Drill Holes Deflection Determination for Small Diameter Bits in Wood-Based Materials

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The growing interest in wood accessories has focused scientific research attention on wood cutting with small diameter tools. A problem that may arise when drilling wood is the phenomenon of wandering – when the hole is not made in the designed place. The difficulty in studying small diameter drill holes (0.5 mm to 0.9 mm) is due to the difficulty of automatic measurement. The development of an appropriate methodology may allow for the observation of this phenomenon without the need for high-class hardware and expensive software. This article presents the results of tests carried out on nearly 500 samples made of various wood-based materials (high-density fiberboard (HDF), medium-density fiberboard (MDF), chipboard, and plywood) in terms of the usefulness of the OpenCV computer vision library for the determination of wandering.

Keywords: Computer vision; Wood-based materials; Machining; Drilling; Deflection

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Dedication: To Cecylia Król, Grandmother

INTRODUCTION

Regarding mechanical wood processing, the drilling process should be divided into three stages. The first stage occurs during the time before the drill tip encounters the workpiece. The second stage is the skidding, which includes the first few revolutions of the drill bit after touching the wood and ends with the stabilization of the drill position. As a result of skidding, this position is usually deflected. The third stage occurs when the wandering takes place, and it is mainly responsible for the quality of the hole made (Wijeyewickrema *et al.* 1994).

There is very little literature on the topic of drilling in wood with small diameter bits. This is probably due to the difficulties in accurate measurement, or because there is little practical interest in the topic. However, growing consumer demand for wooden accessories due to their eco-friendliness and naturalness (Hrovatin and Hrovatin 2020) can be seen in wood products such as watches, glasses, and jewelry. In addition, the growing popularity of sustainable products has spurred interest in this topic in a scientific sense. Increasing interest in wood-epoxy composites as the material for the production of table-tops, accessories, and jewelry can be expected to foster interest in the machining of wood composites with small diameter tools (Białowąs and Szymanowski 2020). The possibility of measuring the phenomena related to the processing of wood with small diameter tools may be interesting also from a scientific point of view. It can be considered as an extension of the study of tools with diameters used in industrial conditions, and therefore for a better understanding of this process.

Wood-based materials have different characteristics. They can have a range of densities much wider than that of solid wood and with different structures. In the case of fiberboards, such as medium-density fiberboard (MDF) and high-density fiberboard (HDF), this structure is relatively uniform in each direction. In the case of plywood, the surface layer is similar to that of solid wood of the same species. Chipboard has a unique surface layer and structure that consists of wood particles that are glued together. An integral stage of particleboard production is the pressing stage, where the board obtains its thickness and structure. The pressing stage imparts a U-shaped density profile on the particleboard, where the outer layers are much denser than the inner layers. This effect can be increased by the use of finer chips for the surface layers or natural material type (Borysiuk *et al.* 2019). These homogenic properties make wood-based panels an ideal material for preliminary research. In the long term, natural wood can be used instead.

It was found that the influence of the spindle rotational speed was practically negligible on feed force in contrast to the type of material and feed rate. The decisive factor was the type of workpiece and the feed per revolution (Podziewski and Górski 2011). This can be found as another argument for using homogeneous materials.

Initial attempts have shown that computer vision technology is capable of detecting holes in wood-based materials. However, the accuracy of computer vision technology is limited, depending on various factors, and it requires the appropriate selection of parameters and the appropriate processing of the input images for this purpose. OpenCV (Intel Corporation, Santa Clara, CA) is an example of a computer vision technology library that can facilitate the above analyses (Bradsky and Kaehler 2008; Król and Król 2020).

The purpose of this work was to present a possible way to measure the deflection of drill holes 0.5 to 0.9 mm in size in different wood-based materials and with various drill bit diameters. As a result of this research, some consistent and useful data were concluded.

EXPERIMENTAL

Wood-based Panels and Drill Bits

Four standard types of wood-based panels were used in the research: HDF (790 kg/m^3), MDF (760 kg/m^3), particleboard (664 kg/m$_3$), and pine plywood (609 kg/m^3). Drill bits with width × working length dimensions of 0.5 × 7, 0.6 × 9.5, 0.7 × 9, 0.8 × 9.5, 0.90× 10, and 3.175 mm × 10.5 mm were used. The wood-based panels were obtained from Pfleiderer Polska Sp z o.o. (Poland) except for plywood, manufactured by Paged Pisz Sp. z o.o. (Poland). Smaller drill bits (0.5 to 0.9 mm) were manufactured by Evanx (China), while 3.175 mm drill was manufactured by MPK Kemmer GmbH (Germany). All drills were symmetrical, two-blades, uncoated carbide.

CNC Drilling

The drilling was performed on a printed circuit board (PCB) milling machine (custom-made) with a movable table in the X and Y axes. The milling axis is based on stepper motors with direct drive (screw with nuts anti-backlash). The resolution is 1600 steps per millimeter.

Two milling programs (gcodes) were used for the reference holes and to drill the holes with a diameter of 0.5 mm to 0.9 mm. The coordinate system was in inches, and the movement of the spindle over the material for each hole was made from the same direction. This procedure was designed this way to minimize the impact of eventual backlash. Six samples were made on an element measuring 50 mm × 70 mm (HxW) with one program (Fig. 1). The programs accounted for the gap between scanner sensors. The reference holes were drilled through the entire material thickness and 6 mm for particleboard. The remaining holes were drilled at depth of 0.078 in, approximately 2 mm, with the second program. All the holes were drilled at a feed rate of 2 in/min (50.8 mm/min). Spindle speed was set at 9.000 RPM.

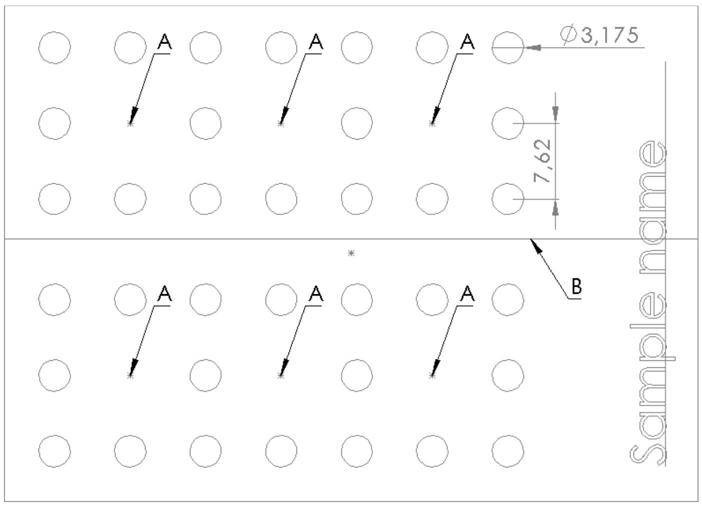

Fig. 1. A diagram of the sample. A – The center of the small holes, B – The scanner sensors gap, dimensions in mm.

Image Acquisition

The obtained dust-cleaned samples were scanned using a 4800 dpi high-resolution scanner (CanoScan LiDE 200; Canon, Tokyo, Japan) with the aid of ScanImage software (v1.0.27; Vidrio Technologies, Arlington, VA). The obtained images were stored for further analysis. The samples were covered to prevent external light from showing through the reference holes.

Most contact image sensor scanners, such as the one used in this study, suffer from a disadvantageous gap between the scanning modules. This creates a gap in the received images with a width of a few pixels – approximately 40 µm (7 px to 8 px at 4800 dpi resolution) wide (Zamoyski *et al.* 2020).

Images Analysis

The acquired images were cut and analyzed with GNU Octave (v4.4.1) software with mexopencv (v3.4.1) and OpenCV (v3.4.1). As a result of sample analysis, two files were created; *sample_name*.txt contained all the results and *sample_name*.png was an image with the marked theoretical and empirical circles.

The first stage of the scripts required splitting the source images (complete board scan) into samples by constant coordinates. Next, all the samples were converted to greyscale and adjusted to improve holes contrast with the following script,

```
[~, tr] = min(imhist(gr_highRes)(25:100));
bw_gray = cv.threshold(gr_highRes, tr+75, 'Type', 'Trunc');
bw_gray = imadjust(bw_gray);
```

The resulting *bw_gray* image was tested in a loop with *Param2* of the *cv.HoughCircles()* function decreasing from 50 to 10 until the resulting number of circles was equal to 8. The radius of the searched circle was limited to a hole size ± 5 px (~26 µm). For *Param2* < 10, the sample was rejected as unrecognized. These 8 holes were used as position reference. The set of reference hole coordinates was next corrected. The correction consisted of matching the theoretical set of coordinates to empirical ones by moving (by one px) and rotating (from -2° to 2° every 0.01°) it in a loop. The coordinates with smallest *dSum* (sum of the distances between the received and real coordinates) were used to calculate the new reference. *Param2*, the correction coordinates for all reference holes, the correction average, and the rotation were written to file.

The 300 px × 300 px (~1.6 mm × 1.6 mm) image around the theoretical center of the sample was cut as a new image and searched for a hole. The testing approach was similar to the approach for the reference holes, but this time *Param2* was tested until only one circle was found and no corrections were done. The *Param2* and center displacement coordinates of the recognized hole were written to file. The output images were manually checked for a mistakenly designated position of the hole.

Statistics

The obtained data were subjected to statistical analysis using an open-source spreadsheet program (LibreOffice Calc 6.3.5.2). The average, standard deviation, and standard group error for the series, material, and tool dimension were all analyzed. The formula for the standard group error can be seen in Eq. 1,

$$\sigma_g = \frac{s}{\sqrt{(n_h \cdot n_d \cdot N)}} \cdot \sqrt{(n_d)} = \frac{s}{\sqrt{8 \cdot 2 \cdot N}} \cdot \sqrt{2} = \frac{s \cdot \sqrt{2}}{4 \cdot \sqrt{N}} \tag{1}$$

where σ_g is the standard group error, s is the standard deviation, N is the samples number, n_h is the reference holes number, and n_d is the dimension number.

Further statistical analysis, such as the determination of the linear, power, and exponential models as well as the determination of the R^2 coefficients were performed using GNU Octave (v4.4.1), a numerical computation software. The model's visualization was also analyzed to avoid influential observations.

RESULTS AND DISCUSSION

As a result of the research, 474 samples of holes made in 4 types of material with the use of 5 drill diameters were obtained. The minimum number of samples per series was 23, the maximum was 24, and the average was 23.7. The effectiveness was 98.75% (3 samples manually rejected, 3 samples unrecognized). The average analysis time was 174 s per sample.

The lowest standard deviation for coordinates correction (in the *x* and *y*-axis) for the reference holes was observed in particleboards, at 6.75 px (~35.7 µm). The standard deviations for HDF, MDF, and plywood were 7.34 px (~38.8 µm), 7.04 px (~37.3 µm), and 7.28 px (~38.5 µm), respectively. The average standard error was 0.51 px (~2.7 µm) for series, which is a factor that allows or prohibits the identification of differences between the series. All the series results are shown in Fig. 2.

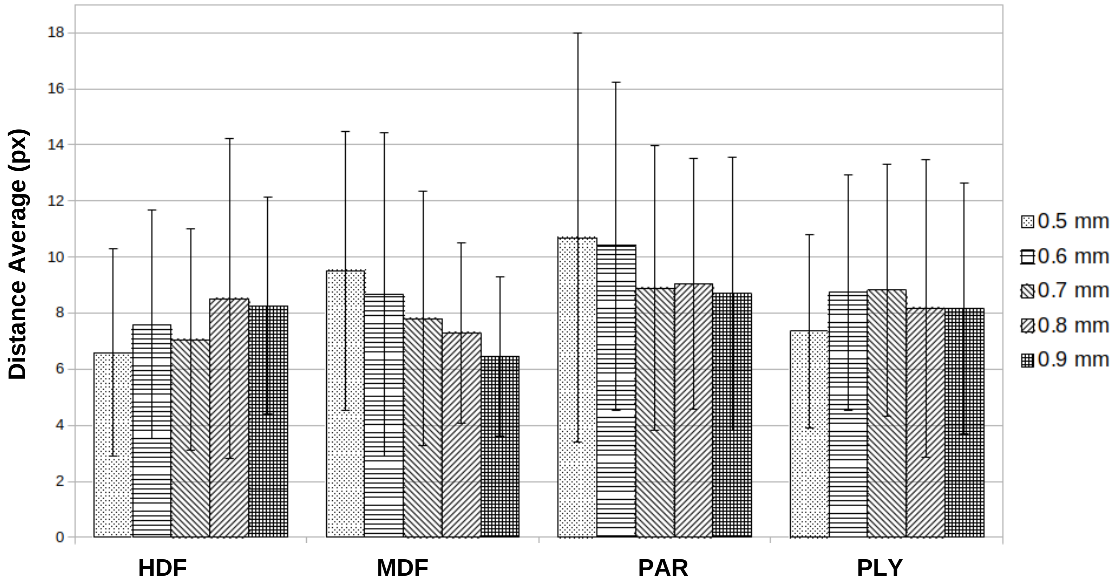

Fig. 2. The dependence of the deflection depending on the processed material and the diameter of the tool. Due to high standard deviation, standard error of 0.51 px (~2.7 µm) was used in further analysis.

Standard deviation for series was within range of ±25% (except for PAR 0.5 to 154%, MDF 0.8 to 68% and MDF 0.9 to 60%, PLY 0.5 to 73%) of standard deviation of all samples. This suggests that testing more samples will give similar results. This allows the use of a different mean difference indicator – average standard error.

Of the observed materials, the MDF performed the most consistent with the theory that the deflection decreases as the tool diameter increases. The difference of the mean in the groups with diameters different by at least 0.2 mm exceeded the standard error by at least twice (and at least almost once between all diameters groups). The coefficient of determination (R^2) for all the regression types was *greater than* 0.99.

The particle board material was performed differently than predicted. The mean difference for the particle board exceeded the standard error by at least twice for a diameter difference of 0.3 mm. The R^2 value was *greater than* 0.83. As a result of the regression visualization, the 0.7 mm tool diameter was removed, and the analysis was repeated. In the second analysis, the R^2 value was *greater than* 0.98 for all the regression tests.

The diversity within the plywood material was usually in the range of 1 to 2 standard errors, while the linear and exponential regression reached a coefficient of R^2 *less than* 0.08 (with a positive slope). The power regression R^2 value was 0.71. These results make it difficult to draw further conclusions about this dependency.

The HDF material exhibited inconsistent results. Only 5 of the 10 pairs had a difference that was more than twice the threshold of the standard error. The R^2 value was *less than* 0.71 for all the HDF regressions. The R^2 value trended higher as the tool diameter increased. As with the plywood material, further conclusions about this dependency in HDF material are difficult to conclude.

The cumulative data for the tool diameters and the materials are shown in Fig. 5.

The average standard errors for the materials and the tool diameters were 0.23 px (~1.2 µm) and 0.26 px (~1.4 µm), respectively. These factors allow or prohibit the identification of differences between the result groups.

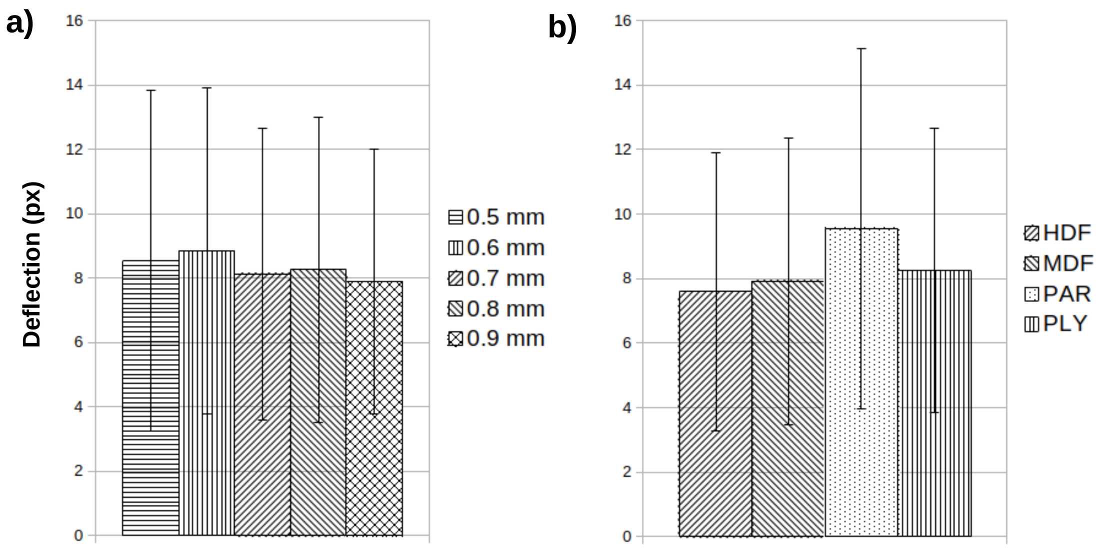

Fig. 3. The deflection dependence on the a) tool diameter and the b) processed material. Due to high standard deviation, standard error of 0.51 px (~2.7 µm) was used in further analysis.

Although the differences between the series are visible on the chart, a downward trend was visible. However, this correlation was not confirmed by the statistical analysis. The R2 value was less than 0.68 for all the regression types. Only the 0.6 mm diameter drill bit *vs*. others and the 0.9 mm drill bit *vs*. the 0.5 mm drill bit exceeded the standard error by at least a factor of two. This may have been due to inconsistencies in two of the four wood board materials. Because these results were not statistically shown to be significant, it is difficult to draw conclusions from the data.

From the analysis of the mean differences for the cumulative data of the materials, it can be concluded that there were clear differences between the HDF, plywood, and chipboard materials. These differences were confirmed by statistical analysis, where the differences between the average values for the chipboard and the other materials exceeded the standard error by at least five times. In the case of the HDF and plywood materials, this difference exceeded twice the standard error. Therefore, the conclusion can be drawn that chipboard had the greatest impact on the deflection, followed by plywood. The HDF material had the smallest impact on the deflection, while the impact of the MDF material was not clear.

CONCLUSIONS

1 The methodology used in this study appeared to be useful when measuring the deflection of small diameter drill holes (*less than* 1 mm).

2 The standard deviation from the marking of reference holes was characterized by a relatively high value, the negative effect was compensated by the number of holes used to define the center of the sample

3 The high standard deviation suggests the need for further work on the accuracy of the hole markings in order to obtain a narrower range of values.

4 The drill deflection in the MDF and particleboard materials was characterized by a linear dependence on the diameter of the tool in the range of 0.5 mm to 0.9 mm.

5 The drilled holes with small diameters (0.5 mm to 0.9 mm) in the particleboard material were characterized by the highest deflection, while the drilled holes in the HDF material exhibited the lowest deflection among the tested materials.

6 Further investigation on the nature of particleboard influence on deflection should be considered.

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Article submitted: October 30, 2020; Peer review completed: March 20, 2021; Revised version received and accepted: April 3, 2021; Published: April 9, 2021.
DOI: 10.15376/biores.16.2.3808-3814