Effect of misalignment on the cutting force signature in drilling

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Abstract

This paper presents a study which investigates the effect of misalignment between the axes of rotation of drill and the workpiece on the steady-state and dynamic of the axial cutting force and torque. A novel methodology has been proposed to measure the misalignment between the axes of rotation of the drill and the workpiece. This uses a laser-based system to measure this misalignment, where a reference beam has been generated by a laser tube, which is held in the chuck of the machine using a special enclosure. The laser beam is captured by a photo sensor camera having a video capture card. To study the effect of the misalignment, the starting bush was intentionally misaligned by moving the pressure head over the carriage using the lead screw of the cross slide. © 2002 Published by Elsevier Science B.V.

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1. Introduction

The relative position and motion between the tool and workpiece may affect both the steady-state and dynamic cutting forces dramatically. Thus it becomes difficult to distinguish between the cutting signature due to the dynamic response of the cutting process and that due to the noise originating from any inaccuracy in the position of the workpiece relative to the cutting tool. Surprisingly, there has been little attention paid to this effect in previous studies. Some of the scatter in the cutting force measurements reported in the literature may be partially explained by the mentioned inaccuracy. This becomes particularly important if a new model of chip formation has to be verified by experiments.

In deep-hole drilling (BTA), the relative location of the tool and the workpiece is defined by the relative location of the axes of rotation of the tool, workpiece and starting bush as shown in Fig. 1.

Sakuma et al. [1–3] investigated run-out in deep holes drilled under different misalignment conditions. The authors kept changing between gun drills and BTA drills when running experiments with different setups. Thus the work has no clear reference to a particular type of tool or tool geometry. Further to this no information was provided on the rigidity of the boring they used in the experiments.

In tool rotating systems the misalignment of the pilot bush or a tool shank support makes the path of the tool deviate and causes the axes to deviate from a straight path [4]. Being a self-guided machining process, the straightness error on the hole axis is further affected by the rigidity of the tool–work–machine system. The straightness of the hole axes produced by BTA drilling is usually measured as the run-out measurements are influenced by the setting errors while drilling, namely offset and nonparallelism of axes of tool and workpiece. Therefore, a different approach is necessary to study the error on the straightness of the axis, eliminating the setting errors [5].

Katsuki et al. [6] studied the influence of the shape of the cutting edge on axial hole deviation in deep drilling.

So far, there has been no systematic study of the overall effect of misalignment on tool wear and tool performance, except for the study on its effect on run-out [3]. In general, authors attribute a variety of undesirable effects to misalignment but mostly as experience-based guesswork. Common problems include the cutting edge flaking or chipping, leading pad wear, poor surface finish, straightness and roundness. Also, literature sources cite that misalignment related problems may and may not be accompanied by excessive vibration [7].

The section to follow presents the experimental setup and the procedure used to measure the cutting forces in deep-hole machining. This encompasses the elements of the setup such as the machine, the workpiece material, the cutting tool and the dynamometer. This section covers also the measuring setup and its calibration. The next section presents the proposed methodology and the specially designed setup for misalignment assurance, which is followed by the calibration.
of the misalignment assurance setup. This followed by the presentation and discussion of the experimental results. The last section outlines the conclusions of this study.

2. Cutting forces measurement

2.1. Experimental setup

1. Machine. Fig. 1 shows the drilling machine installation used in the experiments. The installation consists of a drive unit, a pressure head, a boring bar and the drill head. The stationary workpiece-rotating tool working method was used in the experiments.

2. Dynamometer. A 2-component piezo-electric load washer (Model 9065) was used to measure the cutting forces. The transducer incorporates two disks, each with a ring of quartz crystals precisely oriented in the circumferential and axial directions. The load washer was integrated into a dynamometer to be held in the chuck. Based on the standard mounting as specified by the supplier (Kistler), the load washer was preloaded by two flanges to 120 kN. At this preload, the range for the axial force measurements was $-20$ to $+20$ kN and the range for torque was from $-200$ to $+200$ Nm.

Fig. 1 shows the schematic arrangement of cutting force measurement setup. The load washer was connected to a charge amplifier (Kistler model 5004) and in turn to a dual-channel FFT spectrum analyser (B&K Analyser Type 2032). The setup was calibrated statically and dynamically. The dynamic calibration of the dynamometer–workpiece–machine–tool system was carried out to avoid measuring the vibration of the tool instead of the force fluctuations and determine the frequency band, over which the dynamometer could be used for reliable measurements. Also, the frequency response was measured to determine the range of frequencies of the cutting forces, which could be measured accurately without distortion. The load washer with allied charge preamplifiers and the FFT analyser was calibrated by
striking the dynamometer with Kistler hammer (Model 912). To examine the validity of the measurement, the coherence function was calculated for the thrust force and the torque.

2.2. Cutting tool

BTAS system partitioned boring heads of 1 in. diameter (Sandvik design) were used. A detailed diagram in Fig. 2 shows the drill design and the geometry. The cutting edge is divided into three sections. The geometry parameters of the drills were controlled according the American National Standard B94.50-1975. Each cutting edge was examined at magnification of 20× for visual defects such as chip or cracks.

2.3. Workpiece material

Stainless steel (AISI 303) was used as workpiece material. The composition, the element limits and the deoxidisation practice were chosen according to the requirements of ANSI/ASME B94.55M-1985 and were requested from the steel dealer.

3. Misalignment measurement setup

The schematic arrangement of the experimental setup on the deep-hole machine is shown in Fig. 3. A photograph of the experimental setup is shown in Fig. 4. A laser-based measurement system was developed to measure the misalignment between the axes of rotation of spindle nose and that of the starting bush of the deep-hole machine. A reference laser beam was generated by a laser tube, which was held in the chuck of the machine using a special enclosure. The laser beam was captured by a photo sensor camera having a video capture card. The output images were sent to image processing software to track the laser beam position by processing these images. The output from the image processing software provided the position of the

Fig. 2. BTAS tools of partitioned cutting edges (Sandvik design).
centroid of the laser beam on the photo sensor in a certain position along the axis of rotation of the machine. The misalignments were calculated by comparing the average centroid of the captured images when the photo sensor camera and starting bush axes coincide and when the camera and nose spindle axis coincide. To align the machine, this centroid had to be brought to coincide with the zero reference point. The zero reference point was established on the axis of the cylindrical camera housing within a reasonable tolerance (0.5 μm). A special accessory was designed to hold the camera in different positions along the axis of rotation of the machine. To study the effect of misalignment, the starting bush was intentionally misaligned by moving the pressure head over the carriage using the lead screw of the cross slide. Fig. 5 shows a photograph of the principal elements of the misalignment measurement setup as follows:

1. Laser (LTT4H adjustable alignment tool, Emerging Technologies, Laseraim Tool Division, Little Rock, AR,
USA). This laser projected a straight beam visible as a “dot” of laser light on distant surfaces. This beam is used as a straight reference line over its entire length. The tool had an adjustable focus feature which can control the laser dot size on a surface located perpendicular to the beam (referred to as the screen). This adjustment allowed the use of the smallest possible dot size at a specific distance, thus facilitating more accurate measurements. Since the focus adjustment was also linear, a change in the focus would not affect the $X$ and $Y$ alignment. In practical terms, this means that the smallest possible dot size could be used close to the tool and then when the screen was more distance, the tool may be re-focused again to the smallest possible dot, keeping the centroid of these two dots on the same plane.

2. A photo sensor digital camera Pulinx TM7 was used as the screen. This camera contained a high resolution interline transfer 0.5 in. CCD (charge-coupled device). The camera was requested from the manufacturer to be of super mini size that allows accurate and convenient mounting within the setup.

3. Laser mounting fixture.

4. A special case was devised to mount the camera in different positions along the machine bed. This case was precisely manufactured to: (a) match the cone in the starting bushing liner, (b) match the diameter of the camera and (c) match the outer diameter of the spindle nose.

5. Video capture card. This card was a single-slot, accelerated, 24 bit-per-pixel, true-colour, designed to capture and display high quality video images. The card provided the complete set of camera control functions required for capturing high quality images. The card is also supported with a fully comprehensive software that allows full exploitation of the hardware architecture. Captured images could be saved as BMP or TIFF files.

6. Image processing software (Matrox Inspector, Version 2.0). The images captured by the camera were processed to find the centroid of the images. The centroid represented the centre of rotation of the boring bar. A typical example of the captured images and the processed images along with the results of the processing is shown in Fig. 6.

4. Calibration of the misalignment measurement system

To ensure the repeatability and reproducibility of the proposed technique, special care was paid to the calibration of the proposed system. The first step in the calibration procedure was to align the laser beam parallel with the case of the laser. This provided parallelism at any distance and could be used as a reference over the entire length of the beam. To align the laser, a V-block was used to check that the projected dot image was concentric and centre of the dot should remain in the same position. The second step was to check that the laser coincided with the axis of the chuck by adjusting the beam using the $X$ and $Y$ micrometer heads until the projected dot image was concentric with the chuck. The third step was to calibrate the laser–camera–image processor system. To do this, a coordinate device was designed as shown in Fig. 5. The setup of the calibration is shown in Fig. 3. The camera was mounted on the coordinate device and was displaced in the $X$- and $Y$-directions by the micro-meter heads. The image produced by the laser beam was captured and processed. The results of the image processing were compared with the actual displacements (intentionally displacement) of the coordinate device. Fig. 7 shows the calibration curves for the system. It can be seen that an excellent agreement between the actual displacements of the coordinate device and the measured values of the proposed system was achieved.

5. Experimental procedure

To obtain different misalignments, the starting bush was intentionally misaligned by moving the pressure head over the carriage using the lead screw of the cross slide and then the misalignments was calculated by comparing the average centroid of the images which was captured when the photo sensor camera and starting bush axes coincide and when the camera and nose spindle axes coincide. To align the machine, this centroid has to be brought to coincide with the zero reference point. The zero reference point was established on the axis of the cylindrical camera housing within a reasonable tolerance (0.5 μm). Under each misalignment (15, 205, 422 and 856 μm) value the autospectra of axial cutting force and the torque was measured for
Fig. 7. Calibration of the proposed misalignment measuring system in the horizontal and vertical directions.

### Table 1
Effect of misalignment on the measured steady-state axial cutting forces

<table>
<thead>
<tr>
<th>Rotational spindle speed (rpm)</th>
<th>Cutting speed (m/min)</th>
<th>Feed (mm/rev)</th>
<th>Measured axial cutting force (N) for misalignment of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 μm</td>
</tr>
<tr>
<td>626</td>
<td>50</td>
<td>0.08</td>
<td>2020.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12</td>
<td>3056.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.16</td>
<td>3907.5</td>
</tr>
<tr>
<td>939</td>
<td>75</td>
<td>0.08</td>
<td>1950.6</td>
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<tr>
<td></td>
<td></td>
<td>0.12</td>
<td>3002.5</td>
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<tr>
<td></td>
<td></td>
<td>0.16</td>
<td>3811.4</td>
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<tr>
<td>1253</td>
<td>100</td>
<td>0.08</td>
<td>1900.4</td>
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<tr>
<td></td>
<td></td>
<td>0.12</td>
<td>2983.4</td>
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<tr>
<td></td>
<td></td>
<td>0.16</td>
<td>3778.4</td>
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### Table 2
Effect of misalignment on the measured steady-state cutting torque

<table>
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<tr>
<th>Rotational spindle speed (rpm)</th>
<th>Cutting speed (m/min)</th>
<th>Feed (mm/rev)</th>
<th>Measured cutting torque (N m) for misalignment of</th>
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<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>0.08</td>
<td>19.49</td>
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<td>0.16</td>
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<td>0.16</td>
<td>37.45</td>
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<tr>
<td>1253</td>
<td>100</td>
<td>0.08</td>
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<td>29.78</td>
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<td>38.32</td>
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</table>
different combination of feed (0.08, 0.12 and 0.16 mm/rev) and rotational speed (626, 939 and 1253 rev/min).

6. Results and discussion

Tables 1 and 2 quantify the effect of misalignment on the steady-state axial cutting force and cutting torque, respectively, for different cutting regimes and misalignment. The data in these tables are obtained from the frequency autospectra of the axial dynamic cutting force and dynamic cutting torque at frequency of 0 Hz. As seen from these tables, the misalignment affects the results dramatically since an increase in the steady-state axial cutting force and cutting torque can be noted as the misalignment increases. In particular, the axial cutting force and cutting torque increase with increasing cutting feed much more significantly than with the cutting speed. The experimental

![Graphs showing the effect of misalignment on cutting axial force signature. Cutting conditions: feed 0.12 mm/rev, rotational speed 1253 rev/min.](image)
results readily explain the significant scatter in the reported experimental results on the steady-state cutting force measurements in deep-hole machining [3,8–11]. Since in the literature, the misalignment has never been reported, this makes correlation of different reported results very difficult. Also, the present results suggest that previous studies present an incomplete picture of the BTA. Deep-hole machining combines two processes: drilling and burnishing and the forces generated in drilling are used to complete burnishing. As shown by Griffiths [9], burnishing defines the quality of the machined surface in terms of its roughness, roundness, residual stresses, etc. It is also known that this process is relatively sensitive to the burnishing force applied. For a given drill design, the ratio “cutting force:burnishing force” is constant and therefore a change in the cutting force directly affects the corresponding change in the burnishing forces.

Fig. 9. Effect of the misalignment on the cutting torque signature. Cutting conditions: cutting feed, 0.12 mm/rev; rotational speed, 1253 rev/min.
force. This simple consideration explains a significant scatter in the reported results on quality in the machining surface in deep-hole machining. This also explains the relatively poor productivity of deep-hole machining since the same tools are used in the machines having different misalignments that causes the scatter.

Figs. 8 and 9 show the frequency autospectra of the axial dynamic cutting force and dynamic cutting torque, respectively, under the same cutting feed and cutting speed for different misalignments. The misalignment shows up as a series of harmonics associated with the running speed. Comparing the autospectra of the axial cutting force under different misalignments for the same cutting feed and spindle rotational speed show that the misalignment introduce a series of different amplitude harmonics at frequencies associated with the multiple of the running speeds (2X, 4X, 6X, etc.; X is the frequency corresponding of the running speed). For example at 1253 rev/min, the misalignments show up at 42, 84, 168 Hz, etc. In the case of the cutting torque, the misalignments also show up as a series of different amplitude harmonics but at frequencies associated with an odd number of the running speeds (3X, 5X, 7X, 9X, etc.; X is the frequency corresponding of the running speed). For example at running speed of 1253 rev/min, the misalignment shows up at 63, 105 and 147 Hz, etc.

From these figures it was easy to distinguish between the harmonics caused by the misalignment and that caused by the imperfections of the machine by comparing frequency autospectra of the axial dynamic cutting force and dynamic cutting torque when the machine is near perfect (misalignment: 15 µm) and when the machine is under misalignment of 205, 422 and 856 µm.

Comparing the autospectra of the axial cutting force and cutting torque under different misalignment for the same cutting feed and spindle rotational speed show that the amplitudes of the different harmonics increase as the misalignment increases.

Also, it can be noted that in the case of the axial cutting forces, the dominant amplitude is associated with the second harmonic (2X) of the operating speed where the amplitudes of the spikes which are observed at the forth, sixth, etc., harmonics are seen to be progressively lowered. In the case of torque, the dominant amplitude is associated with the third harmonic of the operating speed. This spike which was observed at the third harmonic was also seen at fifth, seventh, etc., though the amplitude was seen to be progressively reduced.

7. Conclusions

The important conclusions which follow from the obtained results are:

1. The deep-hole machining system has very distinct dynamic signatures under different misalignments. As seen from the results, if the deep-hole machining system is aligned, it is much more dynamically stable. In practical terms this means that there is a reduced possibility of lobbing which is considered as an inherent feature of deep-hole machining [3, 10, 11] to occur. Unfortunately, in the known literature on these common defects, the misalignment has never been considered.

2. The misalignment changes the autospectra in such manner that it becomes difficult to distinguish between the spectra that reflects the cutting process contribution and the spectra that come from other sources.

References


