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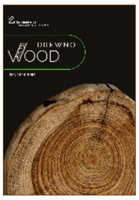

Effect of Wood-based Material Type on Drilled Hole Diameter

Maciej Sydor*
Adam Zasuwik

Poznań University of Life Sciences, Poznań, Poland

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This study examines the influence of furniture board material type on real drilled hole dimensions. Five samples were fabricated from two medium-density fibreboards (MDF), two particleboards, and plywood. Fifteen holes were drilled in the side surface of each sample using a 12 mm drill bit, a rotational speed of 3000 rpm, and a feed rate of 0.67 mm/rev. For each hole, the diameter of the cylindrical plug gauge was identified to determine whether it could be inserted freely, partially, or not at all. The results showed that in each case the effective hole diameter was smaller than the nominal drill diameter. The smallest plug gauge diameters were observed in plywood (a plug gauge with a diameter exceeding 98.8% of the drill bit diameter could not be freely inserted). Particleboards exhibited varying usable hole diameters (99.2-99.6%), while MDF showed the largest diameters of freely insertable plug gauge (99.6%). The observed differences between the plug gauge diameter and the nominal drill bit diameter can be attributed to variations in material structure. Adhesive layers in plywood and structural changes induced by drilling in particleboard likely contribute to the reduced practical hole diameter. In contrast, MDF's more uniform structure results in minimal deviations. These differences in hole diameter are crucial for the design of self-assembly furniture, as they can impact the fit and assembly process.

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Introduction

Engineering tolerances are the allowable margin of error in the dimensions or positioning of components in a manufactured object. Geometric tolerance specifies the allowable variation in a feature's shape, orientation, or location, while dimensional tolerance specifies the allowable variation in the size or length of a feature. The tolerance arrangement determines the fit type between two mating parts, specifically the clearance or interference between their surfaces (Ballast, 2007). Choosing the correct clearance or interference between parts is crucial for assembly and end-product functionality (Cao et al., 2018). Ideally, parts should be highly accurate (low tolerance value) to ensure smooth assembly and customer satisfaction. However, this approach rapidly increases manufacturing costs (Jeang, 1997). Even if tolerances are designed correctly, unfavorable changes can occur during the production or storage of parts for assembly (Eckelman, 1998). Deviating from designed tolerances leads to assembly issues and product malfunctions. For instance, undersized holes require excessive force to insert dowels, compromising the assembly process. Conversely, oversized holes create loose joints,

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[*] Corresponding author: **maciej.sydor@up.poznan.pl**

negatively impacting product functionality. In essence, engineering tolerances balance the desired level of precision and the cost of achieving it.

Drilling is a crucial process in furniture manufacturing, creating pilot or mounting holes to accommodate screws, dowels, and other fasteners (Pakuła et al., 2024). These holes facilitate the assembly of furniture components and the attachment of functional hardware such as hinges, drawer slides, and handles. Several factors can cause drilled holes in wooden and wood-based elements to deviate from their intended tolerances:

- Tool design – the drill bit's tip angle, type, and diameter are crucial for the results of the drilling process (Bedelean et al., 2023).
- Processing issues – incorrect machining parameters, machine imbalance, tool wear, and others worsen dimensional accuracy (Wilkowski et al., 2022).
- Environmental factors – changes in moisture content and temperature degrade wooden parts' dimensional accuracy during long-term storage (Turbański et al., 2021).
- Product use conditions – deformation under load and wear affect mating part cooperation (Kulman et al., 2021).
- Wood material type – for example, susceptibility to delamination (Szwajka & Trzepieciński, 2017) or facilitation of drill wandering can cause unintended adverse drilling results (Sydor et al., 2020).

Innovative methods of drilling wooden materials include vibrating cutters, high-velocity liquid jets, and laser beam cutting (Szymani & Dickinson, 1975). Despite many years of development, these methods have not replaced standard industrial "mechanical" processing with twist drills. These drills remain the go-to tool used extensively in multi-spindle drilling machines, CNC centers, and drill presses. Therefore, industrial furniture manufacturers often use twist drills to create holes.

Developing drill condition monitoring systems for wood-based panel machining enhances manufacturing efficiency by reducing tool wear and improving product quality through real-time monitoring and analysis (Wilkowski & Górski, 2011; Górski, 2022). Improving drilling can involve artificial neural network modeling and response surface methodology for wood particleboard processing (Bedelean et al., 2022). The main results of these activities are improved dimensional accuracy of holes and reduced likelihood of delamination (Jegorowa et al., 2022). Tolerances for drilled holes are also considered in terms of location relative to the designed nominal values (Sydor et al., 2020).

Changes in wood moisture have the most significant impact on wooden elements' dimensional accuracy, because their moisture content follows changes in ambient air parameters (Eckelman, 1998; Zhou et al., 2007). Wei-Lian and Hui-Yuan (2022) investigated the mechanical behavior of oval mortise and tenon joints in outdoor wooden furniture. The study found that the moisture content and the direction of the wood grain significantly affect the contact force in oval mortise and tenon joints. It was observed that the impact of the interference fit on the contact force varies with the moisture content, indicating that the fit must be carefully considered during the design process to ensure joint effectiveness.

Cyclic, multiply repeated changes in environmental parameters affect the dimensions of wooden elements. Turbański et al. (2021) investigated the effect of varying storage conditions on the moisture-induced cyclic dimensional changes of furniture elements made of pinewood and their subsequent impact on the precision of robotic assembly in furniture manufacturing. The research results showed that reversible, humidity-related changes in the wooden elements' dimensions make their assembly into furniture difficult after several drying–wetting cycles. The moisture content fluctuations in wood change the external dimensions of wooden furniture parts and even the hole shape. Sydor et al. (2021) investigated the impact of moisture changes on the effective diameter of holes drilled in pine blanks. The authors confirmed that wood swelling and shrinkage due to moisture fluctuations can significantly alter the effective diameter of holes. Holes' dimensional accuracy is more sensitive to decreases in relative humidity (RH) than to increases. Pine planks exhibit asymmetrical swelling and shrinkage, but this does not directly correlate with changes in hole diameter. The authors highlighted the importance of considering moisture changes and wood material properties when designing furniture or other wood products that require precise hole dimensions. In another study, the authors used a 3D optical scanning method and revealed the holes' moisture-induced, complex-shaped deformations (Sydor et al., 2023). These were reported to be the result of wood properties, processing conditions, and the influence of changes in environmental conditions.

Wood deformations under load affect the structure by influencing bending strength and strain distribution (Bardak, 2018). Displacements at semi-rigid connections of elements in timber structures, with creep effects, cause a decrease in connection stiffness over time (Fabriciuss & Ozola, 2020). Analogous phenomena occur in furniture. Studies recommend interference fit parameters that enhance joint performance. For example, an interference fit parameter of 0.4–0.6 mm is recommended for producing furniture made of alder (*Alnus formosana*) wood (Chen et al., 2015), and 0.1 mm is recommended in the case of white oak wood (Liu et al., 2024). Wood materials have unstabilized physical properties, so studies also explore statistically calculated lower tolerance limits for furniture joint design (Eckelman et al., 2017), estimating sample size for dowel joints with specified confidence levels related to strength (Uysal & Haviarova, 2018).

The influence of factors such as layer or fiber arrangement and moisture content changes on hole quality has also been a subject of significant study. However, a gap remains in understanding how different furniture board materials affect the practical diameter of drilled holes concerning the nominal tool size used. The 'practical hole diameter' refers to the maximum diameter of the cylindrical plug gauge that can be freely inserted into the hole, emphasizing the real-world utility of the holes for accommodating furniture assembly. This knowledge is valuable for furniture designers who specify appropriate engineering fits for various furniture materials. To address this gap, this research investigated and compared how the type of furniture board material impacts the practical diameter of the drilled hole.

Materials and methods

This study focused on five widely used board materials in the furniture industry: two medium-density fiberboards (MDF), two particleboards, and plywood. Table 1 lists their labels, types, literature references for specific properties provided by producers, producers' names, and primary physical properties.

Five panels measuring 320 × 100 × 18 mm were prepared to represent the materials listed in Table 1 and to serve as test samples. These panels were conditioned in a laboratory environment for two months in standardized air parameters (t = 20 ±1 °C, RH = 50 ±5%) to reach equilibrium moisture content. Subsequently, the moisture content of each board was measured using a wood-based board moisture meter with an accuracy of 10% of the measured value (WPS-2, Tanel, Gliwice, Poland). A caliper with an accuracy of ±0.1 mm and an electronic laboratory balance (PA 213/1, OHAUS, Parsippany, NJ, USA) with a measurement uncertainty of ±0.001 g were used to calculate density.

In each sample, 15 blind holes were drilled using a 12 mm twist drill (Extreme 2 DT5557, DeWalt Industrial Tool Company, Baltimore, MD, USA). Figure 1 shows the tip of the drill bit used.

Although the nominal diameter of the drill used was 12 mm, its measured tip diameter was 12.001 ± 0.001 mm. This measurement was obtained using a digital microscope equipped with a micrometer slide table (model Dino-Lite AM4815ZT EDGE, manufactured by IDCP B.V., Almere, Netherlands), which achieved an accuracy of ±0.001 mm.

Hole drilling was performed using an industrial horizontal drilling machine (D-07, WAREMA, Opole, Poland). The spindle speed was 3000 rpm, and the feed rate was 2.0 m/min, resulting in a feed per revolution value of 0.67 mm/rev. Figure 2 depicts sample dimensions after drilling.

Table 1. Materials tested

Label	Material type	Reference	Producer	Moisture content (%)	Density (kg/m^3)
A	MDF (class E1)	(PDS, 2023b)	Egger Brilon GmbH & CO. KG (Brilion, Germany)	6.1	769
B	MDF (class E1)	(PDS, 2023c)	Swiss Krono sp. z o.o (Żary, Poland)	5.3	750
C	Particleboard (type P2)	(PDS, 2023a)	Egger Biskupiec sp. z o.o. (Biskupiec, Poland)	7.2	660
D	Particleboard (type P2)	(PDS, 2022)	Swiss Krono sp. z o.o (Żary, Poland)	6.1	666
E	Beech plywood	(DoP, 2023)	Sklejka-Eko SA (Ostrów Wielkopolski, Poland)	8.0	658

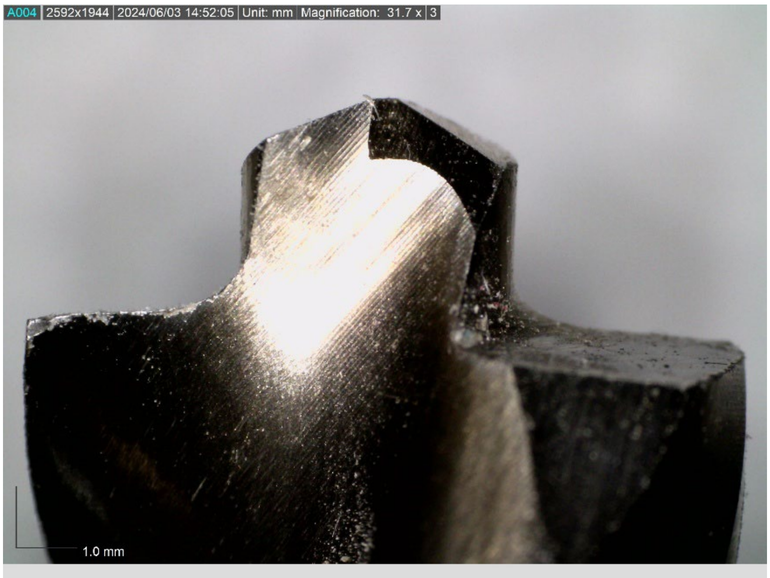

Fig. 1. The tip of the drill bit used

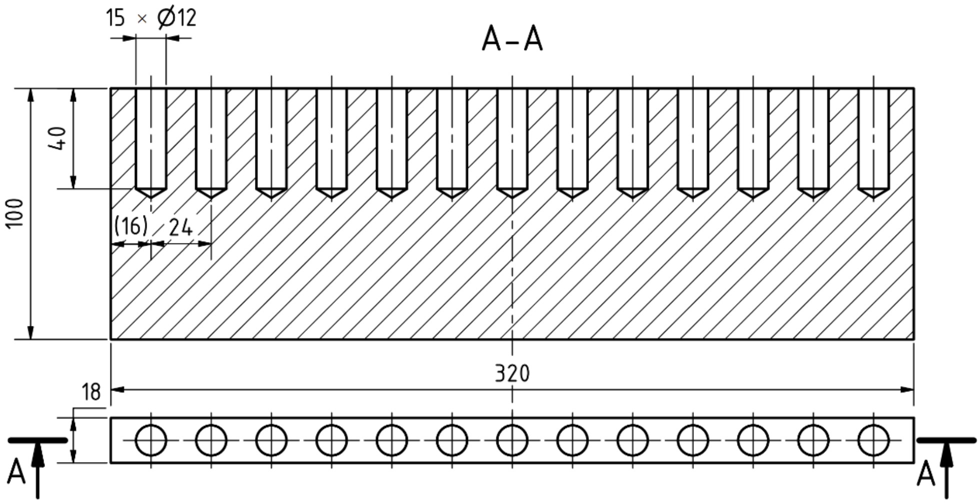

Fig. 2. The test sample design

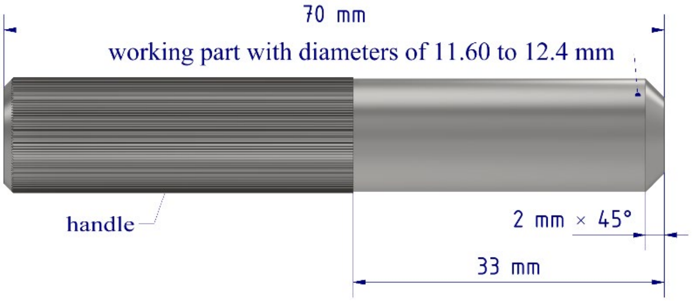

Fig. 3. The plug gauge design

A set of 15 cylindrical plug gauges, made of stainless steel and ranging in working part diameter from 11.6 to 12.4 mm, were used as a primary measuring tool. The working part diameters of the gauges varied in increments of 0.05 mm, while their other dimensions remained constant. Figure 3 illustrates the plug gauge set design.

Immediately after drilling the holes, to minimize any potential environmental influences, the plug gauges were manually inserted into and removed from the holes, starting with the smallest gauge. The diameter of the largest gauge that passed through without resistance, the diameter that encountered significant resistance, and the diameter that did not fit into the hole were recorded. The measurement results were categorized using a three-step fit scale:

1 – clearance (the plug gauge passed through without resistance),

0.5 – transition (the plug gauge passed through with significant resistance, and cannot be positioned completely),

0 – interference (the plug gauge cannot be inserted manually into the hole).

The three-point scale used (clearance, transition, interference) is a standard method for assessing engineering fit. The force required to obtain "transition" or "interference" was relatively low, up to approximately 50 N.

Results and discussion

Table 2 shows the raw measurement results. The letters from A to E label the tested materials (according to Table 1), symbols from #1 to #15 indicate the hole number in the sample, and scores 1, 0.5, and 0 refer to the fit scale and indicate clearance, transition, and interference, respectively. The numbers in Table 2 are the diameters of the corresponding plug gauges.

The data from Table 2 were processed, and are presented in the two accompanying figures. Figure 4 illustrates the median plug gauge diameters for each series of 15 holes drilled in the test samples, while Figure 5 depicts the averages for these series. The fit scale is located on the vertical axes.

Figures 4 and 5 demonstrate that the practical hole diameters vary according to the sample material. Considering the median values in the series of hole diameters (Fig. 4), it can be stated that the practical diameter of the hole is always smaller than its nominal diameter (in other words, the diameter of the freely insertable plug gauge is smaller than the nominal diameter of the drill used to make the hole). The smallest value of the practical diameter of the hole was observed for plywood (material E), being only 11.85 mm; the practical diameter of the hole for both particleboards (materials C and D) ranges from 11.90 to 11.95 mm. In the case of both tested MDF boards (materials A and B), the practical diameter of the hole is the largest (11.95 mm).

Table 2. Raw measurement results (description in text)

Material	Fit type	Hole number														
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
A	1	11.90	11.90	11.90	11.90	11.95	11.95	11.95	11.90	11.90	11.95	11.95	11.95	11.95	11.95	11.90
	0.5	11.95	11.95	11.95	11.95	12.00	12.00	12.00	11.95	11.95	12.00	12.00	12.00	12.00	12.00	11.95
	0	12.00	12.00	12.00	12.00	12.05	12.05	12.05	12.00	12.00	12.05	12.05	12.05	12.05	12.05	12.00
B	1	11.95	11.95	11.95	11.90	11.95	11.95	11.90	11.90	11.90	11.90	11.9	11.95	11.95	11.95	11.95
	0.5	12.00	12.00	12.00	11.95	12.00	12.00	11.95	11.95	11.95	11.95	11.95	12.00	12.00	12.00	12.00
	0	12.05	12.05	12.05	12.00	12.05	12.05	12.00	12.00	12.00	12.00	12.00	12.05	12.05	12.05	12.05
C	1	11.90	11.95	11.90	11.95	11.95	11.95	11.95	11.90	11.95	11.95	11.95	12.00	11.95	11.90	11.90
	0.5	11.95	12.00	11.95	12.00	12.00	12.00	12.00	11.95	12.00	12.00	12.00	12.05	12.00	11.95	11.95
	0	12.00	12.05	12.00	12.05	12.05	12.05	12.05	12.00	12.05	12.05	12.05	12.05	12.05	12.00	12.00
D	1	11.85	11.85	11.8	11.95	12.00	11.90	11.95	11.95	11.90	11.85	11.95	12.00	11.95	11.90	11.85
	0.5	11.90	11.90	11.85	12.00	12.05	11.95	12.00	12.00	11.95	11.90	12.00	12.05	12.00	11.95	11.90
	0	11.95	11.95	11.90	12.05	12.10	12.00	12.05	12.05	12.00	11.95	12.05	12.10	12.05	12.00	11.95
E	1	11.90	11.85	11.85	11.85	11.85	11.90	11.90	11.90	11.85	11.90	11.85	11.85	11.90	11.85	11.75
	0.5	11.95	11.90	11.90	11.90	11.90	11.95	11.95	11.95	11.90	11.95	11.90	11.90	11.95	11.90	11.80
	0	12.00	11.95	11.95	11.95	11.95	12.00	12.00	12.00	11.95	12.00	11.95	11.95	12.00	11.95	11.85

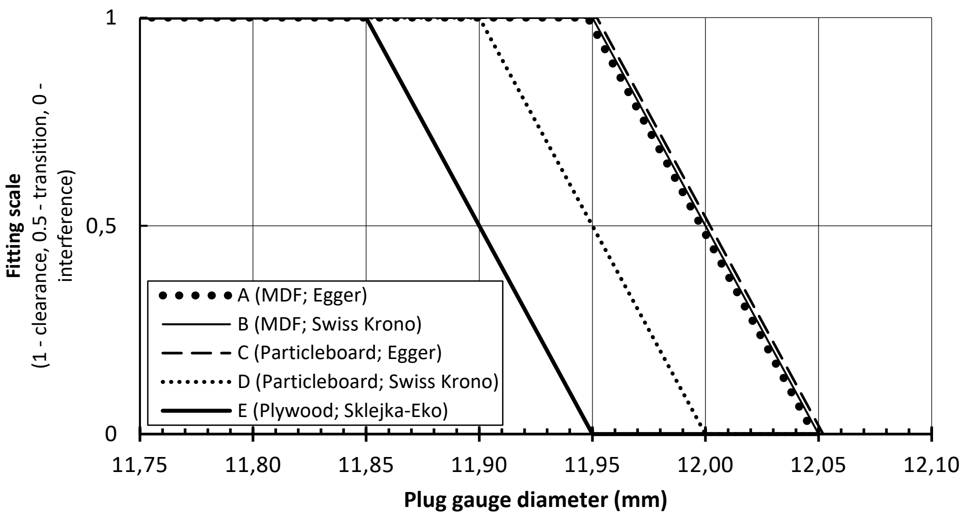

Fig. 4. Degree of fit of plug gauges of different diameters to holes in the five tested samples (median, $n = 15$)

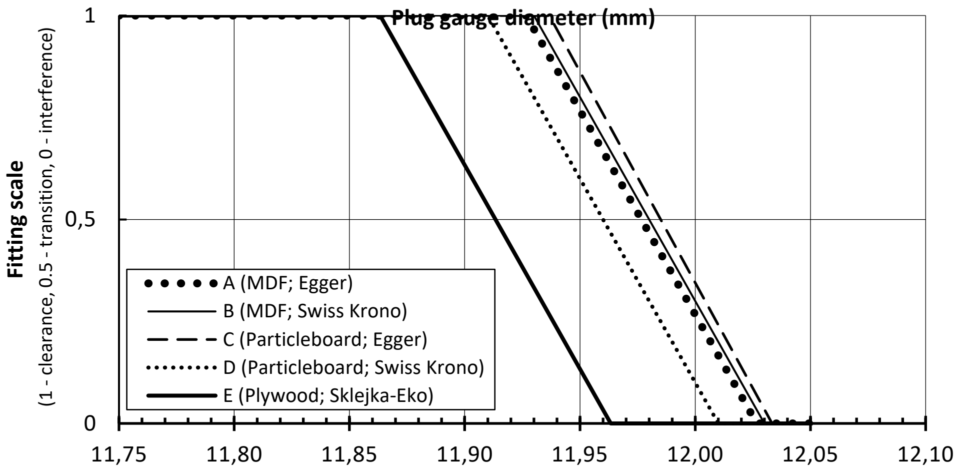

Fig. 5. Degree of fit of plug gauges of different diameters to holes in the five tested samples (means, $n = 15$)

Supplementary information to the medians is provided by the average gauge diameters (Fig. 5). The tendency in the case of the averages is the same as in the case of the medians: the smallest diameter of the freely inserted gauge was observed for plywood (11.87 mm), and the largest for chipboard and MDF (11.92–11.94 mm).

An analysis of the observed diameters of the cylindrical plug gauges revealed a discrepancy between the drilled holes' practical diameters and the nominal diameter of the drill bit. In all tested materials, the diameter of the freely insertable cylindrical plug gauge was smaller than the nominal drill diameter. The most significant difference between the plug gauge diameter and the nominal drill size was found in beech plywood (material E). In contrast, the slightest difference occurred in MDF boards (materials A and B). Particleboards C and D exhibited intermediate behavior between plywood and MDF, varying depending on the manufacturer.

A hole-basis fit is generally considered easier to manufacture for mating furniture elements. Tools (drills) with nominal diameters are used in such an approach. To obtain a given type of fit between the shaft and the hole, the diameter of the shaft, which is a mounting element, such as a dowel or other furniture fastener, is varied. Therefore, understanding the difference between the nominal drill bit diameter and the actual hole diameter is crucial. The study results can be summarized as follows:

- A cylindrical element with a diameter of 98.8% of the hole's nominal diameter can be freely inserted manually into holes drilled in plywood (E); however, if the diameter of such an inserted cylindrical element exceeds 99.3% of the nominal diameter of the hole, its insertion becomes impossible. The diameter of cylindrical elements that are to be manually inserted into holes made in plywood should not exceed 98.8% of the nominal diameter of the hole.

- In the case of the other tested materials (particleboards C and D and MDFs A and B), a cylindrical element with a diameter of 99.2–99.6% of the nominal diameter of the hole can be freely manually inserted into the holes. If the diameter of the inserted element exceeds 99.7–99.9% of the nominal diameter of the hole, manual insertion of such an element becomes impossible. The diameter of cylindrical assembly elements that are to be manually inserted into holes made in particleboards and MDF should not exceed 99.2% of the nominal diameter of the hole.

The observed discrepancy between the practical hole diameters and their nominal values can be attributed to variations in hole dimensional accuracy and the surface layer properties of the holes. As noted in the Introduction, cutting speed, tool sharpness, machine rigidity, clamping force, and thermal expansion during and after drilling contribute to inaccuracies in the drilling effects. These factors collectively influence the final hole dimensions and shape (Podziewski et al., 2021; Bedelean et al., 2024). A complex interplay of machining parameters influences the accuracy of hole dimensions and shape in wood-based materials cutting. For example, excessive feed causes significant damage to the wood layer directly adjacent to the hole, giving it an irregular shape (Sydor et al., 2024); tribo-mechanical reactions occurring on the inner surface of the holes can locally alter material properties (Porankiewicz, 2002); the wear on the drill bit changes its geometry, resulting in inaccurate hole dimensions and shapes (Porankiewicz & Wieloch, 2008). Modeling this wear is complex, and its severity is affected by multiple factors (Porankiewicz, 2014). Optimizing cutting parameters to minimize heat generation, tool wear, and cutting forces is crucial for achieving accurate holes (Bedelean et al., 2022, 2024) and is feasible with current technology (Górski, 2022).

As noted in the Introduction, holes drilled in wood are not perfectly cylindrical but exhibit an irregular shape resembling a slightly flared cone, widening towards the bottom (Sydor et al., 2023). Due to the varying properties of the tested materials, different sizes and shape deformations of the cylindrical shape of the holes are expected, which may also influence the fit of the plug gauges.

All of these factors, combined with the specific properties of individual wood-based materials, cause the shapes and sizes of holes to differ in different materials. This explains the varied results obtained for different tested wood materials.

The results observed for plywood are particularly interesting. The significant reduction in the hole diameter compared to the nominal drill bit diameter in plywood can be attributed to several factors. The layered structure of plywood, with alternating grain directions, influences the drilling process results (Sydor et al., 2020). The wood fibers can resist the penetration of the drill bit, resulting in a smaller actual hole diameter after removing a drill bit. Additionally, beech wood in plywood, known for its hardness and density and "reinforced" by glue, is more challenging to drill than materials like particleboard and MDF. A combination of these factors likely contributes to the observed reduction in hole diameter. Further research and experimentation could help quantify each factor's relative impact.

The study has two limitations.

1. The study focused on common wood-based laminated materials (particleboard, MDF, plywood) with deep blind holes drilled alongside the layers. The results may not apply to solid wood due to its different structure. Drilling shallower holes across the layers might also yield different results.
2. A relatively large diameter twist drill was used; the findings might not apply to other drill designs, such as spade drills or drills that are long and have very small diameters, less than 4 mm, which tend to wander in drilled material.

Conclusions

The study aimed to experimentally measure the usable diameters of holes drilled in various furniture materials (MDF, particleboard, plywood) and to determine the extent to which the observed practical diameters deviate from the nominal diameter of the drill bit. The study shows that the diameter of the cylindrical gauge which can be freely manually inserted in the hole was always smaller than the nominal hole diameter and varied depending on the type of board material. The smallest diameters of the plug gauges were observed in plywood (98.8% of the nominal hole diameter), while larger ones were found in the case of MDF (99.6%). Particleboard gave intermediate values (99.2–99.6%). These results indicate that the type of material significantly affects the possibility of mounting other furniture elements in the hole, such as fasteners. The different structures and properties of the individual materials tested can explain the differences in the observed actual diameters of holes. Analysis of the results leads to the following conclusions:

1. Plywood's specific internal structure and material properties reduce the practical hole diameter to the greatest extent.
2. Warping of the inner surface of the holes in the particleboard is a potential cause of significant differences in the practical diameter of the holes between the holes.

3. The fact that the structure of the MDF board is the most homogeneous among the tested wood materials is possibly responsible for the practical hole diameter being closest to the nominal drill bit diameter used for drilling.
4. The diameter of cylindrical elements that are to be manually inserted into holes made in plywood should not exceed 98.8% of the nominal diameter of the hole. The diameter of cylindrical assembly elements that are to be manually inserted into holes made in particleboards and MDF should not exceed 99.2% of the nominal diameter of the drill bit diameter used for drilling.

The first three conclusions are of theoretical significance, while the last is strictly practical (technological). It underscores the importance of considering the discrepancy between the nominal diameter of the drill and the practical (usable) diameter of the drilled hole when designing and manufacturing furniture, particularly self-assembly or "flat-pack" furniture, where ease of assembly by non-professional buyers is paramount. These findings have practical implications for designing the diameters of fasteners for particleboard, MDF, and plywood for furniture. The methodology used in this study can be applied to test other wooden furniture materials and holes of different dimensions.

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