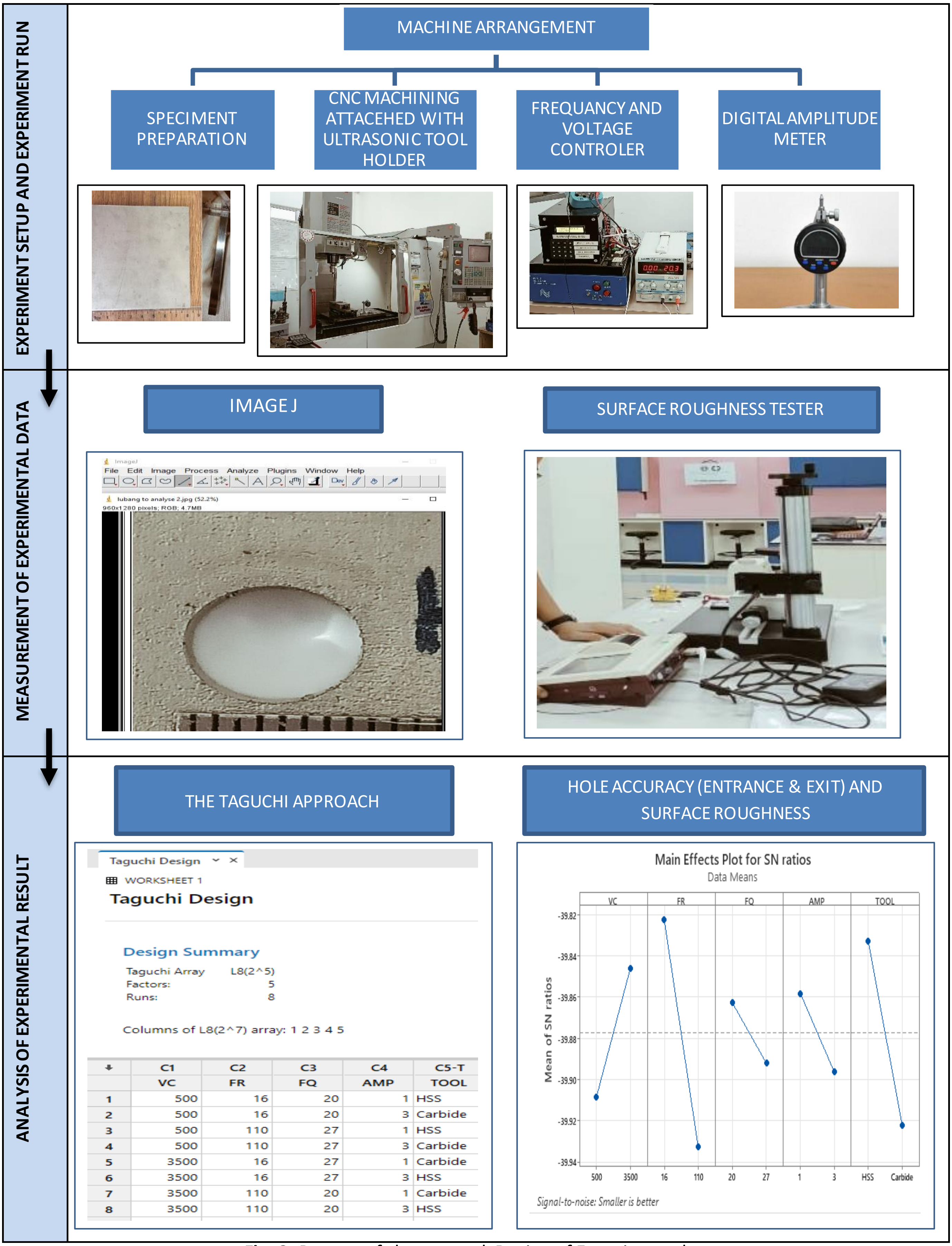


Fig. 2. Process of the research Design of Experimental

3. Experiment Detail

3.1 Work Pieces Material

Titanium alloy Ti-6Al-4V was employed in this research. Ti-6Al-4V is an alpha-beta titanium alloy in which the alpha phase is stabilised by aluminium and the beta phase is stabilised by vanadium. Tables 2 and 3 show the chemical, physical, and mechanical properties of this material, respectively.

Table 2
Chemical composition of Ti-6Al-4V

Weight %	Ti	Al	V	Fe	N	C	O	H
Max.	89.40	6	4	0.25	0.05	0.08	0.2	0.015

Table 3
Mechanical properties of Ti-6Al-4V

Property	Typical Value
Tensile Strength MPa	1000
0.2% Proof Stress MPa	910
Elongation Over 2 Inches %	18
Reduction in Area %	20
Elastic Modulus GPa	114
Hardness Rockwell C	36

As shown in Figure 3, the workpiece is a rectangular bar type with dimensions of 80mm x 80mm x 6mm for this experiment

Fig. 3. Workpiece Flat Bar 80mm x 80mm x 6 mm

3.2 Cutting tool

A cutting tool is any tool used in any machining operation that involves shear deformation and cutting action to remove metal from a workpiece. A cutting tool or cutter must be made of a tougher material than the material to be machined. For each new run experiment, new cutting tools were employed to generate a better outcome from each run with a high surface polish of the machined surface.

In this research, a TiN carbide twist drill with a tool diameter of 8 mm is utilised for drilling operations. Based on industrial uses, the literature and tool manufacturer's advice, a solid carbide twist drill with a 140-point angle and 35 helical angles will be utilised to drill titanium alloy Ti-6Al-4V. The specifications of the cutting tool are listed in Table 4.

Table 4
Specifications of the cutting tool

Base Material	Number of cutting edge	Diameter (mm)	Helix Angle
TiN Carbide	2	8	35
HSS	2	8	35

3.3 Drilling parameter

The Ti-6Al-4V drilling parameters considered in this experiment are cutting speed, feed rate, frequency vibration, and amplitude vibration. The value of each UAD parameter is presented in Table 5.

Table 5
Machining parameters for the experimental run

Machining Parameter		
Cutting speed (rpm)	500	3500
Feed rate (mm/min)	16	110
Frequency vibration (kHz)	20	27
Amplitude vibration (µm)	1	3

The Taguchi statistical technique was utilised to discover the control elements that primarily influence machining performance, such as surface roughness and hole accuracy (entrance and exit). For the experimental design (DOE), the Taguchi approach was employed to determine other major impacts, such as the interaction between drilling machining parameters. It is an effective strategy for resolving problems with a small number of trials.

The drilling parameters used at the screening stage are summarized in Table 5. Besides that, TiN Carbide and High-Speed Steel (HSS) drill bit with 8 mm diameter will be used in the data screening process to assess the effect of the drill bit.

Based on the Taguchi statistical technique, the five (5) factors and two (2) levels employed in this experiment are shown in Table 6, which necessitates the execution of eight (8) runs.

Table 6
Experimental run for parameter screening

Std	Run	Factor 1 Cutting speed (rpm)	Factor 2 Feed rate (mm/min)	Factor 3 Frequency (kHz)	Factor 4 Amplitude (μm)	Factor 5 Tools
2	1	500	16	20	3	Carbide
3	2	500	110	27	1	HSS
7	3	3500	110	20	1	Carbide
1	4	500	16	20	1	HSS
8	5	3500	110	20	3	HSS
4	6	500	110	27	3	Carbide
6	7	3500	16	27	3	HSS
5	8	3500	16	27	1	Carbide

The analysis used in this screening stage is the S/N ratio - the smaller the better, which is based on the results of minimum surface roughness and minimum hole accuracy (entrance and exit) in improving the machining workpiece results. The significant parameter analysed at the screening stage will be used for an experiment run at the optimisation stage.

3.4 Experimental Run

In the early stages of machining, drawings are prepared using AutoCAD software to set the coordinates of the holes to be drilled. These coordinates will be programmed into the CNC machine. At CNC Machine-HAAS (VF-1) 3-Axis vertical, an ultrasonic tool holder BT40 complete with accessories must be mounted. Install the drill bit in the tool holder and tighten the fastener. The workpiece is neatly secured onto the cutting slot. A digital amplitude measuring device is used to set amplitude values based on different frequency values and voltage value adjustments. The minimum and maximum voltages are 15 and 48 volts, respectively. The UAD run was performed as highlighted in Table 6 after the amplitude had been set. Figure 4 depicts an experiment run procedure.

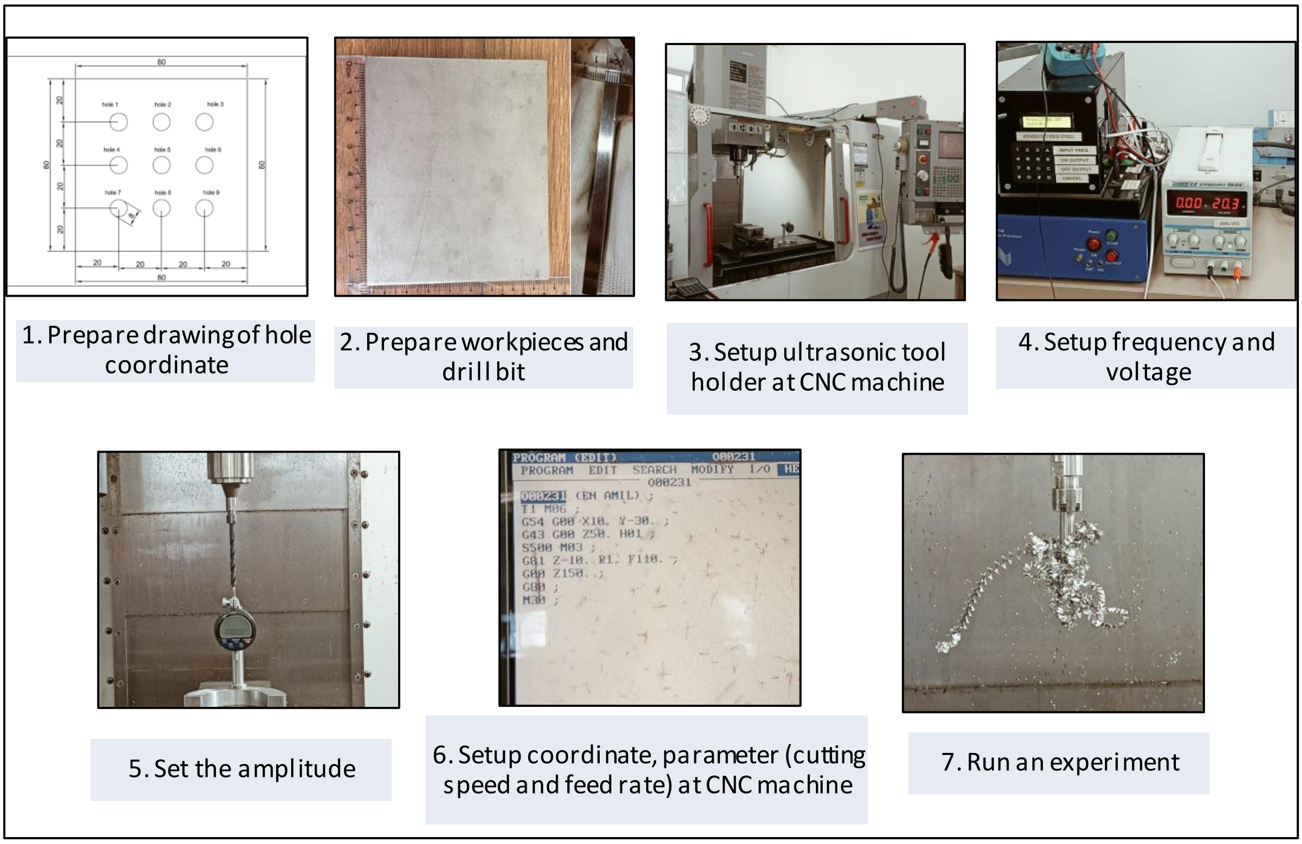


Fig. 4. An experiment run procedure.

4. Results and Discussion

The result discusses three (3) responses: hole accuracy (entrance), hole accuracy (exit) and surface roughness. The findings of the Taguchi Method analysis for five (5) primary parameters, namely cutting speed, feed rate, frequency, amplitude, and tools for the three responses are discussed in this part.

4.1 Hole Accuracy (Entrance)

Figure 5 depicts that the percentage of hole (entrance) accuracy is in the range of 96% to 99%, with hole 6 producing the best hole accuracy (entrance) with an accuracy value of 99.84%. The production of high heat by high-cutting speed is demonstrated in holes 5, 7 and 8 as presented in Figure 6. Therefore, a lower-cutting speed is suitable to produce hole accuracy.

The main effects plot for SN Ratio presented in Figure 7 depicts signal-to-noise: Smaller is better by using the drilling parameters comprising a cutting speed of 500 rpm, feed rate of 110mm/min, frequency of 27 kHz, amplitude of 3 μm and carbide as the tool. This suggests that carbide tools are more significant than HSS.

The main parameters according to the ranking that played a role in the accuracy of the entrance are summarized in Table 7. The main parameter affecting the drilling results of Ti-6Al-4V is the feed rate [22]. The feed rate refers to the cutter's relative velocity as it moves through the material being cut. The feed rate is directly related to the movement of the tool and that of the workpiece. During the drilling process, the contact between the drill bit and the workpiece is minimal at a high feed rate.

High frequency and amplitude result in more precise hole accuracy. As amplitude increases, the hole expansion decreases [23].

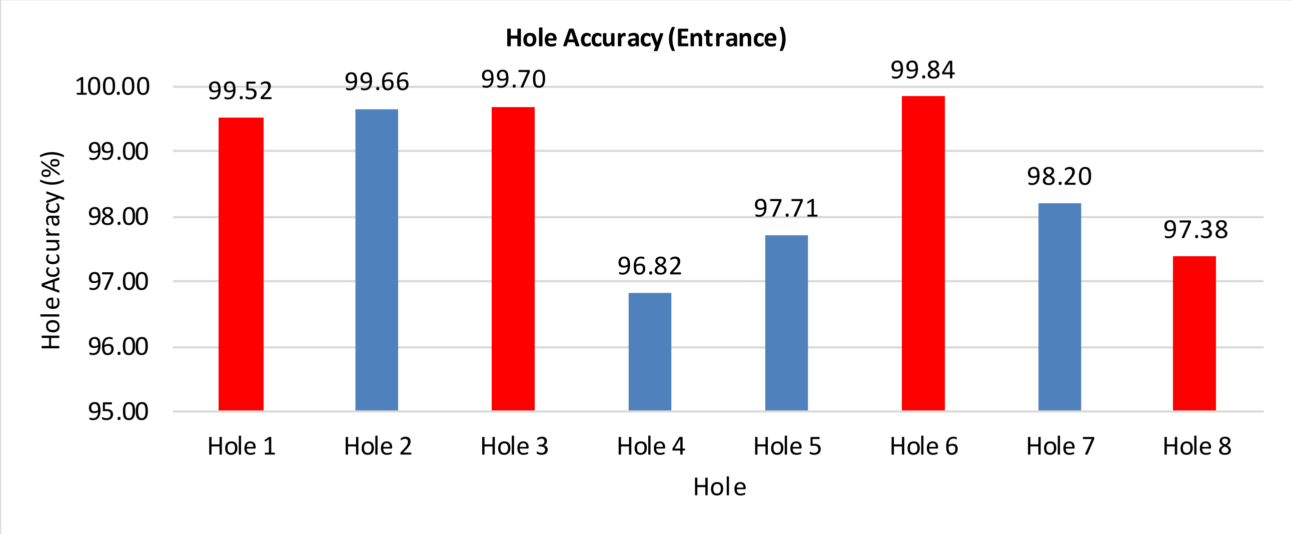


Fig. 5. Graph of Hole Accuracy (Entrance)

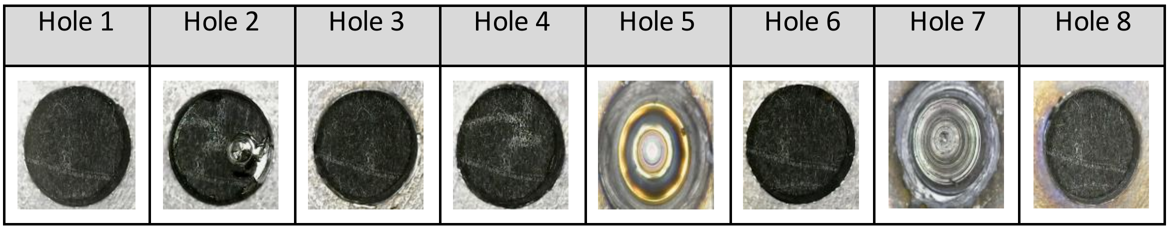


Fig. 6. Pictorial view of the hole entrance

Table 7
Response Table for Signal to Noise Ratios

Level	VC	FR	FQ	AMP	TOOL
1	-39.91	-39.82	-39.86	-39.86	-39.83
2	-39.85	-39.93	-39.89	-39.9	-39.92
Delta	0.06	0.11	0.03	0.04	0.09
Rank	3	1	5	4	2

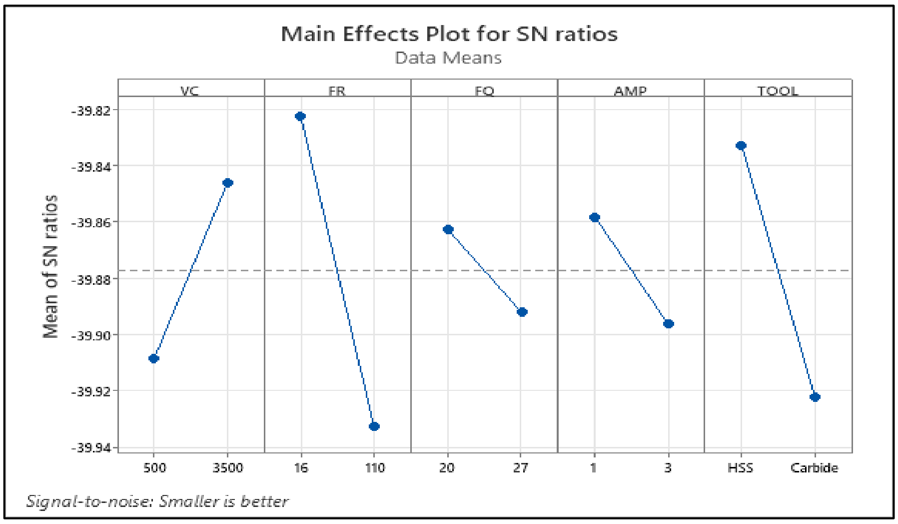


Fig. 7. Signal-to-noise: Smaller is better for the hole entrance

4.2 Hole Accuracy (Exit)

The most commonly utilised materials for drilling titanium alloys are HSS and carbide. HSS bits are suitable for drilling virtually any metal. However, HSS drill bits work optimally only under ideal conditions due to a lack of hardness at elevated temperatures.

Based on Figures 8 and 9, the cutting speed of 3500 rpm is not significant when using HSS-type tools as in holes 5 and 7. The drilling temperature increased in line with an increment in the speed and feed rates. In sustainable drilling (dry condition), high-cutting speed and HSS tools are not suitable for use. HSS drill bits exhibit significant plastic deformation, which contributes to the tool's short life [8].

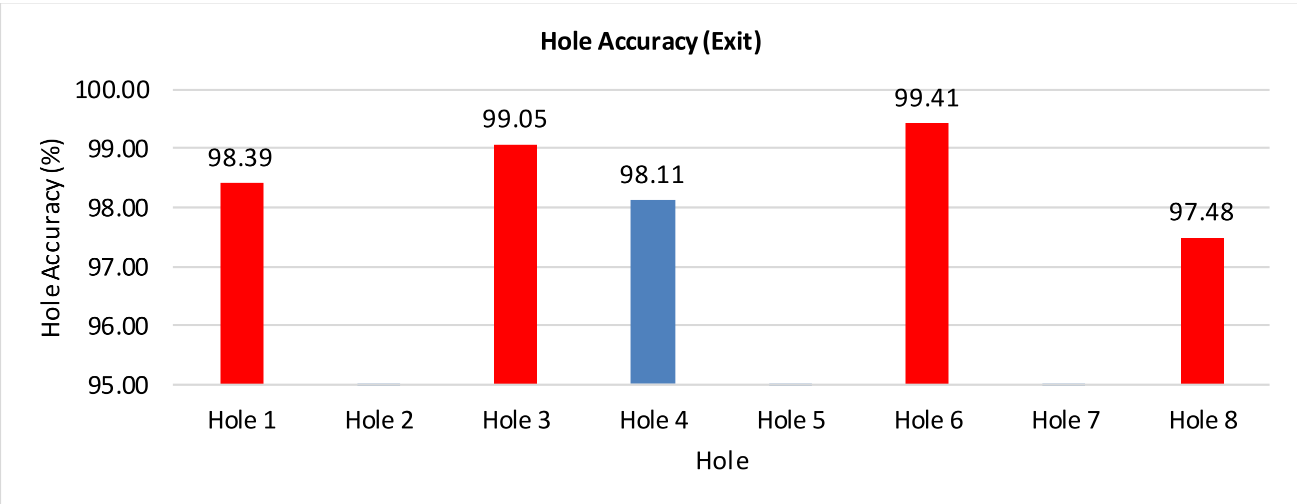


Fig. 8. Graph of Hole Accuracy (Exit)

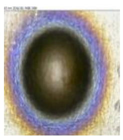
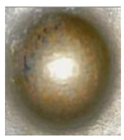
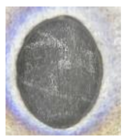
Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6	Hole 7	Hole 8
							

Fig. 9. Pictorial view of hole exit

Hole 6 produces the best hole accuracy (exit) with an accuracy value of 99.41%. The main effects plot for SN Ratio presented in Figure 10 shows signal-to-noise: Smaller is better is to use the drilling parameters namely cutting speed: 500rpm, feed rate: 16mm/min, frequency: 20 kHz, amplitude: 1 µm and tool: carbide. This could indicate that carbide tools are more significant than HSS.

The main parameters according to the ranking that plays a role in the accuracy of the exit hole are depicted in Table 8.

Table 8
Response Table for Signal to Noise Ratios

Level	VC	FR	FQ	AMP	TOOL
1	-39.42	-38.35	-38.39	-39.39	-36.44
2	-36.89	-37.96	-37.93	-36.92	-39.88
Delta	2.53	0.39	0.46	2.48	3.44
Rank	2	5	4	3	1

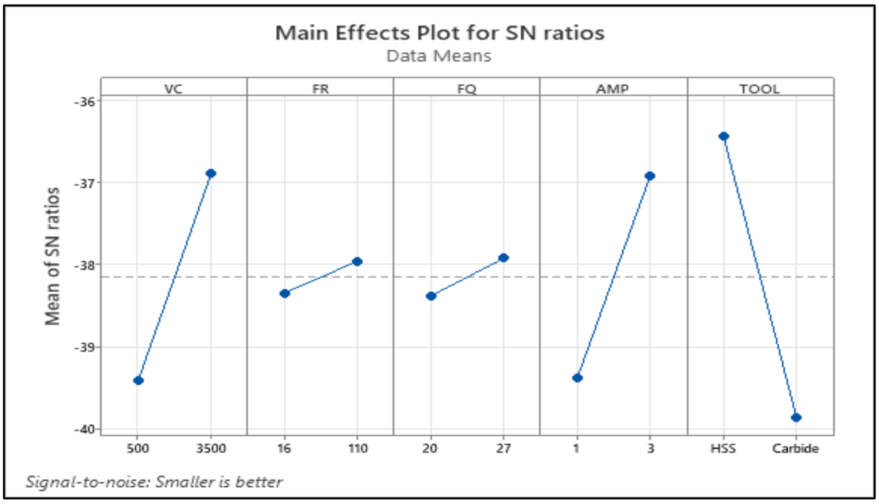


Fig. 10. Signal-to-noise: Smaller is better for hole exit

4.3 Surface Roughness

The roughness of the hole after machining with different parameters was assessed with the roughness profiler to explore the relationship between the surface roughness of the hole and various processing parameters.

The surface roughness of the holes varies with cutting speed, as seen in Figure 11. It can be visualised that when the cutting speed increases, the roughness increases as well. The roughness of the holes varies with feed rates, as illustrated in Figure 12. Resultantly, the roughness of the hole reduces as the feed rate increases. The longer the tool cutting time, the more the damage to the hole wall, thereby producing a rougher hole wall. The roughness of the holes varies with different amplitudes as seen in Figure 13. Results revealed that the roughness of the hole decreases as the amplitude increases. In other words, the surface becomes rougher as the amplitude decreases. Meanwhile, the roughness of the holes varies with frequency as shown in Figure 14. The roughness of the hole increases with increasing frequency.

The friction between the tool point and the workpiece is very high, thereby producing high heat which in turn damages the surface of the workpiece. However, at a high cutting speed and high-feed rate, the surface roughness is lower than at a low-feed rate due to a longer tool contact time with the workpiece, thereby damaging the workpiece surface.

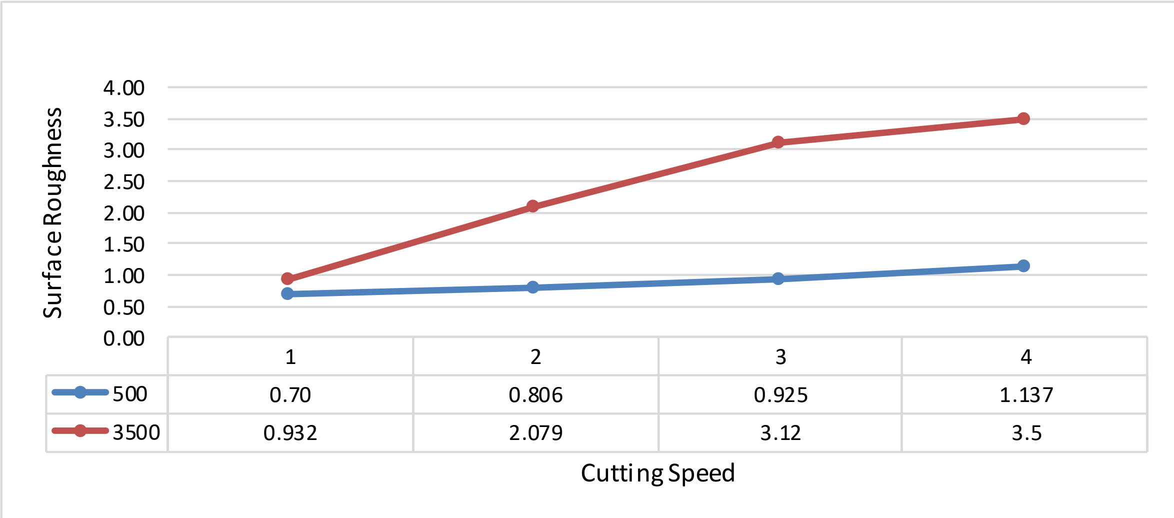


Fig. 11. Graph of cutting speed vs surface roughness

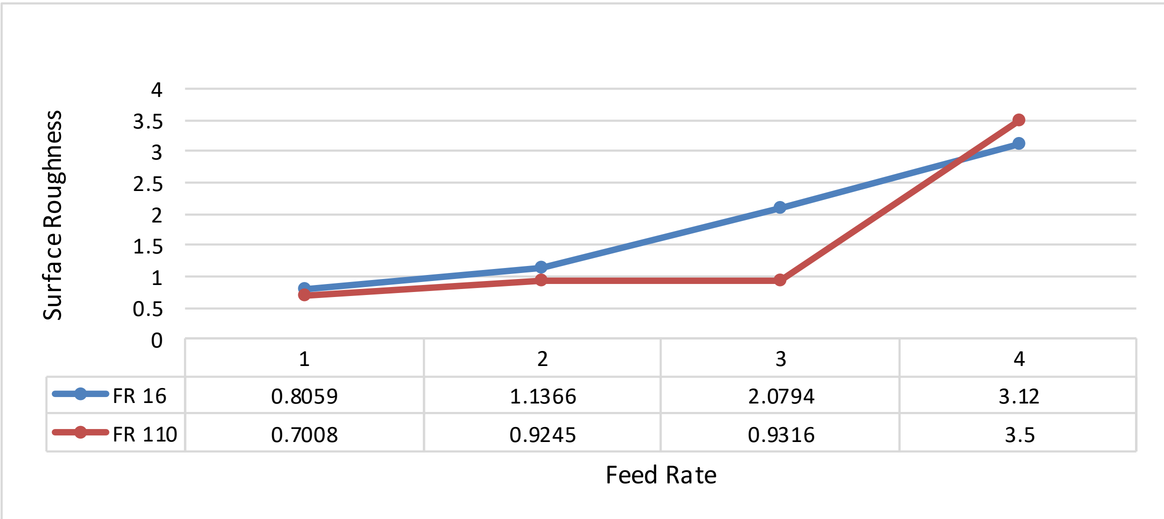


Fig. 12. Graph of feed rate vs surface roughness

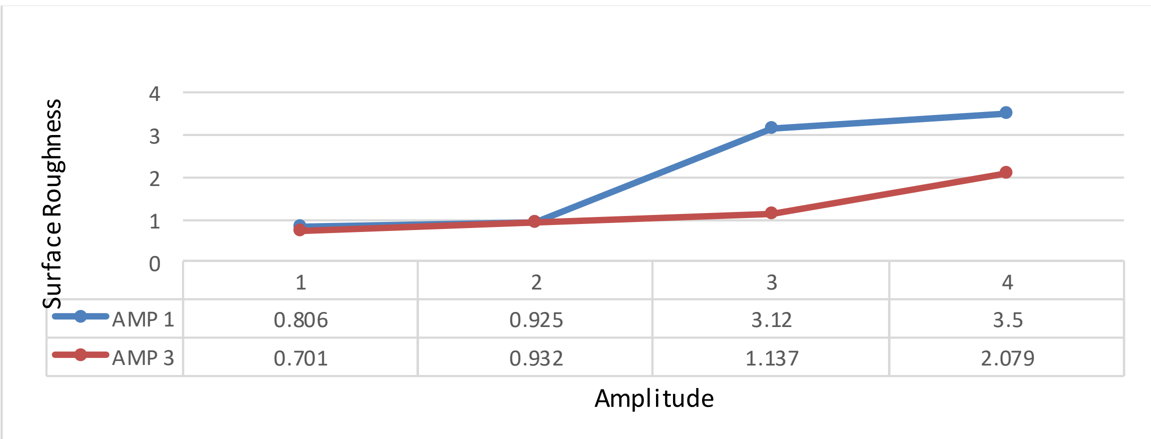


Fig. 13. Graph of Amplitude vs surface roughness

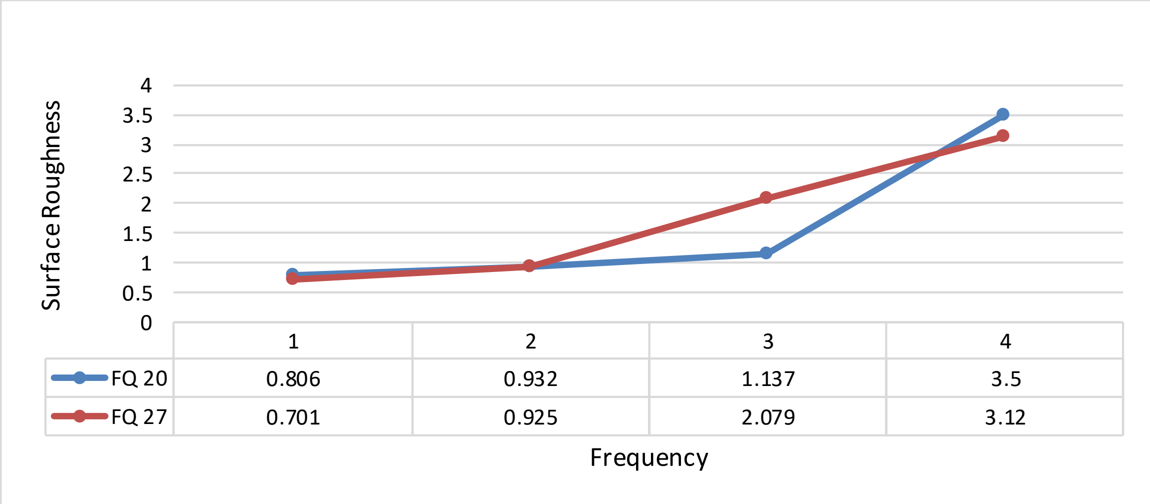


Fig. 14. Graph of frequency vs surface roughness

The main effects plot for SN Ratio presented in Figure 15 shows signal-to-noise: Smaller is better is to use the drilling parameters namely cutting speed: 500rpm, feed rate: 110mm/min, frequency: 20 kHz, amplitude: 1 µm and tool: carbide.

The main parameters according to the ranking that plays a role in surface roughness are shown in Table 9.

Table 9
Response Table for Signal to Noise Ratios

Level	VC	FR	FQ	AMP	TOOL
1	-39.92	-39.84	-39.86	-39.89	-39.81
2	-39.79	-39.87	-39.85	-39.82	-39.9
Delta	0.14	0.02	0.01	0.08	0.08
Rank	1	4	5	3	2

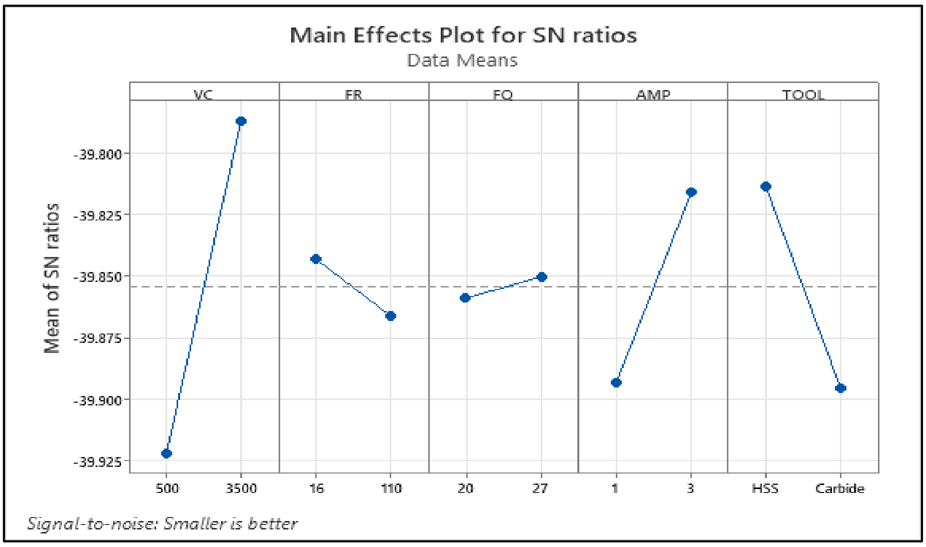


Fig. 15. Signal-to-noise: Smaller is better for Surface Roughness

5. Conclusions

This study aims to investigate the effect of UAD parameters; cutting speed, feed rate, frequency and amplitude, on the machining performance (hole accuracy and surface roughness) for Ti-6Al-4V material. The significant parameters at the screening stage will be used for an experiment run at the optimization stage. Referring to the graph of the signal-to-noise ratio (S/N) for all responses, it can be concluded that the significant parameters are as presented in Table 10.

Experimental studies have demonstrated that a cutting speed of 500 rpm and tool carbide is more significant for all three responses. Therefore, a cutting speed of 3500 rpm and the HSS tool can be discarded in the experiment for optimisation. The lower parameters reflected more significance in terms of hole accuracy entrance and hole exit. Meanwhile, higher parameters appear more significant in terms of response surface roughness.

Therefore, the level of the parameters can be set as in Table 11 for the actual experiment, specifically for the optimization study.

Table 10
Signal-to-noise: Smaller is better for responses

Response/ Parameter	Cutting Speed, VC	Feed Rate, FR	Frequency, FQ	Amplitude, AMP	Tool
Hole Entrance	L	H	H	H	Carbide
Hole Exit	L	L	L	L	Carbide
Surface Roughness	L	H	L	L	Carbide
L= 500 rpm, 16 mm/min, 20 kHz, 1 µm. H= 3500 rpm, 110 mm/min, 27 kHz, 3 µm					

Table 11
Parameters for the experiment of optimisation

Parameter	Level 1	Level 2
Cutting Speed (rpm)	300	600
Feed Rate (mm/min)	16	110
Frequency (kHz)	20	27
Amplitude (µm)	1	3

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