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Material Characterisation

Analysis of the diffracted field near the focal region due to the birefringence of the field flattening lens of the laser scanning system

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ABSTRACT

In most cases of molding with glass or optical polymers, the birefringence caused by the internal mechanical stresses remaining in the molding material is inevitably avoided. The distribution of the residual stress can be annealed through slow cooling, but is disadvantageous in terms of shape accuracy and manufacturing time. In this study, an analytical model is suggested for calculating the diffracted field near the focal plane by considering two primary meaningful parameters: the difference in the orientation angle between the fast axis and the slow axis and the path difference between the two axes. To verify the reliability of the analytical model, the experimental spot profile from the image forming lens of the laser scanning unit with a specific degree of birefringence was compared with the analytical result. Also, based on the validated optical analysis model, the optical performance in the near-focus region was analyzed considering the variation of the orientation angle deviation and the phase delay difference between the two axes.

1. Introduction

In many manufacturing processes for optical components that induce optical phenomena such as transmission, refraction, and diffraction for imaging, the mechanical residual stresses inside the material cause unwanted birefringence and generate aberrations and blurred spots. The problem has become even more serious as the optical materials used in countless applications have shifted from glass to optical polymers to meet the demand for low-cost materials. Although birefringence occurs in both glass and optical polymers, as shown in Fig. 1, it is much more severe in injection molding with optical polymers [1,2].

The major causes of severe birefringence can be divided into two main categories: (1) the difference in the cooling rate inside the polymer when the cooling rate of the polymer melt is increased; and (2) the difference in shear stress due to the high holding pressure applied on the surface of the molding to prevent the volume contraction of the polymer [3,4]. To minimize the cause of this distortion, the long-time cooling process can be employed. However setting the process time to a level that minimizes birefringence is not the best way to address the problem because the process time directly affects the cost of the optical components.

In the case of the application to laser scanning system, most imaging lenses are more than 150 mm long and less than 20 mm thick. Particularly, in the case of the application of the field flattening lens to the wide format scanning exceeding 300 mm long and less than 15 mm thick, if the optical polymer is injected rapidly, severe cooling rate and shear stress deviation can occur [5].

Until now, most of the effects of the amount of birefringence on the performance of the diffracted beam spots have been compared with the resultant image quality based on the experiment results, rather than directly estimating the deterioration of the optical characteristics through theoretical analysis [6–8]. In this paper, an optical simulation method that can calculate the diffracted spot profile considering the refractive index difference and the distorted phase in the case of birefringence is proposed.

First, a numerical calculation method for analyzing the birefringence effect will be introduced. To verify the validity of the proposed analytical technique, the beam spot measurements of the field flattening lens of the laser scanning system, which shows the deterioration of the optical characteristics of the diffracted beam spot by the birefringence characteristics, will be compared. In addition, the

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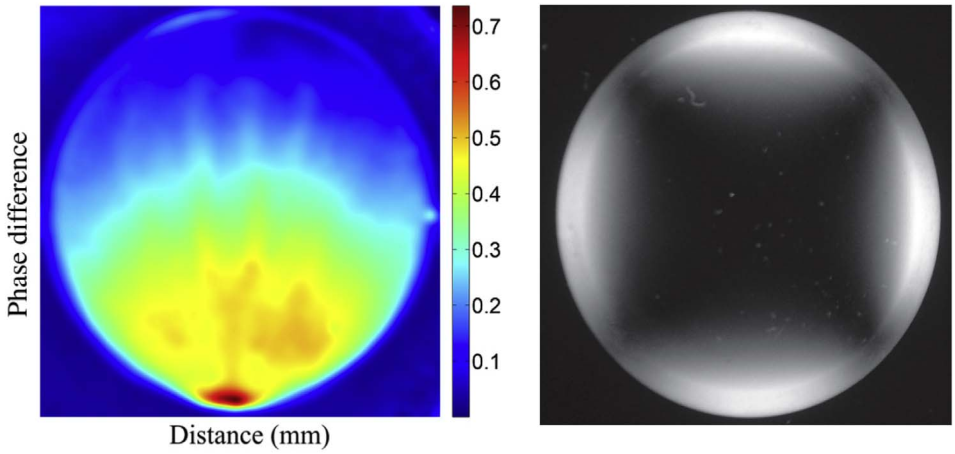

(a)

(b)

Fig. 1. Birefringence induced in the optical components. (a) Residual stress in the injection-molded polymer disk measured with a low-birefringence polariscope. (b) Image of a molded glass lens observed using the polarimeter.

changes in the imaging characteristics of the laser scanning system through the changes in the main birefringence parameters (i.e., the difference in the orientation angle between the fast and slow axes and the phase delay between the two axes) will be analyzed.

2. Theoretical background

As an example for the laser scanning system, a common optical layout of the laser scanning unit (LSU) for electrophotography is shown in Fig. 2. This general layout can be applied to various applications to apparatus for line-exposure. The light emitted from the laser diode is collimated before it passes through the aperture. The light beam shaped by the aperture is focused on the mirror surface of the polygon mirror only in the process direction. The reason for this is to minimize the jitter induced by the periodicity generated by the error of the verticalness of the reflection plane of each surface of the polygon mirror. The flux reflected from a polygonal mirror is imaged onto the imaging plane by field flattening optics. The field flattening lens corresponding to the wide scanning area cannot have high refractive power because it has a continuous shape in the scanning direction. Therefore, to have an F/# with the same level as the process direction, the size of the aperture in the main scan direction is generally made larger than the size of the aperture in the process direction. Needless to say, the main resolution of optical instruments is defined by the wavelength of the laser diode and the F/# of the optics. Generally, the laser diode wavelength is 780 nm, and F/# is 45–55, so the normal resolution is about 60–75 μm of the full-width-1/e maximum of the peak intensity. As the resolution of the optical system is not high, when one piece of field flattening lens is applied to the LSU, the principal plane for both the main scan and the process directions can be approximated to trace the shape of the field flattening lens. Thus, the optical characteristics of the diffracted beam spot when there are changes in the optical parameters of the lens, such as the shape errors and birefringence, can be approximated by modulating the exit pupil of the entire optical system considering the amounts of changes in the optical parameters.

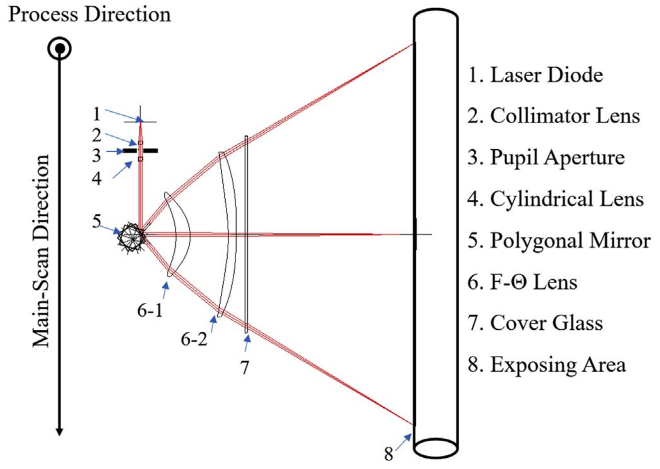

Fig. 2. General optical layout of LSU for electrophotography.

The quality of the optical system for imaging can be characterized by a spot profile near the focal plane. To analyze the focused field near the image plane, the optical configuration shown in Fig. 3 is considered. For an aplanatic system that satisfies the sine condition, the electric field at the Gaussian focus is given by the Cartesian coordinates (x, y, z) near the Gaussian focus, which is given by Ref. [9].

$$E_{img}(x_p, y_p, z_p) = \frac{-i}{2\pi}\int\int_{-kNA}^{kNA}\frac{E_0(k_x, k_y)}{k_z}e^{i\left(\vec{k_x}\cdot\vec{x_p}+\vec{k_y}\cdot\vec{y_p}+\vec{k_z}\cdot\vec{z_p}\right)}dk_x dk_y$$
$$-\,k\mathrm{NA} \le k_x,\, k_y \le k\mathrm{NA}. \tag{1}$$

where $E_0(k_x,\ k_y)$ is the amplitude of a plane wave on the exit pupil described by the propagation vector $k = (k_x,\ k_y,\ k_z)$. The focused electric field at the image position $E_{img}(x_p,\ y_p,\ z_p)$ can be calculated by integrating the diffracted plane waves over the two-dimensional domain of wave vectors, k_x and k_y, considering its maximum numerical aperture, $\mathrm{NA} = \sin\theta_{\max}$. In the case with terms of phase and amplitude modulation by the intrinsic factors of the optical system, such as phase delay or amplitude fluctuation, equation (1) can be rewritten as shown below.

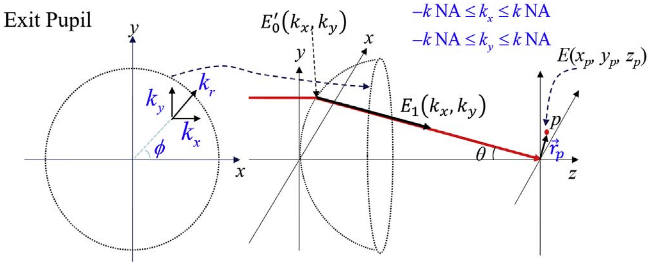

Fig. 3. Conceptual diagram of imaging optics with a multi-layered medium near the focal region. The incident electric field on the entrance pupil is transformed to E0′ on the exit pupil with a constant geometric focal length. On the focal plane, the observation point is denoted as p with the position vector $\vec{r_p}$.