IMAGING WOOD PLASTIC COMPOSITES (WPCs): X-RAY COMPUTED TOMOGRAPHY, A FEW OTHER PROMISING TECHNIQUES, AND WHY WE SHOULD PAY ATTENTION

Lech Muszyński

Wood plastic composites are complex, anisotropic, and heterogeneous materials. A key to increasing the share of the WPC materials in the market is developing stronger, highly engineered WPCs characterized by greater structural performance and increased durability. These are achieved by enhanced manufacturing processes, more efficient profile designs, and new formulations providing better interaction between the wood particles and the plastic matrix. Significant progress in this area is hard to imagine without better understanding of the composite performance and internal bond durability on the micro-mechanical level, and reliable modeling based on that understanding. The objective of this paper is to present a brief review of promising material characterization techniques based on advanced imaging technologies and inverse problem methodology, which seem particularly suitable for complex heterogeneous composites. Full-field imaging techniques and specifically X-ray computed tomography (CT) combined with numerical modeling tools have a potential to advance the fundamental knowledge on the effect of manufacturing parameters on the micromechanics of such materials and their response to loads and environmental exposure.

Keywords: Wood-plastic composites; Imaging techniques; X-ray computed tomography; Inverse problem methodology

Contact information: Department of Wood Science and Engineering, Oregon State University, 119 Richardson Hall, Corvallis, OR 97331, Email: lech.muszynski@oregonstate.edu

INTRODUCTION

The current global economic difficulties make it quite clear that in the rapidly changing global economy with a global labor market, fast technology transfer, and relatively low cost of massive transport the developed countries can hardly maintain their competitive advantage in manufacturing cheap commodities. To regain and maintain the necessary competitive edge in global economy, industries have to be innovative and technologically dynamic (Archibugi et al. 1999). For wood composites industries in the developed countries recovery from the current crisis and long-term growth requires assuming the leading position in developing new, advanced materials and smart technologies and making the innovation a permanent self-sustaining process (Grossman and Helpman 1991).

Wood plastic composites (WPC) resulting from compounding fine wood flour particles with thermoplastic polymer matrix are an example of complex, anisotropic, and heterogeneous materials, which allow a great flexibility in engineering their properties to the requirements of the final use. WPCs also have a great potential for utilizing woody biomass generated in wild forest fire prevention operations and regular forest thinnings, aimed at improving forest health. A key to increasing the share of the WPC materials in the market is not only developing stronger and more durable materials, but also highly engineered composites characterized by mechanical performance carefully tailored to the requirements of the end use. Insofar these have been to some extent achieved by enhanced manufacturing processes, more efficient profile designs and new formulations provide better interaction between the wood particles and the plastic matrix. Significant progress in this area however requires a more holistic approach, and is hard to imagine this progress occurring without better understanding of the composite performance and internal bond durability on the micro-mechanical level, as well as reliable modeling based on that understanding (Wolcott and Muszyński 2008). In this respect, WPCs may become a model for many other wood-based composites as well as for a larger family of other bio-particulate composites. However, despite substantial research effort in material characterization of wood plastic composites, modeling of these complex particulate bio-composites poses a significant challenge. The principle obstacles are the inherent complexity of the individual wood flour particles and of the composite interaction between the particles and polymer matrix on the micro-mechanical level, as well as that the body of quantitative knowledge generated in the field is hardly compatible with the required inputs of available modeling tools.

In this paper, opportunities and principal challenges to development of adequate numerical models for complex particulate composites are discussed, along with couple of promising material characterization techniques based on advanced imaging technologies and inverse problem methodology, which seem particularly suitable for providing necessary input data for such models.

VIRTUAL PROTOTYPING: WHY AREN'T WE THERE YET?

Numerical models are important tools for discovery. Scientific models are created to predict behavior of physical objects and phenomena of various level of complexity. Numerical models are used for prototyping and virtual testing of hypotheses and are particularly desirable whenever physical tests are too complex, impractical, or too expensive. Accurate models capable of correlating our understanding of how various processing regimes and treatments affect morphology and micro-mechanics of the composites with their bulk properties and service performance would be critical for prototyping and developing new, advanced bio-based materials and products. Such models would be also important tools for improving properties of those already present on the market.

It is not surprising then, that modeling many aspects of physical and mechanical nature of wood-based materials has been in focus of quite vigorous research activity. Mackrele in his recent bibliography of finite element (FEA) modeling in wood research lists more than 260 papers published just in one decade between 1995 and 2004 (Mackerle 2005).

So, why aren't we there yet? What prevents the virtual prototyping based on material modeling from assisting the development of the bio-based materials industry?

Levels of Complexity in the Internal Microstructure of the Composites

Modeling of complex heterogeneous particulate composites such as WPCs is not a trivial task. By composite micromechanics standards, WPC morphological structure is closer to that of concrete or randomly-oriented, short-fiber reinforced composites than to conventional particle- or fiber-boards. The short-fiber composite theory is based on the assumption that the mechanical properties of the fibers are known and perfectly elastic, and that the fibers are of uniform regular cross-sections, and form well-defined interfaces with the polymer matrix. Most natural fillers do not fulfill these fundamental assumptions. Moreover, in contrast to fiberboards or paper, most WPCs use fine wood flour (250 to 850 μm particles). Compared to pulp fibers, these particles are larger but irregular and have much lower aspect ratio (average aspect ratio about 2.5). It may be generally assumed that the particles are less effective at reinforcement than fibers, but more effective than round grains. Any attempt at modeling needs however reflect the statistical distribution of sizes in all three dimensions.

Another important feature of wood flour particles reduced in attrition and hammer mills is that the original cellular structure of wood is preserved only in their cores, while on the perimeter it is severely damaged during the process. How do the mechanical properties of the resulting properties compare to that of solid wood is generally unknown. Consequently, composites containing such particles may require special approaches in research, modeling, or testing (Bigg 1985; Friedrich 1985; Fu and Lauke 1998; Lees 1968).

The compounding process, in which the particles are combined with the polymer matrix (extrusion, compression molding, or injection molding) generate another level of material organization. The cellular structure of wood flour particles may be further affected by the shear, pressure, and temperature they are exposed to during processing. Microscopic evidence shows a substantial inter-phase where the polymer penetrates the damaged cell structure on the particle perimeter (Wang 2007). Although there are publications reporting micro-mechanical tests on isolated fibers and properties of fiber-polymer interfaces (Egan and Shaler 2000; Mott et al. 1996; Shaler et al. 1997; Tze et al. 2003), the contribution of the interphase to the mechanical performance of the internal bond between the particles and the matrix, and the composite as a whole are not completely understood.

Such complexity may be best addressed through multi-scale modeling, which refers to correlation of phenomena and properties observed on various levels of material organization (load transfer through the interphase, contributions of individual particles, and properties of bulk composite).

Compatibility between Testing Approaches and Numerical Models

The predictive power of numerical models depends as much on sound constitutive theory as on reliability of the input data: morphology, boundary conditions, and empirical characteristics of the modeled object. In the same time, the prevailing approach in material characterization in the area of wood composites is that of simplified comparative tests responding to the industry's need for inexpensive tools to assess their quality against an accepted standard. In most cases however, this approach does not produce characteristics compatible with the inputs of modeling software based on the principles of theoretical mechanics. The traditional testing and measurement methods, where the bulk mechanical characteristics are determined from relatively simple analytical solutions derived for small deformations in idealized homogeneous and isotropic solids, are generally not adequate for the level of complexity found in particulate bio-composites. Collecting viable input data for modeling of such particulate composites requires better understanding and cooperation between modelers and experimentalists and may require revision of traditional testing practices and approach to material testing.

THE ADVANCED IMAGING TECHNIQUES

The complexity of the internal structure and the compatibility of the experimental output with the requirements of the contemporary modeling techniques can be effectively addressed by application of advanced imaging techniques coupled with 3D numerical modeling of the composite structure.

Digital Image Analysis

By contrast to the traditional methods, recent progress in modern high-resolution non-contact imaging and full-field measurement techniques makes it possible to explore enhanced approaches to experimental procedures. Although many of the imaging techniques discussed below are by no means new, the amount and value of the information carried by images is often underestimated.

High resolution digital microscopy, electron scanning microscopy (ESM), computed tomography (CT) based on x-ray, gamma and neutron radiation (ASTM 2000; Macedo et al. 2002; Richards et al. 2004; Wellington and Vinegar 1987), nuclear magnetic resonance (NMR) relaxometry, and other advanced instruments (Park et al. 2003; Petraud et al. 2003) return digital images carrying a wealth of spatial information coded in discrete color or grayscale values. These values representing method-specific quantities (e.g. real colors, densities, x-ray attenuation, temperatures) assigned to millions of pixels or voxels arranged in two- or three-dimensional arrays. The data may be effectively analyzed by employment of robust algorithms for automated recognition and quantitative characterization of spatial distribution physical features: e.g. various components, phases, inhomogeneities and void spaces resulting from various processing and loading regimes.

A series of images presented in Figure 1 is an example of using RGB color segmentation techniques in order to separate and quantify extensive inter-phase between wood flour particles and polymer matrix. The interphase, where cell walls and lumens appear penetrated by the matrix material, is clearly visible in the original color micrograph, but only the two-stage color segmentation technique allowed automatic recognition of the zone and calculation of relative areas of clear wood, matrix, and the interphase visible as the red zone in the bottom right picture (Wang 2007).

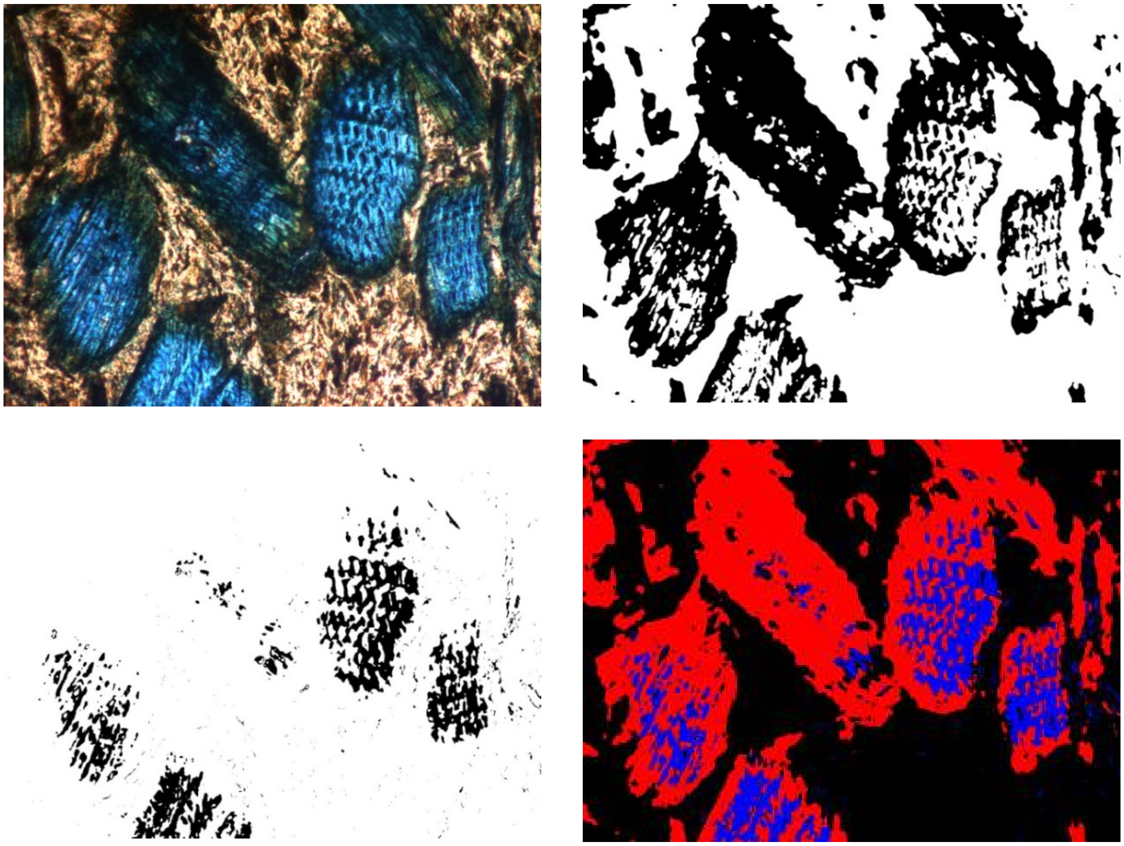

Fig. 1. Color segmentation of a microscopic image of wood particles embedded in PVC matrix reveals extensive inter-phase (red zone in the bottom right picture) where cell walls and lumens appear penetrated by the matrix material (Wang 2007).

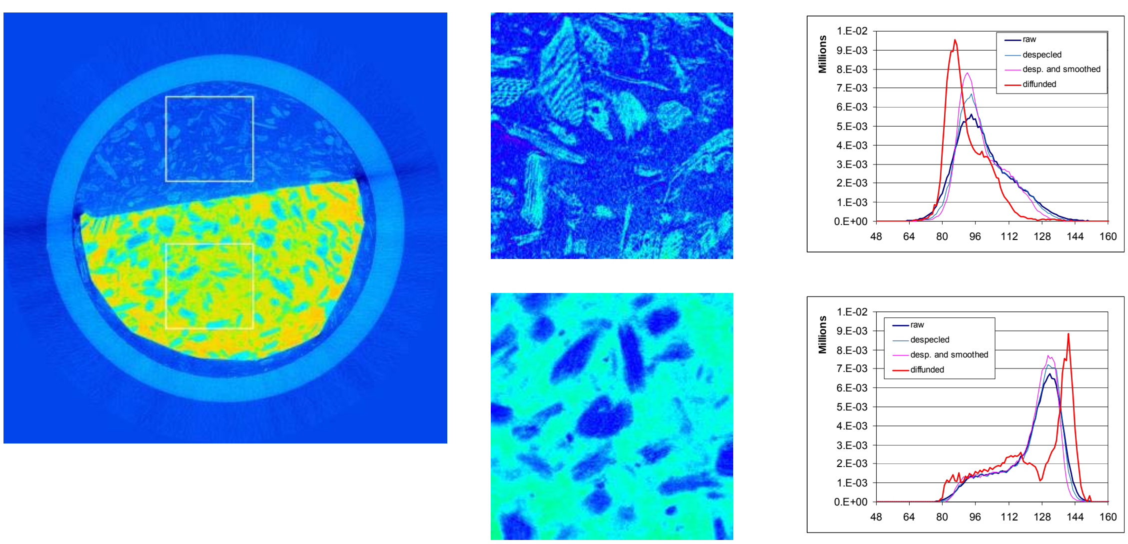

Fig. 2. Loose wood flour and wood/PVC composite in x-ray tomography images illustrate the complex multi-scale morphology of the material. The graphs in the right column show intensity histograms for the sub-areas shown in the left column (Muszyński et al. 2008).

Similar approaches may be employed with X-ray computed tomography (CT) data generated through computational reconstruction of internal feature of heterogeneous samples from a series of X-ray projections of the samples recorded at different angles. In the following example, loose wood flour particles were scanned along a solid sample of wood/PVC composite. A sample cross section of the 3D data is shown in the left image in Fig. 2. Cubic sub-volumes of the loose particles and the composite marked by white rectangles in the first image were then subjected to three different levels of noise removal procedures and then analyzed separately for the grayscale intensity distribution. The graphs in the right column show intensity histograms for the sub-volumes shown in the central columns. Segmentation of the histograms and comparison of the particle volume distributions in both phases allows quantification of the extent of the wood/PVC interphase in the composite (Muszyński et al. 2008).

Furthermore, specialized image processing software bundles offer various machine vision tools for 2-dimensional images, including efficient edge detection and particle analysis algorithms capable of isolating and quantitatively describing multiple particles. Standard particle analysis returns distribution of sizes, areas and orientation of irregular particles. Numerous generalized algorithms have also been proposed for the analysis of 3-dimensional data (Price 1995; Thompson et al. 2006). An example in Fig. 3 demonstrates two stages of particle analysis of a closely packed particulate composite performed on a binarized X-ray CT image of a sample reported by Thompson et al. (2006). The segmentation allows automated statistical analysis of the axial dimensions, volumes, and orientation of all the particles within the analyzed sample.

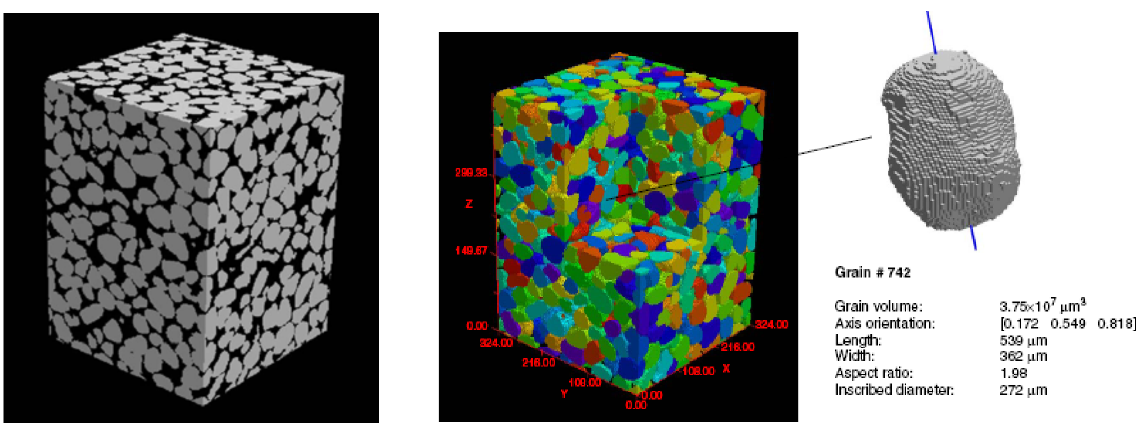

Fig. 3. Segmented and binarized X-ray tomography image of a particulate material and visualization of the segmented particle-scale reconstruction of the volume (Thompson et al. 2006).

Optical Measurement of Deformations and Strains

In addition, digital images and volumetric data are also used for non-contact full-field measurement of deformation and strains in heterogeneous anisotropic solids under various loading regimes with sub-pixel accuracy by means of digital speckle photogrammetry (DSP) based on the digital image correlation (DIC) algorithms (Bruck et al. 1989; Ranson et al. 1987; Sutton and Chao 1988; Vendroux and Knauss 1998). DSP allows determination of displacements of a dense mesh of selected points on surfaces of deformed specimens by comparing successive images acquired during tests and cross correlating the gray intensity patterns of the direct neighborhood of the points (or the reference areas). DSP has been already successfully applied to determine strains in specimens of solid wood subjected to external loads and climate changes (Muszyński et al. 2006), individual wood fibers and paper (Choi et al. 1991; Mott et al. 1996; Sutton and Chao 1988), fiber reinforced plastics (FRP) (Muszyński et al. 2000; Russell and Sutton 1989), concrete (Choi and Shah 1997), and resin films (Muszyński et al. 2002).

Recently, a similar algorithm has been developed for volumetric data dubbed digital volume correlation (DVC: Bay et al. 1999; Smith et al. 2002). DVC allows calculation of 3D internal strain fields in the analyzed volume by comparing data from x-ray tomographic scans of the same specimen acquired in unloaded and loaded states. This method was found to be very accurate in mapping the strain intensities in porous media such as bone tissue polymer and aluminum foams (Bay et al. 1999; Smith et al. 2002; Sutton 2004), though there is no evidence that similar work was ever done on wood or wood composite samples.

Inverse Problem Approach

Two- and three- dimensional full-field methods provide displacement and strain data equivalent to hundreds of strain gages and are capable of capturing localized deformation gradients and strain concentrations that could not be possibly detected through discrete measurements from traditional instrumentation, such as extensometers, LVDTs, displacement gages or strain gages. In addition, the output format is readily compatible with many numerical modeling packages based on FEM, so that the displacement and strain fields measured by means of the full-field methods may be compared with the results of theoretical simulations of the same test configurations using existing models. In this approach, known as the inverse problem methodology, the measured and theoretical strain fields are used as input data in order to determine localized material properties even for heterogeneous anisotropic materials and for specimens of complex geometries (Grediac and Pierron 1998; Lecompte et al. 2005; Pierron and Grediac 2000). The general idea of this method is shown on the schematic diagram in Fig. 4.

In fact, the combination of full-field measurements with inverse problem methodology brings the material testing on a whole different level of efficiency by removing one of the limitations of the traditional test methods, which is the requirement that the mechanical material tests are reduced to simplest load cases. By combining the full-field measurements with inverse problem methodology and careful design of specimen geometries, loading, and boundary conditions, it is possible to determine all involved terms of anisotropic compliance matrices in a single test (Lecompte et al. 2005). The great number of virtual measurement points returned by full-field methods provides enough statistical redundancy for even very complex constitutive models. It follows quite naturally, that the existing models are perfectly suited tools to assist in design and development of such complex test configurations, while on the other hand the results of the tests may provide validation to the models' assumptions.

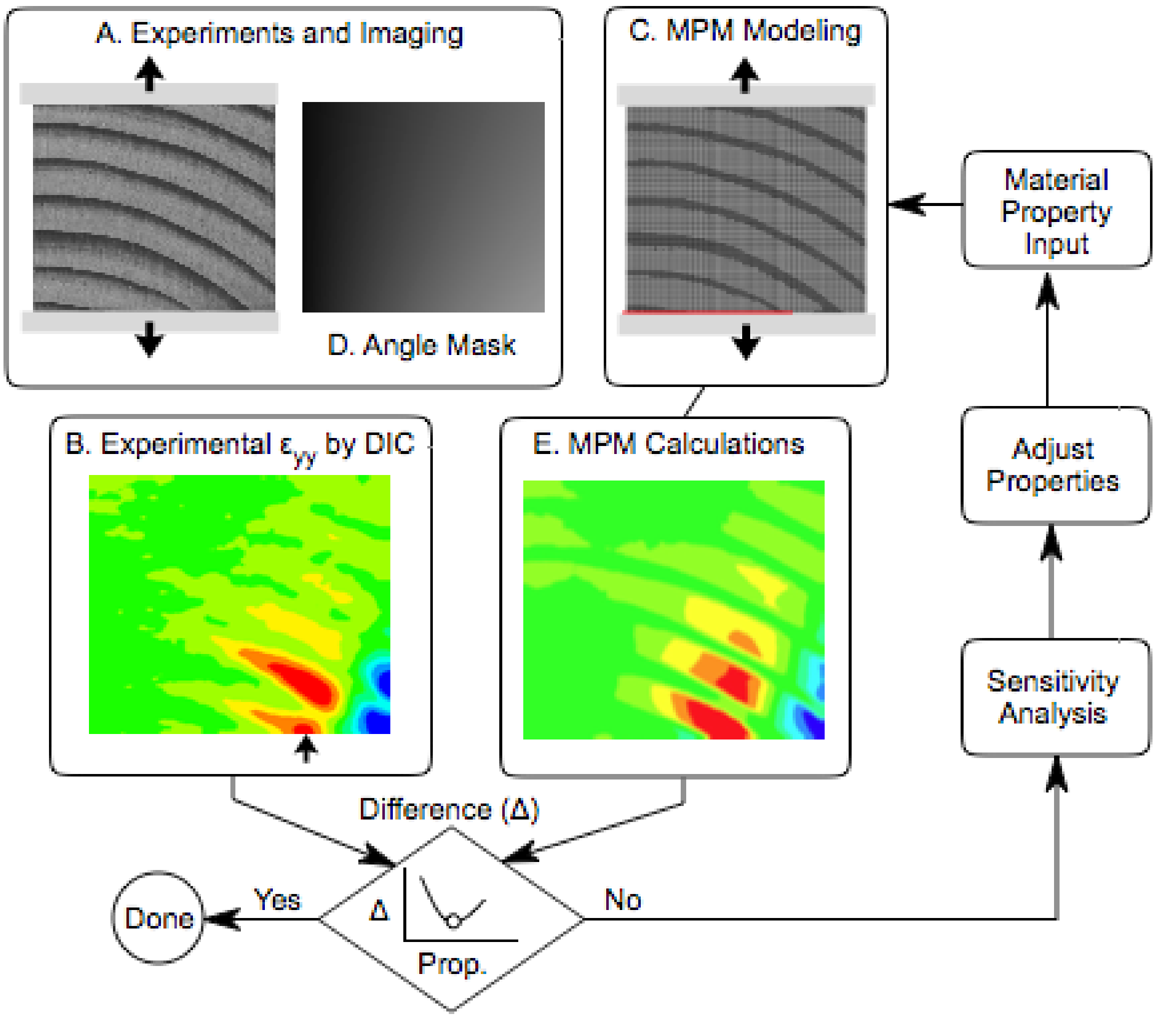

Fig. 4. Flow chart of the material parameter identification problem by coupling full-field techniques in material testing, FEM modeling and inverse problem methodology (Muszyński and Nairn 2008).

New Developments in Modeling

New developments may be also expected in the area of modeling. Recently, a material point method (MPM) was proposed by Sulsky (1994) as an alternative to FEM, which is particularly suited for modeling heterogeneous solids based on their morphology. In this method, digital images of heterogeneous surfaces may be used directly as digitized input of the material geometry removing rather difficult task of generating complex FEM meshes. The MPM method is as suitable for application with the inverse problem methodology as FEM, and was successfully used for modeling wood at various levels of material organization (Nairn 2003, 2005, 2007). The MPM method is as suitable for application with the inverse problem methodology as FEM, and was successfully used for modeling wood at various levels of material organization. An MPM algorithm is available in public-domain as a 3D parallel code (Parker 2002).

CONCLUSIONS

For wood composites industries in the developed economies the recovery and long-term growth requires assuming a leading position in developing new, advanced materials and smart technologies and making the innovation a permanent self-sustaining process. Although numerical modeling seems to be a promising tool in virtual prototyping of new materials, the prevailing empirical practice does not adequately address the complexity of bio-particulate materials such as WPCs, and the outputs are generally incompatible with the requirements of contemporary modeling tools. The innovative material characterization techniques based on advanced imaging technologies and inverse problem methodology seem particularly suitable for complex heterogeneous composites.

Advanced image analysis tools applied to volumetric data acquired via computed tomography techniques provides new means for quantitative and nondestructive characterization of WPCs and similar bio-particulate materials. Such unprecedented insight in the morphology and micromechanics enables a new, comprehensive approach to experimental determination of material characteristics. Combination of full-field measurements with inverse problem methodology brings the material testing on a whole different level of efficiency by removing one of the limitations of the traditional test methods. Such integrated approach to material characterization supports development of morphology-based numerical modeling for rapid prototyping of new enhanced materials and manufacturing processes.

ACKNOWLEDGEMENTS

This research is partly funded by the USDA McIntire-Stennis Program, Project#: CSREES/OREZ-FP-821-U (2006-2011), and the USDA NIR Competitive Grant Initiative (Project # CSREES/USDA NRI CGP # 2008-01500).

The paper is based on Muszyński L. (2007): Imaging WPCs: X-ray computed tomography. An invited presentation in: Wood Plastics Composites Workshop: WPC's 2007 – The changing technology in WPCs, April 1-4, Seattle, WA

REFERENCES CITED

Archibugi, D., Howells, J., and Michie, J. (1999). "Innovation systems in a global economy," *Technology Analysis & Strategic Management* 11(4), 527-539.

ASTM. (2000). "ASTM E 1441-00: Standard Guide for Computed Tomography (CT) Imaging," American Society for Testing and Materials, West Conshohocken, PA.

Bay, B. K., Smith, T. S., Fyhrie, D. P., and Saad, M. (1999). "Digital volume correlation: Three-dimensional strain mapping using X-ray tomography," *Experimental Mechanics* 30(3), 217-226.

Bigg, D. M. (1985). "Effect of compounding on the properties of short fiber reinforced injection moldable thermoplastic composites," *Polymer Composites* 6(1), 20-28.

Bruck, H. A., McNeill, S. R., Sutton, M. A., and Peters, W. H. I. (1989). "Digital image correlation using Newton-Raphson method of partial differential correction," *Experimental Mechanics* 28(3), 261-267.
Choi, D., Thorpe, J. L., and Hanna, R. B. (1991). "Image analysis to measure strain in wood and paper," *Wood Science and Technology* 25(2), 251-262.
Choi, S., and Shah, S. P. (1997). "Measurement of deformations on concrete subjected to compression using image correlation," *Experimental Mechanics* 37(3), 307-313.
Egan, A., and Shaler, S. M. "Fracture and mechanics of fracture for resin coated single wood fibres," Fourth Panel Products Symposium, Llandudno, Wales, UK, 95-103.
Friedrich, K. (1985). "Microstructural efficiency and fracture toughness of short fiber /thermoplastic matrix composites," *Composite Science and Technology* 22(1), 43-74.
Fu, S.-Y., and Lauke, B. (1998). "An analytical characterization of the anisotropy of the elastic modulus of misaligned short-fiber-reinforced polymers," *Composites Science and Technology* 58(12), 1961-1972.
Grediac, M., and Pierron, F. (1998). "T-shaped specimen for the direct characterization of orthotropic materials," *International Journal for Numerical Methods in Engineering* 41(2), 293-309.
Grossman, G. M., and Helpman, E. (1991). *Innovation and Growth in the Global Economy*, MIT Press.
Lecompte, D., Sol, H., Vantomme, J., and Habraken, A. M. "Identification of elastic orthotropic material parameters based on ESPI measurements," SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Portland, OR, paper #: 119/045.
Lees, J. K. (1968). "A study of the tensile strength of short fiber reinforced plastics (Tensile strength of unidirectional short fiber reinforced plastics, extrapolating theory to case of random composite)," *Polymer Engineering and Science* 8, 195-201.
Macedo, A., Vaz, C. M. P, Pereira, J. C. D., Naime, J. M., Cruvinel, P. E., and Crestana, S. (2002). "Wood density determination by X- and gamma-ray tomography," *Holzforschung* 56, 535-540.
Mackerle, J. (2005). "Finite element analyses in wood research: A bibliography," *Wood Science and Technology* 39, 579-600.
Mott, L., Shaler, S. M., and Groom, L. H. (1996). "A novel technique to measure strain distributions in single wood fibers," *Wood & Fiber Science* 28(4), 429-437.
Muszyński, L., Lagana, R., and Shaler, S. M. (2006). "Hygro-mechanical behavior of red spruce in tension parallel to the grain," *Wood & Fiber Sience* 38(1), 155-165.
Muszyński, L., Lopez-Anido, R., and Shaler, S. M. "Image correlation analysis applied to measurement of shear strains in laminated composites," the SEM IX International Congress on Experimental Mechanics, Orando, FL, 163-166.
Muszyński, L., and Nairn, J. (2008). "Coupling advanced imaging analysis and morphology based modeling for integrated characterization of micro-mechanics of wood and wood-based composites," International Conference PHOTOMECHANICS 2008, Loughborough, UK.
Muszyński, L., Wang, F., and Shaler, S. M. (2002). "Short term creep tests on phenol resorcinol formaldehyde (PRF) resin undergoing moisture content changes," *Wood and Fiber Sience* 34(4), 612-624.

Muszyński, L., Wang, Y., and Hussain, F. (2008). "Coupling X-ray computed tomography and advanced imaging techniques for morphological characterization of WPCs," 10th International Conference on Progress in Biofibre Plastic Composites, Toronto, ON, Canada.

Nairn, J. A. (2003). "Material point method calculations with explicit cracks," *Computer Modeling in Engineering & Sciences* 4, 649-664.

Nairn, J. A. (2005). "Source code and documentation for NairnFEM and NairnMPM software." http://oregonstate.edu/~nairnj/FEAMPM. Last update: November 4, 2008. Access date: April 4, 2009.

Nairn, J. A. (2007). "A numerical study of the transverse modulus of wood as a function of grain orientation and properties," *Holzforschung* 61, 406-413.

Park, B.-D., Wi, S. G., Lee, K. H., Singh, A. P., Yoon, T.-H., and Kim, Y. S. (2003). "Characterization of rice husk using microscopic and micro-analytical techniques for rice husk/thermoplastic composites," the 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, 323-331.

Parker, S. G. (2002). "A component-based architecture for parallel multi-physics PDE simulation," International Conference on Computational Science (ICCS2002) Workshop on PDE Software. P. M. A. Sloot, C. J. K. Tan, J. J. Dongarra and A. G. Hoekstra. Amsterdam, The Netherlands Springer-Verlag, Berlin. 2331: 719−734.

Petraud, M., Labbe, N., Lartigue, J. C., DeJeso, B., and Sebe, G. "Nuclear magnetic resonance relaxometry applied to wood fibers," the 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, p. 358.

Pierron, F., and Grediac, M. (2000). "Identification of the through-thickness moduli of thick composites from whole-field measurements using the Iosipescu fixture: Theory and simulations." *Composites - Part A: Applied Science and Manufacturing* 31(4), 309-318.

Price, K. (1995). *Annotated Computer Vision Bibliography*, Institute for Robotic and Intelligent System School of Engineering (IRIS), University of Southern California.

Ranson, W. F., Sutton, M. A., and Peters, W. H. (1987). "Holographic and speckle Interferometry," *SEM Handbook of Experimental Mechanics*, A. S. Kobayashi (ed.), Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 388-429.

Richards, W. J., Gibbons, M. R., and Shields, K. C. (2004). "Neutron tomography developments and applications," *Applied Radiation and Isotopes* 61, 551-559.

Russell, S. S., and Sutton, M. A. (1989). "Strain field analysis acquired through correlation of X-Ray radiographs of a fiber reinforced composite laminate," *Experimental Mechanics* 29, 237-240.

Shaler, S. M., Egan, A., Mott, L., and Landis, E. N. "Fracture and micromechanics of resinated fibers," 4th International Conference on Woodfiber-Plastic Composites, Madison, WI, 32-39.

Smith, T. S., Bay, B. K., and Rashid, M. M. (2002). "Digital volume correlation including rotational degrees of freedom during minimization," *Experimental Mechanics* 42(3), 272-278.

Sulsky, D., Chen, Z., and Schreyer, H. L. (1994). "A particle method for history-dependent materials," *Comput. Methods Appl. Mech. Engrg*. 118, 179-186.

Sutton, M. (2004). "An attempt to track and quantify micro-damage within rigid cellular polyurethane foam under uni-axial compression," Department of Mechanical Engineering, Oregon State University, Corvallis, OR.

Sutton, M. A., and Chao, Y. J. (1988). "Measurement of strains in a paper tensile specimen using computer vision and digital image correlation," *TAPPI Journal* 71(3), 173-175.

Thompson, K. E., Willson, C. S., and Zhang, W. L. (2006). "Quantitative computer reconstruction of particulate materials from microtomography images," *Powder Technology* 163(3), 169-182.

Tze, W. T. Y., O'Neill, S. C., Gardner, D. J., Tripp, C. P., and Shaler, S. M. "Coupling polystyrene and cellulose fibers with hydrophylic and hydrophobic silanes: Effects on interfacial properties," the 7th International Conference on Woodfiber-Plastic Composites, Madison, WI, 29-35.

Vendroux, G., and Knauss, W. G. (1998). "Submicron deformation field measurements: Part 2. Improved digital image correlation," *Experimental Mechanics* 38(2), 86-92.

Wang, Y. (2007). "Morphological characterization of wood plastic composite (WPC) with advanced imaging tools: Developing methodologies for reliable phase and internal damage characterization," Master Thesis, Oregon State University, Corvallis, OR.

Wellington, S. L., and Vinegar, H. J. (1987). "X-ray computerized tomography," *Journal of Petroleum Technology*, August, 885-898.

Wolcott, M., and Muszyński, L. (2008). "Wood engineering challenges in the new millennium - Critical research needs: Materials and wood-based composites," Materials of Pre-Conference Workshop for ASCE Structures Congress, Vancouver, BC, Canada, in press.

Article submitted: April 5, 2009; Peer review completed: April 30, 2009; Revised version received and accepted: July 25, 2009; Published: July 28, 2009.