INVESTIGATION OF VARIATIONS IN CLOSED CELL FOAMED POLYMER COMPOSITE STRUCTURES

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Abstract

The purpose of this research is to study the closed cell foam properties as seen in a cross section of composite structures fabricated from recycled polymer post-consumer/post-industrial waste composed of (High Density Polyethylene) HDPE and (Glass Fiber Polypropylene) GFPP. These structures fabricated using blowing agent enabled extrusion techniques have a solid shell region on the outer surface and a closed cell inner foamed core. The final part performance varies with change in closed cell properties. Understanding of the micro-structural variations from the closed cells will contribute to predicting the spatially varying material properties within the composite structure. Imaging techniques were used to characterize parameters such as cell size geometrical and spatial distribution and spatial variations.

Introduction

Over the past 2 decades recycled polymer composites are being used in many structural applications such as crossties, construction mats, short bridges, board walks and so on. These are manufactured using hybrid extrusion techniques which enable the formation of a solid shell region on the outer core and blowing agents enabled closed cell foamed inner core. The closed cell foamed core has variations in material properties based on cell size distribution and density of the closed cells. These closed cell foams were studied by various researchers (see ex, [1] [2] [3] [4] and [5] and several models were developed to predict the effect of closed cells to material properties and structural behavior.

Zhang et al [6] has reviewed various normalized closed cell foam models for spherical closed cells made from HDPE and compared the measured tensile modulus suggesting that the prediction made by the empirical equation of Moore-Square Power Law and the differential scheme were most accurate within 0-55% volume fraction. The properties of closed cell foams vary with density, crosslinking, foaming agent content and processing conditions with foaming density being the contributing factor for change in mechanical properties [7]. The method used by Zhang does not consider localized volume fraction of the composite but the overall normalized density, shape and interactions.

Material properties prediction for PVC foams was studies by Lo et al [8] where a unit cell representation by introducing an apparent volume fraction replacing the actual resin volume fraction. Laguerre tessellations can be used to generate various models with different cell sizes to study the cell size variations and Redenbach et al found that there is a decrease in the overall elastic stiffness when there is an increase in cell size variations [9]. Closed cell wall thickness also contributes to the foam properties and Barbier et al [10] studied their influence on closed cell foams using tetrakaidekahedral cells and showed that the main deformation mechanism under small strains is caused by wall stretching. This investigation also led to study the effect of density and irregularity of closed cell foam structures on the elastic and plastic characteristics and concluded that in the elastic domain, material properties depend on relative density alone and in the plastic domain, both relative density and perturbation must be considered [10].

Most models previously used in finite element models for predicting foam material properties are obtained using homogenized properties [11]. Researchers are introducing techniques to study the closed cell foams using imaging techniques to predict the localized cell properties so that change in material properties can be predicted. Nasrabadi et al, have studied closed cell aluminum foam samples using a multi-slice scan CT-Scan device. The images where characterized based on the darkness and brightness of the images and densities were used to different parts of the foam samples. The predicted behavior was then validated against experimental testing [11]. Buggenthin et al, researched cell structures to analyze single cell dynamics in high throughput microscopy. To have consistent results, methods using fluorescence based image processing and bright field image studies are used along with image acquisition, background correction, thresholding and object splitting [12].

Bazegari et al, have also studied multiphase aluminum foam formation and have used MATLAB image processing to quantify results to control and predict the density of foams [13]. Zhu et al also proposed a modeling approach using MATLAB image processing from images used from synchrotron X-ray computed tomography (µCT) scanning images with focus on relative density, pore size, micro-defects and strain rate [14]. In this paper, the cross-section of a fiber reinforced crosstie is taken, and localized density and cell size distribution is measured and calculated using MATLAB image processing techniques.

Methodology

One of the structural applications of recycled polymer fiber composite crossties is being used as alternatives to wooden crossties. As discussed, these crossties have a solid shell region on the outside and a closed cell foamed inner core. Crossties are usually made in 0.15×0.22×1.82 (6’’×9’’×72’’) or 0.17×0.22×1.82 (7’’×9’’×72’’) as shown in Figure 1. For this paper a 0.15×0.22 (6’’×9’’) cross-section crosstie is used. The crosstie is cut using an industrial saw and to quantify and predict the material properties of the inner core, MATLAB image processing techniques are used along with Finite Element Analysis to predict the material properties and structural behavior.

Figure 1: Recycled polymer fiber composite crosstie

Image Processing

Taking a cross-section of a crosstie into consideration as seen in Figure 2, the modulus of the shell and the core region vary depends based on the volume fraction of the closed cells. As the closed cells density increases, the density of the crosstie and the elastic modulus in the core decreases. To quantify the number of closed cell and their localized density, the tie cross section is photographed using a canon camera and using MATLAB imaging techniques, the cross-section of the tie is differentiated for contrast in colors and converted to binary images. Based on the Zhu et al, the image processing of scanned images include binary image processing, image enhancement, contour extraction, hole edges extraction, triangle subdivision and importing the obtained results into ABAQUS [14].

Figure 2: Cross-section of the crosstie with varying density and cell sizes

The photographed image is uploaded into MATLAB and a threshold value is chosen based on the quality of the image. The optimum threshold value can be determined based as histogram troughs law, maximum entropy and OTSU segmentation method [14]. Any noise in the image is removed using thresholding and using morphological structural element operations. The cross-section image is converted into a gray scale image and inverted into black and white pixels based on color contrast. The closed cells can be seen in Figure 3, the closed cells can be seen in white pixels and the surrounding surface area with the black pixels. Once the binary image is obtained, the center of the closed cell, major and minor axis as well as equivalent radius of each closed cell can be measured. Periodic geometry is used near the boundaries to account for their densities. With the x,y positions of each cell along with the radius measurements, a circle is drawn around every cell, and the cell size distribution is obtained.

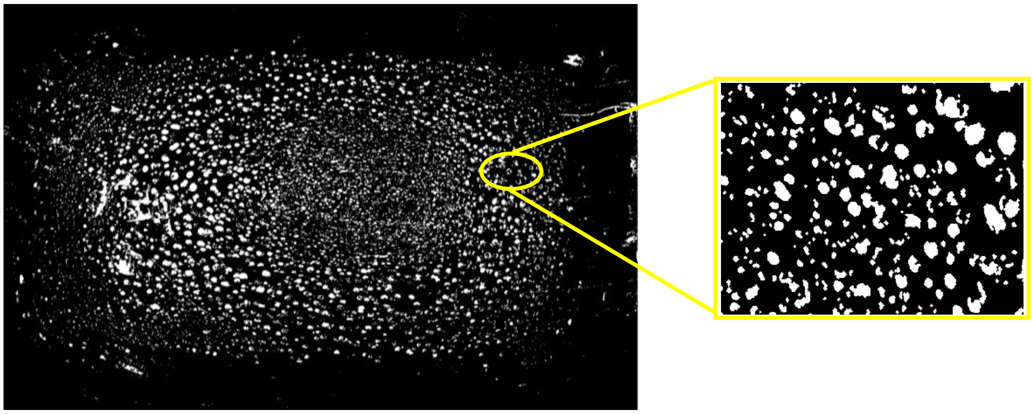

Figure 3: MATLAB image processing showing closed cells in binary image

To calculate the localized density at various points in the binary image, a circle of a fixed radius is taken and all the cells within the circle and the cells on the boundary are selected. The cells are weighted using an exponential decay function as given in Equation 1 and the area of the circles closest to the center have the highest weight and the areas of the circles on the outer radius is least weighed by the decay function.

$$\tilde{\rho} = \int_{0}^{2\pi} \int_{0}^{3R} \psi(r,\theta) e^{-\left({}^{r}/_{R}\right)^{2}} r dr d\theta \tag{1}$$

where $\tilde{\rho}$ is the localized density based on the cell radius r and the fixed circle radius R and $\psi(r,\theta)$ is the probability of finding cells at r,θ. As seen in Figure 4, R is the circle in the green and the cells inside the selected R is shown in blue and the cells on the border of circle R are shown in black. Calculating the area of the cells from 0 to 3R will consider about 99.9% of the area. If the cell size is much lesser than R, the equation of ρ can be represented as,

$$\tilde{\rho} = \sum_{i=1}^{N} A_i \, e^{-\left({}^{r}/_{R}\right)^{2}} \tag{2}$$

where A_i is the area of the cells within the selected R. Using $\tilde{\rho}$, the density ρ can be calculated using the area integral and is shown as,

$$\rho = \frac{\tilde{\rho}(x,y) \, \sum_{i=1}^{M} A_i}{\iint \tilde{\rho}(x,y) \, dx \, dy} \tag{3}$$

where the area summation i=1 to M is the total area of cells in the cross-section, x and y are the points selected along the cross-section.

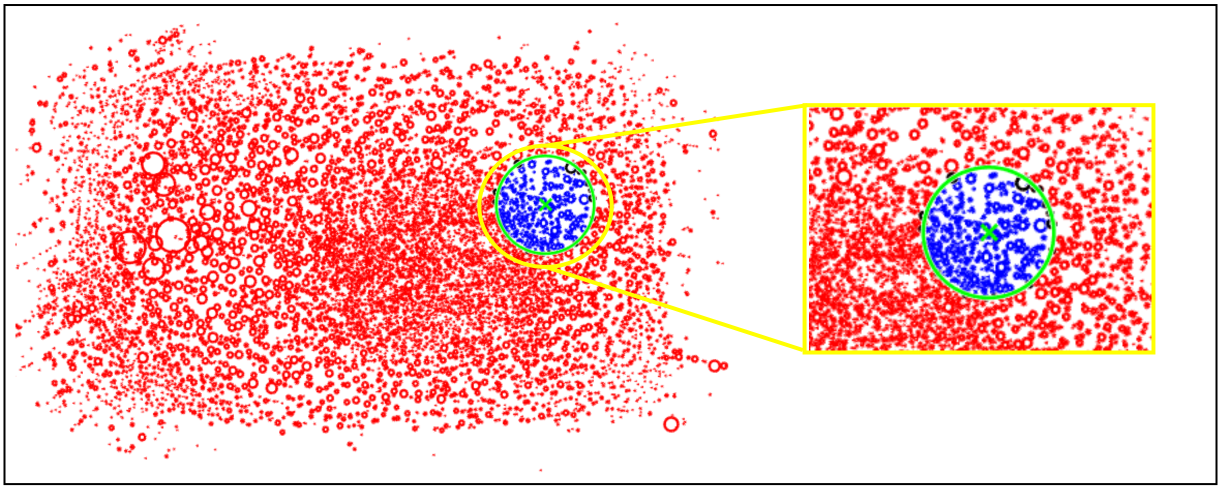

Figure 4: Localized cell density within a fixed radius

Material Properties Prediction

Once the localized area density is calculated and normalized to the actual density measurements, the localized material properties can be calculated using micro-mechanics models. Many tensile samples were cut using a miter saw and the Youngs Modulus of the outer shell is measured using tensile testing according ASTM D 638-03. The foam modulus E_f can be calculated using Youngs Modulus measured by the composite outer shell E_c as given by Zhang et al as shown in Equation 4 and 5. Based on equations given by Mori-Tanaka, the equation is,

$$\frac{E_f}{E_c} = \frac{2(7-5v)(1-f)}{(1+v)(13-15v)f + 2(7-5v)} \tag{4}$$

where f is the volume fraction of the closed cell foams and using the empirical equation given by power law, the equation is given as,

$$\frac{E_f}{E_c} = (1-f)^n \tag{5}$$

where n = 1.96 based on the relationship between power index and Poisson's ratio. Based on the localized stiffness calculations from equations 5, a crosstie was modeled in COMSOL and the cross-section was modeled to represent the localized stiffness of the image data in a finite element model.

Results

From the image processing procedures discussed using MATLAB, the cell size distribution of all the cell radius in the cross-section are measured and can be seen in Figure 5. The histogram shows the size of cells based on pixels and an indication of the type of cells contributing to the overall density and the stiffness of the composite cross-section. It is also evident that there are many smaller cells compared to the larger ones.

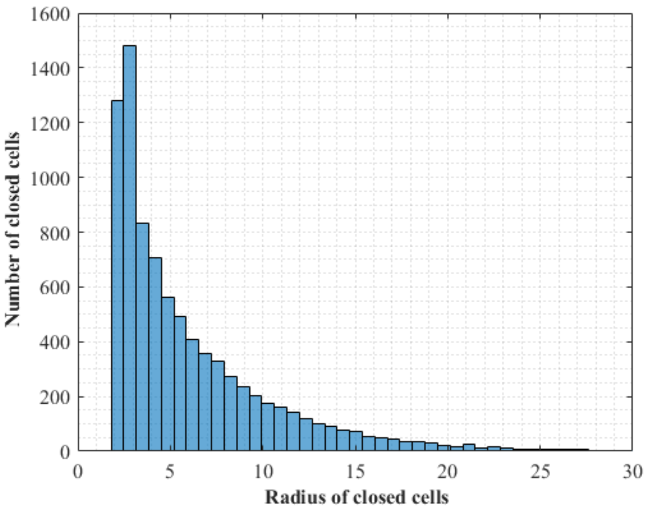

Figure 5: Closed cell size distribution

A mesh grid of points was taken at equal intervals in the cross-section and a localized volume fraction is calculated. The volume fraction of the closed cell foam can be seen in Figure 6 and the blue regions show solid composite and the yellow regions show that there are many cells around the point. It can be seen that the outer parts of the cross-section are solid, and the inner core has varying volume fractions depending on the number and size of cells.

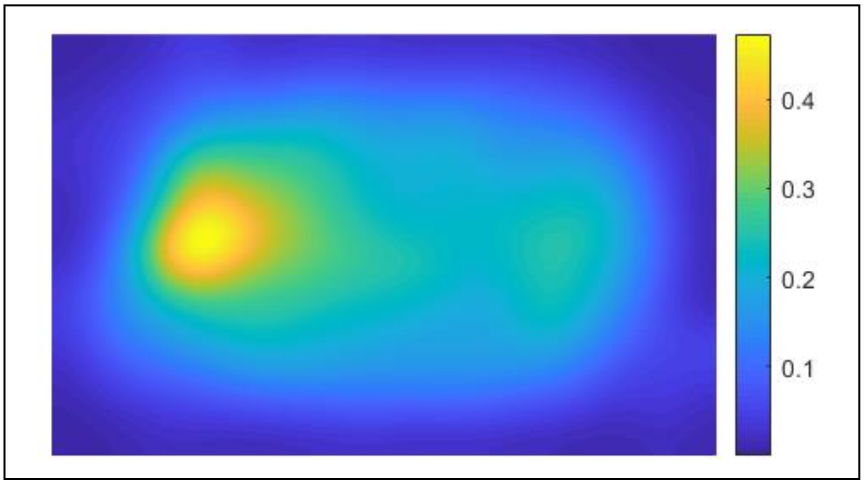

Figure 6: Localized closed cell volume fraction for a crosstie cross section

From tensile testing results of the solid shell samples, the Youngs Modulus values measured is 1.62 ± 0.179 GPa. Solving for foam modulus from equations 4 and 5 at every point, a localized foamed modulus is calculated. A COMSOL model was created with the geometry of a crosstie with a localized density in the cross-section as shown in Figure 7. The modulus changes from 1.6 GPa to 0.6 GPa depending on the localized volume fraction of the closed cells.

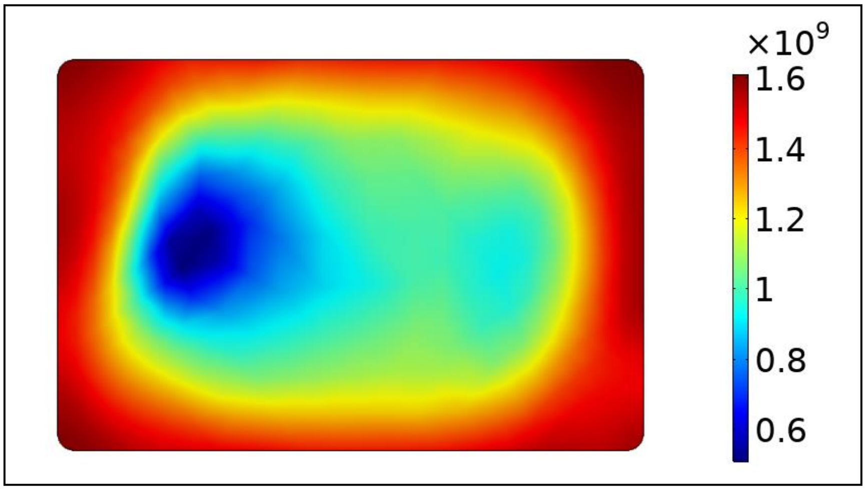

Figure 7: COMSOL model with localized elastic modulus

Summary and Next Steps

In this paper, a localized foam modeling approach was studied to predict the material properties of a closed cell foamed composite structure such as a crosstie using image processing techniques in MATLAB and using COMSOL modeling to apply the localized foam model to study the behavior of a crosstie. This approach includes calculating the density of closed cells in the cross-section with a weighted foamed cell method using an exponential decay function and establishing the localized stiffness of the composite. The next steps will include studying the image collection using various lighting schemes and to validate the image processing techniques using microscopy and to calculate the accuracy of this method.

Acknowledgements

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