Relationship of vibro-mechanical properties and microstructure of wood and varnish interface in string instruments

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Abstract Wood varnish coatings not only are aesthetically important, but also preserve the musical instrument from wear and fluctuations in the ambient humidity. Depending on the thickness, extent of penetration into the wood and the physical and mechanical properties after hardening, varnishes may change the mechanical and also vibro-acoustical properties of the coated wood. Contrary to studies on the chemistry of the varnish and primer used for old and contemporary musical instruments, the physical and mechanical properties of the varnished wood in relation to the geometry of their interface have been poorly studied. We implemented non-destructive test methods, i.e., vibration tests and X-ray tomography, to characterize the hardening-dependent change in the vibrational properties of master grade tone wood specimens after coating with four different varnishes. Two were manufactured in the laboratory, and two were supplied from master violin makers. For a controlled accelerated hardening of the varnish, a UV exposure method was used. It was demonstrated that varnishes increase wood damping, along and perpendicular to the grain directions. Varnishes reduce the

sound radiation along the grain, but increase it in the perpendicular direction. Changes in the vibrational properties were discussed together with results of 3D images of wood and varnish microstructure, obtained from a customized tabletop X-ray microtomographic setup. For comparison, the microstructure of the interface of the varnished wood in the laboratory and of specimens from two old violins was analyzed with the same X-ray tomography setup. Laboratory varnishes with various compositions penetrated differently into the wood structure. One varnish of a master grade old violin had a higher density and was also thicker and penetrated weaker into the wood, which is more likely related to a more sophisticated primer and varnish application. The study demonstrates the importance of the vibro-mechanical properties of varnish, its chemical composition, thickness and penetration into wood.

1 Introduction

The term varnish is generally referred to as “a liquid which, when coated over a solid surface, dries to a transparent film” [1]. Wooden musical instruments are covered by varnish layers often made by different organic compounds. They protect the musical instruments from changes in the relative humidity (RH) and direct contact with the player. Varnishes are aesthetically important for the instrument, and they also influence the acoustics of the instrument by modifying the wood properties, e.g., mass, stiffness and damping.

Wood is the preferred material for most music instruments. It is a hierarchically structured cellular composite, with various anatomies and biochemical compositions depending on the selected species. The density, hygroscopicity and vibro-acoustical properties vary between

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wood species. At the submicron scale, e.g., cell wall sublayers and middle lamella, wood can be seen as a fibrous composite material, whereas the cellulose crystalline microfibrils represent the reinforcing components in a matrix consisting of hemicelluloses and lignin [2]. Briefly speaking, cellulose is mainly responsible for stiffness, while the matrix is more sensitive to humidity variations and contributes to the viscoelasticity and swelling of wood. Microfibrils and matrix are linked by hydrogen bonds and covalent cross-linkages, which enforce the hygroscopicity and dimensional instability of the bulk material. Physical and mechanical properties of wood are different along and perpendicular to the longitudinal cells, i.e., tracheids in softwood. Moreover, Norway spruce ‘tone wood’ used for soundboards of violin families has different properties, i.e., lower density and narrower annual rings than timber used for construction. Thus, it is safe to assume that treating of the surface of this fine material, with a solid, e.g., varnish, will influence the delicate vibro-acoustic performance of a music instrument. To date, we do not exactly know how the microstructure and physical properties of varnish will change the vibration and damping of the treated wood and influence the vibration and acoustics of string instruments.

It is generally assumed that the varnish of old Cremona violins have unique properties which are partly responsible for their superior sound quality. Even though experts agree that the good contemporary violins might sound as good as the esteemed Cremona violins [3], the history and aesthetical features of the old varnishes provides an exceptional added value to old instruments. This encourages further analytical studies to help understand the details of varnishing craftsmanship used for esteemed Cremona instruments. Microscopy of semi-thin sections from historical instruments showed that the wood coating has two principal layers that consist of inorganic or organic compounds: the primers, which are a transparent or lightly colored layer containing mineral particles and then several layers of varnish. In the case of the violin, the varnish can be slightly colored, containing organic dyes, finely dispersed of organic lakes or inorganic pigments [4]. The vibrational properties of the varnished wood depend on (a) composition and thus the time-dependent physico (thermo-hygro)-mechanics of varnish and (b) the extent of penetration of varnish into wood which makes the interface. The chemistry of the layered structure of varnish in historical instruments, in terms of mineral elements and organic compound, has been studied in in-depth in the past [5–7]. Also, the geometry of the interface has been investigated using different microscopy techniques [8, 9] or by applying synchrotron [10, 11] methods. Nevertheless, non-destructive X-ray imaging techniques have a larger potential for documentation and diagnosis of cultural heritage objects such as old violins [12–14]. Also, the physical

and mechanical properties of contemporary and old varnishes and their impact on vibro-mechanics and hygroscopicity of the coated wood are not well studied. Our knowledge on changes in wood properties after coating is mainly based on studies by Haines [15], Ono [16, 17], Schleske [18, 19] and Obataya et al. [20] that examined the vibrational behavior of small wood strips or plates before and after coating. They reported changes in the stiffness and internal damping of the varnished wood and discussed problems regarding the orthotropicity of wood properties, i.e., different stiffness and damping properties along the grain (longitudinal) and perpendicular to the grain (transversal). Considering that the varnish composition is different for each violin maker, an understanding of the relationship between the chemistry of varnish and changes in the physico-mechanical properties of the coated wood is still a challenge. The problem is even more complex, when we note that the criteria used by different violin makers and tone wood retailers for selecting master grade tone wood, even for the most commonly referred properties of tone wood, e.g., internal damping or density, are different.

The main objective of the presented study was to improve our understanding on the changes in vibro-mechanics of coated wood, in relation to the varnish composition and geometry of wood and the varnish interface. Our hypothesis is that changes in mass, stiffness and microstructure of the interface layer influence damping, stiffness and sound radiation of coated wood strips. Twin specimens of Norway spruce tone wood were excised from sapwood and heartwood (the outer and inner part of the tree trunk), and their natural frequencies and internal damping were measured before and after coating with different varnishes at different hardening states. Certain simplified recipes were used for preparation of varnishes in the laboratory. Changes in the vibro-mechanical properties were discussed in comparison with X-ray microtomographic sections, showing the thickness of varnish and its depth of penetration into wood. Moreover, results were compared to the X-ray microtomographs of specimens from two old violins, one from a cello made in Turin, Italy, in 1640/60 and the other from a violin manufactured in Saxony, Germany, around 1920.

2 Materials and methods

2.1 Wood

Twin wood plates with dimensions of 120 mm (R , radial direction) $\times$ 2.5 mm (T , tangential direction) $\times$ 420 mm (L , longitudinal direction) were excised from a plank of Norway spruce wood (*Picea abies* L.), with narrow and even annual rings and perfectly quartered with minimal run

out according to the criteria for ‘master grade’ tone wood for violin making. The tree was felled in autumn 2010, in the Berguen region, Switzerland. Forty quarter-sawn strip specimens of $12\text{ (R)} \times 2.5\text{ (T)} \times 150\text{ (L)}\text{ mm}^3$ were prepared for characterization of the vibro-mechanical properties in the longitudinal direction and also 20 strip specimens of $120\text{ (R)} \times 12\text{ (T)} \times 2.5\text{ (L)}\text{ mm}^3$, for transversal direction. From the 40 longitudinal specimens above, 20 were prepared from sapwood (SW_L), the outermost portion of a tree trunk, which is used for making the central part of violin top plate and 20 from the heartwood (HW_L). Specimens were stored and conditioned in a climate chamber at 30 % relative humidity (RH) at 20 °C. The density at equilibrium moisture content (EMC) was $439.4 (\pm 8.3)\text{ kg/m}^3$ for HW_L, $444.1 (\pm 9.5)\text{ kg/m}^3$ for SW_L and $439.9 (\pm 4.7)\text{ kg/m}^3$ for transversally excised specimens (TR).

In Fig. 1, the selected material illustrated at three different spatial scales, (a) macroscale: sound board, (b) mesoscale: test specimens for the vibrational tests and (c) microscale: microtomography image of the cellular structure of Norway spruce wood, is presented. In the latter, the orthotropic directions and some important anatomical feature of Norway spruce wood are highlighted.

2.2 Varnish and accelerated hardening with UV light

We selected four varnishes, two prepared in the laboratory and the other two were collected from two professional luthiers in Germany. The luthiers made their varnishes in their own workshops, but shared the major components of their varnished and their volume fractions. The prepared and laboratory-made varnishes were designed by Johanna Pflaum, a qualified luthier who studied at Mittenwald in

Germany. The main ingredients of the utilized varnishes were:

- Laboratory_1 (lab_1): 50 g colophony, 30 g linseed oil and 30 g terpentin oil targeting a 77 % resin and a 23 % oil composition
- Laboratory_2 (lab_2): 112,5 g burgundy resin, 37.5 g amber and 150 g linseed oil targeting a 50 % resin and a 50 % oil composition
- Luthier_1 (lut_1): 750 g amber, 200 g dammar, 60 g manila copal and 50 g aloe targeting a 62 % resin and 38 % oil composition
- Luthier_2 (lut_2): 1.5 l linseed oil, 150 g aloe, 500 g amber, 26 g dragons blood, 33 g gamboge targeting a 60 % resin and 40 % oil composition

We used a mixture of egg white, linseed oil and water as a basic primer before varnishing the wood. All specimens were coated first, with a similar quantity of primer, 0.16 g for the longitudinal and 0.12 g for the radial specimens. A drop of primer solution was placed with a pipette onto the wood and spread over the surface with a thin spatula. After 5 days of drying, the same method was implemented for applying one layer of varnish. Our main aim was not to obtain a good quality varnish in the laboratory or to apply it professionally on the wood surface, but to keep the processing method structured, documented and repeatable for our analytic studies.

To speed up hardening of varnish, all varnished specimens were simultaneously exposed to five and two incremental steps of 3 h (a total of 5, 8 and 11 h) in a custom-made UV box. As part of the hygroscopic moisture is desorbed after UV exposure, a waiting time of up to 7 days was required between measurements until the specimens reached EMC at 30 % RH. Thus, the specimens were kept in the controlled 30 % RH chamber between each UV

Fig. 1 **a** Norway spruce tone wood plank, **b** strip-shaped wood specimens and **c** 3D microstructure of Norway spruce wood acquired by synchrotron X-ray tomography

exposure, and their mass measured until gaining EMC. Table 1 shows the mass of varnish layer measured after treating the wood specimens and after 5-, 8- and 11-h exposure to UV light and equilibrium at 30 % RH. Although we intended to coat the wood with a similar quantity of varnish, the total mass of coating was different depending on the varnish type, e.g., significantly higher for lab_2 and reduced after UV exposure.

Moreover, two $1.5 \times 1.5 \times 1.5 \text{ mm}^3$ wood specimens were excised from old violins, for comparison of the spatial geometry of varnish and the wood interface with the varnished specimens treated in the laboratory. One specimen was excised from the spare edge of a Cello made in 1640-60, after being trimmed by luthiers to a more manageable size in recent years. The instrument had been crafted in Turin, Italy, most probably by Henricus Casner, also known as Enrico (also the specimen label in the study), and is still in an excellent condition and sounds wonderful. The other specimen was from a violin manufactured in Markneukirchen, Saxony, Germany, made around 1920. It is a violin of average quality and not worth restoration and thus dedicated for destructive tests.

2.3 Vibrational test setup

We used a free-free resonance flexural vibration test to determine the first resonance frequency (f_R) and internal friction ($\tan \delta$) in beam elements [16, 20]. Non-contact forced-released vibration was enforced through an electro-magnet device, in the face of a thin metallic plate of <20 mg weight. Metallic plates were glued to one end of each wood specimen, and displacements at anti-node of the

first vibration mode were measured using a laser triangulation displacement sensor. Vibration emission and acquisition of data were performed in a custom-developed algorithm in labview (described previously in [21]). A broadband frequency scan was used to detect the first resonance frequency, on which a second, narrow-band scan allowed the determination of the quality factor Q (bandwidth at half-power). Then, the excitation (fixed at f_R) was stopped and the logarithmic decrement (λ) of amplitudes was recorded to compare the $\tan \delta$ in both frequency ($1/Q$) and time (λ/π) domains. Given the high aspect ratio of the samples, the influence of shear and rotary inertia was ignored. Thus, the specific modulus of elasticity was calculated by using the f_R in Euler-Bernoulli equation:

$$\frac{E}{\rho} = \frac{48\pi^2 l^4}{m_n^4 h^2} f_{Rn}^2 \quad (1)$$

where l is the length of the sample, h is the thickness, f_{Rn} is resonance frequency of the mode n and m is a constant equal to 4.730 at the first vibration mode. Also, E is Young's modulus along the specimen length, and ρ is the density of the material; thus, the unit of the specific modulus of elasticity E/ρ is $\text{MPa m}^3/\text{kg}$. All measurements were taken inside a humidity- and temperature-controlled chamber, at 30 % RH and 20 °C, while specimens were at EMC. The primer and varnish were implemented inside the same climatic chamber, and measurements were repeated immediately after varnishing, and also after specimens reached EMC after 5-, 8- and 11-h exposure to UV light. Each measurement was repeated three times, and the mean values calculated. Subsequently, the sound velocity, c , sound radiation coefficient, R , and characteristic

Table 1 Mass of varnish layer (in mg) after treating the surface of wood specimens, and after 5-, 8- and 11-h exposure to UV light

Hardening state	Mass of varnish layer (mg)			
	Wet	5 h UV	8 h UV	11 h UV
HW_L				
Lab_1	93.2 (± 1.6)	86.9 (± 1.1)	84.0 (± 1.4)	82.3 (± 0.9)
Lab_2	101.1 (± 1.1)	93.0 (± 2.0)	92.1 (± 2.0)	92.0 (± 2.0)
Lut_1	84.84 (± 1.7)	71.6 (± 1.8)	72.9 (± 2.8)	70.82 (± 2.9)
Lut_2	83.2 (± 0.6)	70.9 (± 1.1)	72.66 (± 4.1)	69.0 (± 0.6)
SW_L				
Lab_1	97.1 (± 1.1)	90.22 (± 2.1)	87.1 (± 2.1)	85.4 (± 2.3)
Lab_2	102.7 (± 1.4)	92.6 (± 1.9)	91.2 (± 0.9)	90.2 (± 1.7)
Lut_1	87.12 (± 1.9)	73.7 (± 1.6)	72.6 (± 2.1)	70.9 (± 2.4)
Lut_2	86.1 (± 1.8)	72.7 (± 1.7)	71.9 (± 1.6)	70.4 (± 1.8)
TR				
Lab_1	72.8 (± 0.7)	63.7 (± 1.2)	60 (± 0.8)	57.8 (± 0.9)
Lab_2	80.8 (± 1.5)	67.4 (± 1.7)	65.8 (± 1.7)	64.2 (± 1.9)
Lut_1	66.1 (± 1.5)	53.2 (± 2.0)	51.6 (± 1.6)	48.2 (± 2.0)
Lut_2	65.9 (± 0.6)	50.1 (± 0.4)	48.4 (± 0.5)	47.0 (± 0.2)

impedance, z , in the longitudinal ($_L$) and transversal ($_RT$) directions were calculated as:

$$c = \sqrt{\frac{E}{\rho}}; \quad R = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}}; \quad z = c\rho = \sqrt{E\rho} \quad (2)$$

2.4 X-ray microtomography

X-ray tomographies were performed at the center for X-ray analytics at Empa [22] by a microfocus X-ray tube from Viscom XT9160-TXD operating at an acceleration voltage of 80 kV and a tube current of 120 μ A. Thin sections were extracted with a razor blade, with a dimension of approximately $1.5 \times 1.5 \times 1.5 \text{ mm}^3$ from the coated sapwood with different varnishes and also from old violins. All sections were scanned at ambient RH and temperature and reconstructed with the same settings to allow a direct inter-relative comparison. The acquisitions were corrected for artifacts and reconstructed using Octopus reconstruction software [25]. Full-field cone-beam tomographic acquisitions were performed which limited the spatial resolution to a voxel size of $2.5 \times 2.5 \times 2.5 \text{ }\mu\text{m}^3$. In addition to 3D visualization of the microstructure, dependency of the X-ray absorption on the density of material enables certain analysis of the density distribution in the wood cell walls and varnish by comparing the relative gray values.

3 Results and discussion

Figure 2 shows the specific modulus of elasticity, E/ρ versus internal damping, $\tan \delta$ of all wood specimens, 20 (HW_ $_L$), 20 (SW_ $_L$) and 20 (TR) before coating with the

Fig. 2 Relationships between $\tan \delta$ and E/ρ along the grain (HW_ $_L$ and SW_ $_L$) and perpendicular to the growth rings (TR)

primer and varnish. The relationship has the form of a power law, confirming the suggested dashed-line trend by Ono and Norimoto [16]. The average longitudinal E/ρ of heartwood was $35.89 (\pm 0.4) \text{ MPa m}^3/\text{kg}$, of sapwood was $34.0 (\pm 0.8)$ and of transversal specimens $1.93 (\pm 0.14)$. According to Eq. 2, the sound velocity in heartwood was $5991 (\pm 35) \text{ m/s}$, slightly higher than in the sapwood, which was $5832 (\pm 72)$. Also, sound velocity was significantly lower in transversal direction, $1390 (\pm 51) \text{ m/s}$. This is due to the curtain-like acting of the growth rings for sound waves, resulting in a slower speed in the transversal direction. The same argument explains the higher damping in the transversal direction of $0.0168 (\pm 0.0006)$, while it was $0.0056 (\pm 0.0001)$ in the heartwood along the grain and $0.0057 (\pm 0.0002)$ in the sapwood.

In Fig. 3, the box-and-whisker plots of longitudinal E/ρ , and in Fig. 4, the longitudinal $\tan \delta$, before and after coating with different varnished are presented. Also, Fig. 5 shows that the transversal E/ρ and $\tan \delta$. E/ρ in heartwood was higher and less scattered than in the sapwood. After coating of wood with all the varnish types, E/ρ was decreased and subsequently increased as a result of varnish hardening after UV exposure. Nevertheless, it never reached the initial value of E/ρ before coating, even after 11 h of UV exposure. Also, coating increased the $\tan \delta$, in both the longitudinal and transversal directions. UV exposure decreased the $\tan \delta$, though it never declined to the low damping values measured in the material before coating. However, a moderate increase in damping can be beneficial for the sound of violins [23, 24], as high notes are dampened and instruments sound mellow and warm. In the transversal direction, E/ρ was increased after varnishing and also after UV exposure as indicated in Fig. 5. The origin of the dissimilar change in the E/ρ of longitudinal and transversal specimens is related to differences between the magnitude of stiffness in the longitudinal and transversal directions. In the longitudinal direction, E/ρ of raw wood varied between 34 and 36 $\text{MPa m}^3/\text{kg}$, while value of only $1.93 \text{ MPa m}^3/\text{kg}$ was obtained in the transversal direction (Fig. 2). Coating a media with another stiffer layer improves stiffness of the composite, which is more likely the case in transversally excised wood specimens. Thus, we can assume that varnish is stiffer than wood in the transversal direction, even if we did not directly measure stiffness of the varnish coating. The scattering of the measured data was lowest on raw wood and increased after varnishing, especially varnish lab_2, but often reduced after prolonged exposure to UV light. Similar to $\tan \delta$, E/ρ scattered stronger in varnished wood, e.g., lab_2. However, apart from this slight difference, the box-and-whisker presentation did not indicate any other significant differences, i.e., between the changes in the properties in relation to the varnish type.

Fig. 3 Box-and-whisker plots showing changes in longitudinal E/ρ of **a** sapwood and **b** heartwood specimens treated with varnish and after different exposure times to UV light

Column bars in Fig. 6 show the change in the sound radiation and acoustic impedance of wood, after implementing the 4 different varnishes and hardening after 11-h UV exposure. The initial R and z data (averaged between 5 raw specimens) are also labeled closed to each column bars which represent the change in these properties after implementing the respective varnishes. Varnishing decreased the sound radiation, up to 6.5 %, along the grain. In this regard, no significant difference was observed between the sapwood and heartwood. Among different varnishes, changes were most significant after coating with lab_2 varnish, which is the one with the highest oil fraction. Changes in sound radiation were also higher for the varnish prepared in the laboratory, lab_1, compared to the professional makers' varnishes. Contrary to the longitudinal specimens, varnishing increased sound radiation in the transversal direction, and at a higher rate with the professional makers' varnishes. As R describes how the vibration

of a solid body is damped by sound radiation, a higher sound radiation correlates with the emission of a louder sound. Also, the orthotropic changes in sound radiation, i.e., reduction in longitudinal direction and increase in the transversal direction, have an important influence on the resulting sound of the music instrument, as the wood orthotropy is reduced. One should note that in violins, the wood carries a significant load in longitudinal, but also in the transversal direction, which is mechanically less robust. This fact plays a significant role in defining the arching of the violin soundboard by violin makers, for redistribution of forces in the desired directions. In this regard, the stiffening impact of the varnish along the woods weakest direction is likely beneficial. While varnishing has a different influence on the longitudinal and transversal R , the acoustic impedance z always decreased, up to 2.7 % longitudinally and 10.5 % perpendicularly. z relates to the transmission of vibrational energy from the soundboard to

Fig. 4 Box-and-whisker plots showing changes in longitudinal $\tan \delta$ of **a** sapwood and **b** heartwood specimens treated with varnish and after different exposure times to UV light

the air; thus, its reduction is more likely a drawback for the musical instrument. The lab_2 showed the highest reduction in z . Luthiers who play their instruments before and after varnishing report that the instruments often produce a ‘sharper’ sound before varnishing. However, varnishing is an inevitable step of violin making, for the beauty of the instrument and for protecting it from wear and moisture exchange with air, which in turn negatively changes the vibrational properties of wood in the short and long term.

In Fig. 7, X-ray tomography sections of wood specimens treated with 4 different varnish coatings are presented. The thin-wall earlywood tracheids of Norway spruce wood are distinguishable with larger cell lumina with a diameter of approximately 30–40 μm . The latewood tracheids have thicker cell walls, and their lumina were smaller (8–15 μm) than the cells in the earlywood. Red to yellow colors correspond to the higher gray values, due to higher attenuation of X-ray in denser materials, while the

green to blue colors indicate material with a relatively lower density. In this context, all 4 varnished sections had a lower density than wood cell walls. They filled the wood lumina, in a depth of a few hundred micrometers from the surface. No significant differences were observed between the depth of varnish penetration in earlywood and latewood tracheids, even though they have different lumen size and pit structure, and thus different permeability [26]. The varnish lab_2 was different from the other varnishes, as it penetrated deeper into the wood. In the latter case, there were even lumina that were randomly filled up to 400 μm beneath the surface. This may partially explain the inferior properties of this varnish, regarding the impulse changes in the sound radiation and acoustic impedance. However, different varnishes may have different stiffness which may significantly influence the vibro-mechanical properties of the varnished wood. The averaged profile of the gray values over all sections confirms the above observation; gray

Fig. 5 Box-and-whisker plots showing changes in the **a** E/ρ and **b** $\tan \delta$ in perpendicular to the grain direction of wood specimens treated with varnish and after different exposure times to UV light

value of the lab_2 specimens is significantly different from the others, in 200 μm depth from the surface. As we applied only one layer of varnish for simplification and removing additional variables, e.g., discontinuities in manually applying a multilayered varnish, the varnish on top is too small for quantification and further discussions. In Fig. 8a, b, the 3D rendered geometry of the varnished wood from 2 old violins and a middle section from each (inlet) are presented. The labeled specimen as Enrico is extracted from an instrument made in 1640, with a varnish of highest quality, while the other varnish, from the instrument made in 1920s, is of average quality with traces of repair and restoration over the years. The varnish was thick and cracked all over the instrument, the wood was infected by wood worm, and the instrument was in a poor condition and cannot be restored or played anymore. In both cases, the varnish thickness was greater in the laboratory specimens, up to 40 μm in Enrico and 80 μm in

Saxony, as makers always implement several layers of varnish and not only one coating. The varnish also penetrates weaker into the wood, which is likely due to the more sophisticated primer application in a real instrument compared to the laboratory varnish, but also can be dependent in the viscosity of the varnish itself. One interesting observation is different densities of the varnishes, which was significantly higher in Enrico (red–yellow colors), than in the Saxony and all the contemporary varnishes. Wood density, especially in the latewood tracheids, was higher in the Enrico specimen, and the growth rings were narrower, when compared to the Saxony and contemporary tone wood. A layer of glue was observed in the middle of the Enrico specimen, with a density similar to the varnish and a thickness of up to 80 μm . Microcracks, with an opening of below 10 μm , were observed all around the surface of Saxony varnish, which were locally covered by another thin layer with a higher density on top (Fig. 8c). Also,

Fig. 6 Sound radiation (*left*) and acoustic impedance (*right*) after coating wood specimens with different varnishes and after 11-h UV exposure in **a** longitudinal sapwood, **b** longitudinal heartwood and **c** perpendicular to the grain direction

some high density particles with dimensions of few μm were observed on the wood surface and trapped inside the varnish, which are parts of inorganic powders, e.g., Pumice or chalk, used for filling the lumina on the wood surface to avoid the penetration of varnish deep into the wood. The assessment of the detailed chemical composition of these components and also determining their mechanical properties for upscaling the microstructure–property relationships in wood and varnish interface through a coupled numerical and experimental approach are the topics of our future studies.

4 Conclusion

Varnish coating plays an important role for the long-term quality of sound of wooden musical instruments, but as applied on the wood surface, impulse changes in the vibro-mechanical behavior of wood can be recorded. We examined the change in the specific modulus of elasticity of

wood, which is correlated with the speed of sound and also in the internal damping in the material, after coating with 4 different varnishes (professionally made or in the laboratory). It was demonstrated that all varnishes, independent from their original compositions, increased the internal damping of wood, along or perpendicular to the grain. The specific modulus of elasticity and sound radiation were decreased along the grain and increased in the perpendicular direction. After exposure of varnished wood specimens to UV light, the specific modulus of elasticity increased and the internal damping decreased, as a result of hardening of the varnish. X-ray microtomographs showed no significant difference between extent of varnish penetration into the earlywood and latewood tracheids. With all coatings, the varnish penetrated approximately 100 μm into the wood, with exception of the home-made laboratory varnish that had the highest oil fraction (lab_2) and penetrated deeper into wood. The latter varnish caused a larger scattering for all measured vibrational properties, and a more significant reduction in the longitudinal sound

Fig. 7 **a** Reconstructed sections of X-ray tomograms showing the spatial uptake of varnish (*blue*) in early and latewood tracheids and **b** profile of gray value, average of 600 sections

Fig. 8 Showing 3D rendered geometry of wood and a varnish coating on *top* in **a** Enrico specimen from Turin 1640/60 and **b** Saxony specimen from 1920, with a higher magnification slice inlet. **c** Saxony cracks and fillers

radiation. However, the depth of varnish penetration was not the only parameter that determined changes in the vibro-mechanical properties of the varnished wood. Thus,

also the mechanical properties of varnish itself are an important factor, which we will demonstrate in a future study. The orthotropic changes in the sound radiation or

speed of sound makes the continuation of this study on 2D elements such as plates or the real curved soundboard of the instrument important. Characterizing the orthotropic change in vibro-mechanical properties of wood plates after varnishing and numerical simulation of the relation between these changes and the vibration of the violin body are the topic of our next study.

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