Inspection of Micro-Drilling Processes by using the On-Machine vision

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Abstract: In order to inspect burrs and machining quality in micro-drilling processes, a cost-effective method using an image processing and a shape from focus (SFF) methods on the machine tool is proposed. As the on-machine vision units are incorporated with the CNC function of the machine tool, direct measurement and condition monitoring of micro-drilling processes are conducted between drilling processes on the machine tool. Stainless steel and hardened tool steel are used as specimens and twist drills made of carbide are used in experiments. Validity of the developed system is confirmed through experiments.

Keywords: Burr, CCD Camera, Condition Monitoring, Hole Quality, Illumination Unit, On-Machine Measurement, Shape from Focus, Zoom Lens

1. Introduction
Micro-drilling processes have been widely used to produce micro holes such as micro dies and molds, fuel injection nozzles, watches, bearings and printed circuit boards, etc. And it has more attention in a wide spectrum of precision production industries.
The burr (height, width) and hole quality (oversize, location error) have a significant effect on assembly of precision components. Fast and accurate measurements of burr geometry and hole quality are important for the condition monitoring of micro-drilling processes. In order to measure burr and hole quality, measurement systems such as SEM (Scanning Electron Microscope) and confocal microscopes have been used [1-2]. However, these measurement systems are very expensive. They are difficult to apply condition monitoring of drilling holes between micro-drilling processes. In addition, they are not cost-effective.

In this paper, a machine vision technique using the SFF method [3] is applied to measure the micro-drilling burrs and hole quality. In order to obtain clear images and reduce noise due to reflection, a novel illumination unit is devised using the LED array and a halogen lamp. Experiments are conducted with twisted carbide drills, and stainless and hardened tool steel specimens.

2. Hole Quality
Experiments are conducted to investigate the effectiveness of drilling processes by measuring the hole quality after machining. Two aspects, location error and oversize of the hole, of drilling quality are measured. Depending on type of drills and drilling processes, it may occur that the drill walks on the surface of the workpiece before entering the part. Whirling of the drill edge at the time of penetration into the workpiece degrades hole quality as well.
The drilled center location of a hole is determined by the position where the drill comes to a stop after walking. The location error deviated from the desired center location is called the location error of the hole [4], \( E_L \) shown in Fig. 1. Actual diameter is calculated by evaluating the result of least squares technique after scanning the edge through the edge detection and image processing. And location error is measured by the difference between the actual hole center and the desired hole center with comparing the CNC position and image coordination.

In all drilling operations, diameter of the hole is predetermined by the diameter of a drill bit. However, some variation in hole size from the nominal (tool) value is expected to occur even under the best drilling condition because of tool wear and the whirling. The amount of deviation between the actual hole diameter and the nominal diameter is called diameter deviation [4], \( \delta d_e \) as shown in Fig. 1.

Fig. 1 Location error and diameter deviation.
3. Burr Inspection

3.1 Focus and defocus Images

When the object point \( P \) is blurred on the image detector plane ID shown in Fig. 2, the radius \( r \) of the blurred circle \( Q' \) is obtained. This image \( h(x,y) \) is the point spread function (PSF) of the camera. It is also called the blurring function. A two-dimensional Gaussian function is used to approximate this physical model. Then, the blurred or defocused image \( g(x,y) \) at the small image region on the image detector ID is equal to the convolution of the focused image \( f(x,y) \) and the PSF \( h(x,y) \). Hence, if \( G, F \) and \( H \) are the Fourier transforms of \( g, f \) and \( h \), respectively, then \( G=HF \).

\[ H(\omega,\nu) \text{ has characteristics of a low-pass filter where the bandwidth decreases with increase in defocusing.} \]

Defocused images of the object can be obtained by moving the lens every \( \Delta d \) with respect to the reference plane as shown in Fig. 3. The increment of the stage movement \( \Delta d \) is manipulated by the CNC function of the machine tool.

3.2 Shape from focus

In Fig. 3, it is assumed that the reference plane of the block gauge corresponds to the reference focus position of the machine tool. If the camera is moved toward object focus position using the z-axis movement of the machine tool, the image will gradually increase its degree of focus (high frequency energy) and will be optimally focused at the object plane of the block gauge. When the object plane has a perfect focus at \( d \), object height \( d_z \) is given by

\[ d_z = d = N \times \Delta d \]  

This approach may be applied independently to all surface elements to obtain the shape of the entire surface.

3.3 Focus measure operator

It is known that the quality of focus is proportional to the amount of high frequency energy [3]. Several focus measure operators have been proposed [5]. In this study, a Laplacian operator is used because it has good performance with a sharp peak.

The Laplacian of two-dimensional images is given by

\[ \Delta^2 I(x,y) = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} \]  

The Laplacian can be generated by the convolution operation with the \( 3 \times 3 \) kernels \( H_l(x,y) \) in spatial domains as follows:

\[ L(x,y) = I(x,y) \otimes H_l(x,y) \]

where \( H_l = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix} \]

The focus measure at a window is computed as the sum of the modified Laplacian values, in a small window around \((i,j)\), that are greater than a threshold value:

\[ f(i,j) = \sum_{x=-M}^{x=M} \sum_{y=-N}^{y=N} L(x,y) \text{ for } L(x,y) \geq T_l \]  

We shall designate the Eq. (4) to the Sum-of Laplacian (SL). In Eq. (4), parameters of \( M \) and \( N \) determine the window size that is used in computing the focus measure. The window size is selected empirically.

3.4 Illumination unit

One of the most important parts of the hardware configuration is the illumination. For burr and hole quality measurements, the main requirement of system is to provide adequate contrast between burr and background. Intensity of illumination source should be adjusted to accentuate the burr region of interest. In addition to the selection of an appropriate light source, consideration must also be given to the technique that will give the optimum result [6].

In this paper, we apply both the front lighting with coaxial halogen light source and back lighting with LED-array illumination to inspect hole quality and burrs.

4. Experiments

4.1 Experimental setup

Measuring system consists of a CCD-camera with zoom lens attached to the vertical CNC machining.
center, illumination units of both LED and halogen light source, a digital image processing unit, and a microcomputer as shown in Fig. 4.

The image from the CCD camera with zoom has $640 \times 480$ pixel elements with a pixel size $1.49 \mu m$ (H) $\times$ $1.45 \mu m$ (V). The camera axis is perpendicular to the stage, table of the machining center, holding a workpiece. Image acquisition and drilling processes are operated simultaneously by NC program. Images are captured through the CCD camera by a frame grabber with 256 digitized gray levels.

4.2 Calibration

Fig. 3 shows block gauges to calibrate the developed SFF system. First, the difference $d$ of $50.1 \mu m$ is calibrated by an LVDT with resolution of $0.1 \mu m$. After selecting $\Delta d$ to $8 \mu m$ and window size of $30 \times 30$, SL focus measure function is obtained as shown in Fig. 5. From this figure, distances between the reference and the focused object surfaces are 72 and 120 $\mu m$, respectively. Comparing with the calibrated results by LVDT, we can confirm that the developed SFF system has $2.1 \mu m$ error as shown in Table 1.

However, distance estimations through the SL focus measure function gives local values contaminated by noises. Gaussian interpolation with step size of $0.1 \mu m$ is applied to find the optimal values of focus measures [3]. Fig. 6 shows optimal Gaussian interpolation results of the focus measures.

5. Results and Discussion

5.1 Hole quality

In this study, carbide 0.5mm drill bits, stainless steel SUS304 and hardened tool steel SCM4 with 1mm thickness are used as specimens.

Fig. 7 and Fig. 8 show cutting conditions, work materials, original images of holes according to the drilling step. Diameter deviation $\Delta d_i$ of each specimen are listed in Tables 2–3. These results show that location error and diameter deviation increase slightly as drill wear propagates.

5.2 Burr width and height

To measure the exit burr heights, $\Delta d$ of $8 \mu m$ and window size of $3 \times 3$ were empirically selected. Fig. 9 and 10 show original images of burr, measuring points and edges of specimens through image processing. Inspection results of burr geometry are listed in Table 4–5. “–” sign means the burr is located below the reference plane.
Table 2: Hole oversize result of SUS304.

<table>
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<tr>
<th>No</th>
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Fig. 8 Drilled hole images and location error map.

Table 3: Hole oversize result of SCM4.

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Fig. 9 Burr height(BH) and width(BW) of SUS304.

Table 4: Burr height(BH) and width(BW) \([ \mu m ]\) of SUS304.

<table>
<thead>
<tr>
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Fig. 10 Burr height(BH) and width(BW) of SCM4.

6. Conclusions

In order to develop a condition monitoring system for micro-drilling processes, on-machine machine vision system is proposed to measure the burr geometry and the hole quality produced in micro-drilling processes. The machine vision system consists of a CCD camera with zoom lens, a novel illumination unit and image processing units.

Edge detection algorithms are used to measure hole quality. The SFF method is used to measure burr heights and widths. Developed system has resolution of 0.1 \( \mu m \) and accuracy of less than 2.1 \( \mu m \) in the measurement of burr height and width. The reliability of the developed system is confirmed through experiments.

References