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Image analysis for interfacial area and cocontinuity detection in polymer blends

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Abstract

A novel image processing method was developed to extract interfacial area concentration measurements from 2D micrographs of immiscible polymer blends. Although this method can be used for analyzing different types of 2D micrographs such as optical or transmission electron microscopy images, it was designed for analyzing scanning electron microscopy (SEM) images. The method operates by detecting edges within the images and using standard image processing operations to selectively eliminate false edges. SEM images of polyethylene oxide/polystyrene (PEO/PS) blends were analyzed using this image processing method to measure the amount of interfacial area in the samples. Interfacial area per unit volume exhibits maxima for blend compositions at the boundary between droplet and cocontinuous morphologies. In addition to the detection of cocontinuity, the interfacial area measurements facilitated by this method may be used in future investigations of blend dynamics, including coalescence, drop deformation, and blend rheology studies. These measurements may also be used to quantify the effects of compatibilizers on blend morphology.

Keywords: Image analysis; Polymer blends; Cocontinuous morphology

1. Introduction

Polymer blends provide an important route to property combinations not generally available in a single polymeric material [1]. Many blends of polymers are immiscible, resulting in equilibrium phase separation [2]. However, useful non-equilibrium microstructures can form when two polymers are subjected to intense mixing during processing. After processing, the blend can be fixed in a non-equilibrium morphology by cooling one of the phases below its melting or glass transition temperature [1]. Common morphologies include droplet, fiber, lamellar (layered), and cocontinuous microstructures. The distinguishing feature of cocontinuous morphologies is the mutual interpenetration of the two phases.

However, detecting cocontinuity is difficult. Often a single technique is insufficient for unambiguous determination of the blend morphology. For this reason, cocontinuity is often detected using a combination of methods. Previous studies have employed a wide variety of techniques [3–10].

Among the most popular methods for detecting cocontinuity is solvent extraction. Solvent extraction requires that one of the phases be selectively removed from the sample. The change in sample weight during extraction is compared to the amount of the extracted phase originally present in the sample. This fraction is the degree of continuity of the phase. If the degree of continuity of each phase is 1, the sample is cocontinuous. Alternatively, if one phase can be extracted completely and the remaining phase is self-supporting, it can be concluded that the sample is cocontinuous [6]. Unfortunately, solvent extraction destroys the sample and is both invasive and time consuming. It is also difficult to find selective solvents for both phases of many polymer blends since one component is usually more solvent resistant than the other. The more solvent resistant phase usually cannot be removed without damaging the other phase. Hence, solvent extraction typically can determine the degree of continuity of only one of the phases in most systems.

Microscopy followed by image analysis is another popular cocontinuity detection method. Since the size scale of the domains in cocontinuous polymer blends is often 1 μm or less, three-dimensional imaging techniques such as magnetic resonance imaging or X-ray computerized tomography cannot be used [11]. Thus, two-dimensional microscopy techniques such as optical microscopy, scanning electron microscopy (SEM), or transmission electron microscopy (TEM) are commonly used to examine the

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cross-sections of these blends, then image analysis is used to detect cocontinuity [3,4,7–9]. A danger of using two-dimensional microscopy techniques for determining blend morphology is the possibility of misinterpreting the images. For example, if fibers are cut perpendicular to their axis, they appear to be drops instead of fibers. This problem can be circumvented by collecting and analyzing images from three orthogonal sample planes [10]. However, this technique greatly increases the number of experiments required.

Previous studies that have used image analysis to characterize polymer blend morphology have relied on direct detection of objects (usually the phase domains) in the image. The size and shape of the phase domains has been determined using numerous methods. Harrats et al. used opening size granulometry to characterize the size of the phase domains [7]. Images were processed using an opening transformation which removed objects that were smaller than a given convex element. A series of opening transformations with successively larger convex elements were used to remove objects in order of increasing size. The opening size distribution was determined from these results and then used to characterize the blend morphology. Heeschen analyzed each phase domain in binary images by determining its area and convex area [4]. The area was determined from the number of pixels in the domain, while the convex area was determined from the number of pixels enclosed by a 32-sided equiangular polygon that circumscribed the domain. The cocontinuity of the blend was evaluated based on these parameters. This method allowed the degree to which the phases surrounded and interpenetrated each other to be quantified. Lauger et al. divided blend images into sections using parallel lines [8]. The domain size in the sections was determined from the number of pixels in each domain. The average distance between domains was determined from these calculations. Steinmann et al. used a form factor based on the ratio of domain area to perimeter squared to estimate the shape of the phase domains, independent of their size [9]. It was discovered that the distribution of the form factor could be separated into two parts, one dependent on blend composition and one independent of composition. A minimum in the composition-dependent part of the form factor distribution was used to determine the composition at which the phase inversion occurs.

In addition to the size and shape of the phase domains, an important parameter is the concentration of interfacial area within a blend. The amount of interface may influence a variety of blend characteristics including rheological behavior and changes in morphology. For example, the rheological behavior of polymer blends can be predicted and interpreted through several phenomenological models related to the interfacial area [12–14]. The Palierne model [12] uses the radius of drops in a matrix to predict the elastic and loss moduli of emulsions. The drop radius can be estimated based on the amount of interface per unit volume. The theories of Doi and Ohta [13] and Lee and Park [14] use the interfacial area per unit volume as a parameter for predicting the rheology of blends with complex interfaces. Dynamics of cocontinuous morphologies [15,16] including coalescence [17,18] and drop deformation [19] could also be studied by quenching carefully prepared blends during these phenomena and measuring the interfacial area per unit volume.

In this study, the concentration of interfacial area in several blends of polyethylene oxide (PEO) and polystyrene (PS) was determined using a novel method for processing 2D images. Although this method can be used on any type of 2D grayscale images, including optical or TEM micrographs, it was designed for SEM images, such as those analyzed in this study. Blends of various concentrations, from 10 to 90% PEO, were imaged and analyzed to determine the effect of blend composition on interfacial area concentration.

2. Experimental procedure

2.1. Sample preparation and SEM imaging

PEO–PS blends were prepared in a Haake batch mixer. PS (Dow PS 6690, $M_w = 150{,}000$ g/mol) was blended with PEO[1] (Union Carbide WSR N-3000, $M_w = 400{,}000$ g/mol) at 35 rpm (maximum $\dot{\gamma} = 33\ s^{-1}$) and a temperature of 170 °C for 10 min. Immediately following mixing, the product was transferred to a hydraulic press and then pressed at 170 °C and 5 psi for 1 min followed by 1 min at 100 psi. This formed sample disks approximately 1 mm thick. The press was then cooled using cold water, dropping the temperature below 55 °C and crystallizing the PEO within 2 min. This quenched the samples and trapped the non-equilibrium microstructure present in the hot polymer blends.

The resulting samples were then carefully prepared for imaging via SEM. Samples were cryo-microtomed at −120 °C using a glass knife to generate clean, flat surfaces, and provide a clear picture of the polymer surface. Each microtomed sample was then immersed in a solvent bath to remove the minor phase at the surface. Samples containing 50 wt% or less PEO were washed with water for 10 s. PS was removed from the remaining samples by washing in toluene for 2 min. The washed samples were then coated with 50 Å of platinum and imaged at 5 kV with a JEOL JSM-840 scanning electron microscope. SEM imaging was chosen because the size scale of these blends precludes the use of optical microscopy. SEM was favored over TEM because the sample preparation is much less difficult. The

[1] PEO powder was premixed with lithium perchlorate ($LiClO_4$) at 25 rpm (maximum $\dot{\gamma} = 24\ s^{-1}$) and 100 °C for 3 min. The $LiClO_4$ was added to enhance the conductivity of the PEO phase. A description of conductivity and rheology experiments on these blends will be published separately [20].

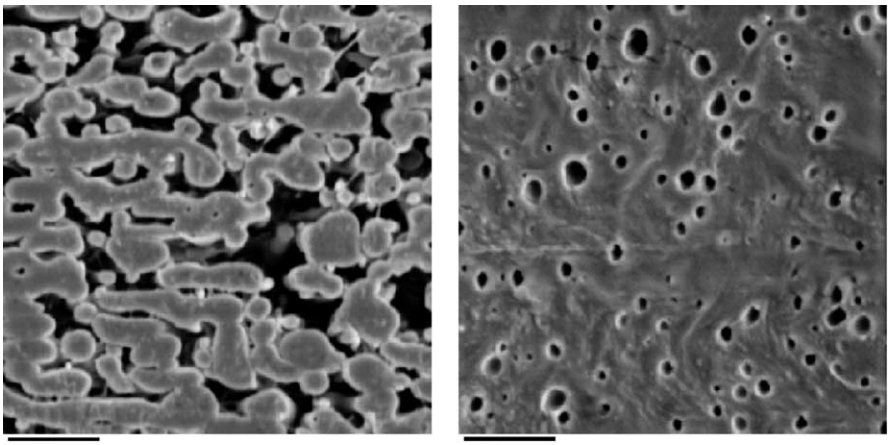

Fig. 1. SEM images of PEO/PS blends: a 50/50 blend with PEO removed by water extraction (left) and a 90/10 blend with PS removed by toluene extraction (right).

SEM samples can be microtomed more easily since thin slices are not required. In addition, staining is not required for SEM.

Sample SEM images of blends with cocontinuous and droplet morphologies are presented in Fig. 1. Contrast between the phases was accomplished by removing the top layer of a single phase using solvent extraction. To accurately measure the amount of interface at the sample surface, washing must be even across the sample and as shallow as possible. This reveals the surface morphology without exposing other features in the sample interior.

Careful sample preparation and SEM imaging ensure that the resulting images can be analyzed using digital image processing. A shallow wash provides good contrast while limiting the appearance of features outside of the surface plane. In spite of this, some features of the SEM images make them difficult to analyze automatically. For example, the images in Fig. 1 show some depth. Many edges look thick because the sides of raised features remaining after the washing step are visible. This will be discussed in more detail in Section 2.2.

2.2. Image analysis

For automated image processing to be feasible, SEM images must have high contrast, uniform lighting and be appropriately scaled so that the phase size is significantly larger than the pixel size. Images meeting these requirements were analyzed using the following image processing technique. The object of this image analysis method is to locate and measure the amount of interface within each image. In the case of these 2D SEM images, the amount of interface is represented by the perimeter of the features present in the image.

In images with excellent contrast, very shallow washing, and little noise, the interfacial area between the components in the blends could be obtained using a simple edge detection filter [21]. Edge detection filters search for areas within the image where the gradient of the brightness of the image is high, and then highlight these pixels as edges. Edge detection routines are available in most major image processing and image analysis packages, including *NIH Image* (National Institutes of Health, Bethesda, MD). However, simple edge detection may fail for SEM images because of the 3D features visible in the image. When a droplet morphology exists, the interface area may appear to be a thick feature rather than a thin edge, and double edges may be detected instead of single edges. In cocontinuous morphologies, some edges may appear thick while others appear thin. A simple edge detection filter will either miss some of the interface within the image or detect spurious edges. This results because packaged routines do not generally allow fine control over the level of edge detection. A more sophisticated algorithm for edge detection is required to accurately locate the interface.

One algorithm that can successfully detect and measure polymer–polymer interfaces for both cocontinuous and droplet morphologies is presented here.[2] It is based on a set of simple, established 2D digital image processing methods, and was implemented using MATLAB (The Mathworks Inc., Natick, MA). Adjustable parameters were used to allow the user to balance the image processing method between over-detection and under-detection of edges, providing accurate estimates of interfacial areas in polymer blends using SEM micrographs. As stated in Section 1, this method could also be applied to other types of 2D grayscale images, given that they meet the requirements discussed above. For example, TEM images with high phase contrast due to staining would be candidates for this algorithm. However, unlike SEM micrographs, TEM images with high phase contrast can often be analyzed using packaged

[2] A listing of the computer code is available to interested readers from the authors upon request.

routines. Samples with smaller or larger phase size than those used in this study could also be used provided that the phase size is much larger than the pixel size and quality micrographs can be obtained.

This image processing method was used to analyze grayscale SEM micrographs. These images are represented by 2D arrays of grayscale intensity values, with each value corresponding to one pixel in the image. For 8-bit images, the intensity values range between 0 (black) and 255 (white). Digital image processing involves changing these intensity values based on mathematical operations. Many digital image processing operations involve the application of 3×3 filters to the image. Filtering is a simple image processing technique in which a small (usually 3×3 or 5×5) matrix or kernel is convolved with the image matrix. The appearance of the new image depends on the type of filter used.

In the first step of the process, a median filter [22] is applied to the image. At each pixel in the image, this median filter replaces the intensity value with the median of all those values in its 3×3 pixel neighborhood. This eliminates isolated specks of noise within the image without degrading the clarity of edges. Next, vertical and horizontal Sobel edge detection filters [21] are applied. The kernels of these filters have the form:

$$\text{vertical}: \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \qquad \text{horizontal}: \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \tag{1}$$

Convolution of an input image with these filters calculates x- and y-derivatives of image intensity. At edges, the gradient of the intensity of the image is high, so the resulting image contains brighter pixels at edges. The results from vertical and horizontal Sobel filtering are combined by taking the maximum value from the two results for each pixel location within the original image. The resulting image is then made binary via thresholding to highlight edge locations within the images. The selection of an appropriate threshold value is left to the user. An appropriate choice ensures that all relevant edges within the image are detected. Where the Sobel filtering results in values above the threshold value, edges are detected and the image is colored black, while the image is colored white at all other points. Typical results for droplet and cocontinuous polymer blends are shown in Fig. 2a.

Unless the original SEM image is extremely clean, spurious edges are detected in addition to the real edges within the image. As can be seen in Fig. 2a, both sides of thick edges may be detected although only one true edge exists. Using further image processing steps on this edge image can eliminate these artifacts and result in good estimates of interfacial area. Double-counted edges can be combined by blurring them together using another image filter. In this case, a 3×3 Gaussian smoothing filter was used [23]. The kernel of this filter is:

$$\text{Gaussian filter kernel}: \begin{bmatrix} 0.0113 & 0.0838 & 0.0113 \\ 0.0838 & 0.6193 & 0.0838 \\ 0.0113 & 0.0838 & 0.0113 \end{bmatrix} \tag{2}$$

When this filter kernel is applied to the 3×3 neighborhood of each pixel within the image, the edge image is blurred, as shown in Fig. 2b. When this filter is passed over the image several times, edges which are sufficiently close to one another blur together. The number of times that this filter is applied to the image is a second user-defined parameter that can be tuned according to the size scale of the image. This parameter should be set so that doubled edges blur together, while distinct edges remain distinct. Once the image has been blurred, a second thresholding operation is performed to find the artificially thickened edges within the image. A median filter is then passed over the result to remove specular noise. The result is a set of thick edge locations.

For the perimeter of features to be easily measured, the edges within the image must be exactly one pixel thick. A morphological thinning routine [24] is applied to thin the thick objects found by blurring and then thresholding the edge image. This thinning operation erodes thick objects until they are only one pixel thick while preserving the shape and connectivity of the objects. This is the final step in this edge detection algorithm. Results for images of cocontinuous and droplet morphologies are shown in Fig. 2c. Notice that the resulting edge maps closely mirror the location of the polymer–polymer interface in the original images.

Since each edge location in the original image is now represented by a black pixel in the final edge image, the perimeter of the interface within this image cross-section can be calculated. The number of black pixels in the image can be counted and multiplied by a calibration factor to determine the total amount of perimeter within the cross-sectional image. For this study, the following calibration factor was used:

$$\text{Calibration factor} = \frac{1+\sqrt{2}}{2}\left(\frac{\text{pixel size}}{\text{total image area}}\right) \tag{3}$$

This factor assumes that adjacent edge pixels are connected in both diagonal and non-diagonal fashions, and that both types of connectivity are equally likely. The pixel size can be determined by dividing the actual width of the entire image by its width in pixels. The image area is calculated by multiplying the actual width and height of the image. For the analysis of the images shown in Fig. 1, the calibration factor was $0.137\ \mu m^{-1}$.

Stereology theory [25] tells us that the average interfacial

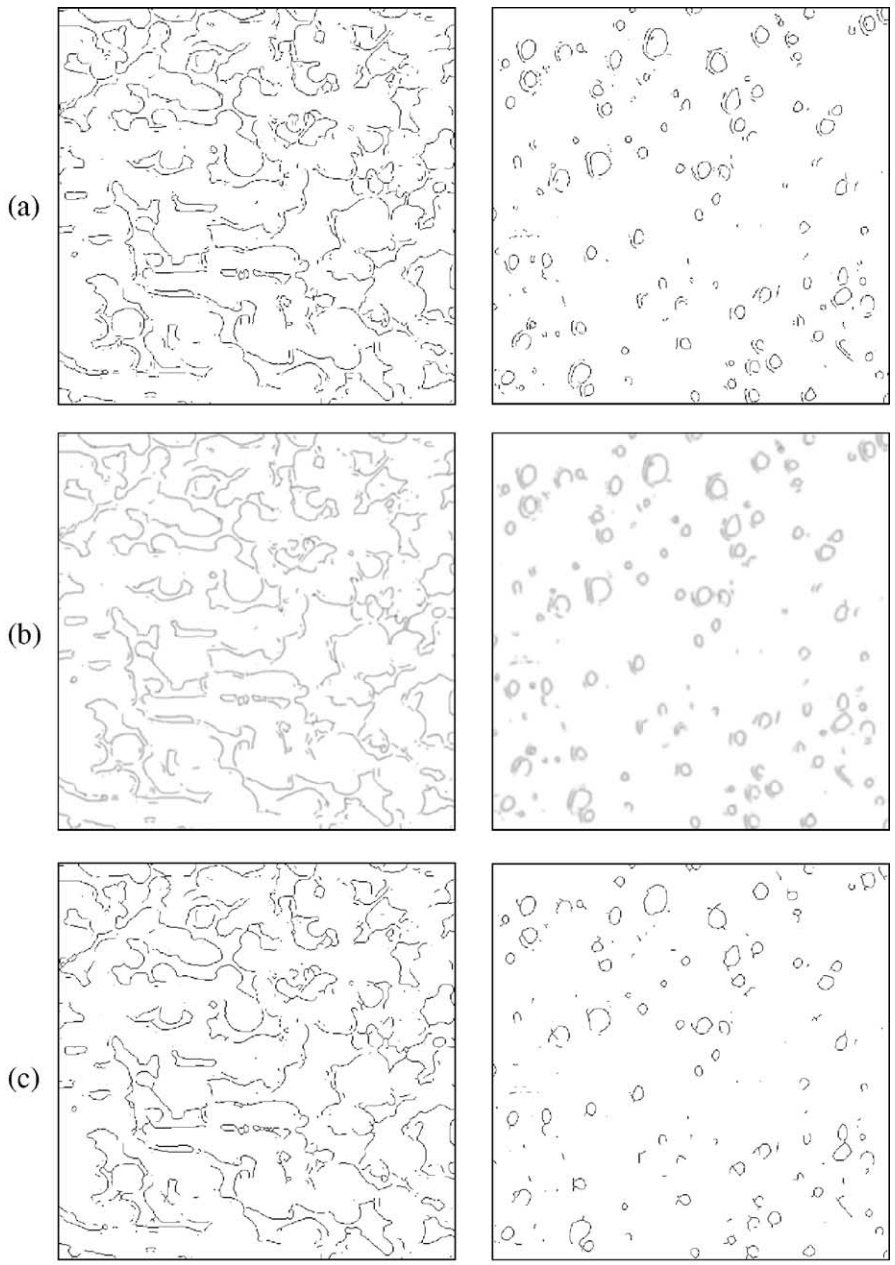

Fig. 2. SEM micrographs shown in Fig. 1 at several stages in the image analysis algorithm: (a) after the first step, application of an adjustable Sobel edge detection filter. In some locations, false double edges have been detected. (b) After the application of Gaussian filters, the second step. Two Gaussian filters were used for the 50/50 blend and ten were used for the 90/10 blend. The false double edges present in (a) have been merged together. (c) After the final step, application of an edge thinning routine. The edges have been reduced to one pixel wide lines and closely resemble the phase boundaries in the original images.

perimeter per unit cross-sectional area within a sample is equivalent to its interfacial area per unit volume, since integrating the perimeter over a parallel set of cross-sections will yield the amount of interfacial area in a sample volume. This relationship holds regardless of the orientation of the cross-sections imaged and the morphology of the sample, for non-lamellar structures. Imaging several cross-sections in each sample improves the statistical reliability of the result. Note that the amount of perimeter per unit cross-sectional area, the amount of interfacial area per unit volume, and the calibration factor have units of inverse length.

3. Results and discussion

This image analysis approach was used to calculate the interfacial area concentration within PEO–PS blends with compositions ranging from 10 to 90% PEO. As demonstrated in Fig. 2c, this automated method successfully detected essentially all of the polymer–polymer interfacial area within the SEM micrographs. The image analysis parameters discussed above, including the two threshold values and the number of iterations for the Gaussian filter, allow for flexibility in the analysis of imperfect SEM

images. The proposed algorithm permits analysis of SEM images with varying brightness and contrast and images of samples with varying levels of surface roughness.

This image analysis method has the advantage that it does not rely on the direct detection of objects, unlike most existing methods for characterizing polymer blend morphology [3,4,26–29]. Instead, the interfacial area between phases is detected. While object detection is useful for characterizing droplet morphologies, it provides an unnatural description of cocontinuous morphologies, since a cocontinuous structure only consists of two objects (phases). Using this new algorithm, both droplet and cocontinuous morphologies can be analyzed and the amount of interfacial area present in both types of structures can be determined. In addition, the importance of obtaining images from orthogonal planes in the sample is minimized, since the detection of interfacial area is not directionally dependent in non-lamellar systems.

The average length of interface per unit area of the micrographs is shown as a function of blend composition in Fig. 3. Two local maxima appear in this plot, one at a blend composition of 35% PEO and another at a composition of 65% PEO. Solvent extraction experiments using well-documented techniques [15,30,31] confirmed that these peaks represent the boundaries of the region of cocontinuity for these PEO–PS blends [20]. Briefly, toluene was used to extract the PS phase and water was used to extract the PEO phase. Blends containing less than 35% PEO disintegrated when the PS (major phase) was removed with toluene, indicating that this composition is a boundary of the region of cocontinuity. Similarly, blends containing more than 65% PEO (less than 35% PS) disintegrated when the PEO (major phase) was removed with water, placing the other boundary at this composition. This shows that, like solvent extraction, interfacial area measurement using SEM with image analysis can be used to detect the region of cocontinuity in a polymer–polymer system.

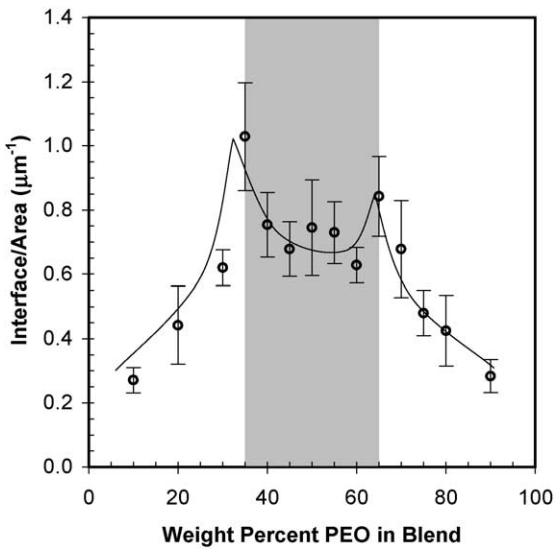

Fig. 3. Amount of interface per unit area of image as a function of blend composition. The peaks correspond to the boundaries of the region of cocontinuity (shaded) at 35 and 65 wt% PEO. Error bars represent the standard deviation of the measurements from several images. The curve shown is a guide for the eye.

The maxima in Fig. 3 can be explained by considering the progression of the morphology from drops to cocontinuous. At 10% PEO, the morphology is drops of PEO in a PS matrix. At 20% PEO, the morphology is still drops, but the amount of interface has increased because the amount of PEO in the blend has increased. However, since the phase (drop) size of the PEO has increased, the amount of interface does not increase in proportion to the PEO weight fraction. As the PEO weight fraction continues to increase, the drops become more elongated and form fibers, and the amount of interface increases more rapidly. As the blend morphology changes from elongated drops and fibers to cocontinuous, a sharp decrease in the amount of interface is observed. This can be explained by considering the increasing connectivity of the blend. As the elongated drops and fibers coalesce with each other, there is a decrease in the amount of interface due to the loss of interface at the point of coalescence. This counteracts the effect of adding more minor phase component to the blend. This effect can explain the other half of the curve as well, although the boundaries of the region of cocontinuity do not necessarily have to be symmetric, due to effects such as viscosity or elasticity mismatches. For example, lower viscosity components tend to surround higher viscosity components, causing the region of cocontinuity to shift toward lower concentrations of the less viscous phase [32].

This method generated a good measurement of interfacial area for the PEO–PS blends studied here. At least 10 micrographs were taken at different locations in each sample to check for reproducibility and to account for local differences in microstructure. These interfacial area measurements had standard deviations of less than 25% of the mean for each sample. Much of this variation was real, due to local differences in microstructure within the samples. In particular, samples with concentrations near the boundary between droplet and cocontinuous morphologies contained some local areas that appeared cocontinuous and others which resembled droplet morphologies.

The accuracy of the image processing algorithm was assessed by comparing a portion of the results with manual tracing of the interface. Five micrographs were randomly selected from each of five different blend compositions (20/80, 35/65, 50/50, 65/35, 80/20) for this comparison. The traces of the original micrographs were scanned as black and white images and the edges were reduced to a width of one pixel using a thinning routine. The number of edge pixels was then calculated as in the image analysis program and multiplied by the calibration factor to determine the amount of interface. This comparison showed that the results of automated detection agreed with manual tracing within 15% for all 25 micrographs analyzed. When the results were averaged for each composition compared, the

Table 1
Comparison of interface length per unit area measured by different edge detection methods

Blend composition	Amount of interface from program (μm^{-1})	Amount of interface from tracing (μm^{-1})	Percent difference between program and tracing	Amount of interface from object detection analysis (μm^{-1})	Percent difference between program and object detection analysis
20/80	0.543	0.580	−6.3	0.552	−1.6
35/65	1.082	1.058	2.3	–	–
50/50	0.858	0.887	−3.2	–	–
65/35	0.851	0.885	−3.7	–	–
80/20	0.487	0.523	−7.0	0.508	−4.2

amount of interface calculated by the two methods agreed within less than 7%. These results are summarized in Table 1. The agreement between these two methods of measuring the amount of interface shows that potential errors associated with digital image analysis have a minimal effect on the results. This also shows that the image-processing algorithm can achieve the same accuracy as commonly used tracing methods in a much shorter period of time. For example, processing images with this algorithm takes less than 3 min per image, while preparing and processing hand-traced images takes at least 30 min per image.

This image analysis algorithm was also compared with the results of a technique based on direct detection of objects. In this method, blends shown in Table 1 with drop morphologies (20/80 and 80/20) were analyzed by directly detecting the drops. Images were prepared for this analysis by first tracing the drops and then coloring them black manually. The program ImageTool (University of Texas Health Science Center, San Antonio, TX) was then used to find the drops in the images and determine their individual perimeters. The total perimeter of the drops was used to calculate the total amount of interface in the blend. As shown in Table 1, the amount of interface measured using object detection in ImageTool was similar to the amount measured by the interface measurement algorithm. When the results were averaged for each composition, the amount of interface measured by the two methods agreed within 5%. These results show that the interface measurement algorithm agrees well with commonly used image processing methods based on object detection.

Although the results of the image analysis algorithm agree with the results of manual tracing and direct object detection, there are some potential sources of error that contribute to variations in the amount of interfacial area measured by the program. The loss of some small features can reduce the amount of interface detected by the program. This can occur when a small feature is located by the edge detection filter, but is collapsed by the application of a series of Gaussian filters. This is generally more common for images of droplet morphologies. If features below the plane of the surface are visible in the image, they are sometimes erroneously detected if the edges are sufficiently sharp. This is more prevalent for images of cocontinuous morphologies. In addition, if true edges are not sufficiently sharp, these portions of the interface can be lost during the edge detection step. Fig. 4 compares the results of the image analysis program with the results of tracing for the 50/50 blend shown in Fig. 1. A comparison of these images shows that while there are some differences in the images, the image analysis algorithm compares well with manual tracing of the interface. Careful sample preparation and selection of input parameters can minimize experimental error.

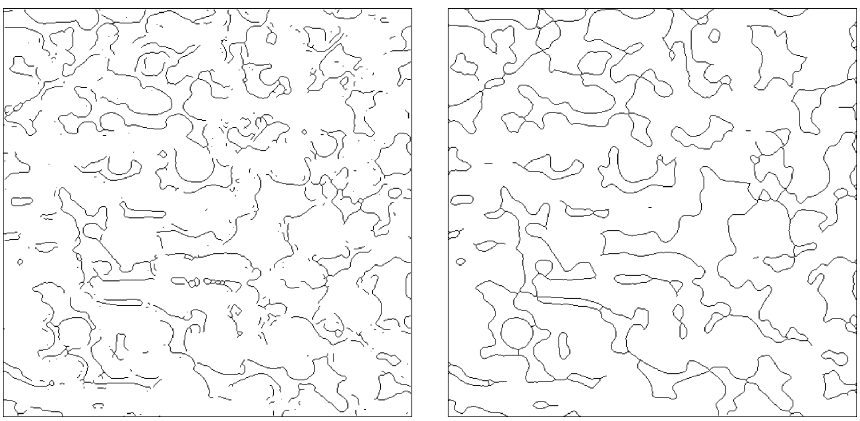

Fig. 4. Comparison of the results from the image analysis algorithm (left) and manual tracing of the interface (right) for the 50/50 blend shown in Fig. 1. Although it includes some regions with spurious edges and areas where some edges were not detected, the result from the image analysis algorithm closely resembles the traced image.

4. Conclusions

A novel image processing approach has been developed to allow for the measurement of interfacial area within polymer blends using SEM micrographs. This algorithm permits analysis of images that cannot be analyzed using routines included in commercial packages. The perimeter per unit area present in the images is calculated using the algorithm and can be related to the amount of interface present in the blends. The use of the amount of interface for analyzing the blends allows for easy comparison between droplet and cocontinuous morphologies, while most other image analysis methods for examining polymer blend morphology use direct object detection, making comparison between these morphologies more difficult. The results from this image analysis algorithm agree with manual tracing of the interface within 7%, showing that the algorithm can achieve results similar to tracing while requiring significantly less time to analyze the images.

Interfacial area measurement using SEM and image analysis provides a powerful, new tool to improve the level of understanding of polymer blend morphology and dynamics. For example, in this study the PEO–PS blend morphology and interfacial area per unit volume were shown to depend on blend composition. It was shown that the amount of interface present in this polymer–polymer system reaches local maxima at PEO concentrations at the boundaries of the region of cocontinuity. These characteristics also depend on several other system variables. The region of cocontinuity may be broadened or narrowed by changing processing temperature, shear rate, component rheological properties, or by the presence of additives. This method can be used to examine how the region of cocontinuity is affected by these variables.

This image analysis technique can also be applied in studies of rheological behavior, changes in blend morphology, and the effect of compatibilizers on polymer blends. Measurement of the amount of interface per unit volume can be used to provide morphological information, such as droplet diameter or the total amount of interface, for use in models for blend rheology. Changes in the amount of interface per unit volume can be used to follow changes in the blend morphology due to phenomena such as coalescence and drop deformation as well as annealing. The effect of adding compatibilizers to blends could also be measured by examining the change in the amount of interface per unit volume. The application of this image processing method to these and other studies in polymer science will provide new insights for examining a wide range of phenomena.

Acknowledgments

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