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Characterisation of laser marks using digital holographic microscopy

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ABSTRACT

The inspection and characterisation of laser marks using digital holographic microscopy (DHM) is presented in this paper. A DHM system in transmission mode was designed and the reconstruction algorithm for this configuration was investigated. The software was developed to provide live reconstruction of holograms for real time numerical evaluation of amplitude and phase contrast images. A CO₂ laser-based marking system was employed to create marks on glass substrates. By analysing the quality, 3D profile measurement, and material distribution of the marked area, the parameters of the laser system could be optimised to achieve the desired mark. The phase contrast images provide quantitative refractive index analysis and 3D profile studies. The results were compared with those obtained using white light confocal microscopy. The capabilities and advantages of the DHM system for the analysis of laser marks are also presented.

Keywords: Laser mark characterisation, 3D profiling, digital holographic microscopy, quantitative phase contrast imaging, confocal microscopy

1. INTRODUCTION

Holography is a well established method of optical metrology for both imaging and measurement applications [1-2]. It has several advantages over other conventional optical methods. Amplitude and phase are two main parameters used to characterise an optical wave. Optical detectors such as photographic films or charged coupled devices (CCDs) can record only the amplitude, and the phase information is lost in the recording process. Holography, on the other hand, records both the amplitude and phase, as proposed by Dennis Gabor [3]. When an object wave interferes with a known reference wave, the recorded interference pattern is called a hologram. The most attractive feature of holography is the recording of the full 3D information about the object in a single hologram. This feature makes holography an ideal tool for imaging and measurement. Digital recording of holograms is much more advantageous than film-based holography. Even though the resolution of the best digital cameras is about 50 times less than that of high resolution holographic films, the benefit of digital holography lies in the possibility of numerical processing. This presents perfect solutions to the limited resolution of the recording system. With developments in digital computers and CCDs, digital holography was proposed [4] to overcome the problems of classical holography. It has received increased attention in the last few years because of rapid improvements in the storage and processing of digital information. The object wave could be numerically calculated from the holograms, with the possibility to quantitatively obtain both the amplitude and phase information separately, which is not possible in conventional holography. Off-axis digital holography has been developed for application to numerical phase contrast imaging [5]. For phase contrast imaging, the numerically defined reconstruction wave must be a digital replica of the reference wave that was used for the hologram creation.

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In DHM, the object beam is magnified and then interferes with the reference wave. The magnification process of the object wave can be performed either by using the lensless geometry [6] or by using microscopic objectives (MOs). The presence of an MO produces a curvature in the object wavefront, which affects the reconstructed phase image. Various digital approaches have been presented to correct the curvature of the MO by using a digital phase mask [7-9]. It has been demonstrated that quantitative phase contrast images are possible and can be used directly for applications in optical metrology [10-12].

In this paper, we present a DHM system used to inspect and characterise laser marks on glass substrates. Laser marking is one of the most widespread industrial applications of lasers. The CO₂ laser is used in marking most plastics and composite materials, and, increasingly, to mark metal and glass. The mark quality is judged by its contrast, depth, and width, and also sputtering and micro cracks. These characteristics are normally assessed by using various microscopy techniques together with a surface analyser/profiler for the depth measurement.

The CO₂ laser-based marking system uses two scanning mirrors and an f-theta lens system to focus the laser beam onto an object to create a mark or pattern. A computer system is used to control the movements of mirrors to direct the laser beam in the x and y directions and to provide precise & clean marks at a high rate. The quality of the laser mark can then be ascertained by inspecting the 3D profile around the marked area. It is important to optimise the laser marking parameters to prevent cracks due to the thermal stress caused by the marking process and, thus, ensure crisp high-quality marks on the substrate.

The algorithm for numerical reconstruction of the object wave and quantitative phase contrast imaging was investigated. The results were compared with those of a white light confocal microscopy system and showed quantitative comparison of the depth of the marks. Some additional advantages of the DHM system over the confocal microscopy system have been highlighted in this paper.

2. DIGITAL HOLOGRAPHIC MICROSCOPY SYSTEM

2.1 Optical system configuration

We have developed the DHM system in both the transmission and reflection modes [13]. In the present study of the laser marks on glass substrates, the DHM system in transmission mode was used. The optical system is shown in fig.1. The output from a HeNe laser (632.8nm) is coupled into a bifurcated single mode fibre. One fibre arm is used to illuminate the object with a collimated beam, and then magnified using an MO. This forms the object beam. The object beam interferes with the collimated reference beam from the second fibre. The polarisation of both the object and reference waves were maintained to get the best contrast for the interference fringes. The interference between the object and reference beams is recorded on a CCD at a frame rate of 15 frames/sec. The CCD contains 1280x960 pixels of 4.65 μm in size. The CCD is placed in between the MO and the image plane, and the reconstruction distance is taken from the CCD to the image plane during the numerical reconstruction process.

An offset angle is maintained between the object wave and the reference wave to separate the real image from the twin virtual image. The limited resolution of CCD sensors limits the angle θ (called the interference angle) between the object and reference beams to only a few degrees. For the exact recovery of the object information during the reconstruction process, the sampling theorem requires that the interference fringe spacing must be larger than the size of two pixels of the CCD, i.e. $\theta < \lambda / 2\Delta\xi$, where λ is the wavelength of the light used and $\Delta\xi$ is the pixel size of the CCD. For efficient utilization of the recording sensor, it is important that the sampling theorem is fulfilled across the entire area. Thus, for the MO, the recording distance should be selected in such a way as to fulfill the sampling requirements.

Let (x, y) be the object plane and (ξ, η) be the hologram plane as shown in fig. 2. The hologram, which is the interference of the object wave $O(\xi, \eta)$ and the reference wave $R(\xi, \eta)$, can be written as

$$H(\xi, \eta) = |O(\xi, \eta) + R(\xi, \eta)|^2$$

$$H(\xi, \eta) = |O(\xi, \eta)|^2 + |R(\xi, \eta)|^2 + O^*(\xi, \eta)R(\xi, \eta) + O(\xi, \eta)R^*(\xi, \eta) \quad (1)$$

O^* and R^* are the complex conjugates of O and R respectively.

The CCD, placed at the hologram plane, records this interference pattern. The recorded pattern is converted into a two-dimensional array of discrete signals by using the sampling theorem [14]. Let $M \times N$ be the total number of pixels of the CCD with the corresponding size $\Delta\xi$ and $\Delta\eta$. Then, the digitally sampled hologram $H(m, n)$, can be written as

$$H(m, n) = [H(\xi, \eta) \otimes \text{rect}(\frac{\xi}{\alpha\Delta\xi}, \frac{\eta}{\beta\Delta\eta})] \times \text{rect}(\frac{\xi}{M\Delta\xi}, \frac{\eta}{N\Delta\eta}) \text{comb}(\frac{\xi}{\Delta\xi}, \frac{\eta}{\Delta\eta}) \quad (2)$$

where $\otimes$ represents the two-dimensional convolution, and $(\alpha, \beta) \in [0, 1]$ the fill factors of the CCD pixels. Thus, an optical hologram is sampled by each pixel over the entire array of the CCD sensor area, giving a digital hologram.

Fig. 1 Optical system of the DHM system

Fig. 2 Coordinate system for digital holography

2.2 Reconstruction methodology

For the reconstruction process, the hologram $H(\xi, \eta)$ is illuminated by the reconstruction wave $R(\xi, \eta)$. The reconstructed wavefield at the image plane (x', y') at distance d' is given by the Fresnel diffraction equation [14]

$$U(x', y') = \frac{e^{ikd'}}{i\lambda d'} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) \exp\left[\frac{i\pi}{\lambda d'} \{(x' - \xi)^2 + (y' - \eta)^2\}\right] d\xi d\eta \quad (3)$$

The impulse response $g(\xi, \eta)$ of the coherent optical system can be defined as

$$g(\xi, \eta) = \frac{e^{ikd'}}{i\lambda d'} \exp\left\{\frac{i\pi}{\lambda d'} (\xi^2 + \eta^2)\right\} \quad (4)$$

Using equation (3), equation (4) can also be written as

$$U(x', y') = e^{i\pi d'(\nu^2 + \mu^2)} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) g(\xi, \eta) \exp[-2\pi i\{\xi\nu + \eta\mu\}] d\xi d\eta \quad (5)$$

Here $\nu = \frac{x'}{\lambda d'}$ and $\mu = \frac{y'}{\lambda d'}$ are the spatial frequencies present in the hologram. Thus, the reconstructed field is simply the Fourier transform of the product of the hologram, the reconstruction wave and the impulse response function, i.e.

$$U(x', y') = \mathfrak{F}\{H(\xi, \eta) R(\xi, \eta) g(\xi, \eta)\} \quad (6)$$

If the reconstructed wave is the complex conjugate of the reference wave, then a real image of the object wave is formed at the reconstruction distance d' which is the same as the recording distance of the hologram.

2.21 Discrete Fresnel transformation

If the hologram recorded with the CCD contains $M \times N$ pixels with pixel size $\Delta\xi$ and $\Delta\eta$ along the coordinates respectively, then the reconstructed field is converted to finite sums as [15]:

$$U(k, l) = \frac{e^{ikd'}}{i\lambda d'} e^{i\pi\lambda d' \left(\frac{k^2}{M^2\Delta\xi^2} + \frac{l^2}{N^2\Delta\eta^2}\right)} \times \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} H(m, n) R(m, n) e^{\left[\frac{i\pi}{\lambda d'} (m^2\Delta\xi^2 + n^2\Delta\eta^2)\right]} e^{-2\pi i \left(\frac{mk}{M} + \frac{nl}{N}\right)} \quad (7)$$

where $k = 0, 1, \dots, M-1, l = 0, 1, 2, \dots, N-1$. Equation (7) is the discrete Fresnel transformation. The matrix $U(k, l)$ is the discrete Fourier transform of the product of $H(m, n)$, $R(m, n)$ and $\exp\{(i\pi/\lambda d')(m^2\Delta\xi^2 + n^2\Delta\eta^2)\}$. Thus, the calculation of the reconstructed wavefield can be done effectively by using the fast Fourier transform (FFT) algorithm. The pixel size of the numerically reconstructed image varies with the reconstruction distance and is given by

$$\Delta x' = \frac{\lambda d'}{M\Delta\xi}, \quad \Delta y' = \frac{\lambda d'}{N\Delta\eta} \quad (8)$$

2.22 Compensation of phase curvature of microscopic objective

The presence of an MO in the system produces a curvature in the object wavefront, which affects the reconstructed phase image. However, there are no such effects of curvature on the amplitude contrast image. In order to remove the phase aberrations numerically, there is a need to create a digital phase mask which has the spherical phase factor. The spherical phase factor can be defined as follows:

$$\phi_{sp} = \frac{2\pi}{\lambda} \exp\left(\frac{M^2 \Delta x'^2 + N^2 \Delta y'^2}{2r}\right) \quad (9)$$

where r is the radius of curvature of the wavefront. This reconstructed wavefront is multiplied by the phase factor and, thus, the reconstructed image is free from the phase aberrations of the MO. The distance r of the phase factor is decided by the optical geometry.

The image intensity can be calculated by squaring the numerically reconstructed wavefield

$$I = |U(k, l)|^2 \quad (10)$$

and the phase is calculated as:

$$\phi = \arctan \frac{\text{Im}(U(k, l))}{\text{Re}(U(k, l))} \quad (11)$$

The numerically reconstructed phase information can be used for the height/depth measurements of the sample. If n is the refractive index of the sample, then the sample height t can be written for the transmission mode as follows:

$$t = \frac{\lambda \phi}{2n\pi} \quad (12)$$

3. EXPERIMENTS AND RESULTS

The hologram of a laser mark, recorded using the optical system of fig.1, is shown in fig.3. The magnification of the MO is 10X. Circular interference fringes could be clearly seen in the hologram. This is because of the collimated reference wave and diverging object wave. These fringes are centered to the side because of the off-axis geometry. In the Fourier domain, the off-axis geometry results in the clear separation among the zero-order and first-order diffraction terms. The first order terms correspond to the real image and virtual image terms. The software was developed to make it possible for either the real or virtual image to be selected for reconstruction while eliminating the other and zero-order terms. The filtered diffraction term is centred, and then numerically propagated to obtain the complex wavefield $U(k, l)$, and, thence, the intensity and phase images.

Fig. 3 Hologram of a laser mark on glass substrate recorded by the DHM system

3.1 Results obtained with digital holographic microscopy system

The reconstructed amplitude contrast image of the object is given in fig. 4(a). Here, the object is a transparent laser mark on a glass substrate. The amplitude image shows the intensity distribution due to the uneven material distribution at the marked location. Some micro cracks can also be seen around this area. The phase contrast image is shown in fig. 4(b), and is significantly different from the amplitude contrast image. It shows the refractive index distribution of the glass material in the vicinity of the laser mark. The wrapped phase can be seen clearly because of the phase jumps of more than 2π .

Fig. 4 (a) Reconstructed amplitude contrast image (b) Phase contrast image

In order to study the depth of the mark, there was need to unwrap the phase contrast image. Fig. 5 shows the unwrapped phase contrast image. The quantitative value of the phase is converted to a length scale using equation (12). It can be directly used for 3D profile measurement of the laser mark. The 3D profile of the laser mark is shown in fig. 6(a). The depth of the laser mark could be identified by plotting the line profile across the centre of the unwrapped phase contrast image and is shown in fig 6(b). Thus, by using only a single hologram, it was possible to reconstruct the amplitude, phase, and 3D profile of the object. The algorithm was developed in C++ to provide real time reconstruction of the digitally recorded hologram.

Fig. 5 Unwrapped phase contrast image

Fig. 6 (a) 3D profile of laser mark obtained with the DHM system (b) Line profile showing the depth of the laser mark ($\sim 7.5\mu\text{m}$)

3.2 Comparison of results with those obtained with confocal microscopy

Fig. 7(a) 3D profile obtained with a white light confocal microscope (b) Line profile showing the depth of the laser mark ($\sim 7.5\mu\text{m}$)

The depth profile of the laser mark measured with the DHM system was compared with the results obtained with a white light confocal microscope, which is in reflection mode. It was necessary for the confocal microscope to scan the object in 3D planes and took a few minutes to generate the 3D profile of the sample. Thus, the confocal microscope is not suitable for real time 3D measurement applications. The 3D profile is shown in fig. 7(a), while the depth profile of the laser mark is shown fig. 7(b). The line profiles across the centre part for the results obtained with the DHM system and the confocal microscope are comparable. The depth of the laser mark was measured to be about $7.5\mu\text{m}$ for both cases.

Laser marks with a depth ranging from sub-micron to $10\mu\text{m}$ were obtained by varying the CO_2 laser power and pulse repetition rate. The white light confocal microscope could not measure 3D profiles which has a depth of less than $6\mu\text{m}$. In contrast, the DHM system could be used to measure all these laser marks. Two of these measurements are given in fig. 8 and fig.9, showing depths of $0.85\mu\text{m}$ and $4.3\mu\text{m}$ respectively.

Fig. 8 (a) 3D profile of laser mark obtained with the DHM system (b) Line profile showing the depth of the laser mark ($\sim 0.85 \mu\text{m}$)

Fig. 9 (a) 3D profile of laser mark obtained with the DHM system (b) Line profile showing the depth of the laser mark ($\sim 4.3 \mu\text{m}$)

4. CONCLUSIONS

A DHM system is presented for the characterisation of laser marks. The methodology for the numerical reconstruction of amplitude and phase contrast images for the system is presented. The results for the study of marks made by a CO_2 laser on glass substrates, when the laser power and pulse repetition rate were varied, are presented, showing the amplitude contrast, phase contrast, 3D profile, and depth profile measurements. Furthermore, the results were compared with those obtained using a confocal microscopy system. The 3D profile of the laser mark showed good comparison between the DHM and confocal microscopy systems for a depth which is greater than $6 \mu\text{m}$. The white light confocal microscope could not measure smaller depth 3D profiles. In contrast, the DHM system was able to measure smaller depths down to the nanometric range. Moreover, the DHM system provided real time reconstruction while the confocal microscopy system took several minutes to generate the 3D profile of the sample. Further tests will be carried out for a more in-depth study to determine the effects that various parameters of the marking process have on the characteristics and quality of the mark.

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