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A SCHLIEREN SYSTEM FOR IN–LINE QUALITY CONTROL IN A FILM EXTRUSION PROCESS

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Abstract: *This paper addresses the problems arising in continuous film extrusion of thin foils that need to result in optical quality but due to processes still not completely understood give suboptimal quality of the resultant foil. The foils show more or less severe chatter marks dependent on certain system parameters like feed rate of the product, temperature of the product casted, spinning rate and differential spinning rate of the rolls, cooling rate and so on. An in–line capable optical quality measurement system is devised that allows to continuously assess the product quality within seconds after the foil is extruded from the casting unit, thus allowing rapid corrective actions if quality declines below a set standard. It also allows for a continuous documentation of the amount of residual chatter marks for each and every inch of product. The system is based upon a schlieren–optical setup able to resolve schlieren–caused refraction of collimated light of less than 1 second of arc.*

Key words: *continuous cast extrusion, chatter marks, schlieren technique*

1. INTRODUCTION

For various reasons that are still not completely understood continuous cast film extrusion of foils result in sometimes very disturbing chatter marks (see Fig. 1 as an example). The phenomena leading to these chatter marks although seen also in rolling mills for steel are very wide spread and can ultimately be attributed to some system nonlinearity [Hilborn] leading to so–called limit cycles [Dutton & Thompson], [Oppenheim & Schafer], small amplitude oscillations in roller separation caused by the interaction of the mechanical system, the controller and the mechanical actuators employed to control the cast gap width. Furthermore the refractive index of the cast material being dependent on its density, composition and also on the cooling rate of the material going from the liquid state over a solidifying intermediate step to the "frozen–stress" solid state is time– and spatially dependent (see section on photo elasticity in [Hecht]). Thus the optical quality of the film needs to be checked by optical means in the transmitted light regime and can not be checked thoroughly by purely analyzing the surface waviness alone. For applications like those described above the application of a schlieren system is the method of choice (as compared to systems sensitive for thickness variations of the product only), since variations in the chemical composition of the material casted as well as instationary cooling rates can cause frozen–in photo–elastic schlieren degrading the optical quality even if no noticeable thickness variation is present.

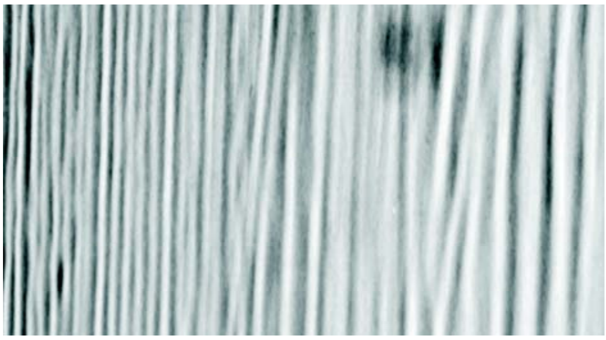

Fig. 1: A shadowgraphy image of a 195 × 56 mm^2 piece of polycarbonate film with 1000 μm thickness digitally processed to exaggerate the effects of varying film thickness resulting in an uneven appearance. The film was extruded in the horizontal direction.

Table 1 lists optical properties the index of refraction for light of the sodium D line (wavelength λ_D = 589.3 nm) of some materials used in extrusion processes. Due to the variation in the refractive index schlieren could form even if the extruded film had perfectly smooth surface properties.

The paper is organized as follows: first of all the optical setup is defined including the definition of a so–called schliere and its quantitative impact on wave propagation thus defining the minimal sensitivity of the measurement system. Then the measurement setup is detailed and some measurement results ob-

common name	refractive index n_D
Polymethylmethacrylate	1.494 – 1.510
PMMA with additional styrene	1.535 – 1.543
SAN with other quantity ratios	1.568
Polycarbonate	1.590 – 1.602
Polystyrene	1.595
Polyethylen	1.510

Table 1: Some properties of materials used in extrusion processes for foils of optical quality (from [Eschenbach]). One can see the variability in the refractive index for some substances hinting at the cause for schlieren formation.

tained are given.

2. OPTICAL SYSTEM

The optical system as considered here consists of the measurement setup and its optical elements and the schlieren causing object under test — a thin optical foil to be measured.

2.1. Refraction Caused by a Schliere

As will be shown in this subsection the effect caused by a so–called schliere essentially is proportional to the gradient of the refractive index of the material the light passes through. The presentation closely resembles the one given in [Settles].

In Fig. 2 the light refracted (angle ε) due to a gradient $\partial n/\partial y$ in the refractive index n is shown. By inspection from Fig. 2 with $s_1 = c/n_1 \cdot \Delta t$ and $s_2 = c/n_2 \cdot \Delta t$ it follows for $n_1 > n_2$ directly that the angle of deflection ε is given by:

$$\varepsilon = \arcsin \frac{(s_2 - s_1)}{\Delta y} \approx \frac{(s_2 - s_1)}{\Delta y} . \tag{1}$$

In Eqn. 1 equal propagation times Δt for both considered paths in Fig. 2 are assumed which are dependent on the local refractive index, n, the speed of light in vacuum, c and the local thickness of the medium Δz (here $\Delta z = L$)

$$\Delta t = \Delta z \cdot \frac{n}{c} . \tag{2}$$

Inserting Eqn. 2 into Eqn. 1 yields:

$$\begin{aligned} \varepsilon &= \frac{(s_2 - s_1)}{\Delta y} \cdot \Delta z \cdot \frac{n}{c} && (3) \\ &= \frac{\Delta z}{\Delta y} \cdot \frac{n}{n_1 n_2} \cdot (n_1 - n_2) . && (4) \end{aligned}$$

Now letting $n_2 - n_1 = \Delta n \to dn$ and consequently $\varepsilon \to d\varepsilon$ gives:

$$d\varepsilon = \frac{dz}{dy} \cdot \frac{dn}{n} . \tag{5}$$

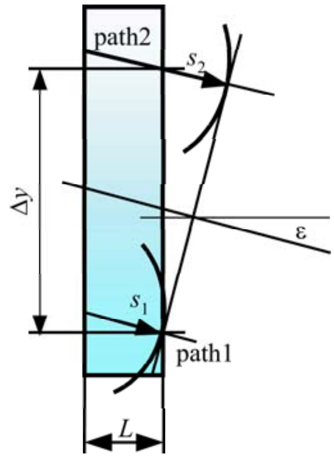

Fig. 2: A wavefront is impinging from left onto an inhomogeneous medium with thickness L exhibiting a gradient $\partial n/\partial y$ in its refractive index n causing the wavefront to be refracted by an angle ε while propagating from left to right.

In the above derivation c, is the speed of light in vacuum, n_1 and n_2 are refraction indices for light traversing paths 1 and 2, respectively of here equal length L, separated by the small distance Δy. The refraction angle is given by the integral (in z–direction) over the width of the media of the gradient of the refractive index. Thus integrating over the depth of a schliere L gives:

$$\varepsilon = \frac{1}{n} \int_0^L \frac{dn}{dy} \cdot dz . \tag{6}$$

Numerical example: For a typical foil thicknesses $L = 600\ \mu$m, a refractive index $n \approx 1.5$, a period y_P, of the chatter marks of 20 mm, and a variation in the thickness $\Delta L = 0.5\ \mu$m, the refraction angle to be accurately measured becomes $\varepsilon = 3.4$ second of arc (equivalent to 0.0000167 radian). This is posing a formidable measurement problem to be solved optically.

2.2. Sensitivity

Subtleties of optical path in a transparent specimen viewed in ordinary transmitted light are not visible simply because the intensity of the illuminating light is so large in relation to light deflected by the very slight optical path gradients. A schlieren system as depicted in Fig. 3 reduces the intensity of the main illuminating light by cutting it off by means of an appropriately placed so–called knife edge thereby greatly increasing the ratio of affected light (due to the path gradient) and the unaffected light focussed right at the knifes edge. With reference to Fig. 3 and following the derivation in [Settles] the sensitivity of a schlieren setup is given by the contrast $C = \Delta I/I$, the ratio of the differential illuminace (cause by an imaged schliere) ΔI, in relation to the background intensity (set by choosing an appropriate knife–edge cutoff) I.

$$C = \frac{f_2}{a} \cdot \varepsilon_y \tag{7}$$

In Eqn. 7 f_2 is the focal length of the second schlieren lens L_2, a is the fraction of light emitted by the source slit able to pass the restricting knife–edge S_2, and ε_y is the refraction (in y–direction) caused by the schliere in the film to be analyzed.

For the numerical example given above and using the optical setup with parameters $f_1 = 600$ mm, $S_1 = 1$ mm, $f_2 = 600$ mm, $S_2 = 1$ mm (skewed by 0.1 mm with respect to slit S_1), the contrast evaluates to

$$C = \frac{600}{0.1} \cdot 0.0000167 = 0.1 \tag{8}$$

which means that a 600 μm PMMA film with thickness variations of 0.5 μm (or with equivalent internal schlieren) with periods as large as 20 mm (which in view of the patterns seen in Fig. 1 is on the upper and less sensitive end of the spectrum) can still be discerned with a contrast–ratio C at the photo detector of 10 % or larger. As can be seen from Fig. 8 typical periodicities are in the range of 3 to 8 mm.

2.3. Measurement Setup

The optical system used to measure the quality of the film extruded is based on Toeplers schlieren system [McCallum], [Haferkorn]. It consists of a high intensity incandescent lamp (20 W @ 24 V) with a 2.3 mm long narrow filament oriented parallel to the used source slit that allows to vary the systems sensitivity by changing its width (see Fig. 3). A condenser system (f = 150mm / 4.5) to collect and redirect the emitted light toward the so–called source slit S_1 whose width can be varied from 0.1 mm up to 2.0 mm to adjust the systems sensitivity to refraction effects within the object under test O. The source slit effectively forming a virtual line source thus — as will be seen later — rendering the system sensitive only for schlieren oriented orthogonally to the slit, which is chosen to be perpendicular to the direction of extrusion. Lens L_1 (f = 600mm / 5.6) is used to collimate the light passing the slit illuminating evenly the object under test. Lens L_2 (f = 600mm / 5.6) re–images the light source (the slit) on a second slit (actually a cut–off forming knife edge) S_2 which cuts the image opposite to that of the first obscuring edge and also images the sample onto the projection screen (or a well placed photo detector) if a homogeneous object is placed into the beam of collimated light. The photo detector used is a 0.8 mm^2 PIN–type Si–diode with an integrated preamplifier giving a bandwidth $B \geq$ 10kHz and a sensitivity of 20 mV @ 1 lx. Its signal is fed into a National Instruments USB–6008 multifunction data acquisition unit attached to a standard PC providing the necessary signal processing and data visualization capability.

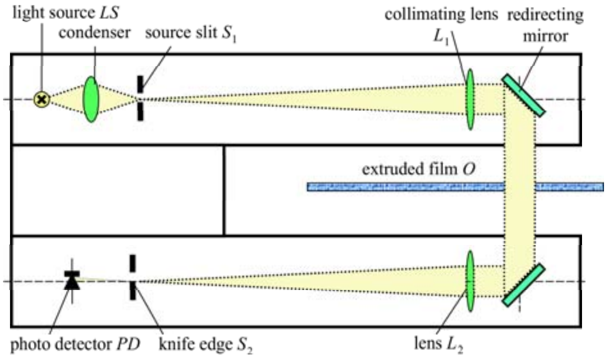

Fig. 3: Toeplers schlieren setup consisting of a high intensity light source (LS), a condenser system focusing the emitted light onto the source slit, S_1, a collimating lens, L_1, the transparent object under test, O, the projecting lens, L_2, a limiting aperture (usually a second slit oriented parallel to the source slit), S_2, and a projection screen PD.

Figure 4 shows a photo of the actual measurement head with a size of approximately 1050 mm × 450 mm × 150 mm.

3. MEASUREMENTS

In this section some measurement results acquired with the setup shown in Fig. 3 are presented. Figure 5 shows a schlieren image of a 1000 μm PMMA film that clearly displays strong residual schlieren. This image was taken by a similar setup having the photo detector replaced by a digital camera to enable a twodimensional image acquisition. It is further on analyzed to derive schlieren periodicities that could hint on the mechanical parameters responsible for the quality defects seen. In Fig. 6 a surface plot of the intensity image (Fig. 5) is shown. One can clearly see the relative contrast in this image which amounts to approximately 10% corresponding to the numerical example given above.

Fig. 4: Photo of the schlieren optical measurement head.

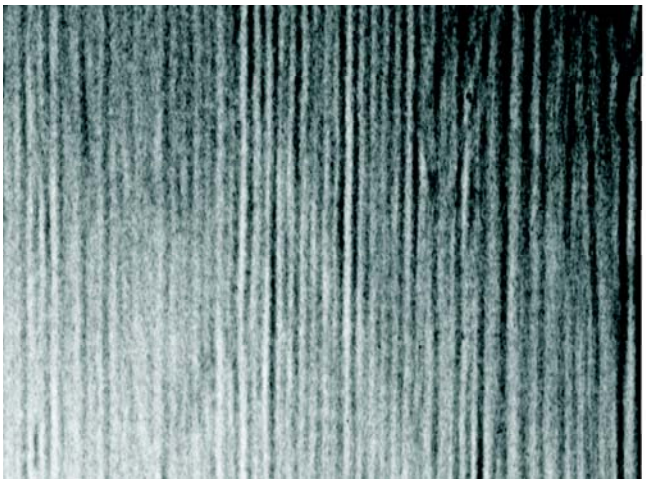

Fig. 5: Schlieren image of a PMMA film digitally processed to enhance image contrast considerable. The imaged foil is 196 × 84 mm^2 in size.

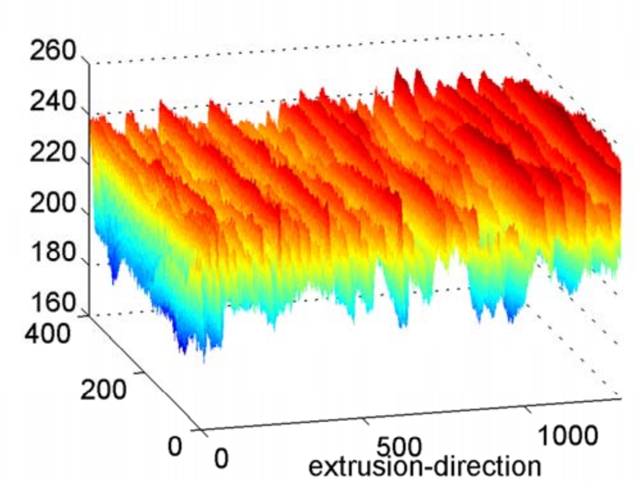

Fig. 6: Surface plot of the intensity image (Fig. 5) clearly exhibiting the relative contrast C within the image on the order of $\approx 10\%$.

Figure 7 shows the temporal intensity variation at the location of the photo detector PD (in Fig. 3) over the duration of 1500 ms. This amounts to a extrusion velocity of approximately 300 mm/s.
Figure 8 gives an example of a spatial spectrum (although displayed in periods and not frequency) measured for a PMMA film specimen. The periodicities clearly visible can hint on the root cause of the vibrations ultimately leading to an improvement in the extrusion mechanics.

4. CONCLUSIONS

In this paper it was demonstrated that an inline–capable schlieren–optical setup is able to image schlieren within extruded material on–line. Due to the rapid nearly instantaneous display of the measurement results corrective actions can be taken in due time if production quality tends to decline for any reason. The system is able to resolve schlieren that cause refractions in the light paths as small as a few second of arc and is thus able to characterize extruded film of highest optical quality used for example in sunglasses.

Future work will extend the systems capabilities to also characterize the polarization states of the extruded film which seems to be necessary for applications utilizing linear polarized light like used in mobile phone display and their covers.

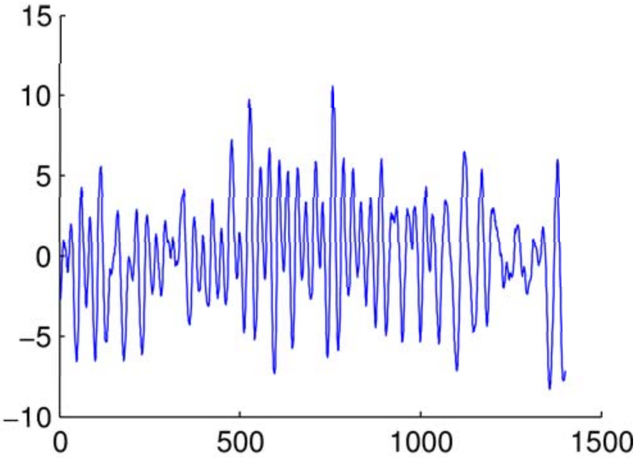

Fig. 7: Temporal intensity variation (in ms) measured at the location of the photo detector in Fig. 3 for a feed–rate of approximately 300 mm/s of the extruded film. The imaged film amounts to a length of 450 mm.

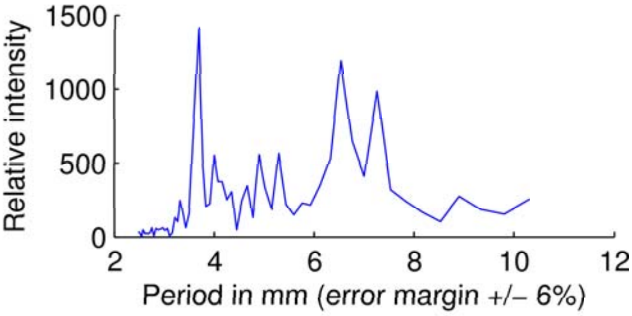

Fig. 8: Spatial spectrum of the PMMA film depicted in Fig. 5.

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