EVALUATION OF STRESS RELAXATION IN BENTONITE FILLED RUBBER UNDER TENSILE LOAD USING SCANNER BASED DIGITAL IMAGE CORRELATION METHOD

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently in candidature for any degree.

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This thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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LISR OF ABBREVIATIONS

Abbreviations	Representation
DIC	Digital Image Correlation
CCD	Charged coupled devices
NR	Natural rubber
NBR	Nitrile-butadiene-rubber
HNBR	Hydrogenated nitrile butadiene rubber
ASTM	American Society for Testing and Materials
NCC	Normalised Correlation Coefficient
EPDM	Ethylene propylene diene rubber
2D	2 dimensional
ROI	Region of interest
RGB	red green blue format
LED	Light-emitting diode

ABSTRAK

Kelakuan relaksasi tekanan getah adalah penting untuk dikaji dan dinilai. Terdapat beberapa kaedah yang boleh digunakan untuk mengkaji kelakuan tersebut seperti ujian tegangan getah konvensional dan ujian mampatan getah denagan menggunakan mesin ujian tegangan. Walau bagaimanapun corak dan pergerakan permukaan getah tidak boleh dinilai melalui cara konvensional. Cara-cara lain seperti penggunaan kamera CCD memerlukan modal yang besar. Objektif penyelidikan ini adalah untuk membangunkan teknologi baru iaitu penggunaan kaedah Digital Image Correlation (DIC) dengan pengimbas flatbed untuk menilai kelakuan fizikal relaksasi tekanan getah asli yang dimuat dengan pelbagai jumlah kandungan Bentonite .Pengimbas flatbed telah digunakan untuk peralatan perolehan imej. Rig ujian bermotor digunakan untuk menjalankan ujian relaksasi tekanan. Ujian rawak dijalanka dengan algoritma MATLAB untuk menyiasat sifat rawak atas corak yang dihasilkan pada permukaan spesimen getah denagn menggunakan saiz subset yang berbeza yang akan digunakan dalam kaedah DIC. Faktor skala ditentukan pada $0.042333\, mm\, /\, piksel$ yang diperlukan untuk digunakan dalam pengiraan panjang. Ujian tegangan spring telah dijalankan untuk mendapatkan pemalar spring untuk pengiraan daya getah. Ujian gelinciran dijalankan untuk mengkaji keberkesanan sistem pengapit rig ujian. Kaedah untuk mengetatkan nut diselaraskan dan digunakan dalam persediaan unjian relaksasi tekanan getah. Ujian tegangan getah dijalankan untuk mengkaji sifat takanan dan ketaganan getah yang mengandungi kandungan Bentonite yang berbeza. Kemudian, ujian relaksasi tekanan dilakukan untuk semua spesimen getah yang mengandungi kandungan Bentonite yang berbeza. Keputusan menunjukkan bahawa makin tinggi kandungan Bentonite, makin banyak tekanan getah dapat dikurangkan dalam masa yang tetap. Kaedah DIC dengan algoritma MATLAB digunakan untuk menilai permukaan getah semasa relaksasi tekanan dan hasilnya menunjukkan keupayaan DIC untuk digunakan bagi menunjukkan perubahan dan corak pergerakan permukaan. Semua dapatan kerja penyelidikan ini menunjukkan keupayaan kaedah baru yang dibangunkan untuk menilai kelakuan relaksasi tekanan getah dengan penggunaan kaedah DIC dengan pengimbas flatbed.

ABSTRACT

Rubber stress relaxation behaviour is important to be studied and to be evaluated because it deals with the properties and function of rubber under stress condition. There are several methods that can be used to study rubber stress relaxation behaviour such as conventional tensile test and compression test. However, the surface deformation pattern and movement cannot be evaluated using these methods. The objective of this research is to develop a new method using scanner-based Digital Image Correlation (DIC) to evaluate the effect of various percentages of Bentonite loading in natural rubber on the physical stress relaxation behaviour. A flatbed scanner was used for the image acquisition. A motorized test rig was used to carry out the stress relaxation tests. Randomness test MATLAB algorithm was developed to investigate the randomness of speckles created on rubber specimen using different subset sizes. Scaling factor was determined at $0.042333\ mm/pixel$ which was needed to be use in length calculations. Spring tensile test was carried out to determine spring constant for rubber force calculation. Slip test was carried out to investigate the effectiveness of the clamp system of the test rig. Rubber tensile tests were carried out to study different Bentonite loading rubber specimen stress-strain behaviour. Then, stress relaxation tests were carried out for all the rubber specimens. The results shows that the higher the Bentonite loading, the more the stress of the rubber decreased for a given period. DIC MATLAB algorithm was developed and this method was used to evaluate the rubber surface during stress relaxation and the results shows the ability of DIC to indicate surface abnormality and surface movement pattern. All findings form this research work indicate the capability of the new method developed to evaluate rubber stress relaxation behaviour.

CHAPTER 1

INTRODUCTION

1.1 Background

Viscoelastic properties of filled rubber have been gaining so much interest since few decades ago. Various scientific investigation effort is to be deployed to dive into the unrevealed area of rubber behaviour. It is due to the high dependency on rubber in real life applications requires a series of studies and research in order to not only enhance the rubber performance, and also to determine the long term behaviour of rubber after went through degradation.

Generally, virgin rubber seldom to be used because the rubber properties is insufficient to cope the material properties requirement in basic durable. One of the magnificent breakthrough in material science is the enhancement of rubber properties via fillers. In rubber industries, amorphous silica and carbon black are the most common form of reinforcing fillers for decades. Reinforced rubber is critical in various fields of applications such as gasket and rubber damper in automotive industry. The continuation in research further progresses the effort to search for unconventional fillers such as Bentonite. Bentonite is a type of clay mineral which is the current trend in filler research field. Based on the research work by Pajtášová et al. (2017), the article mentioned the current trend of research includes polymers in combination with clay minerals. Small amount of clay mineral can have beneficial effect on modification of the physical and chemical properties relating to polymeric materials compared to conventional filler such as Carbon Black (CB).

With the enhancement of the mechanical properties of rubber, tensile strength and stress-strain behaviour of rubber are not enough for us to fully understand the behaviour of rubber. Indeed, the fundamental understanding of rubber cannot assist us to figure out the rubber long term behaviour. Instead of continuously to explore overwhelmed information relevant to the aspect mentioned before, it is more important to analyse time-dependent behaviour of rubber such as creep and stress relaxation. It is because the information and can help us to predict the lifetime and also the performance of rubber in future.

During stress relaxation, the filled rubber will undergo physical deformation with constant strain applied. This occurs due to the relocation of the filler and rubber chains when subjected to deformation (Abu-Abdeen, 2010). Since we know that the stress within the material structure during stress relaxation will decay in term of time, it effects the functionality of the rubber**.** Hence, this property is very critical especially in the application of rubber in sealing devices. The sealing rubber must properly deformed to meet the sealing effect. However, if the stress relaxation property causes the rubber deformed abnormally with increasing in time, failure or malfunction of the whole system will occur which is unpredictable.

Stress relaxation behaviour of rubber with the interaction of fillers has been studied by some researchers. Without any doubt, the addition of rigid filler particles, even in small amounts, to an elastomer strongly influences its response to mechanical behaviour (Meera, Said, Grohens, Luyt, & Thomas, 2009). The interaction between fillers and rubber also prone to alter the stress relaxation behaviour of filled rubber. In Meera's study, her study showed the rate of stress relaxation increases with increase in filler loading. Besides, numerical investigations were also conducted on filled rubber. The study done by Laiarinandrasana et al. (2012) was to understand better the experimental evidence from test on filled rubber materials that showed the higher the rigid particles content, the higher the rate of stress relaxation. The numerical analysis via finite element analysis concluded that the experimental data was confirmed.

The development of optical technology initiated the use of Digital Image Correlation (DIC) method to study the deformation behaviour of rubber. DIC is the non-contact optical method to measure full-field displacement and deformation which cannot be done by conventional tensile testing instrument which mostly applied in mechanical testing on rubber. DIC techniques first acquire digital images of an object at different loadings using digital imaging devices such as charge coupled device (CCD) camera and then perform image analysis with correlation-based matching algorithms and numerical differentiation approaches to quantitatively extract full-field displacement and strain responses of materials (Pan, 2018). The advantage of this method is that one can conduct measurement without contact with the specimen yet stress relaxation test is very time consuming regardless the methods used. Because of the benefit of DIC over conventional method, more and more researchers have used this method to study mechanical behaviour of rubber for example large-strain tensile properties, Poisson's ratio and creep. However, the application of low cost DIC method aided by scanner to evaluate stress relaxation behaviour of rubber is not yet to be reported.

1.2 Problem Statement

The conventional tensile and compression testing method are limited to stress measurement, they cannot be used for physical stress relaxation deformation evaluation. Also, testing instrument for stress relaxation test needs to be reserved for a long period until the completion of the test. This impact greatly reduces the availability of the testing machine for other application during the testing period of time. For conventional DIC method, comprehensive setups such as proper lighting and CCD camera equipped with lenses are necessary for a good performance of the method. Hence, a low cost scanner-based DIC method is believed to be capable enough to overcome this barrier at the same time it is also able to evaluate the physical stress relaxation.

1.3 Objective

The objective of this research is to develop a new method, known as scanner-based Digital Image Correlation (DIC) to evaluate the effect of various percentages of Bentonite loading natural rubber on the stress relaxation behaviour under constant strain.

1.4 Scope of Work

Firstly, all the informations and methods which specifically related to stress relaxtion and DIC and Scanner-based DIC are to be gathered. Experiment specimens will be prepared at School of Material and Mineral Resources Enginineering. Then, randomness test MATLAB algorithm is developed to investigate the randomness of speckles created on specimen surface. The method to create the speckles is standardized. A preliminary randomness test is carried out to investigate the speckles randomness using testing rubber specimens with different subset sizes.

Next, microcontroller is programmed which used to control the motor rotation and the test rig is set up. MATLAB algorithm is developed for scaling factor determination to convert pixel unit to millimetre unit which is needed for length calculation. A slip test is carried out to investigate the effectiveness of clamping system for the test rig.

MATLAB algorithm for DIC is developed. A preliminary test is carried out using test rig and strain is applied to testing specimen. Scanner is used to scan the specimen and DIC algorithm is then performed on the scanned images.

Spring tensile test is carried out on springs to determine the spring constant which is needed for stress calculation. After the preparation of Bentonite loading natural rubber specimens, rubber tensile test is carried out to determine the respective stress-strain behavior. Speckles is created on the Bentonite loading natural rubber specimens for final randomness testing. Speckle randomness test is to be carried out to test the quality of speckle with different subset sizes.

Finally, rubber stress relaxation test is carried out to study the behaviour of Bentonite loading rubber specimens using test rig and scanner. DIC evaluation is performed using the images of specimens scanned at different periods of time.

CHAPTER 2

LITERATURE REVIEW

2.1 Rubber Stress Relaxation and Measurement Method

Stress relaxation is the decreases of deformation stress applied on a structure to maintain a fixed strain. The viscoelastic rubber, when strained at a constant rate to a fixed deformation, the stress required to maintain the strain decays with time. This is referred to as stress relaxation (Maria et al., 2014). Abu-Abdeen (2010) also mentioned that when a real viscoelastic rubber is strained at a constant rate as rapidly as possible to attain a fixed deformation, the stress required to maintain that fixed strain is found to decay with time.

Maria et al. (2014) studied about the stress relaxation behaviour of organically modified montmorillonite filled natural rubber (NR)/nitrile rubber (NBR) nanocomposites. The effects of loading, blend composition, filler polarity and temperature on stress relaxation of organically modified clay (OMt) reinforced natural rubber NR/NBR nanocomposites were carefully measured. Stress relaxation measurements were carried out via tensile testing machine (Tinius Olsen H50KT). Specimens were prepared according to ASTM D 638 M standard. Strain rate was applied at constant $500\ \mathrm{mm\ min^{-1}}$ crosshead speed. Strain was fixed at 50% for a period of $90\mathrm{min}$. Fernandes & Sir Focatiis (2014) investigated the role of deformation history on relaxation of rubber through time-dependent experiments following a range of deformation histories. Two grades of carbon-black filled EPDM were prepared and uniaxial mechanical deformation was carried out via tensile testing machine. Both studies show that the tensile testing machine must be held for a long period until the completion of the experiment for each specimen since stress relaxation experiment is time dependent. This caused the testing machine to be unavailable for other applications during the whole stress relaxation experiment journey.

Mostafa et al.(2009) studied the influence of carbon black (CB) loading on the creep and relaxation behaviour of styrene butadiene rubber (SBR) and nitrile-butadiene rubber (NBR). Relaxation tests were carried out according to ASTM D 674 standard at 100% fixed strain on five different compositions for SBR and NBR with $0, 20, 30, 50$ and $70 phr$ of CB. The ingredients that were added into the composition of carbon black filled SBR and NBR systems were according to ASTM D15 standard. Each specimen was tested under stress relaxation condition for two days. Load cell was used to generate output signal of stress at that instant. The limitation on the test apparatus which designed, manufactured and assembled for the testing is the apparatus unable to evaluate the physical deformation of the specimen under stress relaxation. Moreover, the test apparatus remained unavailable for other applications for a very long period just to complete the testing.

Da Rocha et al. (2018) determined the effect of the hybrid-system filler on the stress relaxation of nitrile rubber composites. The fillers consisted of metakaolin and carbon black. Tensile and compressive loading were applied for tensile and compressive stress relaxation tests. Tensile stress relaxation tests were carried out using a universal testing machine. Type C dumbbell specimens according to ASTM D412 standard were used to conduct stress relaxation testing. Strain rate was applied at constant 500 mm min^{-1} crosshead speed. The strain applied was fixed at 100% for a duration of 60min.

Oman & Nagode (2014) conducted a study on the influence of different load sequences on the creep and stress relaxation process. Dumbbell test specimen was a blend of filled natural rubber, polybutadiene rubber and styrene butadiene rubber.

Measurements on stress relaxation were carried out in room temperature using Zwick Roell Z005 device which equipped with load cell. Stress relaxation was measured at four different strain level $(50\%, 200\%, 250\%, 300\%)$. The measurement and stress relaxation test were taken into account of ASTM: D3767-03(2008) and ASTM: D1646-07(2012) standards respectively.

Akulichev (2017) conducted a study of stress relaxation behaviour of hydrogenated nitrile rubber (HNBR) at nominal compressive strain up to 0.4 and temperature above and below the glass transition temperatureT_g. Different carbon black loading filled HNBR with 36% acrylonitrile content were investigated in the experiment. Stress at the instant of time was measured using load cell. Compression stress relaxation were carried out on a test rig illustrated in Figure 2.1.

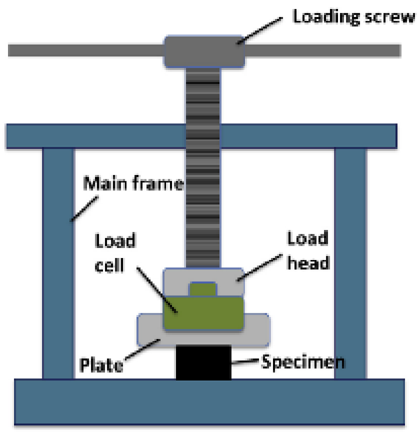

Figure 2.1: Schematic of the compression rig. (Akulichev et al., 2017)

Zhao et al. (2015) investigated the effect of thermo-oxidation on the continuous stress relaxation behaviour of nitrile rubber. The stress relaxation measurements were carried out using Elastocon relaxation system in tension mode which setup according to ASTM D6147-97(2008) standard requirement. The experiments were carried out in different temperatures, original strains and atmospheres.

Dong et al. (2017) studied the effect of stress relaxation on the sealing performance of the fabric rubber seal under different pressure and comprehensive displacement. They used universal tensile testing machine as shown in Figure 2.2. The fixed tensile strain was 50% and the specimen loaded for $7200s$. The result was shown in Figure 2.3.

Figure 2.2: The stress relaxation experiment of rubber via universal tensile testing machine. (Dong et al., 2017)

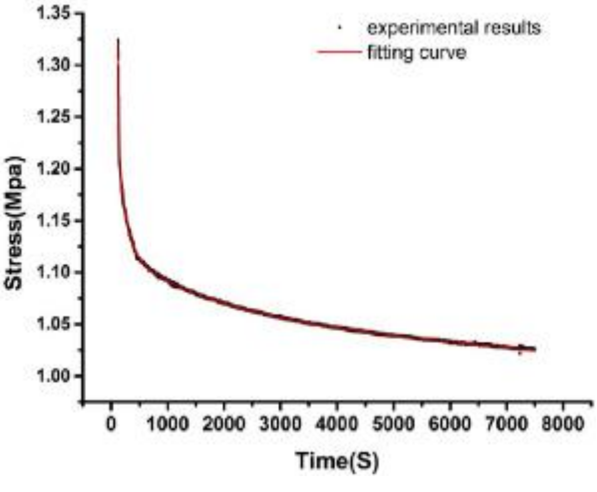

Figure 2.3: The stress relaxation experimental result and fitting curve calculated from equation. (Dong et al., 2017)

The articles that discussed above have similar limitations. The tensile test experiments that conducted cannot be used to evaluate the physical surface deformation of the specimen under stress relaxation. This caused the results obtained can only be used for stress change analysis but not physical deformation evaluation. Furthermore, the testing machine which used for stress relaxation test needed to be reserved for a very long period for just to complete the tests for each specimen. This caused a very inconvenient situation for the availability of the machine for other application.

2.2 Digital Image Correlation (DIC)

Digital Image Correlation method is one of the optical technique which has been used ~~to~~ for strain and displacement measurements. It is a typical non-interferometric optical metrology tool for deformation an shape measurement (Pan & Li, 2011). This method was first published in the early 1980s by Peter and Ranson (Nowak & Maj, 2018). DIC also referred to white light speckle technique according to Lecompte et al. (2006). The technique uses image capturing system to capture the digital images before and after the deformation and compare both of the images. Displacement due to deformation at the surface of the object can be determined. DIC can provide a full-field deformation measurement of the object. Figure 2.4 shows the general DIC set up.

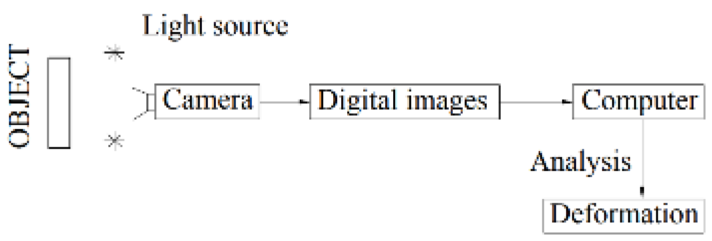

Figure 2.4: General set up for DIC method. (Dinh, Hassan, Dyskin, & Macnish, 2015)

Bing et al. (2009) used DIC method for the measurement of coefficient of thermal expansion of film. They explained the DIC principle in the test method they used. A square reference subset of $(2M + 1) \times (2M + 1)$ pixels centered at the current point $P(x_0, y_0)$ from the reference image is chosen and used to find its corresponding location in the deformed image. Once the location of the target subset in the deformed image is found, the displacement components of the reference and target subset centres can be determined which shown in Figure 2.5. The differences of positions of the reference subset centre and target/deformed subset centre yield in-plane displacement components u and v. The tracking and searching process can be done by calculating the correlation criterion.

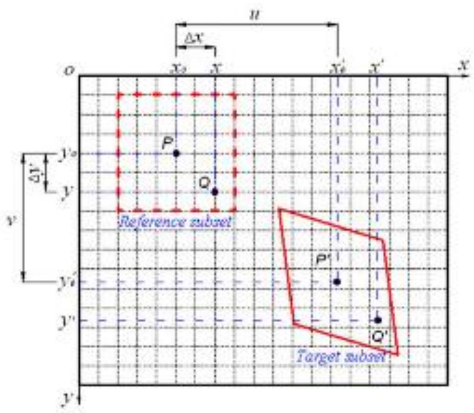

Figure 2.5: Schematic figure of reference square subset of reference image and deformed subset of the deformed image. (Bing et al., 2009)

Gu (2015) also explained the concept of DIC in his study of random speckle pattern simulation models in DIC. The principle is shown in Figure 2.6. The basic principle of the standard subset-based DIC is to match the same physical points imaged in the reference image and the deformed image. A square subset of $N \times N$ pixels (or the so-called regions of interest-ROI) surrounding the tested physical point in the initial image is selected and used to find its corresponding location in the deformed image. The matching process can be done according to the maximum value of the calculated correlation coefficient. The vector between the reference subset centre and the target subset centre is the in-plane displacement vector at the interested point $P(x, y)$. A correlation coefficient distribution is acquired by moving the reference subset through the searching subset continuously and calculating the correlation coefficient at each location.

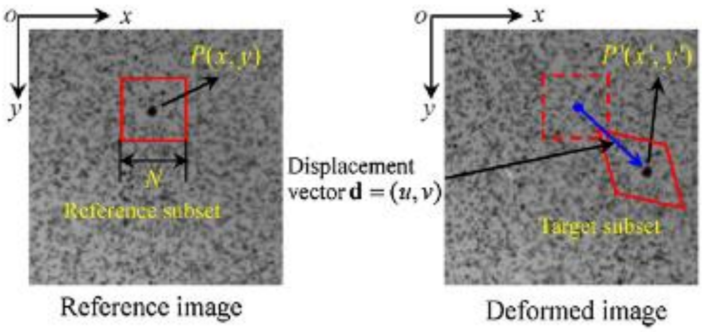

Figure 2.6: Schematic of relation of pixel point in reference (or undeformed) and target (or deformed) subsets (Gu, 2015).

Grytten et al. (2009) used 3D image correlation method with two camera and stereo vision to determine the full-field displacements of ductile thermoplastic during uniaxial tensile tests on the specimen. The purpose of using two cameras was to determine the in-plane as well as the out-of-plane displacement of the surface of the specimen. Random white speckle was applied on the surface of the specimen on both front and lateral side using mat spray paint. Camera were mounted to an angle that both front and lateral side of specimen were visible to both cameras.

Farfán-Cabrera et al. (2018) evaluated the creep degradation of four sealing elastomers by using digital image correlation technique in a creep experiment to determine the changes in creep behaviour of elastomers. Two charged-couple device (CCD) cameras were used for different configurations of image acquisition. Farfán-Cabrera, Pascual-Francisco, Barragán-Pérez, Gallardo-Hernández, & Susarrey-Huerta (2017) applied DIC method to determine creep compliance, creep recovery and Poisson’s ratio of sealing elastomers. Two CCD cameras and proper lighting were required to support the application of DIC. Figure 2.7 explained the setup of DIC.

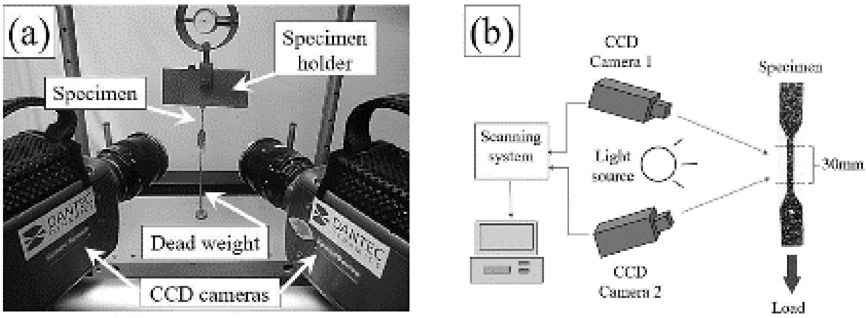

Figure 2.7: (a) Experimental set-up for creep compliance determination by means of DIC (b) diagram of the experimental set-up. (Farfán-Cabrera et al., 2017)

Jerabek et al. (2010) carried out a strain determination of polypropylene (PP) and PP composites (PP-C). They used three dimensional DIC method consisted of two high speed camera which equipped with lens to record the images. To allow for sufficient optical signal detection and to avoid heating effect on the specimen, a proper lighting that used ib this experiment ws provided by a cold light system Dedocool. Both cameras were mounted on a displaceable frame which attached directly to the test mechine. Disadvantage on this setup was repoted that the oscillations from the drive system and fan of the temperature chamber may directly influenced the performance of the cameras. The setup shown in Figure 8.

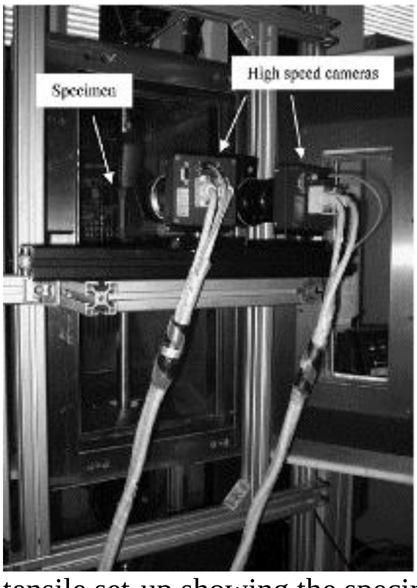

Figure 2.8: Picture of the tensile set-up showing the specimen fixed in the grips and the two high speed cameras of the DIC system mounted on the displaceable frame

ensuring a fixed relative position of the two cameras and the specimen. (Jerabek et al., 2010)

Parsons et al. (2004) studied the large-strain tensile behavior of polycarbonate and polycarbinate filled with several volume fraction (f) of rubber particles via two dimensional DIC method. Local displacement gradients and full-field displacements during a uniaxial tension test were determined. A camera was only used in this study to acquired digitized images of the specimen surface during tensile test. The limitation is the test needed to be repeated twice for front and lateral surface in order to capture the deformation on both surfaces. This is because 2D-DIC method can only measure in-plane displacment.

Although DIC was proven to be a very powerful method to study the strain deformation, but the conventional DIC method which applied by those researchers mentioned above similarly required comprehensive setup. Those setups included high speed cameras and proper lighting or external light source. Moreover, evaluation on physical deformation under stress relaxation of filled rubber yet to be reported. It is to believe that a low flatbed scanner is capable enough to replace camera to be implemented in a lower cost DIC method. Hence scanner-based DIC method will be discussed in the follwing section.

2.3 Scanner-based Digital Image Correlation (SB-DIC)

Goh et al. (2016) proposed and applied 2D scanner-based DIC method to map large in-plane deformation and determine Young's Modulus of vulcanized rubber. The article mentioned that conventional DIC method which using camera has such a limitation that the large deformation of high-strain material could cause the domain under study to go out of field-of-view of the camera. Although such limitation can be solved using a camera lens with shorter focal length but the lens will cause image distortion and reduce the image resolution. Therefore, SB-DIC method is a better solution for this limitation. Somehow, the article also mentioned that SB-DIC did have some drawbacks. Firstly scanner-based DIC method is limited and applicable to only high-strain material for example rubber and elastomers. Besides, the strain which can be applied under this method is only 350%.

Goh et al. (2017) studied the method of mapping large strains in rubber using DIC in a single step without the need for a series of deformation images. Incremental DIC method which apllied in the past prone to cumulative errors since the total displcement is determined by combining the displacements in numerous stages of deformation. The result from the study also showed that the proposed single-step SB-DIC method can be used to map the strain distribution accurately in large deformation materials at much shorter time compared to the incremental DIC method. This atricle had the same limitations that discussed before in the previous article in this section.

Although the excisting method using scanner can solve the problem of image distortion and reduction of the image resolution, SB-DIC also have some drawbacks. Firstly scanner-based DIC method is limited and applicable to only high-strain material for example rubber and elastomers. Besides, the strain which can be applied under this method is only 350%.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The equipment used for image acquisition is outlined in Section 3.2. Motorised test rig is discussed in Section 3.3. Speckle randomness test which includes speckle creation, randomness test algorithm, plotting of normalised correlation coefficient graph and preliminary randomness test are discussed in Section 3.4. Section 3.5 discusses the method on how to calculate scaling factor. Spring tensile test is outlined in Section 3.6. Slip test and rubber tensile test are discussed in Section 3.7 and 3.8 respectively. Last but not least, stress relaxation test and digital image correlation evaluation on stress relaxation test are discussed in Section 3.9 and 3.10 respectively.

3.2 Image Acquisition Equipment

In this research, Canon Canoscan 5600F Flatbed Scanner as shown in Figure 3.1 was used for image acquisition process. This scanner was used to scan the specimen to obtain the images for image processing. It uses high luminance white LED as light source which enhanced the image brightness with proper exposure and can solve the problem of conventional CCD which needs a proper light source in order to capture high quality image. Line scan technology which utilized by the scanner able to provide wide scanning width with linear CCD scanning element and a nominal 600dpi resolution. It is also more affordable compared to conventional CCD camera which used for DIC experiment.

Figure 3.1: Canon Canoscan 5600F Flatbed Scanner.

3.3 Motorized Test Rig

A motorized test rig was used to perform stress relaxation test. Figure 3.2 shows a test rig which positioned on the flatbed scanner.

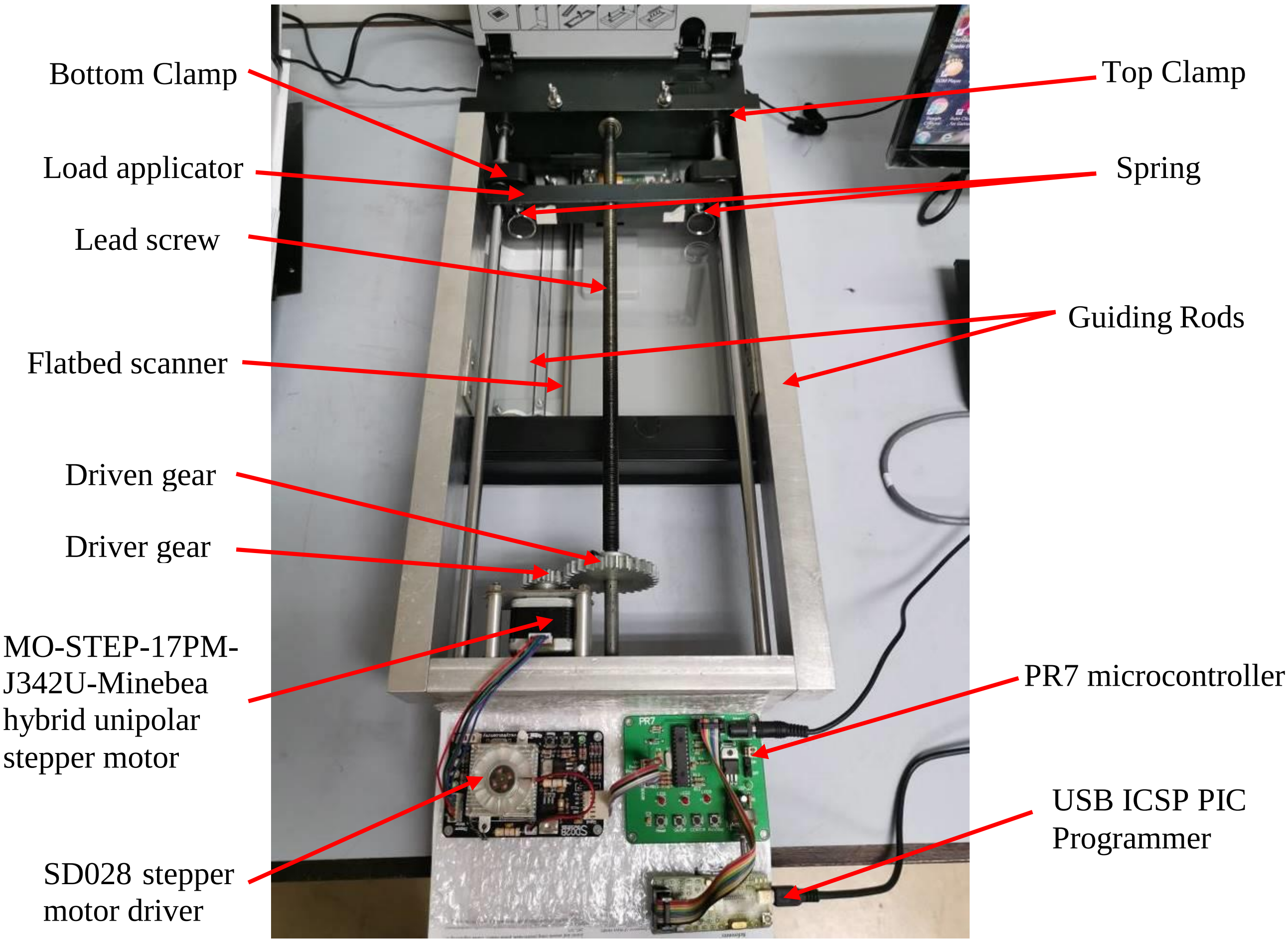

Figure 3.2: Motorized test rig positioned on scanner.

A stepper motor was used to rotate a lead screw and the lead screw transferred the torque to load applicator. Load applicator pulled the springs and the bottom clamp moved downward. Then, the rubber specimen which clamp on bottom clamp was stretched and strain was applied. Stepper motor able to apply constant rate of torque so that the rubber specimen can be stretched in constant rate. Besides, a black cover board was placed on top of test rig during image acquisition. Figure 3.3 shows the side view of the set up.

Top Clamp

Rubber Specimen

Bottom Clamp

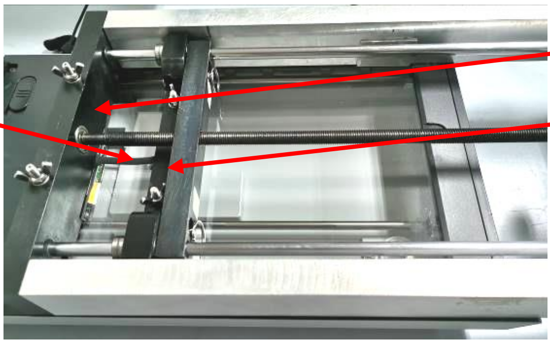

Figure 3.3: Side view of test rig set up.

3.4 Speckle Randomness Test

Speckle randomness test was carried to investigate the speckle randomness and select the suitable subset size to be used in Digital Image Correlation (DIC) operation. Normalised correlation coefficient was used to carry out the randomness test. Value of normalised correlation coefficient directly proportional represents the degree of similarity. Di Stefano et al. (2003) proposed an improved Normalised Cross Correlation (NCC) for matching template sub-image into a given image. They mentioned the original formula of NCC which stated below Equation 3.1:

$$\boldsymbol{NCC(x,y)} = \frac{\sum_{j=1}^{N}\sum_{i=1}^{M} I(x+i.y+j)\cdot T(i,j)}{\sqrt{\sum_{j=1}^{N}\sum_{i=1}^{M} I(x+i,y+j)^2}\cdot\sqrt{\sum_{j=1}^{N}\sum_{i=1}^{M} T(i,j)^2}} \tag{3.1}$$

where $I(x,y)$ and $T(i,y)$ represent the sub-image under examination and the template, respectively.

Di Stefano et al. (2003) also mentioned the same cross correlation technique in his article with the same equation as in Equation 3.1. The reason why this technique is popularly being used because of its wide application in computer vision task such as stereo vision, motion tracking and image mosaicking. The most important is it is much more robust to noise and already be normalised to allow matching independent of scale and offset in the images. It is also applicable in the case of brightness and contrast variation.

Two types of algorithm were developed which were randomness test and plotting of normalised correlation coefficient distribution to get different results for testing. In general, each template image extracted from the sample image was compared with the reference image to calculate the normalised correlation coefficient, $\boldsymbol{\gamma(\Delta m,\Delta n)}$. The range of $\boldsymbol{\gamma(\Delta m,\Delta n)}$ is $-1<\gamma<1$. Negative value indicates the inverse correlation of two images. Zero means there is no correlation between the two images. The more the positive the coefficient value, the higher the degree of positive correlation of the two images. The formula for normalised correlation coefficient is shown in Equation 3.2.

$$\boldsymbol{\gamma}(\Delta \boldsymbol{m}, \Delta \boldsymbol{n}) = \frac{\sum_{m,n}[f(m,n)][g(m+\Delta m, n+\Delta n)]}{\sqrt{\{\sum_{m,n}[f(m,n)]^2 \sum_{m,n}[g(m+\Delta m, n+\Delta n)]^2\}}} \tag{3.2}$$

where $f(m,n)$ and $g(m+\Delta m, n+\Delta n)$ are intensity values of template image and reference image respectively at pixel coordinates m and n.

3.4.1 Speckles Creation

Speckles was created on the experiment rubber specimen. White glossy ink was sprayed on the specimen to cover the whole area of specimen. The distance between the spray and the specimen was maintanined at 30 cm height and the nozzle was perpendicular to the rubber specimen. The white ink was sprayed only once across the specimen surface. The spray was pressed before approachinig specimen and released after the end of the specimen. The ink was dried under hot air blower for 5 sec to speed up the drying process. Speckles was created on 0%, 10%, 30%, 50%, 70% Bentonite loading specimen as shown in Figure 3.4 (i) to (v).

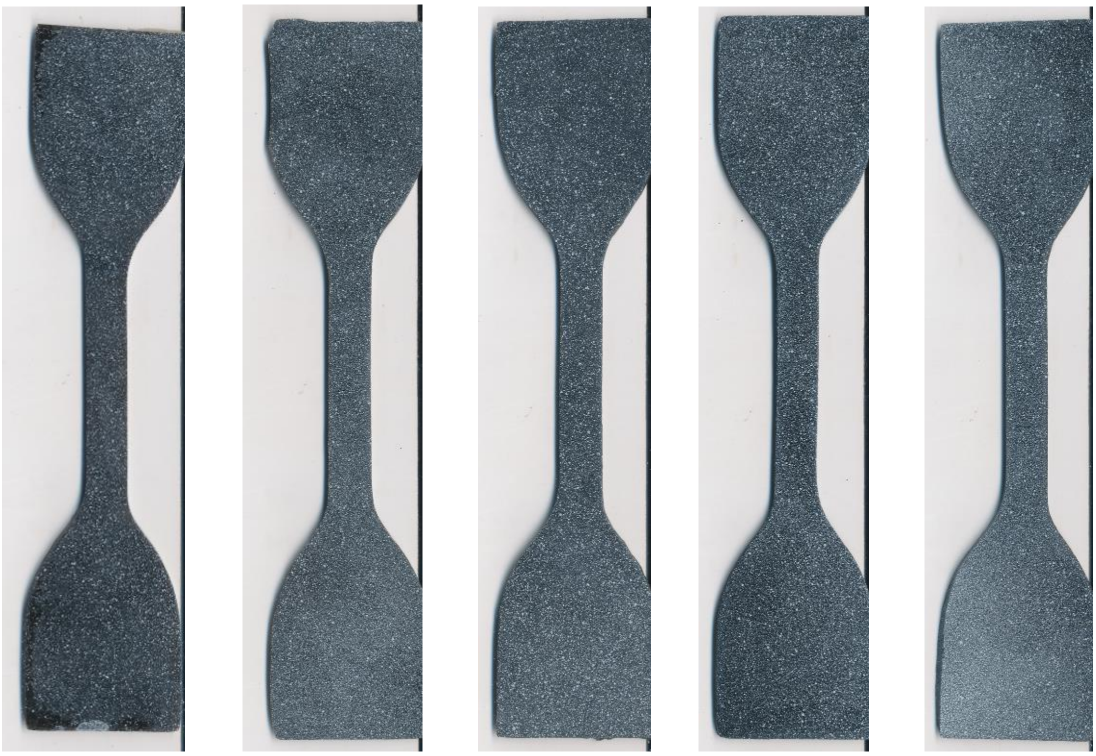
(i) (ii) (iii) (iv) (v)

Figure 3.4: Speckles created on the surface of rubber with Nemtonite loading percentage (i) 0%, (ii) 10%, (iii) 30%, (iv) 50% and (v) 70%.

3.4.2 Randomness Test Algorithm

Randomness test was conducted on each Bentonite loading rubber specimens. The scanned image in Figure 3.5 was converted in to grayscale image in Figure 3.7. The region of interest (ROI) was cropped out from the grayscale image with 500×155 pixels as shown in Figure 3.6. Anticlockwise $\mathbf{90}^{\circ}$ rotated ROI in Figure 3.7 was then converted to binary form via thresholding function *im2bw* as shown in Figure 3.8. Threshold level was determined as 0.4353 via Otsu's method, *graythresh*. Subset image, $\boldsymbol{f}$ with centroid $(\boldsymbol{C_m}, \boldsymbol{C_n})$ where $\boldsymbol{m}$ *and* $\boldsymbol{n}$ were pixel coordinate which also known as template image was defined from the binary image. It was then correlated with the adjacent and subsequent subset images, $\boldsymbol{g}$ which known as reference images with centroid $(\boldsymbol{C_{m+i}}, \boldsymbol{C_{n+j}})$ where $\boldsymbol{i} = 0,1,2 \ldots, n - (subset\ size/2)$ and $\boldsymbol{j} =$

$1,2 \ldots, m - (subset\ size/2)$ to calculate the normalised correlation coefficient $\boldsymbol{\gamma}$. A total of seven subset sizes were used in seven sets of randomness test. Those subset sizes were 21×21, 31×31, 41×41, 51×51, 61×61, 71×71 and $81 \times 81\ pixels$. If the correlation coefficient calculated from one of the template image with reference image was higher than the threshold 0.7, the loop will be stopped and the command will prompt out the statement of 'Randomness Issue Occurred'. If the correlation coefficient was not higher than threshold value, then the loop will continue to calculate the correlation coefficient for different sets of template image and reference image until it reached the last template image. The system will call out the statement of 'No Randomness Issue' for no randomness issue at the end of test.

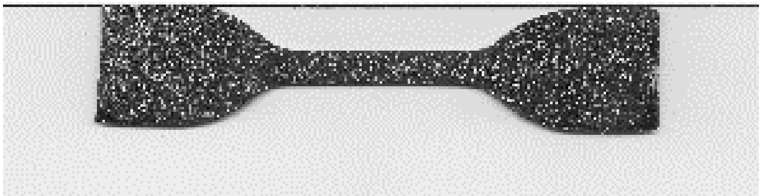

Figure 3.5: Grayscale image of scanned image.

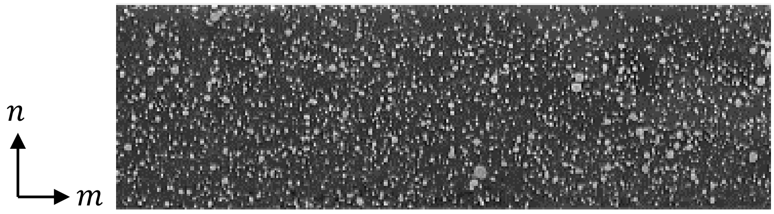

Figure 3.6: Region of interest (ROI) cropped out from the grayscale image.

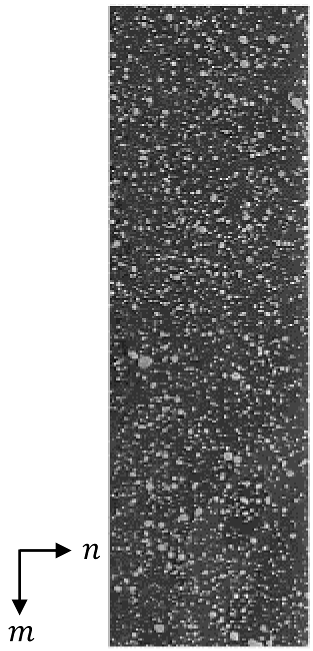

Figure 3.7: ROI was rotated $\mathbf{-90}^{\circ}$.

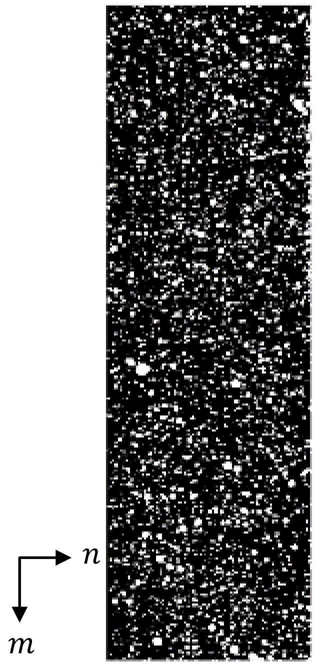

Figure 3.8: Binary form of ROI.

Figure 3.9 below showed the randomness test algorithm.

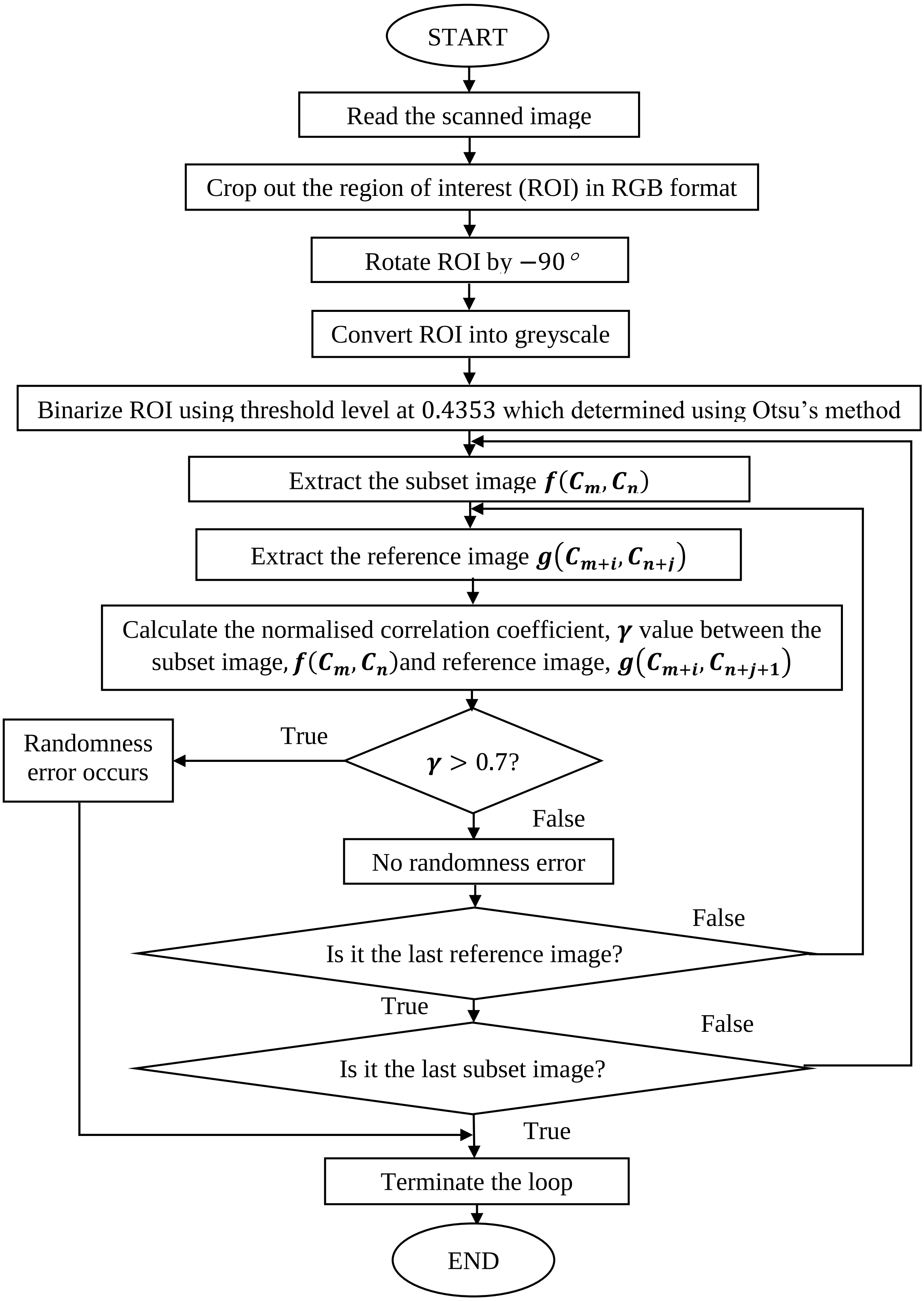

Figure 3.9: Flowchart of Randomness Test Algorithm