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Machinability Study on Dry Drilling of Titanium Alloy Ti-6Al-4V using L_9 orthoganal array

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Abstract

In modern manufacturing technology, a lot of extensive research work has been carried out in drilling operations for achieving better hole quality. Drilling is one such machining processes which is widely used in aeronautical and automotive industries for structural assembly. Titanium alloy (Ti-6Al-4V) is attractive for many applications due to their superior properties. However, they are regarded as hard-to-machine materials. Drilling is an important machining process since it is involved in nearly all Titanium alloy applications. It is desirable to develop cost-effective drilling processes for Titanium alloy and improve the cost-effectiveness of currently-available processes. In the view of above facts, an attempt has been made to study the machinability during dry drilling of Ti-6Al-4V. The main objective of this study is to determine the favourable drilling conditions for Ti-6Al-4V hole quality (surface roughness, and burr) and chip type based on design of experiments.

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*Keywords:*Dry Drilling,Titanium alloy; Surface roughness; Chip thickness,Burr Fomation, Design of Experimetns

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1. Introduction

Today aerospace industry and automobile industry is focusing on titanium and its alloys (Ti-6Al-4V) due to usage in structure of the F-22 fighter and many parts in gas turbine engines (such as blades, discs, and rotors) and also for many non-structural applications in aircraft (such as floor support structure, tubes or pipes, clips and brackets).

The main source for the increasing popularity of Ti-6Al-4V is its superior properties such as high strength/weight ratio, high compressive and tensile strength, and low density, high fatigue resistance in air and seawater, and exceptional corrosion resistance (Kumar, 2000; Schutz et al., 1987; Yang and Liu, 1999). Among all Ti-6Al-4V machining methods, drilling is very important due to large percentage of all machining processes and is essential for many applications (Cotton et.al. 2002).

During drilling process, about 90% of the work of plastic deformation is converted into heat, producing very high temperatures in the deformation zones and the surrounding regions of the interfaces between the chip, tool and work piece (Ezugwu, 1997). Hole quality in drilling Ti is evaluated in terms of hole diameter and cylindricity, surface roughness, and burr (Machodo et al., 2001). Ti is generally used for parts requiring the great reliability and resistance of wear, and therefore high hole quality must be maintained. Higher surface roughness can possibly lead to severe wear, catastrophic fatigue, and lower ability to resist corrosion. However, the surface of Ti is easily damaged during machining operations (Zareena et al., 2001). Damage appears in the form of micro cracks, plastic deformation, heat-affected zones, and tensile residual stresses (Kahles et al., 1985; Narutaki and Murakoshi, 1983).Most Ti drilling processes will create a burr on both entrance and exit surfaces. In most cases the main concern is the exit burr which is much larger in size. Burr formation in Ti drilling is troublesome in aerospace applications. It is estimated that up to 30% of the cost of some components is due to deburring operations (Dearnley et al., 1986).In twist drilling and vibration assisted twist drilling, the Ti chip could be entangled around two flutes of the drill and bent by the tool holder. This chip entanglement will cause difficulty for smooth chip ejection (Chi-Haron., 2001).it was also analysed that Lower feed rate produced larger exit burrs. The burr height was proportional to thrust force for a same feed rate (Min et al., 1988).Cutting speed had a significant influence on surface roughness when drilling Ti (Kim and Ramulu, 1988). When using carbide drills, higher cutting speeds could produce lower surface roughness (Yang et.al., 1999). However, (Yang et.al., 1999) observed that increased cutting speed produced higher surface roughness significantly with HSS-Co drills but not much with carbide drills.

This paper concentrates on machinability study in dry drilling processes for Ti-6Al-4V on hole quality (surface roughness, and burr), and chip type.

2. Experimental details

The drilling experiments on Ti-6Al-4V work piece specimens were carried out using vertical drilling /boring machine of 0.75 H.P, 415 Volts, 0.75K.W as shown in Figure 1.The solid carbide drills of 8 mm diameter with point angles of 90^o, $104^o$and 118^o were used to carry out the drilling experiments. The drills used in the present study are shown in Figure 2.Ti-6Al-4V work piece specimens popularly known as Titanium alloy in the form of cylindrical plate of thickness 15 mm and diameter 75 mm is used for drilling test as shown in Figure 3. The Figure 4 shows the microstructure and chemical composition of the Ti-6Al-4V specimen is shown in Table 1. Specification and mechanical properties of test sample is shown in Table 2. Table 3 shows the levels and factors of drilling parameters selected.The surface roughness (R_a) of the drilled hole was measured by Taylor-Hobson Surtronic +3 surface roughness measuring instrument.Burr thickness and chip thickness has been measured using Trinocular Inverted Metallurgical Microscope.Micro hardnesshas been measured using Digital Micro Hardness Tester.

Fig. 1 Experimental set up

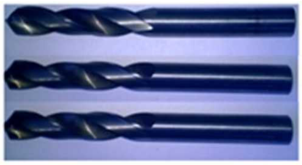

Fig. 2 Solid Carbide Drill Bits

Fig. 3 Work piece specimen

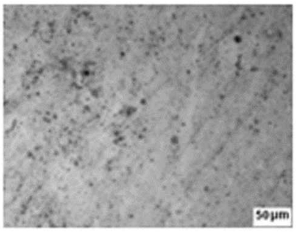

Fig. 4 Microstructure of Ti-6Al-4V

Table 1.Nominal chemical composition of Ti-6Al-4V

Elements	Ti	Al	V	Fe	O	C	N	Y	H
Weight (%)	Bal	6.1	4	0.16	0.11	0.02	0.01	0.001	0.001

Table 2.Specification and mechanical properties of test sample

Tensile Strength (MPa)	955
Yield Strength (MPa)	900
Reduction of Area (%)	42
Elongation in 4D(%)	18
Hardness [BHN]	305

Table 3.Levels and factors

Levels	(A) Cutting Speed(m/min)	(B) Feed(mm/rev)	(C) Point angle (Degrees)
1	10	0.05	90
2	15	0.10	104
3	20	0.15	118

3. Design of Experiments

Design of Experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analysed to yield valid and objective conclusions. The analysis is made using the popular software specifically used for DOE applications known as MINITAB 15.

3.1 Taguchi's method

Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design requires the use of a strategically designed experiment which exposes the process to various levels of design parameters.

Experimental design and manufacturing methods were developed in the early years of 20th century and have been extensively studied by statisticians since then, but they were not easy to use by practitioners Phadke, [1989]. Taguchi's approach to design of experiments is easy to adopt and apply for users with limited knowledge of statistics; hence it has gained a wide popularity in the engineering and scientific community. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization; some of the previous works are listed Nian et.al, [1999]; Davim, [2003]; Ghani et.al, [2004]. In particular, it is recommended for analysing metal cutting problems for finding the optimal combination of process parameters Ghani et.al, [2004]. Further, depending on the number of factors, interactions and their level, an orthogonal array is selected by the user. Taguchi has used Signal–Noise [S/N] ratio as the quality characteristic of choice. S/N ratio is used as measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also deceases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by Eqs. (1.1)– (1.3), when the characteristic is continuous.

Nominal is the best characteristic $$\frac{S}{N} = 10\log\frac{\bar{y}}{s_y^2} \quad (1.1)$$

Smaller is the best characteristic $$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \quad (1.2)$$

And larger the better characteristic $$\frac{S}{N} = -\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad (1.3)$$

Where

$\bar{y}$ =The average of observed data,
s_y^2= The variation of y ,
n = The number of observations, and
y = The observed data.

For each type of the characteristics, with the above S/N ratio transformation, the smaller the S/N ratio the better is the result when we consider tool wear, surface roughness, thrust force, drilling temperature, built up edge, chip thickness and stress.

For the elaboration of experiments plan, the full factorial experimental parameter design increases with increase of process parameters which is time consuming and costly. In order to simplify the above problem, Dr.Genichi Taguchi, a Japanese quality management consultant proposed a special designed orthogonal array (OA) to study the entire parameter space with small number of experiments. The proposed methodology saves not only time as well as cost substantially. In this paper, Taguchi L_9 orthogonal array design has been used and shown in Table 4.

Table 4.Taguchi L9 Orthogonal Array

Run Number	Factor A	Factor B	Factor C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

3. Results and discussion

In order to compare the machinability on dry drilling of Ti-6Al-4V alloy the following were measured and analyzed after drilling: (I) Chip Morphology, (II) Micro Hardness, (III) Burr Thickness (IV) Surface Roughness.

3.1 Analysis of Chip Thickness

Chip shape is the most important factor for the smoothness of a drilling process. The drilling process will be smooth if chips are well broken. Chip shape and chip thickness at low cutting speed was spiral cone chip with lesser thickness which is easier to be ejected, as the cutting speed increased Long ribbon like chips with increasedchip length and chip thickness were obtained (Figure 5).

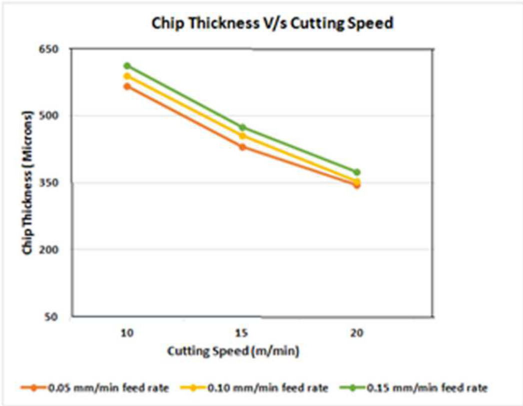

Fig. 5 Variation of chip thickness with cutting speed for different feed and point angle

From the main effects plot Figure 6 for chip thickness indicates the selection of higher cutting speed (20 m/min), lesser feed rate (0.05mm/min) and lesser point angle (90^{o}) result the best combination to get lesser chip thickness value under different drilling conditions of Ti-6Al-4V alloy.
Table 5 shows the ranking of each drilling parameter using the response Table for Signal to Noise Ratios (smaller is better) obtained for different parameter levels.
On the examination of the percentage of contribution (P%) of the different factors(Table 6), for chip thickness it can be seen that cutting speed has the highest contribution of about 96.96%, thus cutting speed is an important factor to be taken into consideration while dry drilling Ti-6Al-4V alloy. It can be seen that feed rate (mm/min) (P=0.0004%) and point angle (^{o}) (P=2.9452%).

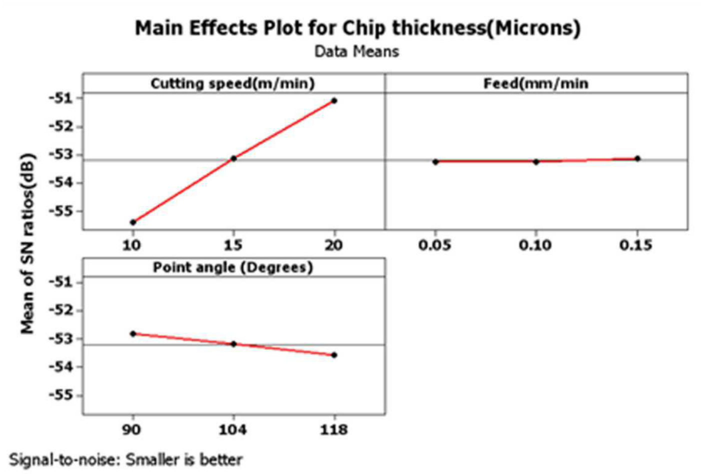

Fig.6 Mean S/N Graph for Chip Thickness

Table 5.Response Table for Signal to Noise Ratios (Smaller is better)

Level	Cutting Speed (m/min)	Feed(mm/min)	Point Angle(Degrees)
1	-55.40	-53.23	-52.83
2	-53.12	-53.24	-53.18
3	-51.06	-53.12	-53.58
Delta	4.34	0.12	0.76
Rank	1	3	2

Table 6.Analysis of Variance for S/N ratios for Chip Thickness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
Cutting Speed(m/min)	2	28.2608	58.2608	14.1304	13502.4	0.00	96.96
Feed Rate (mm/min)	2	0.0261	0.0261	0.0130	12.45	0.07	0.0004
Point Angle (degrees)	2	0.8584	0.8584	0.4292	410.13	0.00	2.9452
Residual Error	2	0.0021	0.0021	0.0010			
Total	8	29.1474					100

3.3 Analysis of Burr Formation

Most drilling processes create a burr on both entrance and exit surfaces. The entrance burr is much larger in size and is the main concern and a major problem such as deburring and re-assembly. Preventing, or at least minimizing (or controlling) the formation of drilling burrs is therefore very important. Burr formation in drilling has not been as extensively studied. Most studies are concerned with tool wear and don't consider burr formation. Although a number of investigations have been conducted, there are still major questions remaining regarding the basic formation of burrs in Ti alloys and the influence of process parameters.Generally four burr types categorized by cross section shape created under different machining conditions. Type I is a uniform burr which has uniform height and thickness. Type II is similar to Type I but has a "leaned-back" cross section. Type III has a severe rolled back shape and Type IV is also rolled-back but has a relatively small burr height.

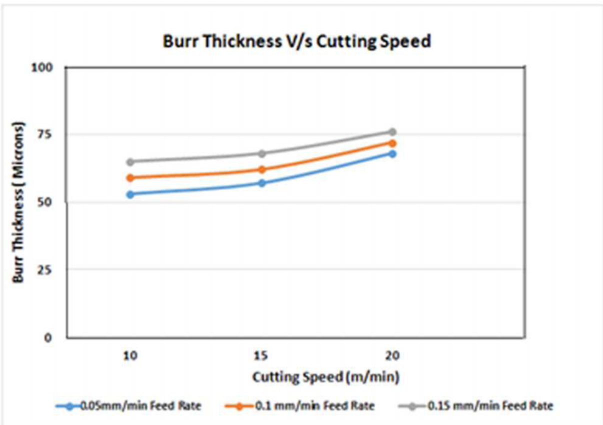

Fig.7 Variation of Burr thickness with cutting speed for different feed and point angle

From the experimental results it has been observed that the low thermal conductivity of the material inhibits heat dissipation. Thus, there should be a localized temperature increase at the inner surface of the burr. This temperature increase and resulting thermal expansion is believed to be the main cause of the lean back and roll back phenomena

observed. The amount of heat generation and temperature rise is proportional to cutting speed and feed rate. Higher feed rate and cutting speed will generate more heat, and result in more rolling-back as observed here.
It was also observed during measurement of burr thickness, as the cutting speed and feed increased burr thickness increased to 76 microns as shown in Figure 7.
From the main effects plot Figure 8 for burr thickness optimum value for minimul burr thickness is selection of cutting speed (10m/min), feed rate (0.05mm/min) and point angle (90^o) result the best combination to get lesser burr formation value under different dry drilling conditions of Ti-6Al-4V alloy.Burr thickness and burr formation viewed under Trinocular Inverted Metallurgical Microscope under different cutting speed is shown in Figure 9 -Figure 10.

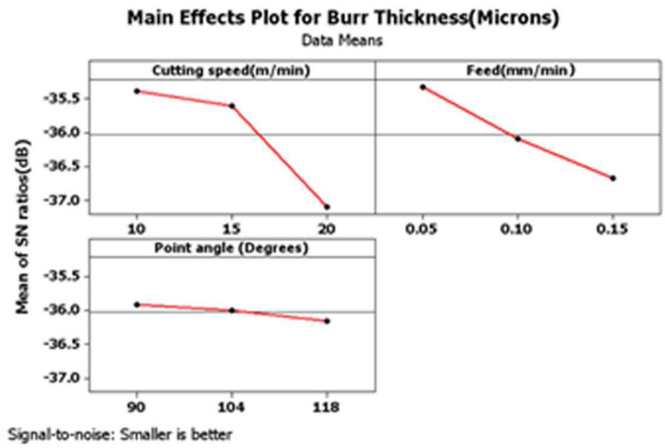

Fig.8 Mean S/N Graph for Burr Thickness

Table 7.Response Table for Signal to Noise Ratios (Smaller is better)

Level	Cutting Speed (m/min)	Feed (mm/min)	Point Angle(Degree)
1	-35.39	-35.32	-35.92
2	-35.60	-36.09	-36.00
3	-37.09	-36.67	-36.16
Delta	1.71	1.34	0.24
Rank	1	2	3

Table 8.Analysis of Variance for S/N ratios for Burr Formation

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
(A)Cutting Speed (m/min)	2	290.667	290.667	145.333	145.33	0.007	66.97
(B)Feed (mm/rev)	2	140.667	140.667	70.333	70.33	0.014	32.41
(C)Point Angle(Degree)	2	2.667	2.667	1.333	1.33	0.429	0.006
Residual Error	2	2.000	2.000	1.000			
Total	8	436.000					100

Table 7 shows the ranking of each dry drilling parameter using the Response Table for Signal to Noise Ratios (smaller is better) obtained for different parameter levels.
On the examination of the percentage of contribution (P %) of the different factors (Table 8), for burr thickness it

can be seen that cutting speed (66.97%) and feed rate (P=32.41%) had the highest contribution while drilling Ti-6Al-4V alloy. It can be seen that point angle (^{o}) (P=0.006%) had the minimal effect.

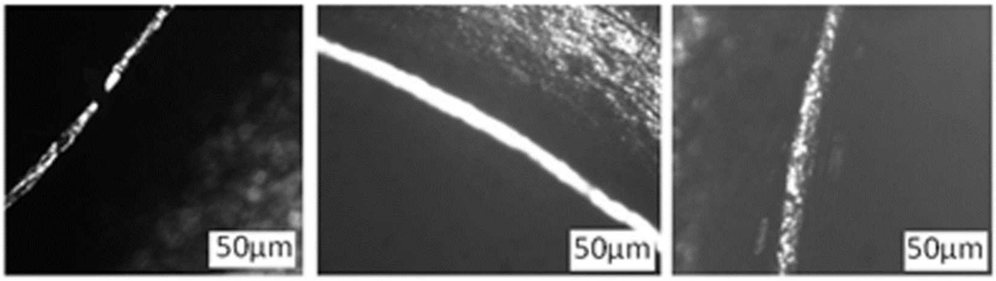

Fig 9 Burr thickness viewed under Trinocular Inverted Metallurgical Microscope

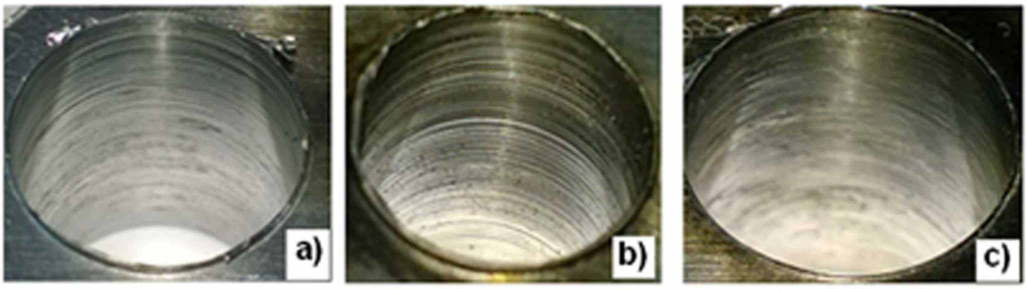

Fig 10 Images of Burr formation under different cutting speed.

3.4 Analysis of Surface Roughness

There are three essential parameters in a surface roughness; arithmetical mean deviation of the profile (R_a), maximum height of the profile (R_{max}) and height of the profile irregularities in ten points (R_z). It is believed that the higher surface roughness value is responsible for the decrease of the fatigue strength of the machined surface.

During experimental analysis from the Figure 11. It is clear that at higher cutting speed, could contribute to the improvement in surface roughness values.In addition, as the cutting speed increases; more heat is generated thus softening the workpiece material, which in turn improves the surface roughness. However, at lower cutting speed there is the formation of built-up edge and hence deteriorates the machined surface.

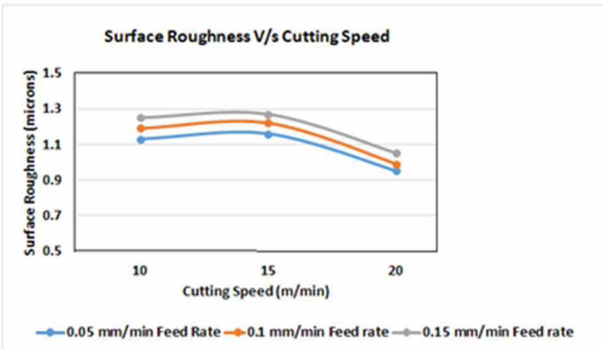

Fig.11 Variation of surface roughness with cutting speed for different feed and point angle

From the main effects plot Figure 12 for surface roughness indicates the selection of higher cutting speed (m/min), lesser feed rate (mm/min) and point angle (degrees) result the best combination to get lesser surface roughness value under different dry drilling conditions of Ti-6Al-4V alloy.

Table 9 shows the ranking of each dry drilling parameter using the Response Table for Signal to Noise Ratios (smaller is better) obtained for different process parameters.

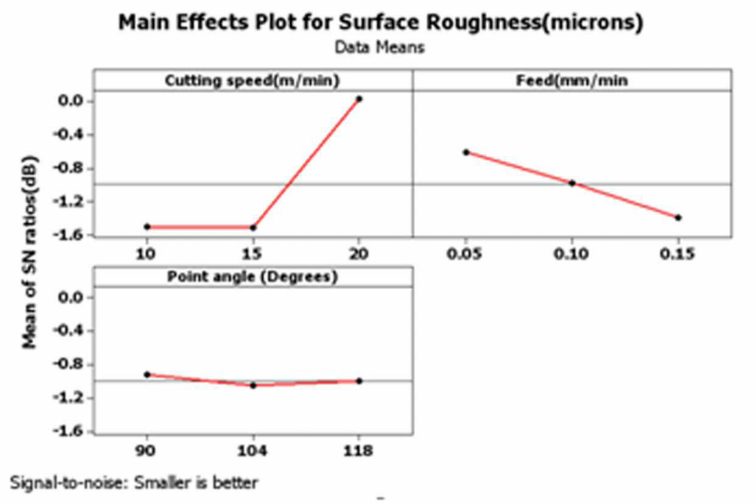

Fig.12 Mean S/N Graph for Surface Roughness

Table 9.Response Table for Signal to Noise Ratios (Smaller is better)

Level	Cutting speed (m/min)	Feed (mm/rev)	Point Angle(Degree)
1	-1.50357	-0.61000	-0.92412
2	-1.50767	-0.97819	-1.04956
3	-0.03635	-1.38670	-1.00120
Delta	1.54401	0.77670	0.12544
Rank	1	3	2

Table 10.Analysis of Variance for S/N ratios for Surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
(A)Cutting speed (m/min)	2	4.75533	4.75533	2.37766	680.71	0.001	83.64
(B)Feed (mm/rev)	2	0.90570	0.90570	0.45285	129.65	0.008	15.93
(C)Point Angle(Degree)	2	0.02401	0.02401	0.01201	3.44	0.225	0.004
Residual Error	2	0.00699	0.00699	0.00349			
Total	8	5.69203					100

On the examination of the percentage of contribution (P%) of the different factors (Table 10), for surface roughness it can be seen that cutting speed has the highest contribution of about 83.64%, feed rate (mm/min)(P=15.93%) and point angle (^{o}) (P=0.004%) thus cutting speed is an important factor to be taken into consideration while dry drilling Ti-6Al-4V alloy.

4. Conclusions

- Chip shape and chip thickness at low cutting speed was spiral cone chip with lesser thickness, as the cutting speed increased Long ribbon like chips with increased chip length and chip thickness were obtained.
- Main effects plot for burr formation indicates the selection of lower cutting speed for drilling of Ti-6Al-4V alloy gives minimum burr formation.
- Main effects plot for chip thickness and surface roughness indicates the selection of higher cutting speed for drilling of Ti-6Al-4V alloy gives minimum chip thickness and surface roughness.
- There was increase in micro hardness of the surface layer, as a result of high cutting speed, feed rate this could be associated by the high rubbing load between the drill bit and the machined surface and also due to consequent work hardening effect.
- From the experimental results it has been observed that the low thermal conductivity of the material inhibits heat dissipation. Thus, there should be a localized temperature increase at the inner surface of the burr. This temperature increase and resulting thermal expansion is believed to be the main cause of the lean back and roll back phenomena observed. The amount of heat generation and temperature rise is proportional to cutting speed and feed rate. Higher feed rate and cutting speed will generate more heat, and resulted in more rolling-back as observed here.
- From the experimental results it is clear that at high cutting speed, the cutting temperature increases due the small contact length between tool workpiece interfaces. This could be due to the decrease in the value of coefficient of friction, which results in low friction at the tool-workpiece interface. These factors could contribute to the improvement in surface roughness values.
- In addition, as the cutting speed increases, more heat is generated thus softening the workpiece material, which in turn improves the surface roughness. However, a low cutting speed may lead to the formation of built-up edge and hence deteriorates the machined surface.

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