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AUTOMATION OF RESIDUAL STRESS MEASUREMENT IN TABLEWARE GLASS PRODUCTION

Key words

Automatic Optical Inspection, photoelasticity, tableware glass.

Abstract

The paper presents an analysis of the capability of developing a system for on-line automatic measurement for residual stresses in tableware glass products. In the first part of the article, conventional techniques of photoelasticity together with its limitations are briefly presented. Furthermore, methods based on digital image analysis for the determination of stresses are generally described. Based on conducted research, a concept of in-line machine vision system is propose. Lastly, example experimental results for a selected inspection technique are discussed.

Introduction

Today's market demands have made manufacturing organizations move towards competitive issues of quality improvement, production speed, and cost reduction. From the point of view of the client, *quality* means reliability and satisfaction of use. From the perspective of manufacturers, it is conformity with the technical specifications. Ensuring high quality products has a direct impact on the level of user satisfaction and the simultaneous benefits of reducing costs by reduced the number of defects, waste products, and items requiring rework. As reported in U.S.A., the glass industry roadmap indicates a number of challengers that are critical to manufacturing performance such as advances in process modelling, quality inspection, and control systems. The established goal for the glass industry for the year 2020 is to achieving Six Sigma quality of glass products [1] among others. Consequently, solutions are sought that are designed to replace statistical control through the control of all manufactured products. The use of automated inspection systems allows increasing performance and reliability by eliminating the human factor due to lack of repeatability, fatigue, subjectivity, and efficiency [2]. Currently available glass tableware automatic vision systems are capable of examining geometrical and optical faults at a speed from 140 to 240 articles per minute [3, 4]. Dimensional fault identification includes measurements of height and diameter, thickness, ovallity, axis faults, and slanted and uneven rims. Surface defects are optical failures that disturb the overall image or even the function of the article. Among the described in-line defect detection, quality control during the tableware manufacturing process also covers manual statistical measurements of such parameters as weight, residual stress, and the presence or absence of glass coatings. Since glass is a brittle material, the measurement of residual stresses is of great importance to product conformance. Usually these kinds of measurements are performed by skilled technical personnel. With the development of imaging techniques and progress in images analysis, several attempts have been made to automate this process for preventing the subjectivity of results and increasing the frequency of measurements. In this article, a review of current progress in this field will be presented along with a concept of a fully automated residual stress measurement system integrated into a production line of tableware glass.

1. Conventional photoelasticity methods

Measuring the residual stress is a fundamental quality control operation for annealed or tempered products. Birefringent materials like glass act as a temporary wave plate [5], refracting light differently, depending upon the state of stress in the material. The phase difference δ (Fig. 1a) between the orthogonal components of light that entered the material from the back is given by the following:

$$\delta = h \cdot C(\sigma_1 - \sigma_2) \tag{1}$$

where: h – thickness of the material, $C = \frac{2c}{\lambda}$ – stress-optic coefficients, c – relative stress-optics coefficient (Brewsters), σ_1, σ_2 – principal normal stresses.

This equation (1) is often written in terms of the number N of complete cycles of relative retardation ($N = \delta/2\pi$). Since stressed glass exhibits temporal double refraction, photoelasticity techniques are commonly used for imaging the spatial distribution of residual stress levels. In those methods, the birefringence effect is analysed with the use of an optical device known as *polariscope*. Two types of polariscope are commonly employed – plane (Fig. 1a) and circular (Fig. 1b).

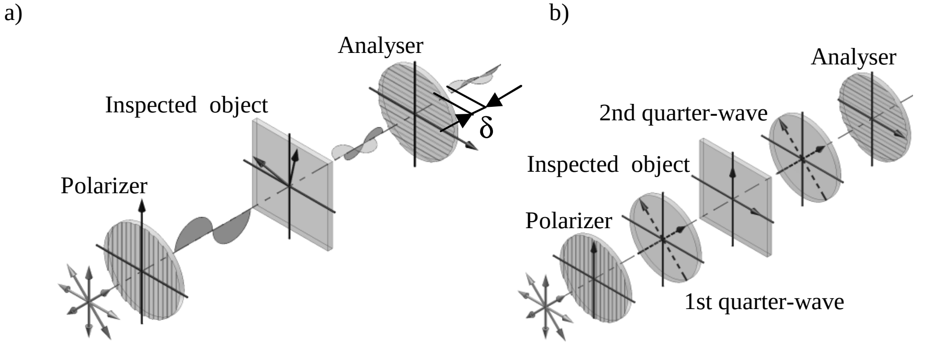


Fig. 1. Optical arrangements of polariscope: a) planar, b) circular

According to applied methodology, monochromatic or white light sources can be applied for observation of the stress redistribution on an inspected object. For the presentation of overall photoelasticity technique principles, it is good to use an example of a circular disc under diametral compression. Depending on type of optical setup used and the stress level present, different patterns will be perceived. For the simplest system consisting of plane polariscope and a monochromatic light source, an image formed after light passes the analyser will contain two types of fringes: isochromatic and isoclinic. Isochromatics are contours of a constant principal stress difference $(\sigma_1 - \sigma_2)$, and isoclinics are fringes of a constant principal stress direction with respect to a reference axis. It is fundamental for photoelasticity techniques that rotating the polarizer and analyser together create movement of the isoclinics contours enabling the determination of the direction of the principal stress at all points of inspected object. However, as can be seen on Figure 2a in a considered optical arrangement, dark isochromatics are superposed onto dark isoclinics making them hardly distinguishable. Using a circular polariscope arrangement, optically removes isoclinics enabling full visualization of fringes of constant principal stress difference (Figs. 2 b, c).

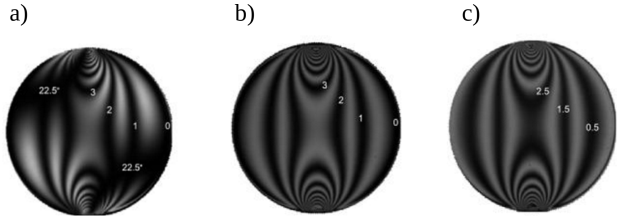
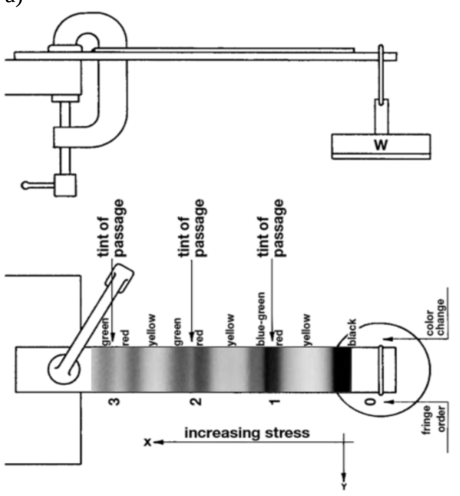


Fig. 2. Transmission photoelasticity images observed by a) plane polariscope, b) dark-field circular polariscope, c) bright-field circular polariscope [6]

Nevertheless, correct fringe order labelling using only one exposure in monochromatic light is still not clear, especially for more complex cases of stress distribution. To overcome this issue in conventional photoelasticity, illumination by all the wavelengths of the visible spectrum is used for the determination of the zero-order fringe and fringe gradient direction. As it can be seen on Figure 3b, as the stresses and birefringence increase in a inspected object, a colour sequence is observed on the photoelastic coating with the use of a white-light source [7]. However, it should be mentioned that this method is highly subjective and requires experience. Visual observation of colours limits the precision and reliability of inspection; therefore, it should be only used for qualitative evaluation of stress in the object.

a)



b)

TABLE 1 — ISOCHROMATIC FRINGE CHARACTERISTICS

Color	Approximate Relative Retardation		Fringe Order
	nm	in x 10^{-6}	N
Black	0	0.0	0.0
Pale Yellow	345	14.0	0.60
Dull Red	520	20.0	0.90
Red/Blue Transition	575	22.7	1.00
Blue-Green	700	28.0	1.22
Yellow	800	32.0	1.39
Rose Red	1050	42.0	1.82
Red/Green Transition	1150	45.4	2.00
Green	1350	53.0	2.35
Yellow	1440	57.0	2.50
Red	1520	60.0	2.65
Red/Green Transition	1730	68.0	3.00
Green	1800	71.0	3.10

Fig. 3. Analysis of a cantilever beam with use reflection polariscope: (a) mechanical load setup, (b) isochromatic fringe characteristics [7]

To improve the reliability of the process of assignment, isochromatic fringes to retardation level compensation techniques can be used. Commonly quantitative measurements methods in the glass industry are based compensator devices (Babinet, Babinet-Soleil) or on methods based on the rotation of the analyser [8]. The latter have the advantage that no additional equipment is required. Using the circular polariscope, Tardy's procedure can be applied. In this method, accuracies within ±1/25th fringe are readily obtained by visual observation. A similar technique for the fractional fringe order analysis is the Senarmont method in which only one quarter-wave is used. Although methods using a compensator and a rotating analyser are considered accurate, they are prone to human factors, because the determination of fringe centres and analyser rotation angle is a subjective process. For this reason, during the inspection of the same product by different quality control workers, the obtained results may vary significantly. The solution to this issue can be digital photoelasticity.

2. Digital photoelasticity methods

Conventional photoelasticity generally allows for accurate local point-by-point analysis of stresses in inspected objects but requires trained technician personnel. In the early development of digital photoelasticity, computer systems were used to automate the presented above procedures that were previously done manually. Progress in digital cameras and image processing enabled the development of new techniques using various polariscope arrangements for automatic full-field stress analysis. The existing digital techniques can be broadly classified into the frequency-domain (usually demanding many images to be analysed) and the spatial-domain (requiring fewer images) [9]. The most common automated methods of photoelasticity can be classified as follows [10]:

- Phase Shifting Methods
- Spectral Content Analysis
- Gray Field Polariscope
- Tricolor Photoelasticity
- RGB photoelasticity.

From the vast number of solutions available, only those that require single exposure without rotating any elements of the polariscope have be taken into further consideration for application in the on-line inspection system. One of the first approaches that was based on the analysis of intensity information for fringe ordering was a technique known as *half-fringe photoelasticity* (HFP) [11]. In this method, a circular polariscope arrangement with a monochromatic light source was applied. In a dark-field setup, the intensity of the transmitted light emerging from the analyser is given by following equation:

$$I = K \cdot \sin^2 \frac{\delta}{2} \tag{2}$$

where: K – a constant, δ – phase difference between two components of light.

According to this methodology, the image analysis system can distinguish grey levels in any interval between 0 to π/2, π/2 to π, and so on. The drawback of this solution is that which half-fringe corresponds to the recorded intensity on an image cannot be identified. Therefore, the stresses in the observed object should be in a range of $0<N<0.5$ for unambiguous results. However, in tableware glass quality control systems, it is not necessary to exactly measure the higher stress levels but to determine if a certain value (I_g) was exceeded (Fig. 4), which for annealed products should be less than about 120 nm/cm. Assuming the continuity of stress gradient further, the risks of not detecting a faulty product is minimal. It is also worth pointing out that in the original form of this method 256-gray level images was used but in currently available industrial cameras 12-bit dynamic range and more is commonly available, which can significantly improve the accuracy of the measurements.

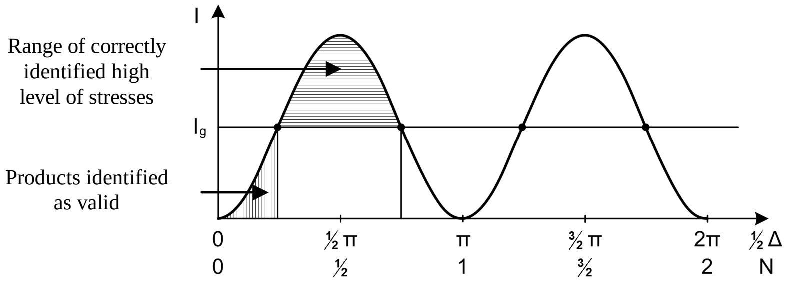


Fig. 4. The intensity values in the half-fringe photoelasticity method

For the determination of a higher fringe order, a RGB photoelasticity method can be applied. In this technique, a single acquisition by a colour camera of white light isochromatics in a circular polariscope is used. The camera decomposes the white light into three primary colours in three levels of intensity, which are usually denoted by the symbols R, G, and B. The determination of the relative retardation δ by means of a mathematical equation is not easy so a procedure based on a LUT (Look-Up Table) search is commonly used. Table 2 shows a typical progression of colours observed using a dark-field arrangement of polariscope. As it can be seen in the range of low levels of retardation, the isochromatic fringes appear in grey levels so that the R, G, and B levels for each value of δ are similar values. In this case, high errors in the evaluation of the retardation can occur using RGB photoelasticity, which is based on the analysis of colours.

Table 2. Look-up table for RGB photoelasticity method [12]

(1) Observed Colors	(2) Retardation Δ (nm)	(3) Relative Retardation $\delta = \Delta/\lambda_0$ $\lambda_0 = 590$	(4) R	(5) G	(6) B
black	0	0	5	4	5
gray	50	0.09	8	10	12
white	200	0.34	25	26	28
yellow	400	0.68	25	19	10
orange	450	0.76	22	13	6
red	500	0.85	16	6	12
tint of passage 1	590	1.00	7	11	24
blue	650	1.10	8	19	28
green	700	1.19	13	23	27
yellow	800	1.36	24	27	19
orange	900	1.53	28	22	8
red	1000	1.70	26	13	18
tint of passage 2	1180	2.00	11	18	26
green	1300	2.20	12	25	16
yellow	1400	2.37	21	24	12
pink-red	1550	2.63	27	14	24
tint of passage 3	1770	3.00	16	20	18
pale green	1800	3.05	14	22	16
pink	2100	3.56	25	18	19
tint of passage 4	2360	4.00	16	20	23
pale green	2500	4.24	19	19	21

The R, G, and B values stored in the LUT and the values acquired in the model to be analysed are influenced by many factors related to the characteristics and regulations of the hardware, the chromatic properties of the photoelastic material, and the gradient of the stress in the points of the model. Therefore, a precise calibration procedure should be performed for the determination of RGB values for a specific application [10]. It also worth noting that quarter-wave plates used in a circular polariscope setup are efficient for stress analysis using monochromatic light source, but they introduce errors with white light. These errors cannot be eliminated completely without using achromatic quarter-wave plates, but they can be minimized if calibration is performed at an isoclinic of 22.5° [13].

A similar method to the RGB photoelasticity is the tricolour technique [14]. In this solution a dark field plane polariscope is illuminated by a source that emits three narrowband wavelengths (Red at 619 nm, Green at 546 nm and Blue at 436 nm). Using a single acquisition and combining the light intensity detected at the three wavelengths, the retardation and the isoclinic parameter can be determined.

A different approach for the analysis of images is used in the Fourier transform method, which is based on the acquisition of isochromatics with the use of a circular polariscope setup equipped with carrier fringes. The significant limitation of this technique is the restriction to the orientation of the principal stresses that need to be aligned in the model and in the carrier [15].

3. Concept of in-line residual stress measurement system

In order to inspect tableware glass in-line there is a need to lift the object to expose the bottom, which is the area with the highest risk of the presence of a high level of residual stress. To fulfil this task, a gap transporter can be used (Fig. 5). This type of conveyor usually has two independent mechanisms to adjust the width for different sizes of inspected products. In this sort of solution, it is important to properly synchronize the speed of all conveyors.

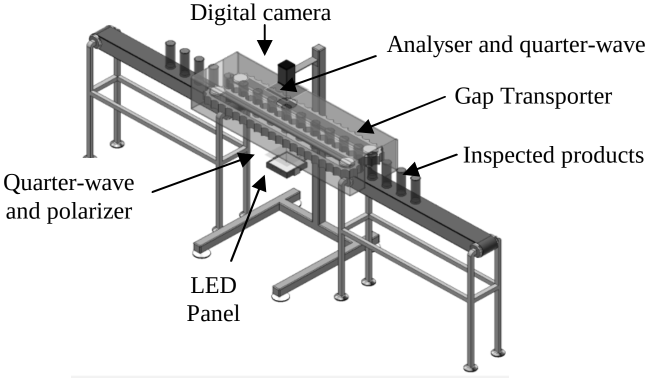


Fig. 5. The concept of an on-line residual stress measurement system

Another important aspect is ensuring a required speed of image analysis with respect to the production rate. For the inspection of non-stationary objects, the problem of image blur should also be solved. The magnitude of the image blur (B) depends on the velocity of object (v), the size of the field of view in the direction of movement (FOV), the sensor size (Ns), and the camera exposure time (Te). The equation given below enables one to calculate the parameters of a vision system:

$$B = \frac{v \cdot T_e \cdot N_s}{FOV} \tag{3}$$

For the typical production conditions of tableware glass production, the following values are assumed for calculation: the object speed v = 1 m/s and FOV=200 mm. In order to ensure a blur smaller than 1 pixel for a camera with a frame size of Ns=1000 pixels, the exposure time should be less than 0.2 ms.

4. Laboratory experimental setup and results

In order to validate the capabilities for on-line vision inspection of the residual stress levels in tableware glass products, an experimental set-up was made (Fig. 6). In the conducted tests, a dark-field plane polariscope arrangement was used. Depending on the applied method, a colour or monochrome camera was placed over the controlled product. Below the camera lens, a polarizing filter module (analyser) was installed, which is rotated using a stepper motor. A lightning unit (white or monochrome red) was located below the inspected article. On the surface of the LED panel, a polarizing filter film sheet (polarizer) was fixed.

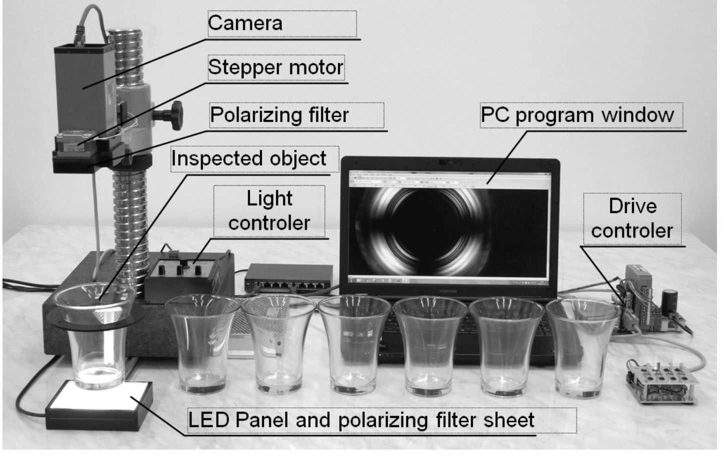
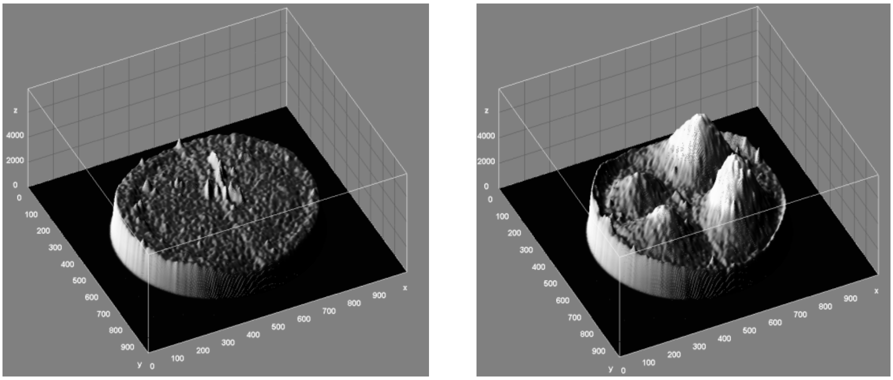


Fig. 6. Laboratory experimental setup for residual stress measurements

To determine the required angular position for the analyser, a stepper motor was used with a simple algorithm for searching a minimal intensity of acquired images. After that, without changing the intensity of the illuminator and the angular position of the analyser, a set of images of glass articles was recorded. Products selected for the test have been inspected by a qualified glassworks quality control worker and divided according to plant standards into two groups of faulty and correct articles. In the first stage of the tests, a colour camera was applied. However, the low levels of residual stresses in the tested annealed products did not produce the appearance of any expressive colours on the recorded images. Therefore, the implementation of a process of converting RGB values into the corresponding level of stresses would only introduce measurement errors. Additionally, it is worth noting that, due to the construction of RGB sensor (which has a relatively small area of individual pixels) and the demand for a short exposure time, this solution would require a more powerful light unit. Therefore, the RGB photoelasticity method was rejected from further consideration. In the subsequent studies, an industrial monochrome camera was used which captured 16-bit gray-level images with a resolution 1024x1000 pixels. The recorded images were filtered to remove local outliners caused by contaminations on the inspected products. The 3D plots below shows the intensity values (z-axis) on example images of tested articles. On an image of a valid product (Fig. 7a), the intensity is uniform in the analysed region of interest. On a second object where there are high levels of residual stresses, major changes in the intensity level and a characteristic isoclinic cross were observed (Fig. 7b).

a) b)



x, y – pixel coordinates on selected region of interest of image; z- 16-bit value of recorded intensity

Fig. 7. 3D visualization of intensity values in recorded images of (a) valid, and (b) faulty product

From a group of dozens of tested products, a simple image thresholding operation and a BLOB (Binary Large OBjects) detection algorithm were sufficient to correctly classify the valid products and the defective ones. Nevertheless, it should be pointed out that, for precise determination of the rejection level (I_g), a calibration procedure of the vision system should be conducted.

Summary

Customer requirements for quality have led tableware glass manufactures to seek solutions for inspection techniques that enable an on-line control of all manufactured products. Testing for residual stresses is an important element of the process of ensuring high quality articles. The purpose of this research was the assessment of the utility of digital photoelasticity methods for on-line inspection. After examining the state of the art from a large number of existing solutions, methods that meet the conditions of application in industrial environments have been selected. The experiments performed on a laboratory setup allowed the confirmation of the possibility of using a machine vision system for residual stress level measurements of tableware articles. However, further work is necessary for developing calibration procedures for the proposed system. Additionally, it is necessary to conduct supplementary tests with a circular polariscope arrangement and products moving at production rates in order to determine the effect of image blurring on the measurement results. Nevertheless, it can be concluded that the proposed on-line residual stress measurement system can be used to observe trends in the manufacturing process or to reject products with significant deviation from the norm.

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Automatyzacja pomiaru naprężeń resztkowych w produktach szklanych

Słowa kluczowe

Automatyczna Optyczna Inspekcja, elastooptyka, szkło użytkowe.

Streszczenie

W artykule przedstawiono analizę możliwości opracowania systemu do automatycznego pomiaru on-line naprężeń w produktach szklanych. W pierwszej części przedstawione zostały konwencjonalne techniki elastooptyki wraz z ich ograniczeniami. Następnie zaprezentowane zostały metody pomiaru naprężeń oparte na cyfrowej analizie obrazu. Na podstawie przeprowadzonej analizy zaproponowana została koncepcja systemu wizyjnego do pomiaru naprężeń resztkowych zintegrowanego z linią produkcyjną. W ostatniej części artykułu zaprezentowane zostały przykładowe wyniki pomiarów uzyskane na opracowanym eksperymentalnym stanowisku laboratoryjnym.