SIMULATION OF FORM TOLERANCES USING CMM DATA FOR DRILLED HOLES
- AN EXPERIMENTAL APPROACH

Abstract: Drilling is one of the important processes for the production of a high-precision workpiece with quality holes. Main areas of application of drilling process are in the defense, aircraft, and automobile industries. In this study, the effect of cutting parameters on the hole quality and tool wear during the drilling of Al7075 and Ti-6Al-4V specimens with HSS and carbid insert drills have been investigated. The dynamic cutting force excites the cutting tool shaft, inducing a vibration/deflection which causes inaccuracy such as hole tolerances and circularity error. The cutting forces can cause tool/workpiece deflection and vibrations, and these vibrations will lead to errors in hole diameter, circularity and cylindricity. Hence, form tolerances in drilled holes need to be monitored and quantified; if not quality drilled holes will be affected. A coordinate measuring machine (CMM) is employed to measure the hole diameters, circularity, and cylindricity. A comparison has been made regarding the quality of the hole between cutting tools based circularity error and cylindricity error. It is observed that there is a decrease of agreement between tool performance and hole quality at high cutting speed and feed rate at different test combinations. A correlation is established between measured and simulated error results. Effect of spindle speed, feed rate, and the vibration amplitude on circularity and cylindricity are critically studied in the present work. The obtained results are quite encouraging, showing a correlation between measured and simulated values.

Key words: Coordinate measuring machine (CMM) Circularity error, cylindricity error, tool wear, surface metrology, simulation, drilling.

1. INTRODUCTION

Drilling is one of the fundamental machining processes of making holes, and it is essentially for manufacturing industries like aerospace industry, manufacturing industry, and automobile industry. Especially drilling is necessary for industries in assembly related to mechanical fasteners where hole diameter and circularity error plays a very crucial role. At various machining conditions, quality of the drilling process is studied [1]. Particularly in automotive industry demand for quality requirements is increased high-frequency [2]. Cylindrical, circular, or spherical features are fundamental geometric features in engineering. As precision requirement becomes more stringent, it is not sufficient to consider only size tolerance of circular and cylindrical parts along with their tolerances as well [3]. The cylindrical conditions typically exhibit errors from the ideal design specifications in both the axial and radial directions [4]. The cylindricity error is essentially caused by the roundness error in cross section, the form error such as taper, barrel, banana, and concave in the axial section as well as the diametric variation in the cylindrical section [5].

In modern industry coordinate measuring machine become a basic instrument for modern metrology. It is a universal, fast and accurate device, applicable for various measurement tasks [6] low-frequency and free-form surface as well [7]. Chandrashekhar et al. [8] predicted the roundness error of the drilled workpiece based on helical grooves, but there were discrepancies between theoretical and experimental results. Turgay Kivak et al. [9] an experimental investigation is presented in which error from circularity of the holes is
the result of the deflection, vibration, lack of lubrication and increased tool wear. Azarhoushang and Akbari [10] studied the effect of ultrasonic assisted drilling on the circularity, cylindricity, surface roughness, and hole oversize in Inconel 738-LC work pieces. Two different types of vibration can be distinguished in drilling, low-frequency vibrations associated with lobed holes and high-frequency vibration (chatter). One of the most common roundness problems in drilled holes is the existence of the spaced lobes [11]. It is also found that lobed hole profiles exist even in the absence of chatter and at very low cutting speed. The low-frequency vibration is significant for drilling because it directly affects hole quality. Circularity the s [12]. Now a day coordinate measuring machines (CMMs) are used extensively for carrying out on-line and off-line inspection with least measurement uncertainty. To yield critical geometric errors of the measured part, data obtained by a coordinate measuring machine must be analyzed or interpreted using suitable algorithms, which should confirm to the specifications laid down in the ISO/1101 standard [13]. In this study, a new roundness and cylindricity modeling of drilling using commercial surface metrology software TrueRond and its characteristics are investigated. By comparing with the experimental lobe results with simulated lobe profiles, the reliability of the proposed method proved. Complete features of drilling for the Al7075 and Ti-6Al-4V alloys with the different cutting tool and the accuracy of form tolerances for holes investigated. Modern mass production in the automotive industry is very sensitive towards fabrication tolerances [14]. In present day industries due to the high cost associated with materials like Ti-6Al-4V and Al7075A limited. Hence, it is required to develop an automatic evaluation method for form tolerance evaluation based on CMM data. The limited amount of literature is available on tolerance simulation methods to investigate the hole quality and stability of the machining processes.

As part of present work, simulations conducted must produce results that are closer to reality. For this purpose measurement data (CMM data) and simulation data (TrueRond) have to be compared to varying both work materials and cutting tools as well. This is important to get more know-how of simulations behavior to use the tools more precise. The present paper is organized as follows: circularity and cylindricity errors are measured using CMM based on the minimum zone solution method are formulated. Then tolerance simulations are generated using surface metrology software TrueRond for circularity and cylindricity error evaluation is proposed.

2. PROBLEM DEFINITION
EXPERIMENTATION DESIGN AND
PROPOSED METHODOLOGY

The ultimate objective of the present research is to evaluate the measured form tolerance errors with simulated profiles in the drilling operation. The simulated values are obtained by using form measuring software named TrueRond. It enables designers to analyze in measuring form errors that are caused due to vibrations and cutting forces in machining operation through PC rather than the shop floor using trial and error. Recently tolerance simulation has gained importance at the leading companies. Today's competitive pressures require companies to take advantage of every tool at their disposal.

Figure 1 gives the various stages in the present proposed research work. The drilling operation is carried out according to tool maker's recommendation for a specific workpiece and cutting tool combination. Global performance 070705 DEA CMM is employed to measure the circularity and cylindricity of drilled holes. Measured CMM data used as a basis for tolerance simulation using TrueRond software for evaluation of results. The procedures for the step by step simulation of form errors are showcased in the further chapters more clearly. The present work is aimed to predict the form errors in various work materials when drilled with HSS and WC with different materials drilled in combination.

3. EXPERIMENT DETAILS

Drilling tests were carried out with drills of 10 mm diameter using a radial drilling machine under dry cutting conditions, blind holes of 8 mm depth drilled by employing different test conditions. Regarding the hole diameters and the circularity measurements, a comparison is made relating to the quality of the hole between cutting tools. It is identified that there is a reduction in tool performance and hole quality at high cutting speed and feed rate combinations. A significant increase in tool wear is observed when increasing
cutting speed. The utmost wear type was seen in the form of flank wear and chisel edge wear. The purpose of experiments is to evaluate the measured and experimental roundness and cylindricity errors obtained under different drilling conditions as listed in Table 1.

<table>
<thead>
<tr>
<th>Rotational speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Depth of cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>455</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>705</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>1250</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>2200</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Workpiece materials</td>
<td>Ti-6Al-4V150mmx150mmx10mm</td>
<td></td>
</tr>
<tr>
<td>Drilling bit</td>
<td>Carbide Tip 6X10X10</td>
<td>HSS 6X10X10</td>
</tr>
</tbody>
</table>

Table 1. Test conditions selected for experimental investigation

Most commonly used materials in aircraft and automobile industry such as titanium alloys (Ti-6Al-4V) and aluminum alloys (Al7075) of dimensions (150mmX150mm X10mm) are selected as specimens for experimental investigation. Both HSS and tungsten carbide drill bit of Ø10mm diameter are used as cutting tool materials. The details of test conditions and experimental set-up are given in Table 1. The tests are carried out on 38 mm cap radial drilling machine, manufactured by Siddharupa machine tools, Gujarat, India. Major specifications include: Drill Capacity: 38 mm drill head, Spindle nose: MT 4, Spindle Travel: 220, the number of spindle speed: 8, Range of spindle speed: 62-1980 rpm, Range of Power feed (mm/Rev): 2, working table: 380mmx300mmx300mm. The cutting parameters are selected according to the tool supplier's recommendation for tool and workpiece combinations. Experimental tests are carried out at dry machining conditions. Cutting velocity and feed rates are selected based on the tool manufacturer's (Sandvik) recommendations for workpiece material and tool combination. The experimental setup for the drilling operations is shown in figure 2.

Throughout the experiment, depth of cut is kept constant. Both cutting speed and feed rate are varied according to the design of experiments for different work piece-tool combination. A non-contact vibration transducer Laser Doppler Vibrometer PolyTec 100V with a data acquisition scheme is kept at a constant distance from the machining zone to measure the shift during the drilling process. To measure the developed cutting forces a Kistler® 9272 4-component dynamometer with a multi-channel analyzer is placed below the workpiece. Vibrations and cutting forces influence the hole quality and form tolerances, but discussion about these factors is intentionally not included in the present work. The form errors are measured along the length of drilled hole using a CMM, which utilizes the minimum zone circle method MZC to express a hole profile.

3.1 Measurement of the roundness for the hole profile based on MZC method using CMM

Various researchers have attempted to develop methods for establishing the reference feature and to evaluate the circularity error. Several measurement techniques are available to estimate the reference feature (circle). These include the Minimum Circumscribed Circle (MCC), the Maximum Inscribed Circle (MIC), the Minimum Zone Circles (MZC) and the Least Squares Circle (LSC). In the present work, roundness error is evaluated from the measured points using Minimum Zone Circles (MZC) method that one among the four internationally defined methods. The MZC method is to determine a pair of concentric circles, the region between which contains all the measurement points with the minimum radius separation. The radius difference is defined as the roundness error, illustrated in Figure 3a. The hole roundness error is an index for hole quality, which can be examined only by experiments. The probe of the DEA CMM can be positioned independently in two or three axes simultaneously, and it is presented in figure 3b. This probe is either positioned manually, or automated positioning is intended by virtual display after the ruby ball probe is manually set to zero. The probe in finding the errors is brought in contact with four different points of a single hole as shown in figure 3b. The probe is moved and brought into contact with four different points of a single hole in every test specimen. The measurement of roundness is done according to ISO 12181:2003.
Then the roundness error $R_{MZC}$ is represented by

$$R_{MZC} = R_{\text{max}} - R_{\text{min}}$$

where $R_{\text{max}}$ and $R_{\text{min}}$ is the maximum and minimum distance between the MZC circle and the measured profile. Different combinations of workpiece materials and drill bit are used in the experiment. Specimens with drilled holes are inspected under DEACMM for hole diameter, circularity and cylindricity and it is presented in figure 4.

Figure 4 gives the different combinations of workpiece materials and drill bit and they used in the experiment.

3.2 Form tolerance error evaluation using PC-DMIS software

The fitting requirements of the cylindrical component are very important in the precision assemblies. The size tolerances and the form errors such as circularity error and cylindricity error all affect the fitting conditions. The PC-DMIS software interlinked generated the readings in RTF and an online screen snap of real-time error generation. The tools in software are defined through symbols for an easy and efficient understanding of the application of software as shown in figure 5. Roundness error profile is presented in figure 5a, and figure 5b gives the cylindricity error profile. PC-DMIS software calculates the form errors using software tools in measuring cylindricity, roundness, concentricity, etc. The drilled holes are assigned an ID for each hole, i.e., CIR 1, CIR 2, CIR 3, CIR 4 as shown in figure 5.

4. RESULTS AND DISCUSSIONS

TrueRond is highly interactive surface metrology software that provides a common user interface to operate and generate all of the gauging measurements. It generates profiles either of LIC, MZC, MIC and MCC of harmonic roundness in different machining processes. TrueRond can easily interface with metrology equipment (DEA CMM) and PC-DMIS software. It is possible to make the calculation of roundness and cylindricity along with all other form tolerances.

4.1 Evaluation roundness error and cylindricity error profiles with using TrueRond:

Figure 6 presents the profile with roundness errors in cross sections that have three, four, and five lobes, respectively in one of the test conditions in the present
study. These profiles with lobes are generated based on measured data using CMM of the drilled holes in Ti-6Al-4V and Al7075 specimens. Figure 6 gives the typical profile of the drilled hole with a cylindricity error in microns. The roundness data collected at 4 or 5 levels in the depth of each drilled hole by using CMM. Based on this data, cylindricity error is simulated, and they presented in figure 7. Cylindricity profile shown in figure 7 is corresponding to the test case of the AL7075 specimen is drilled with HSS drill bit. It is observed that as the depth of the hole is increase the peak of the profile is observed to be deviated from the tolerance zone by maximizing the error.

In this section, simulation profiles with TrueRond are presented in figure 8a to figure 8d. Among this, figure 8a gives the roundness profiles when holes drilled on the Al7075 specimen by HSS drill bit and figure 8b shows the simulated profiles of roundness when Ti-6Al-4V specimen drilled with HSS drill bit. In Figure 8a, profiles have only roundness errors in cross sections that have three, four, and five lobes, respectively. It is found that in general, the harmonics from the second up to the fiftieth are sufficient to represent a circular profile satisfactorily by removing only the effect of measurement [15].

Figure 8c and figure 8d shows a hole roundness error recorded by simulated by TrueRond when carbide drill is used in drilling holes on Al7075 and Ti-6Al-4V specimens. The comparisons of values are made between simulated, and measured values by CMM are presented in Table 2. Figure 8c and figure 8d shows the influence of drill bit rotational speeds on the hole roundness error. It reveals that the higher the rotational speeds, the bigger the roundness error. The reason for this is the shaft vibration and whips at higher speeds.

Error from circularity of the holes is the result of deflection, vibration, lack of lubrication and wear. Error from circularity means fluctuations on the surface. Similar to roundness error, cylindricity error needs to be evaluated for drilled holes as part of the present results evaluation. Cylindricity error is measured as the minimum radial separation between two coaxial cylinders enclosing all the cylindrical profiles. Figure 9a and figure 9d shows that variation in the simulated profiles of the cylindricity error for Ti-6Al-4V workpiece when drilled with HSS drill bit and tungsten carbide drill bit. Influence of feed rates on the hole cylindricity error at a constant depth of the hole is clearly evident in all cases presented in figure 9. It is observed that the higher the feed rate, the greater the roundness and cylindricity error. This is because at higher feed rate the chip load becomes larger and the tool bears greater cutting force. The trend conforms to the results reported by Chandrasekhar et al. [15]. Figure 9a presents the cylindricity error of Ti-6Al-4V/HSS drill bit combination and cylindricity found to be varied between 10 μm to 55μm. Moreover, the roundness errors at entry are higher but decrease with penetration depth. These may be due to the unstable beginning of drilling process.

Figure 9b showed the simulated cylindricity profile when drilling operation carried out on Ti-6Al-4V workpiece with tungsten carbide drill bit as a cutting tool. Figure 9b shows the typical form errors in the axial direction in the cylinder, such as taper, banana, barrel, and hourglass.
Simulation results of the Al7075 specimen are presented in figure 9c and figure 9d. Simulated cylindricity profile for Al7075, when drilled with HSS drill bit, is presented in figure 9c, and figure 9d gives the simulated profiles of the Al7075 specimen when is drilled with tungsten carbide drill.

Figure 9c. Simulated cylindricity profile Al7075/HSS drill bit

Figure 9d. Simulated cylindricity profile Al7075/Tungsten Carbide drill bit

The cylindricity error variation in carbide and HSS tools is examined clearly, and the wear difference is more with HSS tool. These results presented in Table 2 also indicate the same. Drill wear is measured with Opto mech vision inspection device, and this is presented in figure 10.

The relation between roundness error and different cutting speeds in all test conditions are presented in figure 11 and figure 12 gives the progression of tool wear in relation with roundness error in the experiment.

Figure 10 Drill wear under Opto mech vision inspection system

Figure 11 shows the influence of rotational speeds on the hole roundness error. It reveals that the higher the rotational speeds, the bigger the roundness error. Highest cylindricity error values are obtained in the drilling of Ti-6Al-4V with HSS drill bit and shown in Table 2 this is due to increased tool wear.

Figure 11. Roundness errors versus rotational speed

Figure 12. Roundness error versus tool flank wear

Figure 13 presents the comparison graph from which the closeness of measured roundness errors (CMM data) with simulated values is presented. The difference between the measured and predicted response are illustrated in figures 13.

In other words, carbide drill bits showed a better performance than HSS drill bits concerning roundness error and cylindricity error. From the results table 2, it is found that an increase in cutting speed led to an increase in form tolerance due to increased tool wear on the cutting edge.

Hence, both the roundness error and cylindricity error values increased. Besides, it also observed that both roundness error and cylindricity error are influenced by feed rate.
The accuracy of the evaluation of circularity and cylindricity played a significant role in determining the Form tolerances error evaluation with simulation production line, so as to assess the machining process.

Experiments show that measured holes from the measured points within a region on the workpiece under test. The evaluation result is verified by comparing with the result given by TrueRond. Findings of the present work, obtained very accurate and stable results for the cylindricity error. Findings of the present work, providing a solution for assessing the quality of drilled holes from the measured points by coordinate measuring machine, for precision cylindrical components like roundness, cylindricity, gear teeth or free-form surface, 8th International conference on advanced manufacturing operations, 225–231.


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Table 2. Experimental and simulated results

<table>
<thead>
<tr>
<th>Workpiece Cnt (number)</th>
<th>A71075 BRSS drill bit</th>
<th>Ti-6Al-4V BRSS drill bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole ID</td>
<td>Roundness Error, CMM (μm)</td>
<td>TrueRand Error, Flank Error, VBR (μm)</td>
</tr>
<tr>
<td>CIB 1</td>
<td>11.61</td>
<td>17.70</td>
</tr>
<tr>
<td>CIB 2</td>
<td>32.22</td>
<td>23.00</td>
</tr>
<tr>
<td>CIB 3</td>
<td>15.64</td>
<td>20.54</td>
</tr>
<tr>
<td>CIB 4</td>
<td>37.91</td>
<td>41.13</td>
</tr>
<tr>
<td>Cylindricity Error, CMM (μm)</td>
<td>CIB 1</td>
<td>21.32</td>
</tr>
<tr>
<td>Cylindricity Error, CMM (μm)</td>
<td>CIB 3</td>
<td>12.18</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Present work involves the monitoring the drilled hole status of A71075 and Ti-6Al-4V materials based on circularity and cylindricity, with tool rejection criterion parameter flank wear. Both experimental and simulated approaches used to monitor the drilled hole status based on output parameters. This paper described a method for evaluating roundness and cylindricity errors from the measured points by coordinate measuring machine, providing a solution for assessing the quality of drilled holes from the measured points within a region on the workpiece under test. The evaluation result is verified by comparing with the result given by TrueRond simulations. Experiments show that measured roundness and cylindricity error values agree well with the simulated values. This method can be applied to estimate the selected form tolerance errors in the production line, so as to assess the machining process. Form tolerances error evaluation with simulation method played a significant role in determining the accuracy of the evaluation of circularity and cylindricity error. Findings of the present work, demonstrate that the proposed method can be used to obtain very accurate and stable results for the evaluation of roundness and cylindricity.

6. REFERENCES