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# Detection and root cause analysis of minor tread defects in tire manufacturing using optical laser profilometry and fault tree analysis

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**Abstract**

Tire tread quality plays an important role in tire performance, safety, and service life. Minor tread defects, characterized by local surface irregularities and thickness deviations, remain a common challenge in tire manufacturing due to their impact on dimensional consistency. This study presents a method for detecting minor thread defects using a non-contact optical laser profilometer, with a measurement accuracy of 0.1 mm, to obtain high-resolution tread surface profile mapping. The purpose of this study is to address the issue of minor tread defects by integrating a non-contact optical laser profilometer with Fault Tree Analysis (FTA). After improvements to the method, the results show that the average percentage of defects can be reduced from an average of 0.07% to an average of 0.03%. The factor causing severe tread defects is the material with a small volume in the tread thickness. In tread measurement, laser triangulation technology generates contour data without physical contact, preventing deformation and enabling measurements of elastic materials. The scanned data were processed using a contour-extraction algorithm and geometric deviation analysis to identify anomalies, such as variations in tire tread depth. Experimental results showed a thickness deviation of −0.69 mm at a width of 15 mm, exceeding the permissible tolerance limit of +0.3 mm, indicating a condition significantly outside the specifications or standards for the tire tread material. The measurement system demonstrated high repeatability and sensitivity in detecting local surface deviations that could not be identified through visual inspection. Furthermore, integrating the optical laser profilometer with FTA enabled the systematic identification of the root cause of the defect, traced to a dimensional mismatch in the tire tread extrusion die. The implementation results could reduce or decrease light tread defects and the total percentage of light tread defects in tires.

**Keywords:**
Light tread, optical laser profilometer, non-contact measurement, light defect detection, tire tread.

## 1 Introduction

Tire tread plays a critical role in determining vehicle traction, braking performance, and driving stability under various road conditions. The geometric accuracy of the tread surface is particularly important because even small deviations in tread contour or groove depth may influence tire performance, increase rolling resistance, and reduce service life. Therefore, maintaining dimensional consistency and surface uniformity during tire manufacturing is essential for ensuring product reliability and compliance with industrial quality standards.

During tire manufacturing, several types of defects may occur due to variations in raw materials, tooling conditions, or process parameters. One defect that frequently appears in production is the light tread defect, characterized by localized reductions in tread thickness or deviations in groove depth from the design specification. These irregularities may originate at multiple stages of the production process, including tread design, material extrusion, tire building, and curing. If such defects are not detected early, they may propagate into the final product and negatively affect tire durability and safety performance.

To improve inspection reliability, modern manufacturing industries have increasingly adopted optical metrology technologies for surface inspection and dimensional measurement. Among these technologies, laser-based measurement systems are widely applied because they enable high-precision measurements without physical contact. Optical laser profilometers operate on the principle of laser triangulation, enabling the acquisition of detailed surface profiles and high-resolution contour data. Compared with conventional contact measurement systems, non-contact optical measurement methods offer several advantages, including faster inspection speed, higher repeatability, and the ability to measure soft or elastic materials without causing deformation.

Previous studies reported that laser triangulation and optical scanning technologies provide effective solutions for surface geometry inspection and dimensional analysis in industrial applications [1], [3], [17]. These technologies have been widely implemented in manufacturing quality control systems because they enable rapid data acquisition, automated inspection capability, and accurate identification of geometric deviations [4], [5]. Furthermore, optical profilometry allows the generation of digital surface models that can be analyzed using computational algorithms for contour extraction and dimensional evaluation [6], [7].

Despite the extensive use of optical metrology in industrial measurement systems, the application of non-contact laser profilometry for detecting tread defects in tire manufacturing remains limited. Most previous research has focused on dimensional inspection of rigid components, whereas studies of geometric irregularities in elastic rubber materials, such as tire tread, remain relatively scarce. In many tire manufacturing facilities, defect inspection is still performed using visual inspection or conventional contact measurement tools. These approaches often lack sufficient sensitivity to detect subtle surface deviations and may depend heavily on operator experience.

Another limitation observed in previous studies is that defect-detection techniques are often applied independently of systematic root-cause analysis within the production process. As a result, although dimensional deviations can be detected, the relationship between the defect and its origin in the multi-stage manufacturing system is not always clearly identified. This limitation highlights the need for an integrated approach that combines high-precision surface measurement with structured analytical methods to identify defect sources within the production workflow.

Therefore, this study investigates the application of a non-contact optical laser profilometer for detecting light tread defects in tire manufacturing. The research focuses on analyzing tread surface geometry by evaluating contour deviations obtained through high-resolution laser scanning. In addition, Fault Tree Analysis (FTA) is employed to systematically identify potential root causes of the defect across multiple stages of tire production, including the design process, material manufacturing, construction operations, and curing. By integrating optical measurement and structured root-cause analysis, this study aims to develop a reliable inspection methodology that supports defect identification and quality improvement in tire manufacturing industries.

Despite the extensive application of optical metrology in industrial inspection systems, most existing studies focus on rigid materials and dimensional verification rather than defect detection in elastic components such as tire tread. In addition, previous research generally applies defect detection techniques independently without integrating them with structured root cause analysis methods.

Therefore, the novelty of this study lies in the integration of non-contact optical laser profilometer with FTA to simultaneously detect geometric defects and systematically identify their root causes within a multi-stage tire manufacturing process. This combined approach not only improves detection accuracy but also enhances decision-making in process troubleshooting and quality improvement.

Compared to conventional visual inspection and contact measurement methods, the proposed method offers higher sensitivity, repeatability, and the capability to detect sub-millimeter deviations in elastic materials.

## 2 Research methodology

This study aimed to analyze the defect-detection process in tire treads using an optical laser profilometer. It also provides guidance on how to address and resolve similar problems if they occur in the future.

### 2.1 Background of the study

During the tire production process, a defect known as light tread may occur in the tread area. The tread is a critical component that maintains traction, stability, and vehicle safety during operation. Fig. 1 illustrates an example of a light tread defect occurring at the center position of a tire.

Fig. 1. Light tread problem on tires.

### 2.2 Case study

To analyze the defect's origin, this study applied FTA to evaluate potential contributing factors across multiple stages of tire production. The light tread defect was detected only after the curing stage, indicating that the root cause likely originated from earlier manufacturing processes. Structured analytical methods such as FTA are widely used in industrial systems to trace defect sources across complex production chains [3].

Based on the tire manufacturing workflow, four primary process stages were evaluated.

#### 2.2.1 Design process (construction)

The design process is the initial stage of tire development, during which tread geometry, groove configuration, and structural dimensions are defined. Parameters such as tread thickness distribution, groove depth, and pattern pitch are determined to satisfy performance and safety requirements.

In this study, design verification was conducted by reviewing engineering specifications and prototype validation results. The tread design had previously undergone prototype testing during the pre-production stage, ensuring that the geometry complied with the required performance standards. The verification results confirmed that the design parameters were consistent with the approved specifications. Therefore, the probability that the defect originated from the design stage was considered low.

#### 2.2.2 Curing process

The curing process transforms the green tire into a finished tire by applying controlled temperature and pressure inside a mold. During this stage, the tread pattern is formed on the tire surface.

To evaluate the possibility that the defect originated from curing, the mold used for the affected tire type was inspected. The mold surface was examined for contamination, wear, or mechanical damage that could influence tread formation. A cleaning procedure was performed to remove dust particles and rubber residues from the mold cavity. After cleaning, several tire samples were produced using the same mold. However, the defect persisted at the same location, suggesting that mold contamination or curing conditions were unlikely to be the primary cause.

#### 2.2.3 Building process

The building process involves assembling various tire components, including the tread, carcass plies, sidewalls, and beads, to form the green tire prior to curing. During this stage, the tread strip is applied to the tire structure using a tire-building machine.

In this investigation, machine operation parameters and production traceability records were examined using a barcode-based production tracking system. The inspection confirmed that the machine operated within the specified parameters and that the tread application procedure followed the Standard Operating Procedures (SOP). No abnormal process conditions were identified during this stage.

#### 2.2.4 Material process

The material process includes producing the tread compound and extruding the tread material. Since the previous stages did not reveal any significant issues, further investigation focused on the tread material itself.

Initial visual inspection showed no visible abnormalities on the tread surface. However, because visual inspection may fail to detect small geometric deviations, a detailed measurement was conducted using a non-contact optical laser profilometer. The scanning results revealed a localized depression near the tread center, indicating a dimensional deviation not detectable by visual inspection alone. This observation suggested that the defect likely originated in the tread extrusion process or in the tread die geometry.

### 2.3 Evaluation

Based on case studies for each process, we identify the root causes of potential light tread defects using root cause analysis techniques, including FTA, as shown in Fig. 2.

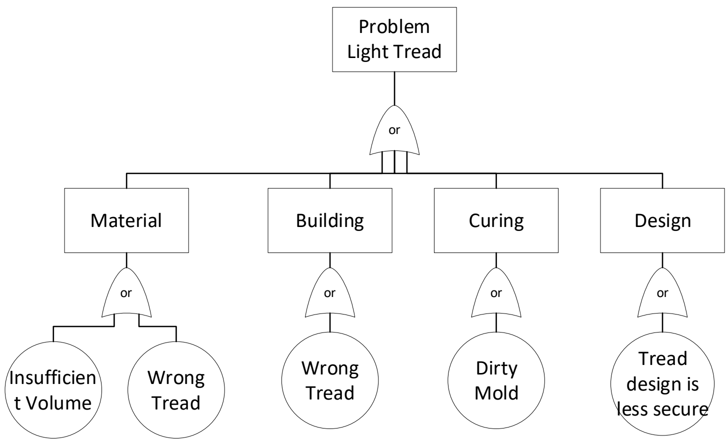

Fig. 2. FTA diagram of the light tread problem.

Indentation based on the FTA diagram, inspections were carried out at each process stage as:

Design process (construction): tread design process. Based on the design specification verification, testing had already been conducted prior to regular production, namely during the prototype (pre-production) stage.

Curing process: process from green tire to finished tire. The curing validation process was performed by inspecting the mold used for the problematic tire size. Validation was then carried out by cleaning the mold to ensure that dust and curing residues were completely removed from any contamination. After completing this process, product testing was conducted with green tires; however, the light tread problem persisted.

Building process: assembly process of tread material into green tire form. During the building process, inspections were conducted on the building machine operation by tracing the production flow through barcode scanning. The process was confirmed to be in accordance with standard operating procedures.

Material process: tread manufacturing process. Material inspection was performed using two methods: (1) visual inspection of the tread showed no detectable abnormalities (Fig. 3); (2) Using a non-contact optical laser profilometer, a depression was identified near the center point along the reference line.

Fig. 3. Visual inspection of tread material.

After applying the improvement pattern to the detection method and root cause analysis of light tire tread defects in tire manufacturing using optical laser profilometer and FTA The effectiveness of the implemented improvement was evaluated using production data collected before and after the corrective action, as presented in Table 2, which has decreased the number of light tire tread defects.

Based on the findings in the material process, the analysis of the light tread problem was focused using a non-contact optical laser profilometer. Scanning is an essential part of the reverse engineering method and 3D digital reconstruction process [20], [21]. This method helps extract physical models into computer-readable formats using either contact or non-contact scanning techniques (Fig. 4). The data are then extracted through cloud-based data acquisition techniques.

Due to their high measurement frequency, laser triangulation sensors play a crucial role as a foundation for process control, particularly for controlling dimensional and geometric tolerances and surface quality. Similar applications of laser-based profilometers and non-contact metrology systems have been reported in automated manufacturing environments [9], [15], [16], [19]. Laser triangulation enables the measurement and extraction of complex geometries into graphical formats, thereby improving manufacturing speed and making the overall process easier and more cost-efficient.

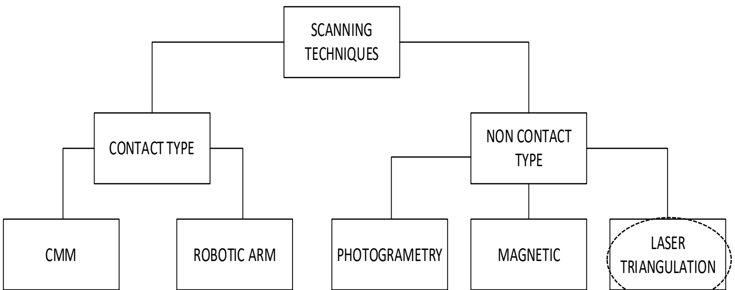


Fig. 4. Types of scanning technique.

Previous studies have demonstrated the effectiveness of optical scanning technologies for dimensional verification and geometry reconstruction in manufacturing applications [8], [10], [11], [23]. One widely used method for accurately measuring distance to a target is laser triangulation. Laser triangulation is widely applied in industrial dimensional inspection because of its high accuracy and measurement speed [18], [22], [23]. This method is referred to as triangulation because the laser emitter, the target surface, and the sensor detector form a triangular geometric configuration.

In this technique, a laser beam is projected from the sensor toward the target surface. The emitted beam is diffusely reflected by the target and subsequently captured by a collection lens positioned at a fixed distance from the laser emitter. The reflected light is then focused by the lens onto a linear-array detector, which observes the measurement region at a specific viewing angle, depending on the sensor design.

The position of the reflected laser spot on the detector pixels varies according to the distance between the sensor and the target. By analyzing this positional shift using either digital or analog signal processing, the system can accurately determine the distance to the target surface. The detector integrates the incident light intensity, allowing longer exposure times to enhance sensitivity when detecting weak reflections. Because the reflected beam is observed from an offset position relative to the emitter, the apparent location of the laser spot changes proportionally with variations in the target distance.

As shown in Fig. 4, the scanning technique employed is a non-contact method. The scanning process in this study used a non-contact laser scanner, and data acquisition was performed with a 2D output configuration.

In the detection and analysis of the root causes of tire tread defects in the tire manufacturing process using an optical laser profilometer with a bytewise machine. The principle used in laser-measurement machines for profile shape and dimensions is shown in Fig. 5. The measuring system consists of five laser beam projectors that emit light onto the measured surface, and a Charge-Coupled Device (CCD) camera that captures and processes the reflected light.

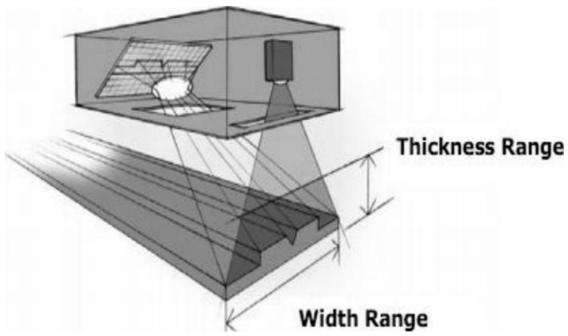


Fig. 5. Principle of using a machine for measuring shape and dimensions (bytewise measurement systems, 2004) [24].

This device is most often used offline, meaning the extrusion line must be stopped before a piece of the rubber profile can be cut and measured. The measurement process is shown in Fig. 6. The laser field is reflected from the measured profile and recorded on a screen. Here, the user can see both the nominal profile shape and the actual shape produced by the reflected laser field.

Fundamental to this system's operation is the PC used to acquire data. This data is used to synchronize the motor controllers of the two drives on the two-dimensional manipulator. Additionally, the PC's A/D converter receives measurement signals from the laser distance sensor. Specialized PC software processes the measured data set and compares it to predetermined values.

The schematic and connection diagram for the laser profilometer are shown in Fig. 5. The key element is the laser sensor. This sensor moves along the main axis beam, measuring the distance to the tread surface. The laser sensor is programmed with a predetermined range. The laser sensor's measurement results are displayed directly on the monitor. The profilometer's measurement accuracy is 0.1 mm, while the product tolerance is approximately ± 0.3 mm [24].

The tread scanning process using an optical laser profilometer is presented in Fig. 6. The workpiece was placed on the scanning worktable, and the operator selected the appropriate tread type for surface measurement within the profilometer system. The measurement procedure was initiated via the system interface, enabling automatic scanning.

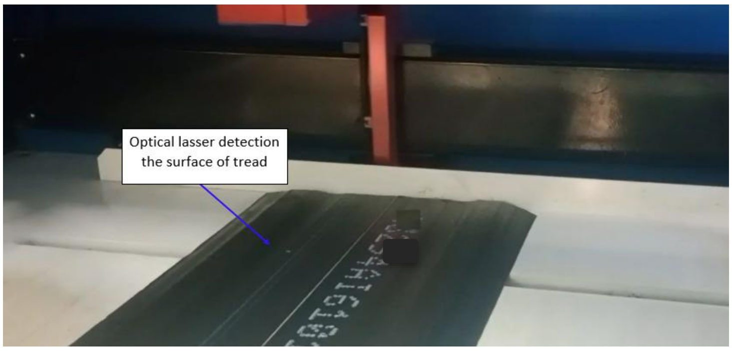

Fig. 6. Optical laser profilometer scanning process on the tread.

The acquired measurement data were subsequently displayed on the monitor screen, as shown in Fig. 7. The visual output in Fig. 7 reveals geometric irregularities, indicating misalignment or dimensional deviations relative to the specified design geometry.

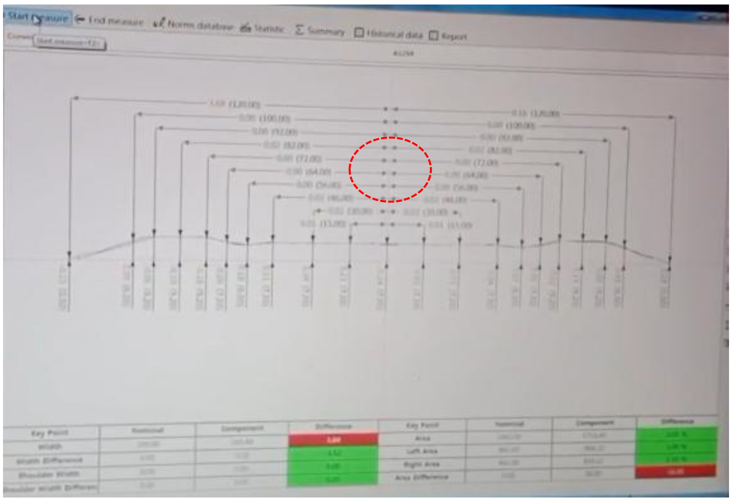
Fig. 7. Tread scanning results displayed on the computer monitor.

The measurement results shown in Fig. 8 were then analyzed using the dimension-addition function in the profilometer menu. These results are detailed in Fig. 8, the center tread section (in the defect area). The analysis indicated an under-volume condition near the tread center, with a thickness deviation of −0.69 mm over a width of 15 mm, highlighted in red. This indicates that the dimensional value in the specified area does not comply with the required standard (out of specification), where the allowable tolerance for tread thickness is 0.3 mm. Based on previous inspections, the light tread defect was consistently identified at the same tire location.

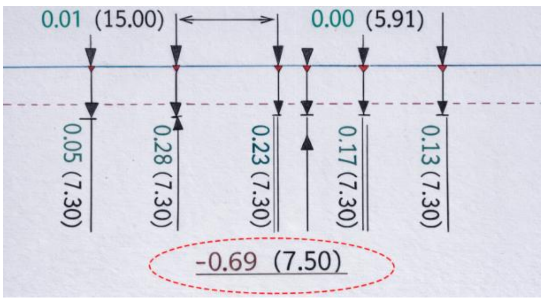

Fig. 8. Dimensions of the groove area near the center of the tread.

## 3 Results and discussion

The optical laser profilometer measurements revealed that the detected defect was consistently concentrated in the center tread region. Quantitative analysis indicated a thickness deviation of −0.69 mm over a width of 15 mm, exceeding the allowable tolerance limit of 0.3 mm. This finding confirms the presence of a localized under-volume condition, which represents a systematic geometric deviation rather than a random manufacturing variation.

The repeatability of the defect location indicated that the deviation was not due to random manufacturing variations but rather to a systematic issue in the production system. Similar observations have been reported in optical metrology studies, where laser profilometry successfully identified systematic geometric deviations caused by tooling inaccuracies or wear [1], [2]. Similar findings have been reported in studies involving surface texture characterization and industrial metrology applications [12], [13], [14], [15].

Furthermore, the study demonstrates that optical profilometry serves not only as a defect-detection tool but also as a diagnostic instrument capable of linking dimensional anomalies to specific manufacturing stages. By combining FTA with high-resolution surface measurement, the investigation establishes a systematic methodology for identifying root causes across multi-stage tire production processes. Such integration enhances decision-making accuracy in industrial troubleshooting and reduces trial-and-error corrective actions.

Therefore, corrective action was required on the tread die (mold) by increasing its thickness or material volume through controlled material removal (grinding/filing), as shown in Fig. 9.

Fig. 9 and Fig. 10 illustrate the structural configuration of the tread die used in the tread extrusion process. The tread die assembly consists of three primary components: the upper plate, lower plate, and second plate, each of which plays a specific role in controlling compound flow and shaping the tread profile during extrusion.

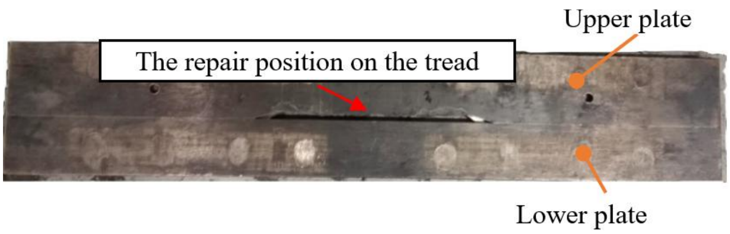

Fig. 9. Front view of die tread.

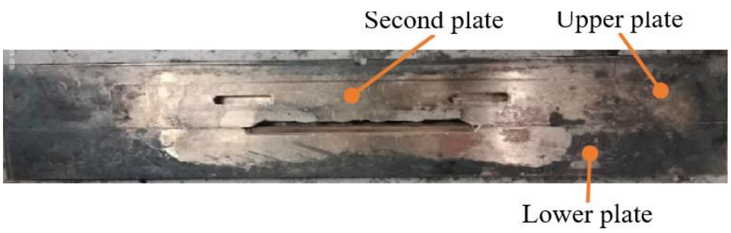

Fig. 10. Rear view of the tread.

The upper plate serves as the outlet channel for the rubber compound that forms the upper section of the cap tread. This component directly influences the dimensional stability and surface profile of the upper tread layer during extrusion. The lower plate serves as the outlet for the compound forming the lower portion of the tread structure. It is mechanically connected to the performer, which acts as the feeder supplying the lower compound stream into the die system. Meanwhile, the second plate is connected to the compound inputs associated with the wing tape tread and the center tread (cap tread). This component plays a crucial role in regulating compound distribution, shaping tread geometry, and directing compound flow forward during the tread-forming stage.

The occurrence of the light tread defect in the center tread region indicates a dimensional inconsistency in the die geometry that affects the tread gauge during extrusion. Therefore, a corrective repair procedure was performed on the upper plate and lower plate sections of the tread die. The repair process implemented on these components is presented in Fig. 11.


Fig. 11. Repair process of tread die.

As shown in Fig. 11, the dimensional correction process was carried out by increasing the tread gauge height in the cap tread region to achieve the desired tread profile specification. Prior to the modification process, the initial and target die dimensions were measured with a vernier caliper to ensure dimensional accuracy and consistency with the required extrusion profile. Subsequently, a precision filing process was applied to the tread die surfaces, particularly on the lower plate and the second plate, in the areas associated with the defect. This process aimed to adjust the die geometry and improve the distribution of compound flow during extrusion.

Following the filing process, the modified dimensions were re-measured using a vernier caliper to verify that the targeted dimensional adjustments had been achieved. The repaired die was then reinstalled in the tread extrusion line and used to produce tread material under the modified die configuration.

Finally, the extruded tread material was subjected to a profile inspection using a tread profile measurement instrument to evaluate the effectiveness of the dimensional correction. This inspection focused primarily on the center tread region, where the light tread defect had previously occurred, to verify improvements in tread gauge uniformity and profile consistency.

Fig. 12 illustrates the process flow of tread material production in the tread extrusion line. In this process, rubber compounds are fed into the extrusion system through three separate channels: the upper, middle, and lower sections. Each channel supplies a specific compound layer that contributes to the final tread structure.

Once the tread extrusion process is completed, the tread material is cut into specified lengths and subjected to dimensional verification. The inspection process is carried out using a tread profile measurement instrument (profile meter) to evaluate the tread geometry and ensure that the produced tread profile meets the required dimensional specifications.

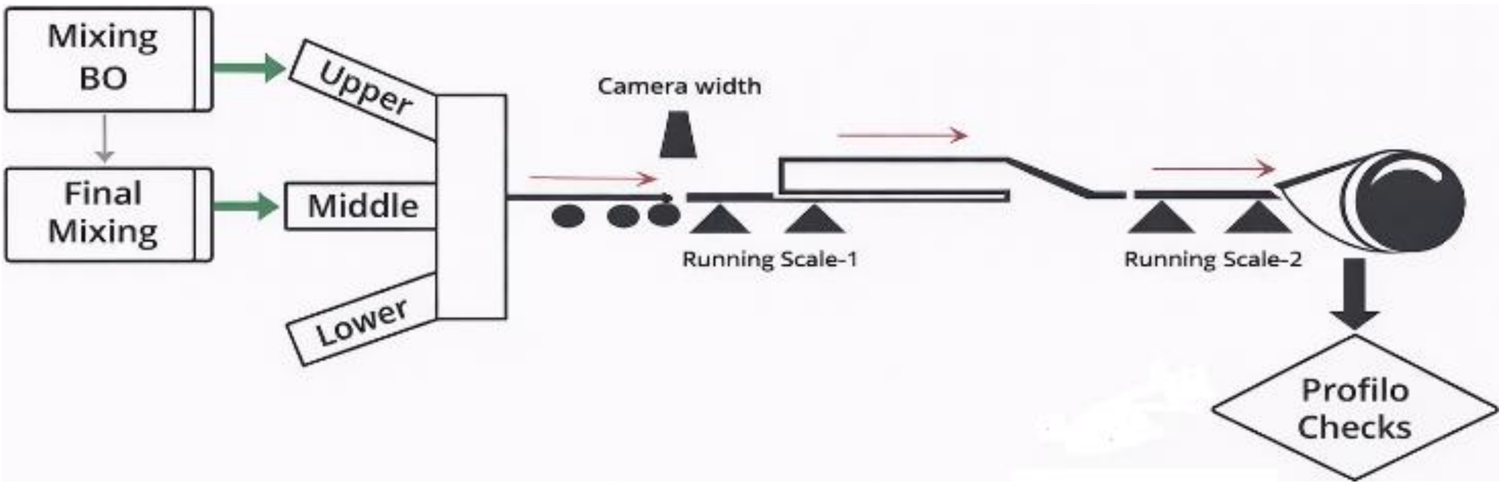


Fig. 12. Schematic of the tread material manufacturing process.

The compound entering through the upper channel forms the wing tape tread, which is located on the outer side of the tread profile. The compound supplied through the middle channel forms the cap tread, which serves as the tire's main contact surface with the road. Meanwhile, the compound delivered through the lower channel forms the under tread layer, which functions as the supporting structure beneath the cap tread and contributes to bonding and structural stability.

After the compounds are combined and shaped within the tread die, the extruded tread passes through several downstream processing stages in the extrusion line, including cooling and conveying, until it is collected in the cartridge, which serves as the storage container for the tread material.

The improvement results are presented in Fig. 13, which shows that the post-repair dimensions met the specified requirements. Based on these results, tread material production was subsequently carried out to enable tire performance testing.

Following the die-tread modification and tread production process, the manufactured tread was assembled into a green tire and subjected to the curing process. The post-improvement evaluation results are shown in Fig. 14, revealing a significant improvement in tread quality. The light tread defect previously observed in the center tread area was no longer detected after implementation of the corrective actions. This confirms that the dimensional deviation of the tread die was the primary root cause of the defect and demonstrates that the proposed improvement method was effective in eliminating the defect and improving overall product quality.

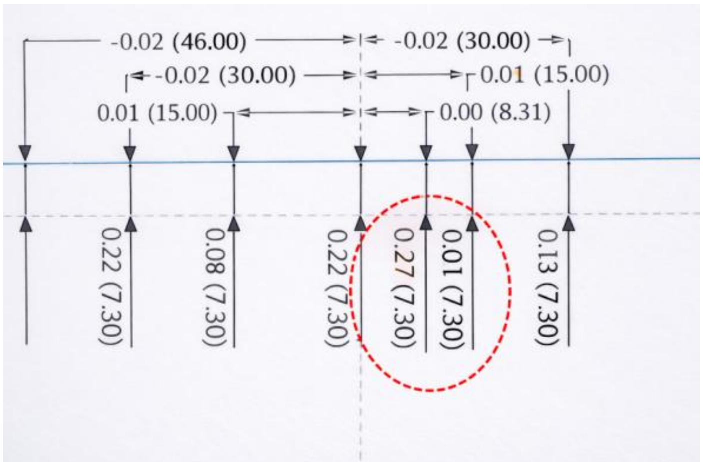


Fig. 13. Tread dimensions after repair.

Fig. 14. Tire results after die repair.

After the repair results are declared OK on the tire, post-repair measurements confirm compliance with the specified tolerance limits in areas that have the potential to cause light tread defects by controlling the tread thickness dimension.

There are 6 dimension checking points in the tread area as shown in Fig. 15. Based on the checking data, the dimensions obtained are 7.30 thick in sections A–F, which as shown in Table 1.

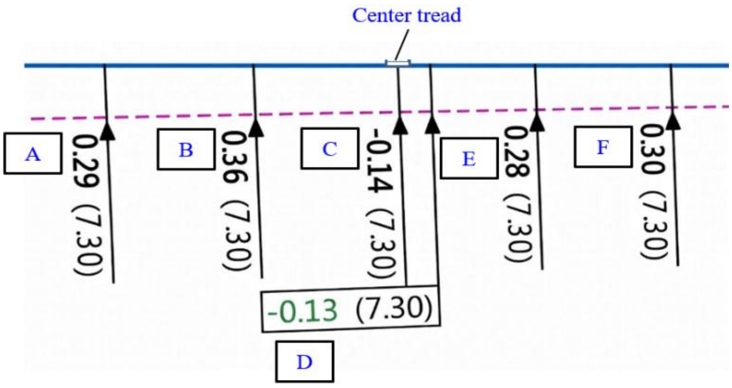


Fig. 15. Dimension checking after die repair.

Table 1. Post-repair check

| Item | Target dimensions | Tolerance | 1st check | 2nd check | 3rd check | 4th check | 5th check |
|---|---|---|---|---|---|---|---|
| A | 7.30 | ±0.30 | 7.29 | 7.28 | 7.27 | 7.26 | 7.28 |
| B | 7.30 | ±0.30 | 7.36 | 7.37 | 7.38 | 7.35 | 7.34 |
| C | 7.30 | ±0.30 | 7.16 | 7.12 | 7.13 | 7.15 | 7.12 |
| D | 7.30 | ±0.30 | 7.17 | 7.20 | 7.18 | 7.17 | 7.16 |
| E | 7.30 | ±0.30 | 7.28 | 7.29 | 7.30 | 7.26 | 7.31 |
| F | 7.30 | ±0.30 | 7.30 | 7.28 | 7.27 | 7.31 | 7.29 |

The results of implementing the above method, based on light tread defect data and production volume in the last four months from October 2025 to January 2026, can be used to calculate the monthly scrap proportion, as shown in Table 2. Based on the table, after improvements and monitoring in February, light tread scrap decreased from an average of 0.07% to an average of 0.03% over two months.

Table 2. Proportion of Light Tread (LT) defects per month

| Item | Month | Qty LT | Production | % LT |
|---|---|---|---|---|
| Before | July-25 | 708 | 899039 | 0.08% |
| | Aug-25 | 678 | 905937 | 0.08% |
| | Sep-25 | 416 | 785175 | 0.05% |
| | Oct-25 | 436 | 709697 | 0.06% |
| | Nov-25 | 537 | 739013 | 0.07% |
| | Dec-25 | 732 | 989529 | 0.07% |
| After | Jan-26 | 319 | 955013 | 0.03% |
| | Feb-26 | 119 | 663778 | 0.02% |

## 4 Conclusion

The implementation of optical laser profilometry and FTA has improved the detection and diagnosis of minor tire tread defects. The results confirmed that the defects were mainly caused by dimensional mismatches during the tire tread extrusion process rather than during the curing stage. Quantitative measurements showed a thickness deviation of −0.69 mm, exceeding the allowable tolerance limit of ±0.3 mm, indicating an out-of-specification condition. The non-contact optical laser profilometer demonstrated high sensitivity in detecting sub-millimeter surface irregularities that could not be identified through visual inspection. Following corrective action, the percentage of minor tread defects decreased from 0.067% to 0.033%.

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