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APPLICATION OF LASER MEASUREMENT METHODS IN THE QUALITY CONTROL OF PACKAGING MATERIALS

Sativaldiev Aziz
Department of Metrology and Light Industry Andijan State Technical Institute, Andijan, Uzbekistan
E-mail:azizsativaldiev@astiedu.uz

Abstract. This article examines modern laser scanning and profilometry methods applied to the analysis of packaging materials. Particular attention is paid to non-contact thickness measurement, microdefect detection, and sealing integrity assessment of polymer and multilayer structures. The principles of laser triangulation and interferometry are presented, along with comparative characteristics of laser and mechanical control methods. Examples of laser system applications in the production of flexible packaging and multilayer polymer films are reviewed. It is demonstrated that the implementation of laser measurement technologies ensures increased measurement accuracy, reduction of production scrap, and the possibility of integrating quality control systems into automated production lines [1–3].

Keywords: laser triangulation, packaging materials, quality control, interferometry, thickness measurement, profilometry, multilayer films.

Аннотация. В данной статье рассматриваются современные методы лазерного сканирования и профилометрии, применяемые для анализа упаковочных материалов. Особое внимание уделено бесконтактному измерению толщины, обнаружению микродефектов и оценке герметичности швов полимерных и многослойных структур. Представлены принципы лазерной триангуляции и интерферометрии, а также сравнительные характеристики лазерных и механических методов контроля. Рассмотрены примеры применения лазерных систем в производстве гибкой упаковки и многослойных полимерных пленок. Доказано, что внедрение лазерных измерительных технологий обеспечивает повышение точности измерений, снижение производственного брака и возможность интеграции систем контроля качества в автоматизированные производственные линии [1–3].

Ключевые слова: лазерная триангуляция, упаковочные материалы, контроль качества, интерферометрия, измерение толщины, профилометрия, многослойные пленки.

Annotatsiya. Ushbu maqolada qadoqlash materiallari tahlilida qo‘llaniladigan zamonaviy lazerli skanerlash va profilometriya usullari ko‘rib chiqilgan. Polimer va ko‘p qatlamli tuzilmalarning qalinligini kontaktsiz o‘lchash, mikrodefektlarni aniqlash hamda choklar zichligini (germetikligini) baholashga alohida e’tibor

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qaratilgan. Lazerli triangulyatsiya va interferometriya prinsiplari, shuningdek, lazerli va mexanik nazorat usullarining qiyosiy tavsiflari keltirilgan. Egiluvchan qadoqlash materiallari va ko‘p qatlamli polimer plyonkalar ishlab chiqarishda lazer tizimlarini qo‘llashga oid misollar tahlil qilingan. Lazerli o‘lchash texnologiyalarining joriy etilishi o‘lchov aniqligini oshirish, ishlab chiqarishdagi yaroqsiz mahsulotlar (brak) hajmini kamaytirish hamda sifatni nazorat qilish tizimlarini avtomatlashtirilgan ishlab chiqarish liniyalariga integratsiya qilish imkonini berishi isbotlangan [1–3].

Kalit so‘zlar: lazerli triangulyatsiya, qadoqlash materiallari, sifat nazorati, interferometriya, qalinlikni o‘lchash, profilometriya, ko‘p qatlamli plyonkalar.

INTRODUCTION.

The modern packaging industry imposes high demands on the accuracy and speed of production processes. The thickness and integrity of packaging barrier layers directly affect product shelf life, tightness, and environmental safety [2].

Traditional contact thickness measurement methods, based on the use of mechanical micrometers and probes, have several limitations: the impossibility of continuous monitoring, the risk of damaging soft polymer materials, and a high dependence of results on the human factor [1]. Consequently, non-contact laser measurement methods have been actively introduced in recent years.

Laser systems enable high-precision real-time measurements at web speeds exceeding 1000 m/min [3]. An additional advantage is the capability of automatic integration into digital manufacturing systems that comply with the "Industry 4.0" concept [6].

Principles of Laser Measurement. Laser Triangulation . The laser triangulation method is based on analyzing the position of the reflected laser beam relative to the receiver matrix. When the distance to the surface changes, the angle of the reflected beam changes, which allows determining the surface profile and detecting defects [4].

This method is widely used for:

* film thickness measurement;
* surface geometry control;
* detection of wrinkles and punctures;
* roughness analysis [5].

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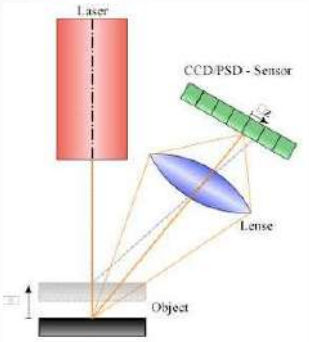


Figure 1 – Diagram of laser triangulation

Laser Interferometry. Interferometric methods are based on the phenomenon of interference of light waves reflected from different boundaries of a transparent material [6]. This method provides submicron measurement accuracy.

The phase difference of the interfering waves Δ_ϕ is determined by the expression:

$$\Delta_\phi = \frac{4\pi}{\lambda}\, d\, \sqrt{n^2 - \sin^2\,(\theta)}$$

where:

- n – refractive index of the polymer material refractive index of the polymer material;
- θ – angle of incidence of the beam;
- λ – wavelength of the laser radiation (typically utilizing stable sources like He-Ne lasers at $632.8 nm or stabilized diode lasers);
- d – thickness of the individual film layer.

Interferometry is particularly effective in analyzing transparent and semi-transparent polymer materials [7].

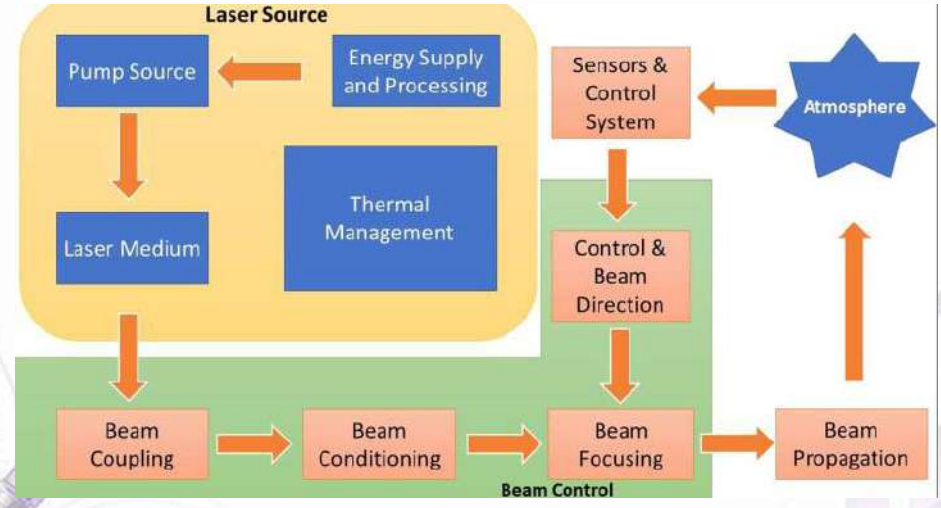


Fig. 2. Generic functional elements of laser beam technology.

Applications of Laser Methods.

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Thickness Control of Multilayer Films. Modern packaging materials consist of several co-extruded functional layers: polyethylene (PE) for sealing, polyethylene terephthalate (PET) for structural strength, aluminum foil for absolute barrier properties, and specialized tie/adhesive layers [8]. The precise thickness of each layer dictates the mechanical strength and gas/moisture barrier properties of the final packaging.

Laser sensors allow:

- Measuring the thickness of individual co-extruded layers simultaneously;
- Detecting cross-directional and machine-directional extrusion non-uniformity;
- Minimizing the overconsumption of expensive polymer raw materials by narrowing operational tolerances;
- Ensuring compliance with international quality standards such as ASTM and ISO [4].

Table 1

Example of multilayer film thickness measurement

Material Layer	Nominal Thickness,mm	Measured Thickness, mm	Deviation, %
PET	12	11.9	-0.8
Al Foil	7	7.1	+1.4
PE	50	49.1	-0.6
Adhesive layer	3	3.0	0

Detection of Micro-punctures and Defects

Laser scanning systems utilizing high-frequency rotating polygon mirrors or line-scan cameras are capable of detecting catastrophic web defects smaller than 10 μm even at maximum web running speeds [5].

The main types of detected defects include:

- Micro-punctures and pinholes (critical in aluminum foil laminates);
- Surface scratches and longitudinal streaks from extrusion dies;
- Gels, unmelts, and foreign carbonized inclusions;
- Air bubbles trapped between laminated layers;
- Material wrinkles and tension-induced distortions.

Table 2

Sensitivity of defect control methods

Control Method	Minimum Defect Size	Inspection Speed
Visual inspection	100–200 μm	Low
Mechanical control	50–100 μm	Medium
Laser scanning	5–10 μm	High

Analysis of Microrelief and Adhesion

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Laser profilometry is used to evaluate the surface microrelief of packaging materials before and after surface treatments like corona discharge [9]. Roughness parameters directly dictate:

- The transfer and anchorage quality of flexographic and rotogravure inks;
- The wetting and uniformity of protective lacquer application;
- The interfacial strength of adhesive bonds during dry lamination

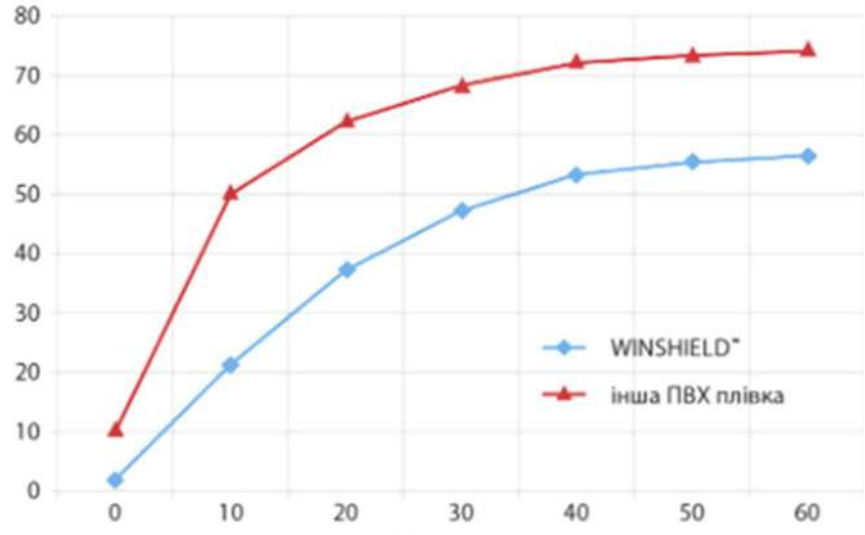


Figure 2 – Surface roughness profile of the film

The measurement of roughness parameters is carried out according to ISO 4287 and ISO 25178 standards [10].

Mathematical Modeling of Measurements

The absolute accuracy of online laser measurements depends heavily on environmental variables, laser wavelength stability, the structural stability of the mechanical frame, and the optical constants of the polymer film [7]. The thickness measurement error Δd can be estimated by the expression:

$$\Delta d = \pm\sqrt{\left(\frac{\partial d}{\partial \phi}\Delta_{\emptyset}\right)^2 + \left(\frac{\partial d}{\partial \lambda}\Delta_{\lambda}\right)^2 \left(\frac{\partial d}{\partial \phi}\Delta_{n}\right)^2 \left(\frac{\partial d}{\partial \theta}\Delta_{\theta}\right)^2}$$

$$\Delta d \approx \frac{\lambda\,\Delta\varphi}{4\pi\sqrt{n^2 - sin^2(\theta)}}$$

where:

- Δd – thickness measurement error;
- λ – wavelength of the laser radiation;
- n – refractive index of the material;
- θ – angle of incidence of the beam;
- $\Delta\varphi$ – error in determining the phase shift.

It follows from the mathematical model that reducing the laser wavelength (e.g., transitioning from infrared to blue lasers) and increasing the signal-to-noise

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ratio of the phase detector dramatically decreases the overall measurement error [6].

Comparative Analysis of Control Methods

Table 3

Comparison of laser and mechanical methods

Characteristic	Laser Method	Mechanical Method
Contact Type	Non-contact	Contact
Risk of Damage	None	High
Measurement Speed	Up to several kHz	Low
Accuracy	Up to 0.1 μm	1–10 μm
Automation	Full	Limited
Real-time Control	Possible	Practically impossible

Economic Efficiency of Implementation

Despite the high initial capital expenditure (CAPEX) associated with acquiring industrial-grade laser sensor arrays, the automated integration of these systems pays off rapidly by optimizing key manufacturing metrics:

1. Scrap Reduction**:** Minimizes startup scrap and roll-change waste by 20-30%;
2. Raw Material Savings**:** Allows operations closer to the lower tolerance limit, saving 2-5% of premium polymer resins;
3. Quality Assurance: Drastically decreases client claims and expensive product recalls due to layer delamination or barrier failures;
4. Labor Optimization**:** Lowers manual quality control labor overhead costs [2].

According to long-term industrial case studies, the return on investment (ROI) and payback period for high-precision laser measurement systems ranges between 1.5 to 3 years, depending heavily on the absolute production volume and plant capacity utilization [8].

CONCLUSION. The integration of non-contact laser measurement technologies into the production lines of packaging materials stands as a foundational milestone in the digitalization and transition of modern factories toward Industry 4.0 [1]. Laser systems deliver exceptional measurement precision, scanning speed, and operational uptime without risking mechanical indentation or deformation on moving web paths.

The synergistic application of laser triangulation for macro-profiling and laser interferometry for submicron layer-by-layer quantification ensures a stable extrusion output, early defect mitigation, and a drastic minimization of material waste [4]. Looking forward, pairing these physical sensors with artificial intelligence (AI) and machine learning (ML) data analysis pipelines will enable

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predictive asset maintenance and fully autonomous, self-healing packaging inspection networks.

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