

EFFECT OF TEMPERATURE ON THE ERADICATION OF HOUSE LONGHORN BEETLE LARVAE IN WOOD BY MICROWAVE TREATMENT

VPLIV TEMPERATURE NA UNIČENJE LARV HIŠNEGA KOZLIČKA PRI MIKROVALOVNI ZAŠČITI LESA

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ABSTRACT

In repressive protection of cultural/historical woodwork, microwaves have many advantages over conventional heating. The research's objective was to examine conditions for eradication of house longhorn beetle larvae (*Hylotrupes bajulus*) in spruce wood (*Picea abies*) using microwaves. Larvae, inserted at different depths of spruce blocks containing 12% and 42% of moisture, were exposed to microwaves. Two apparatuses were used; a 750W commercial microwave chamber and a newly developed horn antenna microwave device with the power of 800W and a frequency of 2.45GHz, for targeted radiation. We discovered that the inner part of wood warmed up quicker than the surface heated to 65°C. For successful suppression larvae in the wood need to be heated to 54.5°C, for 10 seconds. The necessary exposure time increases with increasing thickness of wood. The surface of wood containing more moisture is heated quicker, but increased moisture slows down the penetration of microwaves into the wood specimen. Therefore, larvae in wood of lower moisture (12%) died faster, both those 20mm under surface (1.5min) and those at 130 mm of depth (10.5min).

Key words: wooden objects, repressive wood protection, microwaves, heating, wood moisture content, house longhorn beetle - *Hylotrupes bajulus*

IZVLEČEK

Mikrovalovi imajo pri represivni zaščiti kulturnozgodovinskih lesenih predmetov veliko prednosti pred konvencionalnim gretjem. Namen raziskave je preučiti pogoje uničenja larv hišnega kozlička (*Hylotrupes bajulus*) v smrekovem lesu (*Picea abies*) z uporabo mikrovalov. Mikrovalovom smo izpostavili larve, vstavljene različno globoko v smrekove blokce z 12 % in 42 % vlažnostjo lesa. Uporabili smo komercialno mikrovalovno komoro z močjo 750 W in razvito mikrovalovno napravo z rogasto anteno moči 800 W s frekvenco 2,45 GHz, za usmerjeno obsevanje. Ugotovili smo, da se notranjost lesa bolj segreva kot površina, ki smo jo segrevali do 65 °C. Za uspešno zatiranje je treba larvo v lesu segreti na temperaturo 54,5 °C za 10 sekund. Z debelino lesa se podaljšuje čas izpostavitve. Vlažnejši les se hitreje segreva, vendar mikrovalovi počasneje prodirajo skozi volumen. Zato so larve v lesu z nižjo vlažnostjo (12 %) hitreje poginile, tako 20 mm pod površino lesa (1,5 minute) kot v tudi globini 130 mm (10,5 minute).

Gljučne besede: leseni predmeti, represivna zaščita lesa, mikrovalovi, segrevanje, vlažnost lesa, hišni kozliček - *Hylotrupes bajulus*

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1 INTRODUCTION

1 UVOD

In certain conditions wooden objects are threatened by wood pests such as wood fungi and insects. Chemical agents, suffocations and methods of freezing and heating with moisture regulation are the most common methods used for their eradication (Beiner and Ogilvie, 2005). Microwave heating is one of the thermal methods and had been successfully used decades ago for the treatment of insect-infested (Andreuccetti et al., 1994; Fleming et al., 2005; Henin et al., 2014) or fungi-infected wood (Bech-Andersen in et al., 1992; Strätling et al., 2008; Terebesyová et al., 2010).

Microwaves can effectively destroy wooden pests in all stages of development. (Bini et al., 1997). Microwave heating is one of the fastest and most effective physical methods for subsequent treatment of attacked woodwork. Its advantage lies in the fact that, unlike the conventional methods, wood is heated from the inside out (Zielonka and Gierlik, 1999). However, due to possible adverse effects, treatment of wood with microwaves is still of limited use.

Microwave irradiation can be performed in a chamber (closed system) or using a device with a horn antenna for targeted radiation (open system). In a closed system, the rays deflect from the chamber walls and

thus cover the entire exposed object. Open system is much more useful, because the size of the object and any metal parts do not pose a restriction. However, with rays traveling only in one direction, only a part of the object is irradiated at a time, therefore it is necessary to relocate the device in order to expose the whole object to microwaves.

Since both systems have their advantages, we will compare them with respect to their impact on warming of the insects in the depths of the wood. Microwaves are being absorbed in the direction of irradiation and consumed from the surface towards the interior, so the temperature in the depth of the wood decreases (Makovíny et al., 2012). Therefore we assume that the depth penetration of the microwaves and thereby the heating depend on the orientation and humidity of the sample being irradiated.

Insects are ectothermal organisms, and can survive in a very wide temperature range, from -34 to 64°C. Eradication of different developmental stages of most wood insects requires elevated temperatures between 45°C and 64°C. Temperatures above 55°C cause coagulation of proteins in the larvae cells and the injuries are irreversible (Strang, 1992). Both type and stage of the development have an indirect effect on the lethal temperature of each pest. Tissues in different development stages of insects have different dielectric properties and therefore heat up differently (Ondráček and Brunnhofer, 1984), so the effect of temperature varies depending on the tissue (Denlinger and Yocum, 1998). The relationship between lethal temperature and exposure time is also important. Larvae, throughout the whole cross-section of infested wood, need to be exposed to lethal temperatures from few minutes up to few hours (Grosser, 1985; Strang, 1992). Insects are able to adapt to a slowly changing temperature (Strang, 1992). Consequently, the lethal temperature, achieved in a short exposure time when they do not have time to adjust, is highly efficient (Nelson, 1996). Becker and Loeb (1961) state the sensitivity of the most important dry wood insect larvae to high temperatures with conventional heating. Larvae of common furniture beetle (*Anobium punctatum*) and lyctus powderpost beetle (*Lyctus brunneus*) die when exposed to 58°C in 20 minutes, while for larger and more resistant larvae of longhorn beetle *Hylotrupes bajulus* the following exposures are necessary: 50°C for 300 minutes; 54 °C for 90 minutes or 58°C for 55 minutes. Eradication times of microwaves heating are shorter than hot air heating. Fleming et al. (2003) stated that at the temperature of 60°C eradication of the Asian longhorn beetle with conventional heating takes 123 minutes and with the microwaves 5 minutes. Andreuccetti

et al. (1995) have determined the lethal temperature for longhorn beetle *Hylotrupes bajulus* larvae in a water bath to be between 52 and 53°C. When inside wood, this temperature destroys them within 3 minutes.

In fresh wood of Scots pine (thickness about 10 cm) microwave radiation in a chamber at 2,45 GHz (Fleming et al. 2005) achieves a 100 percent mortality at a temperature of 62°C. Henin et al. (2008; 2014) have exposed the larvae of house longhorn beetle in the boards of 22 mm thickness to temperatures exceeding 55°C. Larvae died, while the surface of the wood heated to 60°C. By using microwave device with horn antenna at a frequency of 2.45 GHz, Kisternaya and Kozlov (2007) and Makovíny et al. (2012) irradiated wood of larger cross-sections. Kisternaya and Kozlov (2007) reached the lethal temperature of 53 to 55°C in about 120 to 240 minutes. In order to successfully destroy larvae, it was necessary to maintain this temperature for at least 30 minutes. In pine samples with 150 mm in cross-section, Makovíny et al. (2012) destroyed larvae in 34 minutes at a temperature of 50°C, and in 19 minutes at the temperature of 65°C, using a radiation power density of 1,0 Wcm⁻². There are also results published for other wood pests: Andreuccetti et al. (1995) for *Oligomerus ptilinoide*, Lewis et al. (2000) for *Incisitermes minor*, Fleming et al. (2003) for the Asian beetle (*Anoplophora glabripennis*), Fleming et al. (2004) for *Plectrodera scalator*, Fleming et al. (2005) and Hoover et al. (2010) for PWN, *Bursaphelenchus xylophilus*, Nzokou et al. (2008) for *Agrilus Pennisi*, Bisceglia et al. (2009) on various types of nematodes and Massa et al. (2011) for *Rhynchophorus ferrugineus*.

In the case of cultural/historical wooden objects treated with various coatings, it is necessary to bear in mind that at temperatures above 60°C there is a risk of natural waxes softening and damages of adhesives, paints and varnishes on polychromated sculptures or furniture (Unger, 2001).

From the carried out research it can be established that the repressive protection with microwave irradiation is effective and reliable. However, it is necessary to optimize the two basic factors - temperature and exposure time. These factors for the particular type of pest directly depend on the dimension of the object, wood moisture and the direction of irradiation.

As the literature shows very different data on the time and temperature necessary to destroy each species of wood insect, and the impact of wood as a material (its humidity and thickness) on their heating is not well known either, we carried out a study on the impact of these factors on mortality of the house longhorn beetle larvae.

2 MATERIALS AND METHODS

2 MATERIAL IN METODE DELA

2.1 Samples preparation

2.1 Priprava vzorcev

For this study we prepared blocks of spruce (*Picea abies*) in two dimensions. For the best possible approximation to the real situation, in determination of the conditions for larvae eradication, we prepared 50 × 40 × 100 mm samples with 12% humidity. Wood was then thickness-wise split in half with a chisel. With a rounded chisel two grooves were then carved in the middle of each piece. The dimension of the groove was adjusted to the size of the larvae. Doing this we tried as much as possible to simulate the real situation (Figure 1). These samples were prepared in XPS. Two longhorn beetle (*Hylotrupes bajulus*) larvae of different sizes were inserted into the groove and then the halves joined. The sample was fixed with a rubber band, taking care that the halves fit to each other well, so that the cross section of wood remained unchanged allowing the moisture to pass through the whole sample while heated. Thus prepared samples have enabled us to quickly view and measure the temperature inside the sample and in the groove.

For estimation of the impact of different directions of irradiation on heating throughout the wood volume we used 150 × 150 × 150 mm samples with 12% and 42% humidity. Sample size was limited to the size of the microwave chamber. Thickness-wise they were split into six approximately equal parts. For chamber irradiation, 5 grooves for larvae insertion were carved into each part using a rounded chisel; one in the middle, other four 20 mm from the surface (Fig. 2a). For longitudinal and radial irradiation we made three grooves on each part – at the depths of 20, 75 and 130 mm (Figs. 2b and 2c). We inserted larvae of approximately

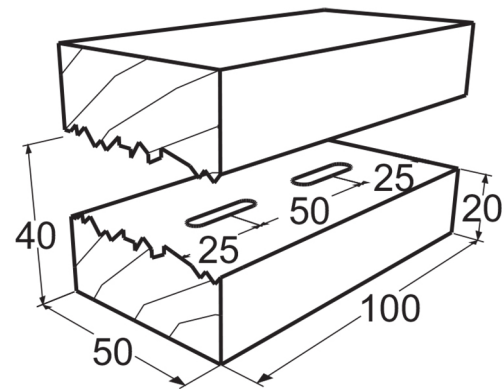


Fig. 1: Sample of spruce sapwood 50 x 40 x 100 mm with 2 grooves for 2 larvae of the house longhorn beetle

Slika 1: Vzorec iz smrekove beljave 50 x 40 x 100 mm z dvema utoroma za larvi hišnega kozlička

the same weight into the same levels to nullify the impact of the larvae size to heating.

2.2 Larvae preparation

2.2 Priprava larv

Larvae weight varied from 0,03 to 0,32 g. Some larvae were taken from the collection of the Department of Pathology and wood preservation at Biotechnical Faculty in Ljubljana, others have been harvested from infested Scots pine (*Pinus sylvestris*) boards. Larvae were temporarily inserted into the samples of spruce sapwood and grown at room temperature until the execution of the experiment. For the initial experiments and method optimization, we also used larvae of Colorado potato beetle (*Leptinotarsa decemlineata* Say) and lesser mealworm (*Alphitobius diaperinus* Panzer), as they were available in larger quantities.

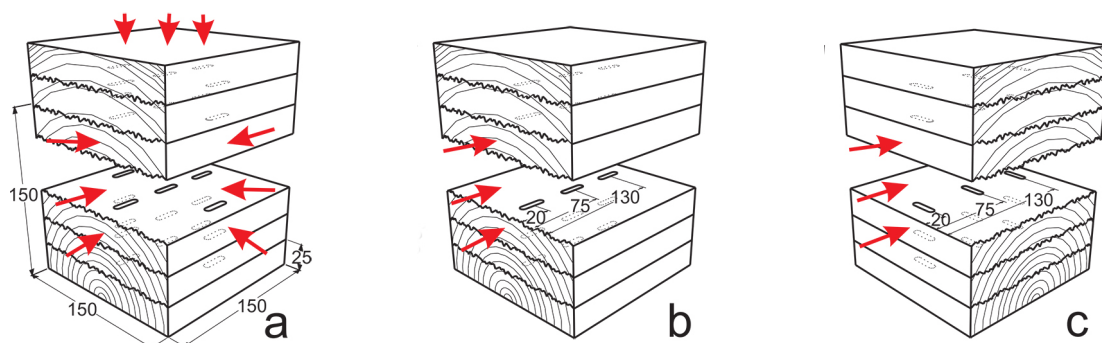


Fig. 2: Spruce 150 × 150 × 150 mm test blocks were split into approximately 6 equal parts with 3 or 5 grooves for larvae each: a- heating in a chamber, b- heating along the fibres (longitudinal), and c- heating perpendicular to the fibres (radial)

Slika 2: Vzorci smrekovega lesa dimenzij 15×15×15 cm, razklan na 6 delov z 3 ali 5 utori za larve na vsakem nivoju: a- segrevanje v komori z vseh strani, b- segrevanje vzdolž vlaken (prečno) in c- segrevanje pravokotno na vlakna (radialno)

2.3 Determination of the impact of a microwave treatment system on the heating of wood and larvae

2.3 Določanje vpliva sistema mikrovalovnega žarčenja na segrevanje lesa in larv

In this study, we used two different systems of radiation. A closed system, where we used a commercial microwave oven Whirlpool AT 329 ALU with the power of 750W and a capacity of 22 litres, and an opened system for unidirectional radiation. For this purpose a commercial microwave Sharp R-613 with an output of 800 W and a frequency of 2.45 GHz was reconstructed and a horn antenna with the dimensions of 300 × 285 mm added, which enabled targeted radiation.

House longhorn beetle larvae were heated in smaller samples (wood and XPS) in order to achieve optimal distribution of heat throughout the wood volume in the microwave chamber, at the power of 750 W, for different time durations: 5, 10, 13, 15 and 30 seconds. After exposure, the samples were opened to measure the surface temperatures of the larvae and the wood interior and to check the viability of larvae.

We heated the surfaces of samples of larger dimensions also to 65°C with both devices. Therefore we used at the beginning different time intervals from 30 to 120 s. With further shorter exposures we achieved and maintained the target temperature of 65°C at the wood surface, until all the larvae died.

2.4 Temperature measurement

2.4 Merjenje temperature

The temperature of the material was measured before and after the exposure to microwave radiation by IR thermal camera Trotec IC 080 LV with a resolution of 384 × 288 pixels. The camera allows temperature measurement in the range of -20°C to +600°C with measurement accuracy of ±2 °C. Regarding the specimens, the camera emissivity was set to 0.94. Infrared camera

provides a complete temperature field display and temperature measurement in one to five selected points. Since it is a surface measurement, in order to establish the wood temperature profile the samples were set apart and the surface temperature of each part was measured, then samples were re-assembled and further irradiated.

To establish the average, more precise measurements and processing of thermographs, the computer program IC IR Report was used.

2.5 Determination of vital functions or the vitality of larvae

2.5 Ugotavljanje življenjskih funkcij oz. vitalnosti larv

After completing the program of the microwave exposure and measuring of temperature, we immediately verified the survival rate of the larvae. Their state was assessed according to the criteria cited by Fleming et al. (2003), specifically: dehydration of the body, change of the colour and opacity, as well as the movement of the body and the jaw. After two to 24 hours at room temperature, the status of larvae was re-checked.

3 RESULTS AND DISCUSSION

3 REZULTATI IN RAZPRAVA

3.1 The material and grooves' influence on the heating of larvae

3.1 Vpliv materiala in utorov na segrevanje larv

In order to explain the process of larvae warming, they were exposed to microwaves in different environments: bare larvae in the microwave chamber, embedded in XPS and in wood. Larvae inserted free in a microwave chamber at full power of 750W achieved a higher average temperature than larvae embedded in XPS. XPS is a material which does not heat up by penetrating microwaves, because it does not contain water molecules. Thus, the microwaves heated only larvae,

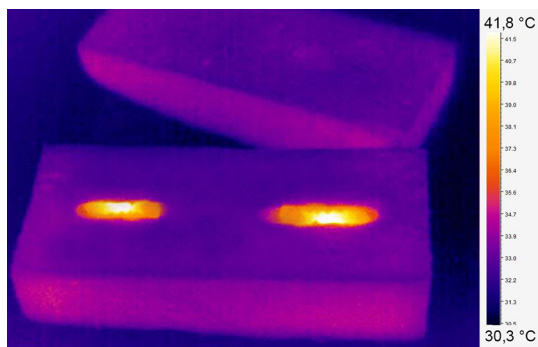


Fig. 3: Heating of larvae in the sample of XPS

Slika 3: Segrevanje larve v vzorcu XPS

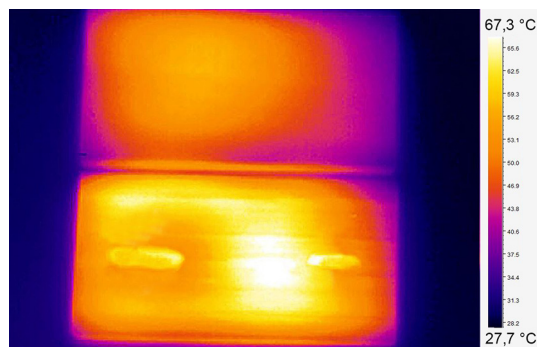


Fig. 4: Heating of larvae in the wood sample

Slika 4: Segrevanje larve v vzorcu lesa

Table 1: Effect of exposure time and material (XPS, wood) to heating of larvae in a chamber

Exposure time Čas izpostavitve (s)	Level of larvae heating / Stopnja segrevanja larv (°C)		
	Free in chamber Prosto v komori	Embedded in XPS Vstavljene v XPS	Embedded in wood Vstavljene v les
10	40,1	33,2	54,7
20	44,6	41,9	74,8
30	54,6	47,6	91,6
40	/	54,9	/

which were then emitting the heat and moisture to the surroundings and thus heated the groove (shaft) (Fig. 3). Most heated were the larvae inserted in wood (Fig. 4), as they achieved up to a 30°C higher temperature at the same exposure time and power (Table 1). Temperature difference between the heat of the empty groove and groove with embedded larvae in the wood was not found.

Opposite to XPS, where larvae heat the surroundings of the groove, in wood they are heated together. In the initial irradiation larvae get heated faster and more than wood, due to higher moisture content. In short exposures, wood is very unevenly heated both at the surface as in the interior, where the difference was up to 17°C (Figure 4). The process of heating wood with microwaves causes migration of moisture from the interior towards the outer surfaces. This results in accumulation of moisture (and heat, consequently) on the walls of the tunnels (in our case a man-made groove). On average, the groove was by 6°C warmer than the surrounding wood, which further contributes to the rapid death of larvae. On average, the difference between the surrounding wood in some parts and larvae reaches 4°C, which is less than the reported data of Andreuccetti et al. (1994), according to whom larvae

Table 2: Time and temperature of house longhorn beetle larvae eradication in 50 × 40 × 100 mm wood sample

Exposure time Čas izpostavitve (s)	Weight of larvae Teža larve (g)	Average surface temp Povprečna temp. površine (°C)	Wood temp. near larvae Temp. lesa v bližini larve (°C)	Larvae temp. Temp. larve (°C)	Condition of larvae Stanje larve
30	0,32	84,4	90,3	93,1	Dead / ne preživi
15	0,10	65,7	73,3	72,8	Dead / ne preživi
	0,23		69	69,9	Dead / ne preživi
13	0,06	57,5	64,4	67,5	Dead / ne preživi
	0,17		62,2	65,6	Dead / ne preživi
10	0,03	54,1	54,4	57,3	Dead / ne preživi
	0,22		54,6	54,5	Dead / ne preživi
5	0,07	38,3	45,2	51,1	Dead / ne preživi
	0,20		37,5	40,1	Dead / ne preživi

Preglednica 1: Vpliv časa izpostavitve in materiala (XPS, les) na segrevanje larv v komori

in dry wood are heated up by 10°C more than the surrounding wood.

3.2 Impact of microwaves on lethality of larvae

3.2 Vpliv mikrovalov na smrtnost larv

At full power of the magnetron (750 W) for 5 seconds, all larvae in 50 × 40 × 100 mm wood samples survived. Longer exposure times lead to higher temperatures and thus to a higher mortality rate of larvae. At wood temperature of 54.6°C (larvae heated to 54.5°C) all larvae died within 10 seconds. Henin et al. (2008) exposed the larvae of a longhorn beetle to temperatures above 55°C and achieved 100 percent mortality within 2 minutes. Fleming et al. (2005) reached 100 percent mortality of longhorn beetle larvae at a wood temperature of 62°C. Our findings regarding the temperature are in accordance with previous studies, but the time required for the larvae eradication is significantly shorter - instead of one minute it is only 10 seconds, which is from the point of conservation more acceptable since the cultural/historical objects get exposed to radiation and high temperatures for a shorter time period. Smaller and lighter house longhorn beetle larvae with an average weight of 0.07 g were heated up to about 1.8°C higher temperatures than the larger larvae

Preglednica 2: Čas in temperatura uničenja larve hišnega kozlička v vzorcu lesa 50 × 40 × 100 mm

with an average weight of 0.23 g (Table 2). A possible explanation is that smaller larvae represent a smaller moisture concentration creating a higher microwaves point concentration resulting in increased heating.

Stronger warming up of smaller larvae is an encouraging result in regard to suppression of the common furniture beetle family, whose larvae are smaller and twice as sensitive to temperature as the house longhorn beetle larvae. The attacks by these insects are much more common on objects of cultural heritage.

When checking the mortality of larvae we did not observe any changes in colour immediately after exposure to microwaves, as already indicated by Makoviny et al. (2012). We assume that the changes did not appear due to the shorter exposure times and lower temperatures. The dead larvae darkened after 24 hours though, which was noticed when the state of survival was re-examined. The larvae dehydration is also not the most effective method for the survival determination, because it is difficult to estimate, so we focused mostly on the movement of larvae. The movement of the irradiated larvae followed a certain pattern; firstly, the larvae became more lively with raising temperature (28-42°C), when the temperature is elevated to about 49°C the larvae calm down, and they finally die when their temperature reaches 54.5°C.

3.3 Impact of wood moisture, depth and direction of irradiation on heating of the larvae

3.3 Vpliv lesne vlage, globine in smeri obsevanja na segrevanje larv

The 150 × 150 × 150 mm samples were heated and

the wood surface temperature kept at a maximum of 65°C, which is still a safe temperature for a brief exposure of surface coatings used on objects of cultural heritage (Nicolaus, 1999), except for waxes, which melt at 62-64°C (Rivers and Umney, 2003). Direction of irradiation, wood moisture and depth penetration affected the speed of wood heating up, therefore we adjusted the interval of heating (of 30 to 120 s) on the heating rate of the wood. Pauses during exposure were maintained for two minutes. This was the time that we needed to carry out interim measurements. Within two minutes, the wood surface cooled down for 8°C.

In the chamber, the samples were heated slowly and more evenly than in the case of direct radiation, since the microwaves are being absorbed over the whole surface and are not concentrated at one point, as in the case of direct irradiation (Figure 5a). The wood with 12% of moisture content (MC) heated faster through volume than wood with moisture content of 42%. Wood with more moisture absorbed and consumed the majority of microwaves on the very surface or just below it. On the other hand, the dry wood surface of wood with 12% MC absorbed only part of the microwaves, while the rest could penetrate deeper into the woods interior. Thus the entire volume of the wood got heated faster and more evenly. The speed of heating the wood affects the intensity of larvae heating.

In both cases all larvae at all five levels were killed before the temperature of the wood surface reached the targeted 65°C. In the wood with 12% moisture the exposure time needed was 2 minutes, while the wood surface heated on average to 51,3°C in radial and

Table 3: Impact of moisture content of wood samples on the heating dynamics of wood and the lethality of house longhorn beetle larvae exposed to microwaves in the chamber

Wood moisture Vlačnost lesa (%)	Surface temp. Temp. površine (°C)	Exposure time Čas izpostavitve (s)	Level larvae Nivo larve (cm)	Temp.larvae Temp.larve (°C)	Wood temp. Temp. lesa (°C)	Number of dead larvae Št. poginulih larv
12%	R=51,3; T=50,6	H= 120	2	65,2-57,7	61,5-54,8	10 / 10
			7,5	60,2-58,2	57,8-54,3	5 / 5
			2	62,4-59,7	57,3-56,1	10 / 10
42%	R=49,9; T=48,6	H= 120	2	58-54,7	56,8-50,1	10 / 10
			7,5	58,7-52,8	55,6-40,8	4 / 5
			2	59,6-55,5	53,6-49,1	10 / 10
	R=52,4; T=50,4	H= 120, P=120, H=60	2	66,3-56,8	63,6-52,9	10 / 10
			7,5	63,8-56,9	60,4-52,3	5 / 5
			2	67,3-58,5	62,6-53,1	10 / 10

Preglednica 3: Vpliv vlažnosti vzorcev na segrevanje lesa in smrtnost larv hišnega kozlička, izpostavljenih mikrovalovom v komori

Legend / legenda: R= radial plane / radialna ravnina, T= transverse plane / prečna ravnina, H= heating / segrevanje, P= pause / premor

50,6°C in longitudinal plane. A somewhat larger gap between heated surfaces shows in a 42% moist wood, where a difference is up to 2°C, while the larvae of the wood along the fibres at a depth of 2 cm on average get more heated than larvae in the radial direction. This could be attributed to the passage of moisture in the wood, since the permeability in the longitudinal direction is greater while in the shaft (groove) more moisture is captured. That results in a more intensive heating of larvae. After a two-minute exposure, only one of 15 larvae survived, so after two-minute break we exposed the samples again for one minute to microwaves (Table 3).

In order to determine the influence of the orientation on the heating of the wood interior, we applied direct current (DC) irradiation of the samples longitudinally (along the fibres) and radially (at right angles to the wood fibres) until reaching the average surface temperature of 65°C. Few millimetres below the surface of the wood was heated the most. This was attributable to lower moisture on the surface of the sample and rapid cooling of the surface, influenced by the surrounding temperature. In the cross section the sample is heated in the form of elliptical paraboloid. On the irradiation side the heating area is wider and narrows with a depth of wood sample. Along the fibres wood heating is more featured with sharper boundaries of heated area in comparison with irradiation perpendicular to the fibres. It was probable that the boundaries in radial direction were blurred due to easier and faster moisture transfer from the interior towards the surface (Figs. 5b and 5c). Also the warming area of the radially irradiated wood was wider than in the radiation along the fibres, because water vapour in moist wood passes from the point of irradiation on each side, thereby allowing deeper penetration of microwaves as the longitudinal when steam is being pushed mostly frontally.

In moist wood, the difference in temperature between early wood, which was heated more, and late wood can be up to 14°C. That contributes to the eradication of larvae as the larvae of the house longhorn beetle eat and stay mainly in the early wood (Unger, 2001). Early wood has large lumens and thin walls through which the microwaves can penetrate more quickly, at the same time the lumens may hold more steam.

In comparison with the closed chamber, the eradication of larvae by DC irradiation needed differently long exposures. In general, the time for the larvae eradication in the open system is longer. When heated in a longitudinal direction (Table 4), the surface of the wood warmed faster compared to the heating in the radial direction (Table 5), but the depth of penetration was slower. Therefore, we used a series of short exposures. Since the area of the heating inside timber narrows down with increasing depth, we determined larvae mortality and temperature only in the middle of the sample in a diameter of 8 cm in the direction of irradiation.

Larvae 2 cm below the wood surface died in 1.5 minutes of exposure time in all samples, except for the radial radiation of wood with 42% moisture content, where wood heating was slower and the larvae died in 2 minutes at an average wood surface temperature of 54,8°C. Meanwhile, at the level of 7.5 to 13 cm, larger differences in the humidity of the wood and the direction of irradiation occurred. In longitudinal exposure we needed shorter heating times to maintain the target surface temperature for eradication of larvae at a depth of 7.5 to 13 cm, in comparison with the heating perpendicular to the fibres. However, in radial direction of irradiation the microwaves were penetrating more quickly in the depth of the wood with 42% moisture content, so the complete eradication of the larvae was achieved in 10.5 minutes. The longest exposure

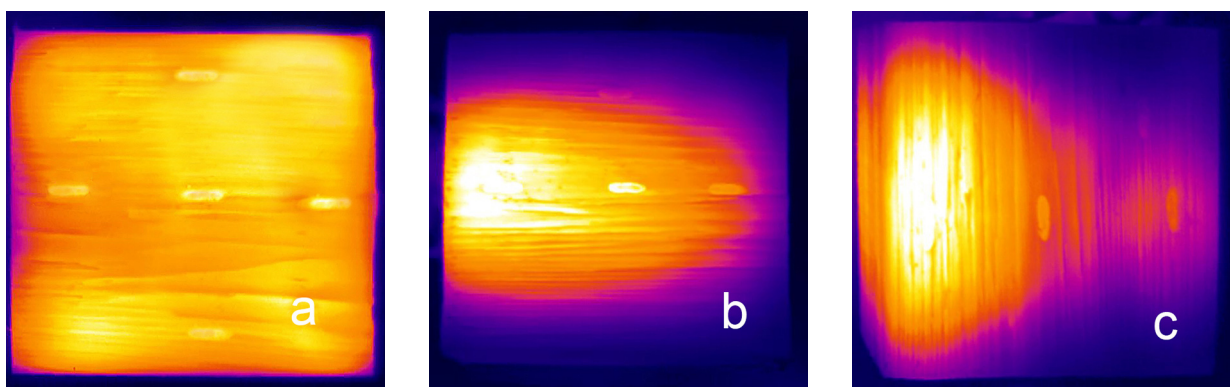


Fig. 5: Heating the interior of the wood: a- heating in a chamber, b- longitudinal heating and c- radial heating

Slika 5: Segrevanje lesa v notranjosti: a- segrevanje v komori, b- vzdolžno segrevanje in c- radialno segrevanje

Table 4: The effect of microwave heating from direct current microwave radiation in longitudinal direction of house longhorn beetle larvae**Preglednica 4:** Učinek mikrovalovnega segrevanja pri enosmernem mikrovalovnem žarčenju v vzdolžni smeri na larve hišnega kozlička

Wood moisture <i>Vlažnost lesa</i> (%)	Surface temp. <i>Temp. površine</i> (°C)	Exposure time <i>Čas izpostavitve (s)</i> H= heating / <i>segrevanje</i> P= pause / <i>premor</i>	Level larvae <i>Nivo larve</i> (cm)	Temp.larvae <i>Temp.larve</i> (°C)	Wood temp. <i>Temp. lesa</i> (°C)	Number of dead larvae <i>Št. poginulih larv</i>
12%	64,9	H= 90	2	70,9 - 60,9	65,9 - 60,8	3 / 3
			7,5	49,6-44,6	47,2-43,2	0 / 3
			13	41,6-33,1	39,9-31,8	0 / 3
	62,9	H= 90, P=120, H=30	2	68,5-61,3	62,7-60,4	3 / 3
			7,5	58,5-52,7	53,1-48,4	2 / 3
			13	48,7-35	40,7-32,4	0 / 3
	62,1	H= 90, P=120, H=30, P= 120, H=30	2	72,3-63,1	67,8-64,2	3 / 3
			7,5	72,3-64,2	65-59,2	3 / 3
			13	58,2-48,9	49,9-40,9	1 / 3
	64,4	H= 90, P=120, H=30, P= 120, H=30, P=120, H=30	2	76,8-70,5	71,6-67,5	3 / 3
			7,5	75,4-69,8	70,8-64,4	3 / 3
			13	63,4-59,4	58,2-54,9	3 / 3
42%	59,3	H= 90	2	60,8-58,9	57,1 - 44,5	3 / 3
			7,5	41,6-37,3	39,2-36,9	0 / 3
			13	34,3-33,5	34,7-33,7	0 / 3
	64,6	H= 90, P=120, H=60	2	74,4-69,3	68,9-64,8	3 / 3
			7,5	56,1-48,2	52,6-44,3	1 / 3
			13	41,5-38,7	38,9-35,5	0 / 3
	63,8	H= 90, P=120, H=60, P= 120, H=40	2	75,9-71,3	70,4-66,8	3 / 3
			7,5	68-64,5	66,2-60,7	3 / 3
			13	51,2-45,1	48,3-42,9	0 / 3
	64,3	H= 90, P=120, H=60, P= 120, H=40, P=120, H=40	2	76,1-71,8	72,5-67	3 / 3
			7,5	69,6-66,5	65,2-60,6	3 / 3
			13	54,1-50,3	51,3-47,9	1 / 3
	62,8	H= 90, P=120, H=60, P= 120, H=40, P=120, H=40, P= 120, H=40	2	78,2-75,3	74,4-72,1	3 / 3
			7,5	73,5-69,3	68,2-65,7	3 / 3
			13	57,4-55,2	54,3-51,6	3 / 3

was necessary for frontal irradiation and it took 12.5 minutes. If the irradiation had not been interrupted for 2 minutes for intermediate measurements, the temperature variations would be lower and probably less time would be required for the suppression of larvae (Tables 4 and 5).

According to irradiation data obtained, we found that the time required for the eradication of house longhorn beetle in relation to the wood volume and moisture content and the direction of irradiation varies too much to be evidenced for all wooden objects of

cultural heritage, which are very diverse. Therefore, at DC radiation we checked the temperatures of surfaces on the opposite side of irradiation. The lowest temperature of the opposite wood surface, at which all the larvae died, was 48.4°C. This is the lowest temperature that we need to reach at the opposite side of the one irradiated to successfully suppress house longhorn beetle, regardless of the humidity, volume or direction of irradiation.

Since the area of the heating narrows with depth, it is necessary to irradiate the entire surface, to move the

Table 5: The effect of microwave heating from direct current microwave radiation in radial direction of house longhorn beetle larvae**Preglednica 5:** Učinek mikrovalovnega segrevanja pri enosmernem mikrovalovnem žarčenju v radialni smeri na larve hišnega kozlička

Wood moisture Vlažnost lesa (%)	Surface temp. Temp. površine (°C)	Exposure time Čas izpostavitve (s) H= heating / segrevanje P= pause / premor	Level larvae Nivo larve (cm)	Temp.larvae Temp.larve (°C)	Wood temp. Temp. lesa (°C)	Number of dead larvae Št. poginulih larv
12%	58,6	H= 90	2	64,3 - 61,5	57,6-54,6	3 / 3
			7,5	45,6-33,7	43-38,2	0 / 3
			13	33,5-32,8	34,8-32,4	0 / 3
	63,5	H= 90, P=120, H=60	2	74-71,4	69,6-66,2	3 / 3
			7,5	60,9-54,1	51,2-44,1	3 / 3
			13	47,2-41,5	40,2-38,2	0 / 3
	64,8	H= 90, P=120, H=60, P= 120, H=60	2	77,3-73,5	70,8-68,2	3 / 3
			7,5	67,7-59,7	62,1-55,9	3 / 3
			13	55,5-48,4	52,4-47,5	1 / 3
	62,9	H= 90, P=120, H=60, P= 120, H=60, P=120, H=30	2	81-75,5	76,4-72,9	3 / 3
			7,5	72,4-64,7	68,5-57,8	3 / 3
			13	58,7-52,8	56,8-48,4	3 / 3
42%	54,8	H= 120	2	59,6 - 54,1	50,1-46	3 / 3
			7,5	44,2-38,3	39,2-36,9	0 / 3
			13	41,7-37,5	36,7-35,7	0 / 3
	62,9	H= 120, P=120, H=60	2	74,4-66	66,9-60,8	3 / 3
			7,5	56,1-48,2	48,6-41,1	2 / 3
			13	51,5-45,7	43,9-41,4	0 / 3
	64,3	H= 120, P=120, H=60, P= 120, H=60	2	75,9-71,3	69,7-65,3	3 / 3
			7,5	64-56,5	53,3-45,7	3 / 3
			13	56,1-48,1	48,5-42,7	2 / 3
	63,8	H= 120, P=120, H=60, P= 120, H=60, P=120, H=30	2	80,2-76,3	76,4-72,9	3 / 3
			7,5	70,6-62,4	66,2-57,6	3 / 3
			13	59,4-55,8	55,4-49,9	3 / 3

microwave device to the areas where the target temperature has not been reached on the opposite side. According to the literature and our assumptions, a few minutes of exposure to temperatures around 50°C is safe for the natural materials used in the surface treatment of furniture, polychromated statues, panel painting and other cultural/historical objects.

4 CONCLUSIONS

4 ZAKLJUČKI

The aim of our study was to optimize technological conditions and factors for microwave heating of spruce wood, infested with larvae of house longhorn beetle *Hylotrupes bajulus*. Our findings show that we can

achieve effective eradication of *H. bajulus* larvae with heating above 54.5°C. The inner part of wood warms up quicker and more than the surface. In a microwave chamber, the wood is heated more slowly and more evenly over the entire volume in comparison with DC radiation. Volume of the irradiated wood has a strong influence on the heating dynamics of wood and larvae. Larvae in smaller samples (5 × 4 × 10 cm) died at irradiation power of 750 W in 10 seconds, whereas in larger samples (15 × 15 × 15 cm) at the same depth in the same conditions death occurred within 120 s, when wood surface was heated to above 50.6°C and larvae of the wood interior reached a temperature above 54.5°C. With DC irradiation the times are slightly longer. Lar-

vae inserted 2 cm below the surface died at a temperature of wood surface above 59.3°C in 1.5 minutes, while the deeper inserted larvae (7.5 to 13 cm) died much later, depending on wood humidity and direction of irradiation. The longest irradiation time was 12.5 minutes in the longitudinal irradiation of wood with 42% moisture content. We found that, in the case of directed radiation, it is necessary to reach the surface temperature above 49°C on the opposite side of the irradiated area, regardless of the time, wood moisture and direction of the radiation, in order to successfully suppress house longhorn beetle larvae. This temperature is quite low and we think that within a few minutes of exposure such a temperature will not cause damage to polychromated materials.

The data obtained will serve for further research of the impact of microwave heating on a variety of surface coatings used in objects of cultural heritage, as well as for application in conservatory work.

5 POVZETEK

Leseni predmeti so v neugodnih razmerah močno izpostavljeni napadu lesnih škodljivcev, med katerimi so najpogostejši lesne glive in insekti. Škodo povzročajo tako v neobdelanem kot tudi v stavbnem lesu in pohištvu, neprecenljivo škodo pa naredijo na lesenih predmetih kulturne dediščine. Zato je njihovo zatiranje na področju konservatorstva zelo pomembno in zahtevno.

Ker les sam po sebi varuje larve pred zunanji vplivi, je za njihovo uničenje treba vzpostaviti ekstremne razmere. Pri tem je mikrovalovna metoda segrevanja lesnih škodljivcev učinkovita in zanesljiva, vendar moramo optimizirati dva osnovna dejavnika, temperaturo ter čas izpostavitve. Ta dva faktorja sta neposredno odvisna od dimenzije in vlažnosti lesa ter od smeri obsevanja.

Cilj naše raziskave je bila optimizacija tehnoloških razmer in dejavnikov segrevanja smrekovega lesa (*Picea abies*) z mikrovalovi, napadenega z larvami hišnega kozlička (*Hylotrupes bajulus*). Uporabili smo smrekove vzorce dveh dimenzij 50 × 40 × 100 mm in 150 × 150 × 150 mm. Manjše vzorce z 12-odstotno vlažnostjo smo razcepili na polovico in na sredini izdoblili dva utora za larve. Takšne vzorce smo pripravili tudi v ekstrudiranem polistirenu (XPS). Večje vzorce z vlažnostjo 12 % oziroma 42 % pa smo razcepili na 6 približno enakih delov. Na lomljenih površinah smo izdoblili 3 ali 5 utorov in vanje vstavili larve ter lomljene dele natančno združili. Vzorce z vstavljenimi larvami smo izpostavili mikrovalovnemu obsevanju v komercialni mikrovalovni komori z močjo 750 W in mikrovalovni napravi

z rogasto anteno moči 800 W s frekvenco 2,45 GHz za usmerjeno obsevanje. Temperaturo smo na površini merili s termokamero Trotec IC 080 LV.

Larve smo izpostavili mikrovalovom v komori pri 750 W v različnih razmerah: prosto v komori, v XPSu in v lesu. Namen izpostavitve larve v XPSu je bil ugotoviti vpliv segrevanja utora na temperaturo larve, saj se XPS med obsevanjem z mikrovalovi ne segreva. Najpočasneje so se larve segrevale v XPSu, pri tem pa se je močno segrel prostor v utoru. Najintenzivneje so se segrevale larve v utoru v lesu. Pri enaki izpostavitvi so se v 30s segrele do 36 °C bolj kot prosto izpostavljene in 42 °C bolj kot v XPSu. Iz tega sklepamo, da k segretju larve pripomore segrevanje okolice utora lesa, v katerem je larva. V procesu segrevanja lesna vlaga iz notranjosti prehaja na površje. Ta vlaga in vlaga, ki jo pri segrevanju oddaja larva, se nabira v rovu (utoru) in pripomore k izredno hitrem poginju larve. Za uničenje larve v vzorcu je bilo treba doseči temperaturo larve 54,5 °C, za kar je bilo potrebnih le 10 sekund. Manjše larve s težo okrog 0,07 g so se segrevale do 1,8 °C bolj kot večje larve s težo okrog 0,23 g. Z globino utora in višjo lesno vlažnostjo narašča čas obsevanja, ki je odvisen tudi od smeri obsevanja.

Večje vzorce dimenzij 150 × 150 × 150 mm smo izpostavili obsevanju v mikrovalovni komori z močjo 750 W in z napravo z rogasto anteno pri moči 800 W za usmerjeno obsevanje. S slednjo smo vzorce izpostavili usmerjenemu sevanju z radialne ali prečne strani vzorca. Vzorce smo na površini segrevali do 65 °C. V mikrovalovni komori se je les segrel počasneje in bolj enakomerno po vsem volumnu v primerjavi z usmerjenim obsevanjem, pri tem pa so larve hitreje poginile. Uničenje larv na vseh globinah vzorca je bilo 100-odstotno uspešno, kadar je površina lesa dosegla vsaj 50,4 °C za 2 minuti pri lesu z 12 % vlažnostjo, medtem ko je bilo uničenje larv v lesu z 42 % vlažnostjo nekoliko manj uspešno (93-odstotno, od 15 larv je preživela le ena).

Pri usmerjenem obsevanju morajo biti časi obsevanja nekoliko daljši. Larve, vstavljene 2 cm pod površino, so poginile v 1,5 minute pri doseženi temperaturi površine nad 59,3 °C, medtem ko globlje v lesu (7,5 in 13 cm) poginejo mnogo kasneje, odvisno od vlažnosti lesa in smeri obsevanja. Za uspešno uničenje je najdaljša izpostavitve trajala 12,5 minute pri vzdolžnem obsevanju lesa z 42-odstotno vlažnostjo. Večina mikrovalov se pri vlažnem lesu absorbira in pretvori v toploto že na površini, s tem pa je prodiranje v volumen lesa počasnejše kot pri lesu z 12-odstotno vlažnostjo. Ugotovili smo, da je treba pri usmerjenem obsevanju na nasprotni strani od obsevane površine za uspešno uničenje larv hišnega kozlička doseči temperaturo površi-

ne nad 48,4 °C, ne glede na čas obsevanja, vlažnost lesa in smer obsevanja, kar je relativno nizka temperatura, in menimo, da takšna temperatura v nekaj minutah ne bo povzročila poškodb na polikromaciji.

Pridobljeni podatki nam bodo rabili za nadaljnje raziskave vpliva mikrovalovnega segrevanja na različne površinske premaze, uporabljene pri predmetih kulturne dediščine, ter za aplikacijo v konservatorstvu.

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