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ACOUSTIC DETECTION OF WOOD-DESTROYING INSECTS DURING

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ABSTRACT

This thesis deals with experimental verification of hot-air preservation efficiency on wooden members of structures against larvae of wood-destroying insects, particularly against larvae of longhorn beetle *Hylotrupes bajulus* L. The verification of hot-air efficiency on mortality of larvae was performed within the process of hot-air preservation of a room of a building in Čeladná, Czech Republic. Parameters of hot-air preservation met the specifications of standards according to which the process is controlled. The efficiency was monitored by means of the Acoustic Pack acoustic system which recorded acoustic emissions of larvae emitted during wood ingestion. To verify the acoustic system and hot-air preservation, the samples were subject to destruction analysis after the preservation. Using a Keyence VHX-S550E digital microscope, the analysis of changes in the structure of larvae before and after the process of preservation was performed. The results showed that designed parameters of hot-air preservation lead to the mortality of larvae.

KEYWORDS: Acoustic Pack, hot-air preservation, *Hylotrupes bajulus* L., wood preservation.

INTRODUCTION

In the infestation of wooden structures, the crucial question is whether the larvae of wood-destroying insects is still active and is therefore still a threat for the design, or it is already in the latent stage. The house longhorn beetle (*Hylotrupes bajulus* (L.)) is a representative of the insect family whose larvae significantly damage structures of historical and other buildings. The invasion of larvae and the damage to coniferous wood which is used as building material for timber structures in most buildings often results in the loss of structural integrity of the infested wood due to the creation of passageways, and financial losses due to the treatment and

replacement of damaged wood. Thermo Sanace responded to the question of possible detection of these larvae by the development of an Acoustic Pack device which is able to detect the activity of wood-destroying insects (Nasswettrová et al. 2015a; Fiala et al. 2014).

The Acoustic Pack records acoustic manifestations that larvae create during breaking of cell walls of wood elements by ingestion. These manifestations are of irregular process with short pauses of different durations (Kočárek 2009). The sound is characterized by the wood structure, moisture of the wooden matter, the age of larva (therefore by its size) and by the depth of its position in the wood structure. The resulting sound of larvae is a combination of the vibration of the wooden matter and the sound spreading through air in the passageway (Nasswettrová et al. 2015b). To obtain the searched for signal in case of surrounding disturbance or in case of smaller larvae or its position in a bigger depth it is necessary to compare the generated spectrum of unknown signal by correlation analysis with the created database of signals (patterns) from in situ environment (e.g. roof) and from laboratory conditions. In this way, it is possible to suppress the influence of unfavourable acoustic emissions (parasitic noise) of the surroundings and calculate the correlation coefficient of conformity, and numerically set the rate of infestation of the structure (Nasswettrová et al. 2015a,b; Fiala et al. 2014). In addition to the sound emitted during the ingestion of the matter, the larvae probably emit sounds by scratching mandibles (or other special sclerosed structures) against the walls of passageways (Kočárek 2009). Although Leiler (1992) believes that the sound is created by hitting the larvae shelter by its head (Kočárek 2009). Acoustic effects, except for sounds caused by ingestion, were only documented in representatives of several groups (Kočárek 2009; Chapman 1998; Crowson 1981). For the Cerambycidae family larvae, they are a rare phenomenon described only in very few species of longhorn beetles of the *Lamiinae* subfamily (Kočárek 2009). Leiler (1992) observed these effects at longhorn beetle larvae (Cerambycidae) and described them in his publications, namely at two species of the *Lamiinae* subfamily - *Niphon pecticornis* Mulsant and *Ceroplesis aestuans*. The author described the sounds audible to humans at a distance of several meters as wood vibrations caused by the two species hitting their head against the passageway (Kočárek 2009). Sound effects were also observed in two other species of the same subfamily - Monochamus alternatus Hope (Izumi et al. 1990) and *M. sutor* L. (Victorsson and Wikars 1996). Both the authors concluded that the sounds are generated by the friction of the mandible against walls of passageways. An open question is the very meaning of larva sounds. The above-mentioned authors expressed an idea that larva ensures itself its food sources by the sounds because by this sound, it repels the other larvae which are potential competitors. Victorsson and Wikars (1996) also observed cannibalism in *M. sutor* larvae when being placed in close contact, which confirms this assumption. According to Kočárek (2009), who described acoustic effects of *Icosium tomentosum* (*Cerambycidae: Cerambycinae*) larvae, the sound is created by the friction of strongly sclerosed mandiblae against bark, while larvae emitted sound spontaneously and independently of the time of the day, but also in response to some external stimuli. Some studies and patents deal with methods for measuring and recording the vibrations (sounds) emitted by insect larvae. Pallaske (1990) describes a method for detecting insects in wood in the company's patent (DESOWAG Materialschutz GmbH), the patent of the authors Masami et al. (1991) deals with methods and equipment for detecting woodworm larvae. Another American author, Betts (1990) designed an electronic sensor for sensing vibrations, however focusing mainly on the activity of termites. For example, Litzkow et al. (1990) and Hickling et al. (1997) dealt with piezoelectric sensing of signal or acoustic sensors for sensing the activity of insect pests in cereal crops.

Kočárek (2009) states the sound frequency value measured in experiments with longhorn beetle larvae at the range of 1-18 kHz and frequencies of greater importance at the range of 3-5 kHz. According to Esser et al. (1999), the frequency emitted by longhorn beetle larvae during

ingestion is approximately 10, in case of woodworm larvae around 20 kHz. Fiala et al. (2014) state the frequency of 1.36 kHz for the longhorn beetle. It is obvious that these frequencies will change significantly with changes in the marginal conditions, namely wood humidity, change in relative air humidity, temperature, and especially the combination of these factors.

It is obvious that remaining to be explained are many behavioural mechanisms of larvae of this wood-destroying insects, whose activity in the structure has the largest share on the destruction of wooden elements (Hein 2008). Selecting the appropriate preservation methods, however, depends on the knowledge of these activities. In terms of the development cycle, the possibility for insect spreading, heterogeneity of the material itself and the presence of the larvae at different depths, hot air sterilization is a suitable method for all wooden structural elements in a preservation stage in terms of complex solution. It is a process recognized by DIN 68 800 Part 4, 1998. The thermal process acts so that due to a sufficiently high temperature throughout the cross-section of wood, all evolution stages of insects, which are in the wood, are killed (eggs, larvae, pupae and adults). For successful killing of biotic pest, the timber must be warmed to the temperature of 55°C and maintain it at this temperature for 60 minutes. At this temperature and over this time, it leads to the coagulation of proteins of insects and their death (Šmíra et al. 2013). The denaturation of proteins manifests in polypeptide chain disintegration, which thus loses its characteristic structure (Grosser 1987).

According to the above mentioned facts, the presented thesis therefore aims at analysing the efficiency of hot-air preservation method through monitoring the acoustic activity of larvae of wood-destroying insects by the Acoustic Pack system.

MATERIAL AND METHODS

To assess the effect of hot-air sterilization of wood on larvae of wood-destroying insects, the fir wood (*Abies alba* Mill.), with the cross-section of 220 x190 mm, was chosen with regard to its use in historical buildings. The samples came from a single structural element to reduce the variability of material properties, namely a beam from the Ropice Chateau, Frýdek-Místek, the Moravian-Silesian Region, Czech Republic. The beam was cut transversally so that the length in the direction of fibres was 200 mm, Fig. 1. The samples did not contain traces of biotic degradation. Eight samples were used for the experiment, which equals the number of available sensors of the Acoustic Pack system. Before the start of larvae infection, the samples were measured in their transversal dimensions (R, T, L) at the accuracy of 0.01 mm, and the initial humidity at the range of 9.57-11.47 % was determined using a MeterLink M0297 dielectric humidity-meter by Extech Instrument.

Fig. 1: Cut-outs of test samples before infecting with the detail of width measurement in the fibre direction.

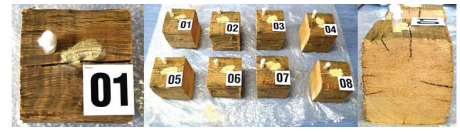

Fig. 2: Infecting the samples with larvae of the longhorn beetle (Hylotrupes bajulus L.)

A hole of 5 diameter and 30 mm length was drilled to each of the eight samples on the front surface for placing a live larva of the longhorn beetle (*Hylotrupes bajulus* L.), (Fig. 2). The depth of the holes for larvae (30 mm) was chosen with respect to the frequency of occurrence and to

good response from detected acoustic signal. Larvae of the longhorn beetle (*Hylotrupes bajulus* L.) were imported from Germany (H.A.P. Handels GmbH) at the size of 20 mm. Before infecting, all larvae were weighed at the accuracy of 0.1 mg and their viability was assessed. Prior to the test the larvae were left in samples for 7 days in an air-conditioned environment. The holes for the larvae input were sealed with a cotton wisp and crushed sawdust. The Acoustic Sensor, which is part of the Acoustic Pack non-destructive system, was mounted at the place of each opening.

With regard to changes in the structure of larvae before and after hot-air preservation, the larvae were analysed by the VHX-KEYENCE S550 digital microscope, Fig. 3.

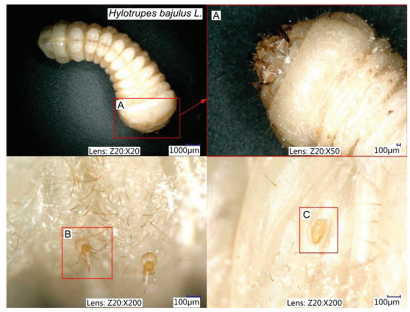

Fig. 3: Hylotrupes bajulus L. larva – detail A) the head with mandible and feelers, B) a pair of simple pentamerous legs, C) a breathing opening with filtration apparatus (stigma).

Fig. 4: Samples in sanitized area with the Acoustic Pack system sensors and with thermoelectric sensors.

Such prepared experimental samples with implanted larvae were moved to the building which was subject to hot-air preservation (Čeladná, reg. Frýdek – Místek, Czech Republic). Thermoelectric sensors for monitoring the reaching of lethal temperatures were placed across fibres into all samples to the geometrical centres, Fig. 4. Thanks to X-ray record, it was possible to lead the bore off the ingesting larva, Figs. 6 and 7. Two thermoelectric sensors were placed freely in the sanitized area for air temperature monitoring. Altogether, ten thermoelectric sensors were installed which conducted the data flow to a PC through the data bus.

Air from a Nolting generating unit with the output of 7500 m^3 of air per hour located outside sanitized area, generating air at the temperature of 120°C, was blown to the closed room with stored samples. Sensing the temperature distribution was also carried out by a FLIR B425 infrared thermal imaging camera which was calibrated for direct reading of temperatures on the outer surface of structural elements. Intermediate temperatures reached inside the samples and the temperature of air were inspected and recorded in regular intervals. During the whole time of thermal preservation the acoustic sensors were actively sensing and recording the acoustic signal emitted by the larvae inside the samples. After reaching the temperature of 55°C inside the cross-section of the samples this temperature was kept for one hour according to DIN 68 800, Part 4 (Šmíra et al. 2013. After the termination of preservation the thermal and acoustic sensors were dismantled and the destructive sample analysis and larva mortality control followed.

Technical description of the device used in the experiment

Device for measuring temperatures during hot -air preservation

Thermoelectric sensors for recording the wood temperature were placed into the geometrical centre of each cross-section (Fig. 4), where the perimeter of the opening was properly sealed so that the distortion of temperature values was avoided. The sensors are used together with an

output to the PC and with catmanEasy software automatically recording the temperature course. Sensing the temperature distribution on the surface of the structural elements was performed by the FLIR B425 infrared thermal imaging camera (Fig. 5) with the thermal sensitivity of (0.08°C) and the image quality of (320 x 240 pixel). The camera saves the thermal images, so called thermograms, as 14 bit images in the JPEG format. The camera is calibrated for direct reading of temperature on the outer surface of samples.

Fig. 5: The thermoelectric temperature sensor, the data bus and the FLIR B425 thermal imaging camera.

Fig. 6: The X-ray device (0.32 - 100 mAs, 0 - 40 kV) and the X-ray panel in the transport case.

X-ray equipment

An EcoRay HF 1040 high-frequency X-ray device (Fig. 6) has the range of exposure voltage 40-100 kV and the range of mAS 0.32 – 50 mAs (Nasswettrová et al. 2015a; Fiala et al. 2014). The mobile equipment with the dimensions of 344 x 191 x 188 mm operates comprehensively together with a DDR image receptor (X-ray panel, Fig. 6) for direct digitalisation of an image model (X-ray image). Software for processing the X-ray imager with an acquisition station for the X-ray panel is placed in a transport case, Fig. 6.

Acoustic Pack

The acoustic equipment is composed of three parts, namely 8 sensors (S1 - S8), an acoustic recording system and software for processing of gained sound footage (Nasswettrová 2015b; Fiala et al. 2014), Fig. 7. The whole system can make several hour long recordings and operate in two modes independently. An acoustic and graphic analysis can be performed by the Cubase Elements 6 software that enables recording the data from all eight sensors on-line thanks to the M-Audio recording card, and these data can be acoustically and graphically analysed at any time, Fig. 7.

Fig. 7: Sensors S1 - S8 on wood samples and the Acoustic Pack system in the process of measuring (Čeladná, the district of Frýdek – Místek, Czech Republic).

RESULTS AND DISCUSSION

Before the hot-air preservation samples 1-8 were taken for X-ray detection to determine the exact position of living larvae. X-ray images help localise the placement of thermoelectric sensors before preservation and they have showed the vitality of a larva and the speed of wood matter ingestion. The surface of the samples was always shot in the clockwise direction in the views marked A – D. Fig. 8 shows the images detected from view A. Besides ingesting larvae, the

images show the drilled openings for larvae entry and wood structure anomalies, such as knots and cracks.

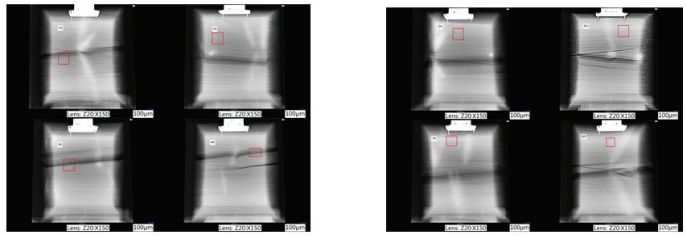

Fig. 8: X-ray images of samples 1 - 8 with infected larvae (Hylotrupes bajulus L.) and the acoustic sensor.

The calibration was performed to obtain the maximal conformity of individual sensors and to ensure their identical transmission properties important for correct evaluation of obtained signals. The gain and filtration were set at every amplifier placed in an aluminium cover with a connector together with the piezoelement so that all the responses in the frequency spectrum showed conformity. Resulting values of transmission characteristics from all the eight sensors are displayed in Fig. 9. The reliability of all acoustic sensors was guaranteed in this way and it was possible to proceed to the experimental measurements.

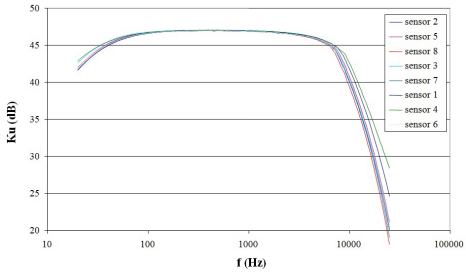

Fig. 9: Transmission characteristics of amplifiers for individual sensors.

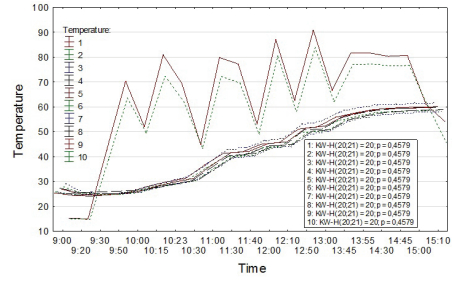

Fig. 10: Temperature distribution for hot-air preservation.

Hot-air preservation of the infected samples took 6 hours, during which at approximately 13:45 the sterilization temperature of 55oC was reached, and then it was maintained for another hour. The graphic display of the temperature course of air and the temperature inside of each sample during preservation is given in Fig. 10. Fig. 11 shows thermograms of the temperature distribution at the perimeter of the cladding of the building when leading the heat by hot-air pipes from the generating unit to the preservation area.

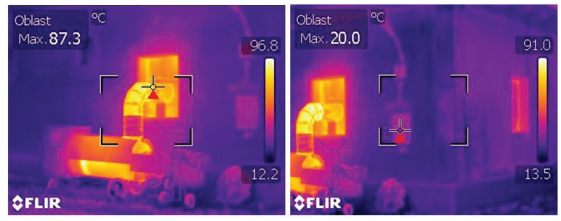

Fig. 11: Thermograms displaying the distribution of temperatures at the outside cladding of the sanitized building.

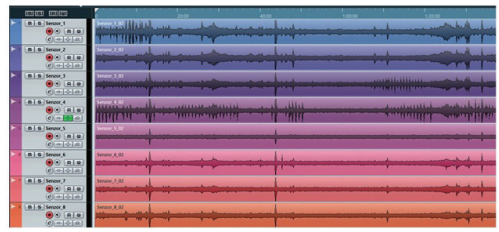

Fig. 12: The record of acoustic emission after 30 minutes of heating.

Fig. 12 shows events of acoustic non-continuous emissions on all the eight sensors after 60 minutes of heating, i.e. at 10:00 a.m. (Fig. 10), as a one and half minute long recording from software Cubase Elements 6. Air temperature by this time was 60°C. The activity is visible on sensors 1, 3 and 4.

During the process of hot-air preservation there were acoustic manifestations caused by cycled switching of the generating unit and by temperature expansion of aluminium pipes through which the hot air was blown to the sanitised area. The generated parasitic noise was additionally joined with acoustic emission caused by moisture voltage that was caused by decreasing the moisture content in the timber structure. Moisture voltage caused the tension stress in the fibres transversally that locally caused the destruction of conductive timber elements. Despite the stated fact, it was possible to monitor the situation at all the eight sensors. Acoustic manifestation of both phenomena, i.e. the activity of insect larvae and damage of timber elements, is similar in respect to duration and also spectral composition of the sound, Figs. 13 and 14. By the combination of methods for signal comparison in time and frequency area with the methods of high frequency signal discrimination it is possible to highlight the differences between given signals and enable their mutual distinction. The acoustic manifestations of larvae, generated by damaging the cell walls of timber elements by ingestion, have irregular structure with short pauses of different duration (discontinuous signal). The character of the sound is given by wood structure, moisture of the wood matter, age of the larva (i.e. its size) and by the depth of its position in the structure. The resulting sound of larvae is a combination of wood matter vibrations and the sound spreading through the air in the passage way. To obtain the searched signal while eliminating the surrounding disturbance and to check the correctness of the output from the Cubase Element 6 software, the obtained spectra of unknown multi-tone acoustic signals generated by insect larvae were compared on the bases of correlation analysis with the created database of signals (patterns) of the authors Leiler (1992) and Chapman (1998). The database consists of signals obtained in the in situ environment as well as signals of larvae obtained in laboratory conditions. In this way, it was possible to suppress the influence of undesirable acoustic emission (parasitic noise) of the surroundings and stress of the wood, and to calculate the correlation coefficient of conformity. In this way, the similarity of spectra of examined signal sources was compared and the visual difference of acoustic emission spectra given by residual stress and larvae ingestion was compared.

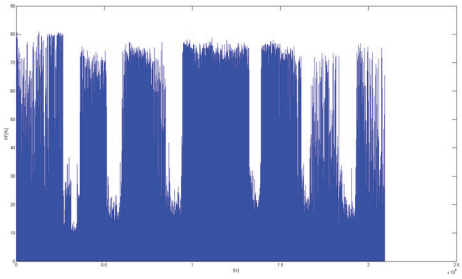

Fig. 13: The value of correlation coefficient from all sound effects.

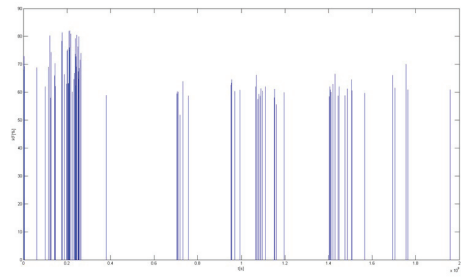

Fig. 14: The correlation coefficient of conformity with the spectrum of longhorn beetle larvae.

The vital activity of the longhorn beetle larvae has a strong component at the frequency of 1 636 Hz with the duration for approximately 50 ms. It is partially caused by the characteristics of the acoustic sensor. Authors' program (Nasswettrová et al. 2015a, b; Fiala et al. 2014) that has the stated database works with the limit values set to control the signal level at 30 before and 80 ms after the given activity at the given frequency. Then, the correlation of the signal with sinus course of 1 636 Hz is created and the resulting course is set to limits. The limit is set to ten multiple of the sinus correlation result and the background noise of the signal. A correlation coefficient is obtained by comparing the unknown signal spectrum with the uploaded pattern. It can reach the values from 0-100. For the spectrum to be considered highly similar, the correlation coefficient value has to be higher than 50. For the correct functioning of the algorithm for the calculation of the correlation coefficient, the analysed signal and pattern must have the same sampling rate. Fig. 14 shows that the correlation coefficient reaches the values up to 80, which can be considered as a high conformity, and it confirms the used work methodology. The longhorn beetle larvae activity at the frequency of 1 636 Hz is typical in several sequences, as opposed to the acoustic emissions caused by wood structure stress or surrounding noise, Fig. 15.

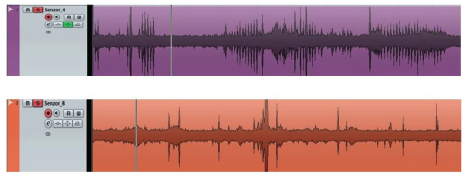

Fig. 15: The discontinuous signal of insect activity (sensor 4) and the acoustic emission caused by the damage of wood structure during the heating process (sensor 8).

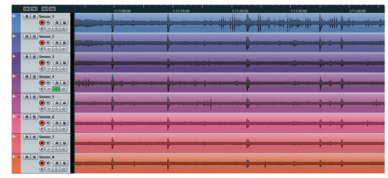

Fig. 16: The acoustic emission record after 83 minutes of heating.

Fig. 16 shows the activity from all eight sensors at the time when the temperature reached 30°C in the middle of each element, which was approximately at 10:23 a.m. according to the graph in Fig. 10, i.e. after 83 minutes of heating. The air temperature was 75°C by this time. Fig. 15 shows a visible activity on sensors 1, 3, 4, 5 and 8. Records were always taken when the hot-air unit was off.

Fig. 17 shows the activity at the temperature of 45°C according to the graph in Fig. 10, i.e. at 12:00 a.m. The air temperature was 85°C by this time. The activity is visible on sensors 1, 2 and 8.

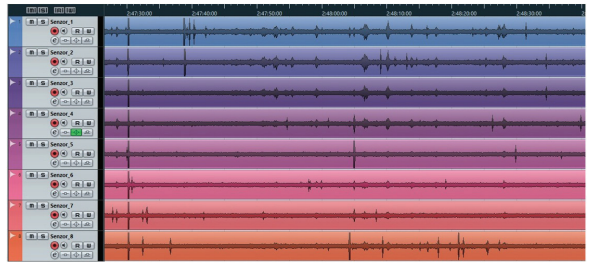

Fig. 17: The acoustic emission record after 180 minutes of heating.

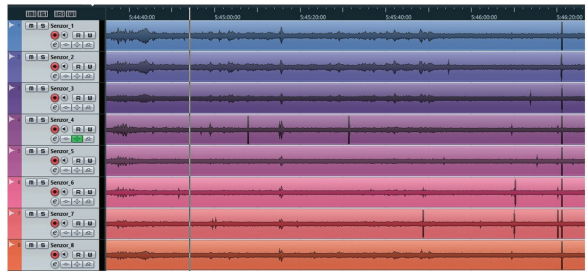

Fig. 18: The acoustic emission record after 285 minutes of heating.

Fig. 18 shows the activity at the time when the sterilization temperature of 55°C was reached according to the graph in Fig. 10, i.e. at 13:45 p.m., then the sterilization temperature was maintained for another whole hour. ie. 14:45 p.m., and then the cooling phase continued. After reaching the temperature of 55, the air temperature was maintained at 80°C for another hour. At the time of switching on the generating unit, the air temperature could be even 90°C before reaching the sterilization temperature. The activity of the longhorn beetle larvae is not visible on any of the sensors.

The cooling phase started at 15:00 p.m. (Fig. 10). Approximately at 15:30 p.m. samples 1 -8 were subject to the destruction analysis. All the samples were split and mortality of infected larvae was checked, Fig. 19.

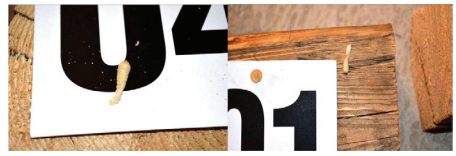

Fig. 19: The documentation of larvae mortality after hot-air preservation.

Fig. 20 shows the protein coagulation of larvae bodies. The protein denaturation is manifested by the decomposition of polypeptide chain which loses its characteristic structure. Their spirals decompose by heat and they create random configurations.

Fig. 20: The larva image (Hylotrupes bajulus L.) before and after hot-air preservation.

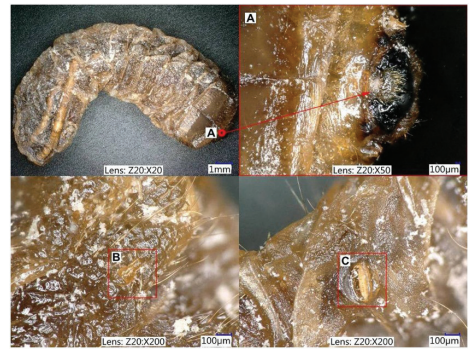

Fig. 21: Larva Hylotrupes bajulus L. – detail A) the head with mandibles and feelers, B) a pair of simple five-segment legs, C) the breathing opening with the filtration apparatus (stigma).

Fig. 19 shows a larva body before the hot-air preservation and 7 days after preservation. Fig. 21 shows the changes of the main parts of the larva body, particularly the head with mandibles, legs and the breathing opening with filtration apparatus.

CONCLUSIONS

The verification of efficiency of hot-air preservation on the mortality of longhorn beetle *Hylotrupes bajulus* L. was performed during the preservation of a room in a building in Čeladná, the district of Frýdek – Místek, Czech Republic. The efficiency of preservation was monitored by means of the Acoustic Pack acoustic recording system that can record several hour lasting recordings through specially developed sensors. It can process the recorded spectra of unknown multi-tone acoustic signals generated by insect larvae. The hot-air preservation of infected samples took 6 hours while the sterilization temperature of 55°C was reached after 5 hours. According to the methodology of DIN 68 800, Part 4, 1998 the sterilization temperature of 55°C which was reached on all thermoelectric sensors then maintained for another hour. Acoustic records were in conformity with the results of the destruction analysis. Using the KEYENCE VHX-S550E digital microscope, the analysis of the change in morphology of larvae was performed before and after the preservation process. The results proved 100 % mortality of longhorn beetle *Hylotrupes bajulus* L. larvae after the action of radiating heat in the process of hot-air preservation. It can be stated that the method is efficient in the control of wood-destroying insects.

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