Photoelastic Stress Analysis of Polyethylene Terephthalate

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Abstract:

Photoelasticity is an experimental stress/strain-analysis method. This technique is based on the photoelastic effect which is a change in the optical indicatrix with mechanical stress. A polariscope is an instrument used for photoelastic stress analysis. In the research performed to write this paper a plane polariscope was used to analyse injection moulded PET samples. The main objective of this work is to investigate the internal stress in PET caused due to thermal contraction (shrinkage) during processing. A new method of data analysis is used where pictures are captured from the samples and then the data from the image is extracted to create a pixel count-intensity graph. Different loads were applied to the samples and the difference in the results between internal and induced stresses were compared. An investigation to verify if thermal healing methods can relieve the concentrations of stress within the material was also performed. The general process was made by inserting the sample into the polariscope, illuminating it with a white light source, capturing an image, saving the image in JPEG file format, converting the JPEG file into text format using a software, and finally analysing the numbers extracted from the digital images. The text illustrates that by extracting data from pictures, it is possible to analyse the stresses by observing the average light intensity in the pixels. The load and thermal healing analysis showed that the change in intensity is indeed depending on the magnitude of stress. Thermal healing also showed to be effective when relieving internal stress. It was also possible to observe the location where the stress is acting.

Keywords: photoelasticity, stress concentration, PET, injection moulding, light intensity, digital images, thermal stress relaxation, polarized light
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# Abbreviations

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<tbody>
<tr>
<td>AVG</td>
<td>Average</td>
</tr>
<tr>
<td>IMM</td>
<td>Injection Moulding Machine</td>
</tr>
<tr>
<td>IMP</td>
<td>Injection Moulding Process</td>
</tr>
<tr>
<td>IR</td>
<td>near-, mid-, and far-infrared</td>
</tr>
<tr>
<td>JEPG</td>
<td>Joint Photographic Experts Group</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene terephthalate</td>
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<tr>
<td>Pixel</td>
<td>Picture Element</td>
</tr>
<tr>
<td>PPL</td>
<td>Plane-Polarized Light</td>
</tr>
<tr>
<td>RGB</td>
<td>Red, Green, Blue</td>
</tr>
<tr>
<td>RP</td>
<td>Reflection Photoelasticity</td>
</tr>
<tr>
<td>TP</td>
<td>Transmission Photoelasticity</td>
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<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
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</tbody>
</table>
**Symbols**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Units [SI]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>C</td>
<td>Speed of light</td>
<td>$[m/s]$</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>$[N]$</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>I</td>
<td>Intensity of light</td>
<td>$[W/m^2]$</td>
</tr>
<tr>
<td>K</td>
<td>Strain-optical coefficient</td>
<td>–</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>$[kg]$</td>
</tr>
<tr>
<td>N</td>
<td>Fringe order</td>
<td>–</td>
</tr>
<tr>
<td>N</td>
<td>Number of molecules per unit volume</td>
<td>–</td>
</tr>
<tr>
<td>n</td>
<td>Refractive index</td>
<td>–</td>
</tr>
<tr>
<td>P</td>
<td>Photoelastic coefficient</td>
<td>–</td>
</tr>
<tr>
<td>P</td>
<td>Internal resultant force</td>
<td>$[N]$</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>$[°C]$</td>
</tr>
<tr>
<td>V</td>
<td>Speed of light in transparent bodies</td>
<td>$[m/s]$</td>
</tr>
<tr>
<td>V</td>
<td>Internal resultant shear stress</td>
<td>$[N]$</td>
</tr>
<tr>
<td>α</td>
<td>Polarizability</td>
<td>$[C \cdot m^2/V^{-1}]$</td>
</tr>
<tr>
<td>δ</td>
<td>Relative retardation</td>
<td>$[nm]$</td>
</tr>
<tr>
<td>$\Delta B_{ij}$</td>
<td>Change in indicatrix under stress or strain</td>
<td>–</td>
</tr>
<tr>
<td>$\Delta I$</td>
<td>Change in maximum intensity (RGB max)</td>
<td>–</td>
</tr>
<tr>
<td>$\Delta s$</td>
<td>Length of a line in an undeformed body</td>
<td>$[mm]$</td>
</tr>
<tr>
<td>$\Delta s'$</td>
<td>Length of a line after deformation</td>
<td>$[mm]$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Strain</td>
<td>–</td>
</tr>
<tr>
<td>$\epsilon_{avg}$</td>
<td>Average normal strain</td>
<td>–</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>$[nm]$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>$[kg/m^3]$</td>
</tr>
<tr>
<td>$\sigma_{avg}$</td>
<td>Average normal stress</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$\tau_{avg}$</td>
<td>Average shear stress</td>
<td>$[Pa]$</td>
</tr>
</tbody>
</table>
A very special thanks to my thesis advisor Mr. Rene Herrmann for all guidance and time invested throughout this research. Furthermore, I wish to express my appreciation to Arcada’s Lectures, in special Mr. Mathew Vihtonen for all the valuable lessons and feedbacks that were essential when writing this work. I would like also to thank Mr. Stewart Makkonen and Mr Erland Nyroth for all advice and direction given during my studies.

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Gabriela dos Santos Kotila
1 INTRODUCTION

When developing a product there are important points to be considered before the design is created. An example is the choice of the best material to be used. There are several methods to determine different properties within a material. Having a good knowledge of the materials limitations is important to prevent failure of the product. Most methods of stress analysis investigate how a material will react under a force. These methods investigate the amount of stress which will cause the material to fail. With photoelasticity it is possible to investigate the stress on the surface and inside the material.

1.1 Background

Photoelasticity is an experimental stress and strain analysis technique based on an optical mechanic property referred as birefringence. [1] This property is possessed by many transparent materials such as crystals, glasses and some polymers. This stress-analysis technique is convenient when investing internal stress in products with complex shapes. The results obtained allow us to modify the part by relieving internal stress or removing materials from areas with low stress.

To perform photoelastic stress analysis a source of light is needed. Light is electromagnetic radiation that when propagates its waves go in all different directions. A polariscope is an instrument used when performing photoelastic analysis. When polarised light passes through a stressed transparent model, interference patterns or fringes are formed. [2]

The specimens used for this research were injection moulded. When injection moulding a product, multiple defects can happen. Some of these defects will cause concentrations of stress throughout the sample. One example of a defect is called thermal contraction of the product (shrinkage). If shrinkage of the plastic cannot be compensated in certain areas,
sink marks will occur during the cooling process causing stress concentrations in the product. [3]

One way to remove the internal stress in materials, is through stress relief. Stress relief can be done in many different ways such as thermal relaxation. In this method the part is heated uniformly in a constant temperature during a period of time. With thermal relaxation it is possible to obtain material yield strength reduction, stress redistribution, and elastic relaxation. [4]

1.2 Methodology

An experiment using PET samples was performed by a student also at Arcada University, however due to small stress concentrations on her samples it was not possible to observe a clear fringe pattern. [5] An experiment in composites using photoelasticity to analyse thermoplastic-thermoset interface (PET/Epoxy), revealed shear stress distribution through isochromatic fringe patterns. [6] Photoelastic coating technique method, also showed good results when used to analyse wooden beams reinforced with carbon fibre reinforced polymers. [7] All the research performed above studied the stresses in the samples by observing and counting the fringe patterns. In this work a different approach is used.

When performing a photoelastic stress analysis, digital images are captured from the samples. A digital picture is a collection of numbers. These numbers can be stored, modified, transmitted and converted into something that it is possible to see. Every scene captured in a digital image is a pattern of light and dark regions. These regions are divided into very little squares called a “pixel”. Every digital picture has numbers which describe the image. These numbers represent the average brightness (intensity) in each pixel, such as that the darkest part of the image is zero, and the lightest is 255. [8] In this research this range value from 0 to 255 is used to investigate the intensity of light in PET samples.
due to stresses influence. Values close to 0 indicate small amount of stress while values close to 255 represent higher stresses.

1.3 Objectives

The research conducted in this paper is a qualitative research. Qualitative research seeks answers to a question, systematically uses a predefined set of procedures to answer the question, collects evidence, produces discoveries that were not determined in advance and produces findings that are applicable beyond the immediate boundaries of the study. Qualitative research is used to interpret and to better understand the complex reality of a given situation and the implications of quantitative data. [9] It is aimed to investigate throughout this paper the internal stresses in injection moulded PET samples. The main goals are

- Use photoelasticy to study the stress concentration caused during injection moulding process, and possible reasons which created the stress.
- Try to relieve the stress concentration using methods of stress relaxation such as thermal relief.
- Apply several loads in the samples and then analyse the difference in light intensity due to induced stresses.
- Extract data from the digital images and analyse the light intensity average in the pixel count caused by stresses in the sample.

This paper is divided into six chapters. The first chapter explains the importance of this research, the utilized methods and its main objectives. The second chapter presents a literature review about major topics needed to understand the research performed in this work. Chapter three describes how the experiments were performed and how the data was collected. In the fourth chapter the results obtained are presented. The fifth chapter discusses the results from the experiments. The sixth chapter concludes the findings of the research and presents alternative methods of analysis.
2 LITERATURE REVIEW

2.1 Mechanics of Materials

Mechanics of materials is the field which studies the effects of stress and strain in a solid body. These effects are a result of an external loading. While stress is associated with the strength of the material, strain is a measure of the deformation of the body. [10] Since Photoelasticity is a stress/strain analysis, it is vital to understand stress and strain definition in a body.

2.1.1 Stress

As described previously, stress is associated with the strength of the material. Let us consider figure 1. A load \( P \) is applied to the bar (c). The load acts through the centroid of its cross-sectional area. This will make the bar deform uniformly throughout the central region of its length. When separating the bar into two parts (d), equilibrium requires the resultant force at the section to be \( P \). Due to the uniform deformation (material is homogeneous and isotropic) of the material, it is necessary that the cross section is subjected to a constant normal stress distribution.

![Figure 1: Applied force on a bar and stress distribution on a sectioned area. [10]](image)
As a result, each small area $\Delta A$ on the cross section is subjected to a force $\Delta F = \sigma \Delta A$. The sum of these forces acting over the entire cross-sectional area must be equivalent to the internal resultant force $P$ at the section. If $\Delta A \to dA$ and $\Delta F \to dF$, then recognizing $\sigma$ as a constant it is obtained: [10]

\[ + \uparrow F_{rz} = \sum F_z; \quad \int dF = \int_A \sigma \, dA \]

\[ P = \sigma A \]

\[ \sigma_{avg} = \frac{P}{A} \quad (1) \]

Where,

$\sigma_{avg}$ = average normal stress at any point on the cross-sectional area ($Pa$)

$P$ = internal resultant force, which acts through the centroid of the cross-sectional area ($N$)

$A$ = cross-sectional area of the bar where $\sigma$ is determined ($m^2$)

Another category of stress is the average shear stress. Shear stress is the stress component that acts in the plane of the sectional area (figure 2) and it can be determined as: [10]

\[ \tau_{avg} = \frac{V}{A} \quad (2) \]

Where,

$\tau_{avg}$ = average shear stress at the section, which is assumed to be the same at each point located on the section ($Pa$)

$V$ = internal resultant shear force on the section determined from the equations of equilibrium ($N$)

$A$ = area at the section ($m^2$)
2.1.2 Strain

As mentioned previously, strain is a measurement of the deformation of the body. The normal average strain is defined as: [10]

\[ \varepsilon_{avg} = \frac{\Delta s' - \Delta s}{\Delta s} \]  (3)

Where \( \Delta s \) (mm) represents the length of a line in an undeformed body and \( \Delta s' \) (mm) represents the length of the same line after deformation of the same body.

2.2 Injection Moulding Process

Injection Moulding is a polymer processing method used to create products in a certain desired shape. The plastic is poured into a hopper, then melted in a screw located inside the barrel. This screw rotates while melting the plastic. Later, the plastic is injected into a mould where it is moulded into the final product. An example of an injection moulding machine (IMM) and injection moulding process (IMP) can be seen from figure 3.
2.2.1 Part Defects

One of the causes for stress concentrations in injection moulded parts is due to poor choice of settings in the parameters of the IMM. It is normal that the amount of stress concentration will probably be localized in the areas with drastic shape change, or where the material is poorly distributed.

Sink marks is one of the reasons for internal stress. Typically, sink marks occur during the cooling process. The cause for this, is because thermal contraction happens when the part is cooling. This is termed as shrinkage. When the product suffers shrinkage, sometimes the plastic cannot be compensated in certain areas. This could be related to slow solidification, not enough time for effective holding pressure, or not enough holding pressure transfer because the flow resistances in the mould are too high. [3] Figure 4 shows an example of sink marks in a product.

Figure 3: Injection moulding process example. [11]

Figure 4: Sink marks due to wall thickness variations. [3]
To prevent sink marks, a change in the settings of the machine is necessary.

### 2.3 Polyethylene Terephthalate

#### 2.3.1 Material Description

Poly(ethylene terephthalate), PET or PETE is an oil based material and it is a widely used semicrystalline polymer from the polyester family. Whinfield and Dickson, (England) were the ones who formed for the first time the polyester. They did this by employing an ester interchange reaction between ethylene glycol and methyl ester of terephthalic acid. [12] Figure 5 shows this reaction.

![Figure 5: PET reaction. [12]](image)

While PET is normally made from the reaction above, it can also be made from the ring opening reaction with ethylene glycol as shown below.

![Figure 6: Ring opening reaction with ethylene glycol. [12]](image)
The microscopic properties of PET such as, thermal, permeation and the most important property for this work the optical property depends on its specific internal morphologies and microstructure arrangement. [13] PET may appear opaque, white or transparent depending on its crystalline and amorphous structure. [14]

2.3.2 Absorption by Visible and Ultraviolet Light

The absorption of photons is associated to their interaction with the outer shell electrons. The photons energies range from 1.6 eV (λ = 800 nm) to about 6.2 eV (λ = 200 nm), where eV is the electronvolt and λ is the wave length. The time scale for absorption is about 10⁻¹⁵ s. There are two prerequisites for the absorption of a photon of energy hν by a polymer. The first requisite is that the molecule must contain a chromophoric group with excitable energy states corresponding to the photon energy. The second is that the transition between the two energy group states is required to cause a change in the charge distribution within the molecule e. g., a change in the dipole moment. [15]

2.3.3 Absorption by Infrared Radiation

The infrared portion of the electromagnetic spectrum is normally divided into the near-, mid-, and far-infrared (IR) regions. In the case of small molecules, the IR photon energies correlate to rotational motions. For large molecules it correlates to collective intramolecular and intermolecular vibrational modes (far-IR), fundamental vibrations (mid-IR), and to overtone and combination vibrations (near-IR). The molecules rotate, and the atoms of the molecules vibrate at frequencies correlating to the discrete energy level. The shape of molecular potential energy surfaces, the mass of the atoms, and the association vibronic coupling determine the discrete level. There are also two conditions necessary for the absorption of emission of IR of frequency ν. In the first condition, the photon energy hν must correspond to the difference of discrete energy levels. The second condition is the same presented in the absorption by visible and ultraviolet light. If the
molecules in the unit cell of crystalline polymers are placed close enough together, the interaction of polymers chains can result in a detectable effect. [15]

2.4 Photoelasticity

2.4.1 Definition

Photoelasticity is an experimental stress analysis. This technique uses amorphous materials (such as crystals, glasses and polymers). Mediums containing this property are isotropic when unstressed and when stressed they become anisotropic. [16] Isotropic materials, contain the same physical and mechanical properties throughout its volume in all directions. [10]. In anisotropic materials the properties change with the direction. This optical effect is referred to as temporary optical birefringence and it was observed the first time by Sir David Brewster (1816). [16]

Photoelastic stress analysis has become a technique of outstanding importance to engineers over the years. Engineers have been able to use photoelasticity as a method of stress/strain analysis to analyse bodies with complicated shapes.

The fringe patterns formed when polarized light passes through a stressed transparent model, provide immediate qualitative information. These informations give us general distribution of stress, positions of stress concentrations and areas of low stress. Once these results are obtained, the designs can be modified. After a photoelastic stress analysis we can immediately notice if stress concentration in the areas of the body needs to be reduced or dispersed, or if excess materials need to be removed from areas of low stress. Photoelastic analysis provides an effective method of failure investigation, reduction in weight and material cost, and often produces valuable information leading to succesful re-design. [17] Figure 7 shows the photoelastic effect.
2.4.2 Photoelastic Properties of Materials.

Photoelasticity has already been defined as a stress/strain analysis technique which utilizes the photoelastic effect. The photoelastic effect was described as a property of some transparent materials. In this section will be shown the property in a molecular level. On the following will be explained why certain materials have this property.

When a material possesses a sizable photoelastic coefficient \( p \), this material is required to enhance the interaction between mechanical strain \( \epsilon \) and refractive index \( n \). The change in indicatrix is defined as: [18]

\[
\Delta \left( \frac{1}{n^2} \right) = p \epsilon \tag{4}
\]

The optical indicatrix is a single-valued surface which specifies the relationships between refractive indices, wave normals, polarization directions, and energy flow directions (= ray directions). [18]

Since strain and refractive index are dimensionless, photoelastic coefficients also are. To clarify the effects of stress on refractive index, it will be considered the effect of
hydrostatic pressure on a crystal cube. The following equation is the Lorenz-Lorentz
equation and it is valid for many cubic materials [18].

\[
\frac{n^2-1}{n^2+1} = KN\alpha
\]  (5)

Where,

K is a proportionality constant
N is the number of molecules per unit volume
\(\alpha\) is the polarizability per molecule \((C \cdot m^2/V^{-1})\)

Differentiating with respect to density \(\rho\) \((kg/m^3)\), gives,

\[
\frac{dn}{d\rho} = \frac{(n^2-1)(n^2+2)}{6n\rho} \left(1 + \frac{\rho}{\alpha} \frac{d\alpha}{d\rho}\right)
\]

This leads to an estimated photoelastic coefficient \(p\) [18]

\[
p = \frac{(n^2-1)(n^2+2)}{3n^4} \left(1 + \frac{\rho}{\alpha} \frac{d\alpha}{d\rho}\right)
\]  (6)

As the pressure increases the atoms will pack together, which will cause an increase in
refractive index. Therefore, it can be concluded that the refractive index is a function of
pressure through density and polarizability. [18]

The photoelastic effect concerns the changes in optical indicatrix with mechanical stress
or strain. For an arbitrary coordinate system \((Z_1, Z_2, Z_3)\) the indicatrix takes the form
\(B_{ij}Z_iZ_j = 1\). The changes in the indicatrix under stress \(\sigma_{ki}\) or strain \(\epsilon_{ki}\) are represented
through the linear relation [18]:

\[
\Delta B_{ij} = \pi_{ijkl}\sigma_{ki}
\]  (7)
Or

\[ \Delta B_{ij} = p_{ijkl} \epsilon_{ki} \] (8)

The coefficients \( \pi_{ijkl} \) and \( p_{ijkl} \) are fourth polar rank tensors. Since stress and strain are related to one another through the elastic constants, \( \pi \) and \( p \) coefficients also are. Both the indicatrix and the strain tensor are symmetric, so that \( B_{ij} = B_{ji}, \varepsilon_{kl} = x_{lk}, \) and \( p_{ijkl} = p_{jikl} = p_{ijlk} = p_{jilk} \). This means that 36 coefficients in a 6 X 6 matrix are sufficient to describe the linear photoelastic effect: [18]

\[
\begin{pmatrix}
\Delta B_1 \\
\Delta B_2 \\
\Delta B_3 \\
\Delta B_4 \\
\Delta B_5 \\
\Delta B_6
\end{pmatrix} =
\begin{pmatrix}
p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} \\
p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} \\
p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} \\
p_{41} & p_{42} & p_{43} & p_{44} & p_{45} & p_{46} \\
p_{51} & p_{52} & p_{53} & p_{54} & p_{55} & p_{56} \\
p_{61} & p_{62} & p_{63} & p_{64} & p_{65} & p_{66}
\end{pmatrix}
\begin{pmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4 \\
\varepsilon_5 \\
\varepsilon_6
\end{pmatrix} \] (9)

### 2.4.3 Two and Three-dimensional Photoelasticity

Two-dimensional photoelasticity means that the thickness of the model is uniform and also small when compared with the other dimensions in the plane. [19] Three-dimensional photoelasticity is related to parts where the stress varies not only as a function of the shape in one plane, but also throughout the thickness. [17] From here on it will be considered the stress analysis made in a model with uniform thickness. Therefore, the importance will be in two-dimensional models.

### 2.5 Transmission Photoelasticity

For many years conventional or transmission photoelasticity (TP) has been a powerful tool in the hands of engineers to make stress analysis. Hearn in his book gives a general idea of what can be done with TP technique.
“A major feature of the technique is that it allows one to effectively “look into” the component and pinpoint flaws or weaknesses in design which are otherwise difficult or impossible to detect. Stress concentrations are immediately visible, stress values around the edge or boundary of the model are easily obtained and, with a little more effort, the separate principal stresses within the model can also be determined.” [17] (p. 182)

Here will be discussed the methods of both (TP) and reflection photoelasticity (RP). The TP method is presented before because RP is only an extension of the TP method used to analyse opaque parts. Once it is clear how TP technique works, it will be only necessary to light up the differences between one and the other.

2.5.1 Light

Before explaining what polarized light is, it will be explained first what light is. A general definition given by encyclopaedia Britannica defines light as “electromagnetic radiation that can be detected by the human eye.” [20]

To perform a stress analysis test using photoelasticity, it is fundamental to have a light source. There are two main sources of light and they are incandescence and luminescence. Incandescence light is defined as the emission of light from “hot” matter (T ≥ 800 K), while luminescence light is the emission of light when excited electrons fall to lower energy levels. [21] Frequency in physics is the number of waves that pass a fixed point in unit time, also, the number of cycles or vibrations undergone during one unit of time by a body in periodic motion. [22] The frequency of light is related to its colour. There are two main groups: monochromatic and polychromatic. [21]

**Monochromatic** light is described by only one frequency. One example of monochromatic light is laser light.

**Polychromatic** light is described by many different frequencies and one example of polychromatic light is white light.
2.5.2 Refraction and Retardation

Light propagates in a vacuum or in air at speed \( C \) of \( 3.00 \times 10^8 \) m/s. When it comes to transparent bodies, the speed (defined as \( V \) for transparent bodies) is lower. [2] In physics, refraction is defined as the change in direction of a wave passing from one medium to another caused by its change in speed. [23] Snell’s law states that “the ratio of sines of the angles of incidence and refraction is equivalent to the ratio of velocities in two media, or equivalent to the opposite ratio of the indices of refraction.” [24] (p.141) Figure 8 shows the refractive index when light passes from one medium to another.

![Figure 8: Refractive index when passing from one medium to another.][24]

The figure above shows the incident wave front represented by a ray that is by the normal to the plane utilizing the geometrical optics approximation. The Snell’s law takes then the form: [24]

\[
n = \frac{\sin \theta_1}{\sin \theta_2} \quad (10)
\]

Considering what was said previously, the refractive index equation can be rewritten using the velocity of light \( c \) of a given wavelength in empty space divided by its velocity \( v \) in a substance. [25]
\[ n = \frac{c}{V} \]  

(11)

where \( c \) is the speed of light \((m/s)\) and \( V \) is the speed of light coming through a transparent medium \((m/s)\). A transparent plastic of thickness \( t \), has the ability to split an incident plane-polarised ray into two component rays, which are called double refraction. This property is only exhibited when the materials are under stress and for this reason it is termed “temporary birefringence”. [17] Consider a specimen that is being analysed, let us take \( X \) and \( Y \) as reference directions of the principal strains at the point under consideration where the light vector splits. If the strain intensity along \( X \) and \( Y \) is \( \varepsilon_x \) and \( \varepsilon_y \), and the speed of the light vibrating in these directions is \( V_x \) and \( V_y \), respectively the ratio \( t/V \) will be the time necessary to cross the plate for each of them. Considering this statement, the relative retardation between these two beams can be defined as: [2]  

\[ \delta = C \left( \frac{t}{V_x} - \frac{t}{V_y} \right) = t(n_x - n_y) \]  

(12)

According with Brewster’s law “The relative change in index of refraction is proportional to the difference of principal strains” [2] (p. 2)  

\[ (n_x - n_y) = K(\varepsilon_x - \varepsilon_y) \]  

(13)

\( K \) characterizes a physical property of the material and is defined as a constant termed “strain-optical coefficient”. \( K \) is a dimensionless constant that is usually established by calibration and may be considered similar to “gage factor” of resistance strain gages. When combining the expressions shown above, the relative retardation for TP is obtained. [2]  

\[ \delta = tK(\varepsilon_x - \varepsilon_x) \]  

(14)

Once relative retardation occurs, the two waves are no longer in phase when emerging from the plastic. The resulting light intensity will be a function of retardation \( \delta \) and the angle between the analyser and the direction of principal strains \( (\beta - \alpha) \). [2]
If the original light source is monochromatic, the fringe pattern appears as a series of distinct black lines on a uniform green or yellow background. These black lines are the points where the two rays are exactly 180° out of phase and therefore cancelled. In the other hand, if white light is used each composite wavelength of the light is cancelled in turn and a multicoloured pattern of fringes called isochromatic is obtained. [17]

For accurate quantitative measurements it is preferable the use of Monochromatic sources. This is because of the high number of fringes (stress concentration) that can be discerned clearly. With a white light source, however, the isochromatic becomes very pale at high stress regions and clear fringe boundaries are no longer obtained. For this reason, white light sources are normally reserved for general qualitative assessment of models. [17]

### 2.6 Polariscopes

In experimental mechanics the main optical arrangements are called polariscopes. Polariscopes can be defined as interferometers that in the final superposition of the light vectors project the vector into a common direction. [24]

#### 2.6.1 Plane Polarized Light

When light propagates, its electromagnetic waves will propagate in all directions. Now it is introduced the meaning of plane-polarized light and its use in the equipment termed polariscope. Let us consider an ordinary light bulb illuminating a polarizer or sheet. When the light passes through it, the polarizer will act like a series of vertical slots. When the light emerges from the polariser, it will vibrate in one plane. This will be the plane of the slots. The light is then said to be plane polarized. [17]

When the plane polarised light (PPL) is directed onto an unstressed photoelastic specimen, it will pass unaltered and may be completely extinguished by a second
polarising sheet. This second sheet is termed analyser, and its axis is perpendicular to that of the polarizer. This is considered the simplest form of polariscope arrangement which can be used for photoelastic stress analysis. This form of polariscope arrangement is termed: “crossed” set-up [17] which is shown in the next figure:

![Figure 9: “Crossed” set-up. Plane polarised. [17]](image)

There is an alternative polariscope arrangement called “parallel” set-up. In this case the PPL will then pass through both the model and the analyser unaltered and maximum illumination will be achieved. [17] An example of a parallel set up is shown below:

![Figure 10: “Parallel” set-up. Plane polarised. [17]](image)
Entering a medium (for example a plastic with thickness $t$), the wave is divided into two waves with their vector $x$ and $y$ vibrating in perpendicular directions orthogonal to the normal of the wave. The analyser transmits only the components along its axis. [24] A plane polariscope arrangement example is shown in figure 11.

![Diagram of a plane polariscope](image)

**Figure 11: Plane polariscope. [2]**

The intensity of light emerging from a plane polariscope is: [2]

$$I = b^2 \sin^2 2(\beta - \alpha) \sin^2 \frac{\pi \delta}{\lambda}$$  \hspace{1cm} (15)

Where,

$\delta$ is the relative retardation (nm)

$(\beta - \alpha)$ is the difference between the angle between the analyzer and direction of principal strains

$\lambda$ is the wavelength (nm)

A plane polariscope setup is used to measure the principal stress/strain directions. [2]
2.6.2 Circularly Polarised Light.

When analysing a sample using plane polarized light, the fringes or isochromatic that will generate in the part will be partially obscured by a set of lines known as isoclinic. If the source of light used is a white light source, these isoclinics are easily identified because of the coloured isochromatic of a white light. With a monochromatic source however, confusion can arise between the black fringes and the black isoclinics. [17] Therefore, it is of greater interest to use a different optical system which will eliminate the isoclinics but at the same time will retain the basic fringe pattern. They are removed optically by inserting quarter-wave plates (a member that behaves exactly like a photoelastic model having uniform birefringence of $N = 1/4$) with their axis at $45^\circ$ to those of the polarizer and analyser. This eliminates all unidirectional properties of the light by converting it into circularly polarized. [19] A circular polariscope arrangement can be seen below.

![Circular polariscope](image)

*Figure 12: Circular polariscope. [2]*

The result is then that the image observed is not anymore influenced by the direction of principal strains. The intensity of emerging light thus becomes: [2]

$$I = b^2 \sin^2(\pi N + \beta)$$  \hspace{1cm} (16)
where $\beta$ is the angle of analyser rotation from the normal (crossed) position. The light becomes 0 ($I = 0$), when $(\beta + \pi N) = 0^\circ, 180^\circ, 360^\circ, etc.$ [19]

### 2.7 Reflective Coating Technique

A reflection polariscope used in PhotoStress analysis, is a tool to observe and measure the surface strains on the photoelastically coated test part. [2] As described before, RP is an extension of the TP. RP technique helps us to analyse samples of materials that do not have photoelastic property.

This adaptation utilizes a thin sheet of a photoelastic material which is bonded onto the surface of a metal component. The material is bonded using a special adhesive containing aluminium pigment which produces a reflective layer. When using a reflection polariscope, polarized light is directed onto the photoelastic coating and viewed through an analyser after reflection of the materials surface. [17]

![Diagram of reflective polariscope](image)

**Figure 13:** Schematic representation of reflection polariscope. [2]

The relative retardation of a reflective polariscope is: [2]

$$\delta = 2tK\left(\epsilon_x - \epsilon_y\right) \quad (17)$$
The technique allows the evaluation of strains under loading conditions. A fringe pattern is observed which relates to the strain in the metal component. Unlike the transmission technique RP gives no information about the stresses within the material. [17]

The selection of PhotoStress coatings and their proper application to the test part are most essential to the success of the analysis. Coating materials are available in both flat-sheet and liquid form for application to metals, concrete, plastics, rubber and most other materials. [2]

2.8 Digital Images

To perform Photoelastic analysis it is necessary to capture pictures from the samples. In this work, the values representing the dark and light regions of an image is used to analyse the stress in the samples. This chapter will describe the relations between the pixels in an image and light intensity.

2.8.1 Pixel and Light Intensity Relation

Inside a digital picture lies a collection of numbers. These numbers can be stored, modified, transmitted and converted into something which is possible to see. A digital image creation can be described in three steps. The first step would be the selection of an area or scene to be captured. Every scene is a pattern of light and dark regions. The process ignores the objects in the pictures and only deals with dark and light. Once the image is captured the second step would be to divide the digital image into little squares. Each square is called a “pixel”, what is an abbreviation for “picture element”. The third step creates the numbers which describe the image. These numbers represent the average intensity in each pixel, such as that the darkest part of the image is zero, and the lightest is 255. There are many small variations on this “digitalization” process and often the range of 0 to 255 is used because each of these numbers can be stored in one byte of
memory. In this work these numbers represent the light intensity, where at 0 there is no intensity and 255 represents maximum intensity.

The range of 0 to 255 is emphasised because this is the range used in the Joint Photographic Experts Group (JPEG) file format. This is the file format used to store the images used for the analyses discussed throughout this paper. JPEG file, represents a series of techniques aimed at reducing the redundancy present in the data, to allow more image to be recorded on a memory card. The brightness value or digital count of two neighbouring pixels is very similar (if not the same) in magnitude. When this is the case, it is not needed to use all the data in an image to represent the information in the photograph. This type of redundancy made by the JPEG file, is called inter-pixel redundancy.

The number of pixels in a JPEG file is represented by the file’s dimension, e.g. an image with dimensions 640 X 480 contains 307200 pixels. It is possible to observe this relation from figure 14. The figure shows a pixel grid 10 by 10 rows and columns.

![10 X 10 Pixel grid.](image)

In a digital image each pixel must contain values representing all the three primary colours RGB (Red, Green and Blue). These values describe accurately the final colour of the pixel. When an image is captured, each pixel on the imaging sensor records only the
value of one of those colours. For this reason, the other values must be calculated based on surrounding values. [26]

2.9 Residual Stress Relaxation Method

As mentioned previously, photoelasticity is a technique which gives us information about the general stress distribution, position of stress concentration and areas where there is low stress.

Based on the results from the photoelastic analysis it might be necessary to make design changes on the product in order to relief stress concentrations in certain areas. Here will be presented a technique called thermal relaxation used for stress relief.

2.9.1 Thermal Stress Relaxation

For thermal stress relaxation there is a technique called isothermal stress relief. This technique involves heating a part uniformly and holding it at a suitable temperature for a certain period of time. The tool used to do this is usually an air circulation furnace with good control over the specified thermal cycle. [4]

With thermal stress relaxation, it is possible to obtain the following stress relief results: [4]

- **Material yield strength reduction.** If the temperature is high enough it will cause a substantial material yield strength reduction. This happens because the plasticity mechanisms through rapid thermal activation will relieve the elastic strain.

- **Stress redistribution.** This is achieved by using lower temperatures. This is possible because at the regions of tensile and compressive stresses can contract or
expand slightly. Classical diffusional creep enables the counterbalancing of these regions.

- **Elastic stress relaxation.** This is obtained by precipitation and ageing effects.

Since all these processes are time dependent, it is really important to know the appropriate temperature and the time duration required to achieve the desired result. The determination of the temperature is often accomplished by experimenting. [4]
3 METHOD

3.1 Materials and Tools

The material chosen to be analysed is polyethylene terephthalate (PET or PETE). The reason for this choice is due to the transparency and optical properties of PET already described in previous chapters. The samples provided for the experiments were injection moulded by Arcada’s lab engineer. There is no information on the parameters used in the IMM when the samples were processed. The samples are dumbbell shaped, with the following dimensions: thickness = 0.003 m, width = 0.019 m and length = 0.17 m. A sample is shown in figure 15.

![Figure 15: PET sample used for photoelastic analysis. Arcada, 2018](image)

The instrument used is composed of a plane polariscope, a white light source, an USB camera, and a computer (figure 16). The general process was made by inserting the sample in the polariscope, illuminating it with the white light, capturing an image, saving the image in JPEG file format, converting the JPEG file into text format using a software, and finally analysing the numbers extracted from the digital image.
3.1.1 Polariscope

The polariscope arrangement can be seen from figure 17.

First step was to insert the sample in the polariscope. To do this the polariscope was unscrewed and the sample was attached inside, then the instrument was screwed back together. The polariscope was then turned in a way where the sample would be in a vertical position. The side with the rotation polarization optics was facing the light source.
and the camera was placed at the back of the polariscope with its USB cable attached to the computer. A paper was used to soften the light brightness and focus its direction (as shown in figure 17).

The polariscope used for our experiments did not have numbers marking the angles. In other words, it was not possible to know accurately the used angle since the tool did not contain any sort of angle indication. Therefore, in order to perform the experiments, the visual lines representing the angles were assigned a variable $\alpha$. When rotating the polariser, a line would be taken as reference, and to this reference line would be assigned a value $\alpha + 0$. From the reference line, the counting would be made in an interval from 10 to 10 until 90 e.g., $\alpha + 0$, $\alpha + 10$, $\alpha + n, \ldots, \alpha + 90$. The following figure shows an example on how the angles were marked.

![Image](image.png)

*Figure 18: Angle's assigned values. Arcada, 2018*

Once everything was adjusted in the correct place the room light would be switched off and the light source used for the experiment would be switched on. Then the angle in the polarizer would be rotated in a way where the least light intensity would come through. This was made with the intention of getting only enough intensity to see the internal stress
within the samples. Once the angle for each sample was adjusted, the same angle would be used for all the other experiments.

### 3.1.2 Images Capture

When the sample is illuminated inside the polariscope the observations of the internal stress is made through the computer. This is done by using the camera placed in the back of the polariscope and connected to the computer. In the settings it is possible to choose the images in colour or black and white. Once the light, the sample, and the angle have been adjusted in the desired way, the next step which is capturing the images can be made.

### 3.2 Experiments

#### 3.2.1 Internal Stress Investigation

The process described above was made with ten different samples. The experiments were also performed with no samples inside the polariscope. For the later one, the polarizer was rotated from 10 to 10 degrees until 90 degrees. This was made to create a graph where the light intensity curve would not suffer interference due a medium. This graph was then used as reference to compare the changes in the light intensity curve due to stress in the load experiment. From the ten samples analysed, three were chosen to perform the load and thermal healing experiments. Samples 2, 7 and 8.

#### 3.2.2 Induced Stress Using Different Loads

The load experiment was performed by making a 5-mm diameter hole in the samples where it was possible to insert a rope with a weight in its end. Figure 19 shows how the weights were attached to the sample.
In total, eight loads and combination loads were used. The different used loads are shown below:

Table 1: Loads used for photoelastic experiment. Arcada, 2018

<table>
<thead>
<tr>
<th>Load [kg]</th>
<th>Load [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.366</td>
<td>3.59046</td>
</tr>
<tr>
<td>1.82</td>
<td>17.8542</td>
</tr>
<tr>
<td>2.546</td>
<td>24.97626</td>
</tr>
<tr>
<td>4</td>
<td>39.24</td>
</tr>
<tr>
<td>5.378</td>
<td>52.75818</td>
</tr>
<tr>
<td>6.832</td>
<td>67.02192</td>
</tr>
<tr>
<td>7.558</td>
<td>74.14398</td>
</tr>
<tr>
<td>9.012</td>
<td>88.40772</td>
</tr>
</tbody>
</table>

Where the loads in N were calculated from: [10]

\[ F = mg \]  \hspace{1cm} (18)

A picture registering the change in stresses was then taken from each sample.
3.2.3 Thermal Healing Experiment

Thermal healing was performed in samples 2, 7, and 8. In the first attempt, the samples were kept in the oven at 50°C for 24 hours. Another attempt aiming to obtain a better result was made by increasing the temperature 30 degrees (80°C), and then keeping the samples again in the oven for 24 hours.

3.2.4 Data Extraction

In order to analyse the digital images, it was necessary to extract the numbers data from the JPEG files. To do this, a software was used. The following command was inserted in the conversion software to convert the files: “convert (file name).jpg -define histogram:unique-colors=true -format %c histogram:info:- > (file name).txt” (figure 20)

The numbers in the text file were then inserted into Excel. After doing this it is possible to obtain the RGB and pixel count values, as shown in Figure 21.
The RGB max was then calculated using Excel’s Max formula:

\[ V = \max(R, G, B) \]  \hspace{1cm} (19)

Once the RGB max is calculated a graph using these numbers can be created. The numbers on the y axis represent the digital count and the numbers in the x axis the RGB max values. The digital count is the number of pixels in a peak located in the graph’s curve and the RGB max represents the intensity range in each pixel (the range from 0 to 255).
It is possible to see below an example of a graph made from a random black and white image:

![Graph example](image)

*Figure 22a and 22b: Black and white image intensity graph. Arcada, 2018*

A higher curve does not mean higher stress, instead it means a higher area of stress. The y axis represents the number of pixels in which the stress is acting. The amount of stress is represented in the x axis by the RGB max which is the average intensity. The higher the number of RGB max the higher the stress is. The following figure represents how a graph will look like with different stresses. Figure 23a, represents how a sample’s graph would look like if no stress would be acting on it. Figure 23b shows a graph representing homogeneous stress. Figure 23c demonstrates how the curve could be like if there is stress distribution in the sample.

![Graph examples](image)

*Figure 23a, 23b and 23c: Representation of different possible stresses in a count-intensity graph. Arcada, 2018*

The data is then ready to be analysed.
4 RESULTS

4.1 Light Intensity Relation

As defined in chapter two in equation 15, the intensity of light emerging from a plane polariscope is

\[ I = b^2 \sin^2 2(\beta - \alpha) \sin^2 \frac{\pi \delta}{\lambda} \]

As described previously, a new method is utilized to analyse the stress data obtained from the experiments. The light intensity is observed from the RGB max calculated from the picture’s data, therefore, this equation is not utilized to analyse the experiment’s results. Even though equation 15 is not used in this work, it is possible to observe its relationship with the graphs. A graph representing this equation will show a group of curve patterns caused by the \( \sin^2 \). If figure 24 is observed, it is possible to see these patterns forming as the intensity is increased. The graph from figure 24, is the graph obtained from the pictures of each angle from 0 to 90 without the interference of a medium. This was made with the aim of using the graph obtained from these pictures to compare with the graph created from the load experiment. The polarizer was rotated in steps of 10 to 10 beginning from \( \alpha + 0 \), \( \alpha + 10 \), \( \alpha + n \),…, to \( \alpha + 90 \).

*Figure 24: Intensity curve represented in a graph. Arcada, 2018*
At 0° it is expected no light intensity coming through the polarizer and at 90° it is expected maximum intensity. From the graph it can be observed that light has its smallest intensity at $\alpha + 0$ (where intensity is close to 0) and its highest intensity at $\alpha + 90$ (where intensity is close to 190).

### 4.2 Internal Stress Analysis

The picture below was taken from one of the samples using an angle where the light intensity was enough to see the fringes patterns clearly. It is possible to observe the patterns forming at the corners. This indicates a high concentration of stress in the corners.

![Figure 25: Fringe patterns caused by internal stress in the PET sample. Arcada, 2018](image)

The following table shows a coloured picture from samples 1 to 10. The angles were chosen such as the least light intensity would come through the sample. This way the intensity is enough to reveal only the internal stress within the samples. Even though the images are somewhat dark, it is still possible to see the fringe patterns forming in the edges. The samples are in the same position (vertical) as the sample in the figure 32. Here the pictures are shown instead of the graphs because the location of the stress is wished to be seen. The graphs show us how big is the area affected with stress and the difference
in intensity due to induced stress. The graph does not show us the exact location of the stress.

\textbf{Table 2:} Samples 1-10 internal stress and used angle. Arcada, 2018

\begin{tabular}{|c|c|c|c|c|}
\hline
Sample & Sample & Sample & Sample & Sample \\
Number & 1 & 2 & 3 & 4 \\
\hline
\(\alpha + 1^\circ\) & \(\alpha + 2^\circ\) & \(\alpha + 2^\circ\) & \(\alpha + 0^\circ\) & \(\alpha + 2^\circ\) \\
\hline
\hline
Sample & Sample & Sample & Sample & Sample \\
Number & 6 & 7 & 8 & 9 \\
\hline
\(\alpha + 0^\circ\) & \(\alpha + 1^\circ\) & \(\alpha + 0^\circ\) & \(\alpha + 0^\circ\) & \(\alpha + 0^\circ\) \\
\hline
\end{tabular}

4.3 Load Analysis

Here is presented the graphs obtained from the analysis made on samples 2, 7, and 8 undergoing different loads.

\textbf{Figure 26a and 26b:} Sample 2 and 7, load analysis graph. Arcada, 2018
By observing the graphs, it is possible to see that samples 8 and 7 had the highest intensities (the minimum intensity is around 132 for sample 7 and 133 for sample 8). For the line representing the load of 17.85 N in figure 26b (sample 7) the intensity is around 166. In figure 27 (sample 8), the line representing the load of 3.6 N shows intensity around 150. When comparing the two samples, the data shows a higher intensity in sample 7, but more variations in the curves of sample 8. By comparing figure 26a (sample 2) and 27, it is possible to see more variation in the curves in the graph representing sample 2, however sample 8 has higher intensity. Based on these results, sample 8 was chosen to perform further investigation.

Sample 8 was analysed using an angle \( \alpha + 0 \). This can be seen from table 2. The angle chosen to analyse the internal stress of the samples was used for all the other analyses. The graphs show some variations due to external light. It was important then, to always use the same angle in all analyses. This way no confusion rises on what is causing the changes in the curve. Using always the same angle help us to know the difference between the changes caused by light interference and the changes caused by the load and thermal healing analysis.

When a load is applied, the stress in the sample will cause a \( \sin^2 \) change in intensity as described before. This means that the applied stress will disturb the \( \sin^2 \) curve, and it will have variations related to the picks where the highest light intensities are located. Below
it is shown the graph extracted from the data of the experiment described in section 4.1 presenting only the intensity coming from the polariscope at the angle $\alpha + 0$ without a medium.

At this angle, it is expected the least amount light coming through the polariscope. This means that the intensity should be close to 0 and not close to 60 as shown in the graph. The variation in the graph is probably due to light interferences caused by other sources such as ambient light.

Below it is presented a separated graph for each load and stresses applied to sample 8. The graphs start from the coordinates which represent the intensity caused by the stress, therefore, eliminating the data information that comes from the empty parts located on the surroundings of the sample. The internal stress was included in all graphs. This way it is possible to observe the variations due to external stresses.
Figure 30a and 30b: 24.97 N and 39.23 N load, sample 8. Arcada, 2018

Figure 31a and 31b: 52.74 N and 67 N load, sample 8. Arcada, 2018

Figure 32a and 32b: 74.12 N and 88.38 N load, sample 8. Arcada, 2018

It is possible to see that sometimes the induced stress curve appears lower than the internal stress curve. This is because the count axis represents the areas under stress. A lower
curve does not mean less stress, it just means that the location and area of the stress is different. It is possible to observe this from figures 29 \(a\) and \(b\) and 30 \(a\) and \(b\). As the load increases and the stress becomes higher there is an increase of the areas under stress, but a decrease in intensity. To observe the changes in intensity due to induced stress, the difference between the maximum intensity caused by internal stress and the maximum intensity caused by the stress created by the loads was taken (Table 4 shows the values for intensity relating the internal stresses of each sample). The results are shown in table 3. From the table, a negative value is obtained at the stresses of 0.689 MPa, 0.93 MPa, and 1.18 MPa. This means that the maximum intensity of the induced stress is lower than the maximum intensity of the internal stress.

<table>
<thead>
<tr>
<th>thickness [m]</th>
<th>0.003</th>
<th>mass [kg]</th>
<th>0.366</th>
<th>Force [N]</th>
<th>3.59046</th>
<th>Stress [MPa]</th>
<th>0.06299053</th>
<th>Intensity ΔI</th>
</tr>
</thead>
<tbody>
<tr>
<td>width [m]</td>
<td>0.019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.82</td>
<td>17.8542</td>
<td>0.31323158</td>
<td>149</td>
<td>6</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>area [m²]</td>
<td>0.000057</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.546</td>
<td>24.97626</td>
<td>0.43818</td>
<td>145</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>39.24</td>
<td>0.68842105</td>
<td>133</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.378</td>
<td>52.75818</td>
<td>0.92558211</td>
<td>131</td>
<td>-12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.832</td>
<td>67.02192</td>
<td>1.17582316</td>
<td>140</td>
<td>-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.558</td>
<td>74.14398</td>
<td>1.30077158</td>
<td>150</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.012</td>
<td>88.40772</td>
<td>1.55101263</td>
<td>151</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The stress was calculated using equation 1,

\[
\sigma = \frac{F}{A} = \frac{mg}{A}
\]

### 4.4 Thermal Healing Analysis

Below it is possible to observe the results obtained from thermal healing. First, it is presented the graphs representing the stress before the treatment (figures 33a, 34a, and 35a). Then, beside the internal stress graphs it is presented the graphs showing the results after the samples were treated 24 hours at 50°C and 24 four hours at 80°C (figures 33b, 34b and 35b).
Figure 33a and 33b: Sample 2, internal stress and thermal healing graphs. Arcada, 2018

Figure 34a and 34b: Sample 7, internal stress and thermal healing graphs. Arcada, 2018

Figure 35a and 35b: Sample 8, internal stress and thermal healing graphs. Arcada, 2018

The difference between the maximum internal intensity before and after the treatment was also calculated:
<table>
<thead>
<tr>
<th></th>
<th>sample 2</th>
<th></th>
<th>sample 7</th>
<th></th>
<th>sample 8</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity (max)</td>
<td>ΔI</td>
<td>Intensity (max)</td>
<td>ΔI</td>
<td>Intensity (max)</td>
<td>ΔI</td>
<td></td>
</tr>
<tr>
<td>Internal stress</td>
<td>130</td>
<td>144</td>
<td>143</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 °C</td>
<td>141</td>
<td>-11</td>
<td>132</td>
<td>12</td>
<td>114</td>
<td>29</td>
</tr>
<tr>
<td>80 °C</td>
<td>34</td>
<td>96</td>
<td>63</td>
<td>81</td>
<td>26</td>
<td>117</td>
</tr>
</tbody>
</table>

There is not a big variation after the samples were treated at 50 °C for 24 hours. It is possible to observe more of a stress distribution rather than a decrease in intensity. However, the samples have a drastically decrease of internal stress after treated at 80 °C for 24 hours. By observing table 4, one can see that the difference between the internal stress and the stress after the 80 °C treatment is significant. To demonstrate that what was said is true, below it is shown a coloured picture of the internal stresses of each sample after 80 °C treatment. There is almost no internal stress and only a small area with a little bit of green colour.

![Figure 36a, 36b and 36c: Internal stresses of samples 2, 7 and 8 after treatment. Arcada, 2018](image-url)
5 DISCUSSION

The method used in section 4.2, was made to allow us to observe where the internal stress is located in the samples. In the literature review chapter, it was described in the injection moulding subchapter that internal stress can occur due to shrinkage. Figure 25 represents clearly a defect caused during the IMP since no external load was applied to the sample. When internal stress is located such as at the area shown in figure 25 and on the figures from table 2, it is certain that the stress is due shrinkage when the sample was cooling. As described previously in this work, this is a result of setting the cooling time in the IMM wrong. The shrinkage happens when the cooling process is too slow. When cooling, the middle of the specimen has a uniform solidification, but the same cannot be said of the corners. If the time is too slow the outer parts of the sample will cool faster than the middle. This in turn cause the shrinkage in the corners, thus causing internal stress concentration.

On the results obtained from the load analysis it was presented that at certain loads the induced stress curve appears lower than the internal stress curve. When the curve representing the applied stress is located under the internal stress curve, the induced stress is relocating the internal stress to other areas of the sample. It was also shown that the intensity decreases as the stress increases. This could be related to the internal stress being removed from the samples when under higher loads. Since it is also shown that the area of stress increases with bigger loads, it also may well be that the stress is being distributed throughout the sample making it more uniform. The reason why the intensity is higher when the load is smaller might indicate that smaller loads do not cause big changes in the internal stress of the samples. When the load is small, it only creates more stress and relocates the internal stress to other areas.

In the thermal healing results, it can be seen from table 4 the difference of ΔI (maximum intensity) between the internal stress before and the internal stress after the samples were treated. There is no doubt that by keeping the samples at 80°C for 24 hours in the oven,
it was possible to decrease drastically the amount of stress. The internal stresses intensity values of samples 2, 7 and 8 before treatment were 130, 144 and 143 respectively. After the treatment the same samples 2, 7 and 8 had their stresses intensity values diminished to 34, 63 and 26 respectively. It is interesting to observe the line representing the thermal healing at 50°C in the graph of sample 2 (figure 3b). The sample has an increase in intensity after the heat treatment. It is only possible to speculate what caused this. It could have been due to shrinkage when the samples were removed from the oven or wrong setup of the equipment when analysing the sample again.

The objectives stated in the beginning of this work were achieved. It has been demonstrated that the samples suffered internal stress during processing. It was established that observing the stress using photoelasticity is possible. The analysis presented revealed that it is possible to extract data from the captured pictures, and that using these numbers one can see the stress variations within the material. The load and healing analysis verified that the average light intensity depends on the stress magnitude. It is possible to see this on the results obtained after the samples were treated at 80 °C. The intensity numbers have a significant decrease showing that it is indeed a result of stress decrease. The thermal healing also shows to be effective when relieving internal stress.
Most stress analysis methods show how a material will react under an applied force. These methods try to investigate the amount of stress which will cause the material to fail. Photoelasticity differs from these methods because it gives us information of the stress already existent on the surface and within the material. This is valuable information since these stresses are related to errors in processing and could also originate failure of the material.

The data analysis method described in this research gives us a quicker way to analyse the data from photoelastic analysis. If a software which creates a count-intensity graph directly from a picture would be developed, the process would be relatively fast. The graph is also useful when the stress in the material is small and the fringe patterns cannot be counted. As mentioned in the literature review section, a set of lines called isoclinic can obscure the fringe patterns causing confusion. With the graph analysis method this would not be a problem since the analysis deals with the light intensity data from a picture.

For the photoelastic stress analysis performed in this research a white light source was used. When using white light, data is registered from around the sample where there is only dark. Therefore, it is expected to obtain only a general qualitative assessment of the samples. Monochromatic sources are preferred when quantitative photoelastic measurements are needed. An example, would be to perform the analysis using laser source. This way, it is possible to focus the light in a point or particular position where it is wished to measure the stress, thus, providing us with an accurate result.

For further studies, it would be interesting to explore the possibility of using polarizing films to do photoelasticity analysis. This method is cheap and fast. A polarizing film of size around 10 x 10 cm, costs an average price of 15€, and the film can be used in non-transparent materials. This method is very simple, it is only needed to glue the film on to material to be analysed and then the sample is ready for testing.
7 REFERENCES


Sample 2 load analysis data. Pictures in black and white. Arcada, 2018
Sample 7, load analysis data. Pictures in black and white. Arcada, 2018