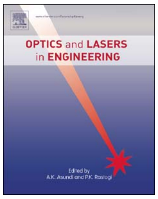
Optics and Lasers in Engineering 96 (2017) 75–82

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



# Industrial resin inspection for display production using automated fluid-inspection based on multimodal optical detection techniques

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## ARTICLE INFO

*Keywords:*
Optical coherence tomography
Optical inspection
Optical instruments
Optical materials
Thin film devices and applications

## ABSTRACT

The large-scale liquid-crystal display (LCD) industry requires an accurate inspection system for identifying defects, as the LCD quality can be drastically degraded because of defects. In particular, the refractive index of LCD panels can be changed by internal micrometer-range substances, which form as a result of defectiveness and the insufficient solidification of industrial liquid resins. Intrinsically, the defect inspection of the raw materials must be performed prior to the LCD manufacturing process. Thus, optical coherence tomography (OCT) based automated fluid-inspection (AFI) methodology was introduced to demarcate and enumerate the defects in industrial liquid resins and the final product (LCD smartphone). The accuracy of the method was enhanced by implementing an intensity-detection algorithm. Subsequently, the optimal solidification rates of liquid resins were investigated using a fluorescence sensor-based ultraviolet hardening method to prevent the formation of defects between the internal layers of the LCD panel. Therefore, AFI can be implemented as an effective and cost-saving method in the smartphone industry for improving the quality of the final product.

## 1. Introduction

Liquid crystal display (LCD) panels, industrial liquid resins, and raw materials have attracted considerable attention in the smartphone manufacturing industries. A mobile phone consists of a LCD panel, which has an active area to display images, along with several other substrates containing liquid crystals and transparent liquid resins in the gel state injected between them. In smartphone manufacturing, several lamination processes are conducted, and a multilayered structure with a gap of 100–250 µm between the layers is ultimately formed [1,2]. Advances in the fabrication and manufacturing process of microscale materials in the LCD industry have led to a diversity of small and compact devices consisting of microstructures [3,4]. Although the manufactured product is compact, the inspection of the final product is important for preventing a drastically degraded LCD quality. This is because during the manufacturing process, LCD panels and mobile phones can be become defective or damaged as a result of defective raw materials and industrial liquid resins. The industrial liquid resins become defective due to fine dirt (dust particles) or impurities, and insufficiently solidified liquid resins between the internal layers (thin films) of a LCD panel. These defects lead to change the refractive index of the LCD panel, which is a major challenge in the LCD industry [5,6]. The defect inspection of the aforementioned raw materials, industrial liquid resins, and compact final products has become challenging and time-consuming owing to the several drawbacks of conventional inspection systems.

Considerable research has focused on visual inspection; machine vision inspection with a charge-coupled device; and X-ray, photoluminescence, and electroluminescence imaging techniques, which suffer from internal micrometer range defect detection because of less resolution and most of the existing methods can be implemented for the defect detection of the topography [7–14]. Also, subjective decisions made by the operator degrade the accuracy of visual inspection methods as well. Furthermore, micrometer resolution was an essential requirement to identify defective foreign substances and internal defects with a micrometer range magnitude in liquid resins and LCD panels, which are difficult to be identified using aforementioned methods. In response to this problem, the expensive methods of scanning electron microscopy and transmission electron microscopy, which require destructive sample-sectioning procedures, have been

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http://dx.doi.org/10.1016/j.optlaseng.2017.04.013
Received 2 November 2016; Received in revised form 15 March 2017; Accepted 26 April 2017

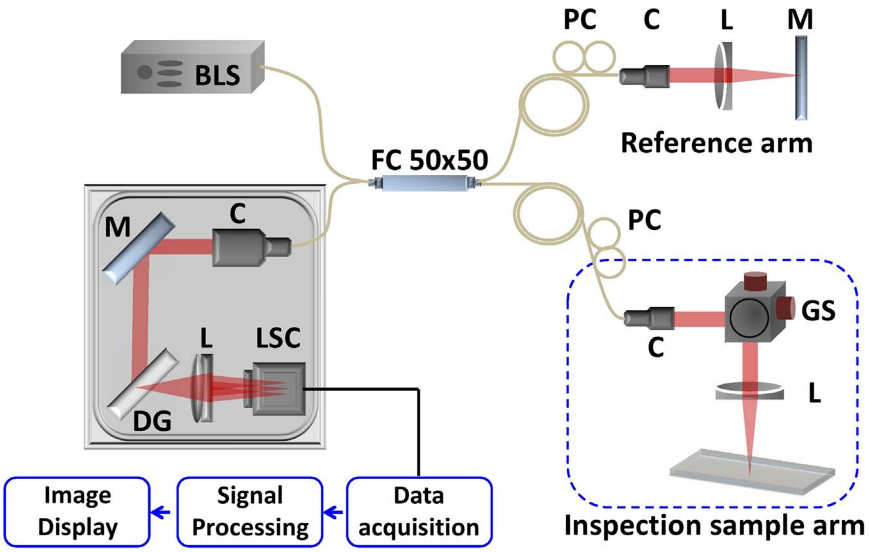

**Fig. 1.** System configuration of the OCT section of AFI method. Abbreviations: BLS, broadband laser source; C, collimator; DG, diffraction grating; FC, fiber coupler; GS, galvanometer scanner; L, lens; LSC, line scan camera; M, mirror; PC, polarization controller.

introduced to obtain a desirable visual effect [15–17]. On the other hand, several approaches have been demonstrated for the defect and quality inspection of industrial products, such as resins and chemical composites. Hence, X-ray microcomputed tomography (XμCT) was used to evaluate density changes, reinforcement filler damages, homogeneity, and cracks in epoxy resin composites. Also, ultrasonic (C-scan) inspection method was used to inspect the microvoids, which are formed during resin transfer molding. However, the difficulty of attaining simultaneous high-resolution images along with high depth penetration limits the inspection capability of micrometer range defects formed in deep structures [18–20]. Therefore, without a precise demarcation method for detecting foreign substances in fluids (industrial dyes and liquid resins), thin films, LCD panels, and LCD surfaces, rigorous defect identification is challenging.

In recent years, the advancement of the latest expensive slim smartphone devices has reached a climax. Thus, reliable and accurate process inspection technology is the most essential requirement for reducing the defects of the product. To overcome the inspection limitations, alternative noninvasive investigation methods have attracted significant attention. Therefore, optical coherence tomography (OCT) was proposed as a defect-inspection method for industrial products [21,22]. Owing to its high-resolution and nondestructive imaging capability, OCT can reconstruct depth-resolved cross-sectional images of a sample with a resolution on the order of microns and a depth range of 3–4 mm [23–25]. To obtain cross-sectional image information about samples, OCT has been employed for the defect inspection of various industrial and agricultural products [26–30]. These studies have demonstrated the capability of OCT in various industrial fields and its potential for nondestructive defect inspection. An initial quantitative assessment for a touch-screen panel was performed by our group to inspect defects three-dimensionally [5,31]. Furthermore, several recent studies have employed OCT as an inspection method for solar cells, glass defects, and paper productions [32–34]. Therefore, OCT can be implemented to detect the accurate localization and precise characterization of various defects within a sample as well as on its surfaces at an ultra-high resolution compared with the existing methods. However, most of the literature regarding OCT involves its use for product-quality verification after the manufacturing process [35,36]. Moreover, the pre-inspection of industrial liquid-resin defects and the initial formation of defective regions due to an inappropriate solidification rate have not been experimentally tested prior to the manufacturing process. Hence, it is essential to inspect the aforementioned parameters at an early stage to prevent the formation of defective regions using a software-based, automated, rapid, rigorous, and noninvasive inspection method, which will simplify the final product-verification process.

In this study, we developed an OCT method-based multitasking automated fluid-inspection (AFI) methodology to demarcate and enumerate defects of industrial liquid resins for LCD production. The proposed system is also applicable for the defect inspection of the final LCD in a smartphone production line. To demarcate defects rigorously, an automated intensity-detection algorithm was implemented to our inspection scheme, which provides an immediate verification about the product as defective or non-defective in real-time. Apart from micrometer resolution OCT image acquisition, we evaluated the liquid resin hardening rate and the stiffness of various liquid resins by integrating a powerful, commercially available analytical optical tool: a fluorescence detector-based ultraviolet (UV) hardening system, which simply provides a numerical confirmation of resin hardening rate to enhance the system capability. It is well-established that fluorescence sensor-based UV-hardening systems play a vital role in analyzing the hardening rate and stiffness of liquid resins. During the aforementioned liquid resin hardening, a polymerization process is occurred and the material becomes stable by emitting the luminescence as fluorescent light, which can be measured using fluorescence sensor. To obstruct the formation of defects, appropriately stiffened internal display layers (window glass layers, optical thin films, and LCD panel) without a change in the refractive index were confirmed according to the UV-based resin hardening rate for each corresponding liquid. To the best of our knowledge, this is the first demonstration of an AFI implemented as a multitasking system that provides a powerful means to the smartphone industry.

## 2. Materials and method

### 2.1. Optical inspection system configuration

A schematic of the AFI optical-detection system configuration is shown in Fig. 1. The system was operated with a broadband light source (BroadLighters T-850-HP, Superlum) having a center wavelength of 860 nm and a full width at half maximum of 165 nm. A 50:50 optical fiber coupler split the laser beam into a sample arm and a reference arm. The interference fringes of the backscattered beam from the sample and reference arms were recorded by a compact spectrometer (Oz-tec, Korea). The detailed configurations of the OCT instrumentation are provided elsewhere [37]. The system axial resolution was measured