Minimization of the hole overcut and cylindricity errors during rotary ultrasonic drilling of Ti-6Al-4V

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Abstract. Titanium and its alloys e.g. Ti6Al4V have widespread applications in aerospace, automotive and medical industry. At the same time titanium and its alloys are regarded as difficult to machine materials due to their high strength and low thermal conductivity. Significant efforts have been dispensed to improve the accuracy of the machining processes for Ti6Al4V. The current study present the use of the rotary ultrasonic drilling (RUD) process for machining high quality holes in Ti6Al4V. The study takes into account the effects of the main RUD input parameters including spindle speed, ultrasonic power, feed rate and tool diameter on the key output responses related to the accuracy of the drilled holes including cylindricity and overcut errors. Analysis of variance (ANOVA) was employed to study the influence of the input parameters on cylindricity and overcut error. Later, regression models were developed to find the optimal set of input parameters to minimize the cylindricity and overcut errors.

1. Introduction

Titanium alloys are used for numerous applications in industry such as automotive [1], [2], medical [3], and sporting goods [4]. This is due to their better strength to weight ratio at high temperatures, hardness, corrosion resistance, heat resistant qualities, superior fatigue strength and stability [5], [6]. However, these distinctive properties of these materials make them difficult and sometimes impossible to machine by conventional machining processes (such as turning, grinding, drilling, milling, etc.). Subsequently, their extensive applications have been stalled by the high machining cost [7], [8]. Titanium and its alloys have been categorized as difficult-to-machine material because the abovementioned properties and the problems for machining these materials are high machining cost, high tool wear rate and low productivity.

Ti-6Al-4V is a typical example of titanium alloys which is very difficult to cut material. It is one of the most commonly used titanium alloy. However, its poor thermal conductivity leads to high cutting temperatures. In addition, low machinability of these difficult-to-machine material causes problems in its manufacturing. Furthermore, often Ti-6Al-4V shows high chemical reactivity with many tool materials at high temperatures leading to a strong adhesion between the tool and work piece resulting into high tool wear rate [9]. Various traditional and nontraditional machining processes have been used to machine Ti-6Al-4V. These methods include laser machining, abrasive water jet machining, electro-discharge
machining, and ultrasonic vibration assisted machining. However, these mentioned processes have several limitations. For example, the surface finish generated by these processes is very poor. Furthermore, dimensional inaccuracies are high besides their undesirable effects on the machined surface such as heat affected zone, recast layer and thermal stresses. From the previous work, it can be concluded that there is a critical need for improving the existing machining processes and developing new processes applicable to machine Ti-6Al-4V. Rotary ultrasonic machining (RUM) has been reported as a promising process to machine hard-to-cut materials [10], [11]. Several studies have been reported on RUM of Ti6Al4V. Effects of input process parameters such as cutting speed, vibration amplitude, feed rate and coolant type on output responses including cutting force, surface roughness, and tool wear have been studied [2], [9].

In this work, the quality of the holes drilled in Ti-6Al-4V via rotary ultrasonic drilling is evaluated by measuring the overcut and cylindricity errors. Parts from Ti-6Al-4V are usually used in advanced applications which require high quality of drilled holes in terms of geometrical accuracies. Two methods are generally applied in determining the quality of the drilled holes, namely cylindricity and overcut errors. The objective of this paper is to study the effect of RUM input parameters including spindle rotational speed, tool diameter, ultrasonic power, and feed rate on the drilled holes' cylindricity and overcut errors and apply ANOVA and regression analysis to minimize the cylindricity and overcut errors.

2. Experimental setup
Machining trials were carried out on Sonic-mill series 10 rotary ultrasonic machine (RUM). The machine has the capability of 20 kHz vibration frequency of the tool and 1000 Watts ultrasonic power can be applied. Figure 1 shows the RUM setup employed for the drilling Ti-6Al-4V. The input variables that were changed during the experiments included spindle rotational speed, tool diameter, ultrasonic power and feed rate. Due to the limitation of the equipment, the ultrasonic vibration frequency was kept constant at 20 KHz.

The drilling tools used were metal bonded diamond core drills from Sonic Mill, USA. Three different tool diameters were used during the experiments. The outer and inner diameters of the cutting tools are summarized in Table 1. The diamond particles size on the drills are 80-100 μm. The dimensions of workpieces used were 50 × 50 × 3 mm. In order to study the effect of machining parameters for rotary ultrasonic assisted drilling of Ti-6Al-4V material, a full factorial method is selected for designing experiments. Tool diameter, cutting speed, feed rate, and vibration amplitude were chosen as the independent input parameters. The studied output responses were the cylindricity and overcut errors which is assumed to be affected by the above input variables. Three levels of each input variable were selected. The input parameters and their selected levels are shown in Table 2. The design of experiment was generated and analyzed using MINITAB® statistical software. A coordinate measuring machine from Zeiss Acura Ltd. USA was employed to determine the overcut and cylindricity errors of the drilled holes, as shown in Figure 2.
Figure 1. Rotary ultrasonic machining setup; (a) Rotary ultrasonic machine (b) Zoomed-in view of the workpiece material Ti6Al4V

Table 1. Properties of diamond tool

| Tools     | Outer diameter | Inner diameter | Length  |
|-----------|----------------|----------------|---------|
| Tool #1   | 3.97 mm        | 6.95 mm        | 12.6 mm |
| Tool #2   | 5.90 mm        | 4.20 mm        | 12.6 mm |
| Tool #3   | 8.90 mm        | 2.40 mm        | 12.6 mm |

Table 2. Machining parameters and their levels

| Input variable               | Level 1 | Level 2 | Level 3 |
|------------------------------|---------|---------|---------|
| Tool diameter, D (mm)        | 8.90    | 5.90    | 3.97    |
| Cutting speed, S (rpm)       | 2000    | 4000    | 6000    |
| Feed rate, F (mm/min)        | 0.1     | 0.6     | ---------|
| Ultrasonic power, UP (%)     | 20      | 40      | ---------|
Figure 2. (a) CMM machine (b) Zoomed-in view of the workpiece material Ti6Al4V probe on CMM

3. Results and Discussion
Table 3 shows the results for the overcut and cylindricity errors for all the performed experiments. The effects of the input variables on the selected outputs were analyzed using the MINITAB® statistical software. A regression model was developed for the outputs based on the full factorial design. Further, the analysis of variance (ANOVA) is performed to find the statistical significance of the input variables on the output responses.
Table 3. Design layout and experimental results for overcut and cylindricity errors [12]

| Run order | Tool diameter (mm) | Ultrasonic power % | Cutting speed (rpm) | Feed Rate (mm/min) | Overcut (μm) | Cylindricity (μm) |
|-----------|--------------------|---------------------|---------------------|--------------------|--------------|-------------------|
| 1         | 8.90               | 20                  | 6000                | 0.6                | 207.5        | 11                |
| 2         | 3.97               | 40                  | 2000                | 0.6                | 119.6        | 62.4              |
| 3         | 3.97               | 20                  | 4000                | 0.6                | 215.2        | 41.2              |
| 4         | 3.97               | 40                  | 4000                | 0.1                | 188.5        | 7.4               |
| 5         | 8.90               | 40                  | 4000                | 0.6                | 185.8        | 7.2               |
| 6         | 8.90               | 20                  | 4000                | 0.6                | 185.2        | 2                 |
| 7         | 3.97               | 20                  | 2000                | 0.1                | 278.7        | 46.3              |
| 8         | 5.90               | 40                  | 4000                | 0.6                | 165.4        | 4.1               |
| 9         | 3.97               | 40                  | 4000                | 0.6                | 192.2        | 3.2               |
| 10        | 8.90               | 40                  | 4000                | 0.1                | 173.7        | 3.1               |
| 11        | 8.90               | 20                  | 6000                | 0.1                | 180.3        | 5.3               |
| 12        | 3.97               | 20                  | 4000                | 0.1                | 176.2        | 9.3               |
| 13        | 3.97               | 40                  | 6000                | 0.1                | 194.7        | 14.3              |
| 14        | 8.90               | 20                  | 2000                | 0.6                | 212.2        | 1.2               |
| 15        | 5.90               | 40                  | 6000                | 0.1                | 179.2        | 14                |
| 16        | 5.90               | 40                  | 4000                | 0.1                | 179.8        | 3.5               |
| 17        | 5.90               | 40                  | 6000                | 0.6                | 173.1        | 13.9              |
| 18        | 3.97               | 20                  | 2000                | 0.6                | 264.5        | 38.4              |
| 19        | 5.90               | 20                  | 4000                | 0.1                | 179.3        | 3.7               |
| 20        | 8.90               | 40                  | 6000                | 0.1                | 180.9        | 11.6              |
| 21        | 8.90               | 40                  | 2000                | 0.6                | 196.4        | 5.9               |
| 22        | 5.90               | 40                  | 2000                | 0.6                | 286.3        | 51.1              |
| 23        | 5.90               | 40                  | 6000                | 0.1                | 174.5        | 6.2               |
| 24        | 5.90               | 20                  | 2000                | 0.1                | 248.8        | 25.1              |
| 25        | 3.97               | 20                  | 6000                | 0.1                | 192.2        | 9.6               |
| 26        | 5.90               | 20                  | 2000                | 0.6                | 269.7        | 27.2              |
| 27        | 8.90               | 20                  | 2000                | 0.1                | 182.4        | 15.2              |
| 28        | 3.97               | 40                  | 2000                | 0.1                | 285.4        | 65.8              |
| 29        | 5.90               | 20                  | 4000                | 0.6                | 193.1        | 30.4              |
| 30        | 8.90               | 40                  | 6000                | 0.6                | 194.1        | 7.8               |
| 31        | 5.90               | 20                  | 6000                | 0.6                | 177.1        | 7.3               |
| 32        | 3.97               | 40                  | 6000                | 0.6                | 183.8        | 21.4              |
| 33        | 8.90               | 40                  | 2000                | 0.1                | 198.5        | 15.2              |
| 34        | 8.90               | 20                  | 4000                | 0.1                | 154.9        | 8.6               |
| 35        | 5.90               | 40                  | 2000                | 0.1                | 259.3        | 44.8              |
| 36        | 3.97               | 20                  | 6000                | 0.6                | 192.5        | 18.6              |
3.1. ANOVA for overcut and cylindricity errors

ANOVA is used to investigate which of the design input variables significantly affects the accuracy of the drilled holes in terms of overcut and cylindricity errors. Table 4 displays ANOVA tables at 95% confidence interval after eliminating some insignificant terms.

| Source          | overcut errors | cylindricity errors |
|-----------------|----------------|---------------------|
|                 | DF  | MS   | P-Value | DF  | MS   | P-Value |
| Model           | 8   | 0.0044 | 0.000 | 6   | 0.0013 | 0.000 |
| Linear          | 4   | 0.0051 | 0.000 | 4   | 0.0013 | 0.000 |
| S               | 1   | 0.0153 | 0.000 | 1   | 0.0024 | 0.000 |
| D               | 1   | 0.0056 | 0.000 | 1   | 0.0025 | 0.000 |
| UP              | 1   | 0.0000 | 0.553 | 1   | 0.0001 | 0.42  |
| F               | 1   | 0.0004 | 0.098 | 1   | 0.0001 | 0.464 |
| Square          | 1   | 0.0076 | 0.000 | 1   | 0.0012 | 0.002 |
| S*S             | 1   | 0.0076 | 0.000 | 1   | 0.0012 | 0.002 |
| 2-Way Interaction | 3   | 0.0027 | 0.000 | 1   | 0.0014 | 0.001 |
| S*D             | 1   | 0.0060 | 0.000 | 1   | 0.0014 | 0.001 |
| D*F             | 1   | 0.0005 | 0.052 | 1   | 0.0001 |
| UP*F            | 1   | 0.0009 | 0.014 |     |       |
| Error           | 25  | 0.0001 |       | 29  |       |
| Total           | 33  |       |         |     |       |

From the above result in Table 4, it was found that the cutting speed, tool diameter and the interaction between cutting speed and tool diameter, and ultrasonic power and feed rate have significant effect on overcut errors because their p-values < 0.05. The model explains 91.64% of variability of the response data around its average. In addition, it can be seen that the cutting speed, ultrasonic power, feed rate and tool diameter have significant effect on hole cylindricity error as well. The interaction of cutting speed with tool diameter, and ultrasonic power with feed rate also have significant effect on cylindricity. The model explains 72.60% of the variation in the response data. It can be seen from the residual plot in Figure 3 that the overcut and cylindricity errors are very close to the normal fitted line so the residuals are normally distributed. Versus Fits most of the points are fill between two parallel lines that can be drawn from the nearest two points from the lower and upper side of the plot so the residuals are with a constant variance. In addition, from histogram and Versus Order Plots, all the residuals are spread approximately equal around the zero so the residuals are with a mean of zero.
The influence of process parameter on the overcut and cylindricity errors were investigated by plotting the main effect plots as shown in the Figure 4. It can be said from Figure 4(a) that the effect of cutting speed and tool diameter is significant and the overcut errors will decrease with the increase of cutting speed, from 2000 rpm to 4000 rpm, after that the overcut errors will increase. In addition the overcut errors will decrease when the tool diameter at high-level. Figure 4(b) shows that the cylindricity first sharply decreases with increase in cutting speed up to the 4000 rpm and then increases. As tool diameter increases, the cylindricity decreases continuously. Like the ANOVA analysis, the ultrasonic power and the feed rate shows very low effect on both the overcut and cylindricity errors.
3.2. Regression model and optimization
Regression analysis has been used to describe the relationship between the input process parameters and output variable. Regression model are also developed to fit the data for the two selected outputs. Equation 1 and 2 are the regression equations that can be used for predicting overcut and cylindricity errors.

Overcut errors = 0.5006 - 0.0001 S - 0.02497 D + 0.000613 UP + 0.0261 F + 0.00 S^2 + 0.000004 S*D + 0.008 D*F - 0.0021 UP*F  (1)

Cylindricity errors = 0.1475 - 0.000042 S - 0.01151 D + 0.000139 UP + 0.00504 F + 0.000002 S*D  (2)

3.2.1. Confirmation test
To confirm the soundness of the regressions models as presented in Eq. 1 and 2, the models were run to predict the cylindricity and overcut errors for all the experimental runs. The comparison of the experimental and predicted values are shown in Figure 5. In addition, two sample t-test with 95% confidence interval was carried out to compare the means of experimental and predicted values. The result show that there is no significant difference in experimental and predicted values.

Figure 5. Plots between predicted and experimental overcut errors
Figure 6. Plots between predicted and experimental Cylindricity errors

The optimization of the input parameters for minimizing the overcut and cylindricity error is carried out by using the desirability method. This method evaluates that how well a combination of predicted input parameters fulfils the objectives for the output responses. Desirability method utilizes an objective function known as the desirability function and converts an evaluated response into a scale free value called desirability. The desirability range varies from zero to one, which indicates whether the responses are inside or outside their satisfactory limits. Therefore, the desirability value of approaching one is preferred. In this research, the optimization was performed to find the optimal set of input parameters for minimizing the overcut and cylindricity errors. Figure 7(a) and Figure 7(b) shows the individual optimization results for obtaining the minimum overcut and cylindricity errors based on the developed mathematical models. The optimum conditions are illustrated in Figure 7. It is found that the combination of spindle speed of 4747 rpm, ultrasonic power of 20% and feed rate of 0.1 mm per minute produced minimum overcut errors. Moreover, it can be concluded that the combination of cutting speed of 4141 rpm, ultrasonic power of 20% and feed rate 0.1 mm per minute produced minimum cylindricity errors. It can be seen that the desirability for optimizing overcut and cylindricity errors is equal to 0.8548 and 1.000. It is means that the obtained solution is acceptable.
4. Conclusion

In the current paper, RUM process has been used for drilling holes in Ti-6Al-4V. Full factorial design of experiments method was employed to study the effect of RUM input parameters including tool diameter, spindle rotational speed, ultrasonic vibration, and feed rate, on the accuracy of drilled hole in terms of overcut and cylindricity errors. The following conclusions could be drawn from the present research:

- Rotary ultrasonic machining can be successfully applied to drill holes with high accuracy in Ti-6Al-4V.
- Spindle rotational speed and tool diameter have significant effect on the overcut and cylindricity. In addition, the interaction of cutting speed with tool diameter, and ultrasonic power with feed rate also have significant effects on cylindricity.
- Regression models have been developed for overcut and cylindricity errors. The results showed that there were no significant difference between the experimental and predicted values for both responses which shows that the accuracy of developed models are high. The developed models can be used to predict responses for different RUM input parameter combinations successfully.
- Desirability method has been used to get the combination of the optimized input parameters that would results in the minimum overcut and cylindricity error. The combination of tool diameters of 9 mm, ultrasonic power = 20%, spindle rotational speed = 4747 rpm and feed rate = 0.1 mm/min will lead to minimum overcut error. Whereas, the combination of tool diameters of 9 mm,
ultrasonic power = 40%, cutting speed = 4141 rpm and feed rate = 0.6 mm/min will lead to minimum cylindricity error.

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