Analysis and optimization of circularity error in drilling Process using statistical technique

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Abstract. Drilling is a complex manufacturing process and its process parameter optimization enhances machining performance. Titanium alloy is extensively used in automobile and aerospace sectors because of its inherent properties. However, it is categorized into difficult to machine because of its properties. In this work, drilling process is carried out on titanium alloy with different machining conditions. Cutting conditions used are dry, wet and dry with cryogenically treated drill. Experiments are executed as per L9 orthogonal array. Statistical approaches such as orthogonal array and Analysis of Variance (ANOVA) are used to find the importance and effects of machining parameters. Process parameters are optimized and the effect of significance is estimated. Input parameters include feed, cutting speed and depth of cut. Output parameter includes circularity error. The result suggests that cryogenically treated carbide tool exhibits better machining performance than the dry and wet of non-treated tool and enhance sustainability in manufacturing.

1. Introduction

In manufacturing, sustainability can be defined as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers”. It can be degraded due to pollutions from the industries caused by traditional and nontraditional manufacturing methods. [1]. Drilling is an essential machining process which is widely preferred for all engineering industries [2]. Titanium alloy is classified into light weight and difficult to machine category. This is one of the light weight materials which possess better mechanical properties, resistance to corrosion and thermal stability. The above reason, titanium alloys are preferred in aerospace and automotive industries [3]. Machining assembly is significantly influenced by dimensional errors. In drilling process, circularity error is an important one. It is also known as roundness error. It can be estimated by the difference between the diameter of minimum circumscribing circle and the diameter of maximum inscribing circle [4]. The main goal of any material removal operation is to find most appropriate machining parameters. To optimize the design parameters and upgrade the quality of products statistical approach is used. Orthogonal ANOVA are used to find significant effect and optimum machining parameters [5].

2. Literature review

Kurt et al. [6] performed dry drilling on titanium alloy and the hole accuracy parameters were analyzed using Taguchi method. Surface roughness and accuracy of hole diameters were considered as output parameters. Orthogonal matrix, signal to noise ratio and ANOVA approach were used to examine the results were obtained. Shetty et al. [7] studied machinability aspects of titanium alloy in drilling process. Chip thickness and surface finish of the drilled hole were analyzed using Taguchi
approach. ANOVA is utilized to determine the significant influence of process parameters on response. Impero et al. [8] compared wet and cryogenic drilling process on polymer and titanium stack. The result concluded that cryogenic drilling was used to reduce the force required to perform drilling process. Samuel raj et al. [9] used cryogenically treated tool on drilling process for machining of titanium alloy. The result concluded that cryogenic drilling was used to reduce the force required to perform drilling process. Samuel raj et al. [9] used cryogenically treated tool on drilling process for machining of titanium alloy. The result concluded that cryogenic drilling was used to reduce the force required to perform drilling process.

Samuel raj et al. [9] used cryogenically treated tool on drilling process for machining of titanium alloy. Minimum quantity lubrication concept was used with nano fluid as coolant. The result concluded that nano fluid had higher thermal conductivity which was used to reduce the chip tool interface friction. Naveena et al. [10] conducted drilling process with cryogenically treated drill for AISI 304 stainless steel. Minimum quantity lubrication and conventional lubricant were used to perform the experiments. The results indicated that cryogenically treated drills lead to reduced tool wear. Singaravel et al. [11] conducted drilling process on titanium alloy using carbide drills. In their work, surface quality, circularity and diameter errors were analyzed. The result showed that tool rated and followed by machining speed were influenced the responses. Also, it was pointed out assembly accuracy of drilled hole were depends on these responses.

It has been observed that, one of the most difficult operations in machining process is drilling of titanium alloy. Cutting environments such as dry and wet conditions are plays a vital role in machining. Additionally, other approach that is cryogenic treated tool with dry condition is reported. In this work, drilling performance with cryogenically treated tool and their performance is compared to dry and wet environments. Hence, the performance of drilling of titanium alloy with dry wet and cryogenically treated tool conditions are attempted as cutting environment with carbide drill.

3. Experimental Setup

Drilling process is performed using vertical machining centre (Figure1). Titanium alloy is used in aerospace industries. Carbide drill is used to perform drilling operation. Figure 2 shows the carbide drill used in this experiment. Drilling process is carried out using Taguchi L9 orthogonal matrix [12]. The input process parameters are spindle speed, feed rate and depth of cut. Table 1 shows the process parameters.

| Figure 1. Vertical machining centre | Figure 2. Carbide drill | Figure 3. Cryogenic and tempering cycle on carbide tool |
Table 1. Process parameters

| S.no | Parameters                  | Level 1 | Level 2 | Level 3 |
|------|-----------------------------|---------|---------|---------|
| 1    | Spindle speed (RPM)         | 600     | 800     | 1000    |
| 2    | Feed rate (mm/min)          | 10      | 20      | 30      |
| 3    | Depth of cut (mm)           | 10      | 10      | 10      |

Figure 4. Coordinate Measuring Machine

Figure 5. Machined sample

Table 2. Experimental Results

| Spindle Speed | Feed rate | Depth of cut | Circularity Error | S/N Ratio | Circularity Error | S/N Ratio | Circularity Error | S/N Ratio |
|---------------|-----------|--------------|-------------------|-----------|-------------------|-----------|-------------------|-----------|
| 600           | 10        | 10           | 0.005             | -52.947   | 0.006             | -49.366   | 0.004             | -57.501   |
| 600           | 20        | 10           | 0.0041            | -56.988   | 0.0071            | -46.171   | 0.0032            | -62.243   |
| 600           | 30        | 10           | 0.0032            | -62.243   | 0.0082            | -43.522   | 0.0012            | -85.312   |
| 800           | 10        | 10           | 0.0026            | -66.824   | 0.005             | -52.947   | 0.0005            | -108.968  |
| 800           | 20        | 10           | 0.0031            | -62.933   | 0.008             | -43.970   | 0.0014            | -81.446   |
| 800           | 30        | 10           | 0.0045            | -55.074   | 0.008             | -43.970   | 0.00052           | -107.846  |
| 1000          | 10        | 10           | 0.0015            | -79.745   | 0.003             | -63.649   | 0.0003            | -124.107  |
| 1000          | 20        | 10           | 0.0016            | -78.169   | 0.005             | -52.947   | 0.0005            | -108.968  |
| 1000          | 30        | 10           | 0.0009            | -92.766   | 0.004             | -57.501   | 0.00019           | -138.477  |
Experiments are performed under dry conditions, wet conditions and cryogenically treated tool without coolant. Cryogenic treatment is a type of heat treatment in which a metal is subjected to a temperature below atmospheric temperature [13]. This treatment is used to change the surface and metallurgical variations in a metal. Carbide drill is treated cryogenically at -196º C and tempered at 150º C. Figure 3 shows the cryogenic and tempering cycle on carbide treated tool. Circularity error of drilled hole is measured using coordinate measuring machine (CMM-CNC-3D-Model prism 5, Germany. Figure 4 shows the CMM used for in this work. Table 2 shows the results of circularity error of drilled holes under dry, wet and cryogenic conditions. The experimental results obtained from the drilled samples are summarized in Table 2. Figure 5 shows the machined sample.

4. Methodology

The following steps are involved in the Taguchi method [5].
1. Deciding the Quality characteristics
   In this work, circularity error is considered as quality characteristic.
2. Factors and levels selection
   Spindle speed and feed rate are the main process parameters considered. Table 1 presents the values of process parameters.
3. Orthogonal array selection
   Three levels of process parameters are selected, hence minimum experimental are required L9.
4. Carry out the experiments
   Experiments are carried out as per L9 orthogonal matrix.
5. Signal-to-Noise (S/N) ratio estimation
   Major types of S/N ratio are smaller-the-better and larger-the-better. Equations (1) and (2) are used to analyze the results for maximization and minimization output parameters respectively.
   Larger-the-better
   \[
   S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}}\right)
   \] (1)
   Smaller-the-better
   \[
   S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_{ij}^{2}\right)
   \] (2)
6. Analyzing the results
   Mean table and main effects plot are used to analyze the results of experiments and to finds the optimum process parameters.
7. Confirmation experiments
   To confirm the optimal process parameters obtained during the investigation the confirmation tests are carried out.

5. Results and Discussion

Three different machining conditions namely dry condition, wet condition and cryogenically treated drills with dry conditions are proposed. Process parameters such as cutting speed, feed rate and depth of cut are used. These values are chosen from the literature and preliminary trials. The significant effect of cutting speed and feed rate on response (circularity error) is analyzed by Taguchi method. Table 2 shows the experimental results. Results are investigated using orthogonal array, S/N ratio and ANOVA. Taguchi method is used S/N ratio for prediction of optimum process parameter and ANOVA for significance of process parameters [14]. Table 3, 4 and 5 are shown the response table of mean S/N ratio for dry, wet and cryogenically treated drill. The main effects plot on circularity error is given in figure 6 and 7.
Table 3. Response table mean S/N Ratio for dry condition

| Cutting parameters | Mean S/N Ratio |
|--------------------|----------------|
|                    | Level 1        | Level 2        | Level 3        |
| Spindle speed      | -57.3927       | -61.6101       | -83.5601       |
| Feed rate          | -66.5052       | -66.0300       | -70.0278       |
| Depth of cut       | -62.0637       | -72.1926       | -68.3067       |

Table 4. Response table mean S/N Ratio for wet condition

| Cutting parameters | Mean S/N Ratio |
|--------------------|----------------|
|                    | Level 1        | Level 2        | Level 3        |
| Spindle speed      | -46.3529       | -46.9626       | -58.0326       |
| Feed rate          | -55.3209       | -47.6962       | -48.3311       |
| Depth of cut       | -48.7613       | -52.2064       | -50.3804       |

Table 5. Response table mean S/N Ratio for cryogenic condition

| Cutting parameters | Mean S/N Ratio |
|--------------------|----------------|
|                    | Level 1        | Level 2        | Level 3        |
| Spindle speed      | -57.3927       | -61.6101       | -83.5601       |
| Feed rate          | -66.5052       | -66.0300       | -70.0278       |
| Depth of cut       | -62.0637       | -72.1926       | -68.3067       |

Figure 6. Speed Vs Mean S/N ratio of circularity Error

Figure 7. Feed Vs Mean S/N ratio of circularity Error
From the result it is noticed, that as feed rate increases circularity error increases with cryogenically treated tool. This is because of increase in feed rate results in decreases of dynamic stability. Decrease of Circularity error with increase in spindle speed is observed as the rotation stability increases with spindle speed. The formation of eta carbides, grain refinement, and transformation of retained austenite into martensite which occurs due to cryogenic treatment will increase the tool hardness [15]. Along with increase of tool life cryogenic treatment also improves the tool resistance to chipping and flank wear resistance. In the alpha phase if the average grain size decreases the tool hardness increases. It can also be said that as the volume of β-phase Co decreases after cryogenic treatment and combine with WC particles to form η–phase carbides that will also increase the tool hardness [9]. Due to micro structural changes of the tool material, cryogenic treatment will have a beneficial or productive effect on the tool performance by avoiding premature wear and chipping. Hence low circularity error is observed in case of cryogenically treated drill bit than that of dry and wet condition. This also enhances the sustainability in manufacturing.

**Table 6. ANOVA table for circularity error at dry, wet and cryogenic condition**

| Source          | DOF | SS    | MS    | F Ratio | P Value | Percentage |
|-----------------|-----|-------|-------|---------|---------|------------|
| **Dry**         |     |       |       |         |         |            |
| Spindle speed   | 2   | 1184.323 | 592.161 | 20.356  | .0468   | 82.94      |
| feed            | 2   | 28.615  | 14.307 | 0.4918  | .6703   | 2.004      |
| depth of cut    | 2   | 156.673 | 78.336 | 2.692   | .270    | 10.973     |
| Error           | 2   | 58.180  | 29.090 |         |         | 4.074      |
| Total           | 8   | 1427.793 |       |         |         |            |
| **Wet**         |     |       |       |         |         |            |
| Spindle speed   | 2   | 259.328 | 129.664 | 78.138  | .012    | 66.85      |
| feed            | 2   | 107.396 | 53.698 | 32.359  | .029    | 27.68      |
| depth of cut    | 2   | 17.825  | 8.912  | 5.371   | .156    | 4.59       |
| Error           | 2   | 3.318   | 1.659  |         |         | 0.855      |
| Total           | 8   | 387.869 |       |         |         |            |
| **Cryogenic**   |     |       |       |         |         |            |
| Spindle speed   | 2   | 4642.167 | 2321.08 | 40.55783 | .024063. | 77.297     |
| feed            | 2   | 1040.143 | 520.071 | 9.087553 | .099133. | 17.319     |
| depth of cut    | 2   | 208.817 | 104.408 | 1.8244  | .354057. | 3.477      |
| Error           | 2   | 114.457 | 57.228 |         |         | 1.905      |
| Total           | 8   | 6005.585 |       |         |         |            |

The effect of individual parameters for entire process can be determined using ANOVA. It consist of degrees of freedom (DOF), sum of squares (SS), mean square (MS) and percentage contribution (P) of input process parameters. Process parameters effect on circularity error, its percentage contribution and error contributions are estimated by ANOVA [16]. The result of ANOVA of the circularity error is shown in Table 6. It is observed that in dry, wet and cryogenic machining conditions spindle speed has highest contribution of about 82.94%, 66.85% and 77.29 % respectively, for circularity error.
Table 7. Results of confirmation test for circularity Error

| Dry condition | Initial Cutting Parameters | Optimal Cutting Parameters | Prediction | Experiment |
|---------------|-----------------------------|-----------------------------|------------|------------|
| Level         | A2,B2,C2                    | A1 B2 C1                    | -50.44441  | 0.0033     |
| Circularity Error | 0.0046                      |                            |            |            |
| S/N ratio     | -54.62700953                |                            |            |            |
| Improvement of S/N ratio | 6.9507211                  |                            |            |            |

Table 8. Results of confirmation test for circularity Error

| Wet condition | Initial Cutting Parameters | Optimal Cutting Parameters | Prediction | Experiment |
|---------------|-----------------------------|-----------------------------|------------|------------|
| Level         | A2,B2 ,C2                  | A1 B2 C1                    | -41.91162  | 0.0058     |
| Circularity Error | 0.0079                     |                            |            |            |
| S/N ratio     | -44.20                      |                            |            |            |
| Improvement of S/N ratio | 5.8228249                 |                            |            |            |

Table 9. Results of confirmation test for circularity Error

| Cryogenic treated tool | Initial Cutting Parameters | Optimal Cutting Parameters | Prediction | Experiment |
|------------------------|-----------------------------|-----------------------------|------------|------------|
| Level                  | A2,B2 ,C2                  | A1 B2 C1                    | -49.5943   | 0.0008     |
| Circularity Error      | 0.0012                      |                            |            |            |
| S/N ratio              | -85.31182193               |                            |            |            |
| Improvement of S/N ratio | 10.596694                 |                            |            |            |

From the results of confirmation test (Table 7-9) circularity error is decreased by 1.5 times in case of cryogenic treated drill bit, decreased by 1.39 times in dry and 1.32 times in wet conditions. The conformation test is performed to find the optimum parameters during the experimentation. The A1B2C1 is an optimum combination of parameters. Therefore, above optimum parameters are considered for confirmation test. The optimum parameters are N=600 RPM, f=20 mm/min and t=10 mm which gives the least circularity error.

6. Conclusions

This study is applied in Taguchi method for selecting the optimum process parameters in drilling operation. The following conclusions are obtained from this analysis:

- The results show the minimum circularity error is achieved at a cutting speed of 1000 RPM, feed rate 30 mm/min with cryogenically treated tool.
- Cryogenically treated tool gives minimum circularity error and leads to sustainability in drilling process.
- Spindle speed is significantly influenced and followed by feed rate.
- Taguchi method is a unique statistical approach which is simple and reliable to predict optimized process parameters.

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