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Testing the tightness of a square joint between oak wood elements

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Abstract: *Testing the tightness of a square joint between oak wood elements.* The study was carried out to determine the tightness of square joints between elements made of oak wood. To determine the degree of tightness of these joints, a device measuring the swelling pressure of oak wood under the influence of water humidification was designed. Checking the tightness of joints was carried out for surfaces obtained by machining through: grinding, milling, machine planing and manual planing. Contact angles at the phase boundary wood-water and their roughness achieved as a result of machining were also determined. During the wood swelling pressure test, the values of the preload of square joints were changed. The analysis of the results showed that the tightness of the square joint is influenced mainly by the roughness of the surface obtained as a result of machining and the size of the force of the initial load exerted on the moistened surfaces.

Keywords: swelling pressure, roughness, tightness of joints, oak wood

INTRODUCTION

Square joints between elements made of oak wood are found mainly in cooper products [Papierowski 1952, Świtkowski 1957, Zenkteler 1971, Dobrowolska, Niemz 2016], used for storage and maturing of noble wine, alcohols, whiskey, port, beer and others.

Due to the specific characteristics of cooper's products, the manufacturing process consists of many operations, including obtaining from logs and bolts elements with appropriate cross-sections, drying process [Bernatowicz, Guzenda and others 1996; Bernatowicz 1996; Glijer 2007 and many others] and surface forming. According to the principles of traditional cooper’s craft, the surfaces of the elements were formed with hand planers and spokes haves. Nowadays, for this purpose, various methods of mechanical processing are used, allowing to obtain a surface that ensures the tightness of square joints [Prządka, Szczuka 1997]. It is possible thanks to proper surface roughness, which is influenced not only by the machining process, but also by the anisotropy and heterogeneity of the wood structure.

The tightness of square joints is also associated with the dimensional stability of the wood during soaking. As a result of moisture exposure, the linear and volumetric dimensions of wood [Niemz , Sonderegger 2017] change. During moisture absorption, the adsorption forces are greater than the forces of intermolecular cohesion and cause swelling of the wood. The restriction of the freedom of swelling leads to the formation of swelling pressure, which achieves its highest value while suppressed in three anatomical directions. Stopping the swelling in one or two directions reduces swelling pressure resulting from the deformation of the material in the other free directions. Unidirectional swelling damping occurs in elements connected by square joints [Prekitny 1951, Raczkowski 1960, Stefaniak 1962, Krzysik 1975, Krauss 1988, 2004]. By applying a sufficiently high preload to the joints, the size of the swelling, and thus the swelling pressure, is reduced [Perkitny 1951, Glijer 2007, Świderski 1966, Rybarczyk, Ganowicz 1974].

The analysis of the literature shows that there is a lack of detailed information on surface properties, such as wettability and roughness, associated with the treatment of oak wood elements, ensuring high tightness of square joints.

PURPOSE OF THE STUDY

The purpose of the study was made to characterize the properties of the oak wood surface which ensures the making of a tight square joint. Above all, attention was paid to the influence of various types of processing and the influence of the initial force pressing the surface on the tightness of the obtained joints. An attempt was to determine the tightness of a square joint between elements made of oak wood with surfaces milled, ground and planed with a manual and machine planer.

The scope of work included designing and construction of a device for testing the tightness of joints by measuring the swelling pressure while moistening wood with water. The significance of the initial load and the influence of roughness and wettability of the oak wood surface on the tightness of square joints were determined during the swelling pressure measurement.

METHODOLOGY

Test material

The samples were made of 1 class (PN-72 D-96002) oak hardwood, without defects, without knots or twisted fibres. The width of the samples was along the radial direction [Fig. 1].

A B

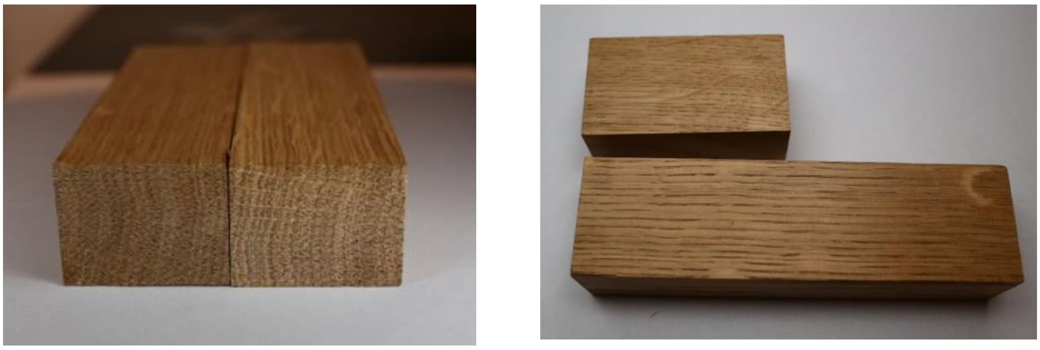

Figure 1: Radially cut oak samples 30 mm×40 mm (A) and 70 mm and 140 mm in length (B)

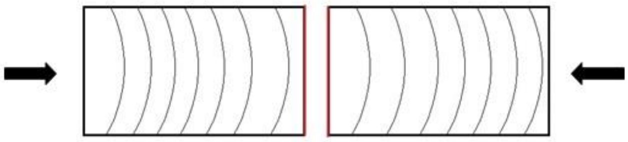

Figure 2: Arrangement of samples for testing the tightness of a square joint taking into account the direction of annual increments

The thickness of the samples was 30 mm and the width was 40 mm, The length of the sample corresponded to the length of the joint being tested and was 70 mm or 140 mm, forming, together with the thickness, a contact area between the samples [Fig. 1].

The device for measuring the swelling force during the single-sided moistening process is designed for a maximum load of 5.88 kN, with a sample length of not more than 230 mm and a contact area of not more than 700 mm^2 [Krzysik 1975, Perkitny 1951]. The length of the samples equal to 70 mm was taken for the first variant of the test and 140 mm for the second variant. The moisture content of the test material was 6%. The average grain size was 2.01 mm with a standard deviation of 0.35 mm, i.e. 17.5% of the average value (the determination was made in accordance with PN-55/D-04110).

The density test was performed on 20 samples of average density of 701 kg/m^3 (at the coefficient of variation for density measurement it is 3.0%), the shrinkage of the oak wood in the radial direction was 4.1% (PN-77/D-04101; PN-82/D-04111).

The arrangement of the samples as shown in Figure 2 when square jointed eliminates any additional forces that may affect the level of the swelling pressure.

Surface treatment and determination of roughness and wettability

The surface of the samples was formed with:

- Shank cutter with a diameter of 50 mm with four blades at the 14.000 rpm,
- Manual plane, thickness cut of 0.3 mm (the blade protrusion) with feed rate about 0.5 m/s,
- Sandpaper of 400 grit,
- Thicknesser with cutter head with a diameter of 100 mm and with four blades at the 4.500 rpm.

The test of roughness of the obtained surfaces was performed on a portable device for measuring roughness “Mitutoyo”. The study distinguished roughness values such as Rz and Ra according to PN-84/D01005 standard. The measurement section was 12 mm and was carried out in places free from cut vessels and medullary ray. The test was carried out along and across the fibres.

The contact angle was also measured in areas free from cut anatomical elements of wood in the form of vessels and wood rays. Lower roughness values mean lower occurrence of micro irregularities on the surface of the sample. The contact angle was examined by goniometric method with a universal goniometer device 300 from Phoenix Surface Electro Optics program-controlled Image XP 5.6. Distilled water was the liquid used in the study. Drops of water with a volume of 1 μl were dropped on the examined area and then a properly set camera recorded the image showing the change in its profile. Photographs of the drops were taken in the first second and after 30 seconds. The test for each surface was repeated 10 times. The angle between the surface of the sample and the tangent to the surface of the droplet was measured using appropriate software for photographic analysis.

Measurement of swelling pressure

A device with adequate stiffness and dimensional stability was designed to test the swelling pressure.

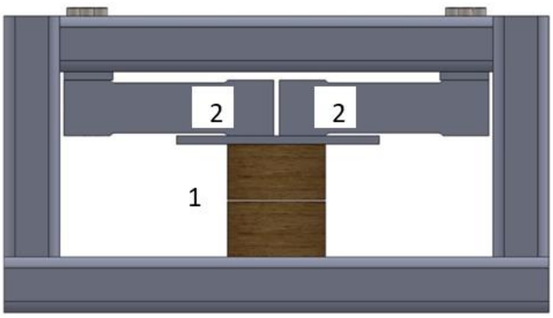

Figure 3. A diagram of a device for measuring swelling pressure and testing the tightness of a contact connection:1-samples, 2-beam strain gauges

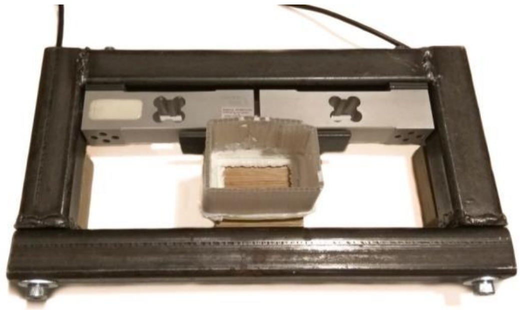

Figure 4. A measuring instrument with samples mounted in it, connected with a square joint, and a vessel with water insulated with silicone

A diagram of the test facility is shown in Figure 3. It consisted of the following components:

- a section of rectangular cross-section 40 mm × 40 mm × 4 mm × 4 mm,
- two strain gauge beam sensors with a force range from 0 to 2.94 kN,
- stainless steel plates of various thicknesses,
- M8 bolts made of hardened steel,
- a microprocessor for communication with a computer and calibration of sensors,
- a liquid storage vessel.

The initial load setting is achieved by installing bolts and washers of different thicknesses. The values of the initial load and the tracking of swelling pressure changes were controlled by two strain gauges, each up to 2.94 kN, giving a maximum force of up to 5.88 kN. The observation of the change in the swelling force made it possible to determine the maximum moisture content and swelling of the test material and the tightness of the joint.

Before each test, the device was calibrated and then two samples were placed in it, which were connected with a square joint with properly prepared surfaces, while maintaining the course of core radii in the same plane (Fig. 4).

Table 1. Variations in preload of samples depending on machining type

Sample No.	Version I		Version II	
	Sample type	Initial load [MPa]	Sample type	Initial load [MPa]
1	Milling	0.09	Milling	0.06
2	Milling	0.18	Grinding 400	0.06
3	Milling	0.30	Thicknesser	0.06
4	Milling	0.36	Manual plane	0.06
5	Milling	0.52	-	-

Washers of different thickness were inserted between the strain gauge and the samples, depending on the expected preload force (Tab. 1). Next, a vessel was placed on the surface of the samples, the edges of which were insulated with silicone and filled with water (Fig. 4).

The results were recorded for over two days with a 5-second interval. The water level in the vessel was supplemented and maintained at a constant level as the samples permeated and evaporated freely. The test lasted until the moment when the swelling force stabilized.

The tightness was assessed by observing the loss of liquid from the vessel irrigating the weld and by observing the seepage of liquid on the weld line in the cross-section. No loss of liquid in the vessel and drying of wood meant tightness of the joint.

TEST RESULTS

Results of conducted analyses include: roughness and contact angle of the surface depending on the machining method and the influence of the initial contact load on the swelling pressure.

The roughness and contact angle of the surface were tested on 140 mm long samples. The surfaces of the samples were prepared by machining: milling, grinding, manual planing by hand or by machine on a thicknesser. Photographs of the surfaces are shown in Fig. 5÷8.

Table 2. Surface roughness measured along the fibres after different types of machining

Measured values		Surface preparation			
		Milling	Thicknesser	Grinding	Planer
Average value	Ra	1.316	3.806	1.326	2.036
	Rz	8.328	20.536	10.312	12.948
Standard deviation	s_Ra	0.298	0.577	0.255	0.609
	s_Rz	1.772	4.473	2.247	3.607
Coefficient of variation	V_Ra [%]	22.7	15.2	19.3	29.9
	V_Rz [%]	21.3	21.8	21.8	27.9

The highest values for roughness, Ra, Rz, measured in the direction along the fibres (Tab. 2) and across the fibres (Tab. 3) are shown by the surface formed by mechanical planing on the thicknesser. In this case, the average value of Ra/Rz, from four measurements, for the direction along the fibres was 3.806/20.536 and across the fibres 2.869/19.052. For milling and grinding, the Ra/Rz values in the direction along the fibres were 1.316/8.328 and 1.326/10.312 respectively and 2.236/14.504 and 1.786/14.046 across the fibres, respectively. The surface roughness after manual planing exceeded the roughness after milling and grinding, equalling 2.036/12.948 along the fibres and 2.236/39.901 across the fibres. The highest surface smoothness was obtained after grinding with sand paper and milling.

Table 3. Surface roughness measured across the fibres after different types of machining

Measured values		Surface preparation			
		Milling	Thicknesser	Grinding	Planer
Average value	Ra	2.236	2.869	1.786	3.427
	Rz	14.,504	19.052	14.046	39.901
Standard deviation	Ra	0.414	0.566	0.449	0.786
	Rz	2.773	3.912	2.547	3.646
Coefficient of variation	Ra [%]	18,5	19.7	25.2	22.9
	Rz [%]	19.1	20.5	18.1	9.1

Figure 5. Contact surface after milling, with visible waves

Figure 6. Contact surface after processing with abrasive paper grit 400, with visibly chipped grain

Figure 7. Contact surface after manual planing, with visible small waves

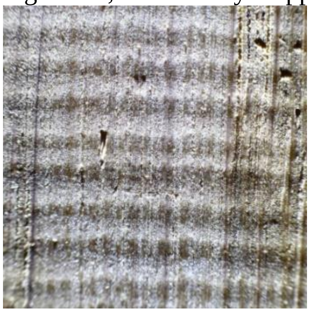

Figure 8. Contact surface formed using a thicknesser, characteristic deep wavy surface visible

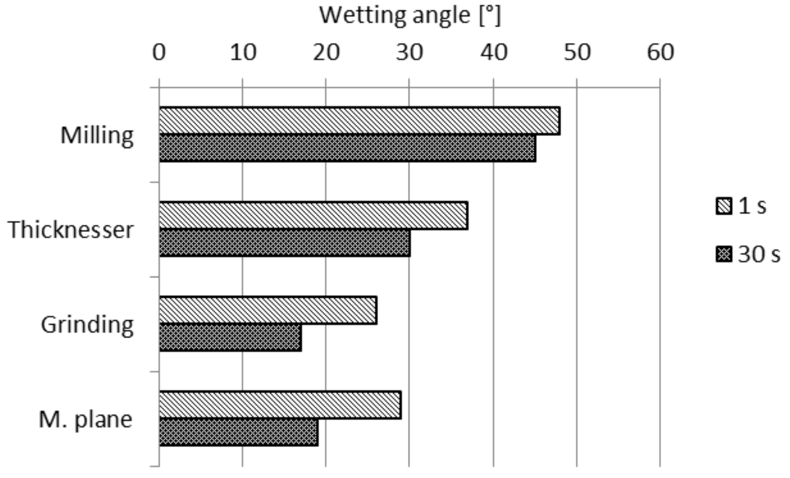

Figure 9. Contact angle for the surfaces of samples for individual processing methods at the beginning of the test (1 s) and after 30 s

A square joint that requires a high degree of smoothness to ensure the exact adhesion of the pressed surfaces eliminates the formation of a gap through which water can percolate. The highest surface smoothness was achieved with milling.

The results of the contact angle measurement are shown in Fig. 9. The highest contact angle was found for the milled surface and the lowest for the ground surface. Absorbent properties of water droplets deposited on the milled wood surface are the lowest in comparison to other methods of its processing. The change of contact angle for the milled surface in 30 seconds equalled 2.8°, and for the sanded paper – 11°. The results of the investigations show that the surfaces in contact with the ground surface will soak faster than those obtained by other methods of machining.

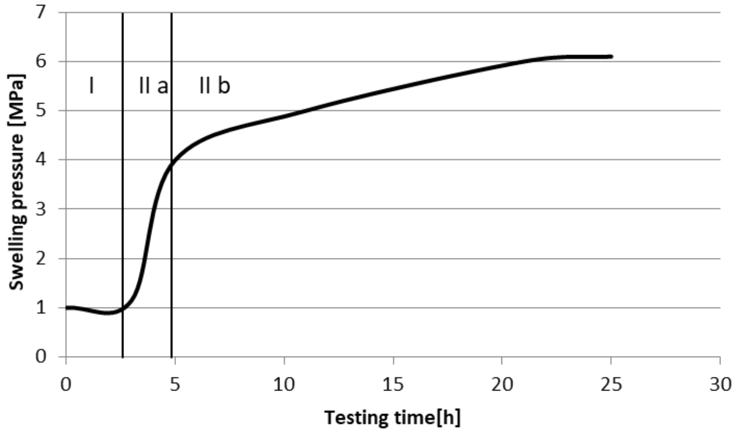

Figure 10. Characteristic areas of change in oak square joint swelling pressure at 0.1 MPa initial load

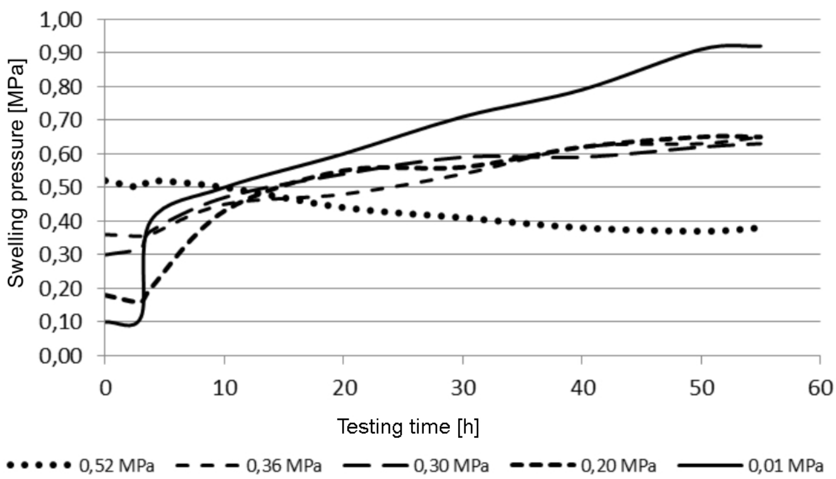

Figure 11. Swelling pressure depending on the size of the preload of the square joint of two oak wood surfaces

The study of the swelling pressure was preceded by an evaluation of the influence of the initial load exerted on the connection of two milled surfaces (Fig. 10). The change of swelling pressure in time, at the initial load of 0.1 MPa, shows a characteristic course which can be divided into three areas.

The first one (I) covers the contact pressure of the samples, which are lightly compressed under initial loading. As the compression ratio increases, the preload force decreases slightly and stabilizes. The second area (II) is related to the direct moistening of the contact surface of the samples and the increase of the swelling pressure, initially very intensive (IIa) due to the rapid penetration of moisture into the wood structure, and then slowing down over time (II b).

The analysis of changes in the magnitude of swelling pressure which occurs at the contact point of two surfaces shows that with the decrease in the initial load force, there is an increased rise in swelling pressure, especially in phase IIa. The swelling pressure increases as the initial load decreases (Fig. 11 and 12).

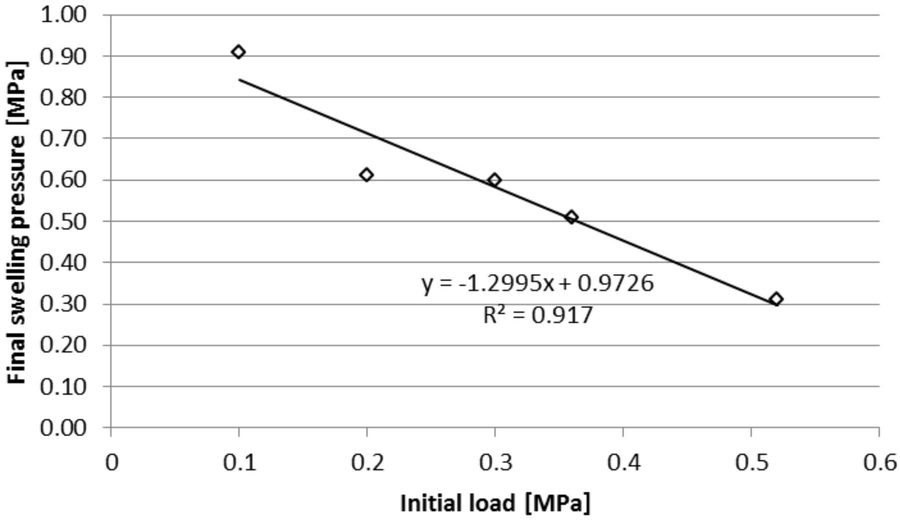

Figure 12. Size of swelling occurring between two surfaces connected by a square joint, at a preload of 0.1; 0.2; 0.3; 0.36 and 0.52 MPa after 55 hours of testing

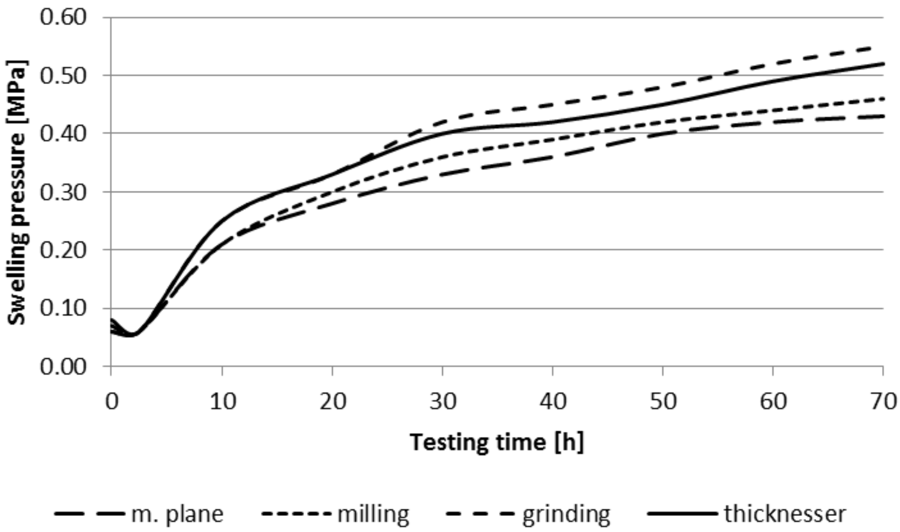

Figure 13. Swelling pressure depending on the different ways of forming the surfaces to be joined by a square joint at a preload of 0.06 MPa

Higher force acting on the contact surface reduces the process of penetration of moisture into the wood structure, causing throttling of swelling. At the highest tested initial contact load of 0.52 MPa, the swelling pressure decreased over time (Fig. 11). At such a high pressure of the combined surfaces of wood, its structures are significantly compressed, limiting the rate of moisture absorption.

Further tests included determination of the swelling pressure occurring at the contact point of surfaces formed with various methods (Fig. 13) with the initial lowest load of 0.06 MPa. The highest final values of swelling pressure and the highest rate of force increase in the initial stage of humidification were observed for the surfaces formed by grinding and using a thicknesser, characterized surface roughness expressed by Rz in the direction along and across the fibres equal respectively 10.312/14.046 and 20.536/19.053. For these variants, the final values of swelling pressure were 0.51 MPa and 0.53 MPa. For the milled surfaces with a roughness Rz of 8.328/14.504 along and across fibres the swelling pressure was 0.46 MPa and for manually planed surfaces it was 0.43 MPa, for which the roughness Rz for both directions was 12.948/39.901.The rate of force rise after wetting e.g. the ground surfaces was 0.03 MPa/h and the milled surfaces 0.02 MPa/h. In both cases, the intensity of soaking and higher final swelling values were affected by increasing roughness and decreasing wetting angle of the surface.

For all the surfaces tested, the joint was sealed at a certain point in time. For samples with ground surface and surfaces planed with a thicknesser, the water leakage ceased from the moment the swelling pressure of approx. 0.50 MPa occurred. In the case of surfaces milled and manually planed, the joint sealing was obtained at the swelling pressure of approx. 0.43 MPa.

A B C D

Figure 14. Moisture penetration through the joint. A – connected to the contact of the samples connected by a square joint prior to moistening, B – moisture penetration directly after pouring water into the vessel, C – after a few hours characteristic moistening of wood zones in the radial direction with moisture penetration through the joint, D – moment of joint tightening and drying of lower zones of the joined elements

The observation of the tightness of the square joint showed that water flowing through the gap moistened the wood zones located in the mainly radial direction (Fig. 14 B, C). The time after which the joint was sealed depended on the initial load and the resulting swelling pressure. For the sum of the initial load and the swelling pressure of less than 0.90 MPa, the joint was sealed after 40 hours and at a total of 0.62 MPa after 20 hours. At the moment of joint sealing, the lower layers of wood dried out (Fig. 14 D). After sealing, the material still partially swelled and the swelling pressure increased but much slower than at the beginning of the test, when the water percolated through the entire joint.

SUMMARY

Obtaining a tight square joint between oak wood elements depends on the properties of the surface, resulting from the way in which they are processed and the size of the initial load on the joint. Among the tested methods of machining, the joint sealing for milled surfaces was the fastest.

The contact of the surfaces was influenced by their roughness and contact angle. At the highest surface roughness expressed by Rz in the direction along and across the fibres equal 20.536/19.052, characterizing the surfaces formed with a thicknesser, the sealing of the square joint took place at a swelling pressure of about 0.50 MPa. For ground surfaces with a roughness Rz of 10.312/14.046 along and across fibres, the maximum swelling pressure was 0.53 MPa. In other cases, for surfaces finished with manual planing and milling, for which the roughness Rz for both directions was 12.948/39.901 and 8.328/14.504 respectively, sealing took place at a significantly lower swelling pressure ranging from 0,46 MPa to 0.43 MPa.

The water percolation through the joint also depended on the wettability of the surface. With a wettability of 17°, which characterises the ground surface, the seepage time over the entire contact cross-section was 30 seconds. For other surfaces with wettability ranging from 30 to 47°, the seepage time was almost ten times longer.

On the basis of the conducted research it was found that the maximum swelling pressure measured at the contact of two surfaces depended on the size of their initial load. With an increase of the initial load there was a decrease in swelling pressure. At the initial load of 0.36 MPa the maximum swelling pressure was 0.58 MPa and at the initial load of 0.10 MPa the swelling pressure was 0.90 MPa. Exceeding the value of 0.52 MPa of the initial joint load at the joint inhibited the increase of wood swelling pressure. The compression of layers occurring in the joint zone significantly reduced water percolation into the wood.

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Streszczenie: *Badanie szczelności połączenia na styk elementów z drewna dębowego*. W pracy przeprowadzono badanie szczelności połączeń na styk elementów wykonanych z drewna dębowego. Do ustalenia stopnia szczelności tych połączeń zaprojektowano urządzenie, mierzące ciśnienie pęcznienia drewna dębowego pod wpływem nawilżania wodą. Sprawdzanie szczelności połączeń przeprowadzono dla powierzchni uzyskanych w wyniku obróbki skrawaniem poprzez: szlifowanie, frezowanie, struganie grubościowe maszynowe i strugiem ręcznym. Określono również kąt zwilżania wodą powierzchni i ich chropowatość osiąganą w efekcie obróbki skrawaniem. W czasie badania ciśnienia pęcznienia drewna zmieniano wartości wstępnego obciążenia połączeń stykowych. Analiza wyników wykazała, że na szczelność połączenia na styk ma wpływ przede wszystkim chropowatość powierzchni uzyskana w rezultacie obróbki skrawaniem oraz wielkości siły wstępnego obciążenia wywieranego na nawilżane powierzchnie.

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