Forces and hole quality in drilling

M. Pirtini, I. Lazoglu *

Manufacturing Automation and Research Center, Department of Mechanical Engineering, Koc University, Sariyer, 34450 Istanbul, Turkey

Received 30 September 2004; accepted 6 January 2005
Available online 2 March 2005

Abstract

Drilling is one of the most commonly used machining processes in various industries such as automotive, aircraft and aerospace, die/molds, home appliance, medical and electronic equipment industries. Due to the increasing competitiveness in the market, cycle times of the drilling processes must be decreased. Moreover, tight geometric tolerance requirements in designs demand that drilled hole precision must be increased in production.

In this research, a new mathematical model based on the mechanics and dynamics of the drilling process is developed for the prediction of cutting forces and hole quality. A new method is also proposed in order to obtain cutting coefficients directly from a set of relatively simple calibration tests. The model is able to simulate the cutting forces for various cutting conditions in the process planning stage. In the structural dynamics module, measured frequency response functions of the spindle and tool system are integrated into the model in order to obtain drilled hole profiles. Therefore, in addition to predicting the forces, the new model allows the determination and visualization of drilled hole profiles in 3D and to select parameters properly under the manufacturing and tolerance constraints. An extensive number of experiments is performed to validate the theoretical model outputs with the measured forces and CMM hole profiles. It is observed that model predictions agree with the force and CMM measurements. Some of the typical calibration and validation results are presented in this paper.

Keywords: Drill deflection; Displacement; Vibrations; Transfer function

1. Introduction

Drilling is one of the most commonly used machining processes. A typical drill has several design parameters such as tip angle, chisel edge angle, chisel edge length, cutting lip length and helix angle. Each one of these parameters affecting the cutting forces and drilled hole qualities in various ways.

It is known that a drill consists of two main cutting edges, namely; the chisel edge and the cutting lips. The chisel edge extrudes into the workpiece material and contributes substantially to the thrust force. The cutting lips cut out the material and produce the majority of the drilling torque and thrust. During a drilling operation, the chips are formed along the cutting lip and moved up following the drill helix angle. The drill geometry has a complicated effect on the cutting forces. In addition to that, the cutting forces depend on the tool and workpiece material properties and machining conditions. The cutting forces are the main reason of the problems related to drilling in manufacturing such as form and surface errors, vibration, tool wear etc.

Previous researchers have developed mathematical models of drilling to estimate thrust and torque. Williams [1] showed that during cutting there are three identifiable zones of interest at the drill point, the main cutting edges, the secondary cutting edges at the chisel edge and an indentation zone about the drill center. Zhang et al. model was based on mechanics of vibration and the continuous distribution of thrust and torque along the lip and the chisel edge of the twist drill [2]. Wang et al. presented a method which involves the development of a dynamic uncut chip thickness for each cutting element at the lips and chisel...
edge. The mean thrust and torque increased as feed increases under constant vibration parameters [3–4]. They concluded that vibration drilling is different from conventional drilling and it is a dynamic cutting process.

Another model was presented for drilling processes by Yang et al. [5]. The model has four parts: the force model for the cutting lip, the force model for the chisel edge, the dynamic model for the machine tool and the regenerative correlation between the force and machine tool vibration. Elhachimi et al. assumed that the chisel edge model results are very small compared with where the cutting process takes places and they found that the thrust force is not sensitive to the variation of the spindle rotational speed. However, the effect of the spindle speed cannot be neglected on the torque. The power and the torque are proportional to the rotational speed. Moreover, thrust force, torque and power increase with the feed [6–7].

More recently, several researches have applied oblique machining theories to drilling by dividing the cutting edges of drill into small segments, performing calculations for each segment, and summing the results [8–9]. Unlike the other models, Stephenson and Agapiou’s model is applicable to arbitrary point geometries and includes radial forces due to point asymmetry [8]. Chandrasekharan et al. [10–11] developed a theoretical method to predict the torque and thrust along the lip and chisel edge. A mechanistic force model can be used to develop models for cutting force system and a calibration algorithm to extract the cutting model coefficients.

A statistical analysis of hole quality was performed by Furness et al. [12]. They found that feed and speed have a relatively small effect on the measured hole quality features. With the expectation of hole location error, the hole quality is not predictably or significantly affected by the cutting conditions. Although the authors did not expect these results, they have the important positive implication that production rates may be increased without sacrificing hole quality.

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. Bayly et al. 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 [13]. Batzer et al. suggested to develop a mathematical model describing vibratory drilling process dynamics and to study the influence of system parameters on the vibratory drilling process [14].

Rincon and Ulsoy [15] showed that the changes in the relative motion of the drill do affect the variations of the forces. An increase in the ranges of drill motion results in an increase in the ranges of torque and thrust. They suggested that drill vibrations can have an effect on drilling performance because increasing vibration during entry can cause poor hole location accuracy and burr formulation.

In this paper, mechanistic modeling approach is presented. Therefore, the specific cutting force coefficients are determined from calibration experiments. The mechanistic force models for each machining process have a calibration algorithm that is unique to the process. In this research, a new and general calibration procedure is developed for drilling. Due to simplicity of the new calibration procedure, a lot of costly experiments can be eliminated when a new tool or workpiece material is used.

In this study, the force model is based on a new calibration method that made it possible to obtain the cutting force coefficients directly from the tests performed with the drill tool prior to the actual cutting. The differential cutting forces are determined using a mechanistic approach for the discrete cutting edge sections. The approach used in the force modeling takes into account the specific cutting force constants that are determined through calibration. The differential forces are transformed into the fixed measurement coordinate system and summed into the total cutting force components. After the total forces are predicted, measured frequency response functions of the tool and the spindle system are utilized for hole profile predictions. The frequency response functions (FRF) of the system are found by experimental modal analysis. Transfer functions determined from the FRF are used to predict the displacement along the drilling and 3D hole profile. Moreover, the model gives the outputs to quantify some properties of holes such as cylindricity, roundness and perpendicularity values.

![Fig. 1. (a) Illustration of the angular relationships. (b) Illustration of the point ('taper') angles.](image-url)
2. Drill geometry

The detailed geometry of a twist drill is shown in Fig. 1. A drill has a chisel edge at the bottom and two helical cutting lips with a tip angle of \( \kappa \). The chisel edge has a width of \( w \) and an angle of \( \psi_c \). Ideally, the cutting lips should be identical to each other so that radial force components should cancel each other and the drill should not observe any net radial force. However, in practice, due to inaccuracies in tool manufacturing, the drill lips are not identical. Therefore, the tip angle and chisel edge angle should be evaluated for each helical flute.

The longitudinal axis of drill is aligned with \( Z_c \) axis (Fig. 1), \( Y_c \) is along the cutting lip directions on the view perpendicular to \( Z_c \), \( X_c \) is considered as the third orthogonal axis in this Cartesian coordinate frame whose origin is located at the drill tip. \( X - Y - Z \) is the fixed measurement frame.

The radial distance (\( r \)) of a point on the cutting edge in the \( X - Y \) plane (Fig. 2) is

\[
r = \sqrt{X_c^2 + Y_c^2} \tag{1}
\]

and considering the bottom of the flute where the lips and chisel edge meet, the cutter radius is

\[
r(0) = \frac{w}{\sin(\pi - \psi_c)} \tag{2}
\]

where \( w \) is the width of chisel edge and \( \psi_c \) is the chisel edge angle.

The cutting edge geometries of a cutter in the model can be presented by using polynomial fitting of CMM data set. The cutting edge coordinates can be measured either using a coordinate measurement machine (CMM) or using a sufficiently magnified picture of the cutting edge. In order to determine the cutting edge geometry, a magnified view of the cutter (two fluted twist carbide drill with 7.698 mm diameter) has been obtained using an optical microscope as seen in Fig. 2. Assuming that the cutting edges of the drill are not identical, cutting edge geometries are obtained for two cutting edges. On the optical microscope image, both cutting edges of the cutter have been divided into grids and 12 distinct points have been taken on the cutting edges to resemble the cutting edges (Fig. 2). The following equations have been obtained between the lead angle (\( \beta \)) and local radius (\( r \)) for the two cutting edges (Fig. 3);

\[
\beta_1 = -0.059382r_1^3 + 0.60252r_1^2 - 2.1645r_1 + 3.0607
\]

\[
\beta_2 = -0.029695r_2^3 + 0.34285r_2^2 - 1.4145r_2 + 2.4455
\]

where \( r_1 \) and \( r_2 \) (mm) are the radius of points on the cutting edges on a plane perpendicular to the cutter longitudinal axis. \( \beta_1 \) and \( \beta_2 \) (rad) are the lead angles between the lines which connect these points to the tip and the lines which are parallel to the cutting edges (Fig. 2). Therefore, by varying \( r_1 \) and \( r_2 \) values from the tip to cutter radius (i.e. \( 0 - R \)), the full cutting edges profile can be determined from the above equations.

After obtaining the cutting edge geometry, by using the same microscope image \( w \) and \( r(0) \) can be measured for

---


Fig. 2. Ø7.698 mm carbide twist drill cutter.

Fig. 3. (a) Measured data points for \( x-y \) planes. (b) Third degree polynomial fit obtained for \( \beta_1(r_1) \) and \( \beta_2(r_2) \).
each cutting edge. Through the use of Eq. (2) the chisel edge angle can be calculated for the two cutting edges. The total chisel edge width can be calculated as follows,

\[ w = w_1 + w_2 \]  

Afterwards in order to evaluate the total tip angle, taper angle of each cutting edge are measured by using CMM. The sum of these taper angles is the total tip angle of the drill,

\[ \kappa = \kappa_1 + \kappa_2 \]  

In Tables 1 and 2, the tip angles and chisel edge angles are given. The tip angles for each cutting edge measured by CMM, the chisel edge angles and chisel edge widths for each cutting edge calculated from the microscope image of drill.

### 3. Chip load model

In order to determine the differential cutting forces at any cutter point in the engagement domain, the chip load for flat surfaces is found as follows,

\[ dA = \Delta bh \]  

where \( \Delta b \) is the differential chip width and \( h \) is the chip thickness per flute in one revolution (Fig. 4). \( \Delta b \) can be written as the following,

\[ \Delta b = \frac{dz}{\cos(\kappa)} \]  

\[ h = \frac{c}{N} \sin(\kappa) \]  

where \( dz \) represents differential chip height along the longitudinal cutter, \( c \) is the feedrate per revolution of the drill and \( N \) is the number of cutting edges.

### 4. Cutting force model

For a differential chip load (\( dA \)) in the engagement domain, the differential radial (\( dF_r \)), zenith (\( dF_\phi \)) and tangential (\( dF_t \)) cutting force components can be written as follows (Fig. 5),

\[ dF_t = K_{tc} dA + K_{te} \Delta b, \quad dF_\phi = K_{rc} dA + K_{re} \Delta b, \quad dF_r = K_{jc} dA + K_{je} \Delta b \]  

where \( K_{tc}, K_{rc}, K_{jc} \) are the tangential, radial and zenith cutting coefficients, respectively \( K_{te}, K_{re}, K_{je} \) are the related edge coefficients.

In order to determine these coefficients, calibration tests were performed with a single cutting edge drill on Al7039 workpiece material, which was also used in the model validation tests. A twist drill with a diameter of 7.698 mm and with a single cutting edge has been divided into five separate disks and cutting constants were individually evaluated for each region by performing incremental drilling with different feeds in the calibration tests.

Once \( dF_r, dF_\phi, dF_t \) were obtained through use of Eq. (8), these cutting force components can be transformed into \( X-Y-Z \) global coordinate system as the following;
\[
\begin{aligned}
&\begin{bmatrix}
dF_X \\
dF_Y \\
dF_Z \\
\end{bmatrix} = A 
\begin{bmatrix}
dF_r \\
dF_\psi \\
dF_t \\
\end{bmatrix} \\
A = 
\begin{bmatrix}
\sin \Omega \cos \kappa & \cos \Omega \cos \kappa & \cos \Omega \\
\sin \Omega \sin \kappa & \cos \Omega \sin \kappa & \sin \Omega \\
\sin \kappa & \cos \kappa & 0 \\
\end{bmatrix}
\end{aligned}
\]  

\[\Omega = \theta + \frac{(n - 1)2\pi}{N_f} - \beta; \quad n = 1...N_f\]

\[
\begin{bmatrix}
F_X \\
F_Y \\
F_Z \\
\end{bmatrix} = \sum_{n=1}^{N} \sum_{k=1}^{K} 
\begin{bmatrix}
dF_X \\
dF_Y \\
dF_Z + dF_P \\
\end{bmatrix}_{k,n}
\]  

where \(\Omega\) is the drill rotation angle, \(\theta\) is the instantaneous angular position of the discrete point on the cutting edge in concern (Fig. 1) and \(N\) is the number of flutes, \(k\) is the discrete point on \(n\)th cutting edge (Fig. 5).

One important aspect of the model to mention here is the additional \(dF_P\) force that is added to \(dF_Z\). This force is assumed to result from a constant pressure value existing over the workpiece as the cutter moved down into the workpiece. Its amplitude equals this constant pressure times the area of the cutter/workpiece contact region. Additional tests have been performed in the calibration phase to detect the constant pressure \(P(f)\) (MPa) as a function of feedrate \(f\) (mm/min).

\[
P(f) = 1.5364f - 103.06
\]  

Calibration procedure was performed on the drill with a single flute. Briefly, in the tests with two flutes, the dynamometer measures the vector quantity of total forces at both lips. The tangential and radial forces on each lip act in opposite directions and would be in equal magnitude. Therefore, the net tangential and radial forces are zero if two flutes are identical. However, as it was the case in the experiments, the cutting edges in practice are not identical. The dynamometer measures forces due to the geometric differences in the cutting edges. In order to measure the cutting forces acting on a single flute in the \(X\) and \(Y\) direction, one cutting edge of the drill was removed by grinding and calibration experiments were performed by using a single fluted drill. Once the tip angle, chisel edge angle and the chisel edge width of each cutting edge are determined, the cutting forces can be simulated for each cutting edge. The main difference in the model is the drill rotation angle and it can be calculated using Eq. (10). At the end of the single flute simulations for each one of the flutes, the cutting forces are

Fig. 6. A summary chart of the proposed mechanistic approach.
The transfer function (Eq. 12) can be expressed by its partial fraction expansion as follows,

\[
G(s) = \sum_{k=1}^{n} \left( \frac{R_k}{s - s_{1,k}} + \frac{R_k^2}{s - s_{2,k}} \right)
\]

(14)

where \( R_k \) and \( R_k^2 \) are the residues for the \( k \)th mode.

After obtaining \( F_x \), \( F_y \), through use of the force model, the displacement in \( X \) and \( Y \) direction can be calculated from Eq. (12) using the dynamic model. The transfer function and the cutting forces in the \( s \)-domain are used to evaluate the displacements in \( X \) and \( Y \) directions. However, in the static model, the cutting forces in the time domain \( F(t) \) are obtained. For that reason, the transfer function in \( s \) domain is converted to the discrete \( z \)-domain in order to calculate the displacement.

Transfer function of the tool and spindle system in Laplace domain is given in Eq. (12) and it can be expressed by its partial fraction explanation in Eq. (14). Considering this transfer function, the impulse response can be found as follows,

\[
g(t) = \sum_{k=1}^{n} R_k(e^{s_{1,k}t} - e^{s_{2,k}t})
\]

(15)

where \( R_k \) is residue and can be determined from Eq. (14), \( s_{1,k} \) and \( s_{2,k} \) is the complex conjugate roots of the transfer function at the \( k \)th mode and can be calculated from Eq. (13).

Substituting discrete time intervals as \( t = mT \),

\[
g(kT) = \sum_{k=1}^{n} R_k(e^{s_{1,k}mT} - e^{s_{2,k}mT})
\]

(16)

Table 3

<table>
<thead>
<tr>
<th>Mode # in X direction</th>
<th>Natural frequency</th>
<th>Damping ratio</th>
<th>Stiffness</th>
<th>Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2116.28 Hz</td>
<td>1.32%</td>
<td>10670721.4 N/m</td>
<td>5.98 x 10^-3 mN</td>
</tr>
<tr>
<td>2</td>
<td>2121.32 Hz</td>
<td>1.30%</td>
<td>1119590.6 N/m</td>
<td>5.35 x 10^-3 mN</td>
</tr>
</tbody>
</table>

where \( U(s) \) and \( F(s) \) are representing the displacement and force, respectively (either in \( X \) or \( Y \) direction), \( m_k \) is modal mass, \( \zeta_k \) is the damping ratio, \( \omega_{h,k} \) is the natural frequency for the \( k \)th mode. \( s^2 + 2\zeta_k\omega_{h,k}s + \omega_{h,k}^2 \) is the characteristic equation of the system that has two complex conjugate roots for the \( k \)th mode,

\[
s_{1,k} = -\zeta_k\omega_{h,k} + j\omega_{d,k} \quad s_{2,k} = -\zeta_k\omega_{h,k} - j\omega_{d,k}
\]

(13)

The transfer function (Eq. 12) can be expressed by its partial fraction expansion as follows,

\[
F(s) = \sum_{k=1}^{n} \frac{1/m_k}{s - s_{1,k}} + \frac{1/m_{k^2}}{s - s_{2,k}}
\]

(14)
Using Eq. (12), the transfer function in discrete \(z\)-domain is found as,

\[
G(z) = \sum_{k=1}^{n} R_k \left( \frac{z}{z - e^{j\omega_k T}} - \frac{z}{z - e^{j\omega_{k+1} T}} \right)
\]

(17)

After obtaining transfer function for \(X\) and \(Y\) directions in discrete domain, cutting forces in \(X\) and \(Y\) direction are transformed to the discrete domain for every cutter rotation angle. Displacements in \(X\) and \(Y\) directions are calculated from

\[
X(z) = G_X(z)F_X(z) \quad Y(z) = G_Y(z)F_Y(z)
\]

(18)

where \(F_X\) and \(F_Y\) are the dynamometer forces that are the vector sum of the cutting forces for two cutting edges of the drill in \(X\) and \(Y\) directions. Hence, as the cutting forces are known, in dynamic module, the displacements can be found for every cutter rotation angle by using Eq. (18). In other words, for every depth and cutter rotation angle, hole profile can be theoretically predicted by using cutting force and structural dynamics module. Obtaining the displacements, and adding the diameter of the drill to those displacements, exact profile of the hole after drilling can be also illustrated.

Addition to the profile, using the CMM data, cylindricity, roundness and perpendicularity can be determined and compared with the dynamic module outputs.

6. Experimental results and validations

The experiments for calibration were performed on Mazak FJV-200 UHS Vertical Machining Center. The cutter was uncoated drill cutter with 7.698 mm diameter, 94.1° total tip angle. The drill (drill # 1) properties can be seen in Tables 1 and 2. The workpiece materials were rigid aluminum blocks (Al17039) of size 250 x 170 x 38 (mm). Kistler 3-component dynamometer (Model 9257B) and a charge amplifier have been used to measure cutting forces.

In order to obtain the cutting forces, a set of drilling experiments at different feed rates were performed. The 44–198 mm/min feed rate interval has been tested in this study. The cutting lip of the drill has been divided into five regions to accurately predict the distribution of the cutting forces. Assuming the tip to be at zero level, these intervals were subsequently at 0–0.3, 0.3–0.7, 0.7–1.2, 1.2–1.7, 1.7–2.2 mm distance from the tip. Each interval has been tested for five different feed rates; 110, 132, 154, 176 and 198 mm/min. The spindle speed was kept constant at 1100 rpm. Data has been collected for 1 s and with sampling frequency rate of 1000 Hz in all tests. Calibration is performed by using single cutting edge. For this purpose, one cutting edge of the drill is grinded along its length.

The values of the cutting coefficients determined from the calibration process for the aluminum material (Al17039) are summarized in Table 4.

Table 4

<table>
<thead>
<tr>
<th>Interval from tip</th>
<th>Coefficients</th>
<th>0–0.3</th>
<th>0.3–0.7</th>
<th>0.7–1.2</th>
<th>1.2–1.7</th>
<th>1.7–2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_{wc}) (N/mm²)</td>
<td>27,134</td>
<td>7235</td>
<td>4632</td>
<td>3744</td>
<td>2254</td>
<td></td>
</tr>
<tr>
<td>(K_{tc}) (N/mm²)</td>
<td>15,226</td>
<td>5462</td>
<td>3984</td>
<td>3063</td>
<td>2326</td>
<td></td>
</tr>
<tr>
<td>(K_{rc}) (N/mm²)</td>
<td>24,635</td>
<td>7428</td>
<td>4283</td>
<td>3316</td>
<td>2147</td>
<td></td>
</tr>
<tr>
<td>(K_{jc}) (N/mm)</td>
<td>230.78</td>
<td>51.23</td>
<td>44.28</td>
<td>25.75</td>
<td>16.24</td>
<td></td>
</tr>
<tr>
<td>(K_{tc}) (N/mm)</td>
<td>73.13</td>
<td>16.83</td>
<td>9.356</td>
<td>7.491</td>
<td>6.663</td>
<td></td>
</tr>
<tr>
<td>(K_{re}) (N/mm)</td>
<td>252.33</td>
<td>43.68</td>
<td>34.85</td>
<td>24.59</td>
<td>18.35</td>
<td></td>
</tr>
</tbody>
</table>

The change in cutting coefficients along the cutting edge is displayed in Fig. 8. It is observed in these plots that the cutting and edge coefficients are relatively higher near the tip. This is due to low cutting speed at the tip, and therefore besides the shearing, plowing mechanism is functioning effectively.

Initial validation tests indicated a difference between force model outputs and the measured forces in thrust. This led to the assumption that the spindle was applying a constant pressure on the workpiece surface through
the cutter which is proportional to the feed rate into the workpiece like an indentation mechanism.

The experimental setup in calibration tests has been used for these investigation runs. Feed values of 110, 132, 154, 176, 198 mm/min were used in determining the pressure. In order to determine the exerted constant pressure on the workpiece surface, the pressure formula:

$$P = \frac{F_z}{A}$$  \hspace{1cm} (19)

has been used where $F_z$ is the net force between the measured force and predicted thrust force due to cutting in the thrust direction and $A$ is the contacting area of the cutter at an instant. The area contacting with the workpiece changes as the cutter penetrates into the workpiece. Since the penetration time is discretized for analysis, the contact area for a time interval is found at any instant.

The constant pressure values were found for all tested feed rates and plotted in order to obtain pressure as a function of feed rate (Eq. 19). The calculated values for the constant pressure can be seen in Fig. 9 together with the fitted function for constant pressure.

The validation experiments were performed on Al7039 with a single fluted drill. Cutting has been realized with different feedrates. Validation tests were performed at

Table 5
Cutting conditions for drilling on Al7039

| Feedrates  | 110–132–154–176–198 mm/min |
| Depth of cut | 2.2 mm |
| Spindle speed | 1100 rpm |
| Drill number | 1 |
| Amplifier gain (channel) | 100 (X) – 100 (Y) – 300 (Z) |
| Sampling frequency | 1000 |
| Sampling time | 1 s |

Fig. 9. Variation of the pressure with feed rate.

Fig. 10. Predicted and measured force components vs. depth of cut for single edge; for feedrate of 132 mm/min (Cutting Condition: Table 5).
Fig. 11. Predicted and measured force components vs. depth of cut for single edge; for feedrate of 176 mm/min (Cutting Condition: Table 5).

Fig. 12. Predicted and measured net forces for double cutting edges vs. depth of cut; for feedrate of 176 mm/min (Cutting Condition: Table 5).
the spindle speed of 1100 rpm and for the feedrate interval of 110–198 mm/min. Cutting conditions are summarized in Table 5. The drill (drill # 1) properties can be seen in Tables 1 and 2. The prediction of cutting forces in all \( X - Y - Z \) and radial directions showed very good agreement with measured force values. Predicted and measured forces for the first cutting edge are plotted along the depth of cut in Figs. 10 and 11.

Validation tests for double fluted drill were also performed at the spindle speed of 1100 rpm and for the feedrate interval of 110–198 mm/min. Cutting conditions are summarized in Table 5. There is an important point that before grinding one cutting edge of the drill along its length, the cutting forces are obtained to measure the vector sum of the two cutting edges. After determining the cutting forces for single cutting edge performing calibration procedure and using mathematical model, the vector sum of the two cutting edges can be obtained by using the tip angle, chisel edge angle and chisel width for each cutting edges in the model. Force plots for the first cutting edge is shown as a validation in Fig. 12.

The measurements of the holes profile were performed on CMM Dia Status 7.5.5 with a probe diameter of 1 mm. The CMM measurements were performed at different levels with selection of longitudinal increment of 0.5 mm at 2° angular increments. As mentioned before, after determining the cutting forces for the drill with two cutting edges using the cutting force model, the displacement of the drilled hole under these forces can be found using the dynamic model. Obtaining the displacement in \( X \) and \( Y \) directions, the drilled hole profile can be determined by enlarging the displacement values by the drill radius. The drill (drill # 2) properties can be seen in Tables 1 and 2. For the cutting and simulation conditions given in Table 6, the validation plots for the displacement in \( X \) and \( Y \) directions are shown in Fig. 13.

In addition to the hole profiles, using the CMM data, cylindricity, roundness and perpendicularity can be determined. These properties of the drilled hole were measured with CMM and compared with the dynamic model outputs. The comparison results are given in Table 7 that contains the prediction, measured values and the cutting conditions. It is observed that theoretical predictions agree reasonably well with the CMM data.
7. Conclusions

In this research, a new mathematical model based on the mechanics of drilling was developed for the prediction of cutting forces. A new method was also proposed in order to obtain cutting coefficients directly from a set of relatively simple calibration tests. Moreover, once the drill parameters and cutting conditions are given, by considering the cutting forces and the structural dynamics of the tool and spindle system, the dynamic model can predict the radial displacements under low frequency vibration. Therefore, hole quality are also predictable in advance.

The outputs of the theoretical model were compared with dynamometer and CMM measurements. It was observed that they agree reasonably well. In today’s competitive market, process simulator based on the mechanics and dynamics of drilling as presented in this paper helps to decrease cycle times and allows achieving tight hole tolerances.

Acknowledgements

The authors appreciate the financial support provided for this research by Arcelik A.S.

References


Table 7
Predicted and measured hole properties for spindle speed of 1100 rpm and feedrate of 132 mm/min

<table>
<thead>
<tr>
<th>Depth of cut (mm)</th>
<th>Roundness (μm)</th>
<th>Perpendicularity (μm)</th>
<th>Cylindricity (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1.33</td>
<td>5.7</td>
<td>1.3</td>
</tr>
<tr>
<td>1.0</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>1.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1.21</td>
<td>8.8</td>
<td>1.3</td>
</tr>
<tr>
<td>1.0</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>1.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>