

Optimization of Multiple Quality Characteristics for Dry Drilling Ti-6Al-4V Using TiAlN-Coated Carbide Tool

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ABSTRACT

The present paper aims at optimization of multiple quality characteristics (dimensional accuracy and surface roughness) in dry drilling Ti-6Al-4V using TiAlN-coated carbide tool while the controllable factors are spindle speed and feed rate. To do so, desirability methodology is used to explore optimum conditions for concurrent optimization of the addressed quality characteristics. Central composite design (CCD) is used for experimentation. In order to create reliable models describing the process behavior, response surface methodology (RSM) is used.

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1. INTRODUCTION

Titanium has superior characteristics, such as high strength, low density, and unique corrosion resistance. In spite of the machining difficulty of titanium, titanium and its alloys are attractive for a diverse field of industries, such as the automobile, medical, military, chemical, and aerospace industries [1, 2]. Titanium and its alloys are classified as difficult-to-machine materials because of the sundry reasons that have been reported by researchers, such as the low thermal conductivity of Ti-alloys, which leads to an increase in the tool temperature at the tool/workpiece interface [1, 2, 3], and the chemical reactivity of Ti alloys at high cutting temperature ($> 500^{\circ}\text{C}$) with almost all tool materials obtainable [4, 5].

Drilling is one of the most important machining processes. Drilling accounts for 40-60% of the total material removal processes, and it is a primary technique in the aerospace industry [6]. Drilling is an immensely used machining process in industry and thus has high economic significance, as it is commonly used in the final steps of the mechanical component fabrication [2, 6]. However, such a crucial machining process coupled with unique and difficult to machine materials such as Ti-alloys results in several technical difficulties. Rui Li [7] reported five technical difficulties when drilling titanium: high drill temperature, drill wear, limited cutting speed, chip ejection, and exit burr formation.

Due to the technical difficulties while drilling titanium, coolants are used for lubrication during drilling to mitigate the effects of high temperature. However, the use of coolants represents the most deleterious pollutant in machining [8, 9]. In addition, the purchasing cost of coolants is responsible for 7.5% of the total

manufacturing cost, and the maintenance cost of coolants is 17% of the total manufacturing cost [8]. Therefore, an ample number of experimental studies have been performed to find alternative methods to the current use of coolants, such as minimizing the use of coolants or drilling without a coolant (dry drilling).

In the aerospace industry, depending on the application, hole quality can be very important. The dimensional accuracy and surface roughness of holes are significant quality characteristics [10]. Poor dimensional accuracy and surface roughness negatively impact manufacturing at the point of assembly.

The hole quality (dimensional accuracy and surface roughness) is essentially dependent on the cutting parameters. As a result, many researchers have concentrated on determining the best cutting conditions. For example, researchers have investigated the effect of drilling parameters to determine the optimum process conditions that produce the most desirable outputs. However, the research studies on the drilling of titanium remain limited and not widely reported compared to the studies on the turning and milling of titanium [6].

El-Gizawy et al. [11] used response surface methodology (RSM) and Taguchi analysis to study the primary influence of the cutting parameters (cutting speed, feed rate and tool condition) on the hole quality (diameter accuracy and surface roughness) when dry drilling IM7/977-3 composite material sheet over 6Al-4V titanium alloy sheet. In general, the study indicated that high speed with low feed rate produces high quality hole [11].

Li et al. [12] studied the effects of supply coolant on the drill life and surface roughness. Their study indicated that dry drilling negatively influences the drill life and produces a poorer surface roughness than does hole drilling with the use of a coolant [12].

Rahim and Sharif [6] evaluated the drilling performance of the coated and un-coated carbide twist drills at various cutting speeds while the feed rate was fixed and coolant was supplied at a constant flow rate. They stated that a TiAlN-coated carbide drill exhibited an outstanding performance of tool life and surface roughness when compared to an uncoated carbide drill [6].

This study of the drilling process of Ti-6Al-4V when using a TiAlN-coated carbide twist drill was performed to determine the optimum conditions of the drilling parameters (cutting speed and feed rate) that produce the best quality of drilled holes (best dimensional accuracy and lowest surface roughness) while using no coolant during the drilling process. In addition, the study indicates the benefits of the coupling of desirability approach and response surface methodology (RSM) based on central composite design (CCD) for the optimization of multiple quality characteristics.

2. METHODOLOGY

In this section, the background of the methods used to design the experiment and to investigate the process is introduced. The experimental setup and procedure are presented. The specimen material and the parameters of the drill considered in this study are defined.

2.1. Response Surface Methodology and Central Composite Design

RSM methodology is a collection of statistical and mathematical techniques that are advantageous for the optimization of a response, i.e., the performance measure or quality characteristic of interest, that is potentially affected by several factors or a number of associated input variables (independent variables).

Central composite designs are widely used for fitting second-order response surfaces because of both their statistical properties and the practical attraction of their expanded coverage around a center point [13]. The second-order model often appears in the RSM because of its flexibility in that it is able to adopt a wide variety of functional forms [13]. In addition, there is considerable practical experience indicating that second-order models work effectively in solving real response surface problems [13]. In the present study, a second-order response surface model (equation 1) is used to formulate a least squares relationship between the input parameters and the output response measures.

$$Z = \beta_0 + \beta_1 X + \beta_2 Y + \beta_{11} X^2 + \beta_{22} Y^2 + \beta_{12} XY \quad (1)$$

Where Z are the observed responses (div. from nom., surface roughness) as a function of the main influences of factors X (spindle speed) and Y (feed rate), their interaction (XY), and their quadratic components (X^2 , Y^2). β_0 and β_i are estimated regression coefficients.

The mathematical steps to compute the second-order model (equation 1) for the responses (dimensional accuracy and surface roughness) as follow:

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

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

Finding estimated regression coefficient by

$$\beta = ((X \text{ and } Y)' \times (X \text{ and } Y))^{-1} ((X \text{ and } Y)' \times Z)$$

Then

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

For this experiment, the upper limit and lower limit of the process parameters (speed and feed rate) were selected based on the initial experiments, which were performed to examine the capability of the cutting speeds and the feed rates that had been recommended by researchers to drill titanium using a carbide tool. El-Gizawy and Khasawench [11] recommended a speed of 600 RPM and a feed rate of 0.72 ipm for the production of quality holes when drilling titanium using a twist drill that has a diameter of 0.25" (6.35 mm). Dornfeld, et al. [14] used two levels of cutting speed, 1835 and 2140 RPM, and three levels of feed rate, 2, 4.3, and 5.5 ipm. Because no coolant was used during the experiment in this study, some sparks and high temperature were observed for cutting speeds higher than 1800 RPM and feed rates higher than 2 ipm. Therefore, the experiment's upper limit and lower limit of the process parameters were established as follows: spindle speed (500-1500 RPM) and feed rates (0.5-1.5 ipm). According to the central composite design, the cutting conditions expressed in terms of coded variables and in terms of natural units of variables are presented in Table 1. In addition, Table 2 presents the complete generation of the experiment designed using central composite design for the drilling process.

Table 1. CCD Range of process parameters for the 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	1.7071

Table 2. Experiment designed using central composite design

Exp. No	Speed (RPM) <i>X</i>	Feed Rate (ipm) <i>Y</i>
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	1.7071
9 (c)	1000	1
10 (c)	1000	1
11 (c)	1000	1
12 (c)	1000	1
13 (c)	1000	1

2.2. Analysis of Variance (ANOVA)

ANOVA is the statistical method used to detect the relative significance of process factors and their interaction on each response. The main elements of an ANOVA table are factors, degrees of freedom, sum of squares, mean square, F-value, and P-value associated with F-value. When the P-value is less than the significance level, it means that the factor is significant. The coefficient of determination (R^2) was determined for each response to indicate how well the data points fit the model curve. Table 3 shows the formulas for a two-factor ANOVA of the second-order model.

Table 3. Formulas for the two-factor ANOVA of the second-order model

Factor	Degrees of Freedom (df)	Sum of Squares	Mean Square	F-value	P-value
Speed (X)	1	SSX	$\frac{SSX}{df}$	$\frac{MSX}{MSE}$	
Feed (Y)	1	SSY	$\frac{SSY}{df}$	$\frac{MSY}{MSE}$	
$X \times Y$	1	$SSXY$	$\frac{SSXY}{df}$	$\frac{MSXY}{MSE}$	
X^2	1	SSX^2	$\frac{SSX^2}{df}$	$\frac{MSX^2}{MSE}$	
Y^2	1	SSY^2	$\frac{SSY^2}{df}$	$\frac{MSY^2}{MSE}$	
Error	7	SSE	$\frac{SSE}{df}$		
Total	12	SST_0			
R^2	$1 - \frac{SSE}{SST_0}$				

2.3. Desirability Approach

A typical problem in product or process development is the location of a set of conditions of the input variables (independent parameters) that produces the most desirable product or process in terms of its responses on the output variables. The desirability approach is a powerful tool for solving such problems; in this approach, all of the objectives are achieved as a definite goal instantaneously [15]. The desirability approach steps are as follows:

1. Assign a low and high value for each response.
2. Convert each response of z_i into an individual desirability d_i , which may vary in the range $0 \leq d_i \leq 1$ (least to most desirable, respectively).
3. Make use of the desirability function, which is the geometric mean of all transformed responses (equation 2).

$$D = (d_1 \times d_2 \times \dots \times d_k)^{\frac{1}{k}} \quad (2)$$

where k is the number of measured responses in the experiment for a specific level of spindle speed and feed rate.

4. Select the combination of parameters that will maximize the overall desirability D, getting as close as possible to 1.

The desirability approach can be used in the following modes: none, maximum, minimum, target, and in range [14]. In the present study, the minimum option is required to locate the optimum conditions of parameters to obtain the minimum responses of quality characteristics (deviation from the nominal value and surface roughness). The definitions of minimum goal parameters are:

- Minimum:

$d_i = 1$ if the response < low value

$d_i = 0$ if the response > high value

$0 \leq d_i \leq 1$ as the response varies in between the low and the high value

2.4. Experimental Set up and Procedure

A CNC milling machine (Accumill) was used for the drilling operations. The G programming language (G-Code) was used to develop the CNC code for drilling holes at the planned positions and under the required experimental conditions. The investigated titanium plate was mounted and secured onto the fixture. The experiments involving the drilling of the Ti-6Al-4V plate using a TiAlN-coated carbide tool were performed at the levels according to the central composite design presented in Table 2. No coolant was used during the drilling operation (dry drilling). Fig. 1 shows the schematic of the experimental setup.