ISSN: 2633-4828 Vol. 5, No. 3, September 2023

International Journal of Applied Engineering and Technology

Determination of the Accuracy of Holes produced by Deep Drilling of Ti-6Al-4V Titanium Alloy

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Date of Submission: 04th August 2023 Revised: 09th September 2023 Accepted: 31st October 2023

How to Cite: Tlhabadira, I., Daniyan, I. A. and Khaled, A. E. (2023). Determination of the Accuracy of Holes produced by Deep Drilling of Ti-6Al-4V Titanium Alloy. International Journal of Applied Engineering Technology, 5(3), pp.171-184.

Abstract**-- Deep drilled holes in titanium alloys are broad in terms of the engineering and fabrication application in various products. The accuracy of deep drilling, tool wear, chip morphology and hole surface-wear are determined in this study. A sequence of machining tests were conducted to examine the deep drilling of Ti6Al4V alloy behaviour. Furthermore, a model that describes and improves the accuracy of holes in deep drilling of Ti6Al4V using High Speed Steel (HSS) drills was investigated, with the upshot of cutting limits on process indicators on tool wear and chips for modern manufacturing industries. The factorial design methodology for experiments was employed to investigate the influence of the cutting parameters on hole accuracy. Drilling were carried out on a solid cylindrical shaft of titanium alloy Ti-6Al4V using a 5-axis, Computer Numerical Control (CNC) milling machine and 13 piece of 10 mm diameter drill bits made from HSS Co and DMU 80 monoblock DECKEL MAHO. The surface corrosion and wear of the samples were also investigated using the Scanning Electron Microscopy (JEOL-SEM). The results obtained indicated that high tool wear results in short tool life when drilling at high speeds and feeds. The 10 mm HSS Co drill fails at high speeds of between 1272-640 rev/min and drill without failure at speeds of 630-318 rev/min for deep drilling of Ti-6Al-4V. The combination of 318 rev/min and 25 mm/min produces the preferred short and discontinuous chips. Thus study can assist drilling operators in obtaining accurate holes during deep drilling of Ti6Al4V.**

Index Terms **- Corrosion, Deep drilling, Factorial design, HSS drills, SEM, Ti-6Al-4V, Wear**

INTRODUCTION

Deep drilling is essential in today's manufacturing. Deep drilled holes in titanium alloys are extensively used in the engineering and fabrication of various products. The machining process of deep drilled holes is becoming more significant in modern industrial applications.

However, the toughness in cutting titanium alloys at high speeds are caused by the intrinsic material properties due to low thermal conductivity. Tool wear and failure leads to fracture and a deviation from the axis of the hole. Tool wear and failure can lead to fracture and a deviation from the axis of the hole, while an extended drill length leads to tool instability and tool axis deviation resulting in the rejection of the end product. However, the toughness in machining titanium alloys at high speeds are caused by the intrinsic material properties due to low thermal conductivity. In addition, an extended drill length leads to tool instability and tool axis deviation result in the rejection of the end products. The machining process parameters of deep holes affect the functionality and quality of the produced hole. Conventional machining processes are regarded as the cheapest processes compared to the more advanced, non-conventional deep hole drilling processes. Therefore, an appropriate model must be employed to enhance the accuracy of deep drilled holes in titanium alloys.

The paper aimed to develop an archetypal that describes the accuracy of holes in deep drilling of Ti6Al4V using HSS drills. The paper also aims to investigate the effect of cutting limits on process indicators such as tool wear and chips by conducting a sequence of machining tests to examine the deep drilling of Ti6Al4V alloy behaviour, which also includes the determination of the accuracy of deep drilling, tool wear, chip morphology and hole surface. Thus study can assist drilling operators in obtaining accurate holes during deep drilling of Ti6Al4V.

The next section presents the literature review of work that has been executed with critical analysis and emphasizes on issues concerning the titanium machining with focus on deep drilling.

Section 3 described the materials and methods employed in this study, while the results and discussion are presented in the succeeding section followed by the conclusion and recommendations.

LITERATURE REVIEW

Titanium and its composites are typical materials broadly used across variety of industries because of the special characteristics such as high corrosive resistance, high weight ratio to strength, excellent fatigue properties, great structural durability, superior resilience elevated to temperatures, excellent fracture properties, thermal stability and compatibility with composite materials which they possess as compared to other materials and their alloys. Normally titanium alloys are classified under three categories of conventional titanium alloys, α alloy and near α alloy, α/β alloys and the β alloys [1]. Titanium alloys are largely used in various manufacturing industries. Ti-6Al-4V is the mainstay of the titanium industry and has been involved in a wide application because of its excellent properties, which includes good fatigue and fracture properties, low thermal conductivity, and provision of weight savings with greater corrosion resistance to aluminum composites and low alloy steels. The material is broadly used in aerospace, marine engines turbines, energy industries, surgical applications, chemical process industries as well as automotive and consumer goods.

Titanium has a low elastic modulus that results in deflection during machining and this impairs its machinability. This is due to extraordinary chemical reaction of Ti with exciting high mechanical strength during machining, good cutting tool properties [2] capacity to load bearing, and have concluded that carbide tool remains the best when turning Ti-alloys and the features make it hard and expensive to machine, while the speed of 100m/min is considered as high speed during milling [3]. It was discovered that stair-formed face wear, chipping, wear of the flank, and the development of built-up edge, were the main wear of the adhesion and abrasion, and they are as well dominant in tool failure patterns, thermal cracking, and sticking formation [4]. Che-Haron and Jawaid, [5] investigated the surface integrity of granular machining T1-6%A1-4%V alloy with uncoated carbide cutting tools. The outcome of the study indicated that the exterior of workpiece damaged easily during the cutting process and the microstructure alterations of the machined surfaces experienced increments on the top layer by ≤10μm. Ikuta *et al.* [6] observed that there was an adhesive properties Ti-6Al-4V and Ti-3Al-8V-6Cr-4Mo-4Zr alloys during machining with chip material on the debased face. Min and Youzhen [7] indicated that the tool debased face during titanium alloys machining is the greatest dynamic wear mechanism for practically all tool materials with adhesive properties, as well as the slitting of particles in the tool materials. Titanium is highly reactive at very high temperatures during machining, which can rise to about 1000 °C at high cutting speeds for Ti6Al4V [3].

Other areas on machining of Ti alloys include chip formation, application of coolant strategies and tool wear which have received a lot of attention by different researchers with successful results. The study of thermo-mechanical coupling effect using analyzed and simulated milling process for titanium alloy with flat-end cutter-work piece under different engagements through optimization method to improve cutting milling efficiency and performance of titanium was investigated by Zhang *et al.* [8]. A highly conductive copper plate was employed as the dry drilling heat sink to compare dry drilling effectiveness of the titanium alloys surface being machined [8].

A comprehensive finite element model was used by Pante *et al.* [10] for investigating the temperature distribution and variable heat ploughing forces at the edge radius of the cutting tool. Ugarte *et al.* [11] used scanning electron microscopy for a single tooth face milling to study coated tools life and wear behaviour. Chandrashekar and Prasad [12] focused on using powder particle through powder metallurgy process for varying samples of cobalt content and conducted experiments on turning to determine the influence of cobalt content on tool life.

Manufacturing machining process industry usually uses a rotary tool (drill bit) to make circular cross section through removal process by drilling of work piece. In the aviation industry, this process represents approximately 40% of the metal removal processes carried out [13]. In the last century, high-speed-steel (HSS) has been developed with excellent coatings and being reasonably cheap, it is widely used in hole production. Researchers have studied the strengthening of HSS more recently with the development of new technologies a thin layer of hard and wear resistant coating, such as titanium nitrite (TiN) has been deposited on the surface of HSS drill bits to increase the drill life. Sharif and Rahim [3] investigated the performance of various cutting speeds for drilling T1-6A1-4V using uncoated – WC/Co and Ti AN-PVD coated carbide twist drill. The authors further determine the effect of the cutting speed on the surface finish, tool life, and tool wear. The results obtained indicated that increased flank wear and shorter tool life was observed with lower cutting speeds of 25 and 35m/min and higher cutting speeds of 45 and 55m/min while drilling with T1A1N-coated drills. In contrast to the uncoated carbide drill, TiA1N-coated drills produced a better surface finish at an average cutting speed although with some cost consequences. Park *et al.* [14] drilled carbon fiber stacked on top of titanium (Ti) with reinforced plastics (CFRP) to determine the wear mechanisms of tungsten carbide (WC) and polycrystalline diamond (PCD) drills. Ghani *et al.* [15] discussed the loading and unloading effect during caused by milling failure mode for a coated carbide cutting edge.

Trivedi *et al.* [16] reported on the analysis of surface integrity in heat sink-based dry drilling of titanium alloy and indicated that high throughput drilling of titanium alloy has not been sufficiently reported. Li and Shi [17] reported that drilling at high tool temperatures increases the rate of tool wear and reduces the drill bit life.

In drilling using HSS drills of less than 6 mm, the speeds recommended for Ti-6Al-4V are 11 m/min compared to 105 m/min for aluminum alloys and 49 m/min for gray cast iron. The chip formation during drilling of Ti has been given attention by a number of researchers for example Barry *et al.* [18] observed the machining of Ti-6Al-4V can cause acoustic emission, chip formation, aperiodic saw chips and chip thickness with low cutting speed values. A change from an aperiodic to periodic saw-tooth chip formation is caused by an increase in chip thickness or cutting speed or combination of both. The work on ultrasonic drilling by Singh and Khamba [19] on three different slurries such as silicon carbide, alumina and baron carbide with stainless steel tool gave the highest rate of material removal rate during machining of titanium alloys. In terms of the optimization of drilling of Ti. Ribeiro *et al.* [20] investigated the optimization of titanium alloy Ti6Al4V machining to search for optimum cutting conditions of the titanium alloy at 90 m/min was superior to 70 m/min used in manufacturing to produce satisfactory machine performance.

Zhu *et al.* [21] investigated the effect of tool geometries during the dry drilling Al/Ti stack on three novel drill multipoint, geometries, step and double cone. Chatterjee *et al.* [22] analyzed the influence of the federate, spindle speed and diameter of drill bit on the thrust force, torque and circularity performance at entry and exit of the holes during the drilling of titanium alloy using coated drill bit. The work of Yi *et al.* [23] on drilling of titanium alloy (Ti-6Al-4V) to examine the effects of the suspended cutting fluid on working mechanisms with on a new graphene oxide. To control the machined borehole quality, a cutting forces model was developed by Rey *et al.* [24] for obtaining the right tool geometry and cutting conditions, while Balaji *et al.* [25] employed the response surface methodology to investigate the effect of drilling feed rate, spindle speed, and helix angle on the workpiece surface roughness, flank wear, acceleration and vibration velocity of the drill. Although drilling is a process that has been in operation for many years, the process has been continually developed to improve drill wear, investigate high speed drilling and hole accuracy.

Deep drilling of a narrow and deep hole is often necessary in a metal for molding and assembly industries [26], hole is considered as deep drilling when a ratio of 5:1 diameter to depth or greater is used. The temperature distribution on drills during deep drilling remains a concern for researchers. Bono *et al.* [27] investigated the highest temperature on the cutting edges, with the use of finite element analysis (FEA) through a model of the friction heat as well as the heat generated on the shear plane. The analyzed temperature profiles along the drill edges proved that the maximum temperature occurred near the chisel edge in contrary to the conventional belief of occurring near the outer corner. Wear monitoring of the tool material has been investigated for years. The reason for tool wear monitoring is to be able to change the drill before failure as this could affect the quality of the final components.

In terms of the application of advanced nonconventional machining techniques (ANMT), some work has been focused on using these techniques for deep drilling. A dialectic-encased wire electrode was used by Kumagai *et al.* [26] to study the plasma-applied drilling of a narrow deep hole in a metal. The findings of the study show that there is a correlation between the shape of the laser produced craters and ablation plume characteristics, while the discovering that the accuracy of micro-machining by ultra-short laser pulses is influenced by nano particles. A new Electrical Discharge Machining (EDM) system with an encased polytetra-fluoethylene (PTFE) composite electrode, which consist of a tungsten rod in a pipe jacket was used to fabricate a narrow deep hole in carbon steel to the depth of 150 mm, the inlet diameter of 0.7 mm and the outlet diameter of 1.0 mm. The inlet and outlet diameters indicated a difference of 30% which was consider high. Brunean *et al.* [28] studied the titanium alloy (T1-6A1-4V) machining on the EDM using different electrode materials such as electrolytic copper, graphite and aluminum. The graphite electrode produced a relatively poorer surface finish, but was helpful to electrode wear, material removal rate and surface crack density. Daniyan *et al.* [29] reported that numerical models can be used for the prediction of surface roughness and cutting temperature during the cutting of titanium alloy (Ti6Al4V). The ANMT was also used by Hasçalik and Çayduş [30] investigated deep hole drilling in electrochemical (DC mode) using an acidified salt solution to replace the acid electron. The study was done on nickel based super alloys with deep holes' depth of 26 mm and drilled diameters range between 2.054 mm and 4.128 mm. The disadvantage of electrochemical deep hole drilling was that the hole profile usually produced, was barrel shaped and had holes a smaller diameter at certain locations. Lubrication plays a significant role during deep drilling, while the minimum quantity lubrication (MQL) in small diameter drilling of deep-hole results in a reasonable tool life [31]. Drilling at high speeds of material removal rate (MRR) is essential to cost effectiveness and increase productivity of long drill bit life. A long drill bit life depends on drill bit correct selection of from drill bit manufactures for the material to be drilled. An incorrect selection will result in early failure of the drill bit. To achieve the required MRR, require feed per revolution and high cutting speed of drilling. Therefore, the cutting feed rate and speed of the drill are important factors in deep drilling. A recent study done by Heinemann *et al.* [32] on the effect of cutting forces on the accuracy and quality of drilled holes established the mechanics and dynamics of the drilling process. The study also presented a mathematical model for the prediction of the hole quality and cutting forces. However, the study only concentrated on shallow depth and not on deep drilling and the materials used for the test were rigid aluminum blocks which were not as difficult to machine as compared to Ti. Pirtini and Lazoglu [33] investigated the near surface structure to determine Ti6A14V drilling process for different process-temperature during.

It was found that the pseudo-temperature occurred at maximum during end of the hole drilling close to the Ti6A14V alloy ß- transus- temperature. Li *et al.* [34] investigated the tool material, process parameters and drill geometry that are necessary to achieve high throughput drilling of Ti6Al-4V. The study shows that it is feasible to achieve high-throughput drilling of Ti-6Al-4V with the use of internal cutting fluid supply to improve the drill bit life. Although titanium alloys handling suitability by EDM is not ideal for deep holes due to the titanium alloy’s low heating conductivity; the machining gap debris cannot be easily eliminated in high tenacity [35]. They concluded that it is more difficult to machine small and deep holes of a ratio of depth to diameter of 10 on materials such as titanium alloys using traditional machines. Several attempts have been made to improve hole accuracy when machining with EDM. Wansheng *et al.* [36] developed combined four axes with an ultrasonic and micro EDM machine tool for titanium alloys small and deep hole with some success achieved. The study showed that such holes having diameters less than 0.2 mm and more than 15 mm for the depth to diameter ratio could be produced without difficulty. The ultrasonic EDM increased machining efficiency, and reduced the taper of the machined holes. The disadvantage with the hole produced remained the taper effect that could only be improved and not eliminated. Existing works have reported on the turning and milling operations of Ti6Al4V [37-40] but there is still a dearth of information on the determination of the accuracy of holes produced by deep drilling of Ti-6Al- 4V titanium alloy. The machining and drilling of titanium and its alloys is difficult because the material’s good mechanical properties retained during machining, Figure 1 shows the general steps of machining titanium. The application of titanium and its alloys is quickly entering other markets and industries and the improvement of its machinability becomes extremely important. The determination of process parameters for a good rate of material removal and hole quality for machining of Ti and its alloys are necessary and more emphasis should be directed to the drilling accuracy of those alloys. The literature surveyed on the machining of Ti and its alloys revealed that most of the research focused on milling and turning operations. Less emphasis has been given to general (shallow) and deep hole drilling hence the need for this experimental work to study the effect of cutting parameters on the hole accuracy and to develop a model for estimating hole deviation during the deep-drilling of titanium alloy material. The study developed an accuracy process model when varying speed and feed, the effect of feed on deviation and speed using a design of factorial experiments including two factors at two levels.

FIGURE 1. GENERAL STEPS OF MACHINING TITANIUM

MATERIALS AND METHOD

The factorial design methodology for experiments was employed to examine the effect of the cutting parameters on hole accuracy which allows all the data from the experiment to be used to study each factor and the interaction of the functions. According to Myers and Montgomery [41] the variable range in a factorial design is divided into highest and lowest between the values. When factors are studied at two levels a common convention is to designate the low level as “-” (minus) and the higher level as “+” (plus). The cutting factors considered are feed and speed. The developed model was checked against its adequacy using the approach of analysis of variance. The program of the experiment was planned using a complete $2^2 +1$ factorial design. The two factors, two levels plus 1 design set up with a number totaling 10 experiments were conducted. The values range was set at two levels of (-1) low and (1) high. A medium single value was considered in order to estimate the curvature presence in the data. The effect of feed and speed on hole deviation during deep drilling of a titanium alloy on a conventional machine was studied and a mathematical model developed was based on statistical analysis. The material used for the experiment is Ti6Al4V. The investigation of the cutting parameters involved the use of the HSS drills. The experiments were done on a DMG 80 machine. Therefore, the developed process models are valid for the same range of cutting parameters when using the HSS drills on machine tools having the same rigidity as the DMG 80.

I. Experimental Setup

The experiments on the drilling were carried out on a 5-axis, CNC milling machine located at the Institute for Advanced Tooling, Gauteng, which is situated at the Tshwane University of Technology, South Africa.

The main elements of the titanium alloy deep hole drilling experimental set-up consists of a solid shaft of titanium alloy Ti-6Al4V, 13 piece of 10 mm diameter drill bits made from HSS Co and DMU 80 monoblock DECKEL MAHO. The work piece material used in the experiment is a cylindrical solid shaft of alpha-beta Ti-6Al-4V titanium alloy, 100 mm in diameter and 100 mm height. The mechanical and chemical composition properties of Ti-6Al-4V are indicated in Table I. Deep drilling was carried out on a DMU 5-Axis 80 monoblock Deckel Maho shown in Figure 2. To ensure that the top and bottom part were perpendicular to the drill and parallel to the bottom surface axis, the work piece was face-milled on the clamp vice as indicated in Figure 3. The machine tool has a power of 28/19 kW at 40/100 % and spindle rotation speed of 18,000 rpm. The M-Code program was generated for the peck drilling process. Figure 4 shows the tool work piece set-up on the machine tool table. During the drilling process the drill was provided with a cooling time of 2 s after every 2 mm depth cut until the drill finished the 121 mm depth.

The drills used for the deep hole drilling process are manufactured by SOMTA cutting tools. The microstructure evaluations of the HSS steel part revealed that it consists of un-dissolved particle of carbides (white parts) in a matrix of tempered martensite with reference to the metals handbook, it indicates that the type of steel used is a *T* range with the chemical compositions C (0.75 – 1.50%), W (12 – 18%), Cr (4%), Co (5%) and V(1%). Speed and feed are the two factors considered in the experiments. The initial sets of parameters selected from the manufacturer's guide were used to drill the holes, while the spindle speeds selected for the experiment in the user guide ranged from 20 to 40 m/min and the feed rate to drill titanium with a 10 mm drill diameter ranged from 0.1 to 0.18 mm/rev. The manufacturers' cutting parameters in Table 2 were employed for the first drill, which immediately failed as a result of overheating and melting of its tip as shown in Figure 5. The tool could not penetrate further than 20 mm, which warranted the ranges of cutting speed and feed to be adjusted to different lower values and further machining trials was conducted until the drill penetrated the whole depth. A water based coolant was applied during deep drilling of the titanium alloy. The second sets of parameters were selected as presented in Table 2 with cutting speed at 318 rpm and 636 rpm with feed rate of 25 mm/rev and 65 mm/rev respectively selected. Different machining trials was conducted with varying set of parameters until ten holes were drilled successfully and the work piece was then examined for the holes' accuracy. The x and y axis hole of the deviation (position error) was measured in the direction as shown in Figure 6. To avoid any influence on the measurement induced by the burr formed as the tool exit at the bottom of the work piece, the measurement were taken 5 mm higher from the tool exit. Figure 7 shows the set up for the measurement of the hole accuracy while Figure 8 shows the ideal and typical hole profiles and measurement arrangement. Figure 9 shows the Ti-6A1-4V in the Scanning Electronic Microscopy (SEM).

The SEM (JEOL-SEM) which has a variable magnification ranging from 10x-300, 000x was used to investigate the corrosion and diffusion wear on the surface of the drilled sample. The technique can assist in the determination of the possible root causes of corrosion and wear in a material. The work pieces were sectioned as presented in Figure 10 using wire EDM.

The simple design in the 2^k series which has only two factors i.e. A and B, with each run at two level scaled the 2^2 factorial design was used because they are simple in structure and through the use of 2^k it is possible to investigate the effect of several variables upon a response (deviation) with a great economy on the number of experiments. The first order regression model of the experiment and the quadratic equation is as expressed in equations 1 and 2 respectively.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \qquad (1)$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 {x_1}^2 + \varepsilon \qquad (2)$$

Where x_1 is the coded variable of A, x_2 coded variable of β , β's are the coefficients of regression for a straight line, and ε represent the errors. The $\beta_{12} x_1 x_2$ introduces curvature in the response functions.

The hole axis deviation (*x* and *y*) were measured using the Cyclone Scanning Machine which has two readings for *x* and *y*, one from a point on the hole, 5 mm deep from the work piece top surface and the second one 86 mm deep from the top surface of the work piece. The *x* and *y* values were used to find the resultant deviation of the hole using equation 3.

$$R = \sqrt{(\Delta X^2 + (\Delta Y^2)} \qquad (3)$$

Where *R* is the deviation, Δ*X* is the difference in the *x values* of top and bottom and Δ*Y* is the difference in the *y values* of top and bottom. The scheme of measurement is shown in Table 3. The values of the resultant deviations were fed into a statistical software package (Stata Version 10) to analyze the data obtained which was performed at 95% confidence limit. Table 4 shows the deviations with respect to the feed and the speed from the table shows that the least axis deviation was recorded when the cutting speed was at its highest speed (636 rpm) and the feed was at its lowest of 25 mm/min and highest when the speed was at 477 rev/min and the feed was at 40 mm/min. It can also be observed that the low speed and feed resulted in reasonably low deviations, which implied that the relationship between the deviation and process parameter was not linear. The plotted values of deviation and speed to feed are scattered randomly as indicated in Table V. Adjusting the speed with a unit increase in feed shows that the deviation increases significantly by about 0.0055. Same with the deviation/speed values as shown in Table V. Average values of speed/feed shown in Figure 12 were used to develop the deviation equation for the effect of feed on hole deviation as shown in equation 4.

$$D = \alpha + \gamma f + \delta f^2 \qquad (4)$$

Tables 5-8 show the average speed/feed values and regress deviation-speed respectively, which are also factor into the equations. The process model deviation for effect of feed rate was found to be equation 5. Equation 6 was used to determine process model deviation for effect of speed data from Table 8 and it was found to be equation 7.

$$D = -0.682924 + 0.435748f - 0.0004236f^2 \qquad (5)$$

$$D = \alpha + \gamma v + \delta v^2 \qquad (6)$$

Where D, denotes vertical hole axis deviation, γ, δ, α denotes the respective constants and *f* denotes feed.

$$D = -0.723345 + 0.0046822v - 4.96e - 0.6v^2 \qquad (7)$$

Where denotes vertical hole axis deviation; γ, δ, α denotes the respective constants and v denotes speed.

FIGURE 2. DMU 80 MONO BLOCK DECKEL MAHO CNC MILLING MACHINE

FIGURE 3. FACING OFF THE TITANIUM WORK PIECE

FIGURE 4. THE TITANIUM WORK PIECE WITH THE HSS DRILL BEFORE DEEP DRILLING

TABLE 1.
PROPERTIES OF TI-6AL-4V MECHANICAL AND CHEMICAL COMPOSITION

Chemical composition		Mechanical Properties	
Al	6.37	Tensile strength (MPa)	960-1270
V	3.89	Yield strength (MPa)	820
Fe	0.16	5D (%) Elongaion	≥8
C	0.02	Area reduction (%)	≥25
Mo	<0.01	Density (g/cm^3)	4.42
Mn	<0.01	Modulus of elasticity	100-300
Si	<0.01	Hardness (Hv)	330-370

TABLE II.
DRILL MANUFACTURER'S PARAMETERS (SOMTA CATALOGUE) AND FINAL SET OF PARAMETERS

Hole	Drill manufacturer's parameters		Final set of parameters	
	Speed (m/min)	Feed (mm/rev)	Speed (m/min)	Feed (mm/rev)
B3	20	0.1	318	25
C1	40	0.18	318	65
C3	40	0.14	636	25
C2	16	0.14	636	65
D1	30	0.08	477	40
D2	30	0.019	318	25
D3	30	0.14	318	65
E1	30	0.14	636	25
E2	30	0.14	636	65
E3	30	0.14	477	40

TABLE III.
READING OBTAINED FROM THE CYCLONE SCANNING MACHINE (CSM)

Hole	X at 5 mm depth	X at 86 mm depth	ΔX	Y at 5 mm depth	Y at 86 mm depth	ΔY	ΔX 2	ΔY 2
C3	0.004	0.013	0.02	24.52	24.68	0.16	0.00028	0.0256
B3	34.82	34.94	0.11	63.31	63.48	0.17	0.01322	0.02924
C1	13.93	13.73	0.2	62.99	63.19	0.19	0.04579	0.03763
C2	34.39	34.11	0.2	63.34	63.80	0.46	0.08294	0.21436
D1	13.96	13.34	0.62	34.83	34.84	0.01	0.38316	1.0E-04
D2	14.41	14.28	0.14	14.21	14.09	0.12	0.0196	0.01368
D3	34.70	34.94	0.24	34.55	34.77	0.22	0.05664	0.0484
E1	14.06	14.14	0.07	34.84	34.84	0.00	0.00532	1.6E-05
E2	34.69	34.88	0.18	34.58	34.89	0.31	0.03097	0.09672
E3	14.32	14.26	0.07	14.15	13.85	0.30	0.00504	0.08702

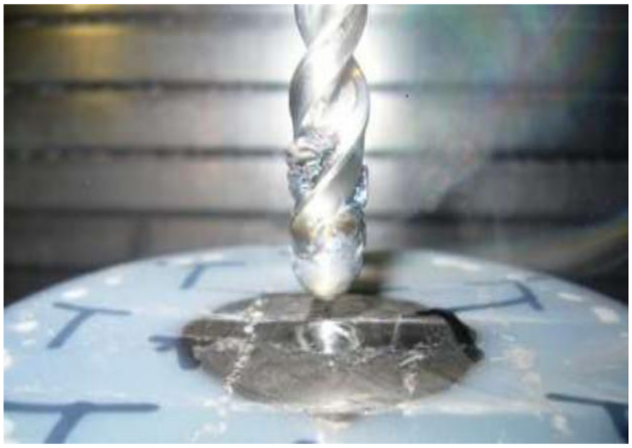


FIGURE 5. TOOL FAILURE AFTER USING MANUFACTURER'S CUTTING PARAMETERS

FIGURE 7. SET UP FOR MEASUREMENT OF HOLE ACCURACY

FIGURE 6. CYCLONE SCANNING MACHINE

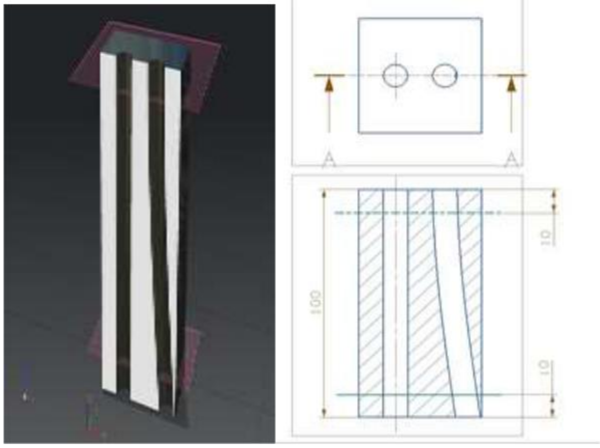


FIGURE 8. MODEL SHOWING IDEAL AND TYPICAL HOLE PROFILE AND MEASUREMENT ARRANGEMENT

FIGURE 9. Ti-6AL-4V IN SCANNING ELECTRON MICROSCOPY

FIGURE 9. SECTIONING OF Ti-6AL-4V IN EDM

Table 5 shows the regress deviation speed – feed while Table 6 presents the Analysis of Variance (ANOVA) of the process model. Table 6 presents the average speed/feed values while Table 7 presents the regress deviation- speed.

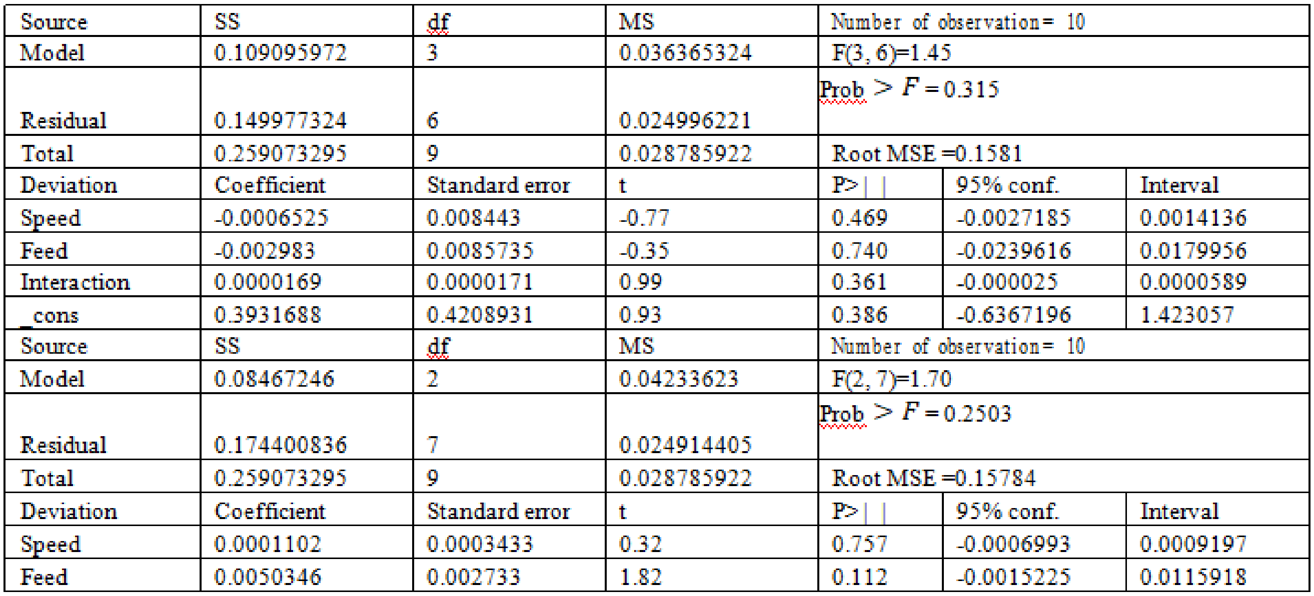
TABLE IV.
CALCULATED DEVIATION VALUES

Hole	Speed (mm/min)	Feed (mm/rev)	Hole Deviation (mm)
C3	636	25	0.161
B3	318	25	0.206
C1	318	65	0.289
C2	636	40	0.545
D1	477	40	0.619
D2	318	25	0.182
D3	318	65	0.324
E1	636	25	0.073
E2	636	65	0.035
E3	477	0	0.303

TABLE V:
REGRESSION DEVIATION SPEED – FEED

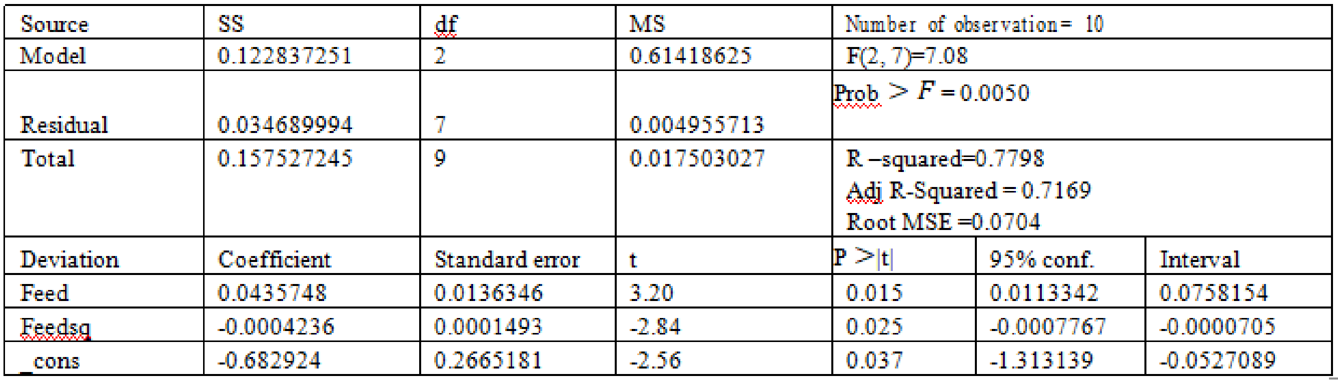
Source	SS	df	MS	Number of observation= 10		
Model	0.122846343	3	0.40948781	F(3, 6)=7.08		
Residual	0.034680902	6	0.00578015	Prob $> F$ = 0.0213		
Total	0.157527245	9	0.017503027	R –squared=0.7798 Adj R-Squared = 0.6698 Root MSE =0.07603		
Deviation	Coefficient	Standard error	t	P>| |	95% conf.	Interval
Speed	0.0056535	0.0021593	2.62	0.040	0.0003698	0.0109371
Speedsq	-5.98e-06	2.28e-06	-2.63	0.039	-0.000116	-4.09e-07
Feed	0.0054525	0.001344	4.06	0.007	0.0021639	0.0087411
_cons	-1.171137	0.4776521	-2.45	0.050	-2.33991	-0.0023646

TABLE VI.
ANOVA OF THE PROCESS MODEL



Source	SS	df	MS	Number of observation= 10		
Model	0.109095972	3	0.036365324	F(3, 6)=1.45		
Residual	0.149977324	6	0.024996221	Prob $> F$ = 0.315		
Total	0.259073295	9	0.028785922	Root MSE =0.1581		
Deviation	Coefficient	Standard error	t	P>| |	95% conf.	Interval
Speed	-0.0006525	0.008443	-0.77	0.469	-0.0027185	0.0014136
Feed	-0.002983	0.0085735	-0.35	0.740	-0.0239616	0.0179956
Interaction	0.0000169	0.0000171	0.99	0.361	-0.000025	0.0000589
_cons	0.3931688	0.4208931	0.93	0.386	-0.6367196	1.423057
Source	SS	df	MS	Number of observation= 10		
Model	0.08467246	2	0.04233623	F(2, 7)=1.70		
Residual	0.174400836	7	0.024914405	Prob $> F$ = 0.2503		
Total	0.259073295	9	0.028785922	Root MSE =0.15784		
Deviation	Coefficient	Standard error	t	P>| |	95% conf.	Interval
Speed	0.0001102	0.0003433	0.32	0.757	-0.0006993	0.0009197
Feed	0.0050346	0.002733	1.82	0.112	-0.0015225	0.0115918

TABLE VII.
AVERAGE SPEED/FEED VALUES TABLE



Source	SS	df	MS	Number of observation= 10		
Model	0.122837251	2	0.61418625	F(2, 7)=7.08		
Residual	0.034689994	7	0.004955713	Prob $> F$ = 0.0050		
Total	0.157527245	9	0.017503027	R –squared=0.7798 Adj R-Squared = 0.7169 Root MSE =0.0704		
Deviation	Coefficient	Standard error	t	P >|t|	95% conf.	Interval
Feed	0.0435748	0.0136346	3.20	0.015	0.0113342	0.0758154
Feedsq	-0.0004236	0.0001493	-2.84	0.025	-0.0007767	-0.0000705
_cons	-0.682924	0.2665181	-2.56	0.037	-1.313139	-0.0527089

TABLE VIII.
REGRESS DEVIATION- SPEED TABLE

Source	SS	df	MS	Number of observation= 10		
Model	0.027710424	2	0.013855212	F(2, 7)=0.75		
Residual	0.129816821	7	0.01854526	Prob $> F$ = 0.5081		
Total	0.157527245	9	0.017503027	Root MSE =0.13618		
Deviation	Coefficient	Standard error	t	P> | |	95% conf.	Interval
Speed	0.0046822	0.003844	1.22	0.263	-0.0044073	0.0137717
Speedsq	-4.96e-06	4.05e-06	-1.22	0.261	-0.0000145	4.63e-06
_cons	-0.723345	0.8324197	-0.87	0.414	-2.691705	1.245015

FIGURE 11. SLICED TITANIUM BLOCK AFTER DEEP DRILLING

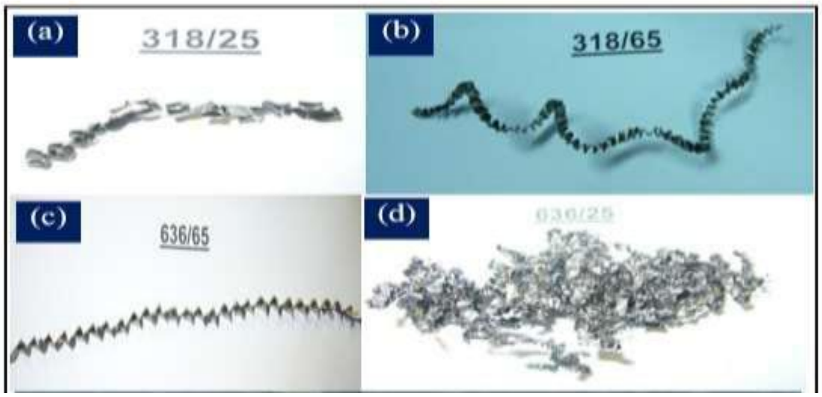


FIG. 12. TYPES OF CHIPS FORMED

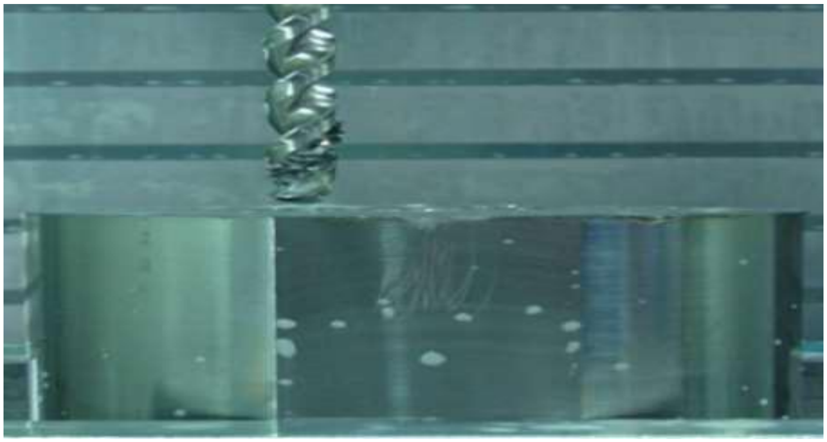


FIGURE 13. TI-6A1-4V MATERIAL WELDED ON THE TOOL

RESULTS AND DISCUSSION

I. Deep Drilling Process Model

On the sliced work piece as shown in Figure 11, which reveals that the top half from the direction of the drill has no sign of corrosion with the shape of the hole as relatively regular, because the tool is still intact and shows the side of the direction from where the holes were started. However, the centre of the total depth to the bottom of the holes are very rough because the tool shows the starting of fail. The holes begin to show sign of roughness which is the part where indications of corrosion are observed on analyzing the color of the material in this region. This is effect of adhesion wear of the tool on the titanium surface. Welded tool material were also observed on the material because of the adhesion wear of the tool to the titanium material.

II. Chip Formation

Figure 12 (a) shows the chip formed when Ti6Al4V was deep drilled at a low speed of 318 rev/min and low feed of 15 mm/min. The chip formed was found to be short and discontinuous because of the low speed and feed effect. This shows that the low machining parameters used were favourable due to the formation of short and discontinuous chip that has the tendency to improve the tool life. Figure 12 (b) shows that the chips formed at the speed of 318 rev/min and high feed of 65 mm/min were log ad continuous with the tendency to weld onto the tool. Figure 12 (c) shows that the chips formed at 635 rev/min and feed of 65 mm/mm were long, continuous with the tendency to weld on to the too because of high speed and feed. Figure 12(d) shows that at a high speed of 635 rev/min and feed of 25 mm/mm, the chips formed were continuous but not straight, clustered on the tool and blocked the helical flute. This result is supported by the findings of Hua and Shivpuri [44] who investigated the chip morphology ad segmentation while cutting Ti6Al4V and found that at low speeds, short and discontinuous chips were found while serrated chips were found at high speeds.

The Ti6Al4V chips came out in different forms, shapes and sizes due to different speeds and feeds. Some were short and discontinuous while some long and continuous with the tendency for the development of built up edges.

III. Tool Failure and Wear Mechanism

Drill wear was only observed and not measured during this study. A time interval of 15s was provided to keep the drill exposed to cooling after every 2mm depth cut. Figure 5 shows a tool that failed after only 20mm of depth cutting. The tool was running at the initial parameters (speed of 1272 rpm and a feed of 123 mm/min).

There was an indication of welding that took place between the tool and material and the edges of the tool completely lost their geometries as a result of wear and heat. This was evidenced by the tip of the tool which shows a sign different colour due to the effect of the high temperatures. It was observed that the drilling and machining of titanium alloys should be generally done at low speeds and feeds (477 -318 rpm and feed 25-65 mm/min). This was also observed by Yang and Liu [42] and Hong and Ding [43] who concluded that the titanium alloy cutting speed should be low to avoid very short tool life and high cutting temperatures promoted thermally-related wear which was the principal cause for the rapid tool wear. Observation of the drilled Ti-6Al-4V under a SEM shows the manifestation of corroded spots on the machined hole surface especially the lower half of the drilled titanium work piece. These observations are important if it is considered that titanium alloys are free from Ferrous. It was concluded that when the drill was deep inside the work piece in the lower half, it experienced high temperatures combined with a difficulty of coolant access to the cutting zone. As a result of that, diffusion wear acted on the tool material.

Diffusion wear is a common phenomenon that takes place at high temperature cutting as presented in the SEM analysis shown in Figure 14. Attention was on the three interesting spots. The first spot A was one of the corroded areas. Spot B and C were basically the heads which resulted from the melting of both the work piece material and tool. This was a strong indication of the extent of heat that was produced at the deep depth inside the hole. Examination of the head B revealed that it consists of a high presence of Fe. Fe has through diffusion adhered to the titanium alloy surfaces where a lot of corrosion is observed. Position C is similar to position B. The titanium shows in the surrounding area. The lighter spot area of interest in high presence of ferrous metal diffused in the titanium alloy. The titanium is in the surrounding area. The dark area is the titanium alloy material Ti-6Al-4V, which shows high presence of Ti is present in the area. The white area was investigated and enlarged as seen in Figures 14-16. The area of interest shows a high presence of three materials, Fe (ferrous), W (tungsten) and Mo (molybdenum). Ti-6Al-4V has no tungsten (W) but have a very small percentage of molybdenum (Mo) in its composition as indicated in Table 1. These elements are coming from the tool which is HSS tool steel and has percentages of W (12-18), Cr (4) and Co (5). This indicates that diffusion of Tungsten (W) of the tool material into Ti-6Al-4V can be observed.

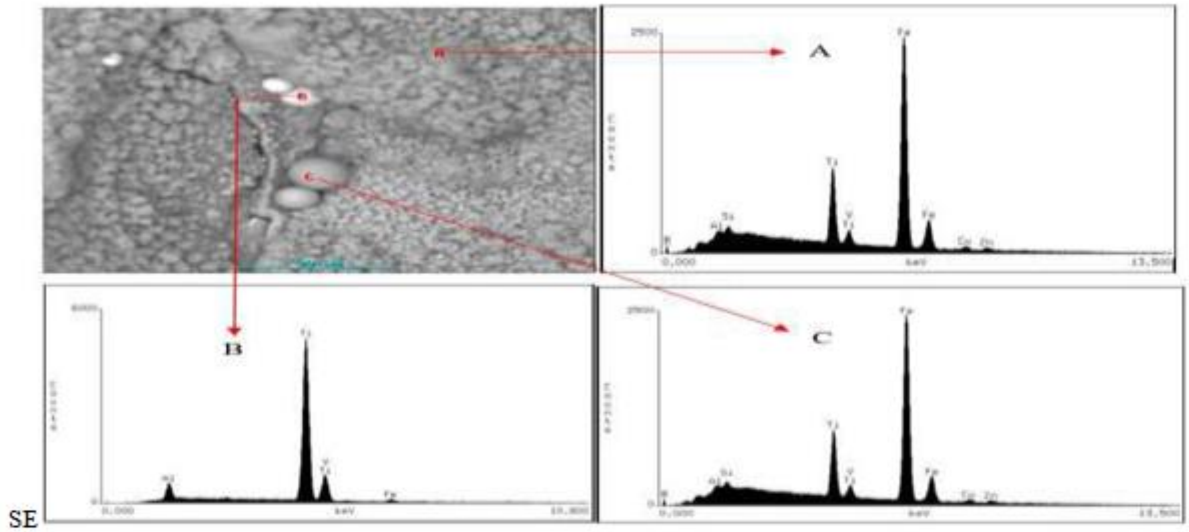


FIGURE 14. SEM RESULTS

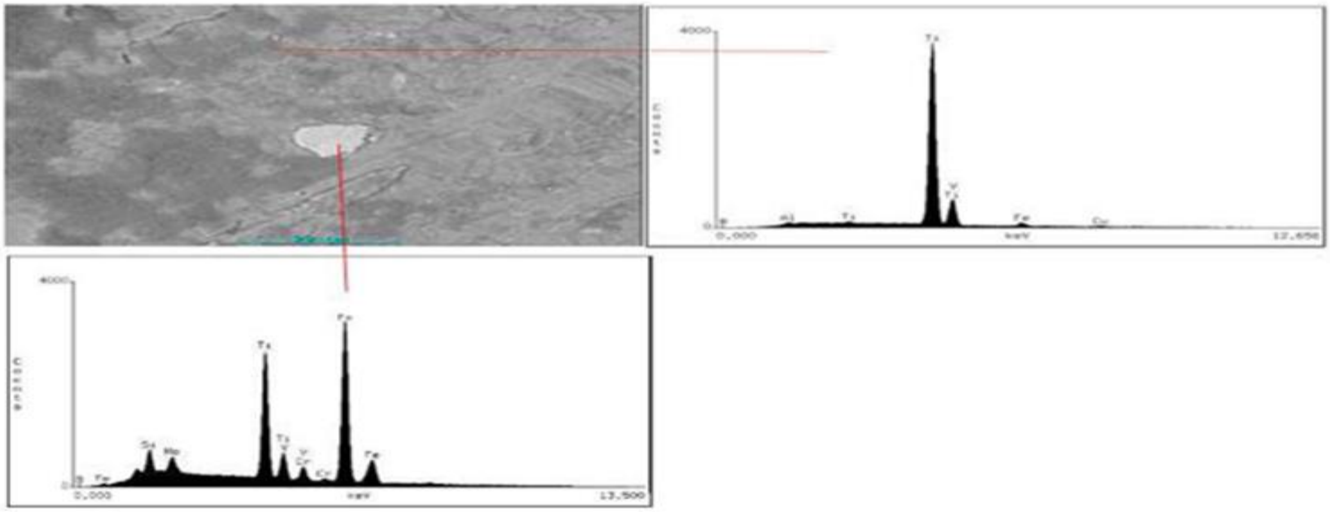


FIGURE 15. SECOND SEM RESULTS

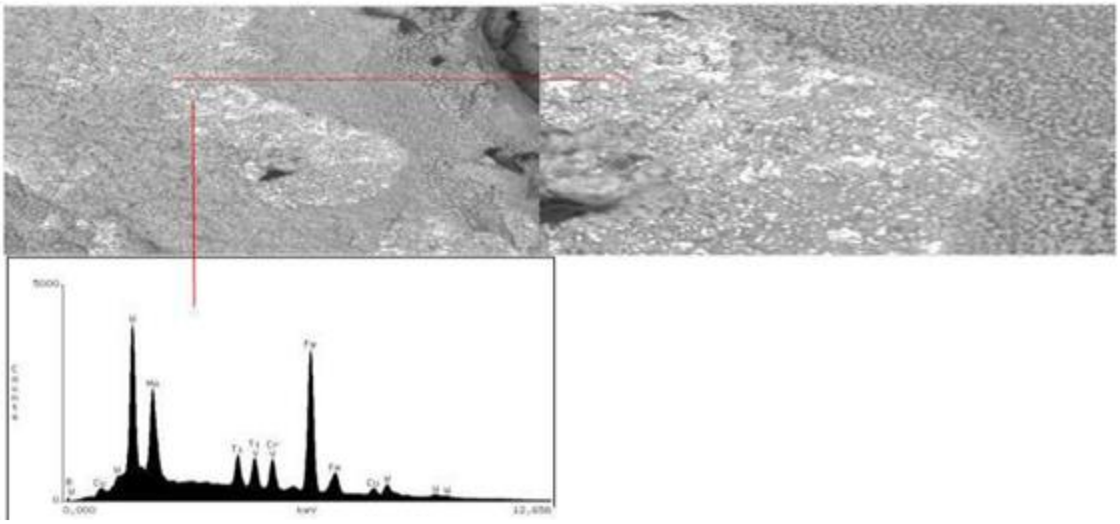


FIGURE 16. THIRD SEM RESULTS

CONCLUSIONS

The aim of this study was determine the effect of cutting parameters on the accuracy of holes produced by deep drilling of Ti-6Al- 4V titanium alloy and to develop a model for estimating hole deviation during the deep-drilling of titanium alloy material. This was achieved by conducting a sequence of machining tests on deep drilling of Ti6Al4V alloy. Furthermore, a model that describes and improves the accuracy of holes in deep drilling of Ti6Al4V using High Speed Steel (HSS) drills was developed. The factorial design methodology for experiments was also employed to investigate the influence of the cutting parameters on hole accuracy. Drilling were carried out on a solid cylindrical shaft of titanium alloy Ti-6Al4V using a 5-axis, Computer Numerical Control (CNC) milling machine. The process was modelled with data analysed with the use of the Stata Version 10 software package, and the results obtained indicated that the feed can provide approximately 77% of the total variation considered at a 95% confidence limit.

During the study, high tool wear resulting in short tool life was observed when drilling at high speeds and feeds. Lower speeds and feeds are highly recommended for drilling Ti6Al4V as observed during the study. The 10 mm HSS Co drill fails at high speeds of between 1272-640 rev/min and drilling without failure was observed at the speeds of 630-318 rev/min for deep drilling of Ti-6Al-4V.

When analysing the drilled titanium surfaces, a high presence of W (tungsten), Fe (ferrous) and Mo (molybdenum) in the titanium work piece was noticed. This clearly indicates that diffusion actually took place from the tool to the material. The combination of 318 rev/min and 25 mm/min produces preferred short and discontinuous chips as they do not block the coolant to cool the tool tip. For every unit increase in feed, the deviation increases significantly by about 0.043. In adjusting the process model for speed with a unit increase in feed, the deviation increases significantly by an amount of about 0.0055. The developed process model also indicates the effect of speed on the deviation. The model shows that about 18% of the total variation at a 95% confidence limit. For every unit increase in speed, there is an increase in deviation of about 0.00468. The feed has a much higher effect on deviation than speed when deep drilling titanium alloys Ti-6A-l-4V. The findings presented in this study can assist machining to establish the feasible range of process parameters that will ensure that holes are drilled to the required precision and accuracy when drilling Ti6Al4V. Tis work is limited to numerical analysis and physical experimentations of the drilling process of Ti6Al4V. Future works can consider the optimization of process parameters for improved tool life.

ACKNOWLEDGEMENTS

Authors would like to acknowledge the Technology Station in Advanced Manufacturing, the Innovative Manufacturing Design Solution Group (IMDSG) at Tshwane University of Technology.

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