Microwave Processing of Polymeric Coatings for Guitar Woods

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Abstract

Microwave energy was used to cure polymer coatings on instrument-grade wood. A processing method was developed that included spray coating the polymer onto raw wood panels and pulling the coated panels through a 2.45GHz multi-mode microwave cavity by means of a low-power motor. Materials characterization and testing used to analyze the feasibility of using microwave processing as a coating method for guitar woods included dielectric property measurements, moisture content measurements, density measurements, and scanning electron microscopy (SEM). Also, vibrational analysis was used to compare the damping characteristics of each coating method, providing further basis for analyzing the feasibility. A comparison was conducted between samples created using the ultraviolet curing method currently used by Taylor Guitar Co. and the microwave samples generated in this study. The results demonstrate that the microwave processing of polymeric coatings for guitar woods is feasible and produces beneficial results. SEM imaging shows enhanced interaction between the polymer and wood in the microwaved samples, which may create a stronger and more durable coating. Vibration testing shows microwave processing produced comparable damping results at half the coating thickness. This decreased coating thickness may lead to a more completely cured polymer, cost savings, and reduce emission during curing.

Keywords: Microwave, Microwave Processing, Wood Dielectrics, Wood Acoustics, Polymer Coatings.

1. Introduction

Taylor Guitars currently uses an ultraviolet (UV) process to cure their protective and aesthetic polymeric coatings. Taylor Guitar Co. knows that the UV polymer they use does not completely cure during processing, meaning that the polymer may not be completely cured when it leaves their factory. This issue, coupled with their desire to increase quality control, lead to an interest in microwave energy as a means to improve on their current processing method. Microwave processing has the potential to improve upon the current UV method in a variety of ways. First, microwave energy induces significant molecular movement in the form of polarization; this phenomenon has been shown to increase the penetration of one material into another[1]. This enhanced penetration, coupled with heating due to microwave interaction with the material, could create a stronger bond between the wood and polymer. Second, microwave energy propagates with a larger wavelength than UV energy. Larger wavelengths penetrate deeper into some materials and can transfer energy further into the material[2]. This behavior could be beneficial in two ways. The deep penetration of energy could enhance molecular diffusion into the substrate material cross-section, as discussed above. In addition, deeper penetration of the microwave energy could lead to a more uniform cure of the polymer. In UV curing, a large quantity of energy may be absorbed at the surface of the polymer causing the surface to cure first.

To determine the feasibility of microwave curing, this project had three goals. First, a microwave was developed for processing the wood provided by Taylor Guitar Co. and the polymer coating. Second, uncoated, Taylor UV-coated, and microwave-processed wood substrates were analyzed for comparison. Third, the wood's damping characteristics were analyzed and a comparison was drawn between the UV-cured and microwave-cured samples.

2. Experimental Setup and Procedure

2.1 Overview

The materials characterization performed at Virginia Tech included dielectric measurements, moisture content analysis, and density testing of the wood before processing. Dielectric characteristics (dielectric loss and dielectric constant) dictate how a material will interact with a microwave field. Materials with a higher dielectric loss will more readily heat because they have an increased ability to dissipate energy transferred to them by an electromagnetic (EM) field (dissipation is often in the form of heat). Materials with a higher dielectric constant will also allow microwave energy to penetrate deeper into the bulk and attenuate within the material, meaning the material has an increased ability to absorb microwave energy[3].

Moisture content was analyzed using thermogravimetric analysis (TGA), and the data was used to determine a temperature for drying wood samples. "Dried wood" was dried for 3-4 hours at the temperature that removed all the free water. Density of the wood was calculated using equation 1 for further understanding of the wood substrates.

$$\text{Density} = \text{Mass/Volume} \qquad (1)$$

Optical microscopy and SEM were used to observe the interaction between the wood and the polymer and to determine if there were any significant differences between UV- and microwave-processed samples. The SEM provided high magnification and high resolution images that could be used to draw conclusions about the wood/polymer interface. Along with the materials testing conducted at Virginia Tech, students at the University of Hartford conducted vibration tests to assess the acoustical quality of the microwave-processed wood. Wood substrates sent from Taylor (both UV-coated and uncoated) were compared to the wood substrates produced by Virginia Tech to determine if microwave processing had any distinct or drastic effects on the acoustic properties of the wood.

2.2 Dielectric Testing

Dielectric testing using a cavity perturbation method-was performed on instrument-grade maple and rosewood samples provided by Taylor. This cavity perturbation technique measures a resonant cavity's frequency shift when a sample is introduced. The equations for calculating the complex permittivity (dielectric loss and constant) have been derived by F. Adams et al[4]. Adams shows that small cylindrical samples can be used to calculate the complex permittivity with less than 5% error at 2.45 GHz, and this error can be reduced by further calibration, accomplishing error values as low as 1% for low loss materials (tan (δ) <=0.3). The theory assumes that the sample is placed in a uniform field and that the radius of the sample is much smaller (approximately 5% or less) than the wavelength of the resonating EM field [4]. This measurement technique is suitable for a wide range of applications including biological materials such as wood[5].

Small cylindrical wood samples, approximately 9 millimeters long and 2.8 millimeters in diameter, were created for use in testing. Six samples of each wood species were tested. The cavity was calibrated using Teflon standards on each day measurements were taken on the wood to ensure accuracy. For clarification, "longitudinal" refers to cut wood samples with grains oriented parallel to the cylinder's axis and "transverse" refers to cut wood samples with grains oriented perpendicular to the cylinder's axis. When placed in the testing chamber, the samples were oriented so that the microwave field propagated in the direction perpendicular to the cylinder's axis.

2.2 Coating

A water-based urethane was selected as the coating for this experiment because its performance in a microwave field was most favorable based on experimental observations. Application of the coating was achieved by obtaining a compressor with a spray painting attachment. The amount of urethane deposited on the surface was controlled by adjusting the pressure settings of the compressor (~50 psi) and the speed at which the sprayer was manually passed over the wood substrates.

2.3 Air-drying of Water-based Urethane

A coated sample was allowed to cure in air for comparison with the microwave sample. Since the polymer system was not the UV-activated composition used by Taylor, a baseline comparison was needed to evaluate the effects of the microwave process, if any resulted. The manufacturer's instructions suggested the urethane could cure in air with no external influence. Each coat was allowed to dry in air (approx. 20°C) for 24 hours. There were three coats and they were sprayed using the same method discussed above.

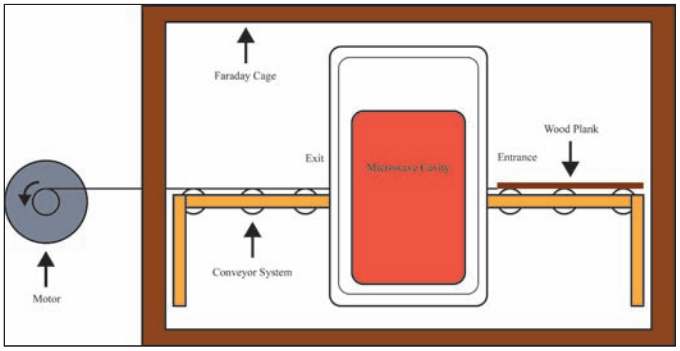

Figure 1. Schematic of complete microwave set-up. The motor can be seen on the left. The microwave with slots and the conveyor system can be seen inside the Faraday cage.

2.4 Microwave Setup

After experimentation with both single-mode and multi-mode microwave cavities, it was determined that a 2.45 GHz multi-mode cavity containing a low intensity electromagnetic field was less prone to burning the wood substrates, contained a broader field distribution allowing for processing of larger samples, and was easily controlled for this particular process. Figure 1 shows the complete microwave set-up used for wood processing. In order to accommodate large panels of wood (six inches by two feet) needed for vibrational testing, slots approximately seven inches long and one inch wide were cut in the sides of the microwave cavity. A pulley and conveyor system was developed and integrated into the microwave design. To contain leaks, a Faraday cage was constructed using wood and aluminum screen.

2.5 Microwave Processing of Maple

Based on dielectric properties, ease of machining, and availability, maple was selected as the primary species for curing experiments. Substrates machined to the correct dimensions were provided by Taylor. Each coating was sprayed manually with the compressor and spray gun to achieve as even as possible coatings. However, some human error in the thickness of the coating was expected. Four samples (6 inches by 2 feet) of maple were successfully processed.

Once the first coating was applied, the wood was attached to the motor using nylon fishing line and was pulled through the microwave at a constant speed. The total time that any part of the wood spent in the microwave was approximately two minutes; this time was chosen based on observational experimentation. After the first coat was microwave-processed; the wood was buffed using a hand-held sander and felt polishing attachments. This process significantly affected the smoothness of the polymer coating, leading to a more aesthetic appearance. Two more coats were applied and microwaved using the same method without additional buffing, resulting in a total of three coats, and an approximate thickness of 100 µm.

2.6 Scanning Electron Microscopy

Cross-sectional fracture surfaces of four different maple samples were imaged to analyze the wood/polymer interface and determine the effects that different processing techniques may have had on the composite system. The four different samples were: 1) uncoated wood, 2) UV-coated wood (prepared by Taylor), 3) air-dried wood (water-based urethane coatings allowed to cure onto the maple in air), and 4) microwaved samples (water-based urethane coatings cured using the microwave process described above). A LEO (Zeiss) 1550 high-performance Schottky field-emission SEM was used in this analysis.

2.7 Vibration Testing

Maple panels (uncoated, UV-processed, and microwave-processed) were provided to researchers at the Acoustical Engineering Laboratory at the University of Hartford. A modal analysis was conducted on each sample to determine the acoustical effects of finishes on wood. Modal analysis is a method of modeling a multi-degree of freedom system as a series of single degree of freedom mode shapes, natural frequencies and damping factors. The selection of the response point, referred to as driving point, was conducted on each sample. The panels were mapped with a rectangular grid that consisted of 40 points from which vibration data were collected. Each of the 40 test points was located with respect to the driving point and tapped with a modal impact hammer while the vibration responses were measured using an accelerometer. To ensure accurate data, the measurements consisted of a linear average of three taps whose coherence, or accuracy between all three taps, was limited to >90 % at all frequency peaks. Finally, the modes of vibration of the predominant frequencies of each sample were identified using a modal analysis program called STAR Struck. The damping factor, a measurement of vibration loss per cycle, was calculated for each of the analyzed modes. Each pair of similar samples was averaged together to account for slight differences in mass and natural differences of wood. Those results can be seen in Table 1 and a photo of the set-up for vibration testing at the University of Hartford can be seen in Figure 2.

Table 1. Damping Results for Uncoated, UV-cured, and Microwave-cured Wood Samples.

Sample	Average Mass (grams)	Average Damping (%)
Uncured	127.5	1.262
UV Cured	134	2.260
Microwave Cured	133.5	2.287

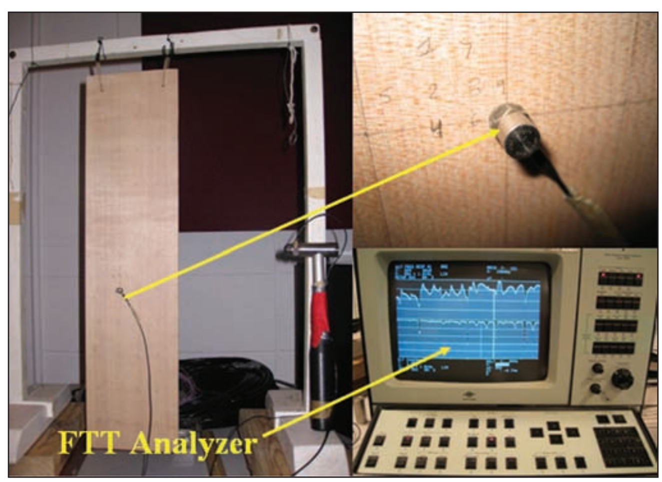

Figure 2.Vibration testing set-up at University of Hartford.

3. Results and Discussion

3.1 Dielectric Testing

The dielectric loss for as-received and dried maple can be seen in Figure 3, and the dielectric constant for the same wood samples can be seen in Figure 4.

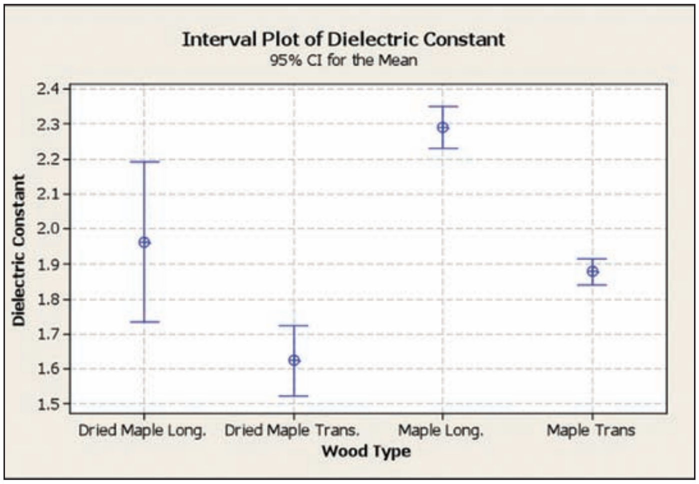

Figure 3. Dielectric constant for as-received and dried maple.

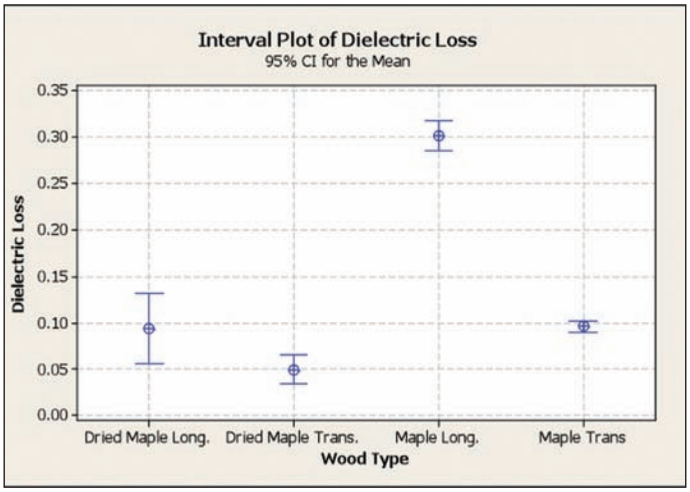

Figure 4. Dielectric loss for as-received and dried maple.

Note that the dielectric constant and dielectric loss change depending on the wood orientation with respect to the EM field. The as-received longitudinal samples showed a larger mean dielectric constant and loss of 2.29 and 0.30, respectively, than the transverse samples, which had a mean dielectric constant and loss of 1.88 and 0.098, respectively. This result implies that the microwave energy will penetrate and heat the wood more effectively in the longitudinal direction. The changes in dielectric loss and constant values due to orientation were attributed to the heterogeneous structure of the wood.

Water content also has an effect on the wood's dielectric characteristics. The dielectric loss of the wood decreases after the wood has been dried. This occurred in both the longitudinal and transverse directions. After drying the wood, the values for dielectric loss of the longitudinal and transverse samples were 0.095 and 0.050, respectively. Water has a high dielectric loss and constant; therefore, it is believed that, when the water is removed from the wood system, the loss decreases because the actual wood structure (excluding the free water trapped in the wood) has a smaller loss. It is also apparent that removing the water had a larger effect on longitudinal direction's loss than the transverse direction's loss. The change in the dielectric loss due to drying was much more dramatic for the longitudinal direction than the transverse direction.

The dielectric constant of the wood behaved similarly to the dielectric loss when the wood was dried. There was a marked decease in the values after drying. The longitudinal sample had a mean dielectric constant value of 1.96, and the transverse sample had a mean value of 1.63.

3.2 SEM Imaging

3.2.1 Uncoated Wood: Figure 5 shows an image of the raw (uncoated) wood taken at 1000X. The structure of the wood is heterogeneous, as expected. Some structural features even appear to be running perpendicular to the grain structure. The fracture surface was relatively smooth and served as a good cross-sectional area for ascertaining information about the wood/polymer interface and interaction. All SEM images of a polymer/wood interface (Figure 6-8) are shown at a 2000X magnification for comparison.

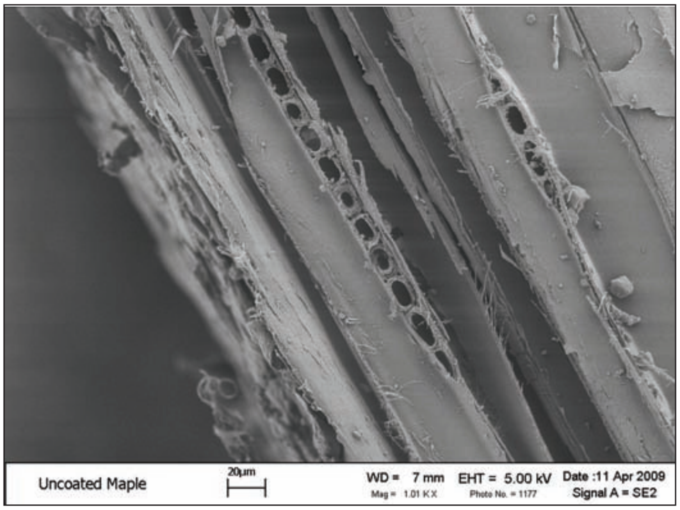

Figure 5. SEM of uncoated maple (1000X).

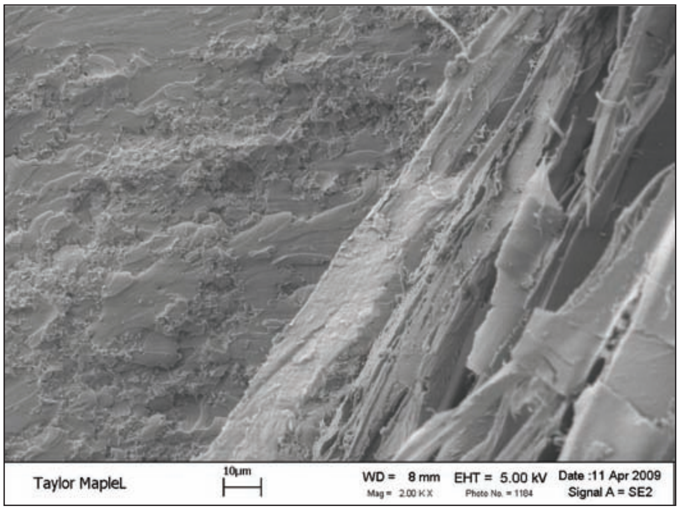

Figure 6. SEM of UV-cured, polymer-coated maple, (2000X).

3.2.2 UV-processed Wood (Taylor): Figure 6 shows maple coated with Taylor's polymer using their UV curing method. Wood structure similar to that seen in Figure 5 was visible on the right. On the left, a darker and more homogenous polymer layer was present. The coating and wood interface was quite distinct; it appears that there was little diffusion nor interaction between the two components. This distinction could result from the fact that Taylor uses a viscous "base coat" that helps create a very smooth coating by filling in small cracks in the wood surface. The viscous layer could resist penetration into the wood. The very distinct interface (little interaction) could also be a result of the nature of UV processing. As stated earlier, larger wavelengths allow more energy to penetrate into a material. Ultraviolet rays have a relatively small wavelength (~10^{-8} m) on the electromagnetic spectrum, leading to more interaction with the surface of highly absorbing materials, thus leading to less interaction at the interface. In other words, a significant portion of the energy was consumed at the surface of the polymer leaving very little energy to help drive the polymer into the wood.

3.2.3 Air-dried Urethane Coating: The air-dried, water-based urethane coating is shown in Figure 7. This image shows a quite defined polymer/wood interface, even more so than the UV-cured sample (Figure 6). The polymer layer looks like it was very loosely bonded with the wood. Gaps between the wood and polymer can be seen at various points along the interface. It appears that the water-based urethane had limited interaction with the wood when allowed to dry in air.

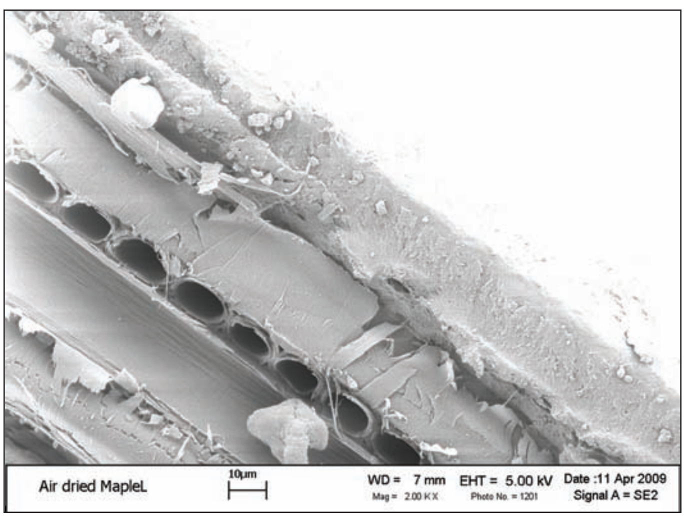

Figure 7. SEM of water-based, urethane-coated maple (air-dried) (2000X).

3.2.4 Microwave-processed Urethane Coating: Figure 8 shows a sample of maple coated with the water-based urethane cured using the designed microwave process. It is apparent that the microwave process has some effect on the interaction between the wood and the polymer. In contrast to Figures 6 and 7, the interface was much more difficult to pinpoint. A slight difference was seen between the wood and the polymer, but was much less defined than the previous images. It is believed that this characteristic is due to the high polymer/microwave interaction, resulting in a very blended composite. Microwave processing appears to drive the polymer into the wood more so than air drying and even UV curing. This difference could result from the large wavelength of microwaves (~10^{-2} m), compared with that of UV (~10^{-8} m), or from the considerable molecular movement that microwave processing induces within the water-based polymer.

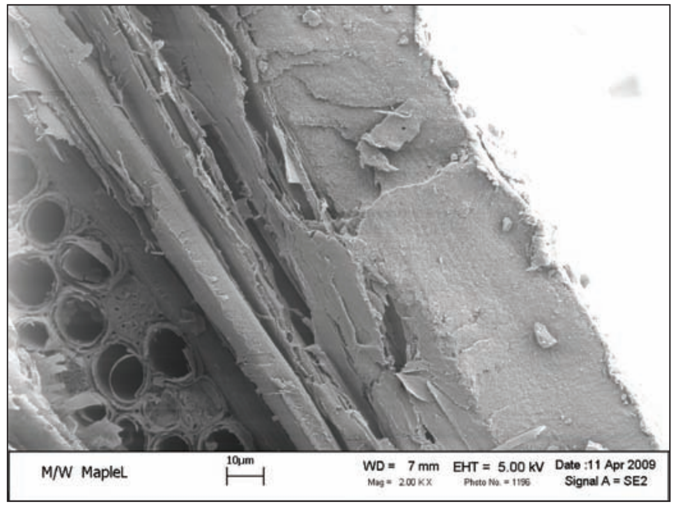

Figure 8. Water-based, urethane-coated maple (microwave-cured) (2000X).

3.3 Vibration Testing

The results indicate a 44% average increase in damping for the coated samples versus the uncoated samples. This result was expected since the finishes applied to the wood have an effect on the amplitude of oscillations that the wood undergoes while it vibrates freely. Note that while the ultraviolet coating has a greater mass than the microwave coating, the microwave samples, with only 3 coats of finish applied, have nearly the same amount of damping. Further research is required to determine the extent to which this increase in damping would affect the acoustical properties of a manufactured guitar. The amount of damping in a finished product will ultimately have an effect on a guitar's ability to resonate.

3.4 Future Work

Future work will include investigating or creating different polymers that interact more favorably with a microwave environment, analysis of the exact effects of microwave processing on the polymer and the wood, and further characterization of the wood/polymer system. Further research is required to understand the process and make in more applicable for Taylor Guitars and the guitar coating industry.

4. Conclusion

Results indicate that microwave processing of polymeric coatings for guitar woods is quite feasible. A process for coating a guitar wood substrate was successfully developed. The dielectric data could prove important in understanding the interaction of the wood with microwave energy. Dielectric testing indicates that wood is a microwave absorber and that by manipulating the water content and orientation, the degree of absorption can be controlled.

The wood/polymer system behaved rather favorably in a microwave environment. Microwave processing appears to create a more coherent wood/polymer interface. This observation agrees with the initial hypothesis that microwaves may increase diffusion and interaction between the wood and polymer. SEM imaging shows that UV-cured and air-dried samples have a more defined interface when compared to microwave-processed samples. These results suggest microwave processing may thus be used to create adherent and strong coatings using less coating mass. Also, vibration testing results show that the average damping of the microwave-processed samples (water-based urethane coated wood) is similar to that of the UV-cured samples from Taylor. This average damping value in the microwaved samples was achieved with half the coating thickness. Decreased coating thickness (less polymer mass) may result in a more completely cured polymer. Decreased coating thickness may result in decreased cost and emissions. Therefore, it is suggested that microwave processing has the potential to improve upon Taylor's current UV process, and can have a significant effect on the processing of polymeric coatings for guitar woods.

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