INVESTIGATION OF THE EFFECT OF TOOL MATERIALS AND PROCESS PARAMETERS ON DRY DRILLING OF Ti-6Al-4V ALLOY

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By

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INVESTIGATION OF THE EFFECT OF TOOL MATERIALS AND PROCESS PARAMETERS ON DRY DRILLING OF Ti-6Al-4V ALLOY

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A candidate for the degree of Master of Science,

And hereby certify that, in their opinion, it is worthy of acceptance.

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To my mother: Fatima Bersaly

To my father: Ahmad Faqeeh

To my wife: Jamilah Al-Saraj

To my sisters: Ahlam (Hayat) &Khloud & Modey & Meznah & Ibtsam & Ehssan

To my brothers: Anas & Amjad
To my sons: Ahmad & Aws

To all the members of Faqeeh & Bersaly Family

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ABSTRACT

Titanium and its alloys are attractive materials for different field of industries because of their outstanding properties. Drilling is one of the most important traditional machining processes and it is a primary technique in aerospace industry. Since drilling process commonly be in the final steps of the fabrication, drilling titanium has economic significance. In addition, using coolant is the most harmful pollutant in machining and it is responsible for high percentage of total machining cost. The dimensional tolerance and surface roughness are significant quality characteristics in drilling operation because the poor tolerance and surface roughness will affect at the point of assembly.

The performance of un-coated and TiAlN-coated carbide tools were investigated when dry drilling Ti-6Al-4V alloy. The investigation had been performed in order to find the best tool material performance when dry drilling Ti-6Al-4V. The effect of spindle speed and feed rate on thrust force, torque, dimensional tolerance, and surface roughness were reported. Response surface methodology (RSM) based on central composite design (CCD) is used to perform the investigation. In addition, RSM based on CCD integrated with desirability function is used to determine the optimum input conditions that produce the most desirable quality characteristics (minimum tolerance and surface roughness) with good productivity. Analysis of variance (ANOVA) is used to detect the relative significance of the input factors on each response.

Chapter 1 : Introduction

Titanium has superior characteristics such as high strength, low density, and unique corrosion resistance. Titanium and its alloys are attractive for different field of industries such as automobile, medical, military, chemical, and aerospace industry [1, 2]. Titanium industry grew rabidly over the last 40 years because of the variety of its industrial applications [3]. In addition, the level of about 0.6% titanium is present in the earth's crust; therefore, it is the fourth most abundant structural metal after aluminum, iron, and magnesium [1].

Regardless the titanium abundance in the earth's crust and its high growth of usage in several industries, the manufacturing of the titanium and its alloys is costly compared to other metals. The complexity of an extraction process, difficulty of melting, and technical challenging during fabrication and machining are the reasons that make manufacturing of titanium and its alloys expensive [4]. Therefore, numerous research efforts have been directed to machining of titanium and its alloys to achieve high product quality with good productivity and effective cost.

1.1 Machinability of Titanium

Titanium and its alloys are generally classified as difficult to machine materials for all traditional machining methods because of the reasons that have been mentioned by researchers:

(1) Low thermal conductivity, which leads to increase the temperature at the tool/workpiece interface [2, 4, 5].

(2) Chemical reactivity of titanium at high cutting temperature ($> 500°$) with almost all tool materials obtainable [3, 7]

(3) Since titanium can maintain its hardness and strength at an elevated temperature, the force and stress on the cutting edge will be higher [2]

(4) The cutting tool starts to wear rapidly because of the low thermal conductivity and high chemical reactivity of titanium, resulting higher cutting temperature and strong adhesion between the cutting tool and the workpiece [11, 12].

All mentioned reasons generated unfavorable machining outcomes such as high roughness and tool failure. Some of the nontraditional machining methods are used to overcome the technical challenges [6]. However, most of the titanium-machined parts are yet made by traditional machining methods [4]. Consequently, traditional or conventional machining methods such as drilling, turning, and milling are worth to be studied more to cope the technical challenges of machining titanium and its alloys.

1.2 Drilling of Titanium

Drilling is one of the most important traditional machining processes. It is responsible for 40-60% of the total material removal processes, and it is a primary technique in aerospace industry [13]. It is a vastly used machining process and has economic significance, as it is commonly be in the final steps of the mechanical component fabrication [2, 8]. Rui Li [8] reported five technical difficulties when drilling titanium: high drill temperature, drill wear, limited cutting speed, chip ejection, and exit burr formation. Due to economic significance and technical challenges, drilling titanium is a very critical process. However, most of the studies about machining of titanium and its alloys have been concentrated on turning and milling operations [13]. The drilling titanium researches are still limited and not widely reported at the point of comparison to turning and milling of titanium.

1.3 Twist Drilling

Twist drilling is the most common hole making method. Twist drills are made of different materials, shapes, dimensions, and tolerances. The low-cost and the large quantity of drill supply are the main features of twist drilling; however, the basic design twist drills are in general restricted to the depth of a hole [2]. A twist drill has a chisel edge and two helical cutting lips at the bottom with point angle, which meet the flutes with a helix angle. The two helical cutting lips expand the hole by removing the material with a constant chip thickness as the drill is fed into the material at specific feed rate then the helical flutes evacuate the chips from the drilled hole [10]. Geometric parameters of twist drill are shown in Fig. 1-1.

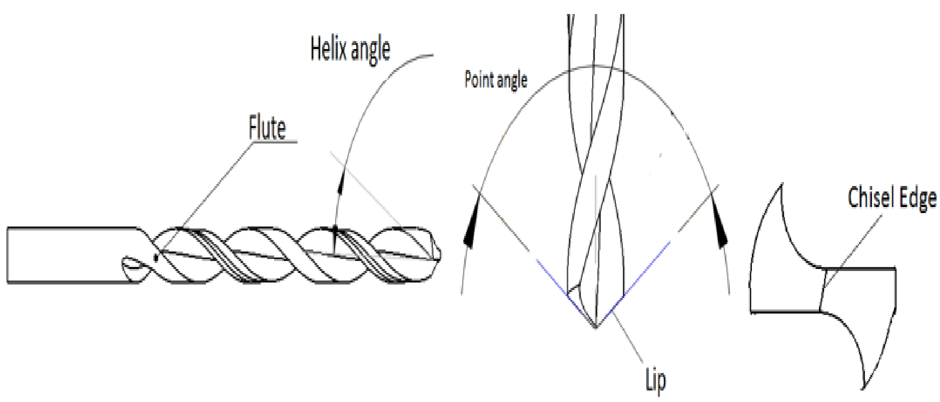

Figure 1-1: Geometric parameters of twist drill

1.4 Literature Review

Materials with unique metallurgical properties such as titanium, stainless steel, and super alloys are difficult to be machined in general and to be drilled in specific. A considerable number of studies has been performed to overcome the technical difficulties of drilling hard to machine materials.

Caydas et al. [18] performed an evaluation of HSS, K20 solid carbide, and TiN-coated HSS tool in dry drilling AISI 304 austenitic stainless steel. They analyzed data based on the result of the surface roughness, tool flank wear, exit burr height, and hole accuracy. The experimental investigation concludes to TiN-coated HSS tool showed the highest performance [18]. Wang et al. [19] investigated the effects of geometrical structure of coated cemented carbide twist drills on the drill tool life when used for drilling 42CrMo ultrahigh-strength steel . The consequence of this study: the most significance parameter of geometric structure, which influences on tool life, is the cutting-edge pattern [19].

El-Gizawy and Khasawneh [20, 23] studied the main influences of cutting parameters (cutting speed, feed and tool condition) on hole quality when drilling IM7/977-3 composite material sheet over 6Al-4V titanium alloy sheet. Response surface methodology (RSM) and Taguchi analysis used to find the optimum process conditions [20, 23]. The study reveals that in order to end up with high-quality holes (low surface roughness with the required dimensional accuracy) of the epoxy composites (IM7/977-3), speed of 2300 rpm and low drilling feed of 0.0078 inch per revolution are recommended [20, 23].

Enemuoh [21] developed a new comprehensive approach to select optimum drilling conditions and drill tool in advanced laminated composite materials [21]. In this study, a multi-objective optimization technique is used to detect the optimum drilling conditions for drilling advanced fiber-reinforced composite materials [21]. The results generated from this research concluding high speed and low drilling feed rate suggested for producing delamination-free and good surface finish holes in epoxy composite [21].

Titanium is one of the most popular hard to be machined materials. Researchers have done a number of studies for drilling processes of titanium and its alloys. Drilling processes include twist drilling, vibration assisted twist drilling, ultrasonic machining (USM), and rotary ultrasonic machining (RUM). In fact, twist drilling of titanium has been studied the most among the other three processes [2]. The studies concentrated on different effects of process parameters such as effects of feed rate, cutting speed, drill geometry, tool materials, and coolant.

Li [8] investigated the drilling mechanism while drilling Ti alloys to increase the productivity. The experimental investigation of this study [8] demonstrated the feasibility of high-throughput drilling of Ti-6Al-4V and the significance of feed rate to improve the tool life. One of the major conclusions was that the limitation of drill life is correlating with the increase of feed rate [8, 14]. In addition, he stated that improving the drill life lead to produce lower surface roughness [8, 14]. The roundness of the drilled holes becomes better as the feed rate decrease; in contrast, larger exit burrs are produced at low feed rate [2]. Furthermore, the increase of feed rate would increase the thrust force and the torque [2]. As a result, Li suggested low values of feed for achieving better tool life, lower surface roughness and preferable hole roundness with considering the limitation of feed rate that produced larger burrs [8, 2].

Rahim and Sharif [15] studied the machinability of Ti-6Al-4V and Ti-5Al-4V-Mo/Fe alloys when drilling by a K-grade WC-Co uncoated carbide tool. They discussed the effect of cutting speed on tool life, tool failure model, cutting force, and surface integrity of the drilled holes. They stated that the improvement of surface roughness noticed at higher cutting speed on both alloys [15]. However, lower cutting speed produced more roundness hole, smaller exit burrs and longer drill life [2]. Moreover, the study reported that the lower thrust force and lower torque were been noticed at higher cutting speed [15, 2].

Li [8] studied the effects of coolant on the drill life, surface roughness, and chip ejection. He found that the external coolant supply had no obvious effect on the drill life and surface roughness, but the internal coolant supply improved the drill life which leads to lower surface roughness and better chip ejection. Larger exit burrs present in the absence of coolant [2]. The best cooling results could be achieved by using coolants containing phosphates due to their good coolant properties [3]. Furthermore, Rahim and Sasahara [17] used MQL palm oil (MQLPO) as a lubricant in the high speed drilling of Ti-6Al-4V. MQL synthetic ester (MQLSE), air blow, and flood condition were selected to make the comparison of performance. The poor result was found at the air blow condition in terms of tool life, which generate higher surface roughness. However, the MQLPO, MQLSE, and flood conditions showed comparable performance in tool life [17]. The lowest thrust force and torque were found at flood condition where the highest were found at air blow condition [17]. However, using coolant is the most harmful pollutant in machining [37,38]. In addition, according to a Germany research report, purchasing cost of coolant is responsible for 7.5% of total manufacturing cost where the maintenance cost of coolant is 17% of total manufacturing cost [37]. Therefore, the proper materials tool and optimum process parameters for dry drilling are worthy to be investigated.

Zhu and Wang [16] performed testes and analysis to determine the optimum drill geometry. They observed that thrust force and torque were higher with greater point angle [16]. On the other hand, the larger helix angle would reduce thrust force, torque, and height and thickness of burrs [2].

The cutting tool of titanium required of tool material, which is high hot hardness to resist the elevated stresses involved, excellent thermal conductivity to minimize thermic gradients, perfect chemical inertness to depress the tendency to react with titanium, toughness and fatigue resistance to withstand the chip segmentation process, and high compressive, tensile and shear strength [4]. Due to these material requirements, many of the materials such as ceramics, cubic boron nitride (CBN), and polycrystalline diamond had no success at machining of titanium [4]. In addition, these types of tool materials showed high reactivity with titanium alloys at higher temperatures [11].

Most of the studies in machining of titanium and its alloys have concluded that straight carbide (un-coated-WC/Co) tool has the best performance when turning [26, 27, 13] or milling [28, 14, 13] titanium alloys at the point of comparison to coated-carbide tools. However, the above consequence might not be true for drilling because of the complex nature of the operation.

Rahim and Sharif [13] evaluated the performance of the coated- and un-coated carbide twist drills at various cutting speeds when drilling titanium alloy. They stated that TiAlN coated-carbide drill showed an outstanding performance of tool life when compared to uncoated-carbide drill [13]. In addition, they observed that the lower surface roughness obtained with TiAlN-coated- carbide drills [13]. However, the data showed that the lower surface roughness resulted with uncoated-carbide drills at higher cutting speeds as shown in Fig. 1-2.

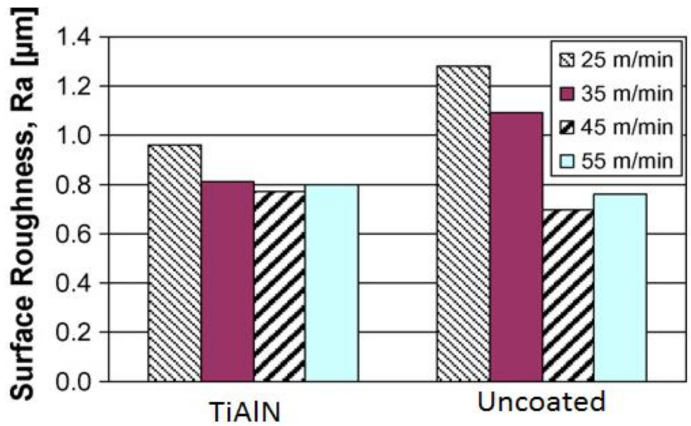

Figure 1-2: Surface roughness using TiAlN-coated and un-coated tool at various speeds when drilling titanium alloy using coolant [13]

1.5 Research Objective

Since the reports of new coated-tools performance when drilling titanium alloys are still lacking, the major objective of this research is to investigate the effect of tool materials and independent variables (speed and feed rate) on dependent variables (tolerance and surface roughness) when dry drilling Ti-6Al-4V. The spindle speed and feed rate are important factors to influence on the surface roughness and dimensional accuracy, so the effect of varying speeds and feed rates on the quality of holes produced (surface finish and dimensional accuracy) will be investigated to determine the optimum process conditions when using un-coated and TiAlN-coated carbide tools for drilling titanium. However, more trial runs are required for investigating the machining characteristics, which increase the time and cost consumption of the experiment. In this research, response surface methodology (RSM) based on central composite design (CCD) has been used to determine the optimum process conditions with lower cost and less time consumption.

Chapter 2 : Experimental Tools and Calibration

In this chapter, tools used to perform the experiment and to measure the responses during and at the end of the experiment are introduced.

2.1 The Work Fixture

The work fixture was designed with a base-plate. The base-plate is made of aluminum (Al6061) for purpose of lightweight of the fixture, but thick enough to appropriately hold the specimen rigid and resist deflections caused by the drilling thrust force and torque. The slot through the bottom of the base-plate allowed the insertion of the keys. The keys used to allow consistent positioning of the fixture on the CNC mill machine.

The configuration and design of the arrays were based on the design of the two interlocking steel cross members that secure the work pieces to the base-plate, while allowing the four relatively large quadrants for drilling. The cross members are secured to the base-plate with 3/4 inch bolts that tighten the cross members to fix the specimen. Around the edge of the specimen 8 L-brackets for further secure. The final design configuration is shown in Fig. 2-1.

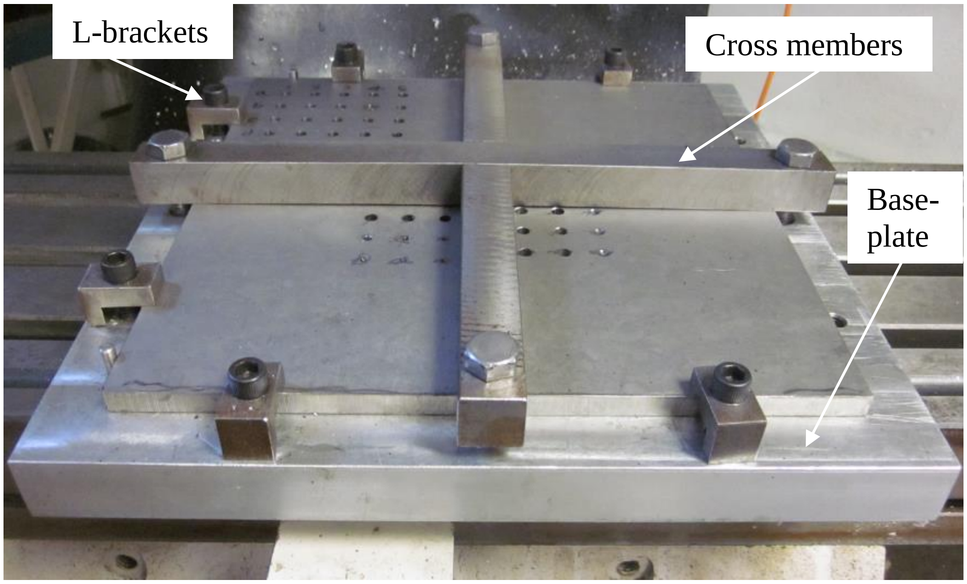

Figure 2-1: Complete final fixture configuration

2.2 The Force and Torque Sensory System

A Torque/Force sensor (Accutorque) was used to measure the thrust force and torque during the drilling operation. The Accutorque sensor is a strain gauge based stator/rotor sensor capable of measuring the torque and thrust force generated in a diversity of machining operations. The sensory components of the system are displayed in Fig 2-2. It consists of three major components: stator, rotor, and gain amplifier. Details of the gain amplifier are depicted below in Fig. 2-1.

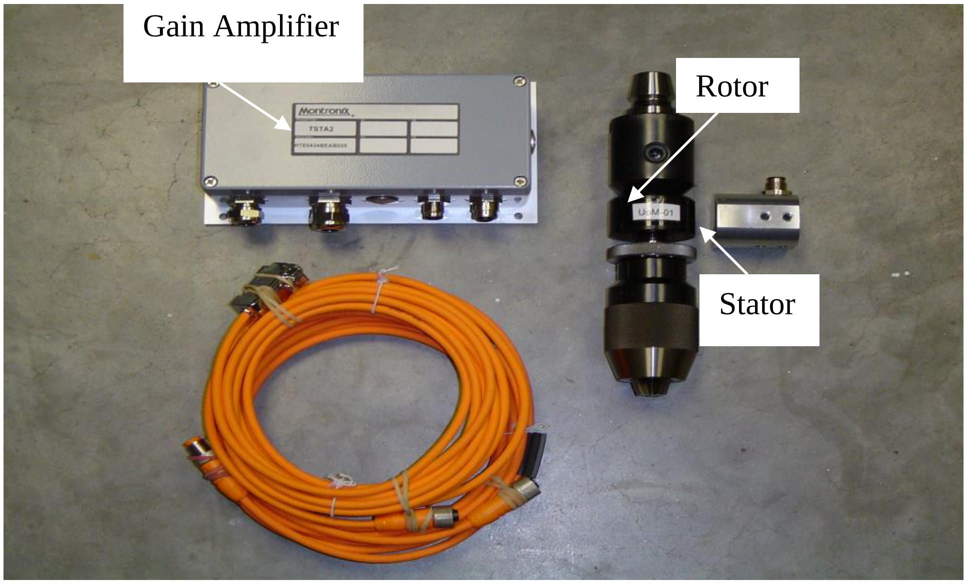

Figure 2-2: Force/Torque Sensor Components (manufactured by Montronix)

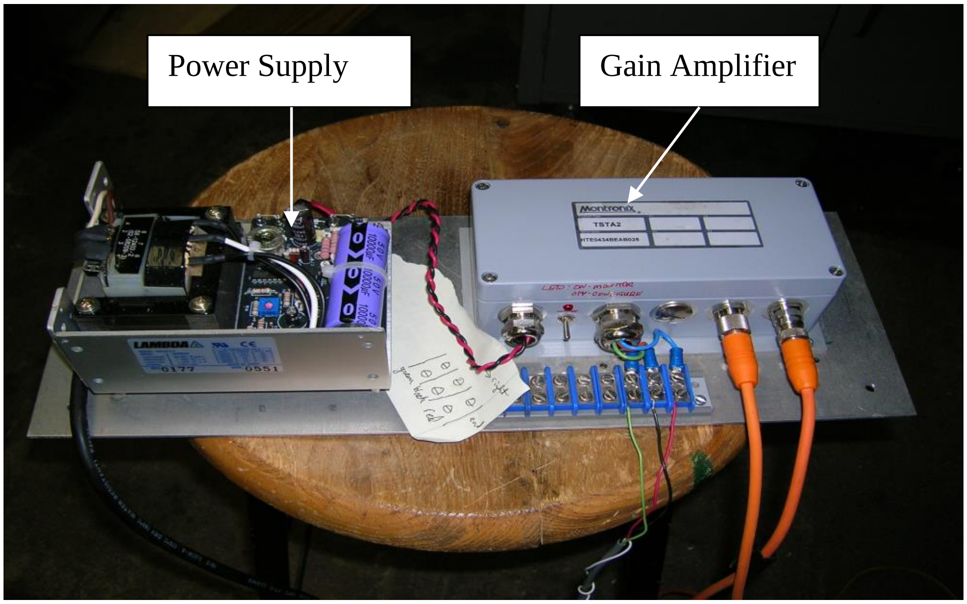

Figure 2-3: Gain Amplifier System

In addition to the Accutorque's components, the data acquisition system were required for the sensor's operation. This system, shown in Fig. 2-4, was designed and built in MU manufacturing laboratory. The system is equipped with LabView 8.5 software, and is used to collect and organize all data obtained from the sensor during testing.

Figure 2-4: Data Acquisition System

2.3 Calibration of the Sensory System

2.3.1 Thrust Force Calibration

The thrust force is calibrated using a simple lever system. In doing so, a force was added in the form of weight to open end of the lever, and the corresponding voltage output is detected by linking the voltmeter to the output wires on the gain amplifier terminal board. The simple lever system is shown below in Fig. 2-5.

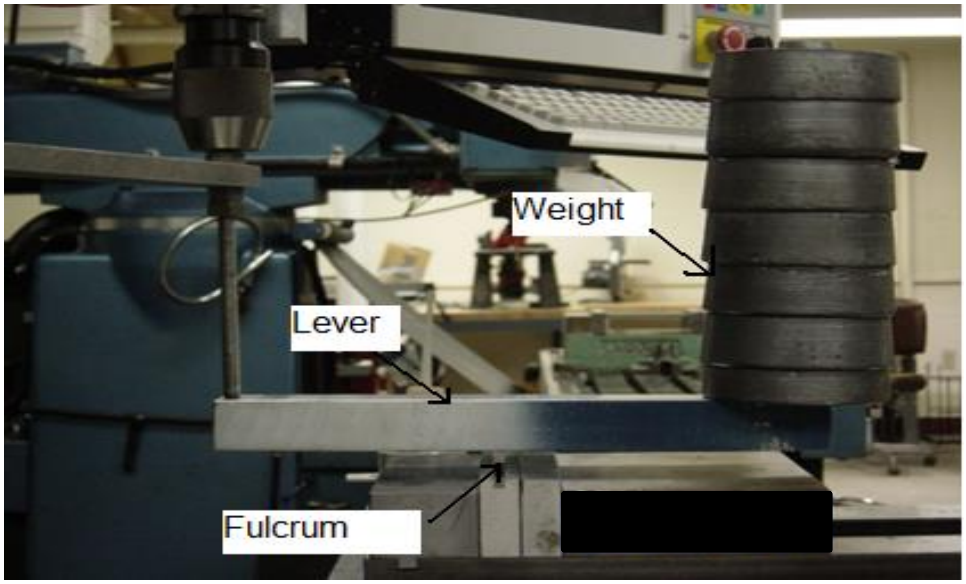

Figure 2-5: System setup for thrust force calibration

A pre-calibrated LabView 8.5 program is used to record the thrust force. The weights were added gradually and recorded through LabView 8.5. Once five different known weights and their correspondent voltage output is recorded, a linear relationship between force and voltage output is developed using Statistica software. The thrust force calibration results and their strong positive linear relationship between force in Ib and force in V with the equation are shown in Fig. 2-6.

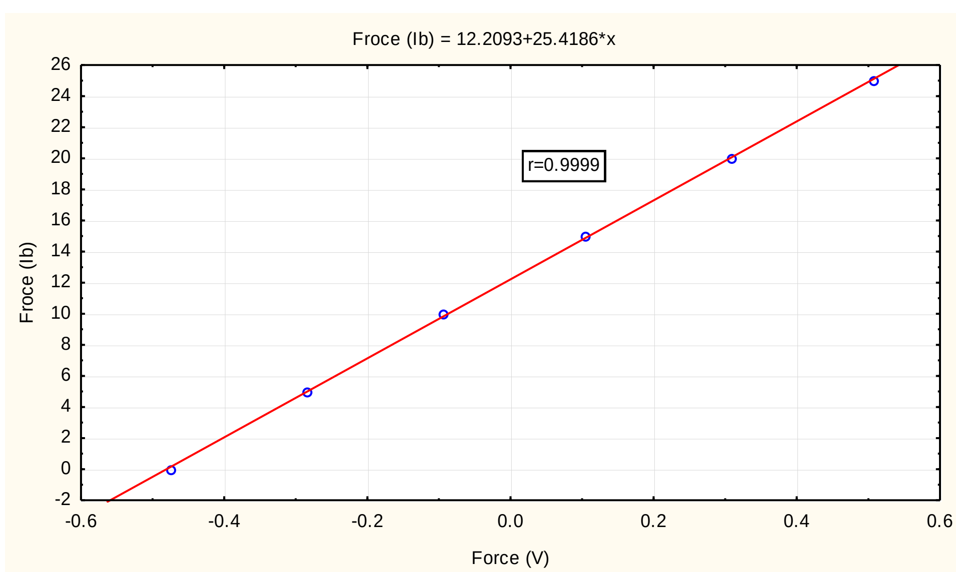

Figure 2-6: A linear relationship between force (Ib) and force (V)

2.3.2 Torque Calibration

The torque is calibrated using a simple pulley system. The total process of torque calibration is similar to that of the thrust force, in that a known torque is applied to the tool holder (chuck), and the voltage output is recorded using the voltmeter. The simple pulley system is shown in Fig. 2-7.

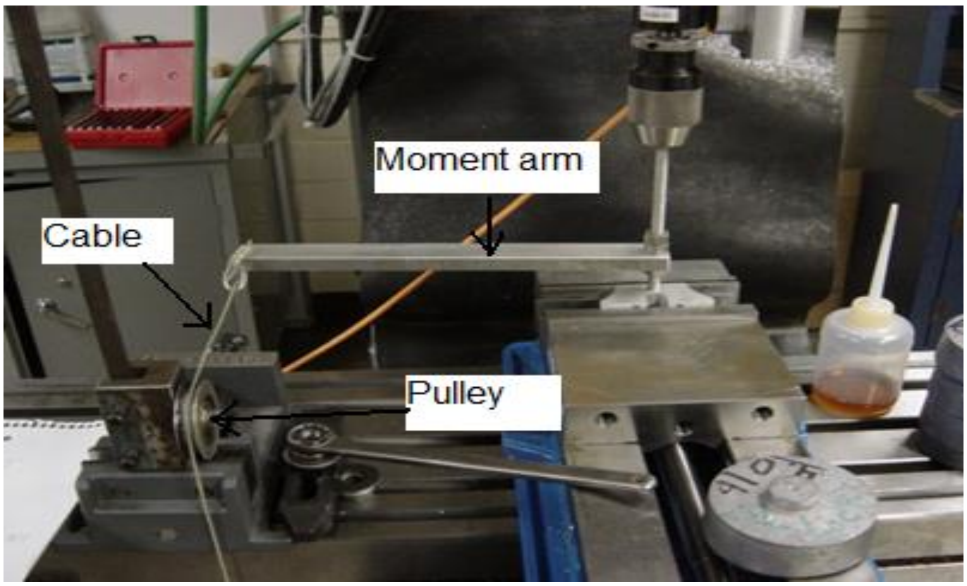

Figure 2-7: system setup for torque calibration

Torque was added gradually and recorded through LabView 8.5. Once five different known torques and their correspondent voltage output is recorded, a linear relationship between torque and voltage output is generated using Statistica software. The torque calibration results and their strong positive linear relationship between torque in Ib-ft and torque in V with the equation are shown in Fig. 2-8.

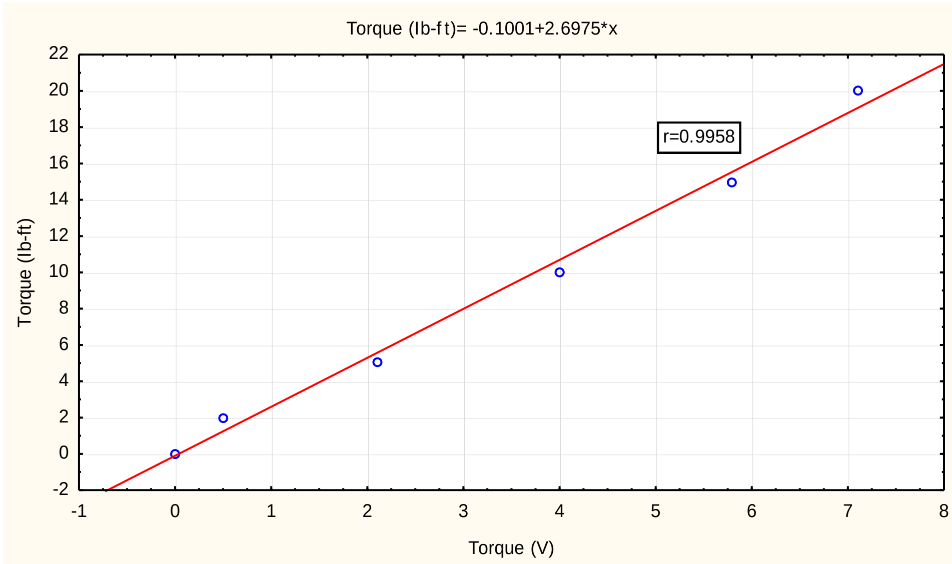

Figure 2-8: A linear relation between torque and voltage

2.4 Measurement Techniques

2.4.1 Holes Accuracy Measurement

To measure hole's accuracy, DP-4 touch probe was used. Hole's accuracy was measured for each drill hole. The technical specification of the sensor used are written in the table below.

Sense directions	+/-X +/-Y –Z(3D)
Overtravel XY	+/-10^{o}
Overtravel Z	-0.15", -3.8mm
Accuracy at 5ipm with a 30 mm stylus	+/-0.0001",+/-2.5µm **(Uni-directional)**
Upon contact	Output closes
Trigger force X or Y	1.75 oz.
Trigger force Z	6.75 oz.
Hysteresis	+/-0.00005", +/-1.25µm

Table 2-1: DP-4- Probe specification

The DP-4 probe slowly and manually moved over the center of the hole, then the Z-axis was slowly and manually moved down to let the tip of the probe be inside the hole. The CNC controller was ordered to start the probing cycle. The stylus gently moved to each quadrant of the hole. The probing cycle finish by returning the stylus to the center of the hole. At the end of DP-4 probe moving, the measured diameter of the hole will appear on the screen. The DP4-Probe is shown in Fig. 2-9.

Figure 2-9: DP4-Probe

2.4.2 Surface Roughness Measurement

A mitutoyo surfest 402 Profilometer which has a ruby tip to contact the surface, used to measure the surface roughness of the drilled holes. Four places approximately 90^o a part had been measured for each hole. The setup of the surface roughness measurement is shown in Fig. 2-10. Table 2-2 displays the specification of the used Profilometer.

Figure 2-10: Setup of the surface roughness measurement

Stroke	0.3mm
Linearity	0.2mm
Tip shape	Conical of 90°
Tip radius	5µm
Force variance ratio	8µm/1µm
Curvature of radius of skid	30mm(1.18")
Measuring force	4mN or less

Table 2-2: specification of the Mitutoyo Profilometer

Chapter 3 : Process Models, Design of Experiments, and Experiment Procedures

In this chapter, background of the methods used to design the experiments and investigate the process are presented. The specimen material and drills' parameters considered in this study are defined.

3.1 Response Surface Methodology (RSM) / Central Composite Design

RSM methodology is a collection of statistical and mathematical techniques advantageous for improving, developing, and optimizing process. In addition, it has significant implementation in the design and development of new products, as well as in the perfection of existing product designs [25, 29, 33]. RSM is useful for modeling and analysis at cases where the objective is optimizing some performance measure or quality characteristic is called the response, which are potentially affected by several factors or a number of associated input variables (independent variables).

Central composite designs are vastly used for fitting second-order response surface because of both their statistical properties and the practical attraction of their expanded coverage around a center point [31, 32]. Therefore, a two variable RSM with central composite design was selected. The second-order model is widely anticipated in RSM because its flexibility of the model, so it can adopt a wide variety of functional forms [25]. In addition, there is considerable practical experience showing that second-order models work effectively in solving real response surface problems [25]. In the present study, a second-order response surface model (equation 3.1) is used to formulate a least square relationship between the input parameters and the output response measures.

$$Z = \beta_0 + \beta_1 X + \beta_2 Y + \beta_{11} X^2 + \beta_{22} Y^2 + \beta_{12} XY \qquad (3.1)$$

Where Z are the observed response (tolerance, surface roughness, thrust force, and torque) as a function of the main influences of factors X and Y (speed and feed), their interaction (XY), and their quadratic components (X^2, Y^2). β_0 and β_i are estimated regression coefficients.

For this experiment, the upper limit and lower limit of the process parameters (speed and feed rate) selected based on the initial experiments which were done to examine the capability of cutting speeds and feed rates that had been recommended by researchers to drill titanium using carbide tool. El-Gizawy and Khasawench [20, 23] recommended speed of 600 RPM and feed rate of 0.72 ipm for production of quality holes when drilling titanium by a twist drill that has a diameter of 0.25'' (6.35mm). Dornfeid, et al [24] used two levels of cutting speed, 1835 and 2140 RPM, and three levels of feed rate, 2, 4.3, and 5.5 ipm. The experiment's upper limit and lower limit of the process parameters (speed and feed rates) used as shown in Table 3-1. According to the central composite design, the cutting condition expressed in term of coded variables and in term of natural units of variables as shown in Table 3-2. Fig. 3-1 shows the experimental design in Table 3-2 graphically. In addition, Table 3-3 displays the generation of experiments designed by using central composite design for drilling process.

Process variables	Lower limit	Upper limit
Speed (RPM)	500	1500
Feed (ipm)	0.5	1.5

Table 3-1: Range of process parameters for experiment

Level of coding	Lowest $-\sqrt{2}$	Low -1	Center 0	High $+1$	Highest $+\sqrt{2}$
Speed (RPM)	292.893	500	1000	1500	1707.107
Feed (ipm)	0.292893	0.5	1	1.5	1.7

Table 3-2: Range of process parameters for experiment

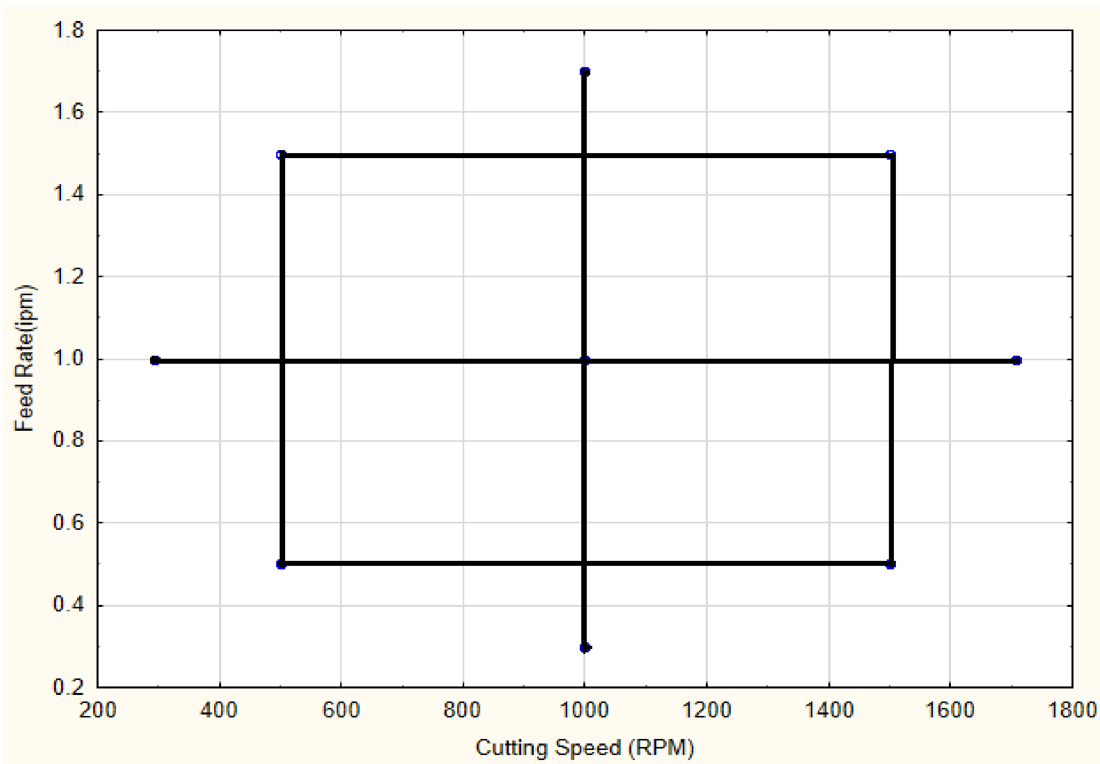

Figure 3-1: Central composite design for the drilling process with speed range of (500-1500 RPM) and feed rate of (0.5-1.5 ipm)

Exp. No	Speed (RPM) X	Feed Rate (ipm) Y
1	500	0.5
2	500	1.5
3	1500	0.5
4	1500	1.5
5	292.893	1
6	1707.107	1
7	1000	0.292893
8	1000	1.7
9 (c)	1000	1
10 (c)	1000	1
11 (c)	1000	1
12 (c)	1000	1
13 (c)	1000	1

Table 3-3: Generation of experiments designed using central composite design for drilling process

The mathematical steps to compute the quadratic model (equation 3.1) for the four responses (Thrust force, torque, tolerance, and surface roughness) as follow:

$$Z = \begin{bmatrix} z_1 \\ \vdots \\ z_{13} \end{bmatrix}$$

$$(XandY) = \begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & y_1^2 & x_1 y_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{13} & y_{13} & x_{13}^2 & y_{13}^2 & x_{13} y_{13} \end{bmatrix}$$

Finding estimated regression coefficient by

$$\beta = ((XandY)' \times (XandY))^{-1}((XandY)' \times Z)$$

Then

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_{11} \\ \beta_{22} \\ \beta_{12} \end{bmatrix}$$

3.2 Analysis of Variance (ANOVA) for Two-Factor

ANOVA is the statistical method used to detect the relative significance of the process factors on each response. The following are the Two-Factor ANOVA hypotheses tests:

1. H_0: There is no interaction between factors.

   H_a: There is interaction between factors.

Test statistic: $F = \frac{MSAB}{MSE}$

2. H_0: There are no factor A main effects (mean response is the same for each level of factor A).

   H_a: H_0 is not true.

Test statistic: $F = \frac{MSA}{MSE}$

3. H_0: There are no factor B main effects.

   H_a: H_0 is not true.

Test statistic: $F = \frac{MSB}{MSE}$

Statistical formula for the present experimental case are typically summarized in the ANOVA table as shown in Table 3-4. When P-value > 0.05, the null hypothesis is not rejected which means there is no interaction or the factor has no main effects. On the other hand, at P-value < 0.05, the null hypothesis is rejected which means there is interaction or the factor has main effects [30]. In addition, the coefficient of determination (R^2) was determined for each response to indicates how well data points fit the curve.

Source	df	Sum of Squares	Mean Square	F-value	P-value
Speed (X)	1	SSX	$MSX = \frac{SSX}{1}$	$F = \frac{MSX}{MSE}$	
Feed (Y)	1	SSY	$MSY = \frac{SSY}{1}$	$F = \frac{MSY}{MSE}$	
$X \times Y$	1	$SSXY$	$MSXY = \frac{SSXY}{1}$	$F = \frac{MSXY}{MSE}$	
X^2	1	SSX^2	$MSX^2 = \frac{SSX^2}{1}$	$F = \frac{MSX^2}{MSE}$	
Y^2	1	SSY^2	$MSY^2 = \frac{SSY^2}{1}$	$F = \frac{MSY^2}{MSE}$	
Error	7	SSE	$MSE = \frac{SSE}{7}$		
Total	12	SST_O			
R^2	$= 1 - \frac{SSE}{SST_O}$				

Table 3-4: ANOVA for Response Surface of Quadratic Model of two factors

3.3 Desirability Function

Derringer and Suich [34] demonstrated a multiple response variables method that called desirability. A typical problem in product or process development is to locate a set of conditions of the input variables (independent parameters), which produces the most desirable product or process in terms of its responses on the output variables. The procedures used to solve this problem commonly compromised two steps: (1) find adequate models to predict outcomes of the process as a function of the levels of the independent variables, and (2) finding the levels of the independent variables that produce the most desirable predicted responses on the dependent variables. The first step was performed by using response surface methodology based on central composite design with second-order model as discussed in section 3.1. The second step use an objective function, D, called the desirability function. This function transforms the predicted values outcome variables into desirability scores that could range from zero for undesirable to one for very desirable, so the desirability value d_i will be in the range $0 \leq d_i \leq 1$.

After transforming the predicted values of the dependent variables at different combinations of levels of the input variables into individual desirability scores, the overall desirability of the outcomes at different combinations of levels for the input variables can be computed. The desirability function is a geometric mean of all transformed responses (Equation 3.2).

$$D = (d_1 \times d_2 \times \ldots\ d_k)^{\frac{1}{k}} \qquad (3.2)$$

Where k is the number of measured responses in the experiment. The overall assessment can be given by the single value of D. Desirability function can be used as : none, maximum, minimum, target, and in range [35]. In the present study, minimum option is needed to find the optimum conditions of parameter to achieve the minimum responses of quality characteristics (tolerance, and surface roughness). The meaning of minimum goal parameters are [35]:

- Minimum:

  $d_i = 1$ if response < low value
  $0 \leq d_i \leq 1$ as response varies in between low and high value
  $d_i = 0$ if response $>$ high value

The desirability profile for dependent variables consists of a group of graphs, one for each independent variable. The graphs shows predicted values for the dependent variables at different levels of one independent variable. The independent variables will be selected at the levels where the predictor variables produce the most desirable predicted response on the dependent variables (quality characteristics: minimum tolerance and minimum surface roughness).

3.4 Experimental Procedures

A CNC milling machine (Accumill) was used for the drilling operations. The G programing language (G-Code) was used to develop the CNC code for drilling holes on the planned position and with the required experiment conditions. The investigated titanium plate was mounted and secured on the fixture. Tastings were then proceed by drilling the Ti-6Al-4V at the conditions obtained by the central composite design in Table 3-1. These conditions used two times: one with un-coated carbide tool and one with TiAlN coated carbide tool. No coolant was used during the drilling operation in both cases of coated and un-coated carbide tool (dry drilling). Thrust force and torque values were recorded during the drilling operation by using the ACCUTORQUE sensor and LabView

8.5 software, in order to have more comprehension of the process behavior. Fig. 3-2 shows the schematic of the experimental setup and data acquisition system.

Subsequent the drilling of all the holes, the diameters of the drill holes were measured by DP4-Probe, the reading of each hole was subtracted from the nominal diameter value $0.25''$ to get the diameter deviation from the nominal value. The surface roughness (R_a) of the drilled holes was measured for each hole using a profilometer. Four readings 90^o apart were taken then averaged for each hol. After the collection of data, the result were interpreted using statistical software (Statistica). The surface equations were obtained and differentiated by using desirability function to locate the optimum process conditions (speed and feed rate) for un-coated and coated tool, corresponding to each output, (tolerance of diameter, and surface roughness). Fig. 3-3 illustrates the steps of the experimental and analytical procedure.

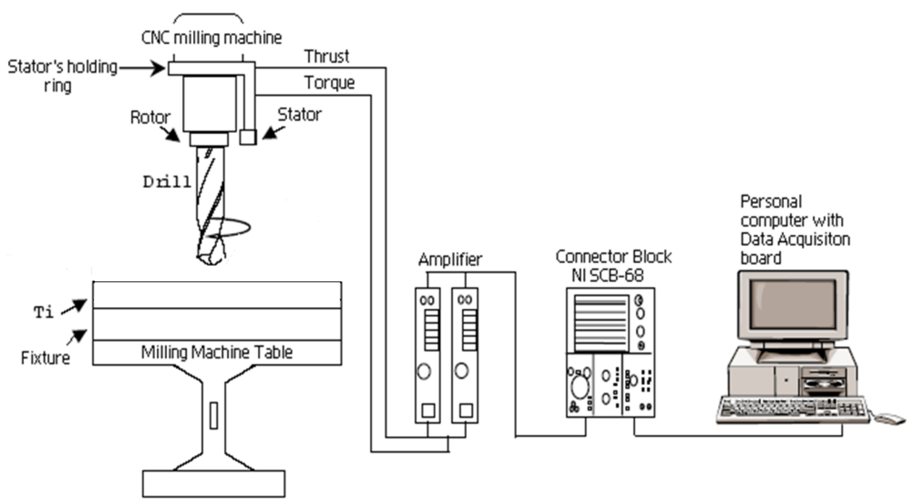

Figure 3-2: Schematic of the experimental setup and data acquisition system

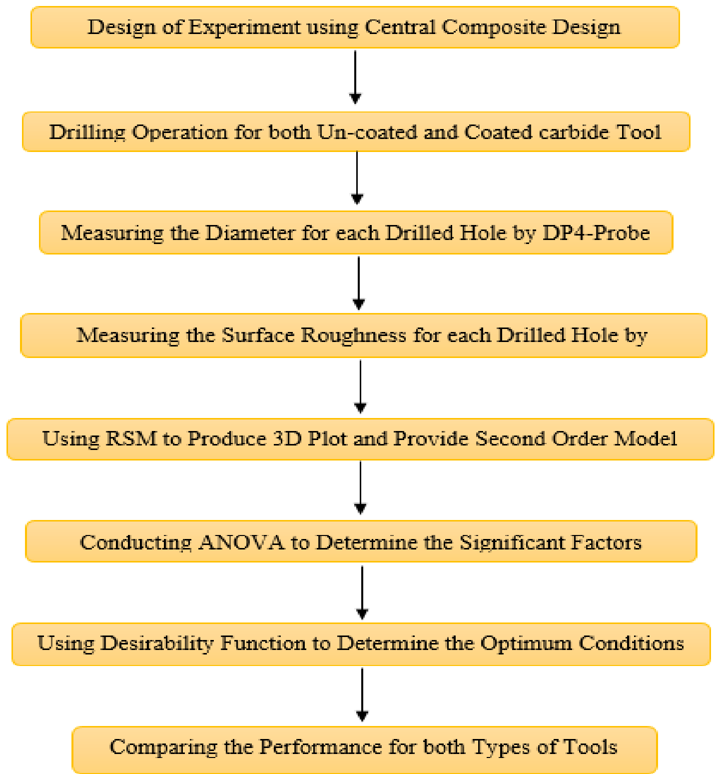

Figure 3-3: Steps of the experimental and analytical procedure

3.4.1 Specimen Material

The material used in this study,AMS-9046 plate, is made out of 6Al-4V titanium alloy. This was supplied by The Boeing Company, after being cut to dimension by water jet $(12'' \times 12'' \times 0.279'')$.

Component	Wt.%
Al	6
V	4
Fe	Max 0.25
O	Max 0.2
Ti	90

Table 3-5: Chemical composition of Ti-6Al4V [36]

Mechanical Properties	
Density	$0.16\ Ib/in^3$
Tensile strength	$138000\ psi$
Yield strength	$128000\ psi$
Elongation at break	14%
Reduction of area	36%
Modulus of Elasticity	$16500\ ksi$
Hardness (H_v)	349

Table 3-6: Mechanical properties of Ti-6Al4V [36]

3.4.2 Tool Material

The drill bits used are manufactured by Kennametal. All the drill tools used were a solid carbide, full tools' specification in Table 3-7.

Item specifications	Un-coated K10	Coated KC7210
Number of flutes	3	3
Diameter	0.25 in	0.25 in
Flute length	1.69 in	1.69 in
Overall length	3.22 in	3.22 in
Performance	High	High
Point angle	130	130
Coating	Bright	TiAlN

Table 3-7: Tools' specifications [36]

Un-coated K10 [39]:

- High degree of temperature resistance.
- Suitable for cast iron material, non-ferrous materials, and titanium alloys.
- High cutting performance, safe drilling process.
- Dry machining also with cooling lubricants.

Coated grade KC7210 [39]:

- Suitable for cast iron material, non-ferrous materials, and titanium alloys.
- Excellent heat resistance with a good level of toughness.
- First choice for high-speed cutting of cast iron materials when dry machining and under cooling lubricants.

Chapter 4 : Results, Investigations, and Discussions

In this chapter, the experimental data were statistically analyzed and presented in three phases: estimation of response function, model interpretation and visualization, and identification of optimum operating conditions. Analysis of variance (ANOVA) was conducted for each model response to detect which process factor has relative significance. The thrust force and torque have been recorded and analyzed to understand the behavior of both types of tool during the drilling operation. Since the dimensional tolerance and surface roughness are quality characteristics, they have been measured and analyzed to identify the optimum operating conditions that result the high quality of them (minimum dimensional tolerance and minimum surface roughness). The full experimental collected data are placed in appendix B.

4.1 Responses of Un-coated Carbide Tool

In this section, the surface response capture the impact of the independent parameters (speed and feed rate) on thrust force, torque, dimensional tolerance, and surface finish of the drilled holes when using un-coated carbide tool to drill Ti-6Al-4V.

4.1.1 Thrust Force Response of Un-coated Carbide Tool

The response surface plot and contour plot of thrust force for the un-coated carbide tool are presented in Fig. 4-1 and 4-2. These plots show the effect of spindle speed and feed rate on thrust force when drilling Ti-6Al-4V. The corresponding fitted equation is superimposed on response surface plot figure. The plots represent that the low level of feed rate (about 0.2 ipm) while high level spindle speed (about 1500 RPM) gives minimum thrust force (less than 28 Ib). In contrast, the maximum thrust force (more than 140 Ib) is shown at high level of feed rate (about 1.8 ipm) while low level speed (about 200 RPM). Moreover, the plots show that the mid-level of spindle speed and mid-level of feed rate (about 1000 RPM and 1 ipm) together creates average thrust force (in between 68-88 Ib). In summary, thrust force decrease when speed increase (inversely proportional) and feed rate decrease (directly proportional).

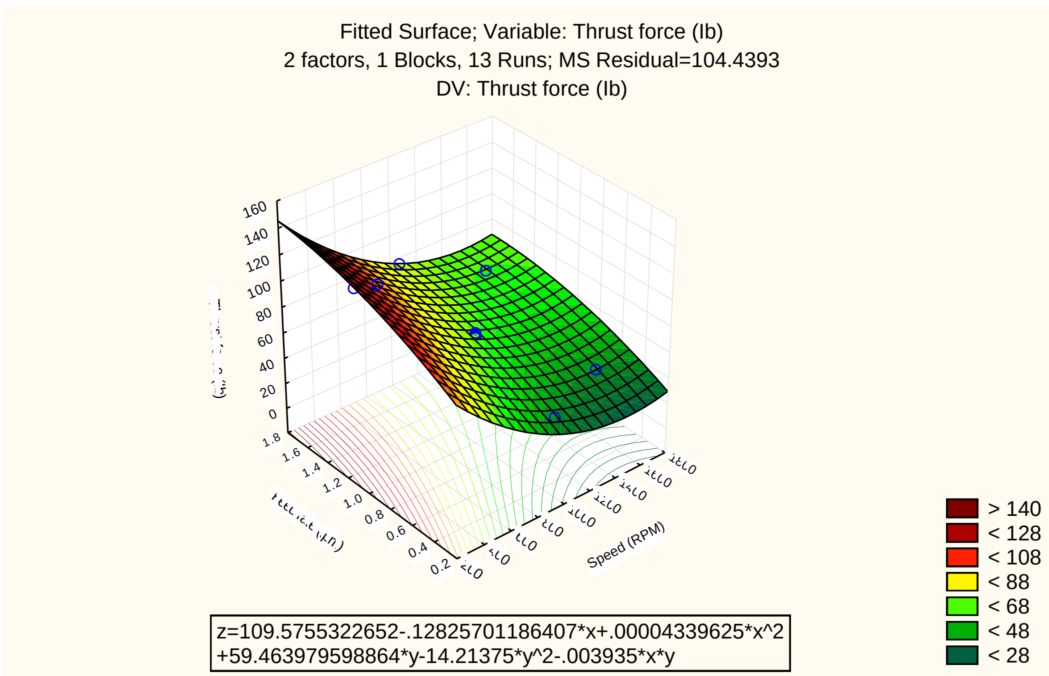

Figure 4-1: Response surface plot of thrust force against spindle speed and feed rate (Un-coated)

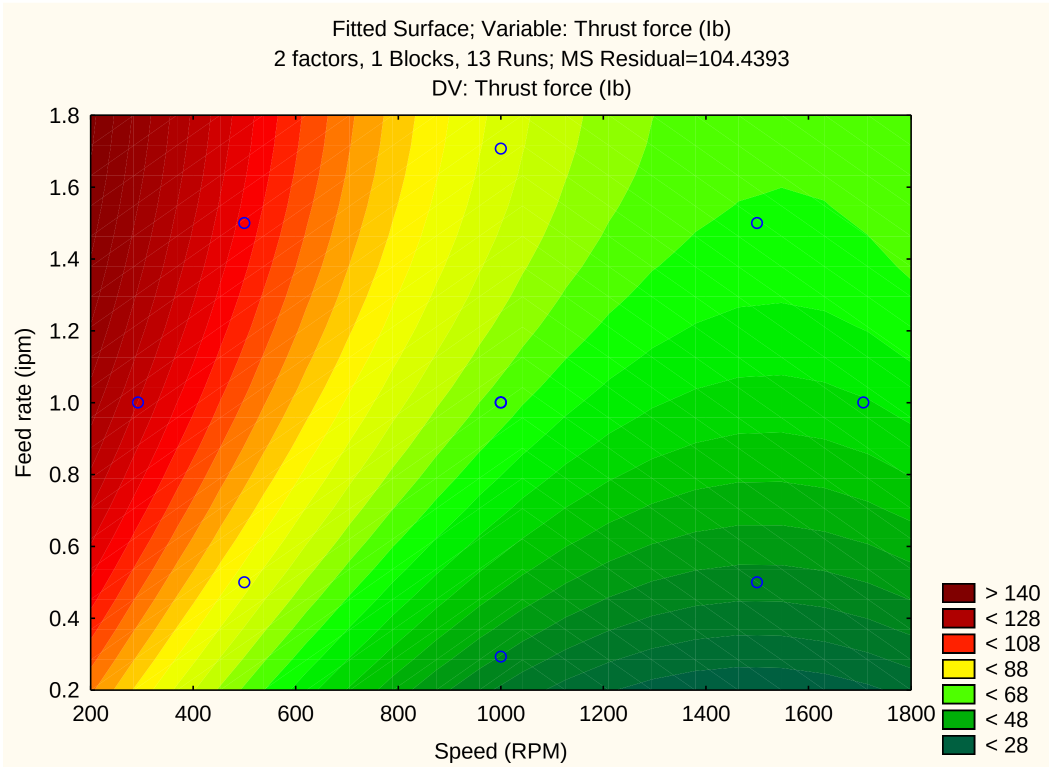

Figure 4-2: Response contour plot of thrust force against spindle speed and feed rate (Un-coated)

Table 4-1 shows the analysis of variance (ANOVA) of thrust force for the un-coated carbide tool. The P-value < 0.05 indicates the model terms are significant. In this case, speed (X), feed rate (Y), and quadratic component of speed (X^2) are significant model terms. The thrust force depends on neither of quadratic component of feed rate (Y^2) and Interaction (XY) since their P-values > 0.05. In addition, R^2 value in the table indicating that the model probably explain a high percentage (about 90%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	4122.23	1	4122.23	39.47	0.00041
X^2	818.8	1	818.8	7.84	0.027
Feed Rate (Y)	1468.98	1	1468.98	14.07	0.0072
Y^2	87.84	1	87.84	0.84	0.39
XY	3.87	1	3.87	0.37	0.85
Error	731.08	7	104.44		
Total	7319.66	12			
R^2	0.9				

Table 4-1: ANOVA for response of thrust force (un-coated)

4.1.2 Torque Response of Un-coated Carbide Tool

The response surface plot and contour plot of torque for the un-coated carbide tool are displayed in Fig. 4-3 and 4-4. These plots illustrate the effect of spindle speed and feed rate on torque when drilling Ti-6Al-4V. The fitted equation is placed on response surface plot Figure. The minimum torque (less than 0.1 Ib-ft) is shown at low level of feed rate (about 0.2 ipm) while mid-level spindle speed (about 1200 RPM). However, the plots represent that the elevated level of feed rate (about 1.6 ipm) while low level spindle speed (about 250 RPM) creates maximum torque (more than 1.8 Ib-ft). In addition, the plots show that the mid-level of spindle and mid-level of feed rate (about 1200 RPM - 0.8 ipm) jointly gives average torque (about 0.7 Ib-ft). In general, torque is directly proportional to feed rate while it is inversely proportional to spindle speed.

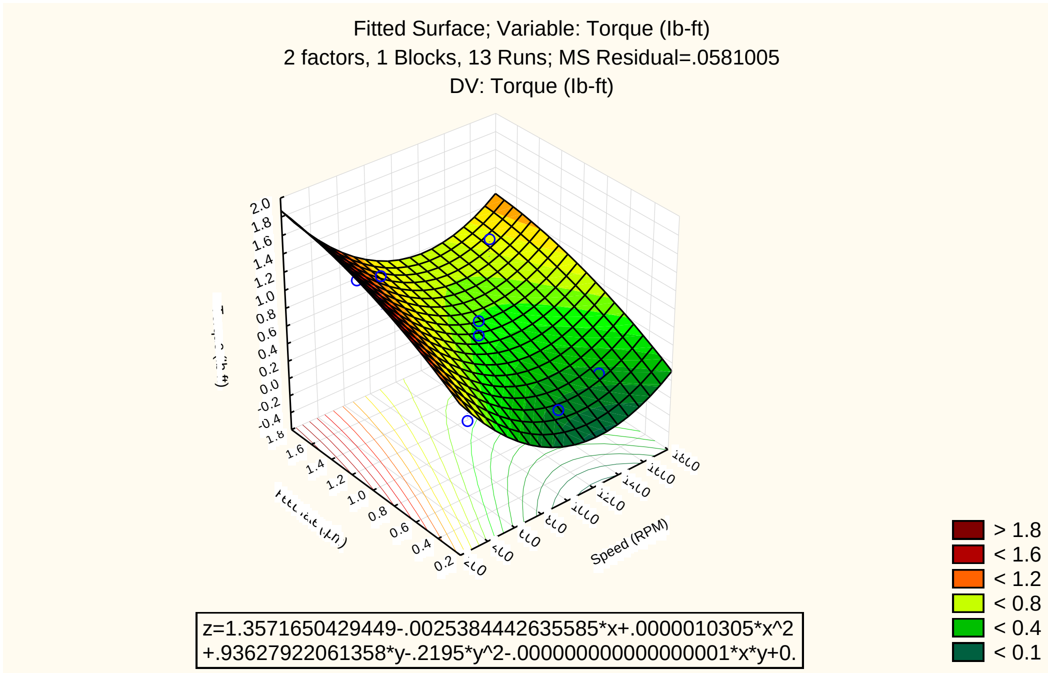

Figure 4-3: Response surface plot of torque against spindle speed and feed rate

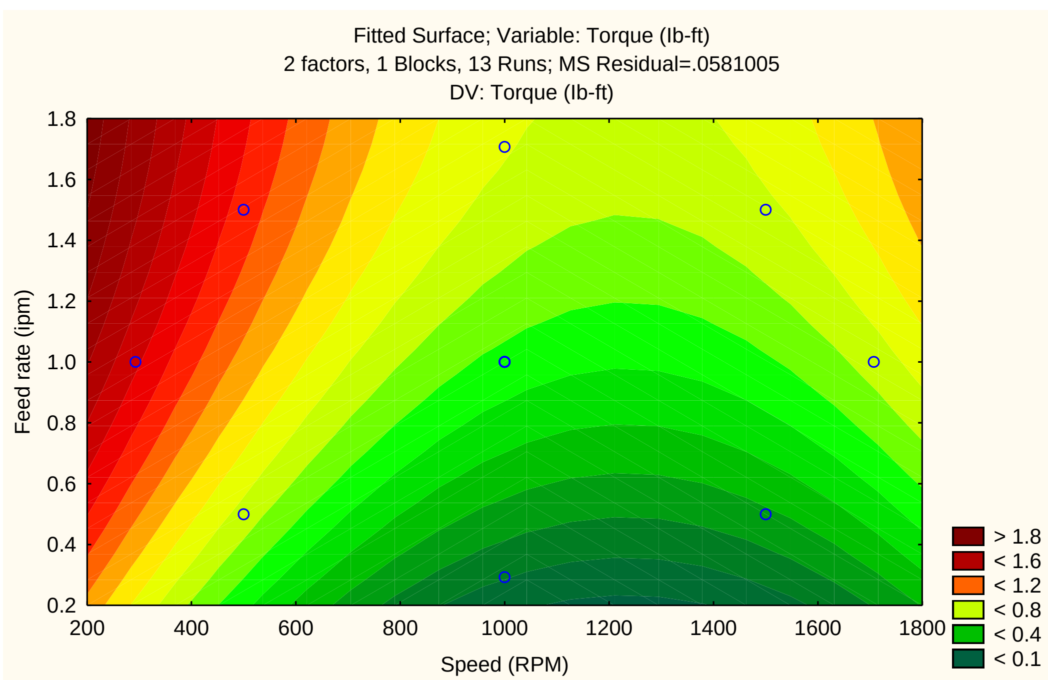

Figure 4-4: Response contour plot of torque against spindle speed and feed rate

Table 4-2 is the analysis of variance for torque response. Same as thrust force, the P-value < 0.05 for speed (X), feed rate (Y), and quadratic component of speed (X^2), so they are significant factor model terms. On the other hand, P-values > 0.05 for quadratic component of feed rate (Y^2) and Interaction (XY), so the torque depends on neither of them. In addition, R^2 value in the table indicating that the model probably explain a percentage (about 78%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	0.46	1	0.46	7.85	0.026
X^2	0.46	1	0.46	7.95	0.026
Feed Rate (Y)	0.49	1	0.49	8.51	0.22
Y^2	0.02	1	0.02	0.36	0.57
XY	0	1	0	0	1
Error	0.41	7	0.058		
Total	1.87	12			
R^2	0.78				

Table 4-2: ANOVA for response of torque (Un-coated)

4.1.3 Tolerance Response of Un-coated Carbide Tool

The response surface plot and contour plot of tolerance for the un-coated carbide tool are presented in Fig. 4-5 and 4-6. These plots show the effect of spindle speed and feed rate on tolerance when drilling Ti-6Al-4V. The corresponding fitted equation is superimposed on response surface plot figure. The plots represent that the intermediate level of feed rate (about 1.1 ipm) with mid-level of spindle speed (about 900 RPM) gives minimum tolerance of diameter (less than 0.0005 inch). In contrast, the maximum tolerance diameter (more than 0.005 inch) is shown at low level of feed rate (about 0.2

ipm) with elevated level of spindle speed (about 1800 RPM). It is obvious from the two graphs that the tolerance minimize with increasing spindle speed and feed rate up to the mid-level of them, then the tolerance starts to be maximized. Therefore, the minimum tolerance is locating at the range of mid-level for both cutting speed and feed rate.

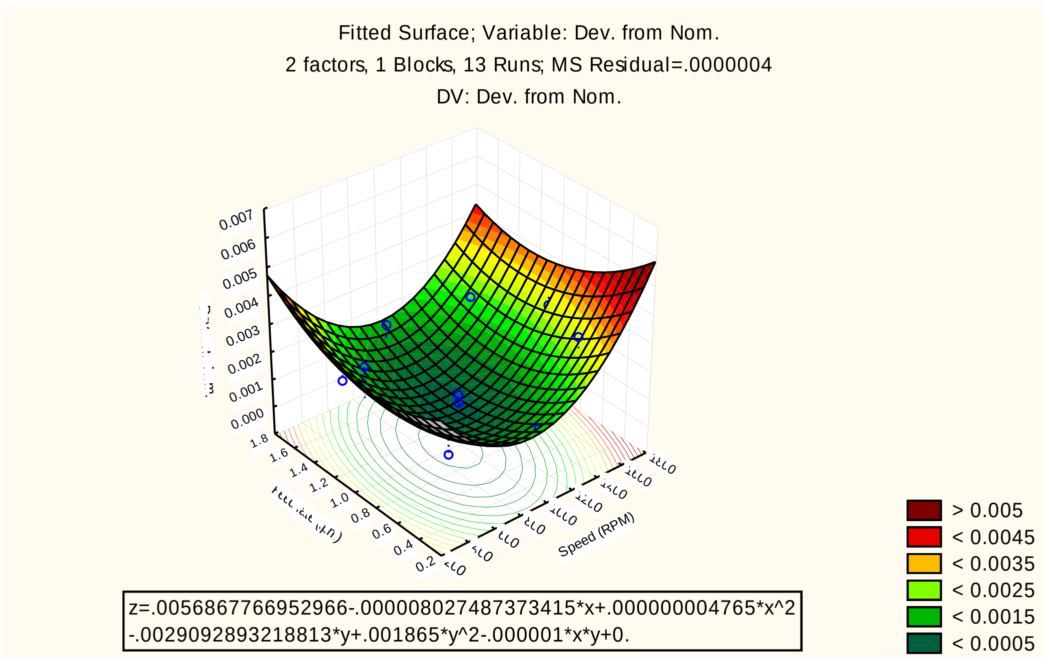

Figure 4-5: Response surface plot of tolerance against spindle speed and feed rate (Un-coated)

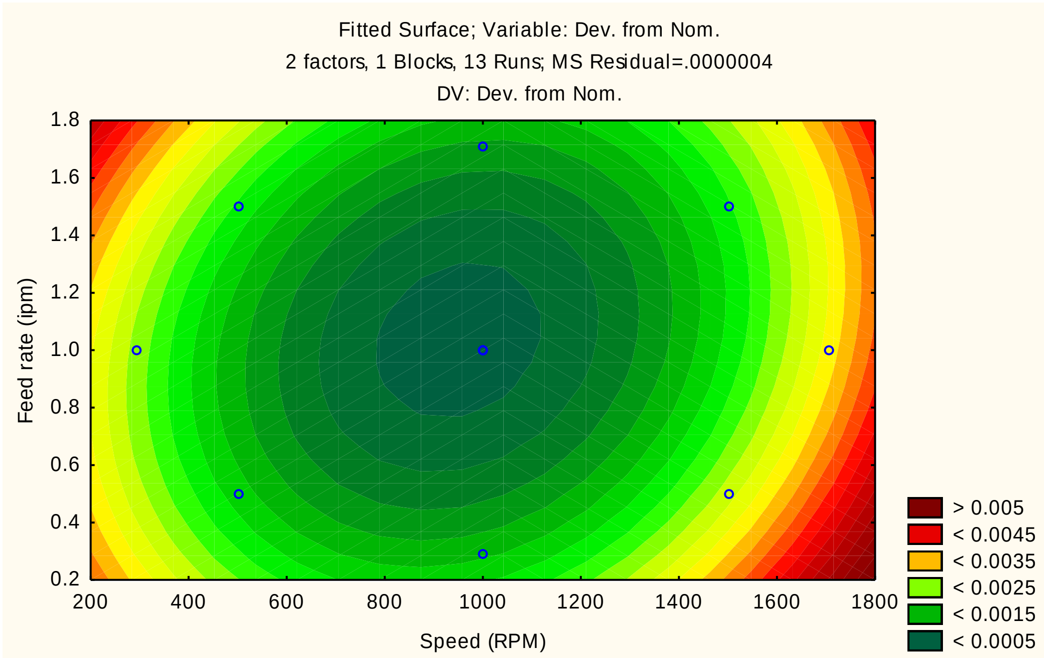

Figure 4-6: Response contour plot of tolerance against spindle speed and feed rate (Un-coated)

Table 4-3 shows the analysis of variance for tolerance diameter response. The only term that show p-value less than 0.05 is quadratic component of speed, so it means that the mean of tolerance response depends on it. None of the remaining factors used in the model has P-value less than 0.05, so it appears that the mean response (tolerance) does not depend on any of them. R^2 value showing that the model probably explain about 80% of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed (X)	0.00000051	1	0.00000051	1.27	0.3
X^2	0.0000099	1	0.0000099	24.81	0.0016
Feed Rate (Y)	0.000000064	1	0.000000064	0.16	0.7
Y^2	0.0000015	1	0.0000015	3.8	0.092
XY	0.00000025	1	0.00000025	0.63	0.45
Error	0.0000028	7	0.0000004		
Total	0.000014	12			
R^2	0.8				

Table 4-3: ANOVA for response of tolerance (Un-coated)

4.1.4 Roughness Response Surface of Un-coated Carbide Tool

The response surface plot and contour plot of surface roughness for the un-coated carbide tool are presented in Figure 4.7 and 4.8. These plots show the effect of spindle speed and feed rate on surface roughness when drilling Ti-6Al-4V. The corresponding fitted equation is placed on response surface plot figure. The plots represent that the intermediate level of both feed rate and spindle speed (about 0.8 ipm - 1100 RPM) gives minimum surface roughness (less than 72 micro inch). In contrast, the maximum surface roughness (more than 140 micro inch) is shown at high level of feed rate (about 1.8 ipm) with elevated level of spindle speed (about 1800 RPM) and at any level of feed rate with low level of speed (about 200 RPM). It is noticeable that increasing the feed rate and spindle speed from the lowest level to the middle level produces better surface roughness; however, increasing the feed rate and spindle speed from the middle level to the highest level produce poor surface roughness.

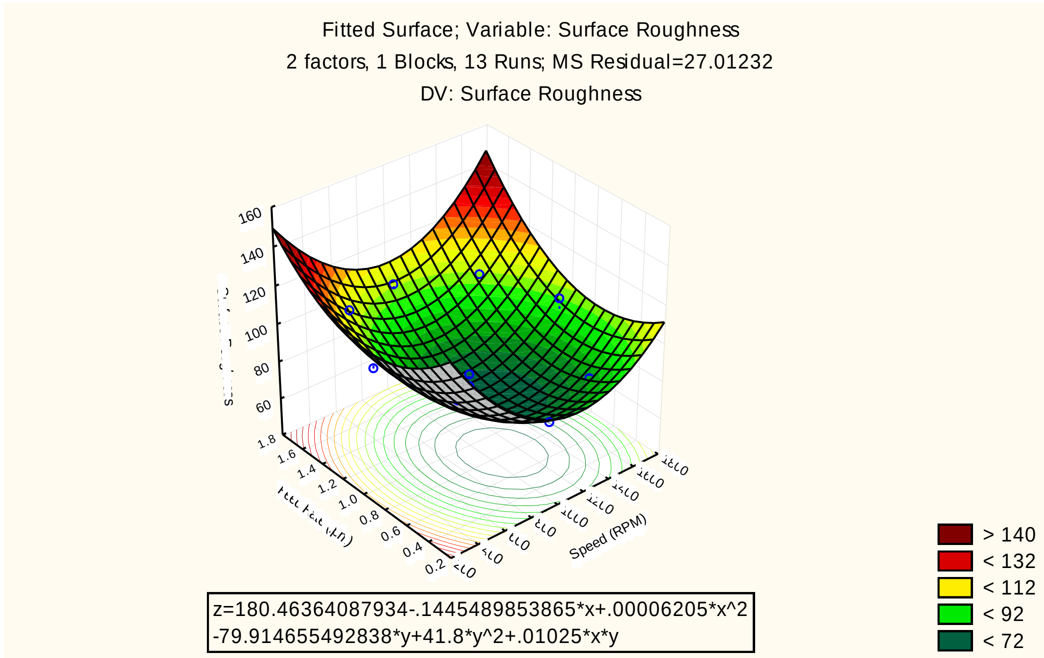

Figure 4-7: Response surface plot of surface roughness against spindle speed and feed rate (Un-coated)

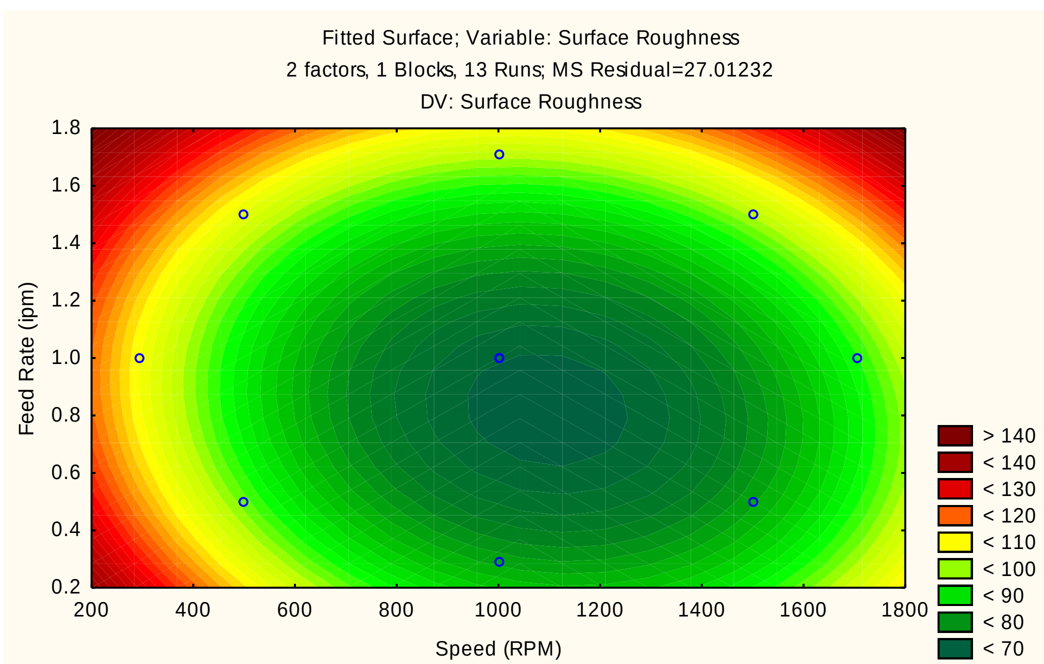

Figure 4-8: Response contour plot of surface roughness against spindle speed and feed rate (Un-coated)

Table 4-4 shows the analysis of variance for surface roughness response. P-values of Speed (X), feed rate (Y), and other quadratic components of speed and feed rate (X^2, Y^2) are less than 0.05, which conclude that surface roughness does depends on all mentioned factors. There is no interaction between spindle speed and feed rate since XY p-value more than 0.05. R^2 value indicating that the model probably explain high percentage (about 94%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	20.04	1	20.04	7.7	0.027
X^2	1674	1	1674	61.97	0.0001
Feed Rate (Y)	388.39	1	388.39	14.38	0.0068
Y^2	759.67	1	759.67	28.12	0.0011
XY	26.27	1	26.27	0.97	0.36
Error	189.09	7	27.01		
Total	2988.3	12			
R^2	0.94				

Table 4-4: ANOVA for response surface of surface roughness (Un-coated)

4.1.5 Desirability Profile of Un-coated Carbide Tool

Fig. 4-9 shows the combined prediction profile for minimizing the quality characteristics or dependent variables (tolerance of diameter and surface roughness) at levels of the independent variables produce the most desirable predicted responses on the dependent variables when using un-coated carbide tool to drill Ti-6Al-4V. In order to locate the optimum conditions only at the actual level that were set during the experiment, the exact grid option was used. The optimum value for both tolerance and surface roughness occurs at speed of 1000 RPM and feed rate of 1 ipm; the optimum value of tolerance is 0.0038 inch and the optimum value of surface roughness is 70.1 micro inch. Surface roughness prediction profile shows very close optimum value for feed rate. It is shown in Fig. 4-9 that feed rate of 1 ipm and feed rate of 0.5 ipm gives the optimum surface roughness, which is about 70 micro inch. However, the feed rate of 0.5 ipm does not show optimum result regarding to tolerance, so feed rate of 1 ipm is more desirable since it produce optimum result for both quality characteristics. In addition, the higher feed rate is more favorable because it makes higher productivity. It is obvious that increasing spindle speed and feed rate improve the quality characteristics, but the improvement reach its optimum point at the mid-level of both independent variables then it starts to move away from the optimum value. In addition, the thrust force and torque are in the average value at those conditions as explained in sections 4.1.1 and 4.1.2.

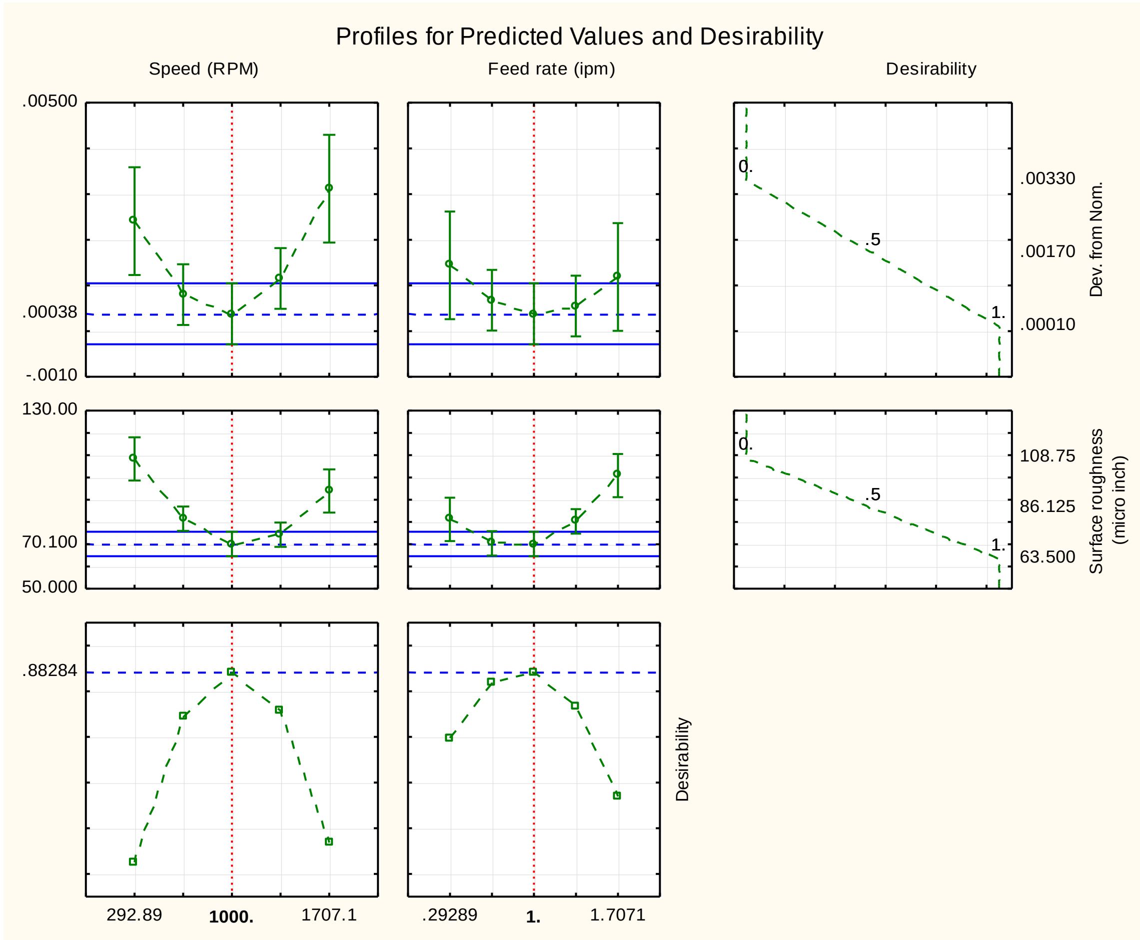

Figure 4-9: Combined prediction profile for minimizing the dependent variables (Un-coated)

4.2 Responses of Coated Carbide Tool

In this section, the surface response capture the impact of the independent parameters (speed and feed rate) on thrust force, torque, dimensional tolerance, and surface roughness of the drilled holes when using coated carbide tool to drill Ti-6Al-4V.

4.2.1 Thrust Force Response of Coated Carbide Tool

The response surface plot and contour plot of thrust force for the coated carbide tool are presented in Fig. 4-10 and 4-11. These plots display the effect of spindle speed and feed rate on thrust force when drilling Ti-6Al-4V. The corresponding fitted equation is shown on response surface plot figure. The plots represent that the low level of feed rate (about 0.2 ipm) while elevated level of spindle speed (about 1400 RPM) gives minimum thrust force (less than 44 Ib). In contrast, the maximum thrust force (more than 200 Ib) is shown at high level of feed rate (about 1.8 ipm) while low level of spindle speed (about 200 RPM). Moreover, the plots show that the mid-level of spindle speed (about 1000 RPM) and mid-level of feed rate (about1 ipm) together gives average thrust force (in between 84-144 Ib). In summary, very similar to the response of thrust force for un-coated tool, thrust force decrease when speed increase (inversely proportional) and feed rate decrease (directly proportional).

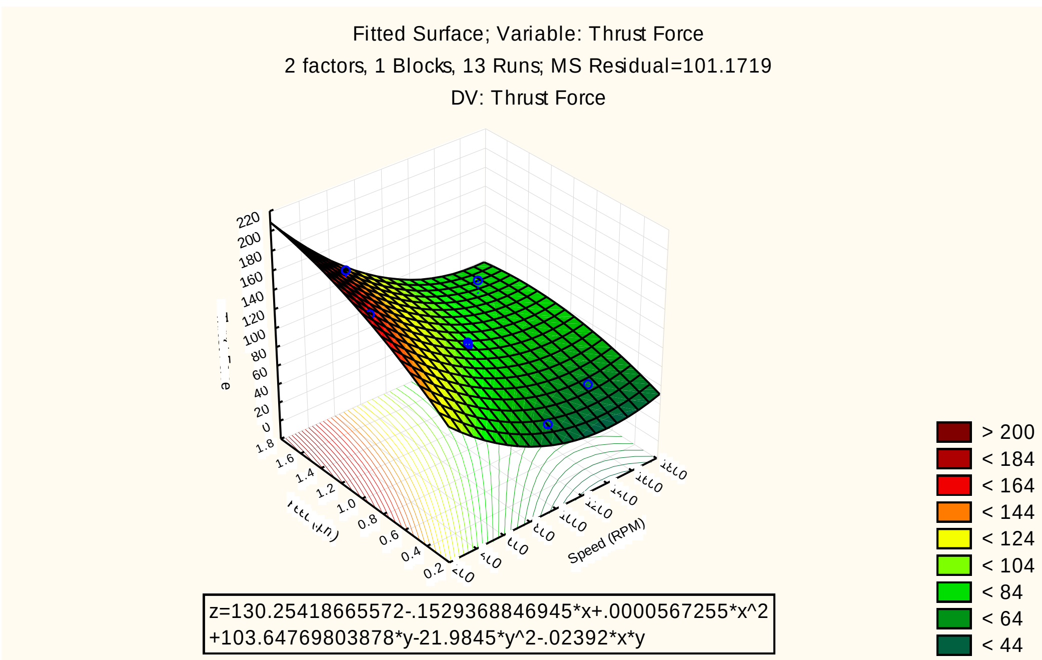

Figure 4-10: Response surface plot of thrust force against spindle speed and feed rate (Coated)

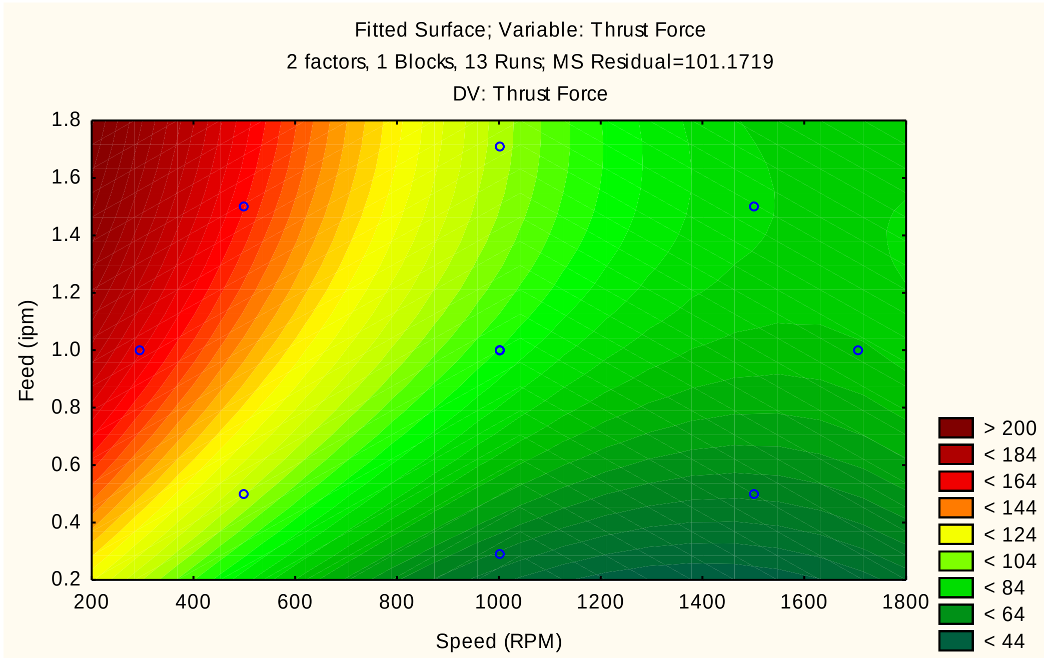

Figure 4-11: Response contour plot of thrust force against spindle speed and feed rate (Coated)

Table 4-5 represents the analysis of variance for thrust force response. The P-value < 0.05 is indicated for speed (X), feed rate (Y), and quadratic component (X^2), so thrust force dose depends on the three of them. In contrast, since P-value > 0.05 for other factors, they are not significant terms of the model. In addition, R^2 value in the table indicating that the model probably explain high percentage (about 95%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	8040.61	1	8040.61	79.47	0.000045
X^2	1399.04	1	1399.04	13.83	0.0075
Feed Rate (Y)	2557.37	1	2557.37	25.28	0.0015
Y^2	210.14	1	210.14	2.08	0.19
XY	143.04	1	143.04	1.41	0.27
Error	708.2	7	101.17		
Total	13230.15	12			
R^2	0.95				

Table 4-5: ANOVA for response of thrust force (Coated)

4.2.2 Torque Response of Coated Carbide Tool

The response surface plot and contour plot of torque for the coated carbide tool are shown in Fig. 4-12 and 4-13. These plots show the effect of spindle speed and feed rate on torque when drilling Ti-6Al-4V. The fitted equation is placed on response surface plot figure. The minimum torque (less than 0.2 Ib-ft) is shown at low level of feed rate (about 0.2 ipm) while high level of spindle speed (about 1300 RPM). However, the plots represent that the high level of feed rate (about 1.8 ipm) with low level of spindle speed (about 200 RPM) creates maximum torque (more than 1.6 Ib-ft). In addition, the plots show that the intermediate level of both spindle speed (about 1000 RPM) and feed rate (about 0.9 ipm) gives average torque (about 0.8 Ib-ft). Same as the torque response for un-coated tool, in general torque is directly proportional to feed rate while it is inversely proportional to spindle speed.

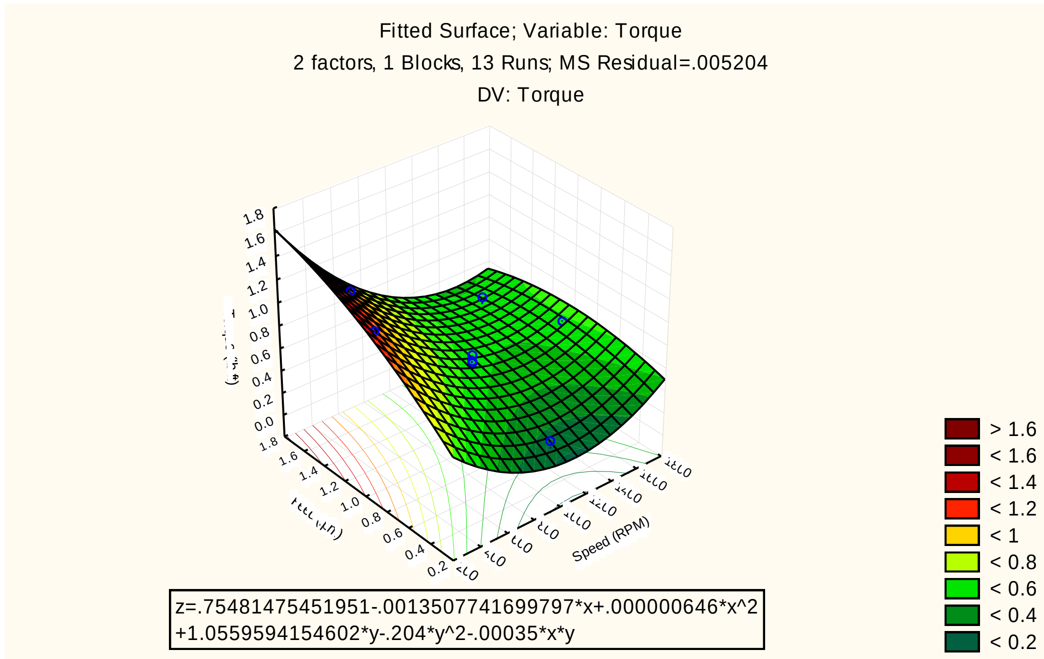

Figure 4-12: Response surface plot of torque against spindle speed and feed rate (Coated)

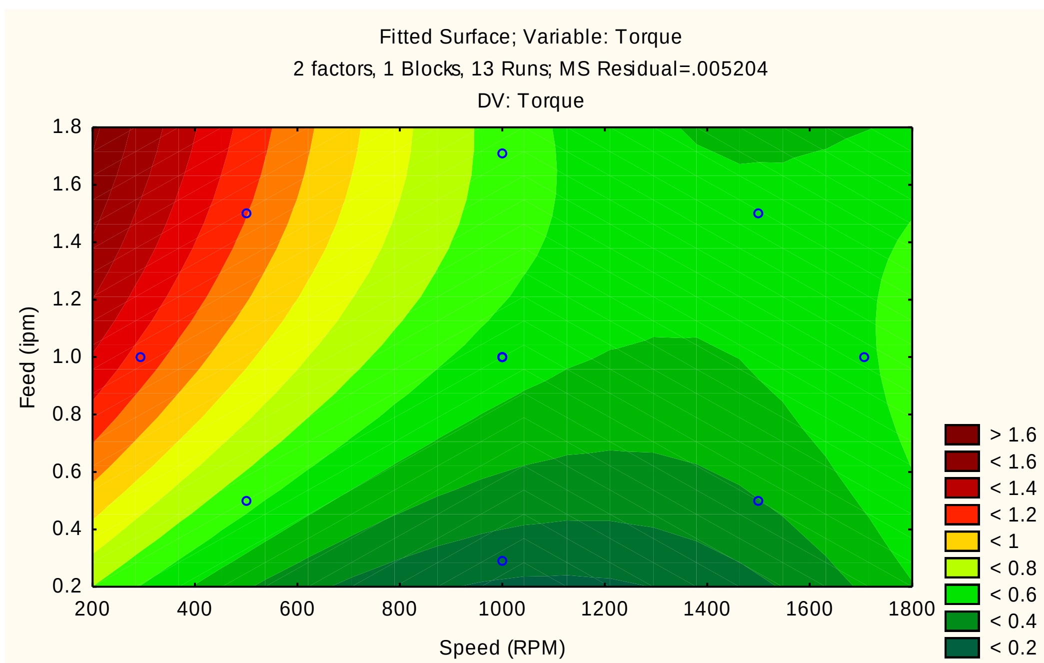

Figure 4-13: Response contour plot of torque against spindle speed and feed rate (Coated)

Table 4-6 showing the analysis of variance for torque response. Since the P-values of speed (X), feed rate (Y), and quadratic component of speed (X^2) are less than 0.05, they are significant factors and the model does depend on them. On the other hand, the torque does not depend on quadratic component of feed rate (Y^2) and there is interaction between factors (XY) since its P-value is equal to 0.05. In addition, R^2 value showing that the model probably explain high percentage (about 95%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	0.33	1	0.33	64.22	0.000009
X^2	0.18	1	0.18	34.87	0.0006
Feed Rate (Y)	0.18	1	0.18	34.12	0.00064
Y^2	0.018	1	0.018	3.48	0.1
XY	0.031	1	0.031	5.88	0.05
Error	0.036	7	0.005		
Total	0.8	12			
R^2	0.95				

Table 4-6: ANOVA for response of torque (Coated)

4.2.3 Tolerance Response of Coated Carbide Tool

The response surface plot and contour plot of tolerance for the coated carbide tool are presented in Fig. 4-14 and 4-15. These plots display the effect of spindle speed and feed rate on tolerance when drilling Ti-6Al-4V. The corresponding fitted equation is superimposed on response surface plot figure. The plots represent that the intermediate level of feed rate (about 0.9 ipm) with mid-level of spindle speed (about 900 RPM) gives average tolerance of diameter (less than 0.0003 in). In contrast, the maximum tolerance diameter (more than 0.003 in) is shown at high level of feed rate (about 1.8 ipm) with elevated level of speed (about 1800 RPM). The minimum tolerance (less than 0.0001) is shown at low level of feed rate (about 0.2 ipm) while high level of spindle speed (about 1800 RPM). Same as the tolerance response with un-coated carbide tool, it is obvious from the two graphs that the tolerance minimize with increasing spindle speed and feed rate up to the mid-level of them, then the tolerance starts to be maximized when the feed rate and speed increased togather. However, decreasing the feed rate with increasing speed produce the smallest value of tolerance.

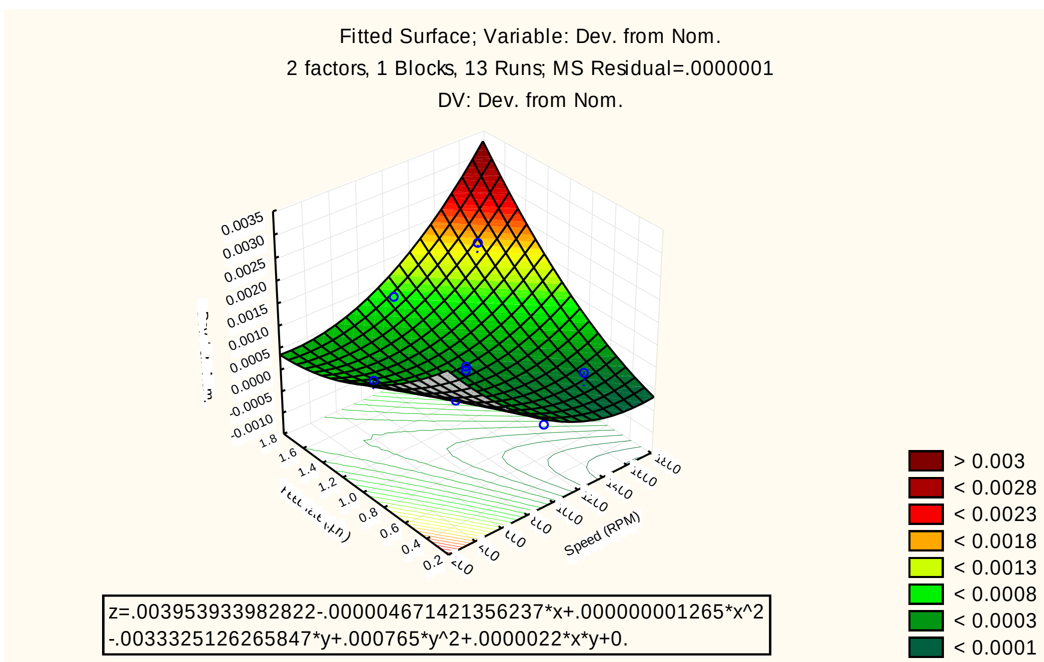

Figure 4-14: Response surface plot of tolerance against spindle speed and feed rate (Coated)

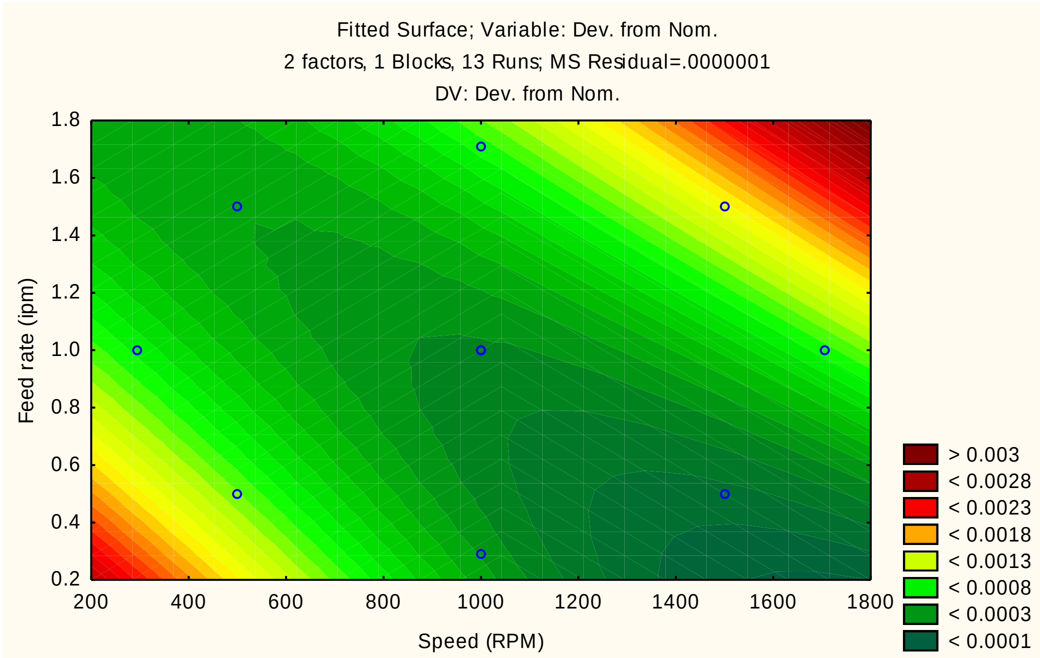

Figure 4-15: Response contour plot of tolerance against spindle speed and feed rate (Coated)

Table 4-7 is the analysis of variance for diameter tolerance response. The P-value > 0.05 for speed (X), and feed quadratic components (Y^2), so none of those two are significant for tolerance diameter. However, quadratic component of speed (X^2), feed rate (Y) and interaction XY have P-value < 0.05; therefore, they are significant terms of the model. R^2 indicating that the model probably explain about high percentage (about 86%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed (X)	0.0000000069	1	0.0000000069	0.13	0.73
X^2	0.0000007	1	0.0000007	12.7	0.009
Feed Rate (Y)	0.00000032	1	0.00000032	5.8	0.047
Y^2	0.00000025	1	0.00000025	4.67	0.068
XY	0.0000012	1	0.0000012	22.2	0.0022
Error	0.00000035	7	0.000000054		
Total	0.0000028	12			
R^2	0.86				

Table 4-7: ANOVA for response of diameter accuracy (Coated)

4.2.4 Surface Roughness Response of Coated Carbide Tool

The response surface plot and contour plot of surface roughness for the coated carbide tool are presented in Fig. 4-16 and 4-17. These plots show the effect of spindle speed and feed rate on surface roughness when drilling Ti-6Al-4V. The corresponding fitted equation is placed on response surface plot figure. The plots represent that the intermediate level of both feed rate (about 0.9 ipm) and spindle speed (about 1100 RPM) gives minimum surface roughness (less than 60 micro inch). In contrast, the maximum surface roughness (more than120 micro inch) is shown at high level of feed rate (about 1.7 ipm) with low level of speed (about 200 RPM). In summary, It is visible that increasing the feed rate and spindle speed from the lowest level to the middle level produces better surface roughness; however, increasing the feed rate and spindle speed from the middle level to the highest level produce poor surface roughness which is very similar to surface roughness response of un-coated carbide tool.

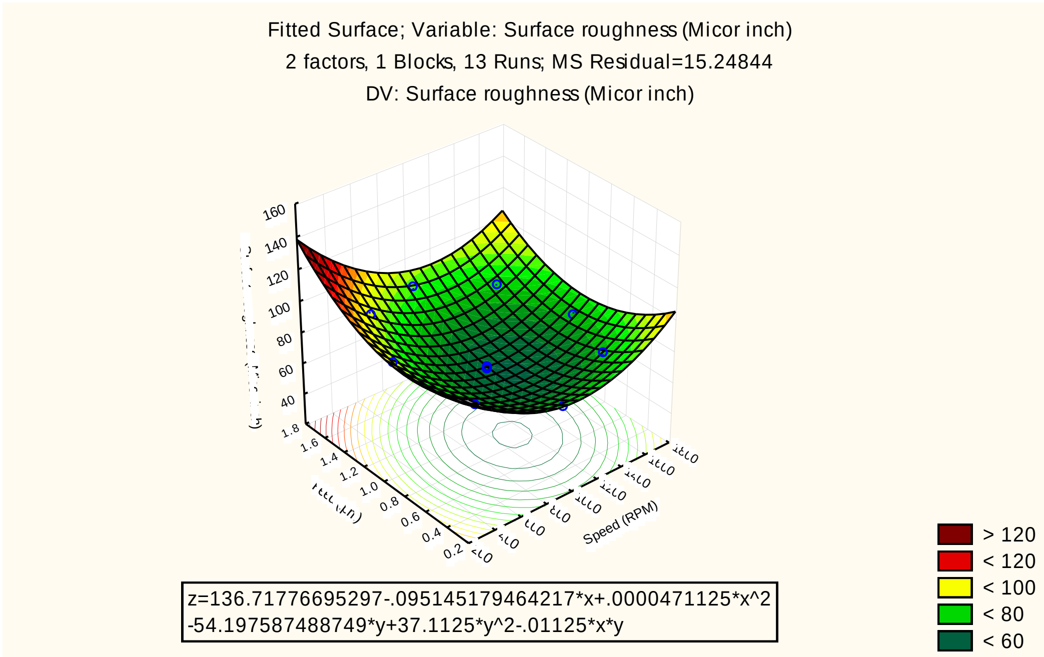

Figure 4-16: Response surface plot of surface roughness against spindle speed and feed rate (Coated)

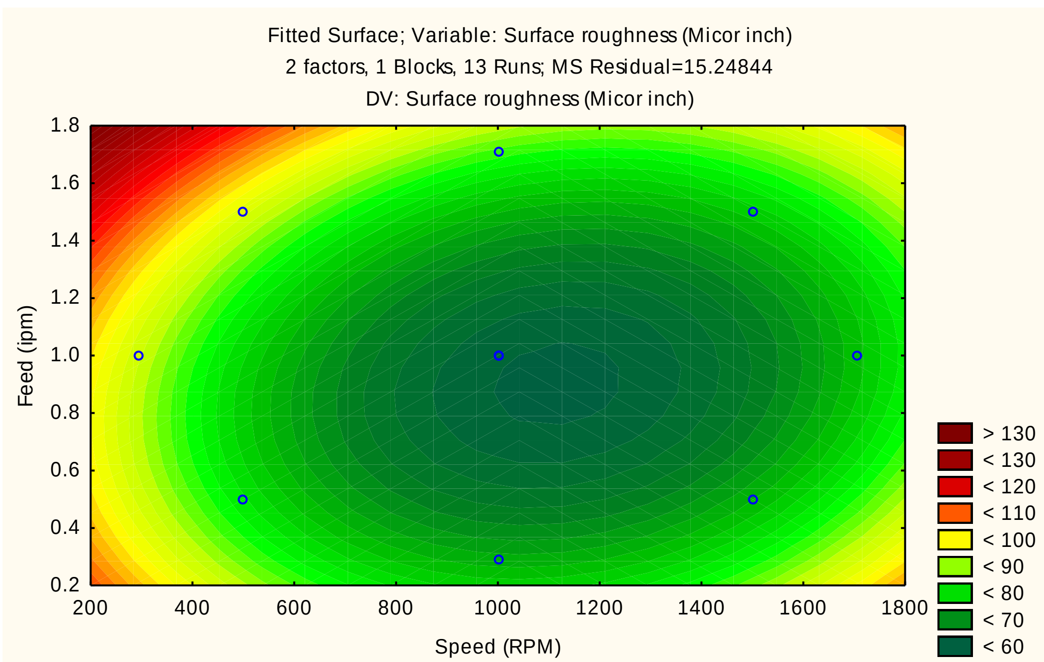

Figure 4-17: Response contour plot of surface roughness against spindle speed and feed rate (Coated)

Table 4-8 shows the analysis of variance for surface roughness response of coated carbide tool. Since P-value < 0.05 all factors: speed (X), feed rate (Y), and other quadratic components (X^2, Y^2), surface roughness does depends on all of them. However, the interaction is not present for the surface roughness response since the P-value of XY > 0.05. R^2 showing that the model probably explain high percentage (about 95%) of the variability in new data.

Factors	Sum of Squares	df	Mean Square	F-value	P-value
Speed(X)	296.23	1	296.23	19.43	0.0031
X^2	965.04	1	965.04	63.29	0.000094
Feed Rate (Y)	154.09	1	154.09	10.11	0.016
Y^2	598.84	1	598.84	39.27	0.00042
XY	31.64	1	31.64	2.08	0.19
Error	106.74	7	31.16		
Total	1977.89	12			
R^2	0.95				

Table 4-8: ANOVA for response of surface roughness (Coated)

4.2.5 Desirability Profile of Coated Carbide Tool

Fig. 4-18 displays the combined prediction profile for minimizing the quality characteristics or dependent variables (tolerance of diameter and surface roughness) at levels of the independent variables produce the most desirable predicted response on the dependent variables when using coated carbide tool to drill Ti-6Al-4V. In order to locate the optimum conditions only at the actual level that were set during the experiment, the exact grid option was used. The optimum value for both tolerance and surface roughness jointly occurs at speed of 1000 RPM and feed rate of 1 ipm; the optimum value of tolerance is 0.00018 inch and the optimum value of surface roughness is 60.35 micro inch. However, the desirability feed rate profile of tolerance shows the minimum tolerance at condition of feed rate about 0.5 ipm. However, this minimum point have not been chosen as the most desirable because of two reason: (1) feed rate about 0.5 ipm does not provide the minimum surface roughness, (2) decreasing feed rate leads to decreasing productivity, so it is not preferable. It is clear that increasing spindle speed and feed rate improve the quality characteristics, but after the improvement reached its optimum point at the mid-level of both independent variables, it starts to move away from the optimum value. In addition, the thrust force and torque are in the average value at those conditions as explained in sections 4.2.1 and 4.2.2.

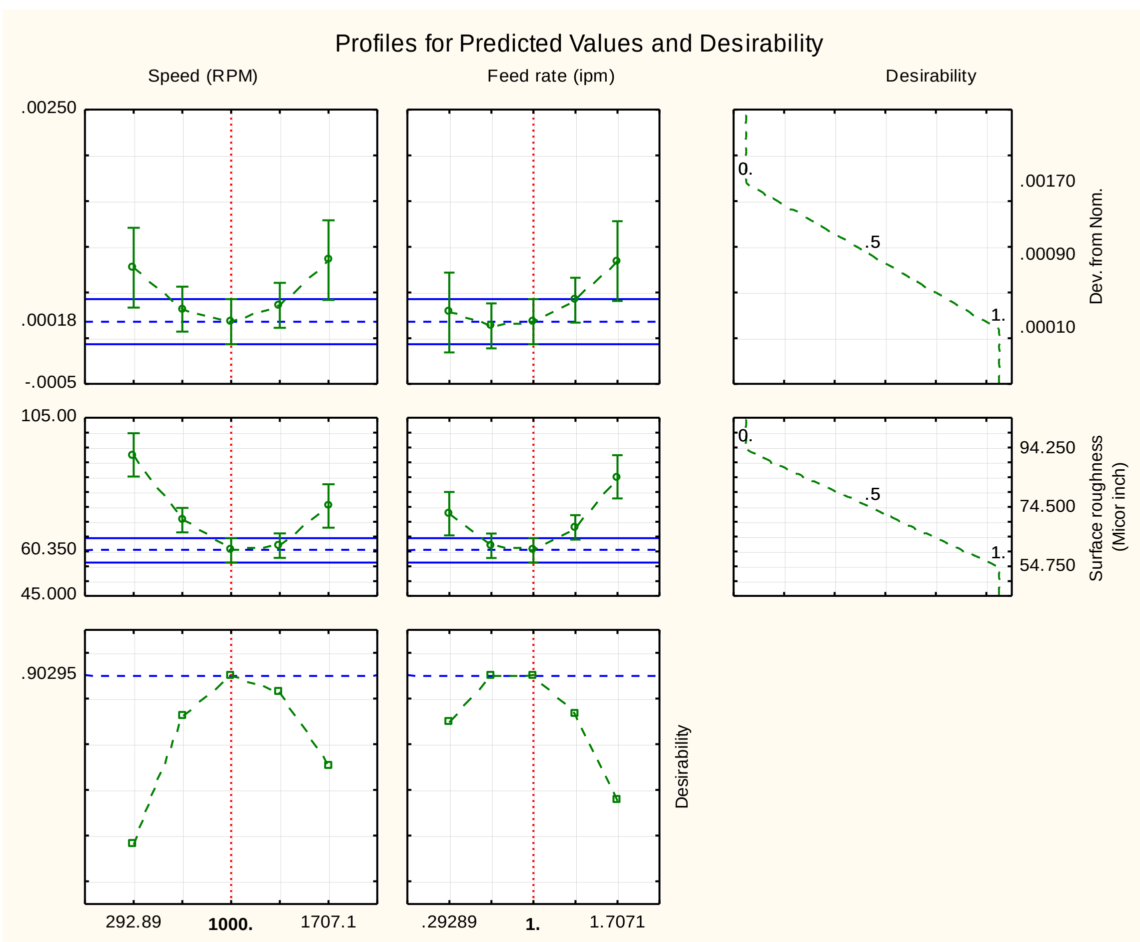

Figure 4-18: Combined prediction profile for minimizing the dependent variables (Coated)

4.3 Performance of Un-coated and Coated Carbide Tool

In this section, the performance of un-coated and coated carbide tools was compared when drilling titanium alloy, Ti-6Al4V at various spindle speed and feed rates. As introduced in section 3.1 that both un-coated and coated tool used to drill 13 holes with different conditions of independent parameters (see Table 4-9).

Hole No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Speed (RPM)	500	500	1500	1500	293	1707	1000	1000	1000	1000	1000	1000	1000
Feed rate (ipm)	0.5	1.5	0.5	1.5	1	1	0.3	1.7	1	1	1	1	1

Table 4-9: Input parameters for each hole

4.3.1 Thrust Force and Torque

Fig. 4-19 shows thrust force comparison between un-coated and coated carbide tool. The higher thrust force was always existed when using the coated carbide tool. The friction coefficient may responsible about that higher thrust force existed at coated carbide tool. It is visible that thrust force increases at decreasing the speed, while it increases at increasing the feed rate for both types of tool. The highest value for both tools was recorded at low spindle speed of 293 RPM and intermediate level feed rate of 1 ipm. The second highest value of thrust force is shown at hole number 2 with condition of 500 RPM and 1.5 ipm. On the other hand, the lowest value of thrust force (42.54 Ib) was existed at hole number 7 (1000 RPM and 0.3 ipm) for un-coated tool while the lowest value of thrust force (56.04 Ib) was existed at hole number 3 (1500 RPM and 0.5 ipm) for un-coated tool. In addition hole number 6 (1707 RPM and 1 ipm) shows very close value of thrust force to the one that recorded for drilled hole number 7. In summary, the lower feed rate with higher spindle speed generates the lower thrust force for both un-coated and coated carbide tool.

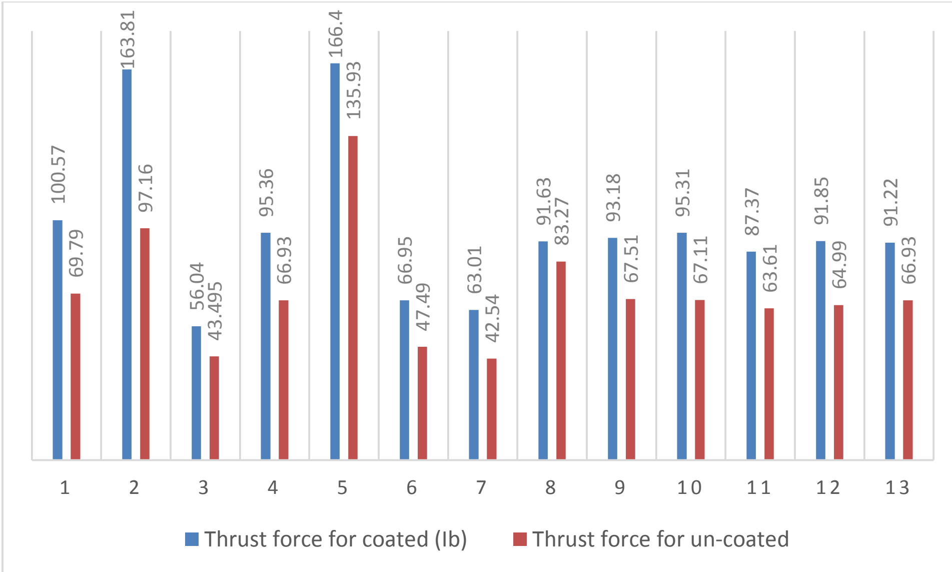

Figure 4-19: Thrust force comparison between un-coated and coated carbide drill

Fig. 4-20 displays torque comparison between un-coated and coated carbide tool. It is showing that torque values were higher when using the un-coated carbide tool at eight points, while the other five points showing the opposite. However, it is obvious that higher speed produced lower value of torque for both types of tool, where decreasing the feed rate gave lower torque for both types as well. The highest value of torque was recorded at hole number 5 (293 RPM and 1 ipm). The minimum value of torque for un-coated tool is shown at hole number 3 with condition of 1500 RPM and 0.5 ipm while the minimum value for coated tool is shown at hole number 7 with condition of 1000 RPM and 0.3 ipm. In general, the higher speed with lower feed rate produce lower torque for both types of tool.

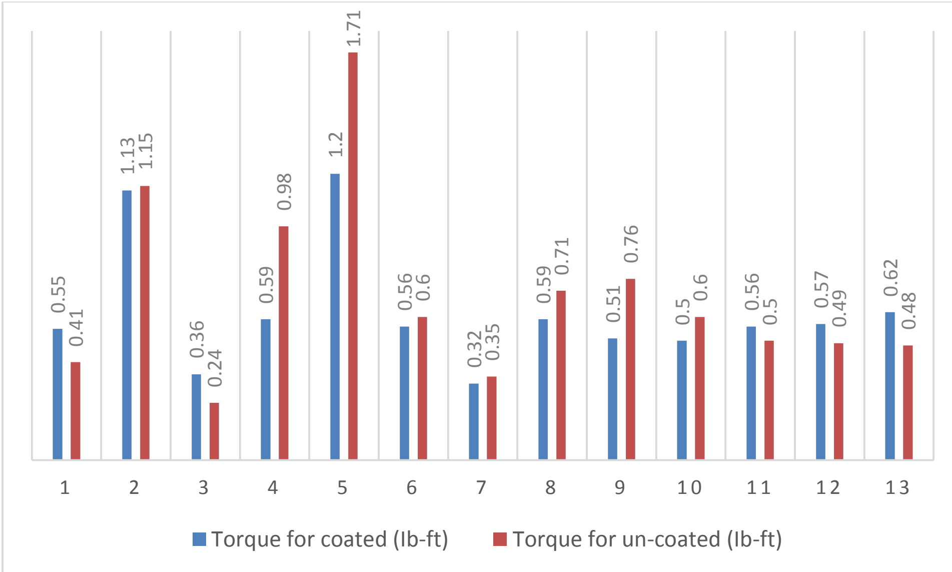

Figure 4-20: Torque comparison between un-coated and coated carbide drill

4.3.2 Dimensional Tolerance

Figure 4-21 shows the dimensional tolerance (Deviation from nominal) performance comparison between un-coated and coated drill. It is obvious that coated drill produced holes with outstanding tolerance performance at most tested conditions when compared to un-coated drill. The coated tool has higher wear and temperature resistance, so that resistances might be the reason of showing better performance to coated tool. At mid-level of spindle speed (1000 RPM) and mid-level of feed rate (1 ipm), both types of tool showed good tolerance performance. For coated carbide tool, the minimum value of tolerance (0.0001 inch) was found at two condition of independent variables (1000 RPM and 0.3 ipm) and (1000 RPM and 1 ipm). On the other hand, the minimum value of tolerance is displayed at one condition of independent variables (1000 RPM and 1 ipm). The tolerance values for coated carbide tool lied between 0.0017-0.0001 inch, while for un-coated carbide tool the range was between 0.0033-0.0001 inch. In addition, as discussed in section 4.1.5

and 4.2.5 that the optimum input parameters for un-coated tool gives minimum tolerance about 0.00038 inch, while the optimum input parameters for coated tool creates minimum tolerance about 0.00018 inch. In summary, both types of tool shows better performance to produce minimum tolerance at mid-level of both spindle speed and feed rate. However, the coated carbide tool shows better performance in general at all the cases in the range of speed (293-1707 RPM) and of feed rate (0.29-1.5 ipm).

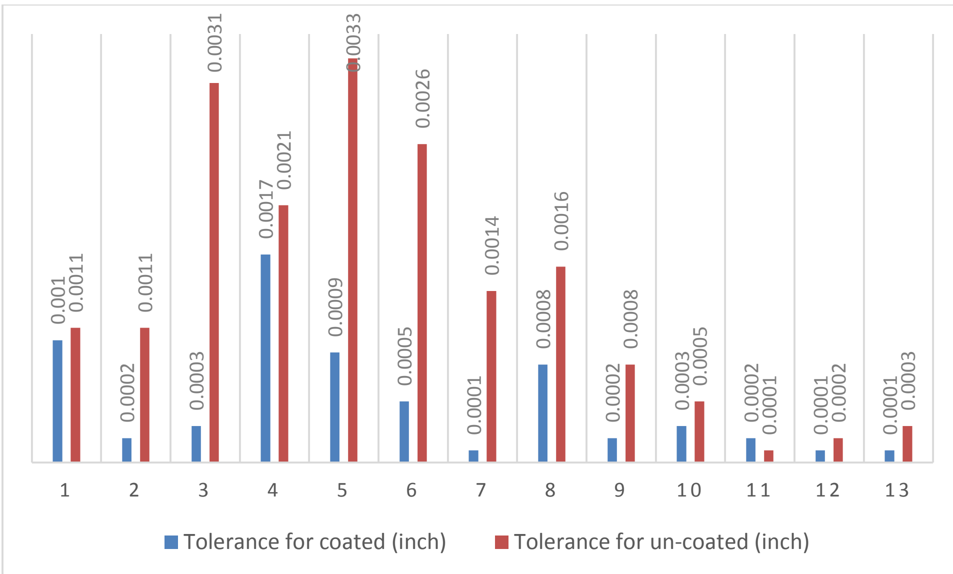

Figure 4-21: Dimensional tolerance performance comparison between un-coated and coated carbide drill

4.3.4 Surface Roughness

Fig. 4-22 shows the surface roughness performance comparison between un-coated and coated carbide tool. Same as tolerance, the higher resistance of wear and temperature of coated tool might be the reason for this superiority of the coated drill. It is evident that TiAlN-coated tool showed superior performance at the point of comparison to un-coated tool. The minimum value of surface roughness for both drill types was at mid-level of spindle speed (1000 RPM) and feed rate (1 ipm). The range of surface roughness for coated tool is 54.75 to 94.25 micro inch, while the range for un-coated tool is 63.5 to 108.75 micro inch. The maximum value of surface roughness existed at spindle speed of 500 and feed rate of 1.5 for both types of tool. Moreover, as discussed in section 4.1.5 and 4.2.5 that the optimum input parameters for un-coated tool produce minimum surface roughness about 60 micro inch, while the optimum input parameters for coated tool creates minimum surface roughness about 70 micro inch. In general, the intermediate level of spindle speed with intermediate level of feed rate produce the minimum surface roughness while the higher speed with higher feed rate produce the maximum surface roughens.

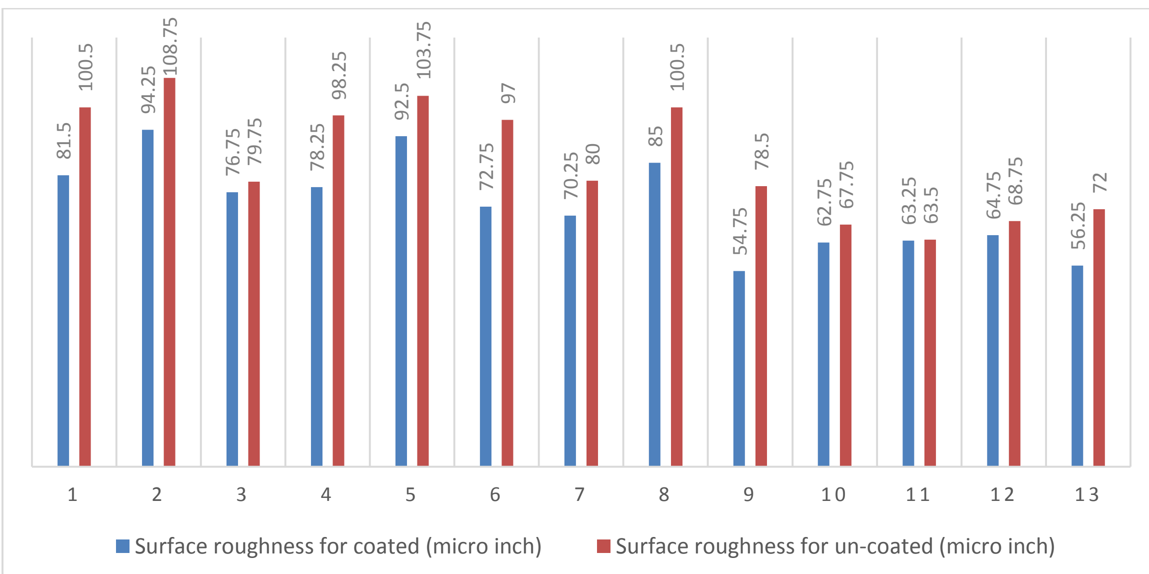

Figure 4-22: Surface roughness performance comparison between un-coated and coated carbide drill

Chapter 5 : Conclusion and Future work

5.1 Conclusion

The objectives of this investigation was achieved successfully: (1) finding the optimum input parameters (speed and feed rate) that produce the minimum dimensional tolerance and minimum surface roughness when dry drilling Ti-6Al-4V by using un-coated carbide tool and coated carbide tool, (2) Evaluating the performance of un-coated tool and coated tool when dry drilling Ti-6Al4V. The optimal conditions for obtaining the minimum output of quality characteristics is spindle speed of 1000 RPM and 1 ipm when using both types of twist drill. At the optimum process conditions for both types of tool, thrust force and torque values are in average value. However, un-coated carbide tool shows lower thrust force and torque at most cases. The TiAlN-coated carbide tool showed outstanding tolerance and surface roughness performance when compared to un-coated tool. The optimum independent parameters when using coated carbide tool, produce drilled holes with dimensional tolerance of 0.00018 inch and surface roughness of 60.35 micro inch, while the un-coated carbide tool produce drilled holes with dimensional tolerance of 0.00038 inch and surface roughness of 70.1 micro inch. ANOVA shows that process responses (thrust force, torque, tolerance, and surface roughness) depend on both speed and feed rate or on one of them.

Response surface methodology based on central composite design and with using desirability function was an effective technique to optimize the process of drilling Ti-6Al-4V. The results generated from the present study are able to be used as process map to select conditions of process parameters and tool material types that satisfy both quality requirements and productivity constraints when dry drilling Ti-6Al-4V alloy in the current ranges for spindle speed (293-1707 RPM) and for feed rate (0.5-1.71 ipm).

5.2 Future Work

The present study gives room for further research in solving optimizing problem during drilling Ti-6Al-4V as follows:

- Apply multi-objective optimization technique on the developed second order model.
- Include more quality characteristic such as minimum burrs and roundness.
- Extend the study by including the effects of drill diameter, tool geometry, and tool wear.
- Extend the study by using external and internal coolant during the drilling process.
- Extend the study by enlarging the speed and feed rate ranges.

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Appendices

Appendix A - CNC codes for the 13 runs

```
N100 ; PROGRAM NAME - TITANIUMKARM

N110 ; DATE -  21-10-2013 TIME -  11:42

N120 ; TOOL - 01   DIA. - .2500   DRILL.....

N130 M25 G49  ; Goto Z home, cancel tool length offset

N140 G17 G40  ; Setup for XY plane, no cutter comp,

N150 G20      ; inch measurements

N160 G80      ; cancel canned cycles,

N170 G90      ; absolute positioning,

N180 T1 M06

N190 S0500 M3

N200 G0 G54 X1.5 Y-.75

N210 G43 H1 Z1

N220 G99 G81 X1.5 Y-.75 Z-.55 R.1 F.5

N230 G80

N240 G81 X2.25 Y-.75 Z-.55 R.1 F1.5

N250 G80

N260 S01500 M4

N270 G81 X3. Y-.75 Z-.55 R.1 F.5

N280 G80

N290 G81 X3.75 Y-0.75 Z-.55 R.1 F1.5

N300 G80

N310 S0293 M3

N320 G81 X4.5 Y-.75 Z-.55 R.1 F1

N330 G80

N340 S01707 M4
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N350 G81 X.75 Y-1.5 Z-.55 R.1 F1

N360 G80

N370 S01000 M4

N380 G81 X1.5 Y-1.5 Z-.55 R.1 F.3

N390 G80

N400 G81 X2.25 Y-1.5 Z-.55 R.1 F1.7

N410 G80

N420 G81 X3. Y-1.5 Z-.55 R.1 F1

N430 G80

N440 G81 X3.75 Y-1.5 Z-.55 R.1 F1

N450 G80

N460 G81 X4.5 Y-1.5 Z-.55 R.1 F1

N470 G80

N480 G81 X.75 Y-2.25 Z-.55 R.1 F1

N490 G80

N500 G81 X1.5 Y-2.25 Z-.55 R.1 F1

N510 G80

N520 S0500 M3

N530 G81 X2.25 Y-2.25 Z-.55 R.1 F.5

N540 G80

N550 G81 X3. Y-2.25 Z-.55 R.1 F1.5

N560 G80

N570 S01500 M4

N580 G81 X3.75 Y-2.25 Z-.55 R.1 F.5

N590 G80

N600 G81 X4.5 Y-2.25 Z-.55 R.1 F1.5

N610 G80

N620 S0293 M3

N630 G81 X.75 Y-3. Z-.55 R.1 F1
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N640 G80

N650 S01707 M4

N660 G81 X1.5 Y-3. Z-.55 R.1 F1

N670 G80

N680 S01000 M4

N690 G81 X2.25 Y-3. Z-.55 R.1 F.3

N700 G80

N710 G81 X3. Y-3. Z-.55 R.1 F1.7

N720 G80

N730 G81 X3.75 Y-3. Z-.55 R.1 F1

N740 G80

N750 G81 X4.5 Y-3. Z-.55 R.1 F1

N760 G80

N770 G81 X.75 Y-3.75 Z-.55 R.1 F1

N780 G80

N790 G81 X1.5 Y-3.75 Z-.55 R.1 F1

N800 G80

N810 G81 X2.25 Y-3.75 Z-.55 R.1 F1

N820 G80

N830 G40

N840 M25 G49 H0

N850 M05

N870 G0 X0. Y0.

; End of program
```

Appendix B1 - Table of thrust force and torque response when drilling titanium by un-coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Thrust Force (Ib)	Torque (Ib-ft)
1	500	0.5	69.79	0.41
2	500	1.5	97.16	1.15
3	1500	0.5	43.5	0.24
4	1500	1.5	66.93	0.98
5	292.893	1	135.93	1.71
6	1707.107	1	47.49	0.6
7	1000	0.292893	42.54	0.35
8	1000	1.7	83.27	0.71
9 (c)	1000	1	67.51	0.76
10 (c)	1000	1	67.11	0.6
11 (c)	1000	1	63.61	0.5
12 (c)	1000	1	64.99	0.49
13 (c)	1000	1	66.93	0.48

Appendix B2 - Table of tolerance response when drilling titanium by un-coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Nominal Diameter (inch)	Measured Diameter (inch)	Dev. From Nom (inch)
1	500	0.5	0.25	0.2511	0.0011
2	500	1.5	0.25	0.2511	0.0011
3	1500	0.5	0.25	0.2531	0.0031
4	1500	1.5	0.25	0.2521	0.0021
5	292.893	1	0.25	0.2533	0.0033
6	1707.107	1	0.25	0.2526	0.0026
7	1000	0.292893	0.25	0.2514	0.0014
8	1000	1.7	0.25	0.2516	0.0016
9 (c)	1000	1	0.25	0.2508	0.0008
10 (c)	1000	1	0.25	0.2505	0.0005
11 (c)	1000	1	0.25	0.2501	0.0001
12 (c)	1000	1	0.25	0.2502	0.0002
13 (c)	1000	1	0.25	0.2497	0.0003

Appendix B3 - Table of surface roughness response when drilling titanium by un-coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Ra 1 (Micro inch)	Ra 2 (Micro inch)	Ra 3 (Micro inch)	Ra 4 (Micro inch)	Surface Roughness (Micro inch)
1	500	0.5	113	96	94	99	100.5
2	500	1.5	121	94	88	132	108.75
3	1500	0.5	77	81	90	71	79.75
4	1500	1.5	103	118	90	82	98.25
5	292.893	1	90	113	120	92	103.75
6	1707.107	1	124	99	84	81	97
7	1000	0.292893	81	75	80	84	80
8	1000	1.7	110	93	108	91	100.5
9 (c)	1000	1	88	88	76	62	78.5
10 (c)	1000	1	75	70	65	61	67.75
11 (c)	1000	1	66	68	59	61	63.5
12 (c)	1000	1	62	61	102	50	68.75
13 (c)	1000	1	92	56	72	68	72

Appendix C1 - Table of thrust force and torque response when drilling titanium by coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Thrust Force (Ib)	Torque (Ib-ft)
1	500	0.5	100.57	0.55
2	500	1.5	163.81	1.13
3	1500	0.5	56.04	0.36
4	1500	1.5	95.36	0.59
5	292.893	1	166.4	1.2
6	1707.107	1	66.95	0.56
7	1000	0.292893	63.01	0.32
8	1000	1.7	91.63	0.59
9 (c)	1000	1	93.18	0.51
10 (c)	1000	1	95.31	0.5
11 (c)	1000	1	87.37	0.56
12 (c)	1000	1	91.85	0.57
13 (c)	1000	1	91.22	0.62

Appendix C2 - Table of tolerance response when drilling titanium by coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Nominal Diameter (inch)	Measured Diameter (inch)	Dev. From Nom (inch)
1	500	0.5	0.25	25.001	0.001
2	500	1.5	0.25	25.0002	0.0002
3	1500	0.5	0.25	25.0003	0.0003
4	1500	1.5	0.25	25.0017	0.0017
5	292.893	1	0.25	24.9991	0.0009
6	1707.107	1	0.25	25.0005	0.0005
7	1000	0.292893	0.25	25.0001	0.0001
8	1000	1.7	0.25	24.9992	0.0008
9 (c)	1000	1	0.25	25.0002	0.0002
10 (c)	1000	1	0.25	25.0003	0.0003
11 (c)	1000	1	0.25	25.0002	0.0002
12 (c)	1000	1	0.25	25.0001	0.0001
13 (c)	1000	1	0.25	25.0001	0.0001

Appendix C3 - Table of surface roughness response when drilling titanium by coated carbide tool.

Exp. No	Speed (RPM) *X*	Feed Rate (ipm) *Y*	Ra 1 (Micro inch)	Ra 2 (Micro inch)	Ra 3 (Micro inch)	Ra 4 (Micro inch)	Surface Roughness (Micro inch)
1	500	0.5	79	80	88	79	81.5
2	500	1.5	93	92	104	88	94.25
3	1500	0.5	78	86	71	72	76.75
4	1500	1.5	80	76	78	79	78.25
5	292.893	1	114	102	80	74	92.5
6	1707.107	1	84	77	61	69	72.75
7	1000	0.292893	66	70	69	76	70.25
8	1000	1.7	83	70	100	87	85
9 (c)	1000	1	98	45	27	49	54.75
10 (c)	1000	1	60	53	72	66	62.75
11 (c)	1000	1	120	41	55	37	63.25
12 (c)	1000	1	121	58	53	27	64.75
13 (c)	1000	1	82	39	61	43	56.25

VITA

Akram Ahmad A. Faqeeh was born on September 30, 1985 in Makkah, Saudi Arabia. He accomplished his elementary, secondary, and high school in Makkah. He earned an Associate degree of Science in Mechanical Engineering Technology degree from Yanbu Industrial College, at Yanbu, Saudi Arabia in 2007. He obtained a Bachelor of Science Degree in Mechanical Engineering Technology in 2010 from the same college. Immediately after he graduated on February 8, 2010, he worked as inspection & corrosion engineer in SABIC (Saudi Basic Industrial Corporation) in Al-Jubail, Saudi Arabia for 5 months. At the end of 2010, he started to work as iterant & students' Clubs supervisor in Yanbu industrial College.

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