Online Strain Measurement during Blown Film Extrusion using Digital Image Correlation

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ABSTRACT

Development of strain during blown film extrusion process was monitored online on the surfaces of high density polyethylene (HDPE) film. The displacement and strain were measured using Digital Image Correlation (DIC) method by following the digital or pixel changes of the marker during the film stretching process. Two different methods of creating random pattern on the surface of the blowing film were studied using a permanent black marker pen ink and grey spray paint prior to the measurement. The reliability of DIC was evaluated by verifying the measured strains and displacement results with those obtained using conventional method. Results showed that black marker pen ink was suitable for creating a random pattern on the blown film surface during extrusion process. The strain values from both conventional and DIC methods were comparable and therefore, proved that the DIC method was reliable enough to be used in a dynamic process such as blown film extrusion process.

Keywords: *Blown Film, Digital Image Correlation, Displacement, Strain*

INTRODUCTION

Blown film extrusion is a very prominent process to the packaging industry which produces high-volume of polymeric films. Plastic bags and films of varying sizes are manufactured with this process. The basic film-blowing process involves extruding molten polymer through an annular die to form a tube. The tube is then blown into a bubble with larger diameter and cooled by

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external air stream to solidify the film. The blown and solidified film is flattened by passing through the take up rolls and wound as plastic rolls [1-3].

During the process, the polymer melts experiences biaxial stretching in axial and circumferential directions. The axial stretching is caused by the drawing force of the nip rolls while the circumferential stretching is affected by the air pressure inside the bubble [1].The blown film will undergo deformation due to the stretching process. Deformation plays important role in controlling the microstructural development taking place in wide range of polymer processing including blown film processing [4].

Over the past decades, many theoretical and experimental studies have been conducted on blown film process by manipulating the take up ratio (TUR) and blow up ratio (BUR) to study on deformation and relating to the microstructural development within the polymer film [4]. To the best of our knowledge, none have linked strain experienced by the film during the blowing process to the understanding of structural development of molecules within the blown film. This might be due to difficulty in measuring strain in the fast moving blown film process.

Digital Image correlation (DIC) is an optical technique used to measure the displacements with sub-pixel accuracies and strain on a surface of a progressively deforming material in a non-contact approach. The correlation process uses the grey intensity pattern which becomes the initial guess to track the displacement. A small subset surrounding this point in the reference image was selected to match the similar subset area in the current image. Then, displacement and displacement derivatives can be retrieved and subsequently the strain can be calculated [5-7].

Therefore, surface patterning is needed in DIC process to track and match the subset location from one image to another. The surface pattern is able to provide random grey level variations and the quality of acquiring the surface pattern is the key to obtain accuracy of the measured displacement data [8, 9]. Generally, the pattern on the surface of deforming object can be of inherent surface texture or artificial random pattern. Creation of artificial random pattern is challenging and depends on the applications. There are many techniques available to produce random patterns such as marked by pen, airbrush guns, via computer simulations and screen printing, spray paint, and so on[10, 11]. Attention should be given in selecting the right technique in producing the pattern as not all the techniques are suitable for certain applications.

Thus, the aim of this research work was to measure the real-time strain experienced by the blown film during the film blowing process. Studies have been conducted to measure the strain experienced by the composite materials during the physical testing using the DIC method[12, 13]. However, to the best of our knowledge, so far there is no studies have been conducted to measure strain during blown film processing using DIC method. In this study, the techniques to produce random pattern on the blowing film were studied using a black marker pen ink and grey spray paint and, the on-line displacement and strains were measured using DIC method. The reliability of the technique was evaluated by comparing the obtained results with conventional method.

EXPERIMENTAL

Material and Film Processing

High density polyethylene (HDPE) resin grade HB0972 with melt flow index of 0.1 g/10 min and density of 0.949 g/cm^3 was purchased from Lotte Chemical Titan (M) Sdn Bhd. The blown film was produced using Queens's Film Blowing Machine; model MIDI-40-500H. Extruder and die temperatures were set at 185±5°C and 195°C, correspondingly. The take-off motor and screw speeds were set at 300 and 250 rpm, respectively.

Digital Image Correlation (DIC)

Prior to DIC measurement, a mark was created on the surface of the blowing film using a black marker pen ink and grey paint spray. Olympus XZ-10 camera was used to record a video for the film blowing process. The camera was aligned parallel to the specimen surface in order to eliminate errors due to out of plane displacements. The reference and current images was respectively extracted from the recorded video and analysed using an open source 2D DIC code based on MATLAB [14].

Conventional strain measurement

The same images captured by the camera to be used for DIC method were analysed. Image analysis software Image J software was utilized to calculate the dimension of the mark in the axial (x) and transverse (y) direction. For both x and y directions, five measurement were taken and the average value was used for the calculation of Lagrangian and Eulerian strain as in Equation 1 and 2. Lagrangian strain is defined as change in squared root of material in terms of the original length and orientation which is preferred in solid mechanics, whilst Eulerian strain gives the change in squared root of material in terms of the final length and orientation which is preferred in fluid mechanics [15].

Lagrangian Strain,

$$\varepsilon = \frac{L^2 - L_o^2}{2L_o^2} \quad (1)$$

Eulerian Strain,

$$\varepsilon = \frac{L^2 - L_o^2}{2L^2} \quad (2)$$

where L_o is initial dimension obtained from reference image and L is the final dimension obtained from current image

RESULTS AND DISCUSSION

Prior to the analysis using conventional and digital image correlation (DIC) methods, a pattern or mark on the surface of blowing film was required to be located on the blowing film surface. Blown film is typically translucent with the absence of inherent surface texture and this feature can be quite challenging in implementing the DIC technique for the deformation evaluation. Thus, an artificial random mark is preferred to track the deformation. Figure 1a(i) and 1b(i) show the two different techniques used to create the marks on the surface of blown film, grey spray paint and black marker pen ink, respectively.

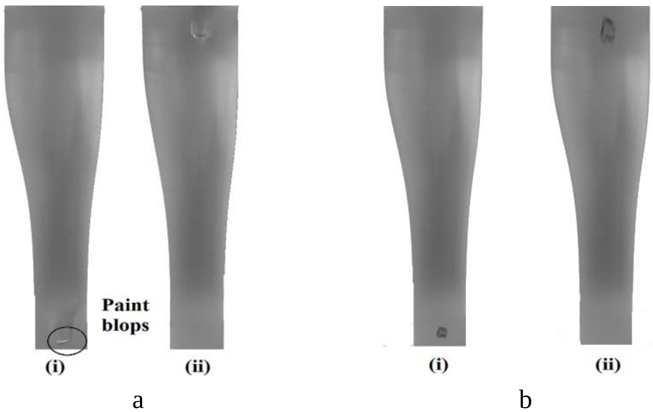


Figure 1: Marking techniques (a) Grey spray paint (b) Black marker pen ink

Figure 2 illustrates the image of blown film and the point where the reference and current images were taken for the strain and displacement calculation. The initial mark was created at point ‘a’ which is referred as reference image or un-deformed image. During the blown film process, the mark moved vertically and the current image was taken when the mark reached the point ‘b’. The current image is referred as the deformed image. Figure 1 a(ii) and b(ii) shows the deformed image of the two marking techniques. The un-deformed image was captured at a point of few millimetres distance from the molten resin extruded through the die. The deformed image was taken after the freeze line height (FLH). FLH is the point where a ring shaped region of frosty appearance has formed on the film surface and resin solidification occurred. Thus, it was referred as the point of transition from liquid to solid in which no or negligible deformation of bubble can occur beyond the FLH [16, 17].

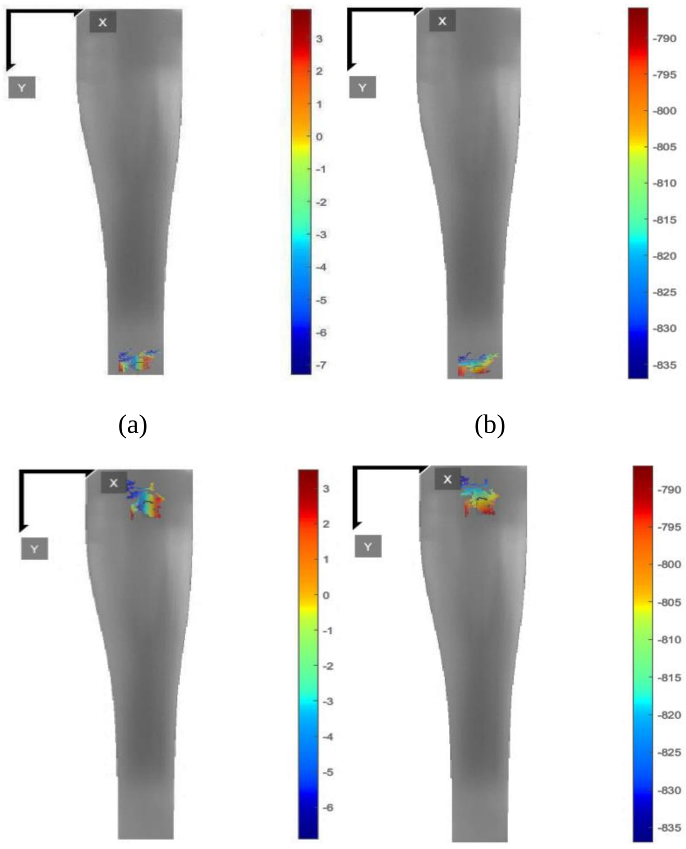
Figure 2: Position of blowing film (a) reference image (b) current image

Results obtained from DIC method is presented in Figure 3-6. A DIC subset size of 21 pixels, subset spacing of 1 pixels and a strain window of 15 pixels were used in the analysis of images with a size of 520×920 pixels. As mentioned in Experimental section, Lagrangian strain is ideal for solid mechanics and Eulerian is for fluid mechanics. The blown film process involves rheology of a viscoelastic material which includes both fluid (viscous component) and solid (elastic component) mechanics aspects, thus both the Lagrangian and Eulerian displacements and strains were taken into consideration.

The displacement contour in transverse (u) direction for both Lagrangian and Eulerian of the film marked by marker pen ink are shown in Figure 3a and 3c. Figure 3b and 3d presents the displacement contour in axial (v) directions for both Lagrangian and Eulerian displacement. From Figure 3a and 3c, it is noticed that the magnitude of u-displacement is similar for both Lagrangian and Eulerian which about 4.68 pixels while, magnitude of v-displacement is about 784 pixels.

Figure 4a and 4c represents the displacement contour in transverse (u) direction which is about 4.48 pixels with respect to both Lagrangian and Eulerian of the film marked by spray paint. Whilst, the magnitude of v-displacment is about 819 pixels as denoted by Figure 4b and 4d for both Lagrangian and Eulerian displacements. Regardless of the marking techniques (spray paint or marker pen), the v-displacement is very large because the mark has been continously moving or evolving along in y-direction while being stretched and deformed. The u-displacement is less compared to v-displacement because it involves deformation around the bubble diameter which does not expand much as seen in Figures 3 and 4.

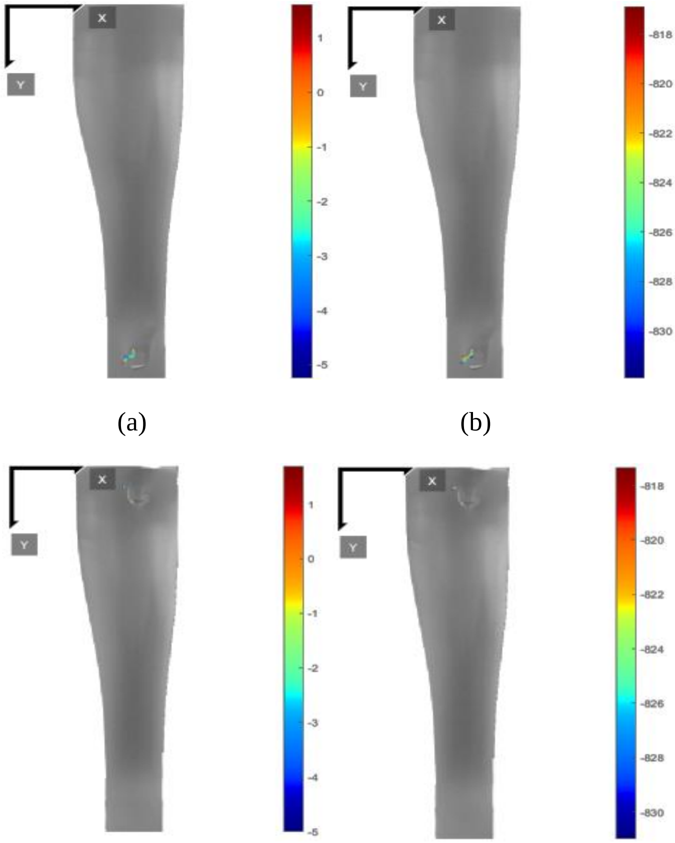
Lagrangian and Eulerian strain contours for film marked by marker pen ink are depicted as in Figure 5. The Lagrangian strain in x-direction (ε_{xx}) and y-direction (ε_{yy}) are 0.4138 and 2.0297 correspondingly. Whilst, the Eulerian strain values are 0.1748 and 0.4348 with respect to ε_{xx} and ε_{yy} strains. For both Lagrangian and Eulerian strains, the ε_{yy} is higher compare to ε_{xx}. This evidences that the take up ratio (TUR) dominates over the blow up ratio (BUR) resulting in more deformation is seen in x-direction giving rise to higher strain values.



(a) (b)

(c) (d)

Figure 3: Lagrangian (a) *u*-displacement (b) *v*-displacement; Eulerian (c) *u*-displacement (d) *v*-displacement of blown film marked with black marker pen ink

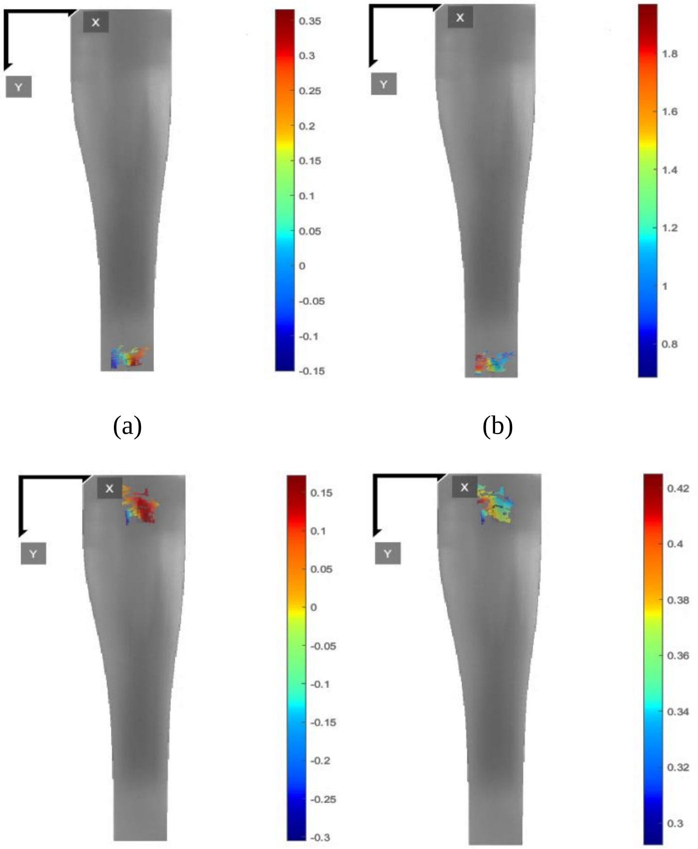


(a) (b)

(c) (d)

Figure 4: Lagrangian (a) u-displacement (b) v-displacement; Eulerian (c) u-displacement (d) v-displacement of blown film marked with spray paint

Figure 6 illustrates the Lagrangian and Eulerian strain contours for film marked by spray paint. The ε_{xx} and ε_{yy} strains for Lagrangian are -0.2138 and 0.0853, respectively. On the other hand, -0.9647 and -0.9926 values are obtained for Eulerian ε_{xx} and ε_{yy} strains, correspondingly. These strain values shows that the film which has been spray painted did not deform while being stretched vertically. Instead, the marked surface region has shrunk which denoted by the negative values obtained, resulted in less strain contours were exhibited by the DIC result. This can be attributed to the formation of larger blobs which led to drips on the film surface during the spraying process. Spray paints require some time to dry. Blown film process is a dynamic process and spraying was done instantly and this resulted in insufficient time for the paint to dry and led to dripping which can be seen in Figure 1a. Thus, it was projected that this occurrence has caused in incorrect strain measurement on the surface.



(a) (b) (c) (d)

Figure 5: Lagrangian (a) ε_{xx} strain (b) ε_{yy} strain; Eulerian (c) ε_{xx} strain (d) ε_{yy} strain of blown film marked with marker pen

Therefore, it was found that a simple mark on the surface of the blowing film using a black marker pen ink to be a better choice compared to the spray paint. This is because the mark was able to deform simultaneously while the film was blowing, stretching and deforming. Literature on pattern's application has reported that ink marker is a good practice because it affected the surface of film minimally and permits measurement of very high strain [18].

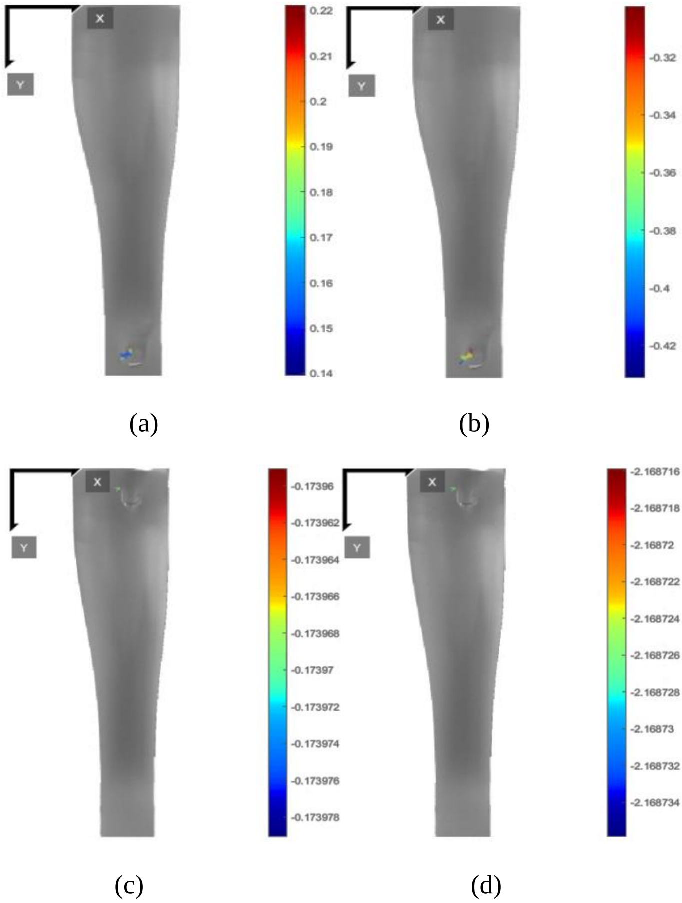


Figure 6: Lagrangian (a) ε_{xx} strain (b) ε_{yy} strain; Eulerian (c) ε_{xx} strain (d) ε_{yy} strain of blown film marked with spray paint

The ε_{xx} and ε_{yy} strains were calculated manually to evaluate the reliability of DIC method in the measurement of strain of blown film. The *u*-displacement and *v*-displacement were also measured manually. The strain and displacement values for both marking techniques are tabulated in Table 1 and compared with the DIC strain results. The strain measurement for film marked with spray paint show little deformation. Again, this was due to the paint blobs on the surface of film which restricted the film from being stretched. On the other hand, the strain measurements using marker pen from both DIC and conventional methods are displaying the same trend in terms of direction but the manually calculated strain values are slightly lower than the DIC. This might be due to DIC method which uses sub-pixel accuracies for the calculation of displacement and strain. Whilst, the manual calculation although being made on digital images, was subjected to approximate estimation of the diameters by the observer and has the tendency to miss out measurement points at the marked edges.

Table 1: Lagrangian (Lag) strain and Eulerian (Eu) strain comparison for conventional and DIC method

Marking Technique			Black Marker Pen Ink		Grey Spray Paint	
Result			DIC	Conventional	DIC	Conventional
Strain	Lag	ε_{xx}	0.4138	0.4140	-0.2138	0.0344
		ε_{yy}	2.0297	1.9431	0.0853	0.0848
	Eu	ε_{xx}	0.1748	0.2294	-0.9647	0.0321
		ε_{yy}	0.4348	0.3977	-0.9926	0.07247
Displacement	Lag	u	4.72	4.00	4.59	2.00
		v	-784.26	838.00	-818.30	807.00
	Eu	u	4.64	4.00	4.37	2.00
		v	-784.29	838.00	-819.40	807.00

CONCLUSION

Black marker pen ink was more suitable for creating a random pattern in blown film extrusion process as compared to grey paint spray. The strain values of black marker pen ink marked film from both conventional and DIC methods were comparable and therefore, can be concluded that the DIC method was reliable enough to be used in a dynamic process such as blown film extrusion process to measure the displacement and strain. The *v*-displacement of the mark was significantly higher compared to *u*-displacement because more deformation were available in axial direction where the blown film was continuously hauled off in the machine direction. The ε_{yy} was higher compare to ε_{xx} for both Lagrangian and Eulerian because the TUR dominated over BUR.

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