7-27-2014

Application of Visual Imaging Correlation-2D to Strain Measurement

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

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JULY 27, 2014

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Acknowledgement

I would like to thank my advisor, Dr. Changfeng Ge for encouraging me to pursue this topic and providing me guidance and supports to accomplish my project.

I would like to thank Haoqi Huang for generously giving me help and being patient to answer my questions all the time. I would also like to thank the lab technicians, especially Baxter for assisting me to prepare samples and operate testing machines.

I would also like to thank my family back in China for their encouragement and support in driving me towards success.

Abstract

The Visual imaging correlation-2D is an innovative software application that can be used for strain measurement of different packaging materials. In recent years, Vic-2D has been increasingly utilized in packaging industry. It is able to break through certain technical limitations of traditional strain testing method and provide a comprehensive strain map that can be suitable for any case of mechanical testing and obtaining the most desired results in the shortest period of time.

In this study, tensile tests are conducted to compare operational performance and functional completeness of conventional mechanical analyzes software, BLUEHILL, with VIC-2D technique. Tensile test is a commonly used method for obtaining strain parameters and mechanical properties of packaging materials. During the test, two strain parameters, Poisson's ratio and tensile strength, are measured. Three different test objects are used: extrusion laminating and coating film (48g PET/Print/10# LDPE/48g Met PET/Pr/7# LDPE/5.0 mil LLDPE), HDPE dog-bone shaped specimen (6.5×0.8125×0.125 inches) and PP dog-bone shaped specimen (6.5×0.1825×0.125 inches).

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1. Introduction

In this chapter a brief review of the development in strain measurement of mechanical properties of packaging materials is presented. Visual Imaging Correlation-2D (VIC-2D) serves as the most innovative strain measurement software and it is introduced to compare with the traditional testing software, BLUEHILL. Due to functional limitation of conventional method and increasingly technical demands of testing tasks, certain advanced and comprehensive functions of Vic-2D such as providing two-dimensional graphical strain map for a specimen or developing plot for a single point in a specimen during deformation, are highly emphasized and recommended.

1.1 Background

It is generally recognized that mechanical properties of packaging materials are major concerns in quality testing, processing, transporting and storage control. Inappropriate materials selection may cause inestimable damage and loss of products. Therefore, to accurately determine the mechanical properties of packaging materials and structural components, it is extremely significant to acquire sufficient data through many different kinds of strain measurements.

People in the field of packaging science have developed a lot of testing methods for strain measurements to characterize the mechanical properties of materials, including tensile testing, compression testing, friction testing, drop impact testing and so on. Among them, tensile test with extensometer is one of the most commonly performed mechanical tests, from which some important material properties and parameters such as ultimate tensile strength, Young's modulus and Poisson's ratio can be determined.

To operate tensile test, a high-quality and fully functioned testing machine with proper capabilities is needed. Universal testing machine is the most prevailing testing machine used in tensile testing. It is able to precisely measure the gauge length and accurately control the speed and force level applied to the specimen to imitate the real world's application.

After the tensile test, testing data are immediately imported into a computer connected to the electronic sensor of universal testing machine and then manipulated and output by strain measurement software to calculate and determine materials properties of specimen.

The accuracy and integrity of testing results largely depend on the functional performance and the capability of presenting various demanding mechanical parameters of software application. The most commonly used strain measurement software application for universal testing machine is BLUHILL series. They work for many different types of testing methods and are able to provide diverse users' experience from changing system administration to determine testing output types to control graphic style and layout of testing results.

Although BLUEHILL is easy to manipulate and has been widely used in laboratory testing around the world, it is still not ideal for all cases with increasingly demands of more comprehensive data-analyze capabilities. When tensile test is condected, for example, it can't provide precision strain over entire area and is lack of data to stretched necking area. Furthermore, by fixing a sample between the clips, an additional force created by the testing machine has been added to the sample surfaces, which may cause damage to the sample and distort the strain measurement results. In order to solve these problems, an innovative technology, Visual Image Correlation (VIC), has been developed. It has several advantages such as non-contact, high precision for strain measurements over entire sample surface, full field, and provide graphical strain maps in both horizontal and vertical directions.

1.2 Visual Imaging Correlation Technique

The Visual image correlation is an optical method that uses a mathematical correlation analysis to examine digital image data taken while samples are in mechanical tests

(Ranson, 2003). This technique consists of capturing consecutive images with a digital camera during the deformation period to evaluate the change in surface characteristics and understand the variation of the specimen undergoing incremental force (Bruck, 2005). To start this method, we need to prepare a random dot pattern structure, which also called speckle pattern, on surface of the specimen. Then a picture is taken and serves as a reference image before loading. After this, a series of continuous pictures, commonly known as deformed pictures, are taken during the deformation process. All the deformed images show distinct random dot patterns that are different with the first reference image. By using computer software to record the differences between patterns and to correlate all the pixels of both the reference image and those of the deformed images, a full-field strain map is generated.

As compared to other optical strain measurement method, visual image correlation technique has many advantages as shown below.

- Easier to set up
- Simple light source requirement
- Lower handling ability
- Wider measurement range
- No extra concentrated force applied on specimen

1.3 Tensile test

Tensile test are significant in determining mechanical properties of materials for packaging engineering. Tensile properties, especially the strength of materials, are the priority concerns to estimate the performance of packaging materials undergoing different forms of tension coming from different directions during handling process, distribution and warehouse storage.

Tensile testing, also known as tension test, is a fundamental mechanical test commonly performed on materials to determine relative mechanical properties. Tensile test is easy to operate and fully standardized. By pulling a sample with a controlled tension until it breaks, the reaction under all types of forces of the sample will be calculated and recorded.

During tensile test, when a sample finally fractures and the point of failure that is often called ultimate tensile strength (UTS), can be directly measured. Other mechanical properties that can be directly obtained from tensile test include the amount of stretch, maximum elongation or reduction of area in the specimen. There are also many mechanical properties that can be calculated based on the results of tensile test such as Poisson’s ratio, yield strength, Hooke’s Law, Modulus of Elasticity, Young’s modulus and Alternate Moduli.

During the application of tension, the total deformation, specifically the elongation or stretch the sample bears, can be determined to calculate tensile strain**ε.** There is no unit for tensile strain because it is the ratio of the change in length to the initial length of the sample. Thus, we have the following equation:

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

whereεis the tensile strain, ΔL is the change in length, L0 is the original length, and L is the final length of the specimen. (Degarmo, 2003)

The prevailing testing method used for strain measurements in tensile test is to clip a sample to the extensometer of a universal testing machine. In this research, all HDPE dogbone-shaped specimens and PP dogbone-shaped specimens were used for tensile tests with a 4301 Series universal testing machine provided by INSTRON. All the extrusion laminating and coating films (48g PET/Print/10# LDPE /48g Met PET/Pr/7# LDPE/5.0 mil LLDPE) were used for tensile tests with a 5567 Series universal testing machine provided by INSTRON.

1.4 Poisson's ratio

If the material is stretched, it usually tends to contract in the directions transverse to the direction of stretching. This phenomenon is called the Poisson effect. Poisson's ratio is a measure of this effect. Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force (Siméon Poisson, 1813).

Assuming that the material is stretched or compressed along the axial direction (the x axis in the below diagram):

$$\nu = -\frac{d\varepsilon_{\mathrm{trans}}}{d\varepsilon_{\mathrm{axial}}} = -\frac{d\varepsilon_{\mathrm{y}}}{d\varepsilon_{\mathrm{x}}} = -\frac{d\varepsilon_{\mathrm{z}}}{d\varepsilon_{\mathrm{x}}}$$

Where ν is the resulting Poisson's ratio, $\varepsilon_{\mathrm{trans}}$ is transverse strain (negative for axial tension, positive for axial compression, $\varepsilon_{\mathrm{axial}}$ is axial strain (positive for axial tension, negative for axial compression).

This research is going to provide the result of how visual image correlation-2D can effectively calculate Poisson's ratio that is one of the most essential parameters of in-plane displacement and strain field measurements.

1.5 Objectives

In view of the increasingly utilization of Visual image correlation method for displacement measurement comparing with traditional optical methods in packaging application, the present study has the following objectives:

a) Collect tensile data by conducting tensile test for three plastic materials (HDPE, PP, laminated films) with conventional mechanical testing machine.

b) Evaluate tensile properties of three materials with traditional software BLUEHILL.

c) Evaluate the effectiveness of Visual Imaging Correlation-2D in strain measurement.

d) Compare the results obtained by VIC-2D with those obtained by BLUEHILL.

1.6 Scope of work

The present study aims at emphasizing the advanced functional achievements of Visual Image Correlation method for strain measurements comparing with the prevailing testing method, BLUEHILL. Tensile test was selected as strain test. Three plastic materials: HDPE, PP and laminated films were chosen for the tensile test. HDPE and PP sticks were standard testing samples without extra preparation. Laminated films were cut using JDC Precision sample cutter. (See Figure 1.1) In this study, the main tensile parameters were tensile strength and Poisson's ratio. The analyze results obtained from VIC were compared with those obtained from the traditional method.

2. Literature review

2.1 Development of Visual Image Correlation

In 1980, Visual image correlation (VIC) technique was first introduced by Dr. Ranson and Dr. Peters at the University of South Carolina. Since then DIC has been widely introduced and applied to diverse scientific fields with its capability of providing two-dimensional measurement results and large amount of user interactions.

In 1982, to increase the functional behavior and to adapt the scientific development, several improvements of VIC were made by Drs. Ranson, Peters and Sutton: Reasonable guess was required compared with the random guess of initial system; first PC version was also introduced with thirty minutes per point correlation rate. From 1986 to 1998, three-dimensional measurement method of VIC was developed with more effective functional completeness. Since then, with the application of VIC system, more complex calibration can be accomplished, various new functions such as distortion correction, visual initial guess generation and fast image analyze ability (1000 points per seconds) were widely welcomed and utilized. VIC system for PC application was evoving towards perfectly constructed.

2.2 VIC-2D and VIC-3D

Since 2003, the development of both two-dimensional and three-dimensional measurement system has reached the most maturity stage. Since then, Nano and micro measurement scale were achieved. The speed of correlation was incredibly increased such as 10,000 frames per second for High-speed correlation and 200,000,000 frames per second for Ultra-high speed correlation.

Both efficiency of correlation and accuracy of analyze of VIC have been highly enhanced.

2.3 Application of VIC to deformation measurement

During last decades, many fundamental applications of this method to various fracture mechanics testing can be found, including studies of fracture mechanics, high-temperature deformation measurement, wood products and inverse stress analysis. In recent year, this technique begins to be applied to the deformation measurement. Nowadays, the main application of VIC is in surface displacement and strain measurement of mechanical testing. Many reports of different types of applications of VIC method for two-dimensional and three-dimensional measurement of strain variation and surface deformation had been published.

The essential principle of visual image correlation in such kind of application depends on the capability of recognize the subtle difference of two images taken before and after the deformation by a solid-state digital camera. Then the strain variation of both images was found out based on the results of analyzing and correlating theses images by using the statistical functions of VIC. In Bruck's study of Newton-Raphson method, he mentioned that deformation of image speckles could be demonstrated by vertical distance and horizontal distance of two speckles after displacement, which is commonly known as strain. (See Figure 2.1).

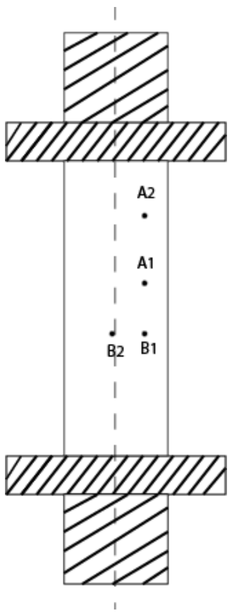

Figure 2.1 Speckle patterns

See equation below:

$$\varepsilon_{Ai} = \frac{l_{Ai} - l_{A0}}{l_{A0}}, \qquad \varepsilon_{Bi} = \frac{l_{Bi} - l_{B0}}{l_{B0}}$$

Where

ε_{Ai} is the vertical strain and

ε_{Bi} is the horizontal strain

l_{A0} and l_{B0} are the initial distance of A1,A2 and B1,B2.

l_{Ai} is the vertical distance of A1A2 and l_{Bi} is the horizontal distance of B1,B2.

This was the basis theory for calculating deformation by using speckles' displacement in VIC.

3. Materials and Methods

3.1 Materials

Three different materials were selected to verify how effectively Vic-2D could accomplish strain measurement of tensile test.

3.1.1 Dog-Bone shaped specimen

Figure 3.1 Example of Dog-Bone shaped specimen

In this study, dog-bone shaped samples were used for tensile test. (See figure 3.1) The unique shape of dog bone specimen was specially designed, which was ideal for mechanical strength testing. Instead of a straight piece, it consists of a narrow mid-section to easily attach the two wide ends into a testing device and to maximum avoid extra reinforce created when conducting tensile test.

3.1.2 HDPE (High Density Polyethylene)

Figure 3.2: HDPE dog-bone shape specimen

HDPE (High Density Polyethylene) is a common packaging material that is often used in the production of plastic container such as beverage bottle, milk jugs and shampoo bottle. It has large strength to density ratio and is able to be recycled. In this study, 6.5×0.8125×0.125 inches HDPE dog-bone shape specimens are used. All specimens are standard testing size without extra cut. (See Figure 3.2)

3.1.3 PP (Polypropylene)

Figure 3.3: PP sticks

PP (Polypropylene) is a thermoplastic polymer that has been widely used in packaging industries. PP has excellent elasticity and flexibility and it is often translucent when no color added.

In this study, 6.5×0.1825×0.125 inches Polypropylene (PP) dog-bone shape specimens were used. All specimens were standard testing size without extra cut. (See Figure 3.3)

3.1.4 Laminated film

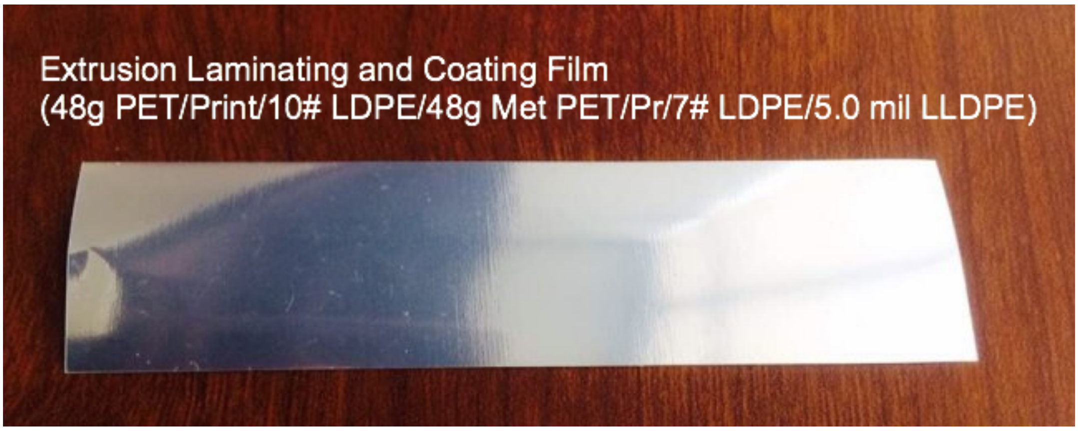

Figure 3.4: Extrusion laminating and coating films

In this study, laminated film samples were also used. The sequence of mechanical processing included press, extrusion, curing and curing. During extrusion, films had been one-side printed and laminated. The final structure of this film samples were 48g PET/Print/10# LDPE/48g Met PET/Pr/7# LDPE/5.0 mil LLDPE.

Each sample had been cut into 2x4 inches. All laminated film samples were cut using JDC precision sample cutter. (See Figure 3.5)

Tensile test were performed with 2 x 4 inches extrusion laminating and coating films (48g PET/Print/10# LDPE/48g Met PET/Pr/7# LDPE/5.0 mil LLDPE), 6.5×0.1825×0.125 inches HDPE dog-bone shaped specimens and 6.5×0.1825×0.125 inches PP dog-bone shaped specimens. (See Figure 3.4)

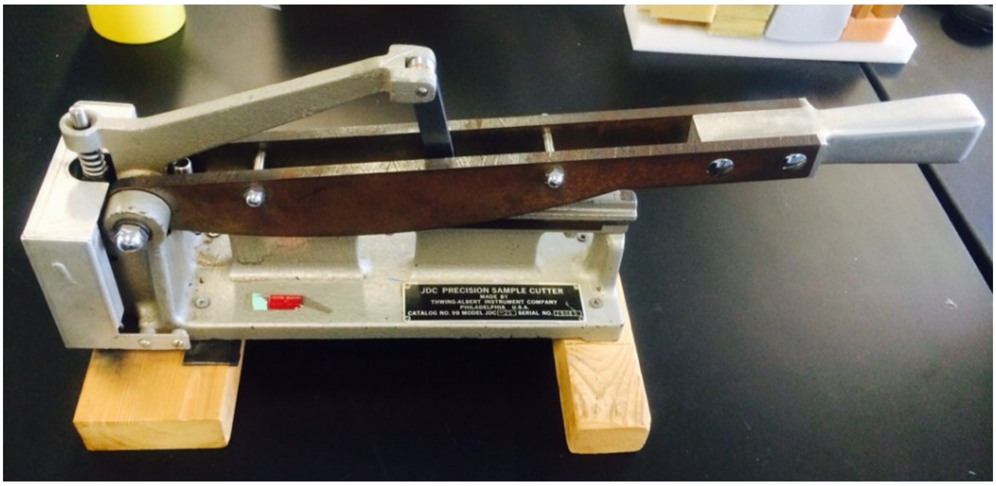

Figure 3.5: JDC Precision sample cutter

3.2 Tests and Parameters

In tensile test, tensile strength and Poisson's ratio were selected as two important test parameters to evaluate the analytical performance of Visual Imaging Correlation.

3.3 Tensile test machine

In this research, all the Polypropylene (PP) and High Density Polyethylene (HDPE) dog-bone shaped specimens were subjected to tensile tests with a 4301 Series universal testing machine provided by INSTRON (See Figure 3.6). All the extrusion laminating and coating LDPE film samples were subjected to tensile tests with a 5567 Series universal testing machine provided by INSTRON (See Figure 3.7).

Figure 3.6: 4301 testing machine

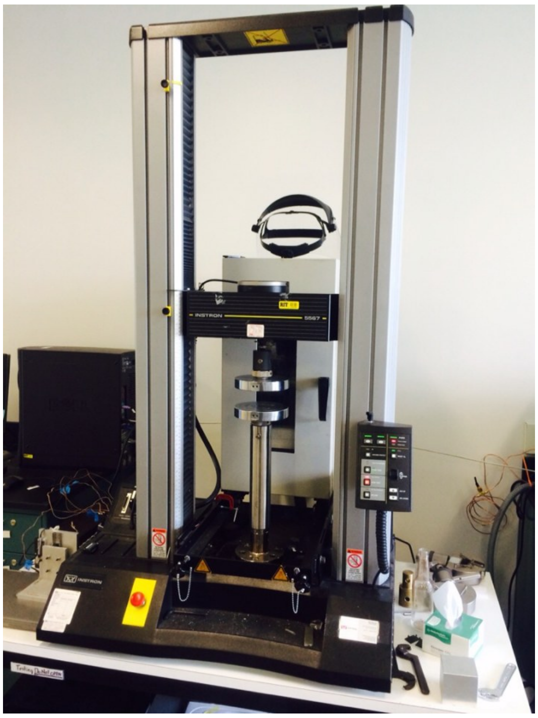

Figure 3.7: 5567 testing machine

3.4 Methods for strain measurement

Two software applications were used for strain measurement. One was BLUEHILL, to which testing data can be directly imported and strain measurement can be calculated and exported as word files simultaneously while performing the tensile test. The other one was Visual image correlation-2D (VIC), based on digital image correlation technique. The principle of this technique is to analyze the images of the specimen taken during the deformation process and then to evaluate the data of contour and strain. Functional effectiveness of these two methods had been compared and discussed. Several advanced features of visual image correlation-2D technique were introduced.

3.4.1 BLUEHILL Software

BLUEHILL is the most prevailing data collective software used for universal testing machine to analyze strain properties. After connecting to electronic sensor of testing machine, test results can be provided graphically and tabular and automatically saved as a word file, which is convenient for later editing.

Before start testing, dimensions of specimen and testing rate needed to be determined. There were many methods for different types of testing. Dell_409_Lab_Winter_2009.im_tens was used for testing HDPE and PP sticks samples, testing rate was 50.00000 mm/min. For composite laminated films samples, testing rate is 19.68504 in/min and testing temperature and humidity are shown below.

Table 3.1: Testing temperature and humidity for LDPE film

Number Inputs: Ambient Temperature	22.0
Number Inputs: Relative Humidity	61.5

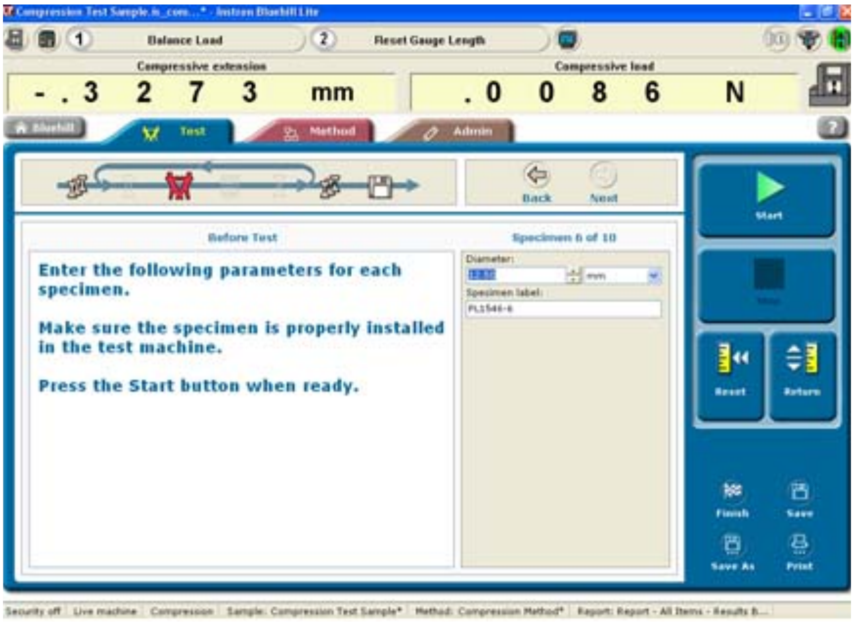

Figure3.8： Testing method in BLUEHILL

3.4.2 VIC-2D

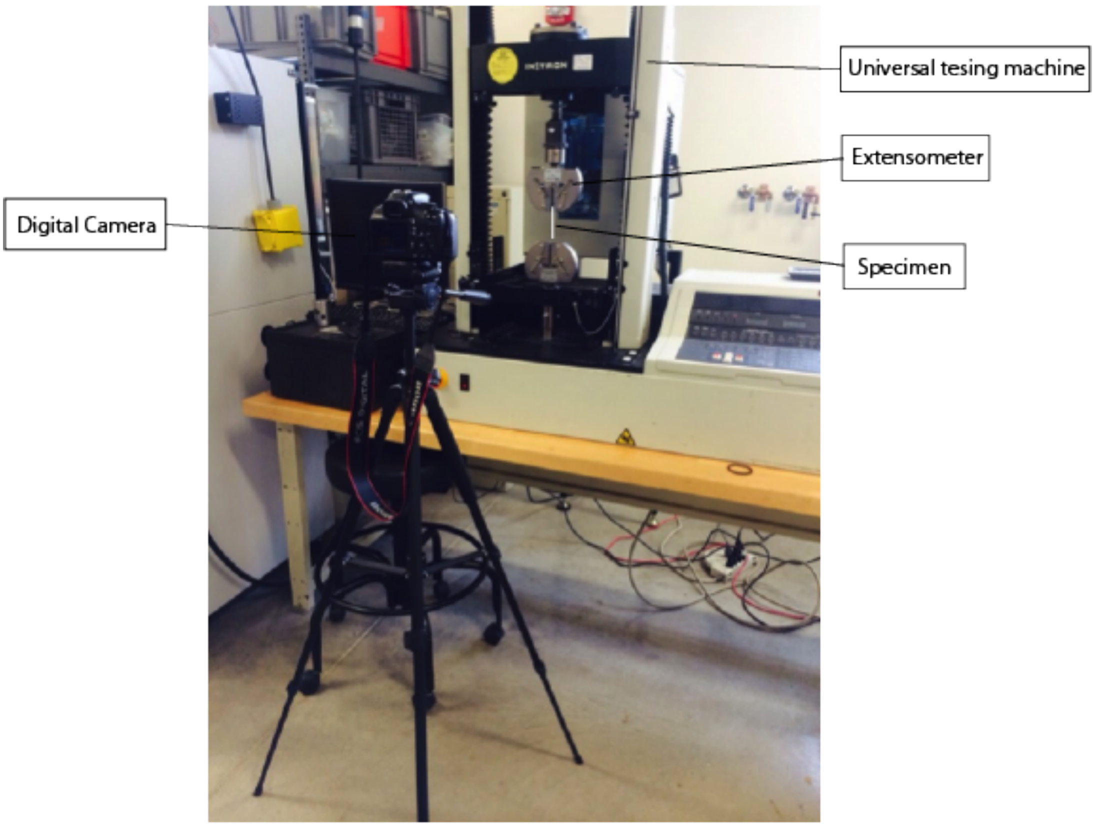

Figure 3.9: Visual imaging correlation-2D setup

In two-dimensional Visual image correlation, deformations were directly observed from digital images of the surface of the sample. The equipment consists of software installed on a data collective device and a high-definition digital camera with appropriate lens and resolution to record motion graphic during deformation process. Adequate light source was necessary to capture accurate data. A reference picture on the surface of specimen was taken before starting the test and then consecutive images were recorded during the deformation process. The setup of VIC-2D experiment is shown in Figure 3.9.

3.4.2.1 Camera setup

Figure 3.10: Canon's 550D

In VIC-2D setup, Canon's 550D high-speed digital camera was used. (See Figure 3.10) This camera performs excellent frame rate motion capture combined with high resolution and high-quality lens. It was also able to continuously take pictures with selectable shooting rate during the deformation period, which was ideal and essential for VIC-2D application. During the deformation, images were taken every 0.5 second. Table 3.1 is the settings for the camera.

Table 3.1: Settings for the camera

Aperture	F 2.0
Frame Rate	25 fps
Image resolution	1920x1080

Clear and high-resolution photos were required to obtain accurate strain measurement from Vic-2D system. To achieve this, aperture range of the lens with lower F-value needs to be set in order to allow the entrance of more light. Beside, digital camera must be fixed in an accessible position with appropriately adjusted focal length, from which the calibration area on the images was taken large enough to observe on the screen of a computer. Figure 3.10 shows the example of clear speckle patterns that was shown on the screen.

An adjustable tripod was highly recommended to guarantee that the digital camera was on the same height with and was close enough to the specimen. In this study, Sunpak PlatinumPlus 5858D' s 58" tripod bought from Best Buy was used. (See Figure 3.11)

Figure 3.11: Clear speckle patterns on the specimen

Figure 3.12 Sunpak PlatinumPlus 5858D' s 58" tripod

3.4.2.2 Speckle pattern

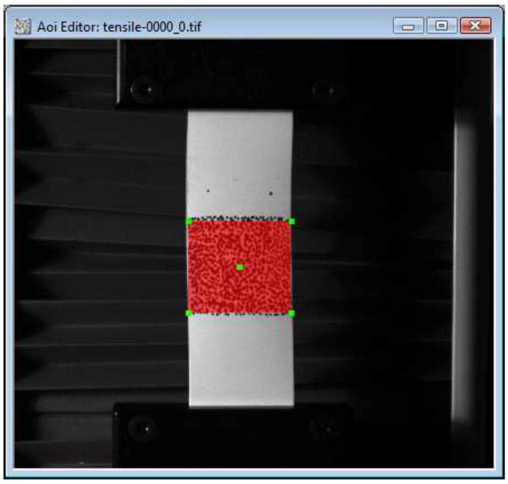

Figure 3.13 Area of interest (AOI)

In VIC-2D measurement, an area of interest (AOI) was chosen to indicate the specific point used to measure displacement during deformation period. (See Figure 3.13) A proper speckle pattern was essential to define the area of interest. If speckle pattern was not naturally occurring due to the types of materials, it was also manually applied with no orientation determined. The ideal speckle pattern should be random and isotropic to obtain more indicative results.

In this experiment, all speckle patterns were applied with black paint by using a black thick marker pen. Three painting methods had been tried and the best one was selected based on the results of analysis. Figure 3.14 and Figure 3.15 are both dots pattern with different density. Figure 3.16 and Figure 3.17 show the pattern of Vertical line and horizontal line, respectively.

Figure 3.14: Dots Pattern 1

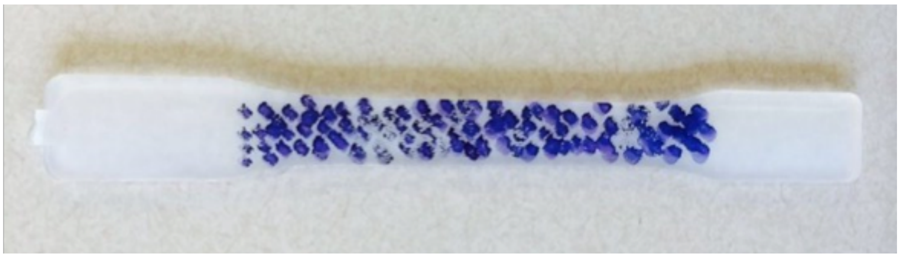

Figure 3.15: Dots Pattern 2

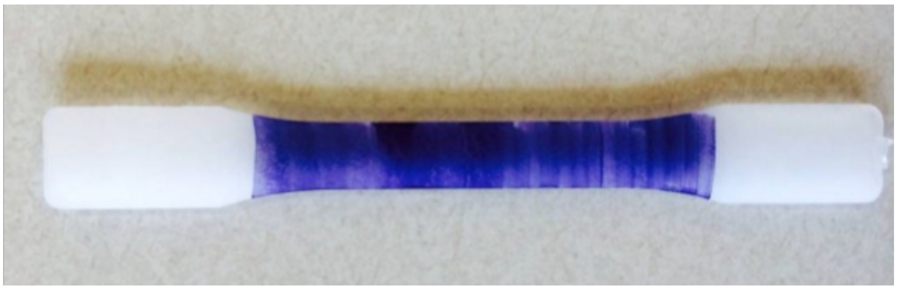

Figure 3.16: Vertical Line Pattern

Figure 3.17: Horizontal Line Pattern

Dots pattern was over scattered due to the thickness of the head of marker and both center point and subsequent points of area of interest were consequently difficult to define. Even the area of interest could be recognized on the reference image, it was still highly possible to get disconnected later during image-analysis process because of the vague boundary between scattered dots.

Line patterns in both vertical and horizontal direction had adequate density and random linear variation. The area of interest can be easily localized and continuously captured during the whole analysis process. In this study, dense line patterns were used.

3.4.2.3 Operation of VIC-2D

After finishing the deformation, all the pictures taken during the tensile test to be opened in the Vic-2D. During the correlation the number of points correlated, the analysis time, an average match confidence and average iterations was shown for every image. (See Figure 3.18)

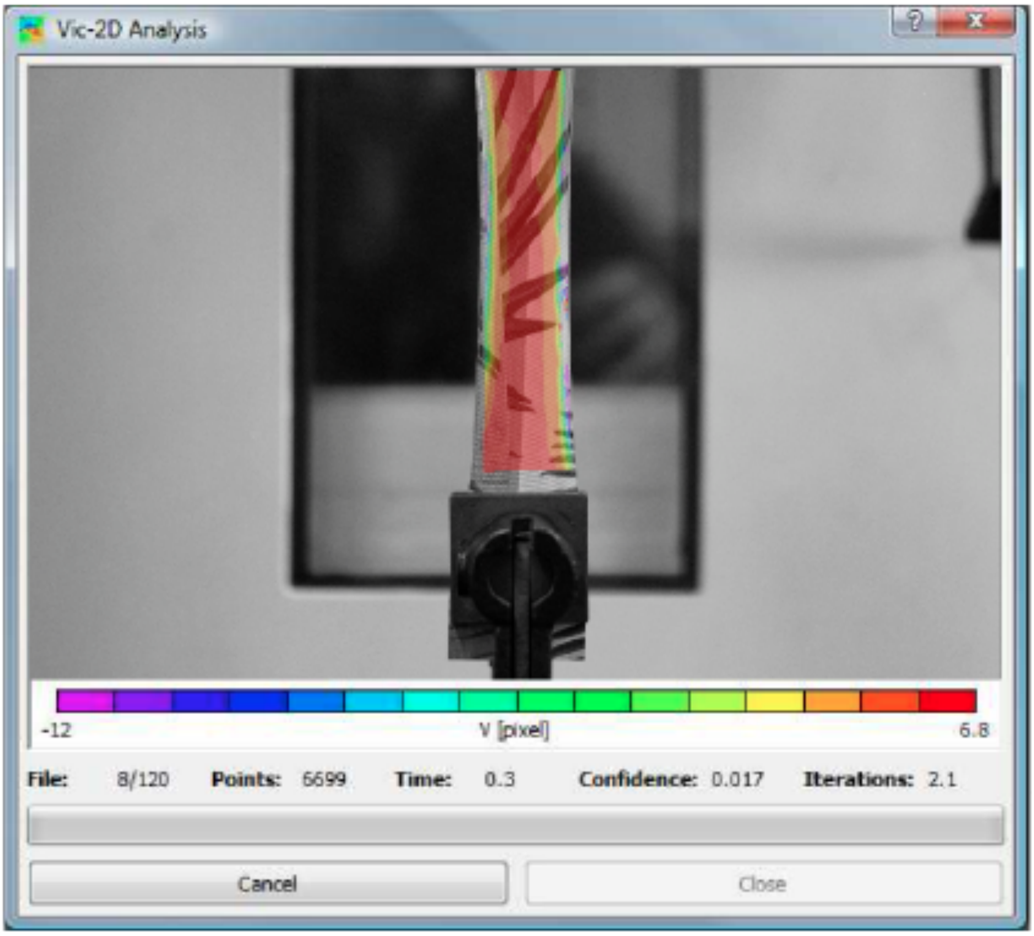

Figure 3.18: VIC-2D Analysis

When the correlation was finished, calibrate the true length of testing area on reference image. True length was the actual testing area on specimens. The true length of the HDPE and PP dog-bone shaped sample was 4.5 in and the true length of the LDPE film sample is 2 inches. The red line shows in Figure 3.19 is the length of calibration area.

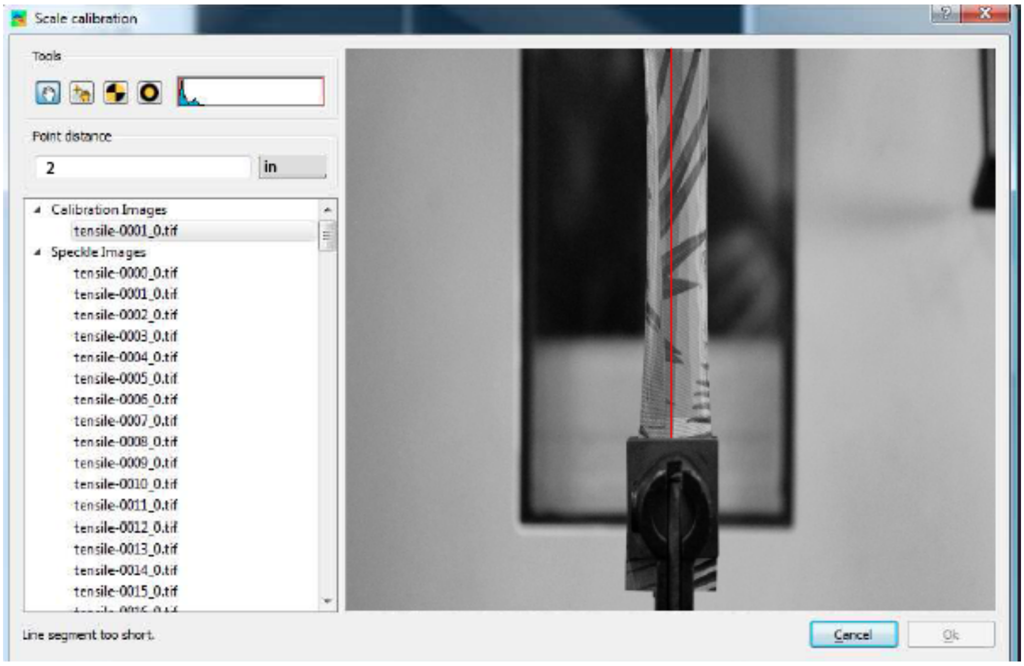

Figure 3.19: Calibrate for scale

The scale and aspect ratio of camera were automatically calculated. Figure 3.20 shows the example of calibrated scale and aspect ratio.

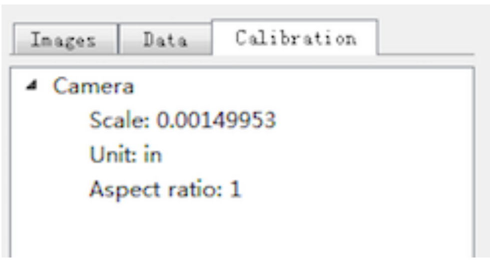

Figure 3.20: Calibration

VIC-2D was able to calculate several different variables based on the specific testing requirements. The available variables are listed below in table 3.2.

Table 3.2: Available variables in VIC-2D

x [pixel]	location on x direction
Y [pixel]	location on y direction

u [pixel]	transversal displacement
v [pixel]	axial displacement
Sigma [pixel]	Confidence interval for the match location
exx	the strain in X
eyy	the strain in Y
exy	the shear strain
e1	the major principal strain
e2	the major principal strain
gamma	The principal grain angle

After calibration, the contour map for each image was displayed. Contour variables were selected to present from submenu. (See Figure 3.21)

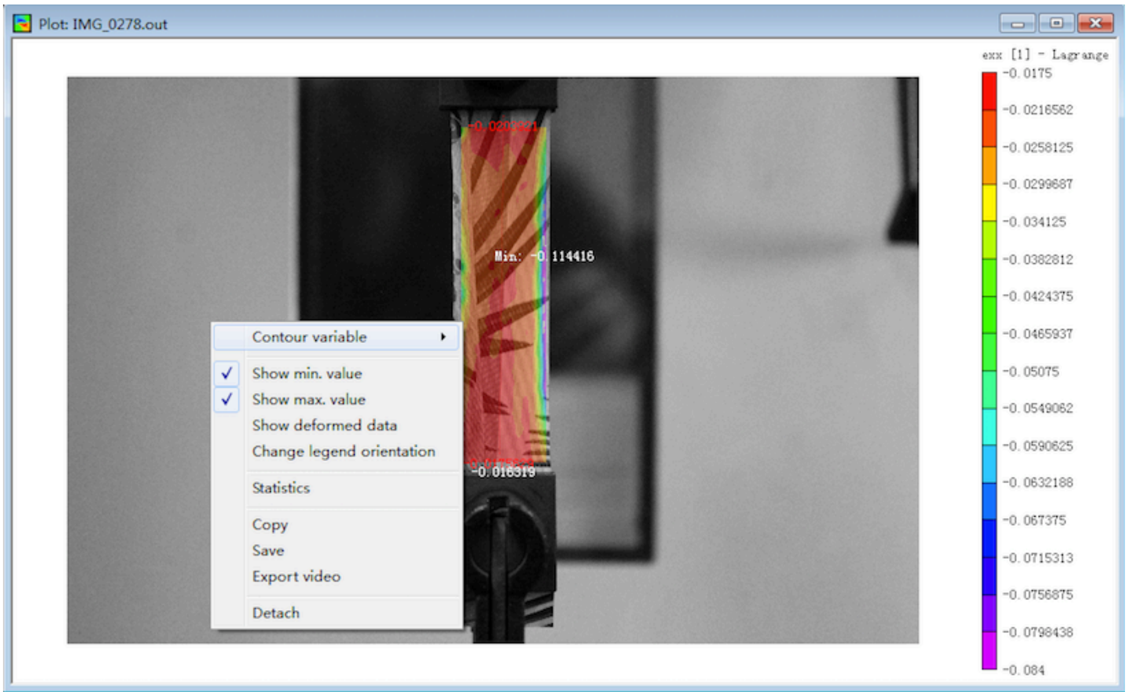

Figure 3.21: Select contour variables from submenu

Variables and value range were also be adjusted by using plotting tools. Figure 3.22 shows the plotting tools settings.

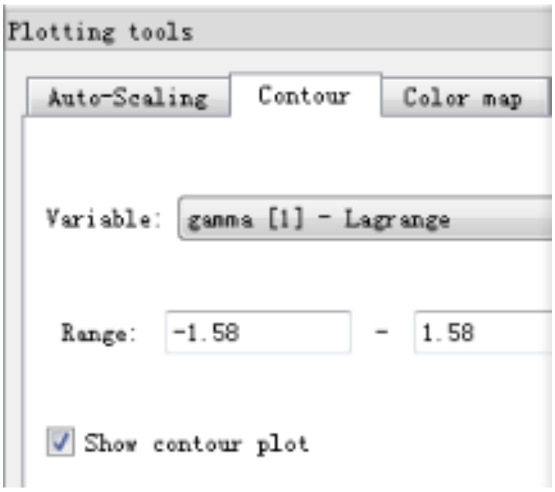

Figure 3.22: Example of plotting tool

During analyzing time, strain computation was automatically processed. Several strain variables and algorithms were available to recalculate strain and to be added in the exported data set. VIC-2D was capable of either calculating strain for all images or showing the effect on a single image by simply adjusting settings. Figure 3.23 shows strain computation of horizontal strain of laminated film sample.

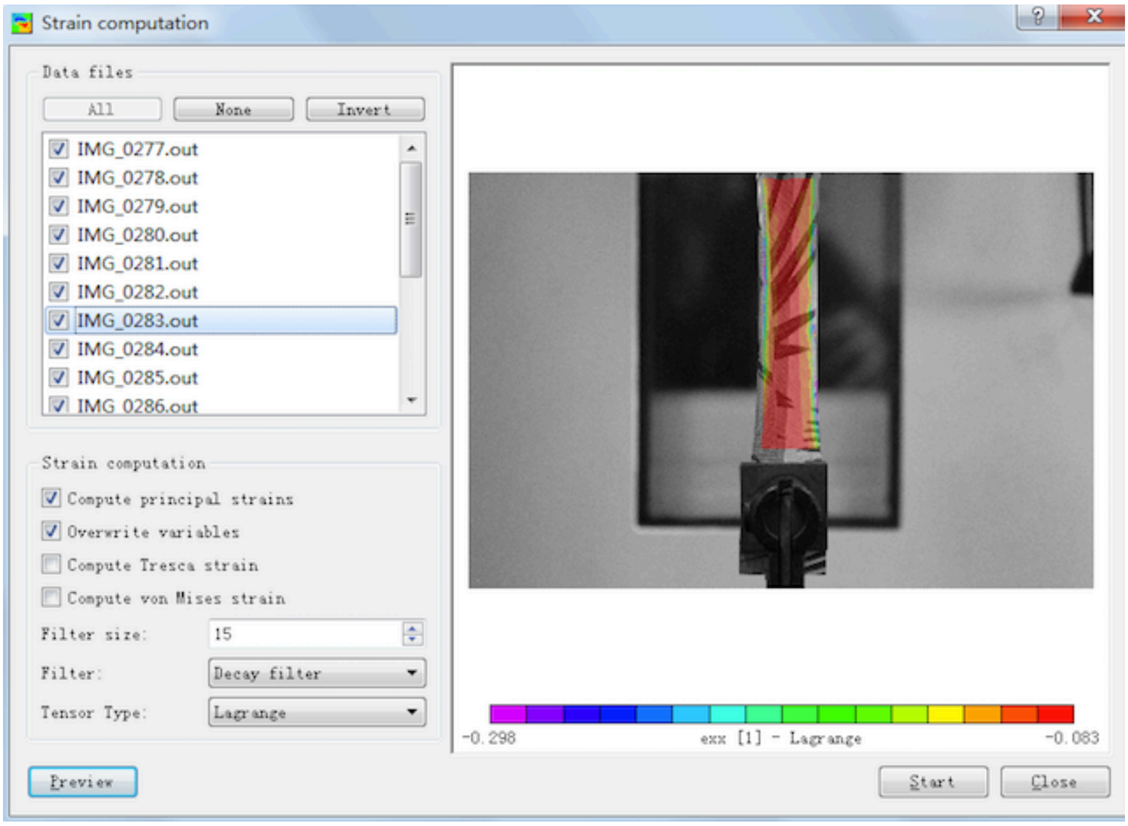

Figure 3.23: Strain computation of horizontal strain of LDPE sample

When the analysis was done, displacement and strain maps in any deformed image can be shown in Vic-2D software. Also, all the deformed image maps in sequence can be shown as a motion graphic.

4 Results and discussion

In this chapter, functional effectiveness of BLUEHILL and visual image correlation-2D are demonstrated and compared by analyzing tensile test data of three different kinds of materials.

Tensile strength and Poisson's ratio are selected as two significant parameters for strain measurement.

Several new features and advanced applicability of VIC-2D that can carry out more accurate and comprehensive testing results, are particularly introduced and emphasized.

4.1 Test results from BLUEHILL

4.1.1 Strain-Stress curve

In order to determine the optimal position for camera set-up, including suitable focal length, right light source and the best distance between camera and specimen, several experimental test were conducted before the tensile test of three materials was finally preceded. Three tensile tests were run for each material.

The data from universal testing machine were plotted on different graphics according to the materials. The stress-strain curves of each test of three materials directly obtained from BLUEHILL software are shown as below. Figure 4.1 and Figure 4.2 show the three tests for the HDPE and PP samples, respectively. Figure 4.3 show the test results of the extrusion laminating and coating film (48g PET/Print/10# LDPE/48g Met PET/Pr/7# LDPE/5.0 mil LLDPE) samples. The area, maximum load, tensile strength at maximum load and tensile strain at Yield of HDPE, PP and laminated film for each test obtained from BLUEHILL are listed in Table 4.1, Table 4.2 and Table 4.3. Average value was calculated.

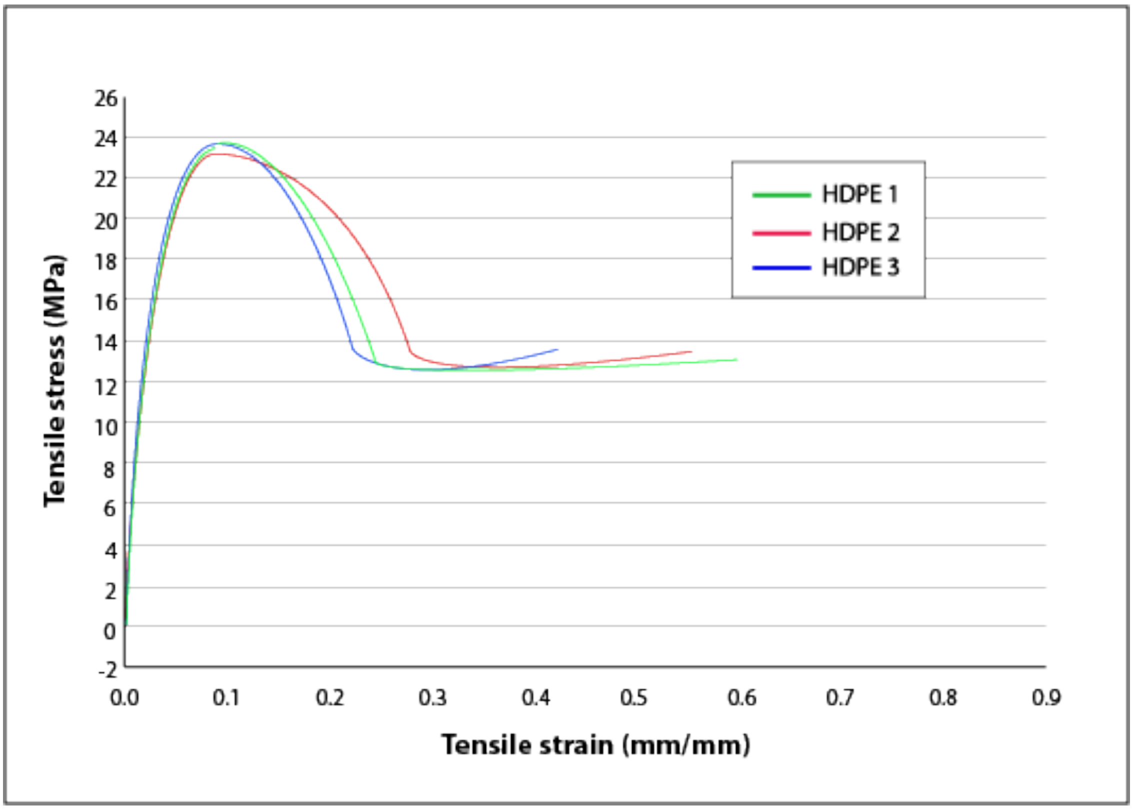

Figure 4.1: Stress vs. Strain curves of the HDPE samples.

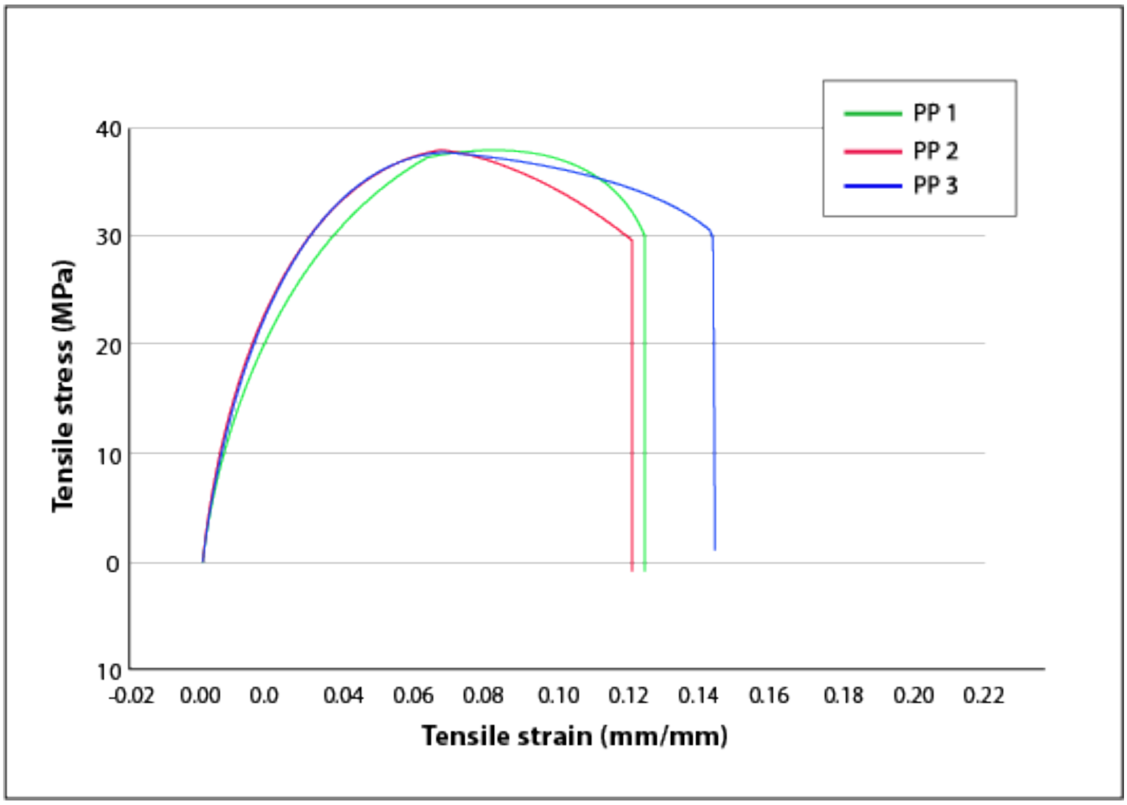

Figure 4.2: Stress vs. Strain curves of the PP samples.

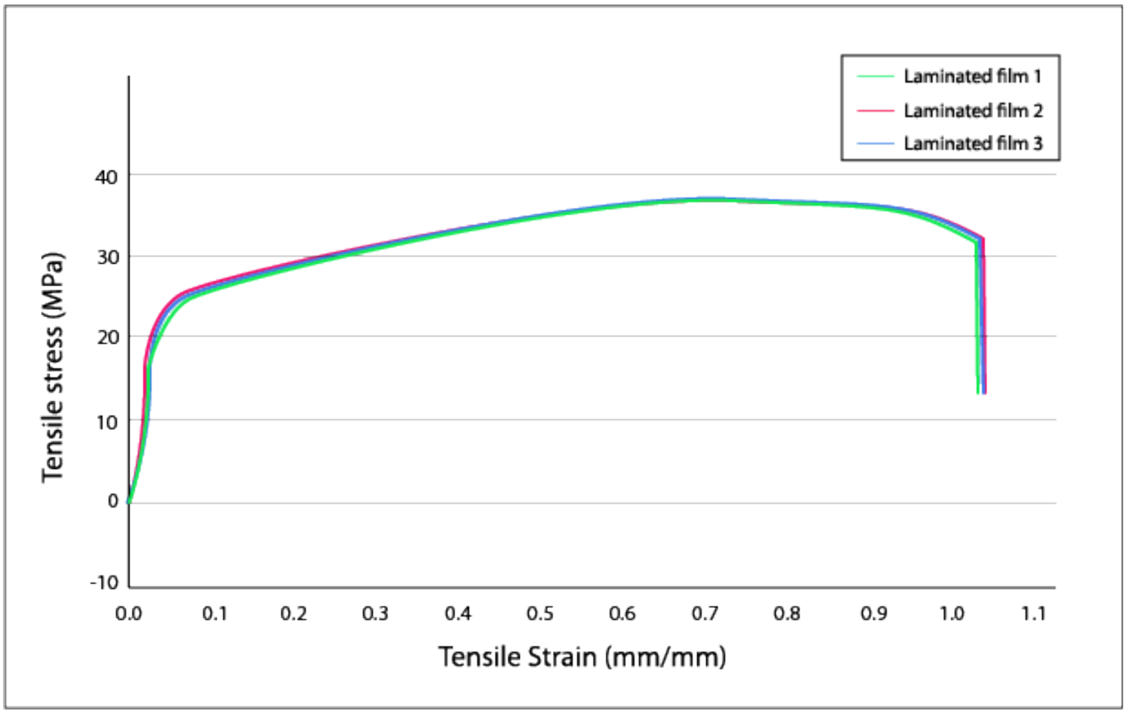

Figure 4.3: Stress vs. Strain curves of laminated film samples.

4.1.2 Tensile properties

Table 4.1 Tensile strain measurement of HDPE sample

Test No.	Area (in^2)	Maximum Load (N)	Tensile strain at Yield (offset 2%) (mm/mm)	Tensile stress at Yield (Mpa)
1	0.06188	939.797	0.08793	23.542
2		975.023	0.08737	24.424
3		919.496	0.09159	23.033
Average	0.06188	944.772	0.08896	23.666

Table 4.2 Tensile strain measurement of PP sample

Test No.	Area (in^2)	Maximum Load (N)	Tensile strain at Yield (offset 2%) (mm/mm)	Tensile stress at Yield (Mpa)
1	0.06188	1512.986	0.07784	37.901
2		1483.730	0.06462	37.168
3		1503.436	0.06847	37.661
Average	0.06188	1500.050	0.07031	37.576

Table 4.3 Tensile strain measurement of laminated film sample

Test No.	Area (in^2)	Maximum Load (N)	Tensile strain at Yield (offset 2%) (mm/mm)	Tensile stress at Yield (Mpa)

1	0.075	819.015	0.05570	35.29901
2		839.736	0.04659	36.63591
3		800.979	0.05640	35.38094
Average	0.075	819.910	0.05289	35.77195

4.2 Test results from VIC-2D

4.2.1 Necking area

For each test, there were approximately 50 to 60 images taken during the deformation period. The pictures were captured simultaneously from the beginning of loads increment of extensometer until the necking area showed up on the surface of samples as shown in Figure 4.4.

Figure 4.4: Necking areas show on HDPE (left), PP (middle) and laminated film(right)

The necking area showed up on laminated film was not as obvious as other two materials due to the strong ductility of film materials.

4.2.2 Two-dimensional Strain maps

In VIC-2D software, there were a lot of different types of strain values that can be monitored based on specific tests' requirements. Corresponding two-dimensional strain maps of sample images taken during deformation process were respectively generated on each image. After analyzing all sample images, an animation of integrated strain maps of deformation during the stretch period of specimen was created and exported as a video format. In our test, normal strain in the horizontal (X direction) and vertical (Y direction) axis was determined.

Samples' strain variation occurred during deformation process was demonstrated by a range of colors in strain maps. In the strain maps, positive strain values indicated tension while negative strain values indicated compression. For tensile strain, the highest value was represented by the red color and the lowest value was illustrated by the purple color. Oppositely, for compressive strain, the highest value was represented by the purple color and the lowest value was illustrated by the red color.

In both x and y axis of each material, three pictures represented three important states of specimens undergoing incremental loading during tensile test were extracted from the deformation animation. They were illustrated on the separate graphics according to the strain directions of each material. Three pictures were extracted at 1 second, 3 seconds and 6 seconds, representing the beginning of the test, force concentration around necking area and the appearance of necking area.

Figure 4.5 and Figure 4.6 demonstrate the variation of normal strain values of HDPE in x and y direction at different time interval respectively.

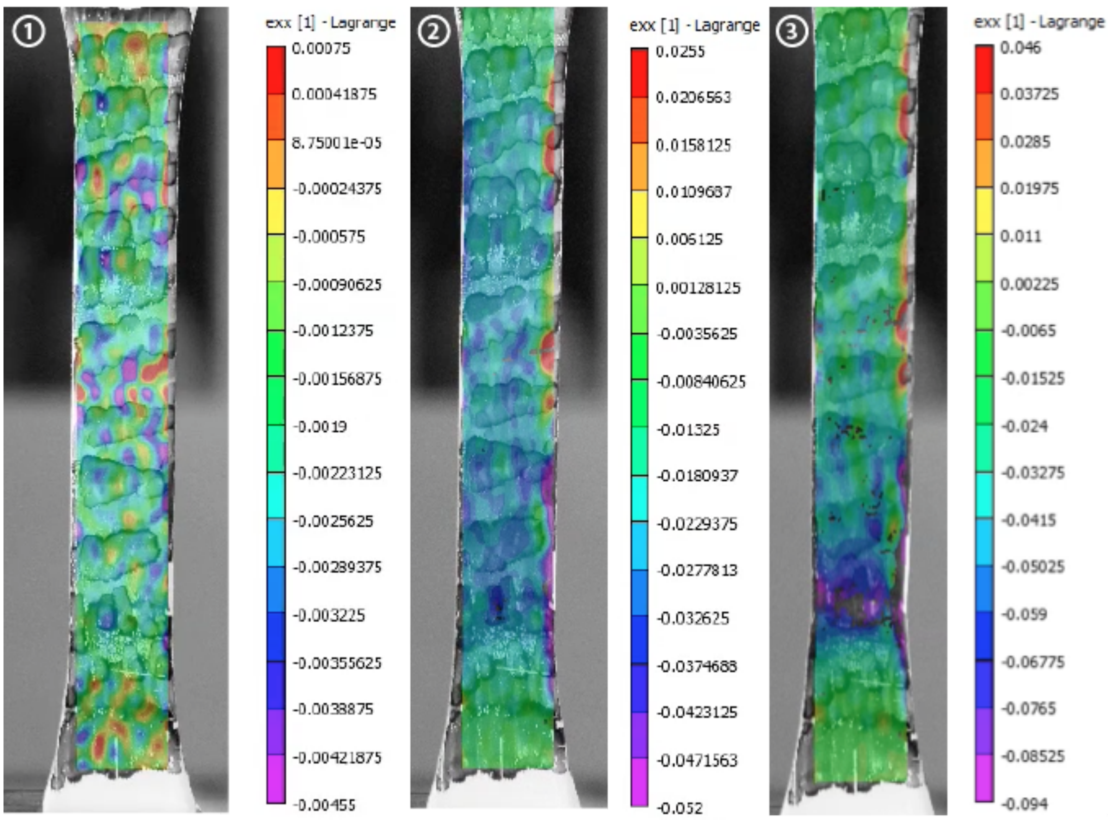

Figure 4.5: Horizontal (X direction) strain variation of HDPE.

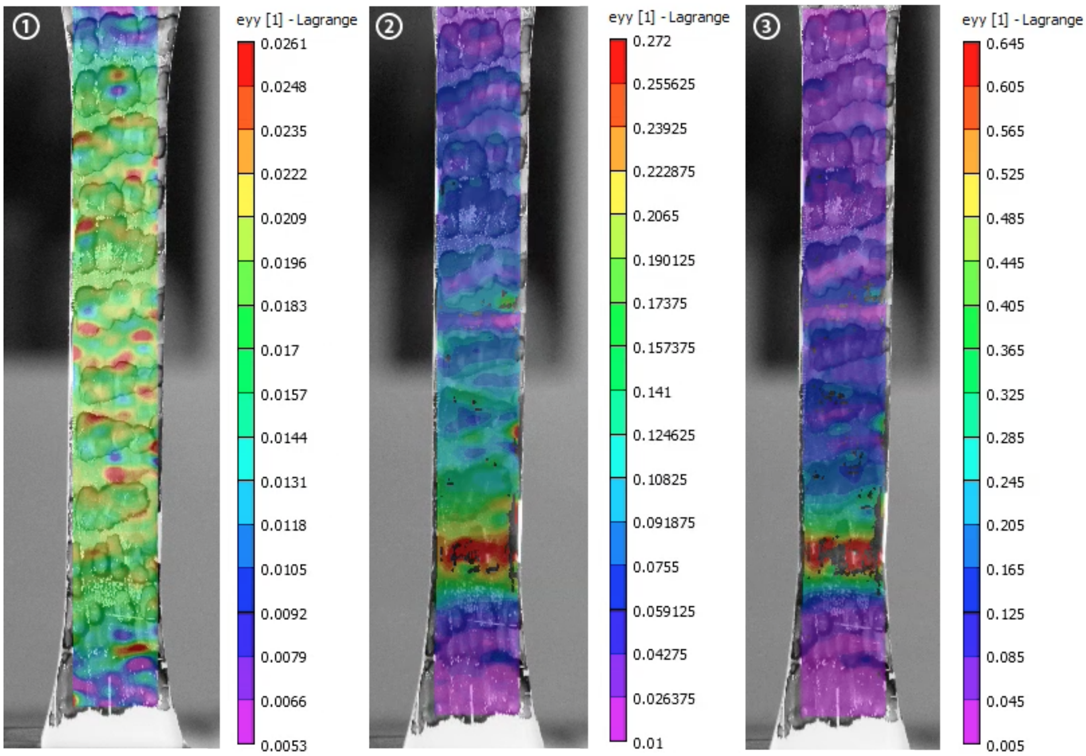

Figure 4.6: Vertical (Y direction) strain variation of HDPE.

Figure 4.7 and Figure 4.8 show the variation of normal strain values of PP in x and y direction at different time interval respectively.

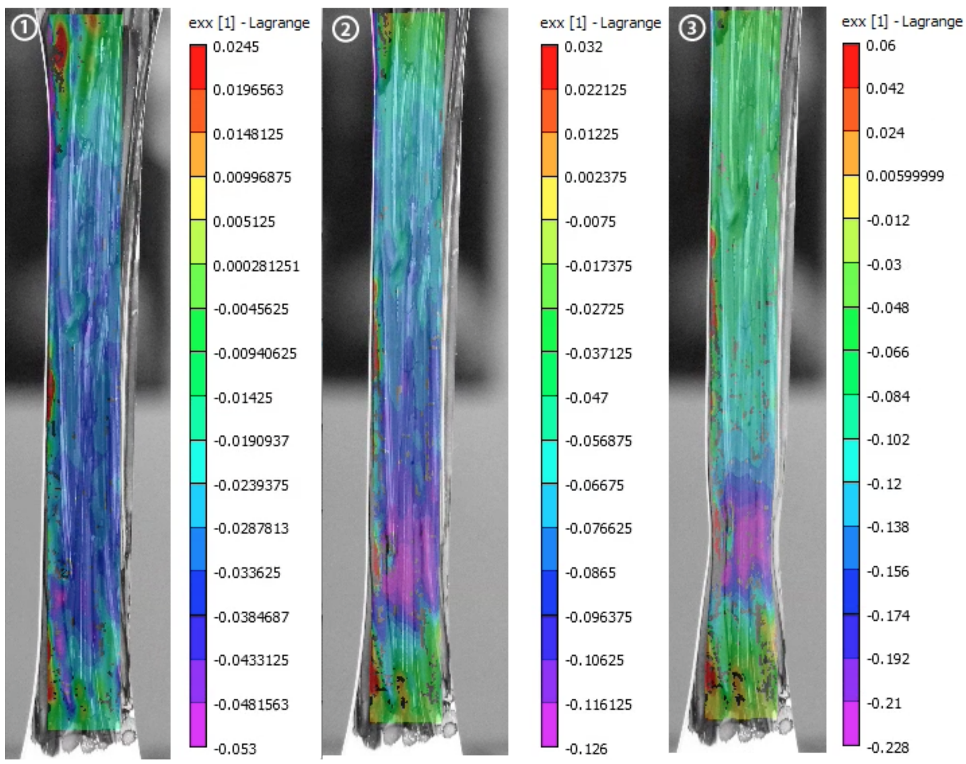

Figure 4.7: Horizontal (X direction) strain variation of PP.

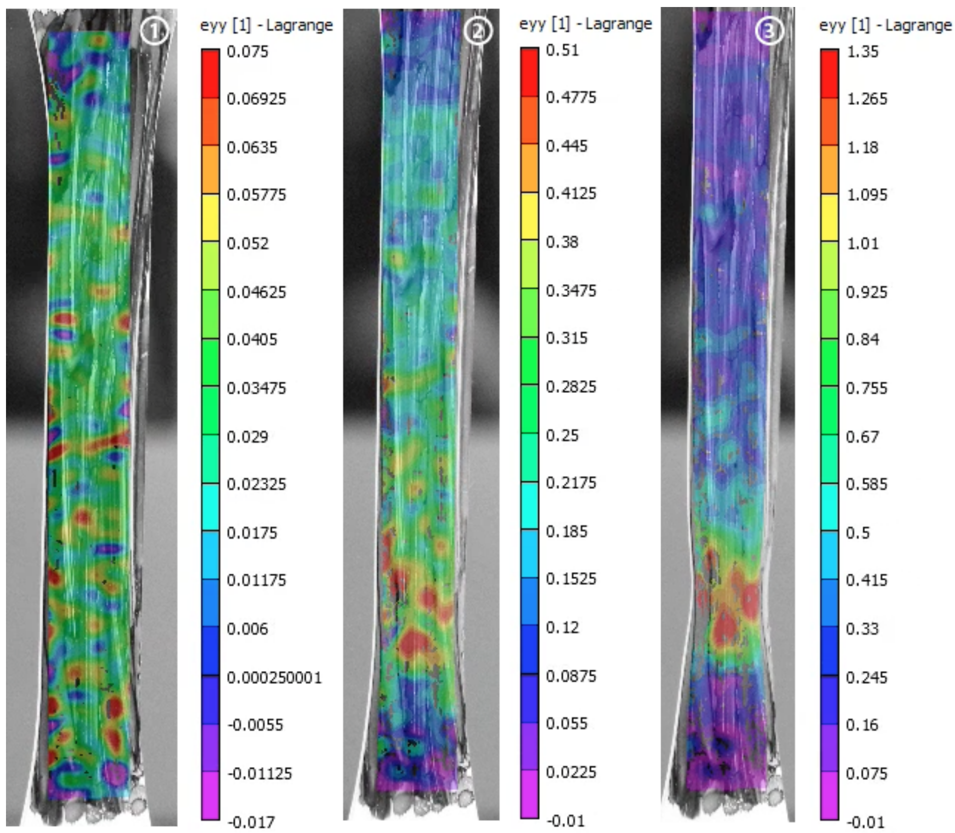

Figure 4.8: Vertical (Y direction) strain variation of PP.

Figure 4.9 and Figure 4.10 show the variation of normal strain values of laminated film in x and y direction at different time interval respectively.

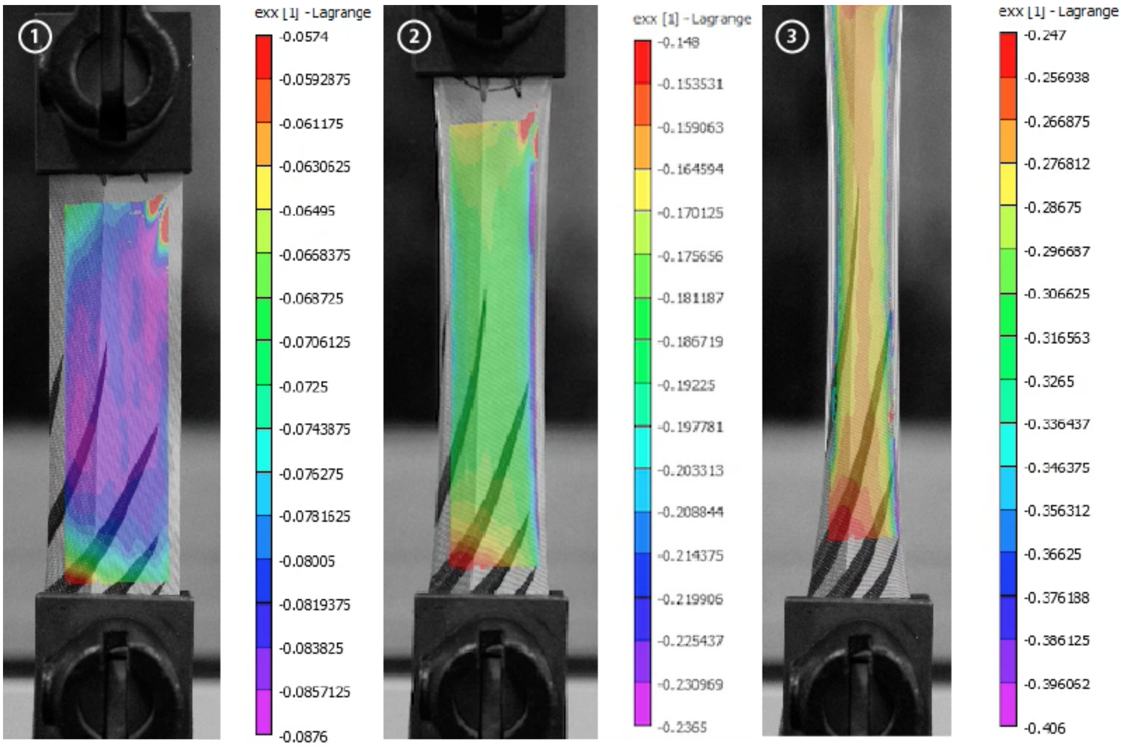

Figure 4.9: Horizontal (X direction) strain variation of laminated film.

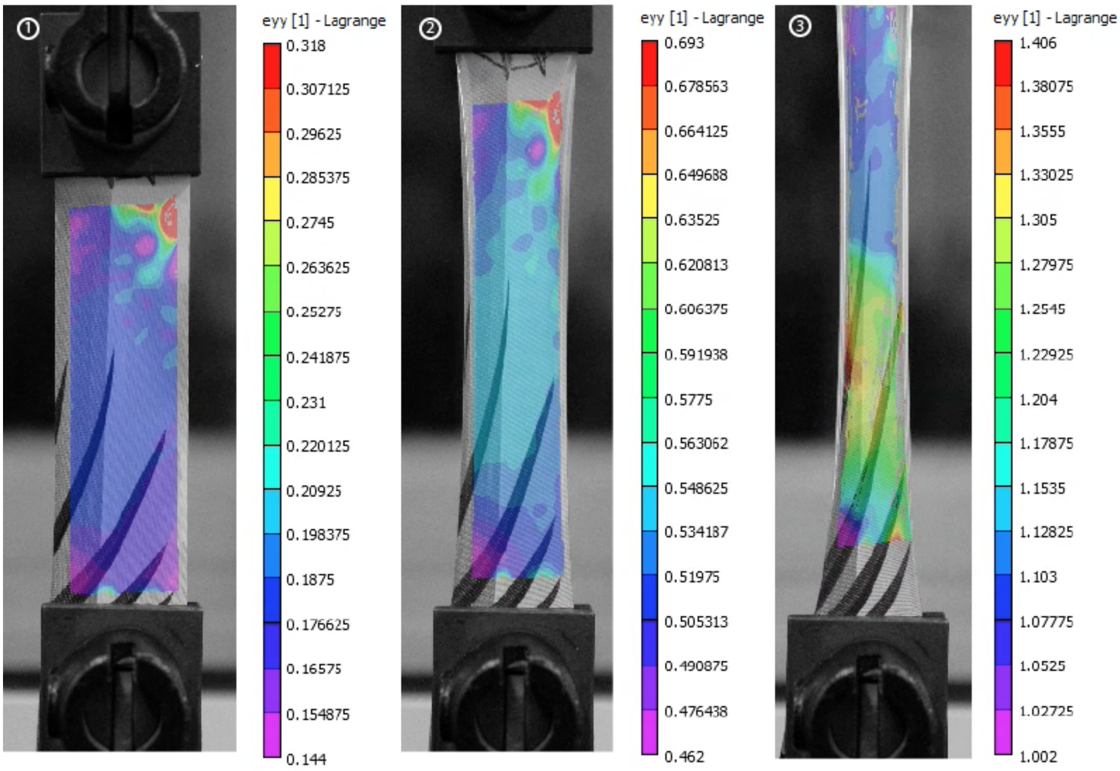

Figure 4.10: Vertical (Y direction) strain variation of laminated film.

4.2.3 Strain measurement

The strain values were exported to Excel document files from VIC-2D. Both the horizontal (X direction) and vertical (Y direction) strains of three tests for each material were calculated to compare the results of VIC-2D with those calculated by BLUEHILL later. The average value was calculated. Results are shown as below in Table 4.4, Table 4.5 and Table 4.6.

Table 4.4： Tensile Strain at yield of HDPE obtained from VIC-2D

Test NO.	Horizontal Strain (X direction)	Vertical Strain (Y direction)
1	-0.09785	0.03886
2	-0.09213	0.03661

3	-0.09776	0.03754
Average	-0.09591	0.03831

Table 4.5： Tensile strain at yield of PP obtained from VIC-2D

Test NO.	Horizontal Strain (X direction)	Vertical Strain (Y direction)
1	-0.07734	0.02977
2	-0.07623	0.02858
3	-0.07441	0.02439
Average	-0.07599	0.02551

Table 4.6: Strain measurement of laminated film obtained from VIC-2D

Test NO.	Horizontal Strain (X direction)	Vertical Strain (Y direction)
1	-0.05817	0.02117
2	-0.05662	0.02021
3	-0.05134	0.01874
Average	-0.05537	0.01994

4.2.4 Poisson's Ratio

The average strain values and the proportion between the horizontal and vertical strains of three tests presented in each strain map according to each sample images taken during the deformation process were used to determine the Poisson's Ratio of each materials.

$$\mu = -\frac{\varepsilon_h}{\varepsilon_v}$$

where μ is Poisson's ratio, ε_h is the horizontal strain, ε_v is vertical strain. (Siméon Poisson, 1813).

In tensile test, horizontal strain is negative because samples undergo compression in x direction. Table 4.7 shows the Poisson's Ratio of each material obtained in the VIC-2D as below.

Table 4.7: Poisson's Ratio of calculated by VIC-2D

Materials	Poisson's Ratio
HDPE	0.40
PP	0.34
Laminated film	0.36

4.2.5 Strain plot

Initial data extracted from VIC-2D can be reduced and demonstrated in two-dimensional contour plots from any of the available variables, strain measurement in both vertical and horizontal direction of each material were presented more visually. Figure 4.11 to Figure 4.16 show the strain plot in both horizontal and vertical direction for each material. The number of points along the line extracted form data file was reduced to ten. Point index refers a systematic computation to present the displacement or location variation of data points extracted from a sequence of data files on one certain image during the testing period. The initial distance and deformed distance are all included to output the ratio of point index and pixels. (1 point index equals 21.6 pixels)

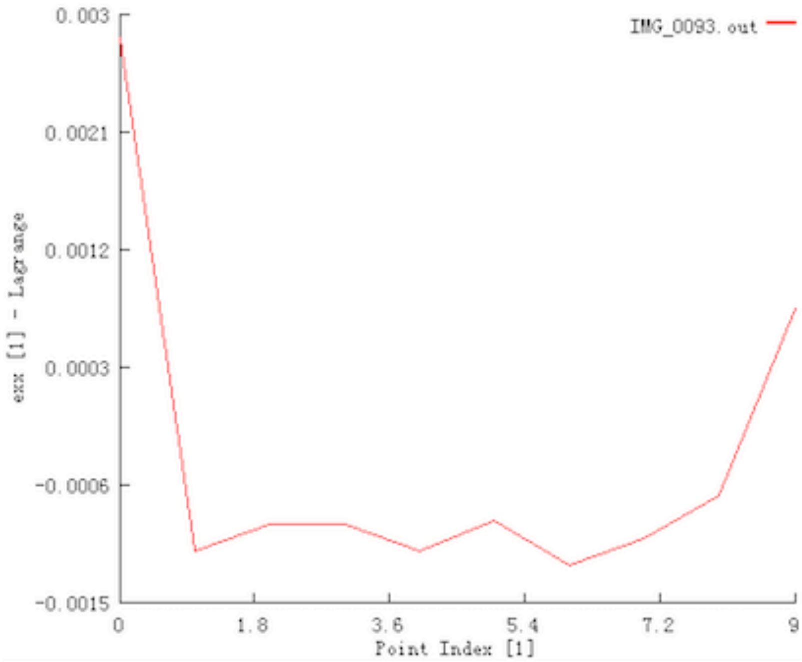

Figure 4.11: Horizontal strain plot of HDPE

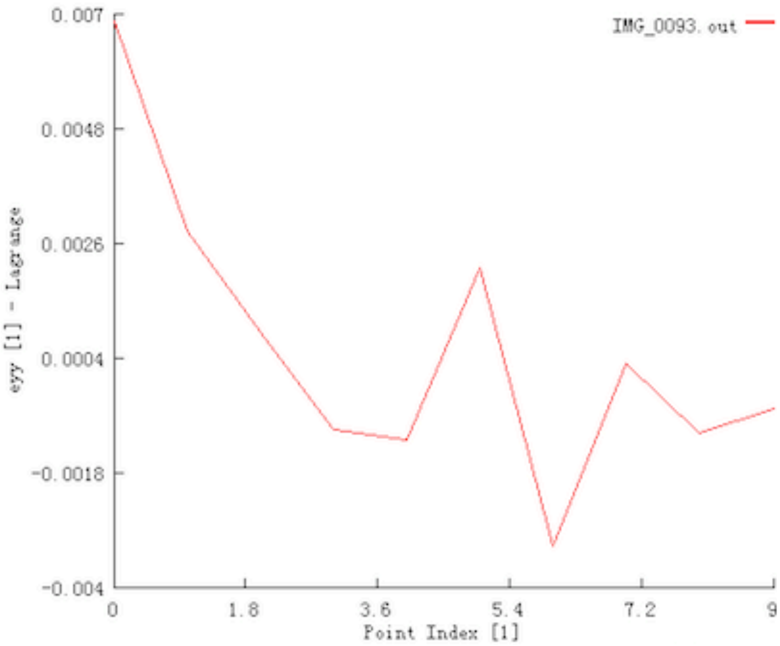

Figure 4.12: Vertical strain plot of HDPE

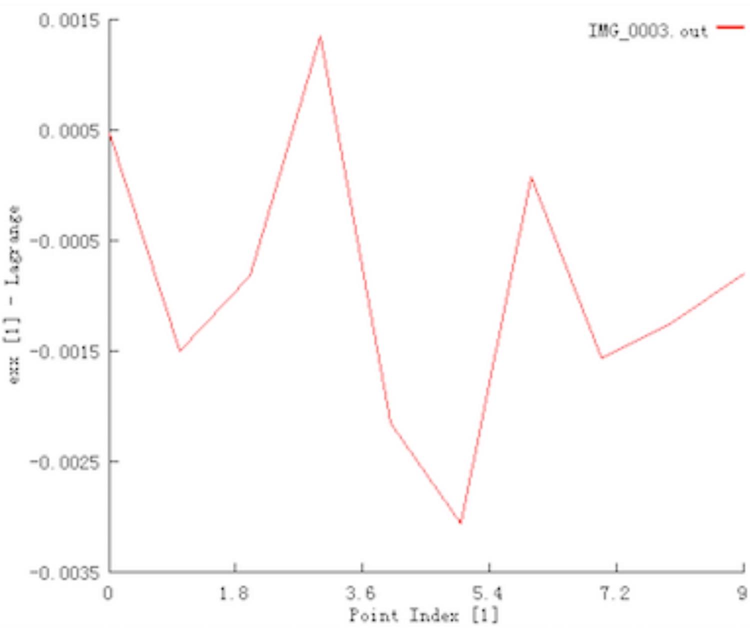

Figure 4.13: Horizontal strain plot of PP

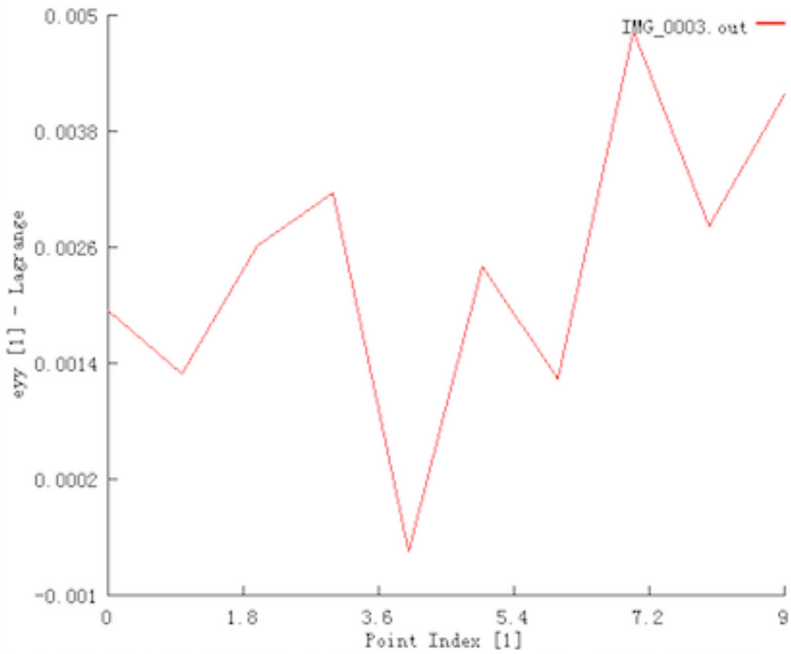

Figure 4.14: Vertical strain plot of PP

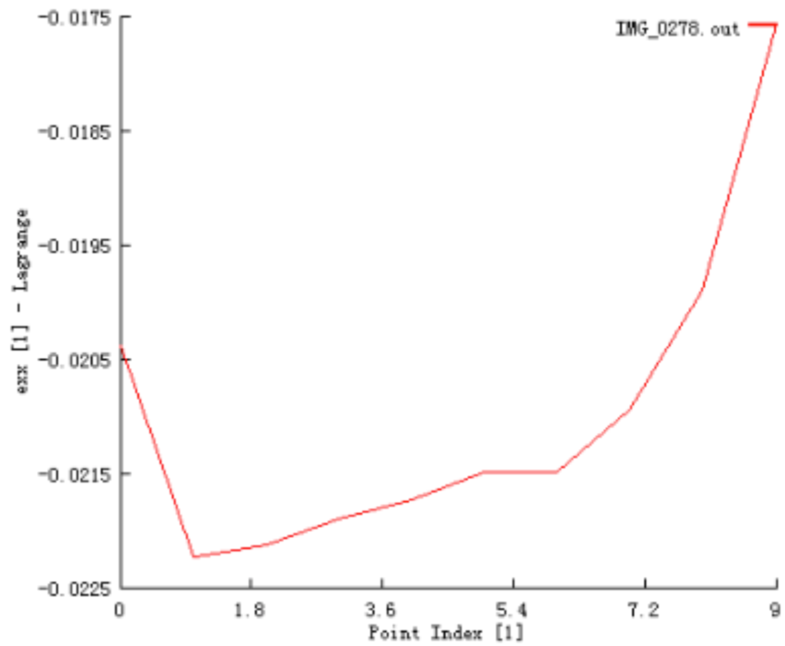

Figure 4.15: Horizontal strain plot of laminated film

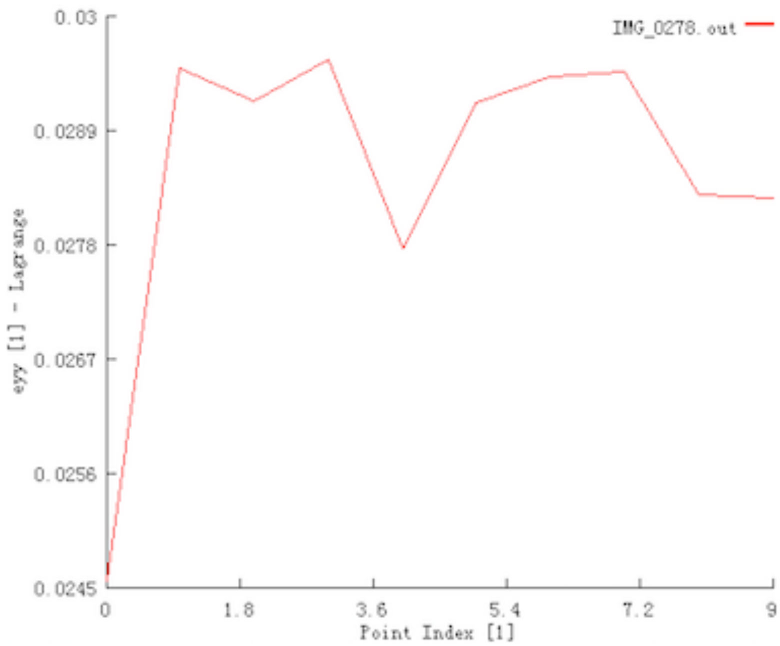

Figure 4.16: Vertical strain plot of laminated film

4.2.6 Strain plot for a single point

VIC-2D can also measure true strain in both horizontal and vertical directions for a single point in the specimen. File number is the random point that has been selected. (See Figure 4.17 to Figure 4.22)

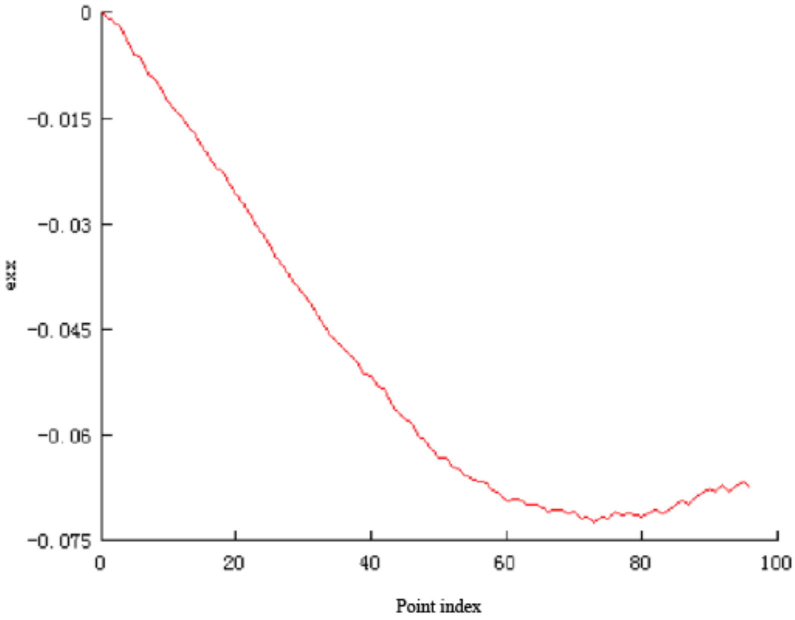

Figure 4.17: Horizontal strain measurement for a single point of HDPE

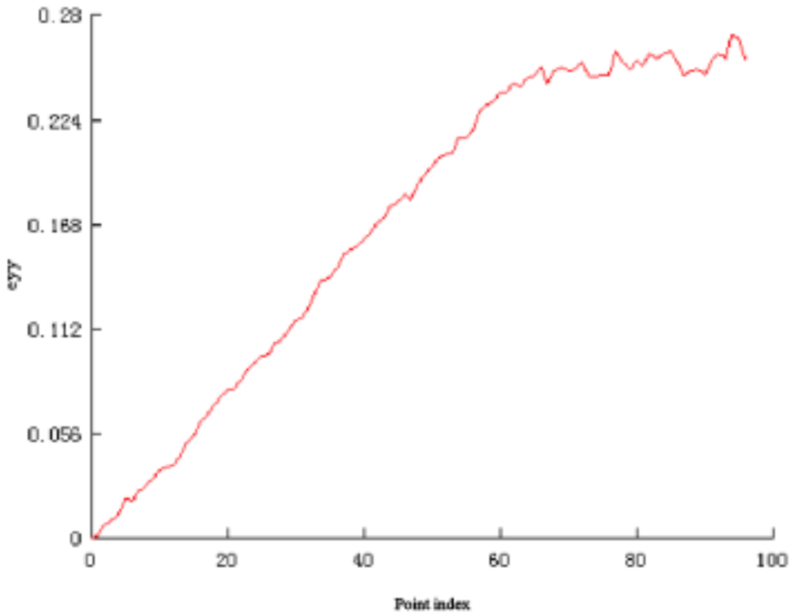

Figure 4.18: Vertical strain measurement for a single point of HDPE

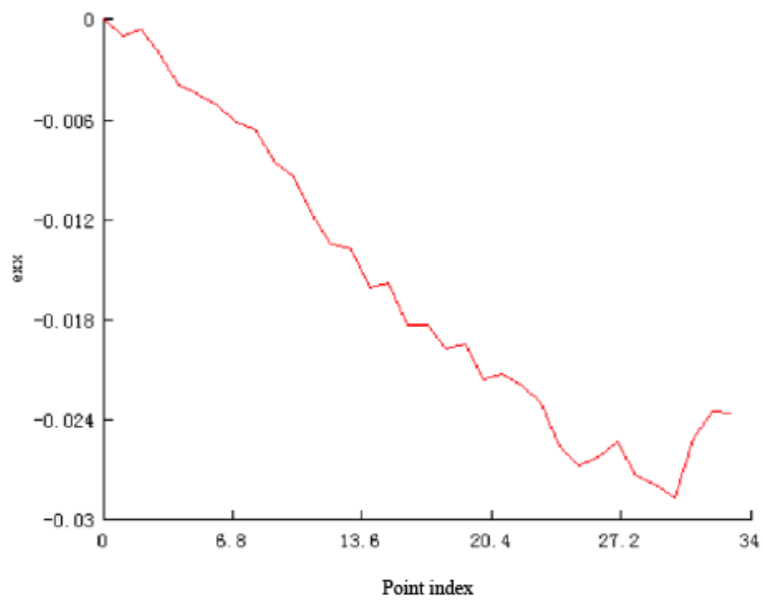

Figure 4.19: Horizontal strain measurement for a single point of PP

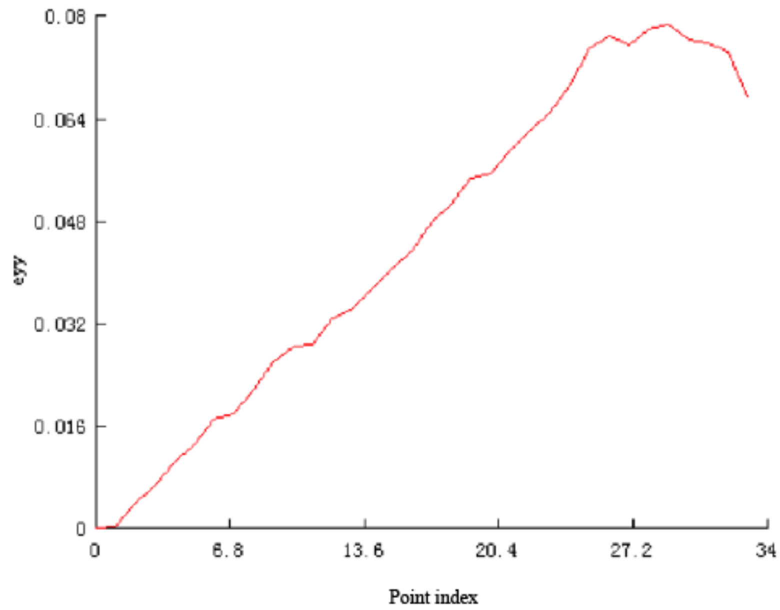

Figure 4.20: Vertical strain measurement for a single point of PP

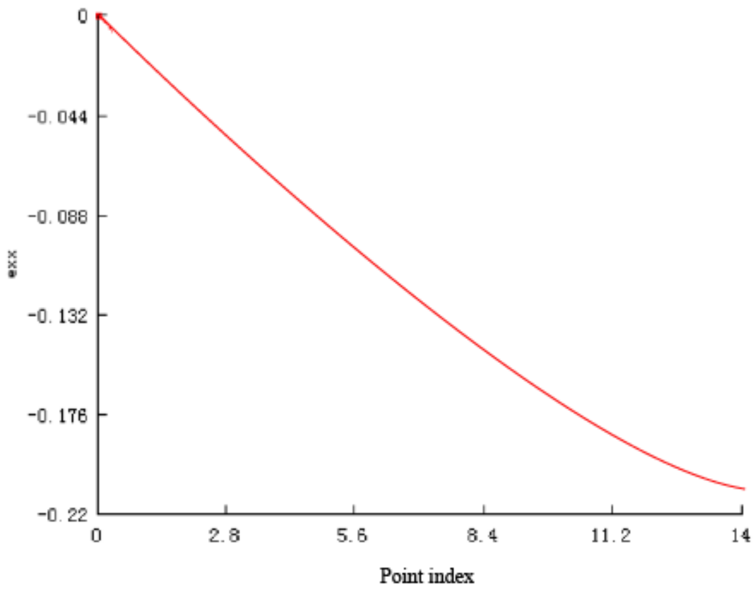

Figure 4.21: Horizontal strain measurement for a single point of laminated film

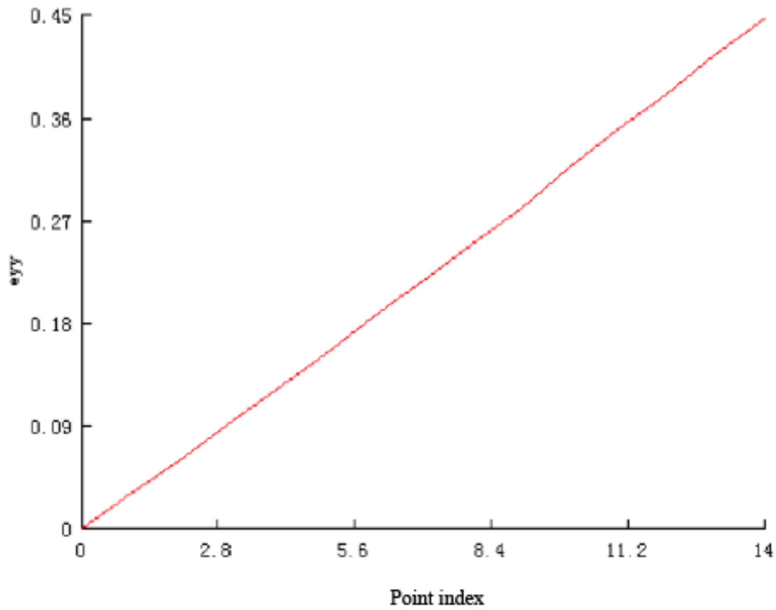

Figure 4.22: Vertical strain measurement for a single point of laminated film

4.3 Comparison of BLUEHILL and VIC-2D

To compare the accuracy and applicability of BLUEHILL methods and VIC-2D strain measurement system, the tensile properties of HDPE, PP and LDPE were determined by analyzing the gradient of the stress-strain curves and variation of Poisson's ratio of each material. The tensile values obtained by the BLUEHILL software served as the reference for those obtained by VIC-2D system. Figure 4.23, Figure 4.24 and Figure 4.25 show Strain-stress curves of HDPE, PP and laminated film obtained by both VIC-2D and BLUEHILL, respectively. Table 4.8 shows the strain measurement of three materials obtained by two methods.

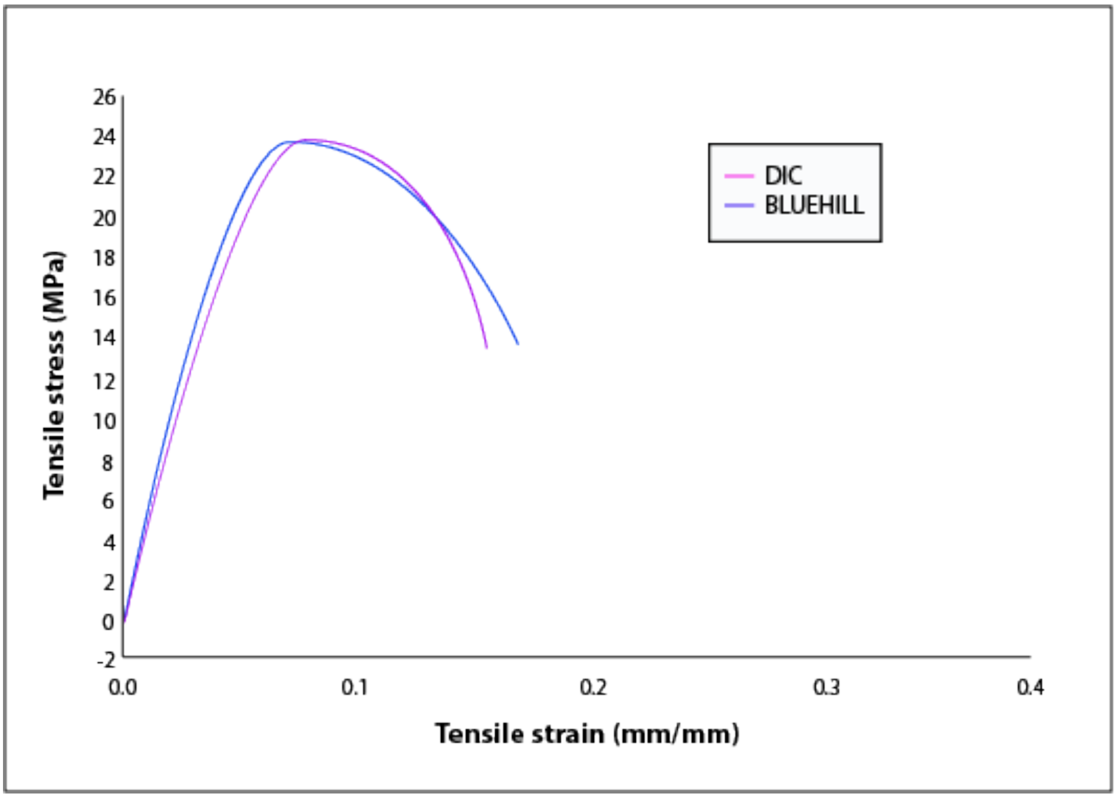

Figure 4.23: Strain-stress curves of HDPE obtained by VIC and BLUEHILL

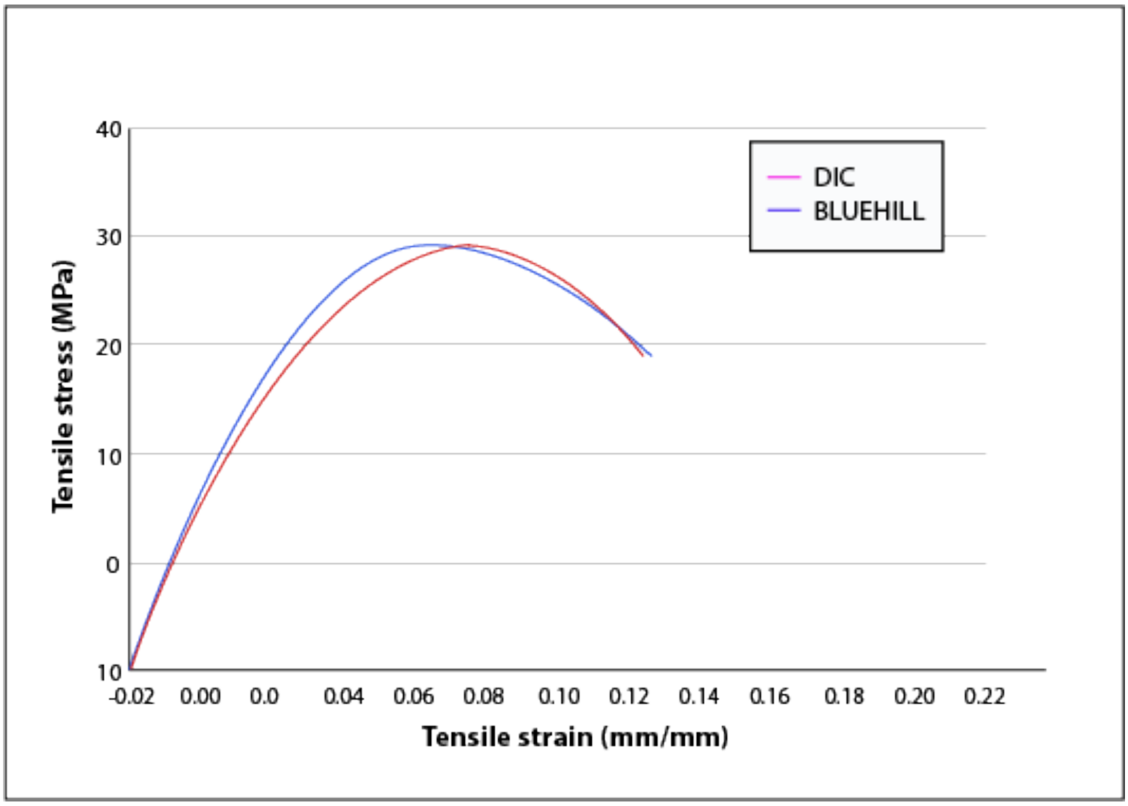

Figure 4.24: Strain-stress curves of PP obtained by VIC and BLUEHILL

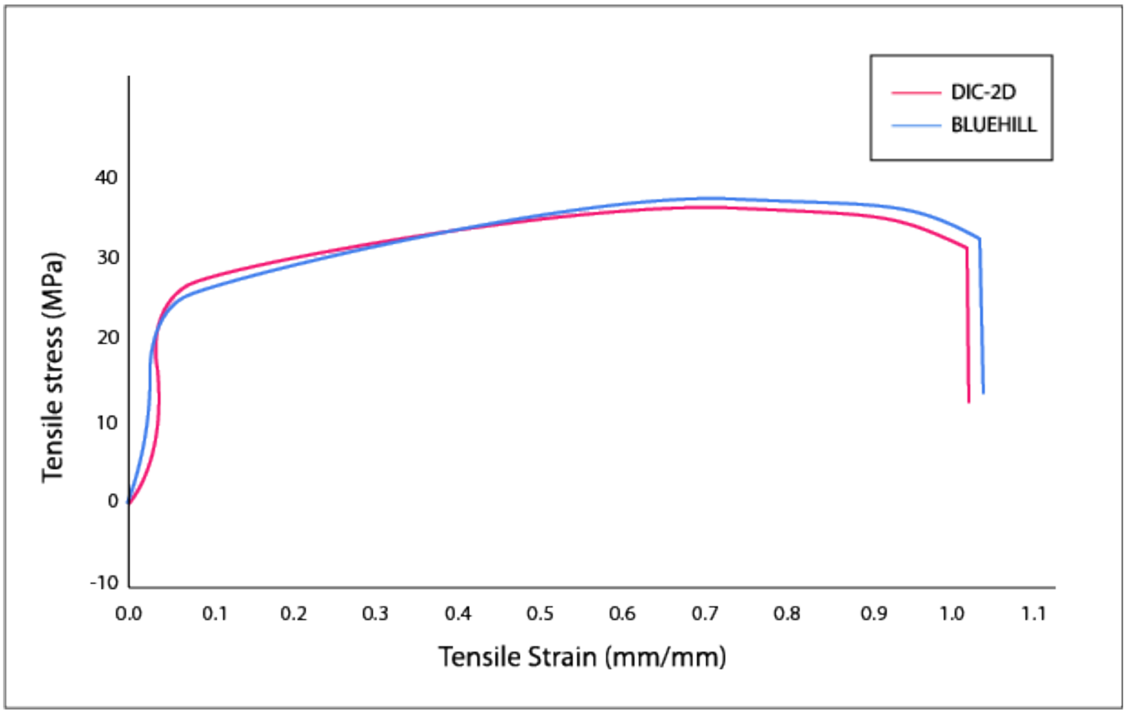

Figure 4.25: Strain-stress curves of laminated film obtained by VIC and BLUEHILL

Table 4.8: Strain measurements of HDPE, PP and LDPE

Materials	VIC-2D	BLUEHILL	Difference
HDPE	0.09591	0.08896	10.7%
PP	0.07599	0.07031	10.8%
Laminated film	0.05537	0.05289	10.4%

At the same stress level, the strain value of HDPE measured by VIC-2D is about 10.7% larger than BLEUHILL; the strain value of PP measured by VIC-2D is around 10.8% higher than BLUEHILL; the strain value of laminated film obtained by VIC-2D is 10.4% larger than BLUEHILL. This is because tensile test was conducted by clipping the sample to the extensometer and slippage would certainly happen between the specimen and fixtures during the loading period. Strain measurements acquired by BLUEHILL were obtained by recognizing all stretching and deformation applied on samples while VIC was capable of calculation strain values directly from gauge length with no influence of slippage. Therefore, VIC was ideal for almost all situations such as certain materials with large extension. However, traditional testing method might not be competent to conduct such testing.

Visual image correlation technique can provide strain measurement in axis and transverse direction and thus Poisson's Ratio can be directly determined based on the average of the horizontal and vertical strains. The Poisson's Ratios of HDPE, PP and Laminated film obtained in VIC-2D were 0.40, 0.34 and 0.36, respectively. By comparing these Poisson's Ratios determined by VIC and those known by theory, the deviations in terms of percentage, which were at most 2.5% off the theory value, had been found to be relatively small. Therefore, VIC had been verified as an accurate and effective technique to calculate tensile properties for different plastic materials.

5. Conclusion

The tensile tests conducted in this study have revealed that the Visual image correlation is an effective method to measure mechanical properties for various materials. The VIC can provide whole field strain measurement and precisely analyze the necking area. VIC has advantages of measuring strain value at any single point in the specimen while the conventional method can only provide average strain values. Furthermore, VIC is able to complete measurement directly on the surface of the specimen and therefore is not be affected by slippage between samples and fixtures.

The Poisson's Ratio of the HDPE, PP and laminated film are successfully determined by using axis and transverse strains obtained directly from VIC. The deviation between the results obtained by VIC and the results known by theory is relatively small, which have proved the accuracy and effectiveness of VIC in measuring strain properties.

In summary, visual imaging correlation is an innovative optical method for strain measurement. It serves as an advanced yet simple tool, which is highly possible to be used in a huge range of potential application for various materials.

6. Reference

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