Photoelastic Measurement of Sub-Surface Stresses using GHz Radiation

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Abstract. Stress measurements using photoelastic techniques form a well-developed branch of metrology. However, applications of photoelasticity generally need a model of the component under test to be made from visibly transparent testing materials. Recent advances in GHz sources, detectors and components make it possible to conduct photoelastic stress measurements on a wider range of materials. These techniques may be applied to high value manufacturing processes of plastics and ceramics that are transparent at GHz frequencies but that are opaque at visible wavelengths. This enables the testing of actual components as opposed to testing a model. To demonstrate this, measurements of the relative stress optic coefficient for teflon [1], polypropylene and polyethylene between 260 - 400 GHz are conducted.

Introduction

Photoelastic measurement techniques are routinely used to visualise stress distributions in visibly transparent materials such as glass. Plane polariscopes are the simplest photoelastic measurement set up. Such a system consists of a light source, a polariser, the sample under test, a second polariser (known as the analyser) and a detector (Fig. 1).

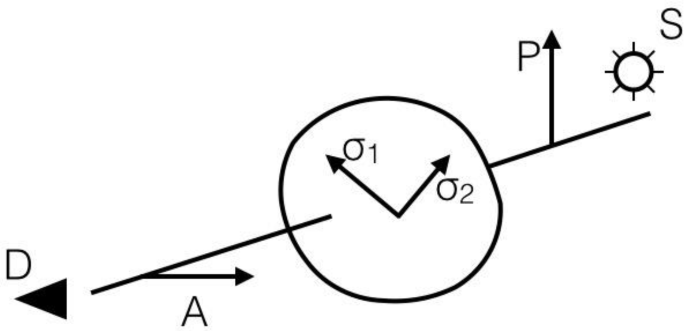

Figure 1: A dark field configured plane polariscope with source S, and perpendicular polariser P, and analyser A. A sample under stress sits between the two, and the principle stress directions (σ_1 and σ_2) cause a phase shift between the decomposed polarisation components. A detector D, records the resulting intensity.

Plane polariscopes can be orientated in a bright field configuration, where the polariser and analyser are aligned, or in a dark field configuration, where they are crossed. Consider a dark field configuration, with the polariser orientated vertically. As light leaves the source it passes through the polariser and becomes vertically polarised. Traveling through an unstressed sample, this light experiences no polarisation modulation. Due to the analyser being orientated perpendicular to the incident light, the detector records a minimum intensity. However, if the sample exhibits stress-induced birefringence, there will be a slightly different index of refraction in the material, dependent upon the principle stress directions. As vertically polarised light passes through the stressed sample, it will be decomposed along both of these directions. Due to the difference in refractive index, a small phase shift will develop between the two polarised components. As these two components reach the analyser, they will be recombined with a relative phase shift. Finally, the analyser transmits the horizontal component of the recombined polarisation state. The intensity of this light can be determined analytically (Eq. 1) [2],

$$I = I_0 \sin^2\theta \sin^2\frac{\delta}{2} \tag{1}$$

where θ is the orientation angle of the polarising axis of the sample when stressed. The phase shift between the two polarised components of light leaving the sample is denoted by δ. Importantly, the phase shift can be related to the principle stresses in the sample by Eq. 2,

$$\delta = \frac{2\pi d}{\lambda} C(\sigma_1 - \sigma_2) \tag{2}$$

where σ_1 and σ_2 are the principle stresses, λ is the free space wavelength of the incident beam, d is the sample thickness and C is known as the relative stress optic coefficient [3]. This coefficient is different for each material and is wavelength dependent.

GHz Photoelasticity Measurement Systems

As GHz sources become more powerful and room temperature detectors become commercially available, experiments once confined to the visible spectrum can be conducted at lower frequencies. Many plastics and ceramics transmit GHz radiation with little attenuation. Some of these materials are used in high value manufacturing processes such as thermal barrier coatings or medical implants. In these processes it is important to understand the stresses before, during and after manufacturing in order to ensure that the components reach and maintain stringent design specifications. In addition, stress induced birefringence caused by sub-surface defects can be detected, aiding in quality and process control. By merging the availability of GHz sources and detectors with photoelastic techniques, stress distributions in GHz transmitting materials may be measured non-invasively and in-situ.

Experimental Description

To demonstrate this process, the relative stress optic coefficient for teflon, polypropylene and polyethylene has been measured between 260 - 400 GHz (λ = 1.15 - 0.75 mm). A Virginia Diodes WR2.8 feed horn was used to generate the source beam, while teflon lenses are used to both collimate the beam onto the sample and then focus the beam onto a Gentec THz-9D detector. Polarisers were supplied by Tydex and a small press was used to apply stress to the samples. Each sample was 100 mm x 50 mm x 6 mm in size. The illuminated spot size on the sample was approximately 20 mm in diameter. The experiment was conducted in an anechoic chamber, while additional care was taken to reduce standing waves and reflections first by rotating the polarisers so that the incident beam angle was 45^{O} and secondly by using absorbing material around the components.

Conclusions

By adapting well known photoelastic measurement techniques to GHz frequency systems, stress distributions in some visibly opaque materials may now be conducted. Many of these materials have uses in high value manufacturing settings, and therefore GHz photoelasticity measurements provide a useful , non-invasive diagnostic tool. To demonstrate these measurement techniques, the relative stress optic coefficient was measured for teflon, polyethylene and polypropylene. In combination with GHz imaging systems, knowledge of the relative stress optic coefficient allow for the measurement of accurate two dimensional stress maps. In addition, three dimensional imaging techniques such as confocal imaging or tomography, in conjunction with photoelasticity measurement techniques, could lead to measurements of three dimensional stress distributions. Finally, advances in this technique will lead to defect detection in production lines improving process and quality control.

References

[1] L. Li, W. Song, Z. Wang, S. Wang, M. He, J. Han, and L. Cong, *Active modulation of refractive index by stress in the terahertz frequency range*, Applied Optics, Vol. 52, No. 25, (2013).

[2] K. Ramesh, *Digital Photoelasticity Advanced Techniques and Applications*, Springer Press, Berlin, (2000).

[3] M. Ramji, K. Ramesh, *Whole field evaluation of stress components in digital photoelasticity - Issues, implementation and application*, Optics and Lasers in Engineering, 46, (2008), 257 - 271.