ACOUSTIC PROPERTY DEVELOPMENT FROM WOOD TO CARBON COMPOSITE

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Abstract

The elastic properties inherent in wood is followed as the native material is converted to a carbon monolith and then to carbon-polymer composite. Acoustic velocities in three principal directions are measured and show that elastic anisotropy is maintained as the material is processed. The degree of anisotropy is reduced as the natural polymers are pyrolyzed to form carbonized wood. After the porous carbon is infiltrated with epoxy to form a composite, the acoustic anisotropy is retained. The acoustic velocities and anisotropy ratios of the resulting carbon/epoxy composite compare favourably to Ebony wood.

Introduction

The use of wood, and other plants, as a template for producing ceramic and composite materials has progressed significantly from when the technology originated in 1995 [1-4]. The natural microstructures lead to modern materials with properties that, in many ways, mimic those of the original plant. Multiple investigators have focused on producing ceramics from wood using sol-gel, vapor, or liquid infiltration and conversion methods. The ceramic processing route has been shown to be capable of producing carbide, oxide, and nitride ceramics with cellular structures that originate from the precursor plant cell structures. In one aspect of the technology, wood is carbonized to form a porous char that is then infiltrated with resin to produce a carbon-epoxy composite [2, 4, 5]. That material is the focus of this paper.

Wood as an anisotropic material has been studied by ultrasonic methods to evaluate elastic behavior [6,7]. This method allows for thorough assessment of elastic properties, particularly when both compression and shear wave measurements are utilized. Many woods can be represented by orthotropic symmetry which means that 9 unique elastic constants exist. When defining the ultrasonic wave velocity in this type of material, terms comprising of these constants combine to give an effective modulus (E_{eff}) and that is combined with the material density (ρ). That allows one to define velocity (v) in any particular direction as

$$v^2 = E_{eff}/\rho$$

depending upon the effective elastic constant applicable for that direction and wave mode. To use this method for finding each of the 9 independent elastic constants requires multiple measurements in specific symmetry directions and is beyond the scope of this communication. What is presented is the effective elastic response, as measured by acoustic velocity, of carbon-epoxy composites in the 3 principal symmetry directions of wood. These are the axial, radial and tangential directions.

In working with composite materials it is common to employ a rule-of-mixture to relate the composite material property to the properties of the individual phases. For elastic moduli the composite modulus (E_c) is related through volume fraction of each phase (V) and modulus of each phase (E) by

$$E_c = V_e E_e + V_{ch} E_{ch}$$

for a composite made from epoxy and carbon char phases. This expression arises from a model of each phase aligned parallel to the stress wave. When the phases are aligned perpendicular to the stress an inverse model is found

$$1/E_c = V_e/E_e + V_{ch}/E_{ch}$$

which also provides a relation between composite property and property of each phase. In either case the elastic modulus can be replaced with an effective modulus when considering an anisotropic medium. By combining the expressions for composite effective modulus with the expression for acoustic velocity it is possible to evaluate composite elastic properties using ultrasonic methods.

In wood, carbonized wood (char) and carbon-epoxy composites derived from wood, the cellular morphology of the plant leads to anisotropy. For the composite axial direction a rule of mixtures applies. In the radial and tangential directions an inverse rule of mixtures is applicable.

Presented are results showing acoustic anisotropy of the composite is retained and compares favorably to Ebony wood. The resulting composite is also black in color, but has an appealing reflective quality. This composite is a likely replacement material for applications traditionally reserved for Ebony (esp. musical instruments). Also presented is an assessment of the evolution of acoustic velocity from wood to char to composite, concluding with a rule-of-mixture assessment of the composite material.

Experimental

The ultrasonic evaluation of samples was performed using contact probes. Transducers with center frequency of 1MHz were implemented in transmission mode. A Panametrics 5055 PR pulser/receiver and Hewlitt Packard 100MHz oscilloscope were used with the transducer pair. Sample dimensions of approximately 20 mm in each principal direction allowed significant transit time without loss of detectability due to attenuation. Samples of wood, carbonized wood, and char infiltrated with epoxy were evaluated to determine compressional wave velocity in three principal directions.

Results and Discussion

Careful carbonization of wood results in a porous structural carbon without cracks or structural defects. Conversion of the celluloses and lignin to solid carbon alters the elastic properties but retains the cellular characteristics. The cellular structure contributes to anisotropic behavior of the bulk material. Results from measurements of Poplar wood, carbonized Poplar, and a carbonized Poplar/epoxy

Table 1. Measured Properties of Phases; Poplar, Char, Epoxy, and Carbon-Epoxy Derived from Poplar.

	Poplar	Char Bulk	Char Solid	Epoxy	Carbon-Epoxy
Density g/mm^3	0.000532	0.000385	0.0019	0.00116	0.00124
Volume Fraction	NA	NA	0.203	0.737	0.06 void
velocity axial	5.88	4.05	NA	2.42	2.55
velocity radial	2.17	2.87	NA	2.42	2.36
velocity tangential	1.53	1.22	NA	2.42	1.7

acoustic velocities in mm/microsecond

composite are shown in Table 1. Values are greatest in the axial direction for all 3 materials. Anisotropy is retained, with the greatest being in the original wood. The values for the composite clearly indicate the influence of the isotropic epoxy. Epoxy causes the velocity values of the composite to fall in between that of the bulk char and the epoxy.

All wood species contain a unique cellular structure that contributes to the bulk properties. The carbon-epoxy composite derived from Yellow-Pine has acoustic velocity values that resemble those of Ebony wood as indicated in Table 2. In this case, radial and tangential velocities are nearly identical, while the axial velocity in the Ebony is greater than that of the composite. This likely stems from the cellulose molecular texture that increases elastic properties along the cell wall axis.

Table 2. Acoustic Velocity for Carbon-Epoxy Derived from Yellow-Pine, and Ebony.

Material	axial vel.	radial vel.	tangential vel.
Ebony	4.42	2.29	2.24
C-Epoxy, Y-P	3.39	2.44	2.48

acoustic velocities in mm/microsecond

Ebony is a very dense wood with a relatively small elastic anisotropy. This is indicated by acoustic velocity measurements and ratios of those as shown in Table 3. Indicated is the fact that radial and tangential values are nearly the same, and when compared to axial are found to be close to half that value. This is similar to the carbon-epoxy composite made from Yellow-Pine where radial and tangential values are similar. While the anisotropy ratios for the composite are lower than that of Ebony, the difference is not nearly as great as for when Ebony is compared to other woods. This is seen by the data for Poplar wood where the ratios are much higher. We can conclude that Ebony is closer to the composite in elastic characteristics than it is to other woods.

Table 3. Acoustic Velocity Ratios for Carbon-Epoxy Derived from Yellow Pine, Ebony and Poplar Woods

Material	axial/radial	axial/tangential
C-Epoxy (Y-Pine)	1.39	1.37
Ebony Wood	1.93	1.97
Poplar Wood	2.71	3.84

Predicting composite properties based upon those of the individual phases is done for the carbon-epoxy composite derived from Poplar wood. The results, provided in Table 4, indicate a fair agreement exists between the prediction and measured value of acoustic velocity. Axial values are from a direct rule of mixtures while the radial and tangential are from an inverse rule of mixtures model. Axial values agree very well while the radial and tangential differ from measured values by 23.3% and 38.2 % respectively. This difference could be explained by considering the reinforcing effect of the epoxy phase on the flexural deformation modes and the fact that there residual stresses from cure shrinkage that can influence elastic behavior in the composite. In addition, the models employed do not account for the shape effect of the cellular solid.

Table 4. Acoustic Velocity for Carbon-Epoxy Derived from Poplar, Compared to Rule of Mixtures Values.

mm/microsecond	axial	radial	tangential
Measured Velocity	2.55	2.36	1.7
RoM Velocity	2.57	2.91	1.35

Conclusions

Changing elastic properties of wood as it is transformed to a carbon monolith and then to a carbon-epoxy composite have been presented. Acoustic velocity is reduced with each processing step, but anisotropy is retained. The resulting acoustic properties of the composite formed from Yellow Pine closely resemble those of Ebony wood. The resemblance is greater than for most other wood species.

The reduction in acoustic velocity from wood to char originates from the altered anisotropy of the cell wall material. Wood cells are comprised of cellulose fibrils of preferred orientation that produce an anisotropic cell wall. That anisotropy is substantially altered with carbonization as the resulting basic structural units of the carbon exhibit very weak texture and thus leads to a nearly isotropic solid. The anisotropy of the char and the carbon-epoxy is a largely consequence of the cellular structure remaining from the wood grain.

References

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