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Monitoring, Control and Optimization of Laser Micro-Perforation Process for Automotive Synthetic Leather Parts

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Abstract: This paper presents a comparative analysis of the laser operating power (P1 and P2) and synthetic leather thickness to achieve the optimal quality of components in the airbag area, produced through micro-perforation laser processing. Within the study, various laser power settings and material thicknesses were investigated to determine the combinations that ensure the best component performance. The experimental results indicate that setting the laser to 25% of its total power (P1, P2) of two kilowatts (kW) represents the optimal parameter setup to achieve parts of superior quality. This configuration is not significantly influenced by the material thickness, suggesting important versatility in practical applications. The overall results indicate the significant influence of the laser power level on micro-perforation processing. The normal analysis of means (ANOM) and factorial design (DOE) provide significant evidence for an interaction, highlighting that the effects of one laser power factor depend on the level of the other laser power factor. These findings are essential in improving production processes, as they allow for the manufacture of airbag components with high precision and consistency, minimizing the risks of material deformation or damage. Thus, not only is compliance with safety standards ensured, but the economic efficiency of the production process is also enhanced.

Keywords: synthetic leather; micro-perforation process; automotive parts; laser parameters; analysis of variance; factorial analysis; quality improvement

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1. Introduction

1.1. Literature Review

Laser processing technology is seen as an efficient method due to its lack of tool wear, fast processing speed, ease of performance, possibilities for flexible automation, high-quality products and contactless nature; it can be employed in various industrial applications, such as drilling, cutting, milling, polishing, etc. [1–3].

Laser processing can be categorized into thermodynamic and non-thermodynamic processes based on the laser pulse width. Thermodynamic processes involve continuous, long-pulse and short-pulse lasers with pulse widths greater than 10–11 milliseconds (ms), leading to heat transfer and diffusion phenomena, such as electron excitation, electron–phonon relaxation and phonon–phonon relaxation. These processes result in material melting, evaporation and removal through thermal effects, causing significant thermal damage to the edges of the laser-processed area. In contrast, picosecond and femtosecond lasers, with pulse durations shorter than the electron–lattice energy relaxation period, operate under a “cold processing” mechanism. During these ultra-short pulses, the laser energy is absorbed by the electrons before any energy coupling with the lattice, leaving the lattice and electrons in a non-equilibrium state. This results in an instantaneous non-thermal phase change, where the material is ejected with the formed plasma before thermal diffusion can occur. This prevents thermal damage and produces clean, precise edges [4,5].

Femtosecond lasers are widely used in various fields. A femtosecond fiber laser for micro-hole drilling and cutting in ambient air was developed in [6]. Initially, the process was examined for both transparent materials (such as glass) and nontransparent materials (such as metals and tissues). The hole shapes and morphologies were characterized using optical and scanning electron microscopy (SEM). The results indicated the successful creation of debris-free micro-holes with excellent roundness and no thermal damage, achieving an aspect ratio of 8:1. Additionally, micro-hole drilling in both hard and soft tissues was accomplished without causing cracks or collateral thermal damage. The study then investigated trench micromachining and cutting in various materials, analyzing the influence of the laser parameters on the trench properties. The findings show that straight and clean trench edges can be produced without thermal damage.

The theoretical and experimental analysis of micro-hole arrays on coated fused silica using a femtosecond laser was developed in [7]. The authors discussed 3D microstructures to underline the advantages and the rapidity of the processing method using an ultrafast laser.

In the laser microfabrication applications field, the authors in [8,9] discussed the power output of picosecond and femtosecond ultrafast lasers, which typically ranges from tens to hundreds of watts, positioning them as primary contenders. This contrasts sharply with continuous lasers, which boast an average power rating of 10 kW. Recent advances in industrial ultrashort-pulse laser technology have led to a substantial rise in the average power levels, surging from a modest 10 watts to several kilowatts. These breakthroughs are anticipated to catalyze significant advancements across multiple aspects, including the processing efficiency, material thickness capabilities and surface area coverage. Moreover, these innovations are expected to enhance the distinguishing characteristics of ultrafast laser technology—notably, its unparalleled precision and quality in processing operations.

Studies referring to analyses across various materials emphasize the effects of the laser parameters on the trench properties. The findings show that straight and clean trench edges can be obtained without thermal damage [4].

The optimization of the processing outcomes was proposed in [10–12]. It is imperative to focus the laser beam precisely on the surface of the workpiece, ensuring that it converges to a single point without any deviation, a state referred to as zero defocus. This alignment guarantees that the laser beam lands directly on the material's surface to be processed, thus maximizing the processing efficacy. It is crucial to note that the power density reaches its zenith under these conditions. When the laser's focal plane is positioned above the surface of the workpiece, it is termed positive defocusing, while positioning it below the workpiece surface leads to negative defocusing. Variations in the focal length lead to energy dispersion and a consequent decline in processing quality, irrespective of whether the defocusing is positive or negative.

Zhang et al. [13] conducted a comparative analysis on the impact of laser irradiation on carbon fiber composite materials in both subsonic airflow and no-flow environments. Their results indicated that the presence of a tangential airflow contributed to a noticeable cooling effect within the processing area. As the air pressure increased, the airflow intensified, leading to more efficient heat dissipation and a consequent reduction in the heat-affected zone.

In a scientific study, Riveiro et al. [14] investigated the efficacy of assisted laser cutting using Ar gas across varying air pressures with a 3.5 KW CO_2 laser. Their findings demonstrated that the gas delivered through both coaxial subsonic nozzles and paraxial supersonic nozzles effectively dissipated the heat, resulting in a reduction in the heat-affected zone.

Furthermore, Yuki et al. [15] explored laser processing using nitrogen, argon and oxygen as auxiliary gases under consistent average power and scanning speed conditions. Nitrogen, with its higher specific heat capacity compared to argon, proved to absorb more heat, thus limiting the expansion of the carbon fiber end face. Additionally, oxygen's inclusion facilitated deeper material incisions, addressing challenges associated with material removal in deeper layers due to lower laser energy.

In their study, Wang et al. [16] utilized a water-guided laser for the processing of a carbon-fiber-reinforced polymer (CFRP). Their findings indicated that the resultant cutting surface of the CFRP exhibited remarkable cleanliness and flatness when processed with a water-guided laser. Notably, minimal fused impurities were observed adhering to both the cutting surface and groove. Furthermore, enhancements were noted in the mitigation of surface heat-affected zones, material delamination phenomena and fiber expansion.

Leveraging the cooling potential of a paraxial water jet, Zhang et al. [17] strategically harnessed it to curtail the diffusion of excess heat generated during laser processing. A morphology analysis revealed a direct correlation between the reduction in the heat-affected zones and the flow rate of water through the system (B). This underscores the effectiveness of water jet assistance in not only facilitating prompt heat dissipation but also elevating the quality of carbon fiber cutting surface processing while concurrently diminishing carbonization.

1.2. Objectives and Scope of the Study

The production and testing of airbag parts involves the use of various specific equipment and technologies. In this context, the aim of this study is to analyze the laser micro-perforation process of airbag components considering the main influencing factors. The obtained results in the pull test are analyzed from the point of view of the influences of the laser power (P1 and P2) and the thickness of the material. The statistical analysis of the experimental data includes a goodness-of-fit test, regression analysis, analysis of variance (ANOVA) and multivariate and factorial analyses. All of these are applied to identify patterns, correlations and outliers within the dataset. Additionally, advanced visualization tools are utilized to emphasize the complex data relationships and trends, aiding in the interpretation of the results and the formulation of actionable insights.

The novelty in the laser micro-perforation process of textile materials refers to recent technological improvements that optimize both the process and the outcomes of this technique. The updated laser technology allows for the creation of extremely precise and uniform perforations, which are essential for applications where the technical characteristics are crucial. Laser micro-perforation systems are much faster, enabling mass production without compromising product quality, thereby making the process more efficient and cost-effective for manufacturers. Additionally, modern technologies offer advanced control over the laser parameters, such as the power, frequency and pulse duration, allowing for fine adjustments based on the type of material and the desired outcome.

This exhaustive investigation represents a significant step towards enhancing the reliability and consistency of airbag cutout laser processing methodologies. The comprehensive analyses and proposed remedial measures outlined herein underscore the collective commitment to quality assurance and process optimization within the automotive safety industry. It is imperative that stakeholders collaborate closely to ensure the seamless implementation of these measures, thereby fostering a culture of continuous improvement and excellence in manufacturing practices. By applying the specific methods, the following outcomes are expected.

- Uniform and precise perforations: The optimization of the laser parameters and rigorous control implementation should lead to uniform and precise perforations across the entire surfaces of synthetic leather parts.
- Reduction in defects and waste: Real-time process monitoring should enable the immediate detection and correction of any issues, thus reducing the quantity of damaged material and minimizing waste.
- Increase in efficiency and consistency: Through parameter optimization and continuous process control, a significant increase in operational efficiency and improved consistency in the quality of end products is anticipated.

2. Materials and Methods

The analyzed CO_2 laser micro-perforation process technology is presented in Figure 1.

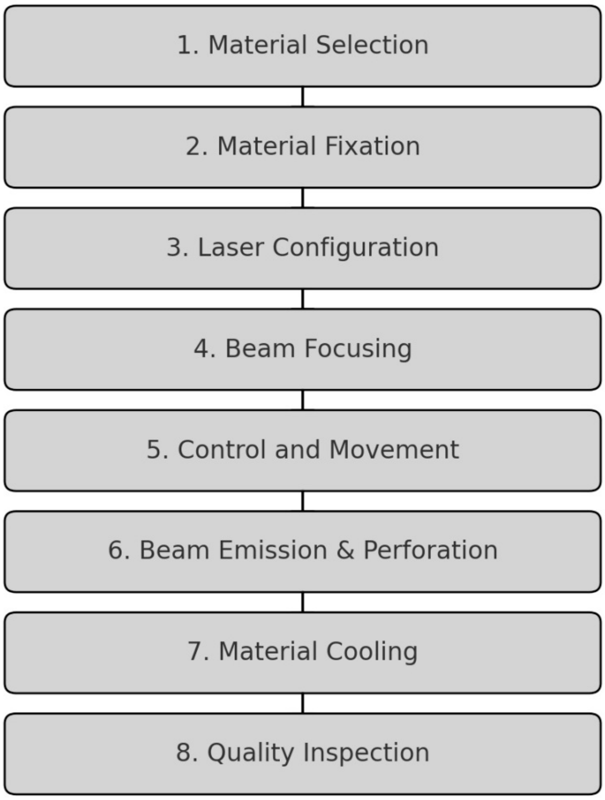


Figure 1. Laser micro-perforation flow process.

Material preparation: The materials used for airbags include robust technical textiles such as nylon or polyester, which are treated for high tear and wear resistance. The airbag material must be securely fixed on a work platform to prevent movement during perforation, ensuring precision perforations.

Laser configuration: The CO_2 laser used for the micro-perforation of airbag materials operates at a wavelength of 10.6 μm. This wavelength is effective for absorption by technical textile materials. The laser power varies depending on the thickness of the material and the perforation specifications, with typical powers ranging from a few watts to hundreds of watts.

Laser beam focusing: The optical system focuses the laser beam using lenses or mirrors to concentrate the beam into a small point. The size of the focused point determines the diameter of the micro-perforation, and the precise adjustment of the focus is essential to ensure high-quality perforations in airbag materials.

Control and movement: A computer controls the movement of the laser and the perforation pattern, allowing the precise programming of the size, shape and distribution of the perforations. The movement system, which may include stepper motors or servomotors, ensures the precise movement of the laser or the platform holding the material, essential in achieving uniform perforations in the complex airbag materials.

Micro-perforation process: The laser beam is emitted and absorbed by the material, causing the rapid evaporation of a small portion of the material and creating a perforation. In airbag materials, the perforations must be precise to ensure the proper and safe deployment of the airbag during an impact. Lasers can operate continuously or in pulses, with short, high-intensity pulses often preferred to minimize the heat-affected zone (HAZ) and increase the perforation precision.

Cooling and inspection: After perforation, the airbag material may need time to cool, especially if the process generates significant heat. Quality inspection is essential, with the perforated material being checked to ensure the size and uniformity of the perforations. Optical instruments or high-resolution cameras are often used for this inspection, thus guaranteeing compliance with the strict standards of the automotive industry.

Important parameters in the micro-perforation process for airbags: The laser power is crucial to ensure precise and uniform perforations in the technical textile materials of airbags. The power must be sufficient to vaporize the material but not so high as to degrade the edges of the perforation or cause excessive material damage.

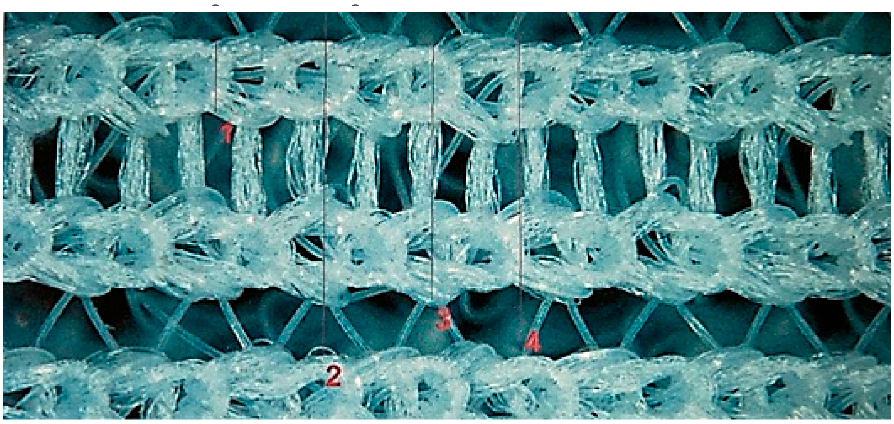
The pulse duration affects the precision of the perforations. Short pulses produce precise perforations and minimize the heat-affected zone (HAZ), essential to maintaining the structural integrity of the airbag material.

The movement speed of the laser affects the size and shape of the perforations. High speeds can produce smaller, shallower perforations, while slower speeds allow deeper penetration and larger perforations.

Beam focusing determines the size of the focused point, and precise focusing produces smaller, more precise perforations. The stability of the focus is crucial to ensuring uniform perforations across the entire airbag material.

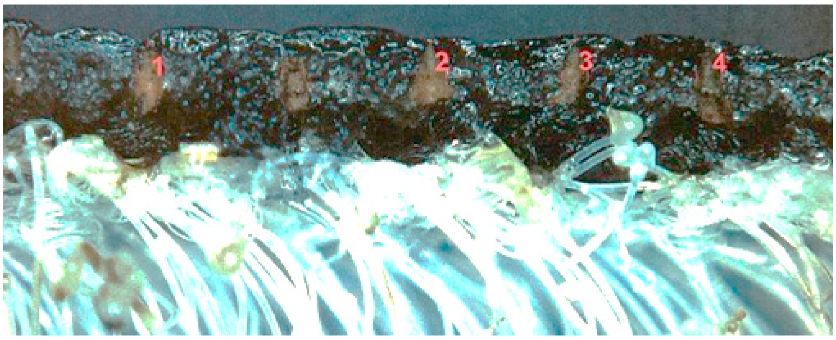
The material type influences the absorption of the laser. The technical textile materials used in airbags have specific absorption rates for the CO_2 laser wavelength, and materials with high absorption require less power for perforation. The thermal properties of the material, such as the thermal conductivity and heat capacity, influence the heat dispersion and the size of the HAZ. The following materials and technology were utilized for the laser micro-perforation process.

- Synthetic leather: The synthetic leather parts used in this study were selected to represent common materials utilized in the automotive component manufacturing industry for airbag production (Figure 2). The sample size was 50 parts for each analyzed parameter: the laser power and material thickness. For the factorial analysis, 950 samples were considered. The material used consisted of synthetic leather produced from polyvinyl chloride (PVC) with a nominal thickness of 1.2 mm. This was laminated with a spacer fabric with a nominal thickness of 2.99 mm, with a specified tolerance of ±0.3 mm.



(a)

Figure 2. *Cont.*



(b)

Figure 2. Analyzed synthetic leather: (**a**) microstructure image of synthetic leather; (**b**) micro-holes after laser micro-perforation into skin. The scale bar is 500 μm.

- Laser process: The micro-perforation process was conducted using a high-precision laser system, enabling precise control of the perforation parameters, such as the power and operating speed (Figure 3).

Figure 3. Laser line.

The main components of the machine setup for laser micro-perforation include a CO_2 laser, mirrors, a laser beam and a gas nozzle. The most important parameters of the laser micro-perforation process are the focus, laser power (P1, P2), impulses, robot speed (ms) and tolerance of material deviation.

The laser utilized in the conducted experiments operated in pulsed mode, exhibiting a pulse duration of 200 femtoseconds (fs) and a repetition frequency of 2 kilohertz (KHz). This configuration facilitated precise control over the laser's output, providing high-intensity pulses conducive to experimental investigations.

The analysis stages consisted of testing based on the following.

- Material characterization: Preliminary tests were conducted to characterize the material properties, including the thickness, texture and temperature resistance, before commencing the micro-perforation process.
- Laser parameter setting: Critical parameters of the laser process, including the power, frequency and beam traversal speed, were optimized to ensure efficient and uniform material perforation.

- Real-time monitoring and control: During the micro-perforation process, monitoring and control systems were implemented to detect and rectify any deviations in the operating parameters, thereby maintaining the quality and consistency of the perforations.

2.1. Methodology

The investigative approach adopted herein involved a meticulously planned and executed series of experiments, orchestrated with precision to closely examine the intricacies of airbag cutout laser processing. The methodology was designed to simulate real-world production scenarios, ensuring that the findings were applicable and relevant to industrial practices. Airbag cutouts, a critical component in automotive safety systems, underwent laser processing precisely 24 h after adhesive application, mimicking the timeline encountered in actual manufacturing settings. However, the key aspect of this investigation lies in the identification of a significant challenge: the inadvertent use of left-hand drive (LHD) parameters for right-hand drive (RHD) components during laser processing. This systemic inconsistency has far-reaching implications, potentially compromising the quality and reliability of airbag cutouts, which are vital for passenger safety. The manifestation of nonconforming (NOK) outcomes during subsequent pull testing procedures underscored the urgency of addressing this issue, prompting a comprehensive examination of the underlying causal factors.

2.2. Laser Processing Investigation

The airbag cutout laser processing investigation detailed in this report represents a meticulous endeavor aimed at comprehensively understanding and rectifying the discrepancies encountered during the manufacturing process. With automotive safety as a paramount concern, the study meticulously delves into the nuanced intricacies surrounding the application of LHD and RHD parameters in laser processing techniques. The optimization of production methodologies within the automotive safety industry is not merely a matter of efficiency but a critical aspect in ensuring passenger safety and regulatory compliance. This investigation, therefore, serves as a critical work in the quest for excellence in automotive safety standards. Through rigorous experimentation and analysis, the study aims not only to identify areas of improvement but also to pave the way for innovative solutions that elevate the standards of airbag cutout manufacturing processes.

2.3. Experimental Design and Setup

The experimental design was meticulously crafted to ensure robustness and reliability in data collection. Airbag cutouts, sourced from diverse production batches, were carefully selected to capture the variability inherent in real-world manufacturing processes. Prior to laser processing, the cutouts underwent stringent quality control checks to ensure uniformity and consistency across samples. Adhesive application was carried out using state-of-the-art equipment, adhering to industry best practices to minimize variability. The laser processing parameters, including the power, intensity and speed, were systematically varied to evaluate their impacts on the processing outcomes. Additionally, environmental conditions such as the temperature and humidity were closely monitored and controlled to minimize external influences on the experimental results.

2.4. Collection and Statistical Analysis

Data collection during the experimental phase was conducted with meticulous attention to detail, employing advanced instrumentation and data logging techniques to capture a comprehensive range of process parameters.

The inferential analyses of the recorded experimental data were performed using the Minitab v17 software (Minitab LLC, State College, PA, USA). Considering a 95% confidence interval (CI) and a significance level of $\alpha = 0.05$, the normal distribution of the experimental data was qualitatively and quantitatively validated by applying the Anderson–Darling (AD) goodness of fit [18,19]. An analysis of means (ANOM) chat [20] for a normal distribution was computed for different laser power levels (P1 and P2). We used an analysis of means for normal data and a two-way design to identify any significant interactions and main effects. The experiments were designed (DOE) [21,22] based on the process' particularities by choosing the main control factors that affected the micro-perforation characteristics, applying a full factorial design.

3. Statistical Analysis of Experimental Data

3.1. Goodness-of-Fit Test of Experimental Data

The pull test results and material thickness were statistically analyzed with a 95% confidence interval (CI) and significance level of $\alpha = 0.05$. The homogeneity of the experimental data was tested by assessing the goodness of fit with a probability plot (Figures 4 and 5). Additionally, the quantitative assessment was performed with a hypothesis test, such as the Anderson–Darling normality test.

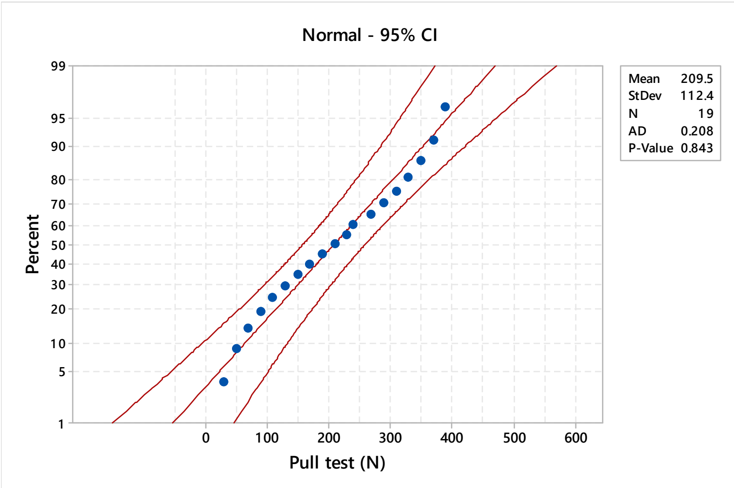


Figure 4. Probability plot of pull test results.

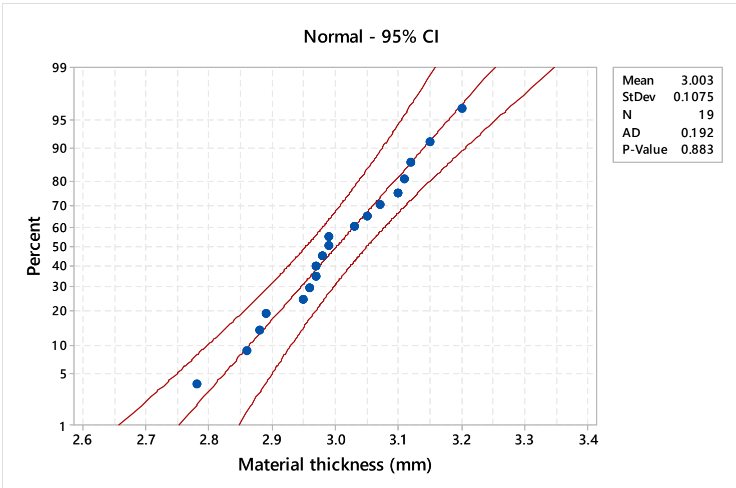


Figure 5. Probability plot of material thickness.

The results of the goodness-of-fit normality test are synthetically presented in Table 1. A parametric distribution analysis was considered in order to estimate the statistical parameters of the pull test and material thickness (Table 2).

Table 1. Anderson–Darling normality test.

Characteristic	AD	A-Squared	Correlation Coefficient	*p*-Value
Pull test (N)	0.208	0.21	0.990	0.843
Material thickness (mm)	0.192	0.19	0.992	0.883

Table 2. Descriptive statistics of analyzed characteristics.

Statistical Parameter	Pull Test (N)	Material Thickness (mm)
Mean	209.5	3.003
Standard Deviation	112.4	0.107
Minimum	30	2.78
1st Quartile	110	2.95
Median	210	2.99
3rd Quartile	310	3.10
Maximum	390	3.20
Skewness	0.014	−0.12
Kurtosis	−1.185	−0.27

Visually comparing the probability plots depicted in Figures 4 and 5, it can be concluded that the experimental data complied with a normal distribution. The points roughly follow the straight line, all of the points are within the lower and upper confidence boundaries, and the p-value is over 0.05.

The estimated mean of the pull test data is 209.5 (95% confidence intervals of 155.31 and 263.64), the standard deviation is 112.4 (95% confidence intervals of 84.91 and 166.18), and the median is 210 (95% confidence intervals of 127.28 and 292.72). Using a significance level of $\alpha = 0.05$, the Anderson–Darling normality test indicates that the pull test data follow a normal distribution.

In the case of the material thickness, the mean is 3.003 (95% confidence intervals of 2.951 and 3.054), the standard deviation is 0.107 (95% confidence intervals of 0.081 and 0.159), and the median is 2.99 (95% confidence intervals of 2.958 and 3.074). Moreover, it can be underlined that the estimated value of the Anderson–Darling statistic is 0.192.

The overall inferential analysis concludes that the pull test results and material thickness are from a normally distributed population.

3.2. Analysis of the Main Factors in the Laser Micro-Perforation Process

The assessment of the main influencing factors on the micro-perforation laser process is based on the analysis of means chart (ANOM) for a normal distribution. An experiment was performed to assess the effects of the most important factors: the level I laser power (P1), the level II laser power (P2), the pull test results and the material thicknesses. The ANOM results are illustrated in Figures 6 and 7.

In the case of first level of the laser power (P1), the pull test results indicate that the lower delimitation limit is 172.4 N and the upper limit is 246.7 N, with a mean of 209.5 N (Figure 6) and standard deviation of 74.2 N. Tested parts that had recorded values below the lower limit value were declared scrap.

The normal analysis of means chart for the P2 laser power (Figure 7) showed a lower delimitation limit of 161 N, an upper delimitation limit of 257.9 N and a mean of 209.5 N (Figure 3) with a standard deviation of 96.9 N.

The computed delimitation limits allow us to take appropriate measures to optimize the laser process. The indicated direction is to optimize the two laser powers, P1 and P2, to ensure the process' stability.

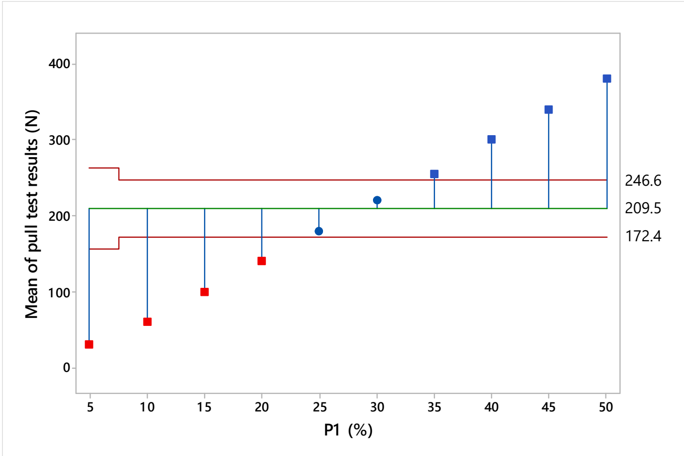


Figure 6. Normal ANOM for pull test results vs. P1 laser power.

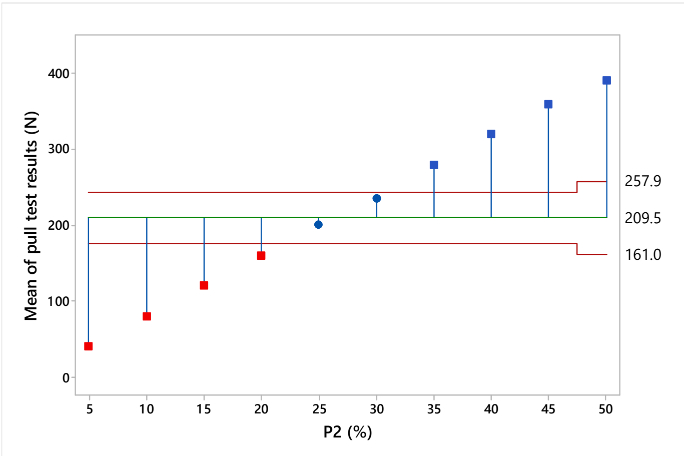


Figure 7. Normal ANOM for pull test results vs. P2 laser power.

The comparative analysis of the two laser powers emphasizes that the optimal level should be set around 0.25 W to ensure a material rupture force during testing. Additionally, quality limits can be easily determined from the comparative analysis: power of 0.20 W—beyond tolerance threshold; power of 0.21–0.24 W—within accepted limits; power > 0.25 W—higher precision, efficiency and stability (covers and removes material defects).

In order to highlight the interaction between the pull test results, laser power and material thickness and its effect on the micro-perforation process, a factorial analysis was designed (Figures 8 and 9). The magnitude and the importance of the effects were determined by applying the Pareto chart of the effects (Figure 10).

The interaction plot indicates that the material with the highest thickness depends on the P1 laser power, while the material with the lowest thickness depends on the P2 laser power. The difference between the P1 and P2 powers is given by the number of pulses. Specifically, a laser power fraction of 5–25% from the nominal laser power has a negative influence on the results of the pull test, while, for a laser power greater than 25%, the tested parts in the pull test are compliant.

In conjunction with an analysis of variance and design of experiments, we examined the differences among the level means for the three analyzed factors. The P1 and P2 laser powers appear to affect the pull test results compared to an overall mean of 209.5 N. A main effect is present because the different levels of the studied laser powers factors affect the response differently. Additionally, the graph for the material thickness shows that there is no main effect present.

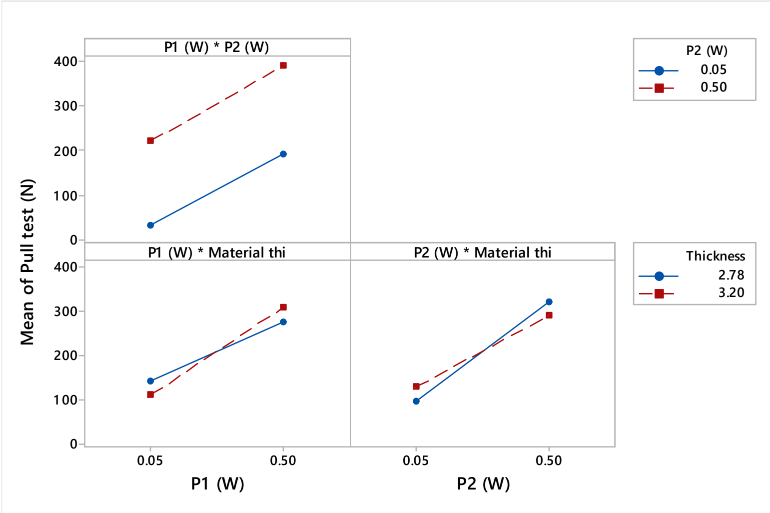


Figure 8. Interaction plot for pull test results.

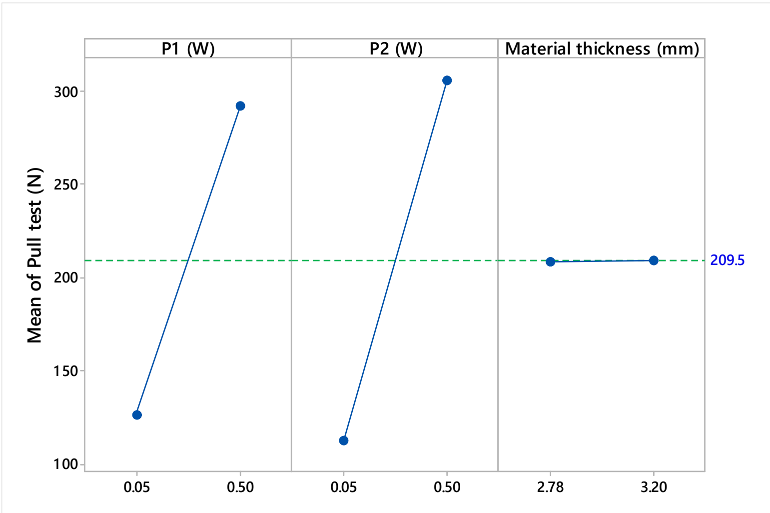


Figure 9. Main effects plot for pull test results.

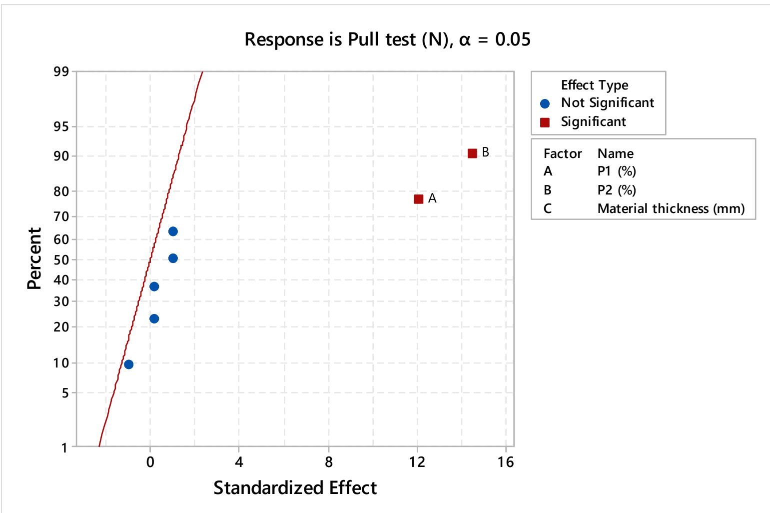


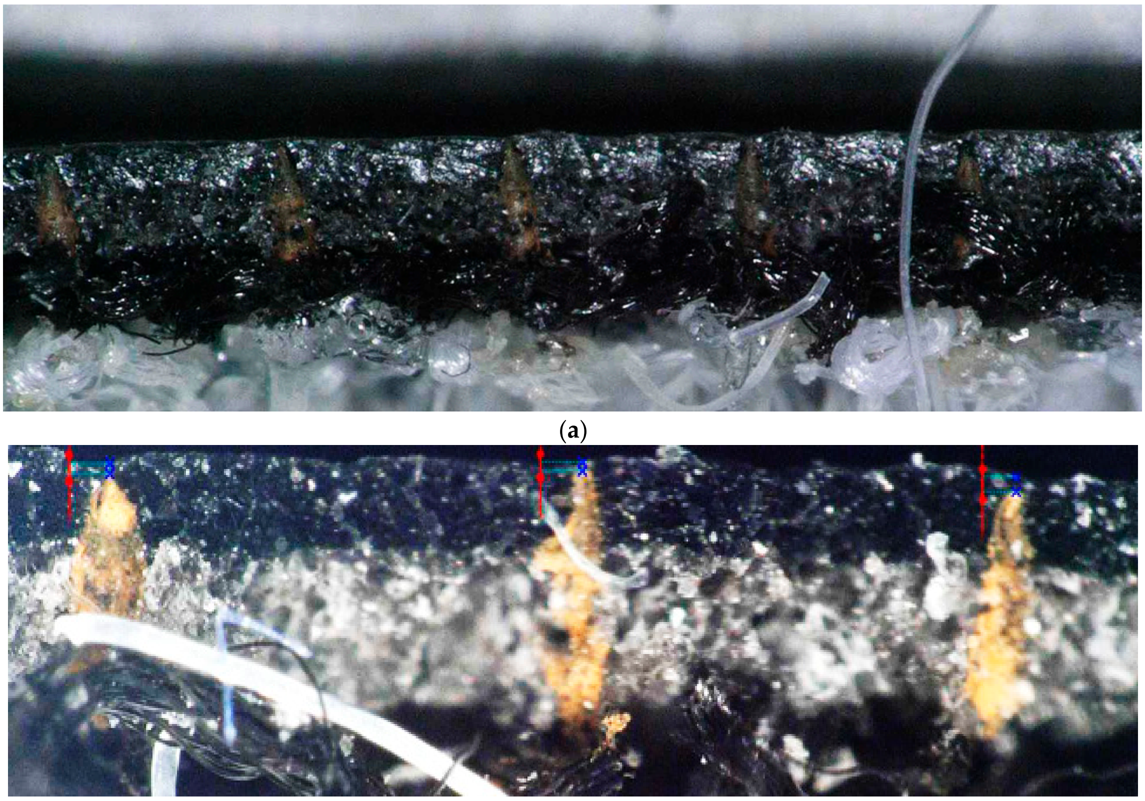
Figure 10. Micro-perforation factor effects.

The absolute effect values compared to the reference line show that the laser powers are statistically significant (Figure 10). Moreover, the standardized effects of the micro-perforation factors show a significant effect of the P2 (90%) and P1 (77%) laser powers.

4. Results and Discussion

4.1. Results and Summary

Nonconforming results (Figure 11): The statistical analyses revealed deviations from the established acceptance criteria during pull testing, indicative of underlying inconsistencies within the manufacturing process.



(**a**)

(**b**)

Figure 11. Microstructure images of nonconforming parts: (**a**) micro-holes in skin; (**b**) completed micro-perforation of micro-holes. The scale bar is 500 μm.

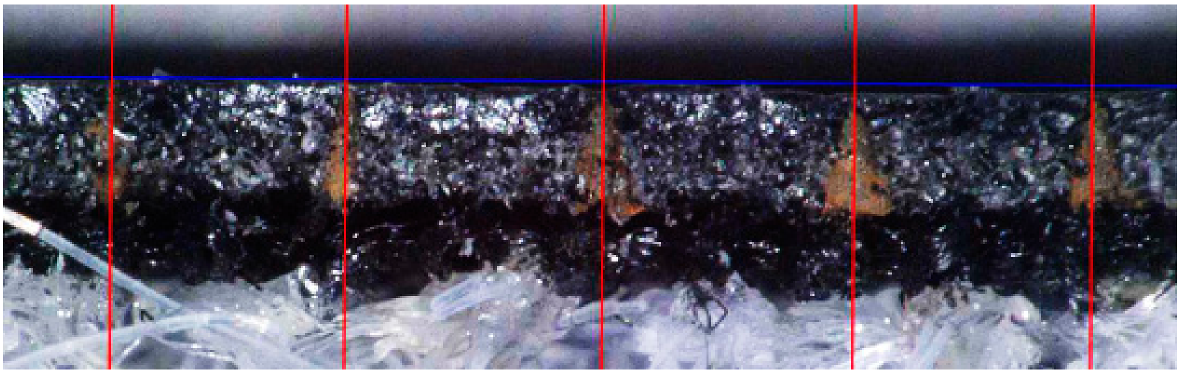
Post-pull-test values: Subsequent evaluations of the post-pull test revealed values within the predefined intervention thresholds, underscoring the need for further investigation to address the root causes.

Further action: This section delineates the ensuing steps, including additional testing protocols and proposed remedial measures aimed at rectifying the identified discrepancies and optimizing the manufacturing practices (Figure 12).

4.2. Proposed Measures and Next Steps

Laser processing with adhesive application on Bluemelt machine: Noteworthy consistency was observed within the specified tolerance limits, affirming the efficacy of this approach and providing valuable insights for future process refinements.

Cross-testing RHD parts on LHD nest: The validation experiments yielded pull test results consistent with the acceptance criteria, highlighting the potential interchangeability of the manufacturing parameters and informing standardized practices.



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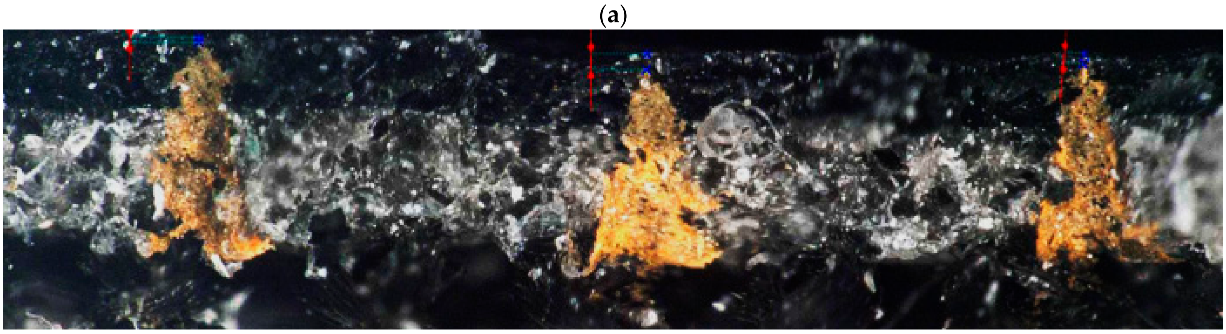

(**b**)

Figure 12. Microstructure images of conforming parts: (**a**) holes in skin; (**b**) completed micro-perforation holes. The scale bar is 500 µm.

New batch of material preparation: The rigorous assessment of the material batch's impact on the pull test tolerances can inform future manufacturing practices and enhance the process' predictability and repeatability.

Adhesive application and laser: The granular examination of the variances after adhesive application and laser processing can identify process optimization opportunities and minimize variability.

4.3. Detailed Analysis

Pull test influences: The in-depth analysis revealed the significant influences of the adhesive application techniques and spacer dimensions, necessitating meticulous control and calibration of the process parameters. The laser power needs to be set and optimized for both the P1 and P2 powers to ensure the coverage of defects from the previous process.

Parameter adjustments: The dynamic nature of the spacer thickness underscored the imperative for frequent iterations and standardization efforts to ensure consistent laser processing outcomes.

Continued research: The ongoing exploration of alternative laser processing scenarios, including variations in adhesive application techniques, is necessary to comprehensively delineate the process dynamics and inform iterative enhancements.

Glue application influence: The differential outcomes observed based on the adhesive application methodologies underscored the need for systematic evaluation and refinement to optimize the process parameters and ensure uniformity across adhesive types.

4.4. Proposed Enhancements

Spacer dimension standardization: The implementation of stringent protocols to standardize the spacer dimensions, minimizing the need for frequent parameter adjustments and enhancing the process' stability and predictability.

Laser line optimization: The precision calibration of the laser line positioning to ensure seamless alignment with the spacer fabric, facilitating consistent pull test results and mitigating variability.

Refinement of glue application: The systematic evaluation of the adhesive application methodologies to ascertain the optimal parameters conducive to uniform outcomes across different adhesive types and enhance the process' repeatability.

Contingency planning: The development of robust contingency plans to preemptively address potential machine-related issues, safeguarding the production continuity and efficiency.

Noise parameter adjustment: The fine-tuning of the noise parameters to optimize the process' stability and minimize adverse effects on the pull test outcomes, enhancing the overall process' reliability and repeatability.

4.5. Discussion

The investigation results indicate several significant findings and implications in the context of previous studies and working hypotheses. The detailed analysis of the airbag cutout laser process revealed substantial discrepancies in the application of LHD and RHD parameters, aligning with the initial working hypotheses. Additionally, other influences on the process, such as the adhesive application techniques and spacer dimensions, were identified.

Interpreting these results in the context of previous studies suggests that a more rigorous and systematic approach is needed to ensure consistency and reliability in the airbag cutout laser process. Compared to previous research, which has indicated similar challenges in laser processing for automotive applications, this investigation adds a new perspective by identifying and documenting detailed issues related to the incorrect use of the LHD and RHD parameters.

The implications of these findings are extensive and could significantly impact the production process across the automotive industry. Optimizing the airbag cutout laser process could lead to significant improvements in the quality and reliability of automotive safety components, thereby reducing the risk of failure and enhancing passenger safety.

Regarding future research directions, this investigation opens the door to several further studies. These include more detailed research into the influence of various process parameters on the final outcomes, exploring alternative adhesive application methods and assessing the impact of introducing new or improved technologies into airbag cutout laser processing.

These future research directions can contribute to the ongoing development of knowledge and practices in laser processing in the automotive industry and provide innovative solutions to improve the production processes and product quality.

Moreover, it is essential to consider the broader implications of autonomous vehicles beyond the manufacturing process. The widespread adoption of autonomous driving technologies has the potential to revolutionize urban mobility, reduce traffic congestion and minimize environmental impacts. By leveraging AI-driven autonomous vehicles, cities can reimagine transportation systems, optimize infrastructure utilization and enhance the overall quality of life for residents.

Furthermore, the ethical and societal implications of autonomous vehicles must be carefully examined. Issues such as liability, privacy and job displacement require thoughtful consideration and proactive measures to mitigate the potential risks and ensure equitable outcomes. Collaborative efforts between policymakers, industry stakeholders and the research community are essential to addressing these challenges and fostering public trust in autonomous driving technologies.

5. Conclusions

- The overall conclusion of the presented study is that the level of the laser power has a significant influence on the micro-perforation process.
- The analysis of the micro-perforation factors provides significant evidence for an interaction. The effect of one laser power factor depends upon the level of the other

laser power. Moreover, the statistically significant difference is highlighted by the design of experiments analysis and main effects plots.
- The laser micro-perforation process is optimal for a percentage of at least 25% of the laser power, with upper limits above 25% beneficial for both process stability and the material's resistance to the pull test. The analyzed parameters for the laser process, including the power (W) and material rupture resistance (N), are of paramount importance due to their critical characteristics (CC), significantly influencing the efficiency and quality of the process.
- The analyses of the experimental results provide valuable insights into the factors influencing the airbag cutout laser processing outcomes. The inappropriate use of LHD parameters for RHD components significantly contributed to process variability, resulting in nonconforming outcomes during pull testing. The correlations between the processing parameters and product quality underscore the importance of parameter optimization for consistent outcomes. To address this, standardized parameter sets tailored to specific component configurations are recommended, alongside enhanced quality control protocols including real-time monitoring. Future research may explore advanced laser processing techniques, like adaptive process control and machine learning algorithms, to optimize the efficiency and quality.

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