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Research Article

Comparative Assessment of Spot Welding and Lock Seam on Automotive Inner Tubes for QCDSM and Product Lifecycle Sustainability

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Abstract

In the automotive manufacturing industry, enhancing quality and productivity is crucial to meet customer expectations while ensuring safety, environmental sustainability, and energy efficiency. This study evaluates the collapse strength of automotive inner tubes following ISO 2941 standards, comparing lock seam design with SGCC material and resistance spot welding (RSW) applied to SECD material. The findings show that the lock seam process improves structural strength by approximately 20%, due to more uniform pressure distribution, leading to better stability. A key advantage of the lock seam is its spiral construction, which contrasts with RSW's localized spot welds, contributing to more consistent performance. Additionally, the lock seam process reduces production costs and minimizes environmental impact by using thinner, cost-effective SGCC material. It also enables faster production, enhancing delivery efficiency. The absence of welding fumes improves safety conditions and boosts operator morale, while contributing to a cleaner working environment. From a Product Lifecycle Management perspective, this study shows that the lock seam process optimizes design quality, production efficiency, and sustainability, aligning with the goals of Quality, Cost, Delivery, Safety, and Morale (QCDSM). These results support the adoption of lock seam technology for sustainable, efficient automotive manufacturing.

Keywords: *Inner Tube, Lock Seam, Spot Welding, QCDSM, Product Lifecycle*

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INTRODUCTION

Continuous improvement in the automotive manufacturing industry is crucial to remain competitive in the global market. The primary objective is to establish a quality management framework. It supports operational efficiency, risk mitigation, and product quality enhancement in accordance with International Automotive Task Force (IATF) 16949 standards [1]. In manufacturing, environmentally friendly products often face complex challenges, particularly in terms of process sustainability and environmental safety [2] and recent studies suggest that integrating eco-innovation initiatives with circular economy principles can significantly boost competitiveness in the automotive sector [3]. Kaizen, a philosophy of continuous incremental improvement through process and design changes. It has been proven to cut operational costs, raise product quality, and shorten production times[4]. One of the critical components in this process is the inner tube, a perforated cylindrical structure that supports the filtration media in automotive filters [5].

Currently, resistance spot welding (RSW) is the dominant method in inner tube manufacturing. This process utilizes Joule heating to join materials, where parameters such as electrode pressure and electric current directly affect the weld quality [6]. The variations in current intensity and material hardness also affect welding outcomes, including melting points and flattening thresholds [7]. RSW has been shown to generate a substantially higher environmental burden, with a cradle-to-gate life cycle assessment indicating its overall impact is roughly 2.7 times greater primarily due to increased steel consumption rather than electricity use [8]. However, an innovative energy-efficiency framework for RSW demonstrated that by carefully optimizing welding current and electrode pressure, the process's carbon footprint can be reduced by up to 15 percent compared to conventional settings [9]. Both the environmental challenges of spot welding and the potential gains achievable through targeted parameter control. The high energy consumption of spot welding significantly contributes to its carbon footprint, especially when powered by fossil fuels [10]. As an alternative, lock seam technology offers advantages by employing a mechanical joining process without requiring excessive heat or electrical energy [11].

This study aims to compare these two manufacturing processes by evaluating their impact on Quality, Cost, Delivery, Safety, and Morale (QCDSM). Furthermore, it integrates sustainable product design and process innovation to enhance competitiveness and production efficiency [12]. By adopting this approach, it is expected that product quality can be improved, customer trust can be strengthened, and operational efficiency can be achieved [13]. Continuous improvement in the automotive industry requires the support of advanced technologies, such as Computer-Aided Design (CAD) and other digital tools. This technology enables the development of more complex designs, improved material efficiency, and higher precision in geometry fabrication [14], and also the adoption of CAD/CAM systems in manufacturing using software such as CATIA, Pro/ENGINEER, and Unigraphics significantly improves design accuracy [15] Beyond the design phase, Kaizen methodologies can further improve the manufacturing process. Recent studies highlight how Kaizen implementation in the automotive sector enhances operational efficiency and product quality through systematic process and design modifications [16].

In the context of automotive filters, inner tube collapse testing frequently reveals discrepancies between theoretical collapse pressure predictions and actual test results. Previous research has analyzed failure mechanisms such as circumferential collapse and buckling, as well as testing methodologies used to assess structural integrity [17]. In engine oil filter applications, inner tube failure is often attributed to internal filter components, such as a stuck bypass valve or malfunctioning oil pump pressure settings. As a result, inner tubes must be structurally reinforced to withstand high-pressure conditions, acting as a last line of defense in case of valve failure. Thin-walled pipes are more prone to local buckling, while spiral-weld techniques do not significantly impact overall performance compared to longitudinal-weld techniques [18].

Despite these advancements, a significant research gap remains, particularly in Indonesia. Where studies on automotive metal sheet products are still limited and primarily focused on service-oriented sectors, one of the reasons for this issue is Steelmaking is the production process with the highest risk [19]. At the global level, most research focuses on process improvement through Kaizen, yet design and testing aspects, particularly within the QCDSM framework, remain underexplored. Additionally, tube manufacturing processes predominantly utilize welding techniques, with limited studies on alternative applications in the automotive sector.

This study seeks to address these gaps by exploring design and process improvements in automotive component manufacturing, specifically inner tubes, while integrating QCDSM principles. By leveraging this approach, the study aims to provide new insights into the development of more effective, efficient, and environmentally friendly manufacturing processes and designs.

METHODS AND ANALYSIS

This study employs a systematic experimental testing method following the approach outlined to evaluate and analyze product performance under controlled conditions [20]. The research focuses on collapse strength testing of automotive inner tube filters by comparing two manufacturing methods: spot welding and lock seam. The designs are developed using CAD software, and the corresponding manufacturing processes are implemented at PT. XYZ, a leading automotive component manufacturer located in Banten. The research was conducted over a one-year period in 2024. To ensure consistency in testing, the materials used in both designs align with automotive industry specifications. The lock seam process utilizes SGCC galvanized steel with a thickness of 0.3 mm, selected for its cost efficiency, while the existing spot welding process uses SECD with a thickness of 0.4 mm, as commonly applied in the automotive industry [21]. The selection of materials considers Product Lifecycle Management (PLM) principles and the Quality, Cost, Delivery, Safety, and Morale (QCDSM) framework to ensure material specifications meet design requirements.

Figures 1 and 2 illustrate the detailed designs for lock seam and resistance spot welding (RSW) methods, respectively. In the lock seam design (Figure 1), a spiral arrangement is implemented with 35 mm spacing between lock seams to optimize load distribution, accommodate machine capabilities, and align with perforation points.

Meanwhile, the RSW design (Figure 2) places discrete weld spots at predetermined intervals (X), typically 10 mm from the tube's edges, in accordance with operator settings and machine constraints. These spacing strategies ensure more uniform stress distribu-

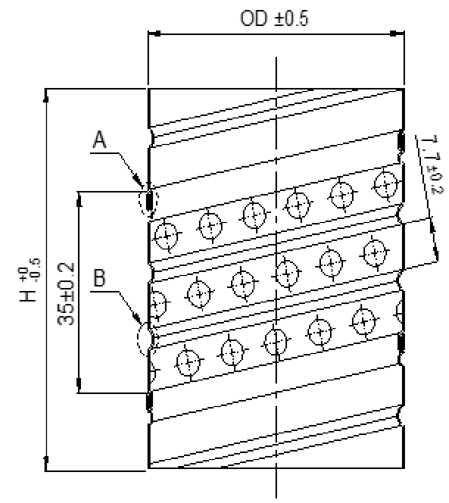

Figure 1. Inner tube specification, made of SGCC using the lock seam process

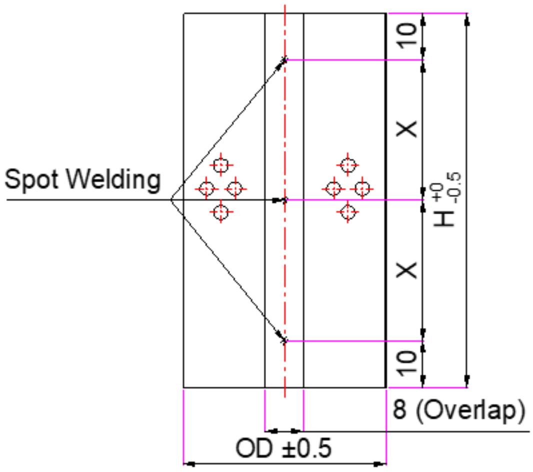

Figure 2. Inner tube specification, made of SECD using the resistance spot welding process

Figure 3. Collapse test apparatus

tion, promote efficient manufacturing processes, and facilitate consistent product quality. Additionally, the specified material dimensions, tolerances, and seam configurations support clarity in both design implementation and subsequent testing procedures.

Once the design and manufacturing process were established, sample specimens were fabricated according to specifications to ensure consistency and accuracy in testing. The collapse test was conducted following ISO 2941 standards, which define the procedure for evaluating the collapse strength of inner tube filters. This process involves gradually applying fluid pressure until the filter element collapses, causing fluid (oil) flow to stop. Figure 3 illustrates the experimental setup, including the controlled fluid pressure system used for testing.

Research Variables and Experiment Procedures

This study evaluates the following independent and dependent variables, for independent variables consist: Inner tube diameter, Inner tube height, Manufacturing process (spot welding or lock seam) and dependent variable focuses on collapse pressure (measured based on ISO 2941 testing procedures). The testing procedure ensures full control over influencing parameters, such as fluid pressure increment rate and environmental temperature stability. The data obtained from the experiments are analyzed to compare the performance of both designs and evaluated using theoretical collapse pressure formulas to determine their accuracy. The final results identify the most effective design and manufacturing process, considering QCDSM principles and their application within Product Lifecycle Management.

The experimental procedure was conducted in compliance with ISO 2941 [22], which defines the collapse test protocol for inner tube filters using the apparatus shown in Figure 3, comparing the collapse pressure results of both manufacturing methods and drawing conclusions based on comprehensive data analysis. The testing phases are outlined as follows:

Fabrication Integrity Test (ISO 2942 Compliance)

Conduct an integrity test on the filter element according to ISO 2942 standards [23]. If the element fails to meet the manufacturer's minimum first bubble pressure, the testing process is discontinued. If the element meets the specifications, the test fluid is evaporated or rinsed using the collapse/burst test fluid, as shown in Figure 4.

Installation of the Test Housing and Measurement of Differential Pressure

After the fabrication integrity test has been completed and all specifications have been met indicating that the element is in good condition and ready for the collapse test the following steps should be performed. Install the filter housing in the collapse test apparatus, following the configuration illustrated in ISO 2941. Measure the differential pressure in the empty filter housing at a flow rate between 50% and 80% of the nominal flow rate, with a test temperature set between 15°C and 40°C. Record the obtained differential pressure values before proceeding with the collapse test shown in Figure 5.

Data Processing and Analysis

This research follows a structured methodology to ensure the accuracy and relevance of the results. The first step involves identifying the core problem in the design and manufacturing process of inner tube filters. This is followed by an extensive literature review to gather relevant references related to design, manufacturing processes, and testing methods based on industry standards.

Figure 4. Fabrication integrity testing process

Figure 5. Collapse testing process

Once the design phase is completed, the manufacturing process is implemented using both spot welding and lock seam techniques. Fabricated samples are produced with varying inner tube heights and diameters to observe the effects of design parameters on collapse pressure. These samples undergo fabrication integrity testing to ensure structural reliability before proceeding with the collapse test to evaluate maximum collapse pressure resistance.

The data obtained from the collapse tests are comprehensively analyzed to compare the two methods, followed by drawing conclusions and providing recommendations based on the findings. To strengthen the validity of the testing results, additional calculations were performed using the theoretical collapse pressure formula (Eq. 1) and the hoop stress formula (Eq. 2) [24], which are applied to assess the elastic stability of the inner tube prior to critical deformation caused by internal fluid pressure. Furthermore, a simple cost-effectiveness analysis was conducted using Eq. 3 to evaluate the economic impact of each method according to Activity Based Costing [25]. The research workflow is summarized in Figure 6.

$$\boldsymbol{P_c = k\frac{E(\frac{t}{R})^2}{1-v^2}} \tag{1}$$

$$P_{max} = \frac{\sigma t.t}{R} \tag{2}$$

$$C_{machine} = R_{machine/minute} \text{ x } Ct_{machine} \tag{3}$$

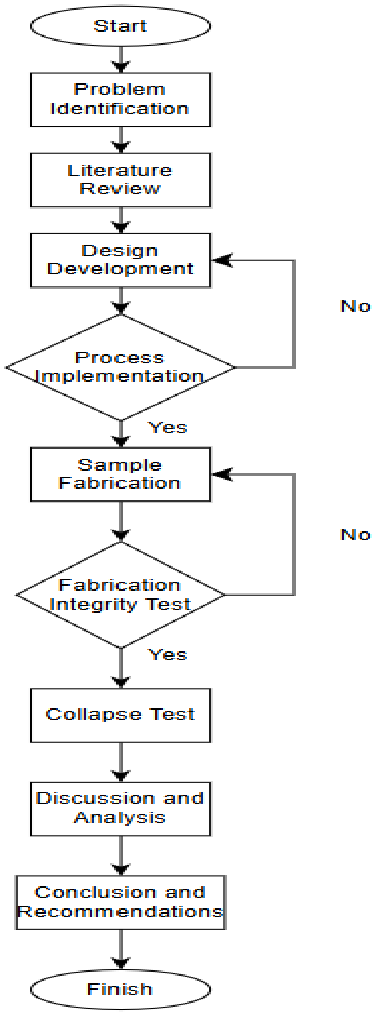

Figure 6. Research methodology flowchart

RESULTS AND DISCUSSIONS

Comparison and Discussion of Test Results

Collapse test results were obtained for two manufacturing methods: resistance spot welding on SECD material with a 0.4 mm thickness and lock seam processing on SGCC material with a 0.3 mm thickness. Preliminary calculations were performed to contextualize the performance of each design. As shown in Table 1, the lock seam design consistently improved the collapse pressure by approximately 20–22% compared to the existing resistance spot welding design. For instance, Part A demonstrated an increase from 83.5 psi to 125 psi (21.88% improvement), and similar enhancements were observed in Parts C (21.82%), D (22.15%), E (21.31%), and B (22.11%).

These findings suggested that the lock seam method significantly enhances the collapse resistance of the inner tube filter. The improved performance of the lock seam process can be attributed to its ability to provide a more uniform stress distribution and stronger mechanical interlocking, even with a thinner material. This is particularly evident in samples with larger element heights, where the structural stability was critical. In contrast, the spot welding method, despite using a thicker material, resulted in lower collapse pressures, indicating a less efficient load distribution.

Overall, these results underscore that adopting lock seam technology in inner tube filter manufacturing can lead to superior quality, cost efficiency, and performance. This improvement aligns with the QCDSM framework, offering enhanced product lifecycle management through more sustainable and effective design and production practices.

Analysis of the data indicated that an increase in inner tube height, housing dimensions, and optimized element diameters positively correlated with improved collapse resistance. In particular, samples fabricated using the lock seam process consistently show a 20–22% higher collapse pressure compared to those produced with spot welding.

This suggested that the lock seam method facilitates a more uniform stress distribution and better structural integrity, even when thinner material (SGCC at 0.3 mm) is employed. The trend implied that careful optimization of geometric variables, such as housing height, tube diameter, and element height played a crucial role in enhancing the overall performance of filter components.

Table 1. Collapse Test According to ISO 2941 Results

No.	Part No	Media Area (m2)	Housing Height (mm)	Housing Diameter (mm)	Element Height (mm)	Tube Diameter (mm)	Element Diameter (mm)	Collapse Result RSW (psi)	Collapse Result Lock seam (psi)	Different Percentage
1	A	0.1092	100	90	65	52	83.5	125	160	21.88%
2	B	0.2527	138.5	92	95	43	83.5	86	110	21.82%
3	C	0.1862	100	80	70	43	73	116	149	22.15%
4	D	0.1904	114.5	80.2	85	43	73	96	122	21.31%
5	E	0.1848	175	80	110	43	73	74	95	22.11%

Moreover, the study highlights the potential implications for design and production within the automotive manufacturing sector. From a production perspective, the faster processing time associated with the lock seam method can lead to more efficient delivery cycles, aligning with the principles of Quality, Cost, Delivery, Safety, and Morale (QCDSM).

Additionally, the integration of these improvements into Product Lifecycle Management (PLM) systems ensures that the benefits of enhanced design and production efficiency are sustained throughout the product's lifespan, further contributing to environmental sustainability and overall competitiveness.

Comparison and Discussion of Calculation Results

This approach is used to evaluate the elastic stability of the inner tube prior to critical deformation induced by internal fluid pressure. The theoretical calculations indicate that the lock seam design using SGCC produces a superior collapse pressure compared to the resistance spot welding design on SECD, despite SGCC having a thinner material thickness. The collapse pressure is calculated using the formula Eq. 1

$$P_c = 0.1\frac{200\ x\ 10^9(\frac{0.3}{0.215})^2}{1-0.3^2}$$

$$P_c = 42.75 \text{ kPa} = 6.2 \text{ psi}$$

In addition, the maximum pressure before material failure is determined using the hoop stress formula Eq. 2. For a tensile strength of σt = 300×10^6 Pa, an inner tube thickness t = 0.3 mm, and an inner tube radius R = 0.215 mm, the calculated maximum rupture pressure is:

$$P_{max} = \frac{397\ x\ 10^6.\,0.3}{0.215}$$

$$P_{max} = 554 \text{ psi}$$

Table 2. Comparative Result Against Actual Results

Design & Process	Tensile Strength (MPa)	Thickness (mm)	Radius (mm)	Buckling Pressure (psi)	Actual Collapse Pressure (psi)	Maximum Rupture Pressure (psi)
Spot Welding, SECD	302	0.4	21.5	8.1	74-132	561
Lock Seam, SGCC	397	0.3	21.5	6.2	95-160	554

Table 3. Machine Cost per Unit Comparison

Design & Process	Rate Machine/minute (Rp)	Cycle Time (minute)	Cost Effectiveness (Rp)	Saving
Spot Welding, SECD	984	0.1	98.4	-
Lock Seam, SGCC	533	0.024	12.9	86.9%

These results demonstrate that the maximum pressure sustainable by the SGCC inner tube is within the predicted range, and the observed increase in collapse pressure (over 20% for several samples) confirms that the lock seam design operates between the theoretical buckling pressure and the maximum rupture pressure. This indicates an optimal design that effectively distributes stress and enhances structural stability, as further illustrated in Table 2.

To quantify the operational expense differences between the two joining methods, cost-effectiveness was evaluated using the machine cost formula:

$$C_{machine} = 533 \text{ x } 0.0243$$

$$C_{machine} = Rp\ 12.9$$

Applying this calculation to throughputs of 41 pcs/min (lock seam) and 10 pcs/min (spot welding), and knowing a Machine Minute Rate of Rp 984/min and Rp 533, yields machine costs of Rp 98.4/unit and Rp 12.9/unit, respectively (see Table 3). This straightforward cost model provides a clear quantitative basis for comparing the operational expenses of both joining methods.

Based on these results, the lock seam process achieves up to a 86% reduction in machine cost per unit compared to resistance spot welding, driven by its significantly higher throughput. Moreover, by utilizing thinner SGCC material (0.3 mm vs. 0.4 mm SECD), material cost calculation (MCC) can be lowered by 45.1% too. These findings demonstrate that optimizing both process efficiency and material use can deliver substantial savings in the production of automotive inner tubes.

Summarizes the discussion and data that has been presented, collapse test results were obtained for two manufacturing methods: resistance spot welding on SECD material (0.4 mm thickness) and lock seam on SGCC material (0.3 mm thickness). Preliminary calculations were performed to contextualize the performance of each design using theoretical models based on buckling for thin-walled cylinders and the maximum rupture pressure.

The theoretical buckling model provides an estimate of the initial elastic limit of the inner tube defining the stability of the material before critical deformation occurs while the maximum rupture pressure indicates the ultimate strength before complete failure.

Experimental data (Table 1) show that the lock seam design using SGCC consistently improves the collapse pressure by 20–22% compared to the spot welding design using SECD. Although there are differences between the theoretical predictions and actual measurements, the actual collapse pressures remain within the range predicted by the two models.

These discrepancies highlight the influence of non-ideal factors such as minor geometric imperfections, especially in perforated designs, that can affect stress distribution. The lock seam process appears to provide enhanced structural stability by distributing pressure more uniformly, even when using a thinner material. This indicates that the lock seam design is not only more cost-effective but also more efficient in sustaining higher collapse pressures. Lock-seam joining relies exclusively on mechanical interlocking and thus avoids molten-metal operations altogether, effectively reducing its process emissions to near zero. Moreover, in RSW, fine-tuning current and electrode pressure has spot-weld carbon footprints by up to standard settings in the manufacturer. Together, these findings underscore that substituting lock-seam for RSW in inner tube assembly can deliver substantial life-cycle emission savings, reinforcing our QCDSM and PLM driven sustainability targets.

While this study provides a quantitative comparison between spot welding and lock seam, it can be strengthened by the future design of innovations, including spiral lock seam geometry optimization and selective reinforcement using spot welds at high-stress zones, as a foundation for hybrid manufacturing strategies. This hybrid approach holds the potential to not only further improve collapse resistance but also offers a new avenue for exploration in the realm of cylinder joint design and manufacturing.

CONCLUSIONS

This research provides a comprehensive evaluation of two manufacturing methods for automotive inner tube filters: lock seam using SGCC material and spot welding using SECD material, with a focus on structural performance, cost, and environmental impact. The results indicate that the lock seam design, despite using thinner material, is more economical and produces superior collapse pressure performance, cost efficiency, and production speed compared to the resistance spot welding process. The experimental findings reveal that the range of collapse pressures predicted by the theoretical buckling formula for thin-walled cylinders and the maximum rupture pressure are distinct, yet the actual collapse pressure remains within this range. This comparison demonstrates that the lock seam design, which consistently achieves a 20–22% improvement in collapse pressure, effectively bridges the gap between the theoretical elastic limit and the ultimate material failure point.

The enhanced collapse performance can be attributed to the more uniform pressure distribution and greater structural stability offered by the spiral lock seam, which encloses the entire circumference of the inner tube. In contrast, spot welding relies on discrete weld points at limited intervals, inherently restricting load distribution based on the number of weld spots determined by the tube's height. This distinction in design geometry and process execution emphasizes the lock seam's capacity to maintain superior load distribution, ultimately leading to improved performance, reduced material usage, and lower environmental impact as a key advantage in advancing automotive filter manufacturing. This finding also has big reduction in carbon emissions not only validates lock-seam's superior collapse performance but also cements its role as a zero emission joining solution that advances sustainable manufacturing. Moreover, the study underscores that a more economical design and process can still yield high-quality products, thereby supporting Product Lifecycle Management and meeting the criteria of Quality, Cost, Delivery, Safety, and Morale (QCDSM). This innovation offers a sustainable solution to enhance filter durability under fluid-induced collapse, reduce production costs, expedite product delivery, and create a safer, more comfortable work environment for operators.

Future studies should also evaluate inner tube performance under real-world conditions (e.g., temperature fluctuations, vibrations, and varying fluid viscosities) and assess the impact of geometric tolerances on structural stability and collapse pressure. However, to compare the carbon footprint between the spot welding and lock seam processes as part of a sustainability assessment is warranted. Additionally, the exclusive focus on SGCC and SECD limits the exploration of alternative materials that might offer a more optimal balance of strength, corrosion resistance, and cost efficiency. Finally, expanding the innovative design lock seam design to other automotive components could further enhance manufacturing efficiency, product sustainability, and competitive advantage in the industry.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

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