Image Analysis Applied to Film Thickness Measurements with White Light Interferometry

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Abstract

White light interferometry yields good resolution in thin film thickness measurements. Hue value variations vs. film thickness variations are complex and furthermore dependent on the power spectrum of the light source.

Absolute film thickness measurements is possible using white light interferometry.

Introduction

Measuring the thickness of a transparent film between a glass plate and a reflecting object by interferometry is an established method, one important application being the study of lubricant film between surfaces in elastohydrodynamic contacts.[1] Interpretations of interferograms to determine film thickness has hitherto been done by manual inspection. The possibility of employing image analysis to determine film thickness has been demonstrated.[2]

The principle of interferometry is illustrated in Figure 1.

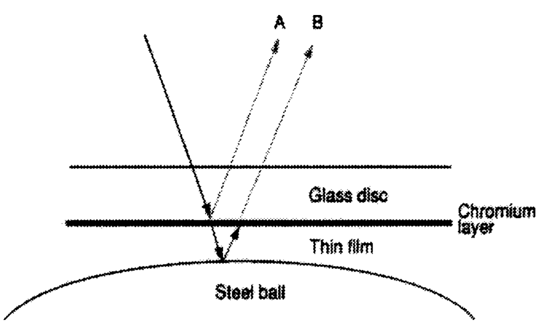

Figure 1. Schematic illustration of interferometry

If monochromatic light is used, rays A and B will interfere to form light and dark fringes. An increase of thickness t by $\lambda/2$ corresponds to the addition of one more fringe in the fringe pattern, thus thickness variations can be studied. An absolute thickness cannot be determined, however, unless additional information is available.

If white light is used, one spectral component in ray A will interfere constructively with the same spectral component in ray B whereas another spectral component will interfere destructively and colored fringes will be formed.

White light interferometry yields more detailed information than monochromatic interferometry—there are several colored fringes between two red fringes in a white light interferogram whereas there is only a dark fringe present between two red fringes in a red monochromatic interferogram. White light interferometry can, however, be used only in a very narrow thickness range, 1 µm is commonly stated as the upper range[1], since the colored fringes become less and less saturated for higher order fringes. Furthermore, a manual inspection of a white light interferogram will possibly yield different results for different people, since color perception is subjective.

One purpose of this paper is to show that the interferogram depends in a complex way on the spectral properties of the white light (white light is here understood to include light which to the human eye and color film appears to be white, but which does not exhibit a constant power spectrum).

A second purpose of this paper is to show that analysis based on an idealized model yields results which exhibit the same characteristics as experimental results.

A third purpose of this paper is to illustrate that an absolute thickness value can be determined through image analysis of a white light interferogram.

Hue Value as a Function of Film Thickness – An Analytical Result

An interferogram recorded on a video tape or on photographic film can be digitized, i.e. discretized into pixels, each represented by three values, the red, green and blue values. Coordinate transformation will yield hue, saturation and intensity values, the natural choice for subsequent image analysis. The application of image analysis will eliminate subjective color perception and yield reproducible results.

In manual determination of film thickness from a white light interferogram the hue is compared with hues in interferograms of films with known thickness. In computer-aided determination of film thickness from digitized interferograms the use of hue is also natural but additional very important information can be gained from the intensity values as well.

Assume that "true" white light, i.e. light with a constant spectral power between λ = 400 nm and λ = 700 nm, is used. Further assume that the reflected light power from both the chromium layer and the reflecting object is white and of the same intensity. Also assume that there is no phase shift in the reflecting surfaces. The film medium is assumed to have an index of refraction n = 1.5.

The reflected light is assumed to be recorded on color film. The spectral sensitivity of the photographic and discretization processes yielding red, green and blue values are assumed to be those shown in Figure 2 (the curves differ between different films; the curves shown can be regarded as generic).

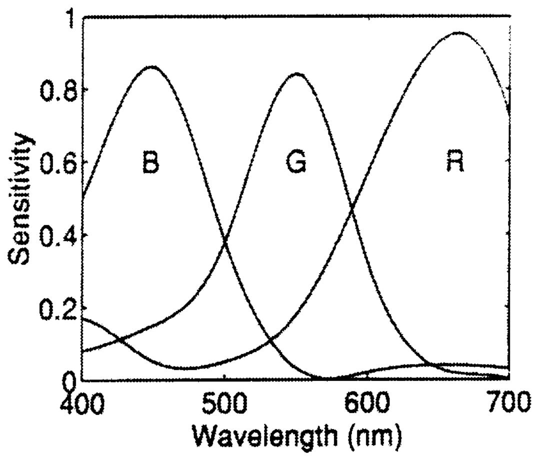

Figure 2. Red, green and blue sensitivities of the photographic and discretization processes

The red, green and blue values and subsequently the hue value are calculated for a range of film thicknesses. Hue as a function of the film thickness is shown in Figure 3.

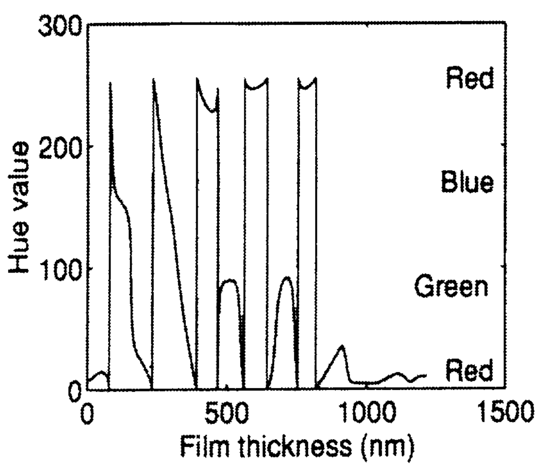

Figure 3. Hue of the reflected light as a function of film thickness

The hue vs. film thickness function shown in Figure 3 is rather remarkable for thicknesses larger than 400 nm, yielding almost constant hue values in bands of approximately 100 nm. The advantage of white light interferometry - good resolution between fringes - is largely lost in this curve for thicknesses larger than 400 nm.

Hue Value as a Function of Film Thickness – An Experimental Result

In Figure 4 an interferogram of a steel ball close to a glass disc is shown. The corresponding hue vs. film thickness function obtained from the interferogram is shown in Figure 5.

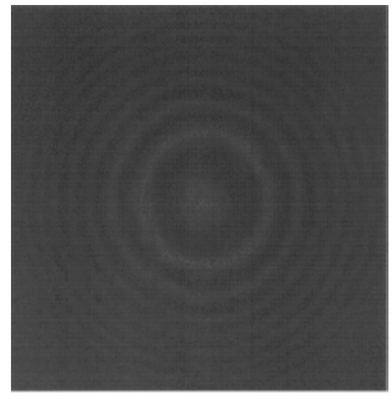

Figure 4. Interferogram of a steel ball

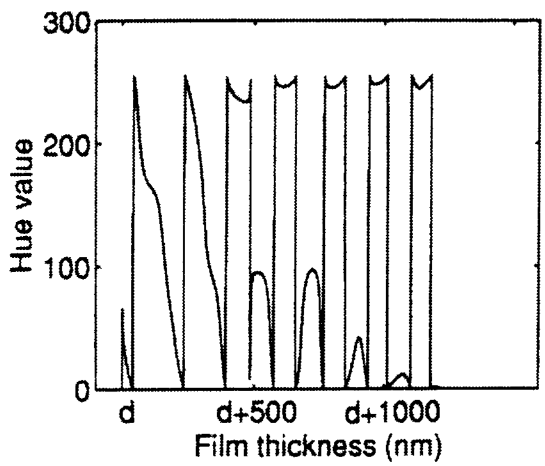

Figure 5. Hue vs. film thickness function obtained from the interferogram. d is the closest distance between the steel ball and the glass disc

Clearly the experimental hue vs. film thickness function in Figure 5 exhibits the same characteristics as the hue vs. film thickness function obtained by analysis of an idealized model. However there are quantitative differences which suggests that a film thickness measurement system based on white light interferometry must use calibration to yield accurate results. Considering the many complications eliminated in the idealized model - multiple reflections, different light absorbtion in films of different thickness, possible dispersion in the film, a non-ideal spectrum of the light source, etc. - this is certainly to be expected.

Hue Dependence on the Spectral Properties of the White Light Source

"White light" is an ideal model for light sources containing many spectral lines or a continuous spectrum. A combination of narrow spectra of red, green and blue light will give the appearance of white light. Such a light spectrum and the hue vs. film thickness function calculated under the same idealised assumptions as above are shown in Figures 6 and 7.

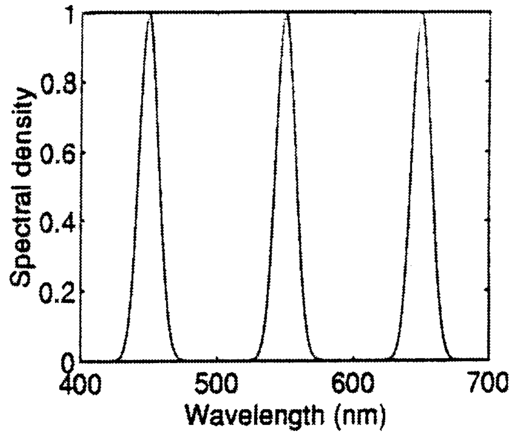

Figure 6. Spectrum of trichromatic "white" light

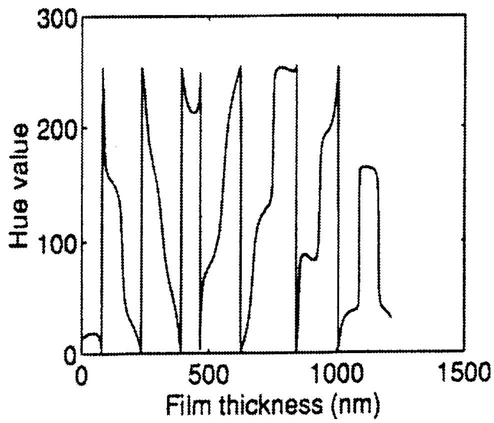

Figure 7. Hue as a function of film thickness

This hue vs. film thickness function offers better resolution than the corresponding function obtained with true white light.

Absolute Film Thickness Measurement with White Light Interferometry

The intensity value of course also varies with the film thickness but in a much more irregular way than in monochromatic light interferometry. In Figure 8 the intensity variation as function of film thickness calculated for the above trichromatic light (solid line) and true white light (dotted line) is shown. The intensity curve corresponding to the true white light can be seen to decay rapidly.

The information in Figures 7 and 8 can be combined in a matrix in which each element is indexed by a hue value and an intensity value and contains a film thickness value. This way film thickness can be unambiguously determined except for a limited number of hue-intensity combinations, the matrix elements of which contains several thickness values. In Figure 9.a and 9.b the hue-intensity curve is shown in a polar coordinate system, increasing film thickness being indicated by arrows. Since most combinations of hue and intensity will uniquely determine a film thickness then continuity arguments can be employed to determine film thickness in the few remaining points.

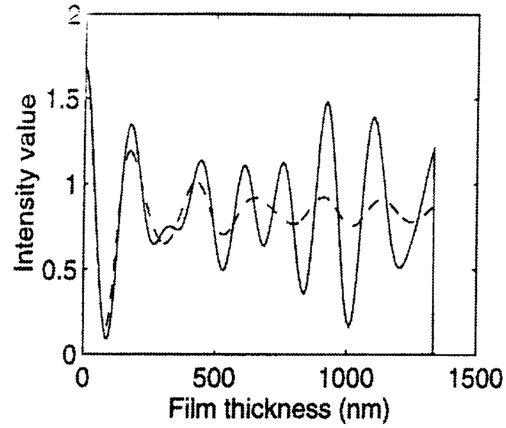

Figure 8. Intensity as a function of film thickness; Solid line: trichromatic light; Dotted line: true white light

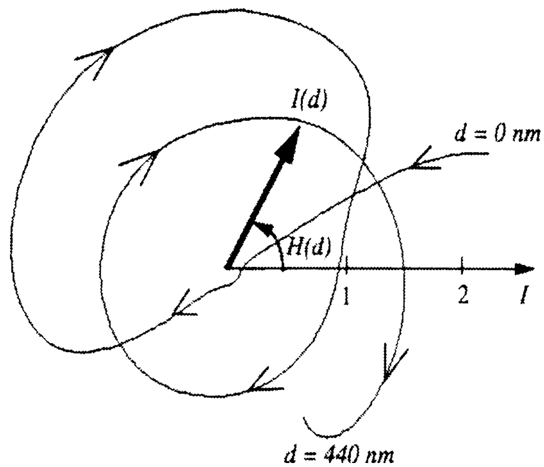

Figure 9a. The hue-intensity curve for the film thickness range 0-440 nm. Hue is the coordinate, 2π rad corresponding to hue = 255

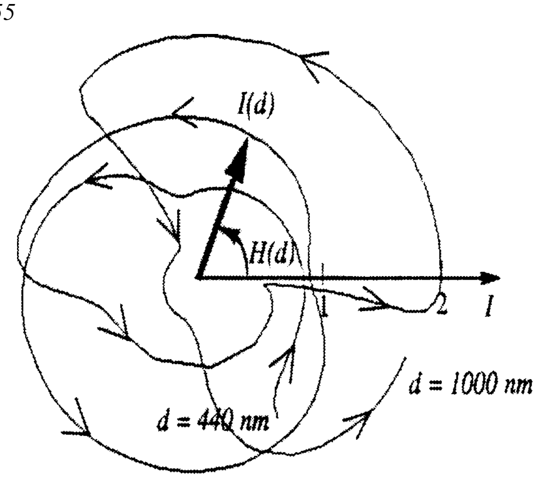

Figure 9b. The hue-intensity curve for the film thickness range 440-1000 nm

Conclusions

White light interferometry yields good resolution in measurements of thin film thickness. The hue variation vs. film thickness variation is however complex and interferograms should be evaluated using calibration interferograms of films of known thickness. Analysis shows that trichromatic light, giving the appearance of white light, will yield better resolution over a wider thickness range than white light with a constant power spectrum. White light also makes absolute film thickness measurements possible.

References

1. Gohar, R., *Elastohydrodynamics,* Ellis Horwood Limited, Chichester, 1988.
2. Gustafsson, S. L., Höglund, E. and Marklund, O., "Measuring lubricant film thickness with image analysis", accepted for publication in *Journal of Engineering Tribology* (*Proc. Inst. Mech. Eng.* Part J)