Ivica Župčić[1], Igor Đukić[1], Matija Jug[2], Mario Jurišić[3], Marin Hasan[1]

The Influence of Different Wood Modifications on Pull-out Force of Rotary Welded Dowels

Utjecaj različitih vrsta modifikacije na izvlačnu silu rotacijski zavarenih moždanika

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ABSTRACT • *The increasing use of modified wood justifies the intention to use it in joints made by rotary welding with dowels. Thermal modification, for example, increases the dimensional stability of wood by reducing its hygroscopicity and water absorption, but it is difficult to glue or to rotary weld due to the appearance of cracks. This can be avoided by changing the optimal welding parameters, which on the other hand directly affects the reduction of the pull-out force by more than 25 % depending on the type of the modified base. In the case of welding wooden dowels into wood modified with citric acid, the reduction in pull-out force is even greater. Due to the significant reduction, the use of this type of modification for wood welding is questionable. When citric acid modification is extended to the dowels, the dowel becomes a problem due to its lower tensile strength, which is even lower than the pull-out force of the welded dowel.*

KEYWORDS: *rotary welding; thermal modification; modification with citric acid; pull-out force; wooden dowels*

SAŽETAK • *Zavarivanje drva trenjem proces je kojim se spajaju dva ili više elemenata drva. Zbog trenja se stvara toplina koja omekša i rastali strukturu drva. Zavarivanje toplinski modificiranog drva zanimljivo je zbog sve veće primjene takvog drva u praksi. Toplinskom modifikacijom zbog smanjenja higroskopnosti i upijanja vode povećava se stabilnost dimenzija drva, ali zbog pojave pukotina u uzorku može biti otežano lijepljenje drva i rotacijsko zavarivanje moždanika. To se može izbjeći tako da se mijenjaju optimalni parametri zavarivanja, što izravno utječe na smanjenje izvlačne sile. Izvlačna sila moždanika zavarenoga u toplinski modificiranu podlogu smanjuje se za više od 25 %, ovisno o vrsti uzorka. Smanjenje izvlačne sile moždanika zavarenoga u drvo modificirano limunskom kiselinom čak je i veće. Zbog značajnog smanjenja izvlačne sile zavarenog moždanika upitna je primjena modifikacije limunskom kiselinom, kao i topinska modifikacija. Pri modifikaciji moždanika limunskom kiselinom vlačna je čvrstoća moždanika manja od izvlačne sile zavarenog moždanika.*

KLJUČNE RIJEČI: *rotacijsko zavarivanje; toplinska modifikacija; modifikacija limunskom kiselinom; izvlačna sila; moždanik*

[1] Author is associate professor at University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb, Croatia. https://orcid.org/0000-0002-3284-8909, https://orcid.org/0000-0002-9546-5024, https://orcid.org/0000-0003-0195-7464
[2] Author is assistant professor at University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb, Croatia. https://orcid.org/0000-0002-4653-1515
[3] Author is a master's student at University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb, Croatia.

1 INTRODUCTION
1. UVOD

When welding wood by friction, it is possible to join wood elements because the heat changes the structure of wood. Friction caused heat softens and melts the chemical structure of wood (hemicellulose, lignin and accessory substances), and cellulose fibres are intertwined in the melt thus formed. The strength of rotary welded joints is comparable to the strength of glued joints. Belleville *et al.* (2013) reported that, when heat-welding the birch and maple wood, the hemicellulose breaks down, and the heat affects the lignin polymer causing its depolymerisation. The efficiency of welding is therefore directly related to the properties of the original wood elements, primarily properties of lignin and hemicellulose. Due to lots of research and developments of different wood modification processes, and due to a wide range of applications of modified wood, the authors thought that it would be interesting to research the possibility of welding the modified wood.

Wood modification is a process in which the chemical, physical and technical properties of wood are changed (Hill, 2006). Nowadays, the modification of wood has progressed considerably and is increasingly being used for commercial purposes. It is also necessary to differentiate the modification of wood primarily for increasing its biological resistance and wood modification for changing its mechanical, physical and/or technical properties. Modification is the action of chemical, biological or physical factors in wood, and as this action changes the chemical composition of wood cell walls, modification improves certain properties of wood (Hill, 2006).

The desired properties of the modified wood are obtained by combining the type of heating medium, duration of the process, final temperature, pressure of the process and modified wood species (the main modification parameters). By reducing the coefficient of swelling and shrinking, the stresses in the coating-wood surface system are reduced and the service life of wood, as well as of products made of modified wood, is extended (Hasan and Despot, 2008). In addition to changes in physical and mechanical properties at a temperature of 433 to 493 K, wood resistance to fungi and climatic influences also increases (Kamdem *et al.,* 2002). Heat treatment of beech wood at different temperatures causes a change in the characteristics and chemical components of wood (Windeisen *et al.,* 2007). Wood deformations caused by changes in water content in modified wood can be reduced by up to 80 %, and water absorption by up to 70 % (Patzelt *et al.,* 2002). The same authors stated that the decrease in water absorption is the result of a decrease in wood density and change in the chemical structure of the modified wood. Beech, pine and spruce had the greatest dimensional stability with the same mass loss. Compared to spruce, beech has a greater mass loss under the same conditions of thermal modification. Due to the presence of oxygen, regular air, as a heating medium of modification, causes a greater degree of decomposition of wood matter compared to nitrogen.

If the modification temperatures are higher than 200 ºC, or if the modification pressure is elevated at the lower temperatures, significant degradation of the wood structure occurs. The share of cellulose remains almost unchanged, while the share of hemicellulose decreases from 21 % to 1.99 % (200 ºC for 10 h). With an increase in the processing time, there may be an increase in the proportion of lignin, since some components formed by degradation are very similar to lignin (Yildiz *et al.,* 2006). The mechanical properties of thermally modified wood are reduced both parallel and perpendicular to the direction of wood fibres. Mechanical properties of modified wood can be evaluated by testing its impact strength. Impact strength of modified wood decreases linearly with the increase of the modification temperature (Rapp and Sailer, 2001; Rapp *et al.,* 2006).

The strength of the welded joint was improved by heating the dowel to 100 ºC to a water content of 1.5 % and welding it into the substrate (Pizzi *et al.,* 2004). The thermal modification of wood (200 °C for 48 hours) affects the reduction of the pull-out force of the dowel (Župčić *et al.,* 2009). The same authors reported that the pull-out force of the modified hornbeam is 46 % lower compared to the unmodified one. Due to the increased brittleness of the thermally modified bases, the bases crack, so it is necessary to increase the welding time to avoid the cracks (Župčić *et al.,* 2009). When wood is heated almost without oxygen, hemicelluloses break down first, followed by cellulose and finally lignin (Tjeerdsma *et al.,* 1998). This cellulose decomposition is one of the factors that affect the strength of the welded joint. Thermally modified samples of beech wood can be successfully joined longitudinally using the rotary welding method (Pizzi *et al.,* 2004; Župčić *et al.,* 2011). The thermal modification affects the reduction of strength of the welded joint. By increasing the heat modification temperature from 140 °C to 180 °C, the joint strength decreases. The vibrational welding is also affected by the thermal modification of wood with a significant reduction in shear strength (Vaziri and Sandberg, 2021). The shear strength of the welded joints was lower in the samples that were modified before welding compared to the samples that were initially welded and then thermally modified. Therefore, thermal modification is not suitable for improving the resistance of the welded joint to the influence of water.

The weak water resistance of welded joints is based on uneven swelling of the weld and adjacent wood, which causes high stresses in the welded joint (Vaziri *et al.,* 2019). The strength of the joint made by vibration welding of thermally modified wood is twice lower than the joint of unmodified wood (Boonstra *et al.,* 2006).

Zhang *et al.* (2018) treated base samples with $CuCl_2$ and this treatment resulted in an increase of pull-out force of % compared to untreated samples, with the same dowel welding time. The same authors reported that by extending the welding time, the pull-out force decreased. The treatment with $CuCl_2$ affects the strength of the joint due to the formation of more molten materials by the depolymerization and pyrolysis of the wood components (Zhang *et al.,* 2018). However, $CuCl_2$ has a negative impact on the environment.

Citric acid is one of polycarboxylic acids, together with butanetetracarboxylic acid (BTCA), used to improve the dimensional stability of solid wood and wood panels, as well as to increase the biological resistance of modified solid wood (Peyer *et al.*, 2000; Šefc, 2006; Hasan, 2010). It is ecologically and economically acceptable and does not contain formaldehyde. The tensile strength of wood modified with citric acid is reduced by up to 50 %, and with a decrease in the concentration of citric acid, the drop in tensile strength also decreases (Šefc, 2006). By increasing the concentration of citric acid up to 10.5 %, the biological resistance of beech and pine wood modified with citric acid against rot fungi increases significantly (Hasan, 2010).

This research aimed to determine the possibility of welding thermally modified wood and wood modified with citric acid. Today, modified wood is successfully used in exterior applications for floors and facades, so it is important to understand the possibilities of welding modified wood due to its wide range of application in construction.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Beech wood (*Fagus sylvatica* L.) was used in the research, randomly selected from the storage of sawn timber, so its origin is unknown. The planks were 50 mm thick without knots, pin knots, irregular heartwood and cracks. The chosen planks were first air-dried and then kiln dried to the final moisture content of (11±1) %. The texture of planks was semi radial / tangential. For wooden dowels production, beech wood grooved rods, 1000 mm in length and 10 mm in diameter, were purchased on the free market.

2.2 Specimens for bases and dowels preparation
2.2. Priprema uzoraka baza i moždanika

The base specimens were made using the technique of sawing, fine planing and cross-cutting to the exact shape and size. Specimens with a cross section of 30 × 30 ± 0.1 mm and a length of 64 ± 0.1 mm were used as a base for welding the dowels parallel to the grain. A hole was drilled in longitudinal direction in the centre of each specimen (Figure 1). Specimens with a cross section of 30 × 30 ±0.1 mm and a length of 200 ±0.1 mm were used as a base for welding the dowels perpendicular to the grain. In each specimen, three holes were drilled perpendicular to the grain, spaced 66 mm apart, and the two side holes were moved from the edge of the specimen by 34 mm (Figure 2). All holes were drilled with a Universal HSS spiral drill of 8.5 mm in diameter, with a rotation frequency of 1520 min^{-1}. The diameter of the holes drilled parallel to the grain was smaller than the diameter of the drill by 0.01 to 0.05 mm, while the diameter of the holes perpendicular to the grain was smaller by 0.06 to 0.1 mm than the diameter of the drill.

The dowels were made by sawing 1000 mm long wooden rods to 120 mm. Each dowel end (cross section) was bevelled for 1 mm at an angle of 45°. The average diameter of the grooved dowels was 10.06 mm measured crosswise at the top of the dowel. The dowels prepared in this way were conditioned in laboratory conditions for more than 30 days before welding and modification.

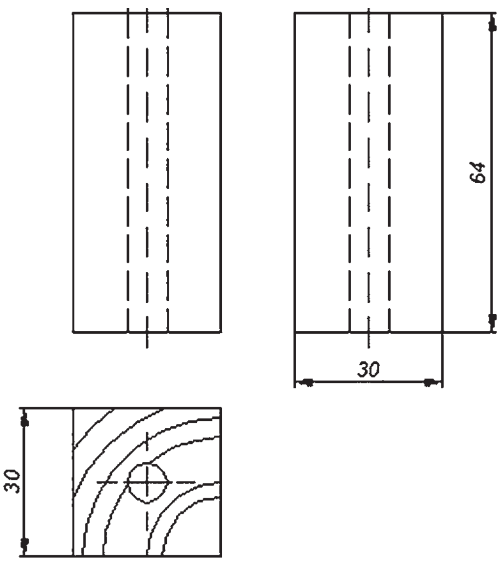

Figure 1 Specimen (base) for welding dowels parallel to grain
Slika 1. Uzorak za zavarivanje moždanika u smjeru vlakanaca

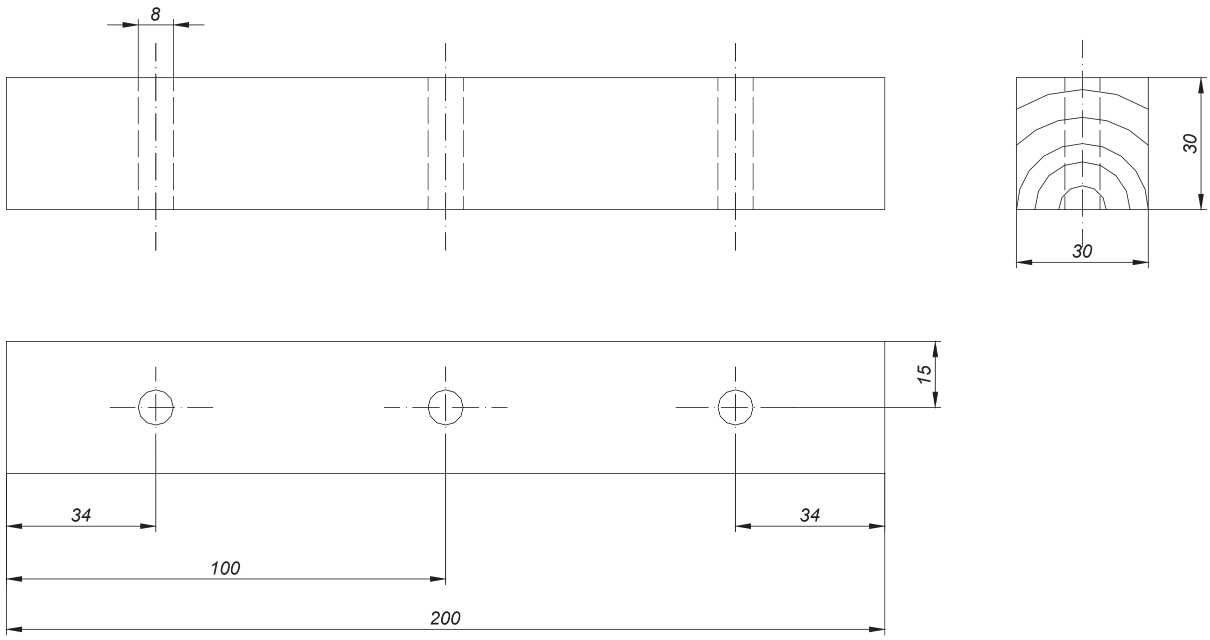

Figure 2 Specimen (base) for welding dowels perpendicular to grain
Slika 2. Uzorak za zavarivanje moždanika okomito na smjer vlakanaca

2.3 Preparation of modified specimens
2.3. Priprema modificiranih uzoraka

To investigate the influence of selected factors on the pull-out force of the welded dowels, 10 different joints were tested (Table 1). Joints were prepared with differently modified sample bases and/or dowels and different directions of welding or gluing of the dowels. Thermal modification as well as thermo-condensation phase of modification with citric acid were performed in air atmosphere. The procedure was carried out by gradual heating of the specimens (bases and/or dowels) up to a temperature of (103 ± 2) ºC to achieve 0 % moisture content. Then the temperature was linearly increased to 160 ºC over a period of 40 minutes. At a temperature of 160 ºC, the wood was thermally modified for 10 hours. After 10 h, the temperature was linearly decreased over the next 40 min to (103 ± 2) ºC, and the modified specimens were cooled to room temperature in a desiccator over silica gel. After modification, samples were weighed on a precise laboratory balance (±0.1 mg), and the moisture content and mass loss of thermally modified wood were determined. The average mass loss caused by thermal modification was 2.6 % (1.4 % to 3.5 %), and after 60 days of conditioning in laboratory conditions the average moisture content in the thermally modified specimens was 6.4 % (min, 4.2 % max. 7.7 % measured according to HRN ISO 13061- 1:2015). After conditioning, the dowels were welded into the bases.

An aqueous solution of 10.5 % of citric acid was prepared with the addition of 7.5 % sodium hypophosphite, SHP ($NaH_2PO_2 \times H_2O$) as a catalyst. The second set of specimens (bases and dowels) were immersed in the prepared solution and impregnated by full cell procedure (vacuumed in the chamber for 2 h, after which the pressure in the chamber was raised to 4 bar and maintained for the next 2 h). After finishing the impregnation, the excess solution from the specimens was wiped with a cloth, and the impregnated specimens were left for 10 days in laboratory conditions for drying and conditioning. After drying in laboratory conditions, the specimens (bases and dowels) were placed in an oven dryer and the temperature was gradually (over 6 hours) increased to (103 ± 2) ºC. Care was taken to prevent the sudden drying of the specimens and the appearance of cracks. Since the drying went well, the temperature was linearly increased during the next 40 minutes to the final thermo-condensation temperature of 160 ºC and maintained for 10 h. After the completion of thermo-condensation (modification of the specimens), the temperature linearly decreased to (103 ± 2) ºC over the next 40 minutes. The final cooling of the modified specimens to room temperature was carried out in a desiccator over silica gel. After 60 days of conditioning in laboratory conditions, the average moisture content in the specimens (bases and dowels) modified with citric acid was 6.0 % (min. 5.1 % max. 6.6 % measured according to HRN ISO 13061-1:2015).

Modified and unmodified dowels were glued and welded into modified and unmodified bases as described in Table 1. For each parameter combination, 36 joints were glued or welded.

Table 1 List of test combinations and sample codes
Tablica 1. Popis ispitanih kombinacija i označivanja uzoraka

O. nu. *Red. br.*	**Test description** /*Opis ispitivanja*	**Code** *Oznaka*
1	Unmodified dowels welded into thermally modified base perpendicular to wood grain *nemodificirani moždanici zavareni u termički modificiranu podlogu okomito na smjer vlakanaca*	MRTV
2	Unmodified dowels glued into thermally modified base perpendicular to wood grain *nemodificirani moždanici zalijepljeni u termički modificiranu podlogu okomito na smjer vlakanaca*	MRTLJ
3	Unmodified dowels welded into thermally modified base parallel to wood grain *nemodificirani moždanici zavareni u termički modificiranu podlogu paralelno sa smjerom vlakanaca*	MPV
4	Unmodified dowels glued into thermally modified base parallel to wood grain *nemodificirani moždanici zalijepljeni u termički modificiranu podlogu paralelno sa smjerom vlakanaca*	MPLJ
5	Unmodified dowels welded into base modified with citric acid perpendicular to wood grain *nemodificirani moždanici zavareni u podlogu modificiranu limunskom kiselinom okomito na smjer vlakanaca*	LKV
6	Unmodified dowels welded into base modified with citric acid parallel to wood grain *nemodificirani moždanici zavareni u podlogu modificiranu limunskom kiselinom paralelno sa smjerom vlakanaca*	LKPV
7	Unmodified dowels glued into base modified with citric acid parallel to wood grain *nemodificirani moždanici zalijepljeni u podlogu modificiranu limunskom kiselinom paralelno sa smjerom vlakanaca*	LKPLJ
8	Dowels modified with citric acid welded into unmodified base parallel to wood grain *limunskom kiselinom modificirani moždanici zavareni u nemodificiranu podlogu paralelno sa smjerom vlakanaca*	MLKPV
9	Control test (8.5 mm) unmodified dowels welded into unmodified bases perpendicular to wood grain *kontrolno ispitivanje (8,5* mm*): nemodificirani moždanici zavareni u nemodificiranu podlogu okomito na smjer vlakanaca*	8,5 RTV
10	Control test (8.5 mm) unmodified dowels welded into unmodified bases parallel to wood grain *kontrolno ispitivanje (8,5* mm*): nemodificirani moždanici zavareni u nemodificiranu podlogu u smjeru vlakanaca*	8,5 PV

2.4 Production of test joints by rotary welding
2.4. Izrada ispitnih spojeva rotacijskim zavarivanjem

All welded joints were made using the rotary welding technique, where the dowel rotates at a certain frequency and is welded into stationary base. The dowels were welded parallel and perpendicular to the wood grain. The rotation frequency of the dowels was 1520 min^{-1}, the welding depth was 20 mm, and the duration of welding was from 0.8 to 1 s (Table 2), depending on the base or dowel modification type. Rotary welding was performed with an average interference fit of 1.6 mm in order to keep the welding times within optimal limits. It was not possible to use a larger interference fit due to the appearance of cracks in the modified bases or breakage of the modified dowels during welding. After the rotation was stopped, the pressure on the dowel was maintained for 5 seconds.

2.5 Production of test joints by gluing
2.5. Izrada uzoraka tehnikom lijepljenja

The samples intended for gluing were of the same dimensions as the samples for welding, except the holes were 10 mm in diameter. The average interference fit during gluing of the dowels was 0.16 mm. One-component waterproof PVAC bond Pattex super 3 (Henkel, Hungary) was used. The gluing process consisted of applying the glue on the dowel and inserting it partially into the hole. Then, using a stopper, the dowel

Table 2 Data on welding duration
Tablica 2. Podatci o trajanju zavarivanja

Type of modification and section *Vrsta modifikacije i presjeka*	**Average duration of welding, s** *Prosječno trajanje zavarivanja,* s	**Feed per revolution, mm** *Pomak po okretaju,* mm
MPV	1.0	0.79
MRTV	0.9	0.88
LKPV	0.9	0.88
LKRTV	0.8	0.99
MLKPV	1.0	0.79
8,5 PV	0.8	0.99
8,5 RTV	0.8	0.99

was pressed to a depth of 20 mm. After pressing, the excess glue was removed. The mass of the applied glue was determined by measuring the mass of the glued joints before applying the glue and after gluing (after removing the excess glue from the joint). The average application of glue for grooved dowels was 244 g/m² per joint. After gluing the dowels, the glued joints were conditioned in laboratory conditions for a minimum of seven days.

2.6 Testing method and data analysis
2.6. Metoda ispitivanja i analiza rezultata

The testing of the undamaged glued and welded joints was carried out on a universal tensile testing machine after its visual control. All prepared joints were conditioned for seven days before they were tested on a computer controlled universal / tensile testing machine Shimadzu AGX-V (AUTOGRAPH Precision Universal Tester AGX-V, SHIMADZU Corporation, Kyoto, Japan). The joints were tested using joint jaws for precise positioning. The movement of jaws during the test was 5 mm/min.

The data obtained from the measurements were processed in the StatSoft Statistica 8.0 software package. If the condition of normality of distribution and homogeneity of variance was satisfied (Table 4), the differences between individual groups of samples were tested by Student's T-test or by analysis of variance. If the condition of homogeneity of variance was not met (Table 7; F-test and Levene's test), the Mann-Whitney U-test or the Kruskal-Wallis test was used to confirm whether or not there was a statistically significant difference between individual groups of samples. Post-hoc tests established statistically significant differences between individual groups of samples if they existed (Tables 5 and 8). The difference greater than 5 % was considered significant. Presentations of comparisons were made using box and whisker graphs (Figure 3 and 4).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

During welding, a part of the wooden tissue of the dowel and base, which is in the zone of an interference fit, is melted (black line in Figure 3). The tip of the dowel is turned upwards, and it is visible that the welded joint becomes conical (Figure 3). Conical shape of the welded joint incurs due to tear off of the tip of the dowel during the beginning of the welding, while no melting temperature is reached.

During welding, modified wood melts much less than unmodified wood. The border of the dowel and the base in the welded joint in Figure 4 is the crack, and the thickness of the melt of thermally modified dowel is visibly smaller than the thickness of the melt of unmodified base (Figure 4).

Figure 3 Sections of welded unmodified dowel into unmodified base; tip of the dowel is turned upwards (Župčić, 2010)
Slika 3. Presjeci zavarenoga nemodificiranog moždanika u nemodificiranu podlogu; vrh moždanika usmjeren je prema gore (Župčić, 2010.)

An average density of unmodified wood of bases was 0.69 g/cm³ (min. 0.62 and max. 0.74 g/cm³; according to HRN ISO 13061-2:2015). Average density of thermally modified wood (bases) was (0.63 ± 0.04) g/cm³, while the average density of wood modified with citric acid was (0.67 ± 0.03) g/cm³. Thermally modified wood has increased dimensional stability, which is certainly a positive characteristic, but also increased brittleness, which is a negative characteristic when wood is to be used for rotary welding. The fragility of wood during rotary welding requires an extension of the duration of the welding process, and it requires the reduction of the interference fit. The optimal interference fit for rotary welding of 10 mm diameter dowels is 2 mm (Pizzi *et al.*,

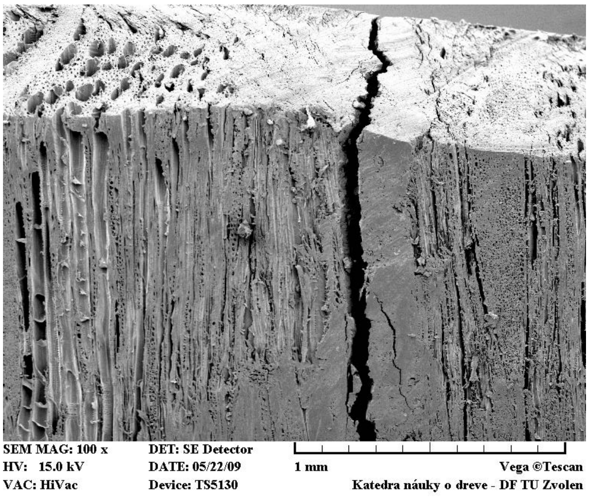

Figure 4 SEM micrograph of transversal section of welded thermally modified dowel into unmodified base: Left of crack - dowel; Right of crack - base (Župčić, 2010)
Slika 4. SEM mikrografija transverzalnog presjeka zavarenog termički modiciranog moždanika u nemodificiranu podlogu: lijevo od pukotine je moždanik, a desno od pukotine je podloga (Župčić, 2010.)

2004). The welding time also affects the strength of the rotationally and vibrationally welded joints (Župčić *et al.,* 2011; Amirou *et al.,* 2020). Within this investigation, an interference fit of 2 mm was not adequate to ensure the optimal movement of the dowel during welding of the modified wood. Therefore, the interference fit was reduced to 1.6 mm, so that the welding time of the modified and unmodified specimens could be approximately the same, considering that the extension of the welding time reduces the strength of the joint. It was not possible to use a larger interference fit due to the appearance of cracks in the modified bases or the breakage of dowels during welding.

Welding the dowels modified with acid into the modified bases was difficult to perform due to occurrences of cracks and splits in the bases or fractures of the dowels. Due to the increased brittleness of the wood modified with citric acid, the dowels crumbled, and the bases split during welding. Splitting of the bases occurred often at the very beginning of welding due to the pressure of the dowel on the walls of the holes. For these reasons, modified dowels were successfully welded only in unmodified bases (Figure 4; but other problems arose during the pull-out test), and welding of modified dowels into modified bases was not carried through.

In addition to the increase in wood brittleness, it was observed that, when welding modified wood, less melt is coming out of the joint and more broken pieces of wood occur. A similar phenomenon occurs with vibrational welding of wood. During vibrational welding, the weld lines of heat-treated wood show intertwined fibres with none or a very small amount of the molten material that is usually observed when welding unmodified wood. In weld lines, obtained by hydrothermal processes during welding, an increase in stiffness and brittleness of the wood cells is observed (Boonstra *et al.,* 2006).

Statistical analysis revealed a statistically significant reduction in pull-out force of welded dowels compared to glued ones in the modified bases, both in a parallel and perpendicular direction to the grain (Tables 3, 4 and 5; 6, 7 and 8). The pull-out force of welded dowels parallel to the grain is 27 % lower, while the pull-out force of welded dowels perpendicular to the grain is 45 % lower than that of glued dowels. Higher pull-out force values were achieved by gluing and welding the dowels parallel to the grain compared to the perpendicular direction, which was expected on the basis of previous knowledge. The results of the research (Figure 5, Table 3) show an additional reduction in the pull-out force of glued and welded joints of specimens modified with citric acid compared to the thermally modified samples, as it was proven by Poljak (2008) who conducted a similar research.

A comparison of the pull-out forces obtained by welding thermally modified and unmodified wood parallel to the grain (Table 6, Figure 6) indicates a 25 % reduction in the pull-out force of thermally modified wood. Specimens modified with citric acid and welded perpendicular to the grain achieve a 32 % reduction in pull-out force compared to unmodified ones. Pull-out force of welded joints of thermally modified wood perpendicular to the grain is reduced by more than 36 % compared to pull-out force of unmodified joints. Welded joints modified with citric acid achieve a 4 % reduction in pull-out force compared to unmodified ones. Such a small reduction in pull-out force indicates an illogical result. Namely, it was expected that the

Table 3 Descriptive statistics of pull-out force depending on modification type and grain orientation of welded/glued joints
Tablica 3. Deskriptivna statistika izvlačne sile u ovisnosti o modifikaciji drva i smjeru vlakanaca zavarenih/slijepljenih spojeva

Code *Oznaka*	**Number of welded/glued and tested joints** *Broj zavarenih/zalijepljenih i ispitanih spojeva*	**Mean pull-out force, N** *Srednja vrijednost izvlačne sile,* N	**Std. Dev, N**	**Min, N**	**Max, N**
MPV	36	3255.1	501.3	2606	4493
MRTV	25	5198.4	481.5	1118	2989
MPLJ	31	4477.6	511.5	3633	5599
MRTLJ	12	4058.6	408.5	3586	4772
LKPV	29	2948.3	351.1	2342	3472
LKRTV	27	3333.5	333.1	2786	4078
LKPLJ	18	3606.3	537.6	2863	4817

Table 4 Levene test of homogeneity of variances of welded/glued joints pull-out forces
Tablica 4. Testiranje homogenosti varijance (Leveneov test) izvlačne sile zavarenih/slijepljenih spojeva

Variable *Varijabla*	***SS* effect**	***df* Effect**	***MS* Effect**	***SS* Error**	***df* Error**	***MS* Error**	***F***	***p***
Pull-out force, N *izvlačna sila,* N	560113.1	6	93352.18	12561687	171	73460.16	1.270787	0.273268

*Orange colour means statistically significant difference at $p < 0.05000$. / *Narančasto su otisnute statistički značajne razlike pri* $p < 0.05000$.

Table 5 Multiple post hoc test of welded/glued joints pull-out forces
Tablica 5. Višestruki *post hoc* test izvlačne sile zavarenih/slijepljenih spojeva

Code *Oznaka*	(1) M=3255.2	(2) M=2198.4	(3) M=4058.6	(4) M=4058.6	(5) M=2948.3	(6) M=3333.5	(7) M=3606.3
MPV (1)		0.000000	0.000000	0.000191	0.297686	0.998258	0.311292
MRTV (2)	0.000000		0.000000	0.000000	0.000008	0.000000	0.000000
MPLJ (3)	0.000000	0.000000		0.295059	0.000000	0.000000	0.000001
MRTLJ (4)	0.000000	0.000000	0.295059		0.000000	0.002571	0.314365
LKPV (5)	0.297686	0.000008	0.000000	0.000000		0.129865	0.001165
LKRTV (6)	0.998258	0.000000	0.000000	0.000571	0.129865		0.690699
LKPLJ (7)	0.311292	0.000000	0.000001	0.314356	0.001165	0.690699	

*Orange colour means statistically significant difference at $p < 0.05000$. / *Narančasto su otisnute statistički značajne razlike pri $p < 0.05000$.*

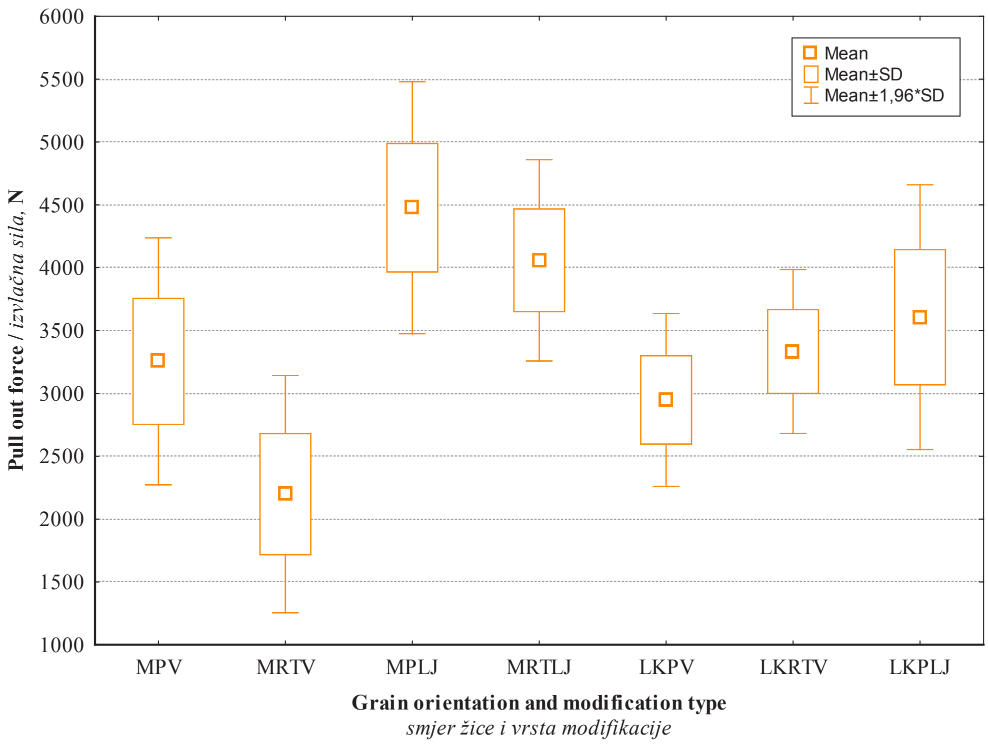

Figure 5 Influence of modification type and grain orientation on pull-out force of welded/glued joints
Slika 5. Utjecaj vrste modifikacije drva i smjera žice na izvlačnu silu zavarenih/slijepljenih spojeva

LKRTV samples would achieve a lower pull-out force compared to the MRTV samples. Comparing LKPV and LKRTV samples, the pull-out force of LKRTV samples is slightly increased (statistically not significant; Table 8), which was not expected. This increase in pull-out force is affected by the growth rings width, density of wood and the reduction of welding time by 0.1 s. Wood welding is a process that depends on nu-

Table 6 Descriptive statistics of pull-out force depending on modification type and grain orientation of welded joints
Tablica 6. Deskriptivna statistika izvlačne sile u ovisnosti o vrsti modifikacije i smjeru žice zavarenih spojeva

Code *Oznaka*	Mean Pull-out force, *F*, N *Srednja vrijednost izvlačne sile*, N	Number of welded and tested joints *Broj zavarenih i ispitanih spojeva*	Std. Dev. (*F*), N	Min (*F*), N	Max (F), N	Q25 (*F*), N	Median (*F*), N	Q75 (*F*), N
8.5 PV	4346.8	30	493.4	3472	5305	4013	4390	4699
MPV	3255.2	36	501.3	2606	4493	2908	3128	3510
LKPV	2948.3	29	351.1	2342	3472	2657	2945	3246
MLKPV	2586.4	25	966.4	774	4063	1886	2742	3269
8.5 RTV	3455.9	30	274.4	3057	3940	3222	3438	3660
MRTV	2198.4	25	481.5	1118	2989	1950	2179	2571
LKRTV	3333.5	27	333.1	2786	4078	3087	3319	3499

Table 7 Levene test of homogeneity of variances of welded joints pull-out force
Tablica 7. Testiranje homogenosti varijance (Leveneov test) izvlačne sile zavarenih spojeva

Variable *Varijabla*	***SS*** **effect**	***df*** **Effect**	***MS*** **Effect**	**SS Error**	***df*** **Error**	***MS*** **Error**	***F***	***p***
Pull-out force, N *izvlačna sila,* N	5278116	6	879686.0	17146604	195	87931.30	10.00424	0.000000

*Orange colour means statistically significant difference at $p < 0.05000$. / *Narančasto su otisnute statistički značajne razlike pri p < 0.05000.*

Table 8 Multiple comparisons of *p* values of welded joints pull-out force
Tablica 8. Višestruka usporedba rangova izvlačne sile zavarenih spojeva

Code *Oznaka*	**Kruskal-Wallis test H (6. *N* = 202) = 119.8847 *p* = 0.000**						
	8,5 PV R:181.03	MPV R:101.96	LKPV R:74.793	MLKPV R:65.980	8,5 RTV R:128.33	MRTV R:26.180	LKRTV R:114.02
8.5 PV		0.000001	0.000000	0.000000	0.010083	0.000000	0.000325
MPV	0.000001		1.000000	0.379561	1.000000	0.000013	1.000000
LKPV	0.000000	1.000000		1.000000	0.009163	0.048516	0.254168
MLKPV	0.000000	0.379561	1.000000		0.001719	0.337619	0.064440
8.5 RTV	0.000000	1.000000	0.009163	0.001719		0.000000	1.000000
MRTV	0.010083	0.000013	0.048516	0.337619	0.000000		0.000001
LKRTV	0.000325	1.000000	0.254168	0.064440	1.000000	0.000001	

*Orange colour means statistically significant difference. / *Narančasto su otisnute statistički značajne razlike.*

merous welding parameters (Pizzi *et al.,* 2004; Leban *et al.,* 2008; Župčić, 2010), such as the duration of the welding process, interference fit, growth rings width, wood density, rotation frequency, welding depth, etc. The average growth rings width of LKPV bases was 2.5 mm and of LKRTV bases 3.0 mm. The average density of LKPV bases was 0.65 g/cm^3, while the average density of LKRTV bases was 0.69 g/cm^3. Increasing the growth rings width of hardwoods increases the density of wood, and the increase in wood density results in a slight increase in the pull-out force (Župčić, 2010), but not significant. Therefore, the density of wood and the width of the growth rings can result in a slight increase in the pull-out force of the welded dowels (Table 6, Figure 6). The results of this research indicate a significant reduction of the pull-out force of welded joints of thermally modified wood and wood modified with citric acid, which raises the question of the justification of welding the modified wood (Tables 5 and 8).

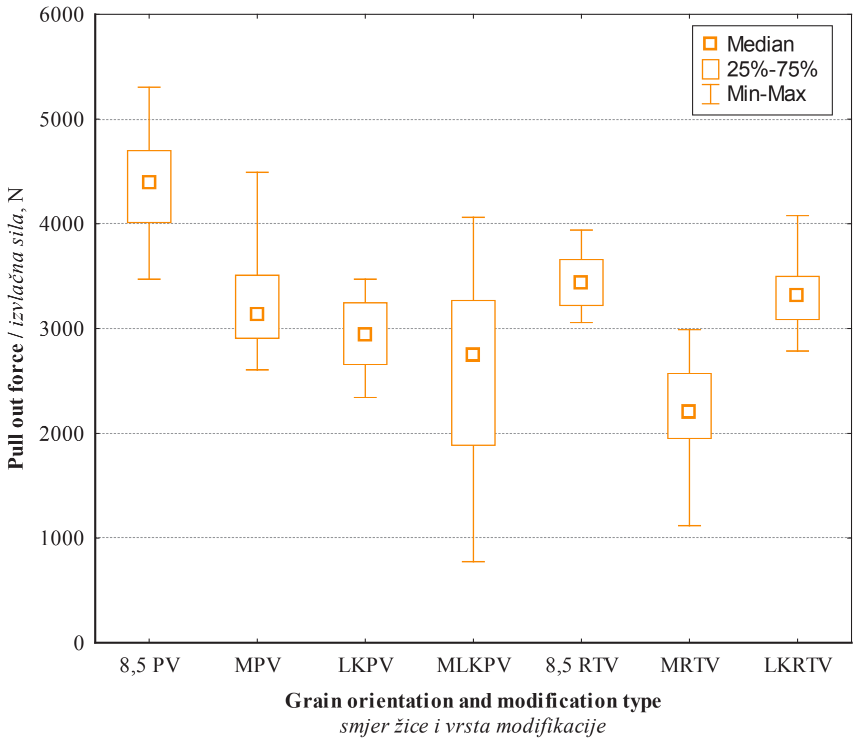

Figure 6 Influence of modification type and grain orientation on pull-out force of welded joints
Slika 6. Utjecaj vrste modifikacije drva i smjera žice na izvlačnu silu zavarenih spojeva

Dowels modified with citric acid can be successfully welded to an unmodified base (MLKPV). During welding, there were no major cracks or splits in the bases. As a result of the modification, some dowels were slightly curved and deflected, which created major problems during welding. If the deflection of the dowel was greater than 1 mm, it was not welded. During pull-out testing, only three, out of 25 welded dowels, were pulled out of the bases. All other dowels were weaker than the welded joint, so the pull-out force could not be measured. High data variability of measured pull-out force is due to the different tensile strength of the modified dowels. The tensile strength of the dowels varied from a minimum of 774 N to a maximum of 4063 N, and the average pull-out force of three dowels that withstood the tension during testing (no fracture occurred in the dowel) was 3420 N, which is comparable to the MRTV and LKRTV samples (Table 6, Figure 6).

4 CONCLUSIONS
4. ZAKLJUČAK

The untreated dowels can be welded or glued into a thermally modified base or a base modified with citric acid. If both the base and the dowel are modified with citric acid, major errors (splits in the bases or breakage of the dowels) occur during welding.

Thermal modification causes a decrease in the pull-out force of welded and glued dowels parallel and perpendicular to the grain. Welded and glued dowels parallel to the grain achieve higher pull-out forces compared to welded and glued dowels perpendicular to the grain.

Modification with citric acid in glued or welded samples parallel and perpendicular to the grain reduces the pull-out force compared to thermally modified samples.

The strength of the welded joints of dowels modified with citric acid is higher than the tensile strength of the modified dowels.

Due to the significant reduction of pull-out force of dowels welded in thermally modified wood or wood modified with citric acid, their use is not recommended for welded joints.

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Corresponding address:

MARIN HASAN
University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska cesta 23,
10000 Zagreb, CROATIA, e-mail: mhasan@sumfak.unizg.hr