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Research Article

Measuring the Thickness of Fiber Mats Using Light Transmittance via Image Processing

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ABSTRACT

Fiber materials possess unique properties, including a large active surface area, high surface-to-volume ratio, high porosity, high mechanical performance, and low density. Consequently, they serve as key components in various applications such as energy production and storage cells, batteries, wastewater treatment membranes, sensors, drug-releasing band-aids, and protective clothing. Electrospinning is a simple and versatile method for producing fiber materials. Despite its simplicity in terms of working principles, it faces challenges in achieving homogeneous thickness (evenly on the entire surface) throughout fiber mats due to inherent bending instability during the process. Non-uniform thickness not only diminishes the efficiency of these mats in applications but also adversely impacts their mechanical functionality. In this study, the aim is to develop a thickness measurement system based on image processing and the principle of light transmittance as a solution to the issues encountered in achieving uniform thickness and thickness control of fiber mats produced by electrospinning devices. To accomplish this, a closed mechanism with a light-impermeable encapsulation method was established. Various fiber mats, produced at different times were placed on the acetate floor built on LED lighting on the base of the mechanism. Using a camera with the adjusted settings positioned at the focal point on top of the mechanism, images of the fiber mats were captured, and image processing techniques were employed to determine threshold value ranges for the mat thicknesses. The actual thicknesses of the fiber mats were verified using an optical microscope, revealing that regions defined with the same color in different samples exhibited similar thicknesses.

Keywords: *Image processing, Fiber material, Electrospinning method, Thickness measurement*

Fiber Matların Kalınlığının Görüntü İşleme Yoluyla Işık Geçirgenliği Kullanılarak Ölçülmesi

ÖZ

Fiber malzemeler sahip oldukları geniş aktif yüzey alanı, yüksek yüzey-hacim oranı, yüksek gözeneklilik, yüksek mekanik performans ve düşük yoğunluk gibi özellikleri nedeniyle enerji üretim ve depolama hücreleri, piller, atık su arıtımında kullanılan membranlar, sensörler, ilaç salınımlı yara bantları ile koruyucu giysiler gibi birçok uygulamada ana bileşen olarak kullanılmaktadır. Elektrospin, fiber malzemeler üretmek için kullanılan

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basit ve çok yönlü bir yöntemdir. Elektrospin yöntemi her ne kadar çalışma prensibi olarak basit bir yöntem olsa da işlem esnasında ortaya çıkan bükülme dengesizliği nedeniyle homojen kalınlıkta (tüm yüzeyde eşit olacak şekilde) fiber matlar elde edilememektedir. Homojen olmayan kalınlık, bu matların uygulamalardaki verimliliğini azaltmakla kalmaz, aynı zamanda mekanik işlevlerini de olumsuz etkiler. Bu çalışmada, elektrospin cihazı ile üretilen fiber formunda matların homojen kalınlıkta üretimlerinde ve kalınlık kontrolünün sağlanmasında karşılaşılan sorunlara çözüm olarak görüntü işleme ve ışık geçirgenliği prensibine dayalı bir kalınlık ölçüm sisteminin geliştirilmesi amaçlanmıştır. Bu amaç doğrultusunda öncelikle ışık geçirimsiz kapsülleme yöntemiyle kapatılmış bir düzenek kurulmuştur. Düzeneğin zemin kısmında LED aydınlatma üzerine kurulmuş asetat zemin üzerine farklı sürelerde üretilmiş çeşitli fiber matlar yerleştirilmiştir. Düzeneğin tepe noktasındaki odak noktasına koyulan çekim özellikleri sabit ayarlanmış bir kamera ile görüntüler elde edilmiş ve mat kalınlıklarına ait eşik değer aralıklarını belirlemek için görüntü işleme teknikleri kullanılmıştır. Fiber matların gerçek kalınlıkları optik mikroskop ölçümüyle doğrulanmış ve farklı numunelerde aynı renkle tanımlanan bölgelerin benzer kalınlığa sahip olduğu belirlenmiştir.

Anahtar Kelimeler: *Görüntü işleme, Fiber malzeme, Elektrospin yöntemi, Kalınlık ölçümü*

I. INTRODUCTION

Fiber materials find widespread applications in diverse fields such as wastewater treatment, energy storage, tissue engineering, drug release, heavy metal detection, and thermal insulation. Their exceptional properties, including a high surface-to-volume ratio, substantial porosity, low density, expansive active surface area, and excellent mechanical performance, make them highly desirable [1]. Electrospinning is a versatile and straightforward technique for fabricating fiber materials. Despite its simplicity in principle, the electrospinning process is influenced by numerous parameters [2-4]. The application of high voltage in electrospinning induces electrical repulsion, leading to bending instability and preventing the production of uniformly thick fibers.

Fiber mats with non-uniform thickness compromise their functionality, resulting in reduced efficiency and inferior mechanical properties in practical applications, such as reduced filtration efficiency or proton permeability [5]. Maintaining the highest functionality necessitates precise knowledge of fiber mat homogeneity and thickness during production.

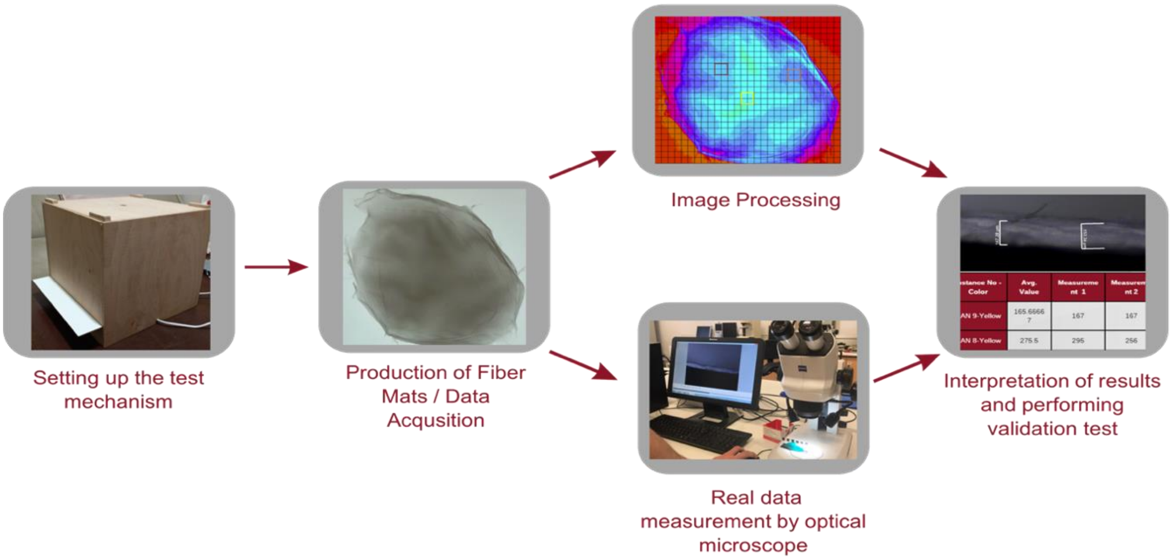
Several established methodologies for measuring fiber mat thickness involve the utilization of distance measurement sensors, employing diverse technologies to ensure accurate and reliable assessments of distance, thickness, and position. These sensors employ light reflection from object surfaces, facilitating prompt and precise measurements. However, such sensors tend to be costly. A review of the literature reveals that methods employed for measuring fiber mat thickness are often complex and expensive. Image processing techniques are used for different applications in areas such as construction and automotive, where fiber materials are also used extensively. Jiang et al. (2020) have developed a new method to characterize the distribution of the film thickness of asphalt mortar, which is a mixture of binder and fine mineral aggregates, which is considered an important indicator in evaluating the durability of the asphalt mixture, through image processing techniques. Internal images of the samples were scanned and analyzed. Mortar film thickness values were measured along the boundary of each aggregate in the scanned images. To characterize the mortar film thickness distribution, mean values (T_m) and standard deviations (SD_t) were calculated and the results were compared based on these values [6]. Cruz et al. (2023) developed a new method to analyze some of the disadvantages, such as edge cracking along the sheet thickness resulting from the creation of components with cutting edges, of advanced high-strength steels, which are becoming increasingly popular in the automotive industry due to their high yield and ultimate tensile strengths. When characterizing the formability of sheet metal materials, hole expansion testing is an industry standard method used to evaluate the ductility of their edges. However, visualizing initial cracking accurately is often difficult and subjective, often leading to inconsistent results and low repeatability. In order to find solutions to these problems, they proposed a new digital image processing method to reduce operator dependency and increase the accuracy and efficiency of hole expansion test results. The proposed approach allows a more precise determination of the hole expansion ratio by detecting the appearance of initial edge cracks by utilizing advanced image processing algorithms [7]. As a result of our research, we have concluded that it is feasible to measure fiber mat thickness at a lower cost using image processing techniques, given the current state of image processing technologies and their successful utilization in numerous industrial applications.

In light of this understanding, our study aimed to develop a thickness measurement system based on image processing, offering a technological solution to challenges encountered in achieving uniform thickness and thickness control in fiber mats produced by electrospinning devices. This system primarily relies on the principle of light transmittance and employs an innovative, light-impermeable encapsulation mechanism. Through this mechanism, we obtained images of fiber mat samples, which were then subjected to various image processing techniques. These processed images were subsequently divided and compared using matrixing methods, leading to the determination of threshold values based on colors. Actual thickness values of the fiber mat samples were measured with an optical microscope, and a color-based thickness scale was established by aligning the threshold value ranges obtained through image processing with the corresponding actual thickness values.

Our study seeks to optimize electrospinning device production parameters by leveraging data collected from the image processing and light transmittance-based thickness measurement system. Achieving uniform thickness distribution in fiber mats produced under optimal conditions is pivotal for sustainability, repeatability, enhanced efficiency, and reduced operational costs through minimized material wastage and energy consumption.

II. METHODOLOGY

The steps undertaken to implement the solution for measuring the thickness of fiber mats using image processing and light transmission are delineated in Figure 1. Initially, we devised a novel testing mechanism tailored for acquiring images of fiber mats. Subsequently, we captured images of fiber mat samples fabricated on acetate substrates at various time points using this newly developed mechanism. These acquired images were then subjected to rigorous image processing techniques, involving matrixing methods and the determination of threshold values based on color analysis. The true thicknesses of regions corresponding to identical color ranges in distinct fiber mat samples were meticulously measured using an optical microscope. The resultant measurements were then subjected to a comparative analysis. This approach allowed us to draw meaningful conclusions regarding the thickness variations across different fiber mat samples.



stance No - Color	Avg. Value	Measurement 1	Measurem nt 2
AN 9-Yellow	165.66667	167	167
AN 8-Yellow	275.5	295	256

Figure 1. *Experimental workflow*

A. SETTING UP THE TEST MECHANISM

A new test mechanism enclosed within a light-impermeable enclosure was designed, comprising a camera at the top (with the camera's focal point and shooting parameters set to a fixed configuration) and LED illumination integrated at the base of the mechanism. The schematic representation of the test mechanism is presented in Figure 2, with the finalized version depicted in Figure 3.

Ensuring that the assembly remained impervious to external light was of utmost importance to achieve precise and processable results. Hence, the test mechanism was carefully encapsulated with an opaque material, completely sealing it from external light sources. Additionally, to ensure consistent and valid results, the camera's position within the upper region of the mechanism was standardized for each data collection, maintaining an optimum focal length and consistent shooting parameters for each photograph [8].

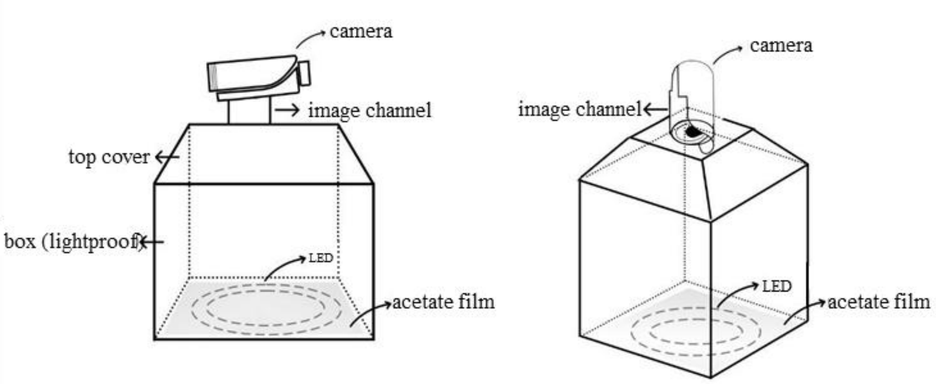


Figure 2. *Drawing of the test mechanism developed for capturing fiber mat images*

Figure 3. *Test mechanism*

B. PRODUCTION OF FIBER MATS / DATA ACQUISITION AND IMAGE PROCESSING

Initially, GMZ Energy produced a set of 11 different fiber mat samples for this study [9]. Polyacrylonitrile (PAN), the most commonly used polymer, was used for the production of fiber mats. While determining the production conditions, the optimum conditions for PAN nanofibers optimized by GMZ Energy were taken into consideration. In all experiments, 20 kV voltage was applied to 8 wt% PAN solution, 0.5 mL/hour feeding rate was used, and the distance between the needle tip and the collector was kept at 12 cm. Aluminum foil on a metal plate of 25 cm x 30 cm dimensions was used as a collector. Fiber mat production was carried out based on different periods of time.

In the subsequent phase of our research, we acquired images of these fiber mat samples with the test mechanism in Figure 3, where a sample of the obtained data is visually depicted in Figure 4. These acquired images were subsequently subjected to grayscale transformation via image processing. The basic image processing technique for grayscale transformation of an image is to take a color image and convert it into grayscale by averaging the color channels [10, 11].

This grayscale conversion served as the basis for creating a color-coded thickness scale, utilizing thresholding methods [12]. In the grayscale representation, pixel values range from 0 to 255, where 0 corresponds to black, 255 to white, and intermediate values represent varying shades of light or dark gray. As a result, the threshold value for areas with higher light transmission, indicative of thinner sections, tends toward 255 [13].

Following grayscale transformation, we proceeded to apply a colorization technique to these images, assigning distinct color values to predefined threshold ranges, as exemplified in Figure 5 [14]. In order to compare the experimental results with the actual values and to enhance precision in presenting our findings, we diligently annotated the areas having the largest area within each color-coded region, as demonstrated in Figure 6.

To optimize our image processing workflow, we leveraged Python, a widely recognized programming language celebrated for its effectiveness in image processing. Python provides an extensive range of libraries and tools specifically designed for image analysis and manipulation, rendering it the optimal choice for our research. Additionally, we employed the Open-Source Computer Vision Library (OpenCV), a prominent open-source software library encompassing computer vision, machine learning, and image processing capabilities [15]. OpenCV played a pivotal role in establishing the necessary threshold values for our image analysis.

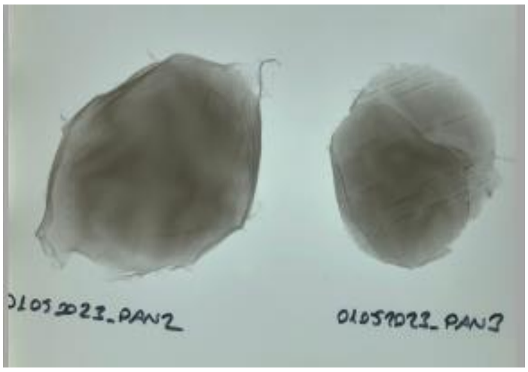


Figure 4. *Data from the mechanism*

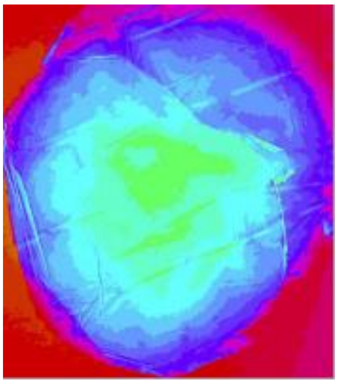


Figure 5. *The data of PAN-3 after image processing*

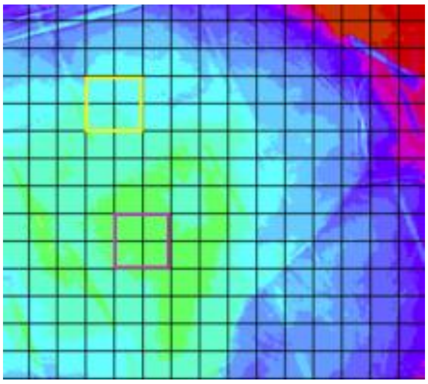


Figure 6. *PAN-3 grid divided into squares and the largest area marked in regions with the same color*

C. COMPARISON OF IMAGE PROCESSING DATA WITH REAL DATA MEASURED BY OPTICAL MICROSCOPE

The physical fiber mat samples were precisely positioned on the images identified in Section B, and regions corresponding to the same color within different samples were carefully delineated and extracted as illustrated in Figure 7. These extracted regions were securely affixed to coverslips using carbon tape, ensuring they were primed for accurate thickness measurements as depicted in Figure 8.

To ascertain the actual thickness of each sample, measurements were conducted employing a Zeiss Stemi 508 optical microscope as shown in Figure 9. Three measurements were acquired for each sample, and the resultant values were averaged to yield the final thickness measurement (Figure 10).

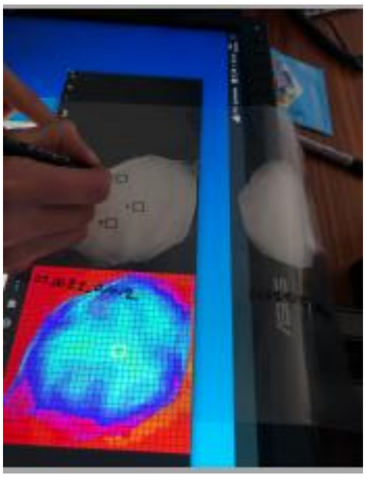


Figure 7. *Marking the measurement areas on real PAN samples*

Figure 8. *Preparation of samples for optical microscopy*

Figure 9. *Optical microscope (Zeiss Stemi 508)*

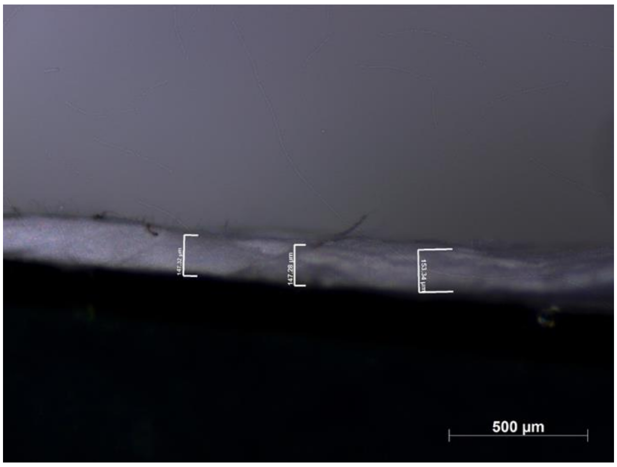


Figure 10. *Thickness measurement with the optical microscope*

III. RESULTS

After obtaining the actual thickness values of the fiber mat samples using an optical microscope, we established a color-based thickness scale, as presented in Table 1 and Table 2. This scale was derived by aligning the threshold value ranges from our image processing outcomes with the corresponding actual thickness measurements of specific regions. When the measurement results were examined, it was determined that the margin of error based on the color scale varied between 0.42% and 6.38% and the average margin of error was 3.8%.

Table 1. *Matching chart of actual thickness values*

Instance No / Color	*Average Value*	*Standard Deviation*	*Measurement 1*	*Measurement 2*	*Measurement 3*
PAN-7 / Yellow	***233.33***	*32.53*	*265*	*235*	*200*
PAN-8 / Yellow	***275.5***	*27.58*	*295*	*256*	*--*
PAN-10 / Orange	***210.5***	*21.92*	*195*	*--*	*226*
PAN-6 / Orange	***191.5***	*3.54*	*194*	*189*	*--*
PAN-3 / Lilac	***239.66***	*23.03*	*262*	*241*	*216*
PAN-1 / Lilac	***242***	*6.24*	*247*	*244*	*235*

Table 2. *Color-based thickness scale*

Mark Colors	*Average Value*	*Error Margin*
Yellow	255	$\pm 11\ \mu m$
Orange	202	$\pm 10\ \mu m$
Brown	310	$\pm 4\ \mu m$
Green	94	$\pm 6\ \mu m$
Claret Red	140	$\pm 5\ \mu m$
Lilac	241	$\pm 1\ \mu m$
White	192	$\pm 11\ \mu m$

Our study's results lead to the conclusion that the actual thickness values of regions marked with the same color, extracted from different fiber mats, exhibit remarkable consistency. This consistency enables us to draw meaningful inferences regarding thickness values associated with the chosen colors. For instance, the average thickness measurements of regions identified in lilac color on PAN-10 and PAN-6 were concurrently recorded as 239 and 242 micrometers, as illustrated in Figures 11 and 12. This exemplifies our success in accurately identifying regions of identical thickness within diverse fiber mats.

Moreover, a comparative analysis of measurements taken from identically colored areas reveals consistent results, further affirming the reliability of our approach. Consequently, our study demonstrates that image processing methods can effectively complement manual processes in thickness assessment.

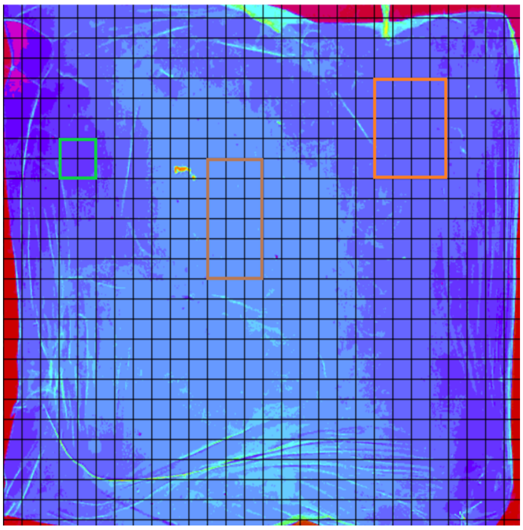


Figure 11. *PAN-10*

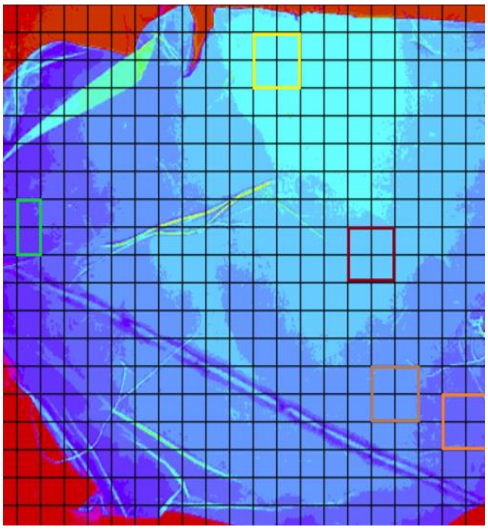


Figure 12. *PAN-6*

IV. CONCLUSION AND FUTURE PESPECTIVES

Within the scope of this study, we have introduced a novel approach for tackling the significant challenge of thickness measurement in fiber mats produced through the electrospinning method. Our innovative method encompasses a thickness measurement system that leverages image processing techniques based on light transmittance. The results of our measurements revealed a noteworthy alignment between the outcomes derived from image processing techniques and the actual thickness measurements conducted using an optical microscope.

Unlike existing systems, the developed thickness measurement system offers a user-friendly and cost-effective solution for determining the thickness of fiber mats produced via the electrospinning method. In forthcoming research endeavors, we plan to expand the applicability of image processing techniques for measuring the thickness of fiber mats crafted from various polymer materials. Additionally, our vision involves the integration of the developed thickness measurement system into existing electrospinning devices, enabling real-time data acquisition during the fiber mat production process through the use of cameras. Furthermore, we aim to establish a monitoring mechanism that will allow continuous thickness assessment during production by implementing a dedicated application within the electrospinning device.

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