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The Analysis of Residual Stresses by Photoelastic Method

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Abstract

Photoelasticity is a practical, fast, low cost technique can be applied effectively in the measurement of residual stresses and helped in controlling the quality of products, it is a visual method for measuring the stress through the full-field and this stress-analysis method is suitable for measuring the internal stresses of both simple and complex shapes. The photoelastic method has based on measuring the birefringence of polarized light as well as depends on the variation of speed and direction of the light velocity through its passing into the polymer sample. Photo elasticity is an experimental nondestructive technique for analysis of stress and strain depends on an optical mechanical property denoted as birefringence, this property has possessed by several transparent materials such as glasses, crystals and some polymers.

Keywords**:** photoelasticity, residual stress, polarization, birefringence, refraction.

1.Introduction

Photo elastic stress analysis has become a technique of outstanding importance to engineers over the years and it is vital to understand stress and strain definition in a body [1,2]. Photo elasticity is an experimental nondestructive analysis technique depends on the photo elastic influence that represents a variation in the optical indication due to the mechanical stress [3]. The discovery of photo elasticity effect is accredited by Sir David Brewster who published the write up of his finding in 1816 through the examination of clear stressed glass with polarized light which exhibited color patterns [2, 4]. This method is cheap, fast and very simple [3].

The photoelastic method has investigated the surface and internal stresses of the material and provides us with (distribution of general stress , sites of stress concentrations and areas of flow stress) as well as the designs have modified after obtaining these results [3]. On the other hand, this method has used to give qualitative assessment of the stress state in the molded products where the colors have generated and the spaces for various contours of color have characterized the regions of high stress [5].

The amorphous mediums are isotropic when unstressed and become anisotropic when stressed [1, 2]. The isotropic materials have contained the same physical and mechanical properties throughout its volume in every direction [6]. In anisotropic materials the properties have changed with direction [2, 4], this anisotropic behavior is calculated due to the chemical configuration and chain conformation, the anisotropic behavior has canceled out on a macroscopic scale if the macromolecules are randomly coiled [7].

2.Literature Survey

Postawa *et al* [2006] investigated the influence of amorphous polystyrene processing on the diversity of the internal stresses from the injection molded piece and used the standardized mold piece designed for the investigations of the processing shrinkage of thermoplastic materials. They prepared the samples by using the Design of Experiment (DoE) and presented a new approach to fast estimation of the residual stresses.

Five elements were studied to explain their effect on the changes in isochromatic layout as(temperature of mold, temperature of injection, pressure of clamping, time of cooling, and the speed of injection). The knowledge on this dependence between the injection conditions and the state of internal stresses in mold pieces is necessary and important especially during the manufacturing of technical mold pieces such as mechanical gearing and fan rotors. They were demonstrated that convene pressure and temperature of injection are the importance worth. The implementation of higher temperature of injection and lower convene pressure was more appropriate[11].

Morantes *et al* [2014] studied the residual stresses in pieces produced by the injection molding . Two factors the molding temperature and time of cooling were taken in study. Two types of crystal polystyrene produced. The reason of choosing polystyrene was the using it for high performance components. The distribution of residual stresses was concluded by using photoelasticity. The residual stresses increased at low temperature because the processes of formation and destruction of intermolecular forces. The internal stresses decreased in polymer parts with great thickness due to the molecular relaxation of polystyrene chains which led to facilitate by the increasing space between the wall and the mold. They reached to the photoelasticity technique can be applied effectively in the measurement of residual stresses for injection molded crystal polystyrene parts. The cooling of thin walls in the molded part is faster than in areas of greater thickness thus the residual stresses are higher at lower thickness. The important element to control the process of injection molding is the temperature. It is caused a higher effect on internal tensions of the parts produced by injection molding. There were comparing between the images obtained ad images of previous studies[8].

Kotila [2018] used a plane polariscope to analyze injection molded PET samples to investigate their internal stresses that caused due to thermal contraction (shrinkage) during processing and this investigation could find practical application in polymer industry for both small and large enterprises. A recent method of data analysis was used where images were captured from the samples and then the data from the image is extracted to create a pixel count-intensity graph. The difference in loads applied to the samples leads to difference in the consequences between internal and induced stresses. [3]

3.Light and Electromagnetic Spectrum

A source of light is needed to perform photo elastic stress analysis, the light is electromagnetic radiation whereas the waves of light have gone in all directions through propagation [3]. The light transfers in a vacuum or air at speed (C=3.00×10^8 m/s), the speed is lower in transparent bodies [3]. The chart of electromagnetic spectrum of various zones is shown in Figure (1) [4].

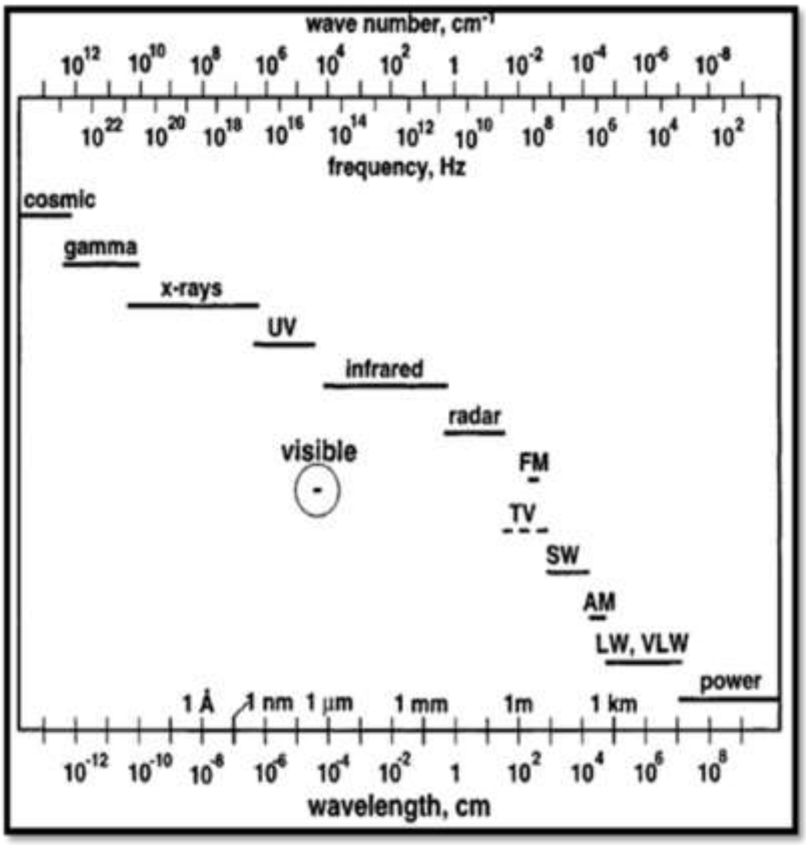

Figure (1): The electromagnetic spectrum [4]

The electromagnetic spectrum covers very wide range from radio to X-ray waves with wavelengths between (1m or more - less than billionth of meter). The optical radiation on the electromagnetic spectrum between radio waves and X-rays have exhibited unique combination of (ray, wave and quantum properties). At shorter wavelengths of X ray, the electromagnetic radiation behaves as particle like while at the other end with longer wavelengths behaves mostly as wavelike, the visible portion has occupied an intermediate position which exhibiting properties of wave like and particle like with different degrees [4].

Monochromatic and polychromatic represent two fundamental series of light. Laser light is an symbol of a monochromatic light which characterized by honly one frequency. Sources of monochromatic are chosen when quantitative photoelastic measurements are necessary. The white light is an example of polychromatic light which had many various frequencies[3].These individual wave lengths or monochromatic lines may be polarized as plane, circularly, elliptically. The white or polychromatic light includes a combination of lights with various wave lengths, the intensity of light is proportional to the square amplitude of vibration [4].

The frequency of light is related to its color [3]. In photo elasticity, the range of band color usually called monochromatic lines which having various frequencies and have distinguished from one another through the color sense, for visible light the entire range of colors frequency in the spectrum approximately between 90 nm (deep red) to 700 nm (deep violet) [4]. There are two convenient ways to describe the propagation of the light and its interaction with materials: electromagnetic wave model and quantum model.

The light comprehensives (infrared, ultraviolet, and radio) waves. It is treated in the form of electromagnetic waves. Whenever, the wave of trains of radiation can be depicted perfectly by two vectors that vertical to the direction of ray travel and perpendicular to each other. The electric and magnetic are these vectors. They exist at the same time at right angle planes such that the intersection line of planes is parallel to the direction of ray light. The term polarization commonly used to denote several kinds of control over the existence of light vector, the ordinary light without any polarizer has the behavior shown in Figure (2) [4].

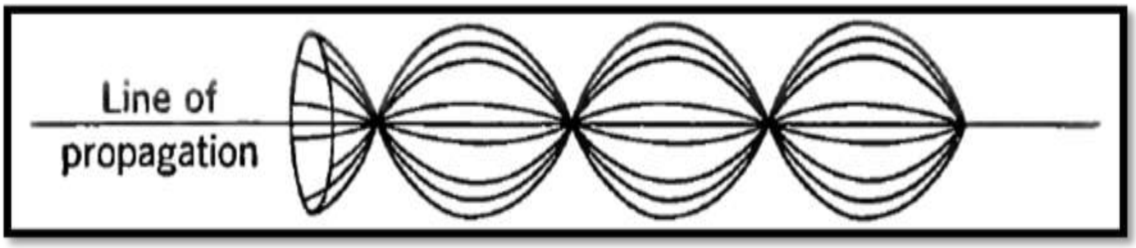

Figure (2): Ordinary light without control over light vector [4]

The relevant standard ASTM D4093 is standard test of photo-elastic technique for measuring birefringence and residual strains into transparent or translucent polymers, this standard for photoelastic measurements deals with quantitative analysis [10,9].

4.The Index of Refraction :

The change in direction of a wave passing from on medium to another and caused by its change in speed is known as the refraction in physics [3]. Figure (3) shows the refractive index when light passes from one medium to another [12].There is a change in velocity according to the passing of light from one medium of certain density to the other medium with different density, the index of refraction is the ratio of these velocities [4]:

$$\text{Index of Refraction} = \frac{\text{Velocity in 1st medium}}{\text{Velocity in 2nd medium}} \qquad \text{Eq.(1)}$$

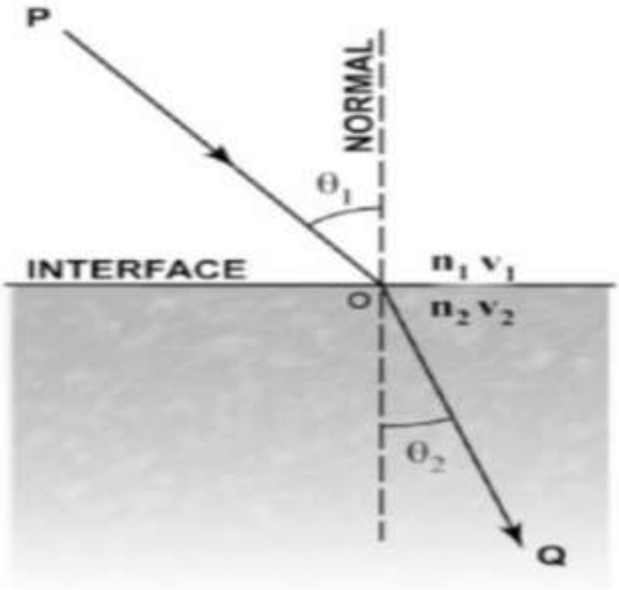

Figure (3):Refractive index while passing from one medium to other [12]

The index of refraction changes with the level of stress and this optical property is making the basis of photo elasticity technique [3]. Isotropic polymers have exhibited a temporary double refractive index when they are stressed [4].

5.The Polariscope Instrument:

The polariscope is a device has used for performing the analysis of photo elasticity [3], The manufactured polariscope has shown in Figure (4) which consists of light source L and polarizator P [4]. Polarimeter is developable segment of device where polarimeter and identification of material are necessary to characterize the constant of material, this material constant is unique for each material and requires non trivial identification proceeding [5].

Figure (4): Polariscope with light source and polarizator [4]

6.The Polarized Light :

The polarized light method is a typical nondestructive measurement method has used for polymer analysis [10]. The qualitative evaluation of stress in a molded or extruded part can be performed inexpensively using polarized light [9]. When a beam of polarized light passes through an elastically stressed specimen which consists of transparent isotropic material . The decomposing of beam into two rays polarized in the planes of principles stresses[15]. The light is plane-polarized when the vector of light is confined to a single plane, the plane that contains vector of light has called as the vibration plane while the plane at right angles has called the polarization plane as shown in Figure (5) [4].

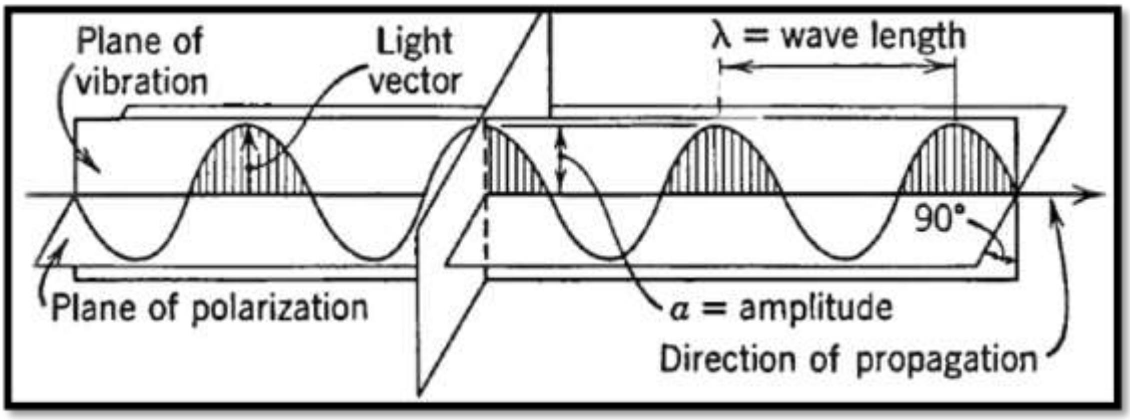

Figure (5): Plane of polarization [4]

The optical polarization of a polymer chain is anisotropic where the polymer backbone has various polarization in the longitudinal and transverse orientations [7]. The fringe patterns have formed when polarized light passes through a stressed transparent model and offered immediate qualitative information [3]. This pattern of birefringence generates a contour of color that related to the amount of present stress through the part cross-section as shown in Figure (6) [5].

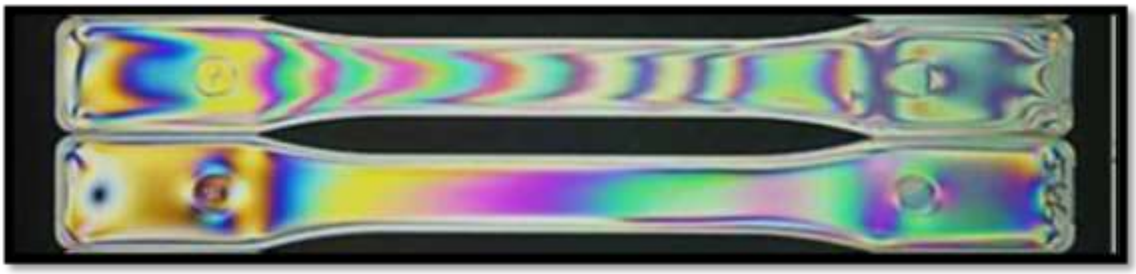

Figure (6): The pattern of birefringence for tensile specimens from polycarbonate [5]

7.Fundamental Optical Laws of Photo elasticity:

Photo elasticity depends on the birefringence phenomenon which denotes to the anisotropy of transparent strained material and consequently the refraction index (n) which has become directional. In this technique, the transmission light through strained materials has obeyed the two subsequent laws that have formed the principle of calculating photo elastic stress:

1. The direction of polarizing light is the principal-stress axes and has transmitted only on the principal stress planes.

2. The transmission of velocity on each principal plane has depended on the intensities of principal stresses in these two planes, while the variation in the refraction index has given due to the subsequent equations [4]:

$$\delta_1 = n_1 - n_0 = A\sigma_1 + B\sigma_2 \qquad \text{Eq.(2)}$$

$$\delta_2 = n_2 - n_0 = A\sigma_1 + B\sigma_2 \qquad \text{Eq.(3)}$$

Where :

δ_i = The index of refraction on i axis

n_0 = The refractive index of material free of stress

n_1 =The refractive index on the principal plane 1

n_2 =The refractive index on the principal plane 2

σ_1 & σ_2 = The principal stresses

A & B =The material photoelastic constants

In this technique, the variation between the refractive indices on the principal planes has given due to [4]:

$$\delta_1 - \delta_2 = n_1 - n_2 = (A - B)(\sigma_1 - \sigma_2) = C_B(\sigma_1 - \sigma_2) \qquad \text{Eq.(4)}$$

Where

C_B =The constant of differential-optical stress

The stress-optical equation has established that the double refraction is proportional directly to the variation in principal stresses that is equal to the variation between two indices of refraction which revealed by the material under stress. Due to the differences between the refraction indices and the stress-optical constant or (Brewster's) constant, it is possible to determine the principal stresses variation. The variation between the indices of refraction has calculated by dividing the retardation value on the material thickness [4]. According to the difference in velocity, the vibrating waves along two principal planes have emerged out of phase, the relative distance or retardation (δ) has given by:

$$\delta = (n_1 - n_2)t = C_B t(\sigma_1 - \sigma_2) \qquad \text{Eq.(5)}$$

or

$$n = \delta/\lambda = C_B t(\sigma_1 - \sigma_2) / \lambda \qquad \text{Eq.(6)}$$

Where:

t=The thickness of material for passing the light through it

λ =The light wavelength that is 570 nm for polymer due to the ASTM standard while the equation has represented the stress-optical law [4].

The retardation (δ_{nm}) due to the light source can be calculated by multiplying the value of compensator (R) and correction constant ($b_{nm/division}$) according to this relation (δnm = R x bnm/division). The residual stress (σ) can be calculated by dividing the retardation value (δ_{nm}) of material which is accounted from the previous relation on the result of multiplication between thickness (t) and stress constant ($C_{Brewster}$) according to each temperature due to the following relation:

($\sigma = \delta_{nm} / (t \times C_{Brewster})$) [10].

8.The Procedure of Measuring Residual Stresses:

Photoelasticity differs from other procedures because it gives us information of the stress already existent on the surface and within the material. Residual stresses are related to errors in processing and could also originate failure of the material [3]. The measurements of photoelasticity have carried out by the sample insertion into the polariscope, lighting it with a source of white light, arresting the image and saving it in format file of JPEG and conversion of JPEG file by using a software into text format and lastly analyzing the extracted numbers from digital images by the data extraction from photos, the stress analysis is possible by noticing the intensity of average light with pixels.

The load and thermal healing analysis has shown that the intensity difference has depended on the stress magnitude, also the thermal healing is effectual during the relieving of internal stress as well as it is possible to notice the location of stress acting [3]. The digital images have captured from the samples when performing stress analysis by a photo elastic method where the digital photo is an assembly of numbers where these numbers have stored, modified, transmitted and converted into something to see. Every part has captured in the digital image form that is a pattern of light and dark areas, these areas have divided into pixels which are very small squares.

Every digital photo has numbers described the image, these numbers have represented the average brightness or intensity at each pixel for example the darkest part of the image is zero and the lightest is 255 [3]. The essential benefit is concentrated on the value of retardation (δ) or reading (r),for which maximal and minimal value of n are get.

If $\delta/\lambda=n$, where n=0,1,2…, the interaction between two waves is called constructive interference. On the other hand, if it takes its minimum value, zero in this ideal case, for $\delta/\lambda=1/2,3/2…$, this situation is called destructive interference and causes dark fringes, the regions of the highest concentration from isochromatic lines have represented the locations of residual stresses [4].

Figure (7) shows a single-wedge model LWC-100 equipment (also called quartz wedge or babinet compensator) has used to determine the retardation value and made of synthetic crystal materials. This compensator exhibits a linearly-variable retardation and when observed in polarized light will show equidistant fringes [4].

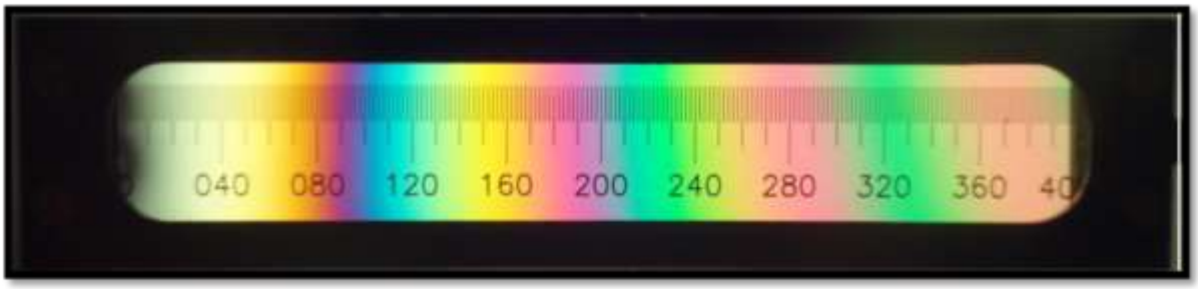

Figure (7): The compensator LWC-100 used to determine the retardation value [4].

A linearly scale of the compensator permits location of these fringes and calibration. The compensator of model (LWC-100) has calibrated by the usage of an interferometer filter that transmitting through band of 10 nm at the standard wavelength that has defined by ASTM (F218 & D4093) standard tests where the wavelength for polymers is 570 nm [4].

Residual stresses are related to errors in processing and could also originate failure of the material [3]. The analysis of residual stresses is complex by the induced molecular orientation during processing. The birefringence technique measures the changing in optical properties of a polymer due to the presence of residual stresses, birefringence has several limitations for opaque materials [13]. However, the residual stresses have resulted distortion and induced anisotropy of polarization that has calculated due to the measurement of birefringence [7]. The resulting birefringence patterns are a qualitative indication of residual stress in the sample [9]. Figure (8) shows the principal of birefringence polariscope that utilized in determining the residual stresses from transparent components of polymer where polarizer & analyzer is set up ± 45℃ direction [14, 10].

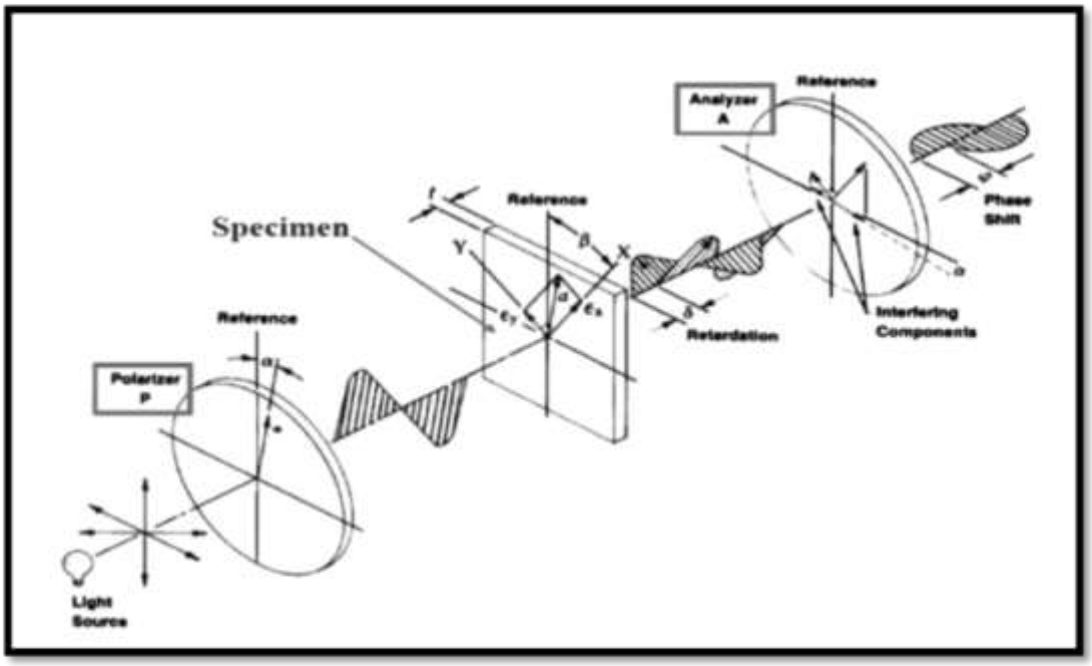

Figure (8): Polariscope for measurement of residual stresses [14]

9.Conclusions

1- The photoelastic method is not effectual for highly crystalline or semi-crystalline (nontransparent) materials.

2- This technique is only possible to analyze parts with a translucent or transparent material which allows light to pass through it .

3-The analysis of residual stresses is complex according to the oriented molecules that caused by manufacturing.

4-This technique has limitations for several amorphous polymers such as acrylic that does not exhibit the birefringence pattern due to the presence of stress.

5-The part geometry should be simple and plate-like structure for best stress analysis.

6- This method cannot be used easily to quantify the residual stress of part.

7- The contour of colors does not recognize between compressive or tensile stresses.

8- In cylindrical specimens, the variable angle of entrance the polarized light and angle of viewing the specimen have reduced the photo elastic analysis into a more qualitative assessment.

9- It is not possible to perform this analysis in manufacturing conditions.

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