National University of Science and Technology "POLITEHNICA" Bucharest
University Center of Pitesti
Faculty of Mechanics and Technology

SCIENTIFIC BULLETIN
AUTOMOTIVE series
year XXXI, no. 35

FMT 50

Defect detection and characterization in spin-welded assemblies for automotive fluid transfer systems

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Article history
Received 10.04.2025
Accepted 01.06.2025

DOI https://doi.org/10.26825/bup.ar.2025.003

Abstract. Spin Welding (SW) is a solid-state joining process widely used for thermoplastic components in automotive fluid transfer systems, offering high mechanical strength, sealing integrity, and full process traceability. However, due to the internal location of the weld interface, conventional optical inspection methods cannot be applied, making defect detection challenging. This study investigates defect detection and characterization in SW tube–connector assemblies, focusing on applications in safety-critical automotive environments. Assemblies were produced using a Mecasonic 72 horizontal SW machine, with process parameters established through Design of Experiments (DOE). A comprehensive evaluation methodology was applied, combining external visual inspection, bright field and polarized light microscopy, X-ray computed tomography (CT), leak testing, and tensile pull-out testing. The analysis identified common defect types, including flash formation, incomplete fusion, interface cracks, and porosity, and correlated their occurrence with deviations in welding time, displacement, and energy input. CT scanning proved most effective for complete circumferential defect mapping, while a combination of bright field microscopy and functional tests was deemed more practical for production environments. The findings provide a technical foundation for subsequent optimization of SW process parameters to reduce or eliminate defect occurrence.
Keywords: Spin Welding, thermoplastic welding, defect analysis, computed tomography, leak testing, automotive fluid transfer

INTRODUCTION

The use of thermoplastic tubing for fluid transfer systems in the automotive industry has increased significantly due to its advantages in terms of weight reduction, chemical resistance, and manufacturing flexibility. These systems are commonly employed in applications such as fuel lines, brake assistance circuits, vapor recovery, AdBlue delivery, and cooling/heating loops.

For high-demand applications, particularly in engine compartments, joint integrity is a safety-critical aspect. Failures in these areas can result in fuel leakage, brake system malfunction, or other hazardous situations. Therefore, the joining method must ensure mechanical robustness, sealing integrity, and long-term durability under variable operating conditions.

Spin Welding (SW) is a solid-state welding process for thermoplastics in which heat is generated through the relative rotational motion between two parts under axial pressure. This frictional heat causes melting at the interface, followed by resolidification under maintained pressure, resulting in a strong bond. The technology provides high tensile strength, good sealing performance, and resistance to environmental conditions. Spin welding is recognized as a rapid, repeatable, and energy-efficient method, requiring minimal surface preparation and suitable for high-volume production [1-2].

Additionally, when implemented with industrial control systems, it enables full traceability of process parameters, as all welding variables can be recorded by the machine's control system.

However, unlike mechanical couplings or externally welded joints, the SW interface is located internally. This makes direct visual inspection impossible, as conventional 2D optical systems only capture the exterior geometry. This limitation necessitates the use of specialized analysis methods capable of revealing internal weld characteristics and detecting defects that may affect performance and safety. Computed Tomography (CT) has proven particularly useful, offering volumetric, non-destructive evaluation of internal features such as voids, inconsistencies in weld flash, and joint geometry deviations [3-7]. In some cases, traditional inspection techniques – such as visual inspection, pressure or burst testing, and microscopy – have been inadequate for detecting subtle flaws, whereas CT scans enabled identification of irregular weld flash, inconsistent joint dimensions, and other critical defects [7].

This paper presents a detailed study on defect detection and characterization in spin-welded tube–connector assemblies for automotive fluid transfer. The focus is on evaluating a comprehensive set of inspection techniques – from visual inspection to computed tomography – to understand what types of defects occur and how they arise under specific process conditions.

MATERIAL AND EXPERIMENTAL METHODS

Materials

The assemblies studied consisted of multi-layer thermoplastic tubes and precision-molded connectors for use in the automotive industry (Figure 1). Welding was carried out only between components made of the same polymer family (e.g., PA12/PA12 or PA6/PA6) to ensure chemical compatibility and compliance with the specifications set for the project.

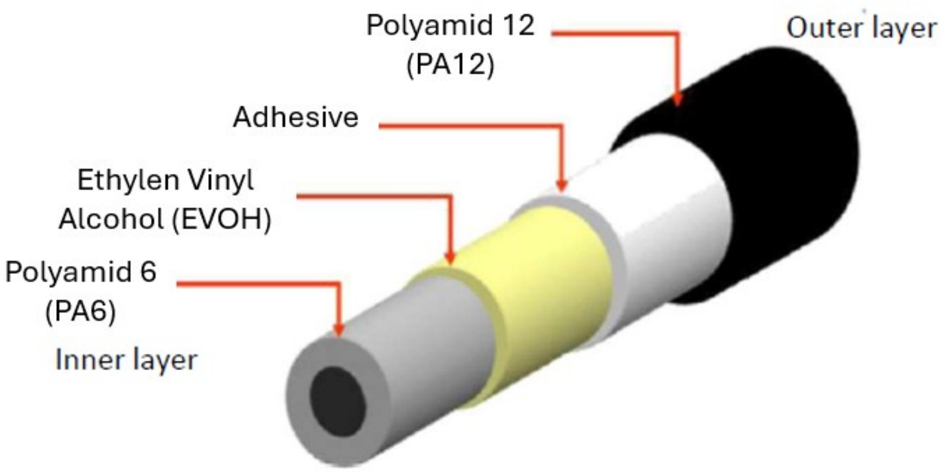
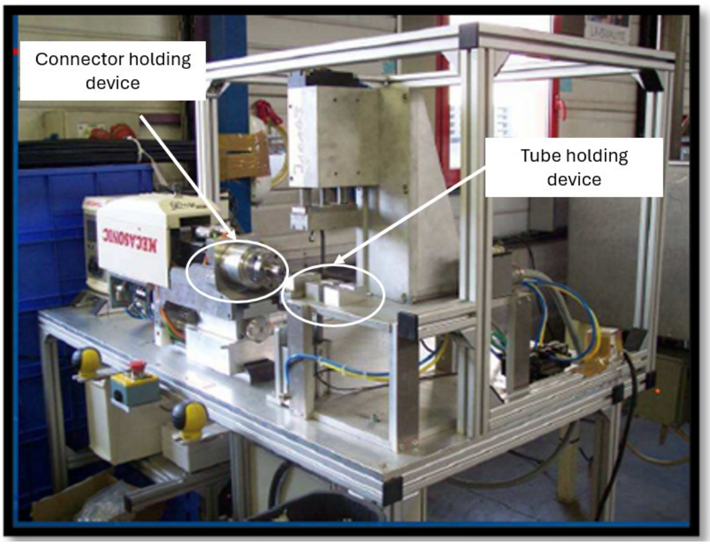


Figure 1. Multilayer tube

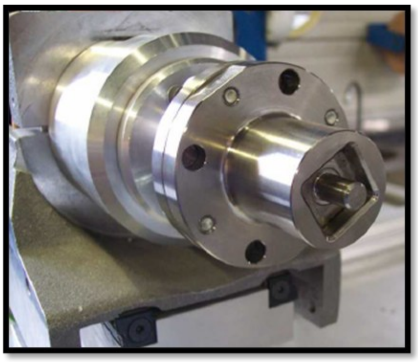
Welding Equipment

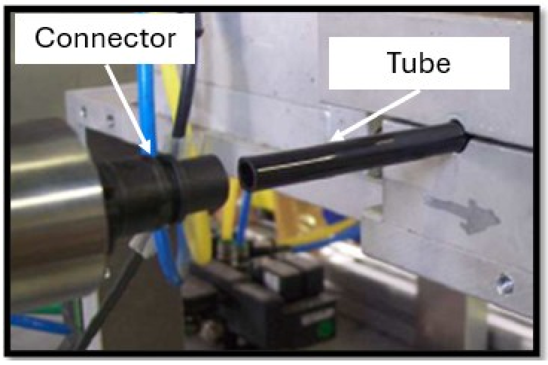
The process was performed on a Mecasonic 72 horizontal spin welding machine shown in Figure 2 which is equipped with:

- A 40 mm pneumatic cylinder,
- Brushless electric motor,
- Titanium connector holders designed to minimize deformation.



a) Mecasonic 72





b) Connector holding device *c)* Held components

Figure 2. Spin welding machine Mecasonic 72

Process control and data logging were managed via Mecawin software (Figure 3), which allows precise adjustment of parameters such as: approach speed and displacement, rotation speed, axial pressures during different phases (initial, welding, cooling, release), cooling time, welding energy and orientation control for proper connector positioning.

Experimental Design

Process parameters were established using a Design of Experiments (DOE) approach. Twenty different parameter sets were tested, each on 10 welded samples, resulting in a total of 200 assemblies.

The key process variables analyzed are listed below:

- Welding time – total rotation phase duration, affecting heat generation;
- Total displacement – sum of all axial movements during welding and holding;
- Displacement to “zero” point – axial travel before initial fusion occurs;
- Welding displacement – axial penetration during fusion;
- Energy input – total mechanical energy converted into heat for melting.

Acceptance criteria for each welded sample included visual appearance, microscopic analysis, sealing, and tensile strength.

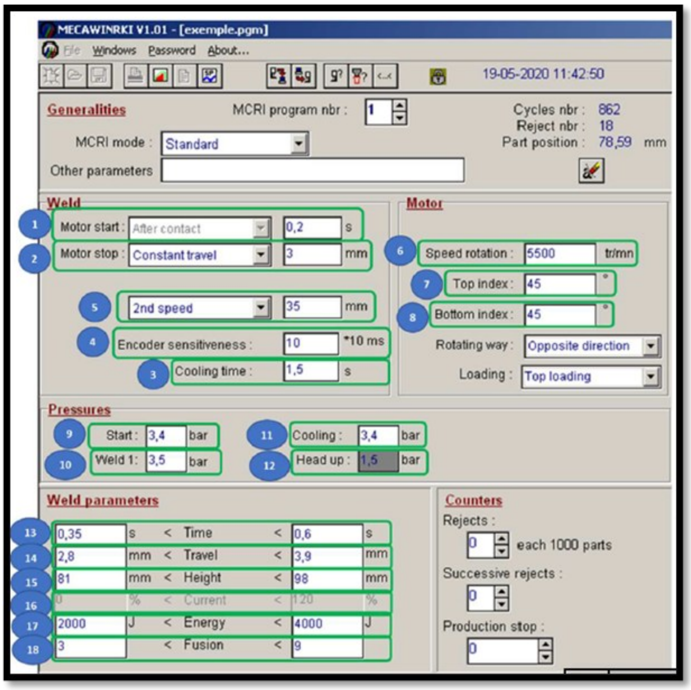


Figure 3. Mecawin software – Relevant parameters: 1. The gap between the point where the two components come into contact and the start of the rotational movement; 2. The point at which the rotational movement stops; 3. Cooling time; 4. Parameter on which the accuracy of the weld starting point depends. Maximum accuracy was selected; 5. Approach speed; 6. Motor rotation; 7. Parameter used to ensure the orientation of the connector in relation to the tube; 8. Parameter used to ensure the orientation of the connector in relation to the tube; 9. Initial pressure; 10. Pressure during the welding phase; 11. Pressure during the cooling phase; 13. Total welding time; 14. Distance over which the weld is made; 15. Total distance over which the machine performs the translational movement; 17. Energy required to perform the weld;

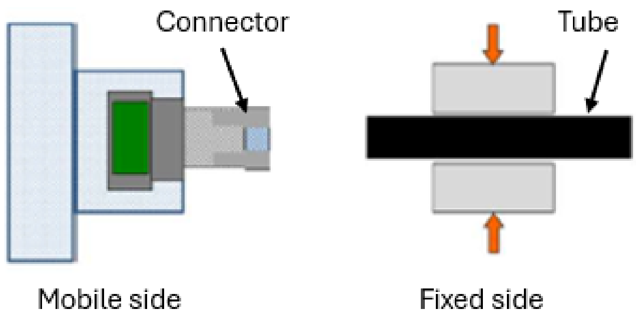
SPIN WELDING PROCESS

The Spin Welding (SW) process for thermoplastic tube–connector assemblies relies on generating frictional heat at the joint interface through relative rotation under axial pressure. The main phases of the process are presented sequentially in Figure 4.

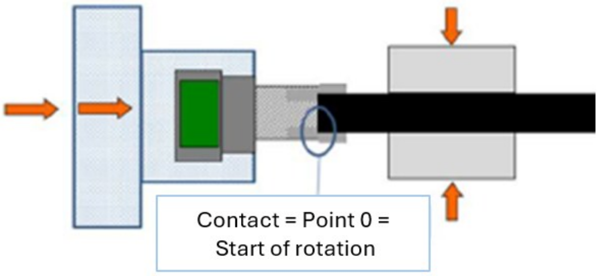
Component loading and positioning described in Figure 4-a begins by placing the connector in the rotating mobile clamp of the SW machine and securing the tube in the stationary fixture. Figure 5 shows the detail of the effective area to be welded in a longitudinal section in connector. The tube end is chamfered to facilitate guidance into the connector's socket. At this stage, precise axial alignment is essential to prevent eccentric loading and uneven heat generation.

Rotation phase – The mobile part advances toward the stationary tube holder at the programmed approach speed. The chamfered tube entry aligns the components, reducing the risk of premature contact between non-functional surfaces. Axial force begins to build as the components meet, marking the onset of the welding cycle (Figure 4-b).

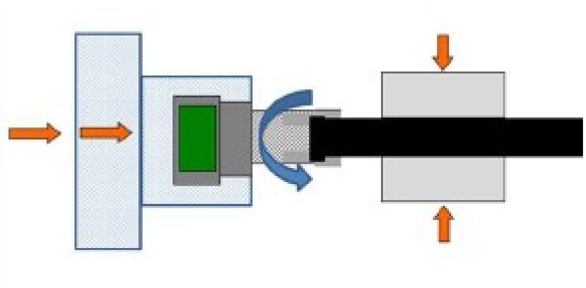
In the next phase – *Frictional heating* – Once contact is established, the mobile part accelerates to the target rotation speed. Friction at the contact surfaces generates localized heat, softening the thermoplastic material. The welding displacement starts to accumulate as the softened polymer layers begin to flow and fill any micro-gaps at the interface. The energy input during this stage is critical: insufficient energy leads to incomplete fusion, while excessive energy causes material degradation or excessive flash.



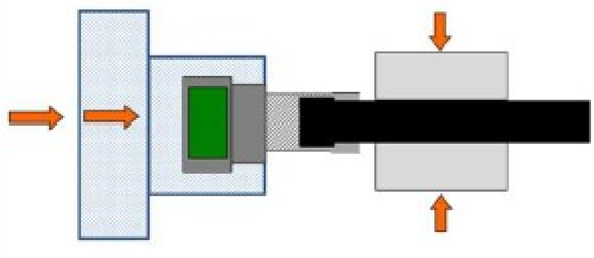
a) Component loading and positioning



b) Start of rotation phase



c) Welding phase of the two materials



d) Dynamic holding step

Figure 4. Assembly principle

Fusion stage and molten material flow (Figure 4-c) – As heat generation continues, the material at the interface reaches a fully molten state, allowing for molecular interdiffusion between the tube and connector polymers. Excess molten material, if generated, is captured in the designed flash collection groove to prevent interference with functional surfaces. This is the key phase for achieving a uniform, continuous weld bead without voids or cracks.

Dynamic holding phase (Figure 4-d) – At the end of the rotation phase, the mobile part continues to advance axially in what is known as dynamic holding. This ensures that fusion occurs across the full circumference and depth of the interface, eliminating unbonded sectors. The axial pressure applied here must be sufficient to expel any residual voids but not so high as to cause excessive displacement.

Rotation stops in static holding and cooling phase in which the components remain pressed together under controlled static pressure. This allows the molten interface to cool and solidify without separation, locking in the molecular bonds formed during the fusion stage. Cooling time is a critical parameter: too short, and residual stress or incomplete solidification may occur; too long, and cycle time efficiency is reduced.

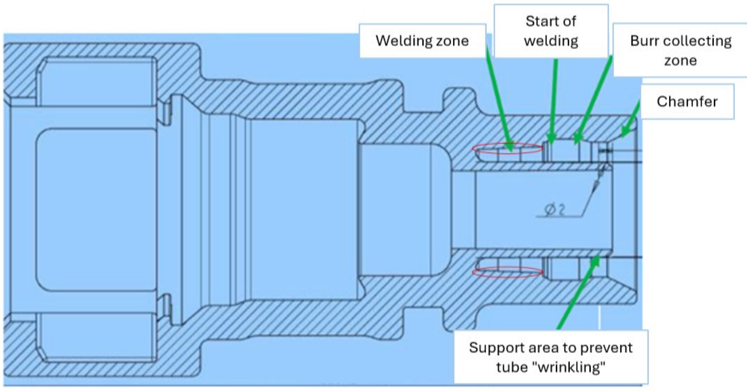


Figure 5. Longitudinal section in connector: *spin weld is correct if the weld is complete between the outer surface of the tube and the connector in the weld area marked in red over a length of ~6 mm*

Part release and extraction is the last phase in which, after cooling, the clamps release the assembly, and the completed joint is extracted (Figure 6). At this point, only the external features (such as flash or burrs) are visible, and the internal weld integrity must be evaluated through the inspection methods described in the next section.

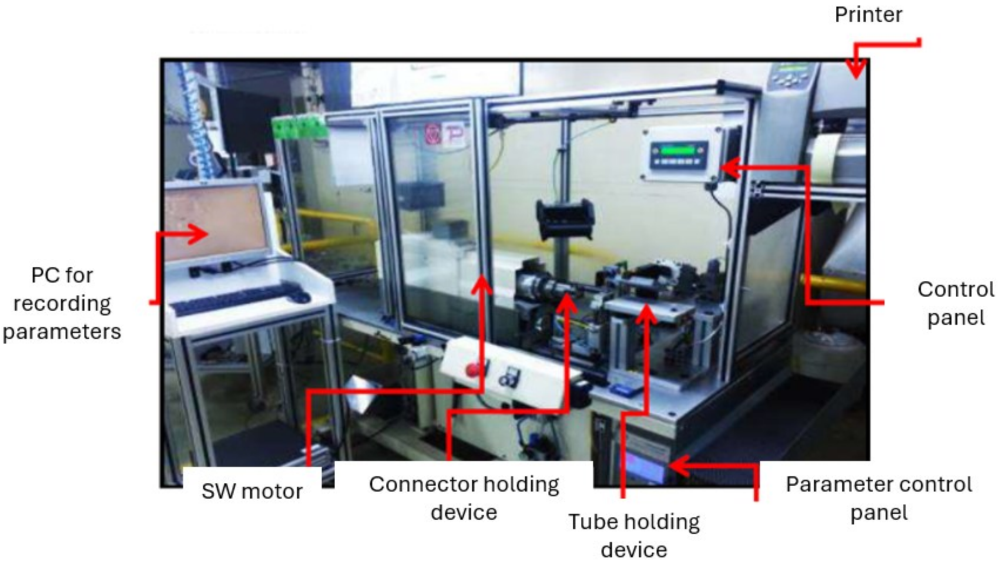


Figure 6. Spin welding assembly machine

DEFECT ANALYSIS METHODS

In this study, the critical factors influencing weld quality are considered to be:

- Material combination (only identical polymer families are weldable according to the standard);
- Heat generation balance (avoiding underheating or overheating);
- Displacement and energy control to prevent defects such as incomplete fusion, cracks, or burr formation.

Thus, considering these critical factors, ensuring the quality of spin welded joints in thermoplastic assemblies requires more than verifying external appearance. Because the fusion zone is fully enclosed within the interface between the tube and connector, internal defects cannot be detected through conventional visual inspection alone. Therefore, a multi-method inspection strategy was implemented in this study, combining non-destructive and destructive evaluation techniques. Each method is described below, including its principle, its general applications in industry, and its specific implementation in this paper.

Visual external inspection

Visual external inspection is the simplest and fastest quality control method, relying on the direct observation of the part's external surfaces under adequate lighting. This method detects surface anomalies such as burrs, flash, surface cracks, discoloration, or dimensional irregularities. In manufacturing, it is often the first inspection step before more complex tests are performed.

In the context of SW joints, external inspection focused on the tube exit area. The goal was to identify:

- Burr formation (Figure 7), which indicates excessive plastic flow due to high displacement or excessive energy input;
- Excess molten material (Figure 8), suggesting overheating or poor flash collection design.

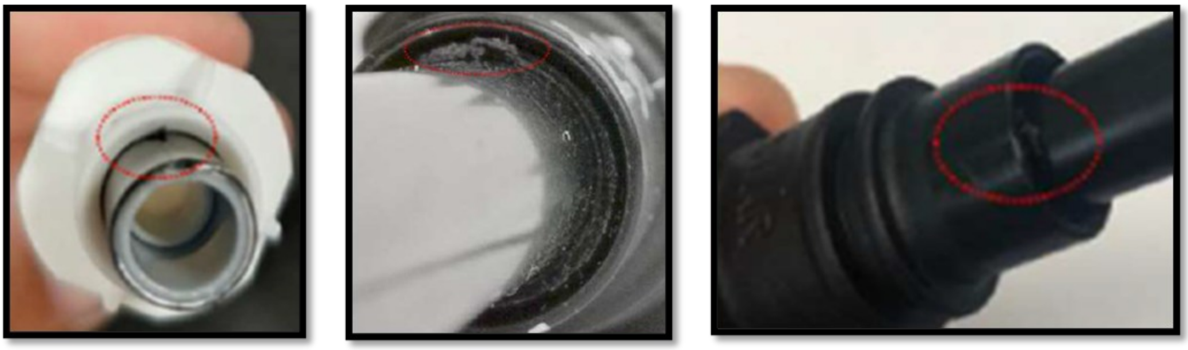


Figure 7. Burrs resulting from the welding process

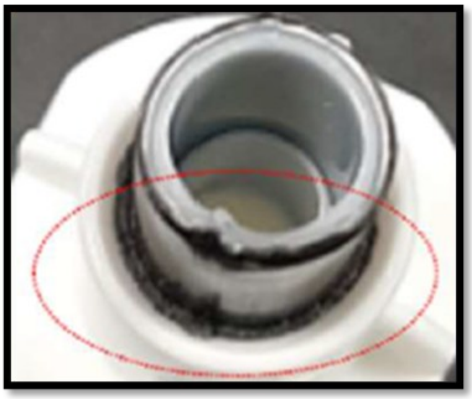


Figure 8. Excess material resulting from the welding process

Assemblies presenting these external anomalies were immediately rejected without further internal inspection, as they were considered indicative of sub-optimal process parameters.

Microscopic analysis in bright field

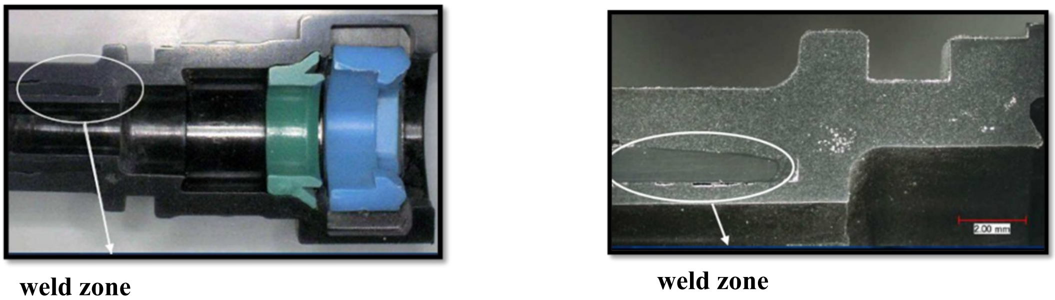
Bright field microscopy is an optical imaging technique where light passes directly through the specimen. It is widely used in materials science for examining cross-sectional features, as it allows detection of cracks, voids, material flow patterns, and general morphology at magnifications typically ranging from 5× to 100×. The method is destructive, requiring sample sectioning and surface preparation.

Cross-sections of SW joints were prepared by cutting the assemblies transversely through the weld zone. Two samples are given as examples in Figure 9 and Figure 10, respectively. Examination was conducted at 5×, 20×, and 30× magnifications. Evaluation criteria included:

- Continuity and uniformity of the weld interface;
- Absence of cracks or unbonded regions;
- Correct axial positioning of the tube against the connector stop;

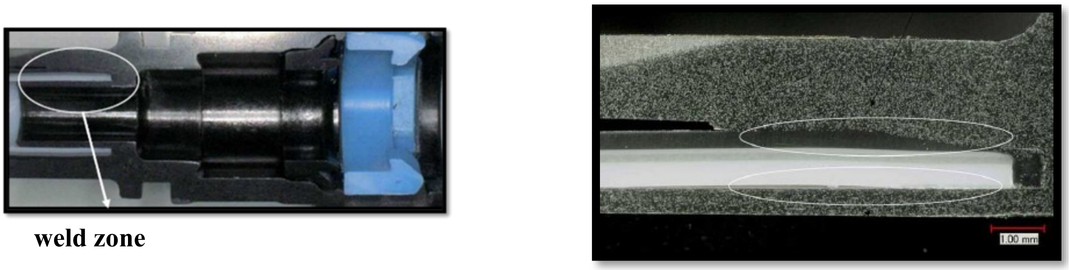
- No material damage from excessive heat or pressure.

Figures 9 and Figure 10 show that the two samples examined are correctly welded, as the outer surface of each assembled multilayer tube is completely welded to the connector over the required length (see Figure 5 for details of correct welding).



a. 5× magnification b. 20× magnification

Figure 9. Microscopic analysis of sample 1



a. 5× magnification b. 30× magnification

Figure 10. Microscopic analysis of sample 2

This method provided a first qualitative confirmation of fusion quality. However, as only selected cross-sections were examined, defects localized in uncut circumferential regions could be missed.

X-ray Computed Tomography (CT)

X-ray computed tomography is a non-destructive imaging technique that reconstructs a three-dimensional model of an object’s internal structure. A focused X-ray beam is passed through the sample at multiple rotation angles, and a detector records the attenuated signal. Reconstruction algorithms then generate volumetric images showing internal density variations, which can reveal voids, incomplete fusion, cracks, and inclusions [8-9].

The SW joints were scanned using a NIKON XTH 225 ST CT system shown in Figure 11.

Figure 11. NIKON XTH 225 ST CT system

For each 360° rotation, 1440 radiographs were acquired, and volumetric reconstruction was performed as shown in Figure 12 using VG Studio Max 3.5 software.

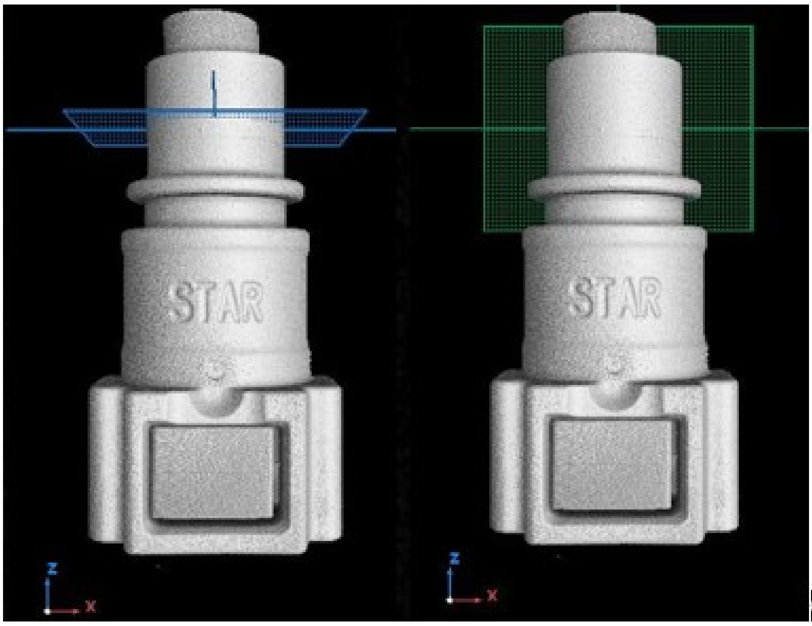
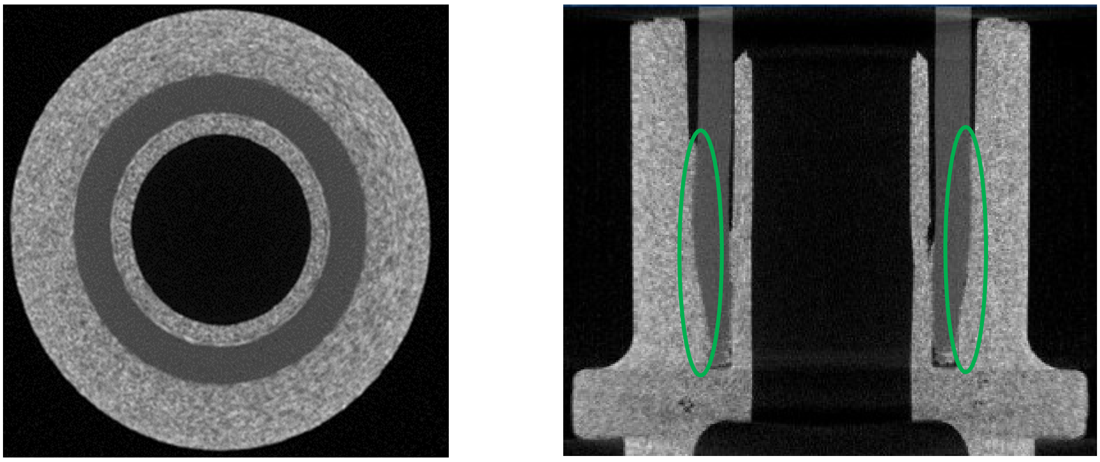


Figure 12. 3D model reconstructed based on X-rays: Blue plan - representation of a transversal section; Green plan - representation of a longitudinal section

The CT analysis enabled:

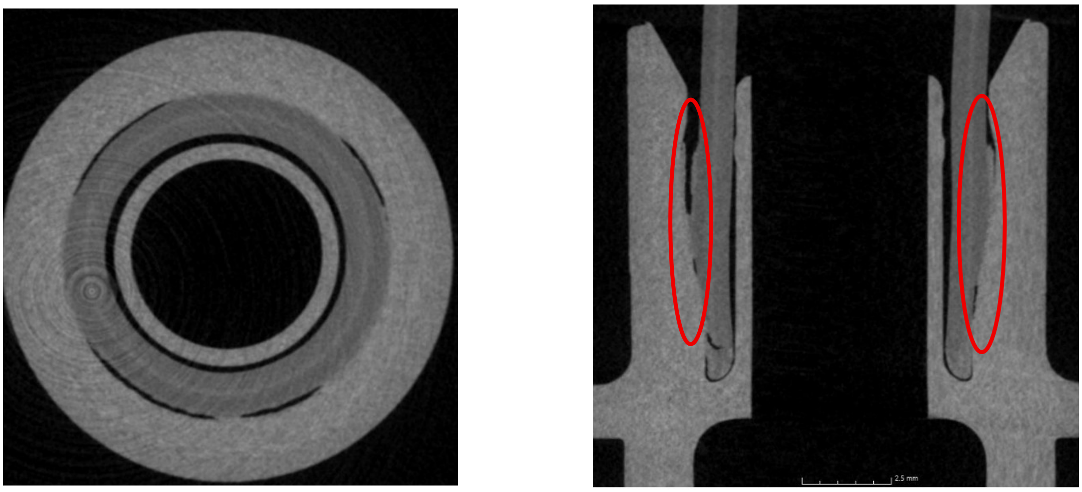
- Complete circumferential inspection of the weld interface;
- Detection of complete welds (Figure 13) versus incomplete welds (Figures 14);
- Visualization of defects along transverse and longitudinal planes.

Although CT provided the most comprehensive defect mapping, its long acquisition time and high operational cost limit its application in high-volume production.



a) Transverse section *b)* Longitudinal section

Figure 13. Representation of two sections in a sample with **complete** welding using X-ray tomography



a) Transverse section *b)* Longitudinal section

Figure 14. Representation of two sections in a sample with **incomplete** welding using X-ray tomography

Polarized light microscopy

Polarized light microscopy uses polarized illumination to enhance contrast in birefringent materials, such as many thermoplastics. When polarized light passes through regions of different molecular orientation or stress states, it is altered in a way that reveals structural differences invisible in bright field microscopy. This technique is particularly suited for measuring fusion zone thickness and assessing the degree of material intermixing.

In this study, after preparing polished cross-sections of the SW joints, polarized light microscopy was employed as shown in Figure 15 to:

- Accurately measure the weld interface thickness;
- Detect subtle unbonded regions;
- Identify stress patterns resulting from uneven cooling.

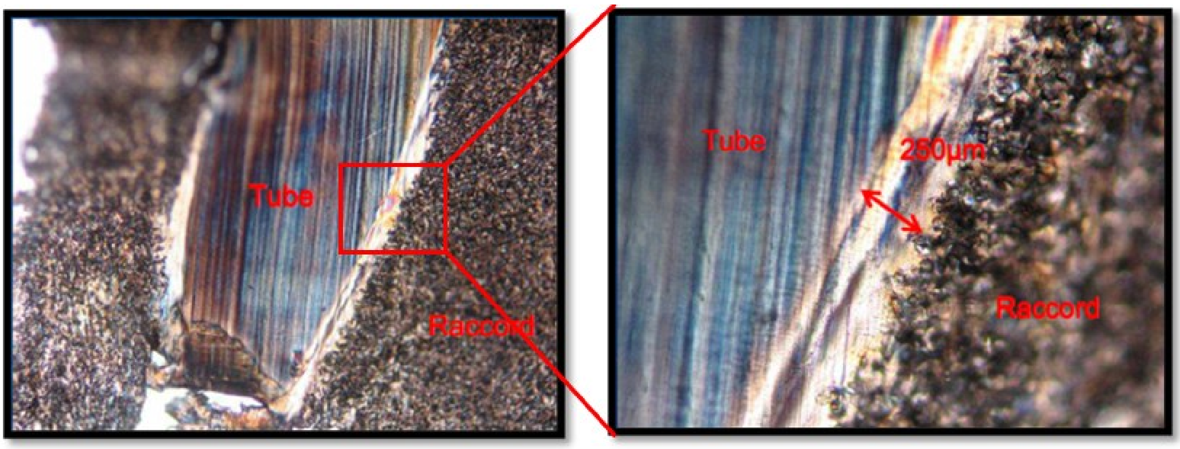


Figure 15. Microscopic analysis with polarized light

This example highlights the correct and complete execution of a weld. Between the tube material and the connector material, the weld seam is visible, with a width of approximately 250 µm. Compared to bright field microscopy, this method allowed more precise detection of incomplete bonding, especially when the defect did not manifest as a visible gap.

Leak testing

Leak testing verifies the sealing performance of a component by pressurizing it and measuring any pressure loss or fluid escape. The method can use gases (often air) or liquids as test media, and measurements can be differential (comparing to a reference) or absolute (against atmospheric pressure).

Leak tests were performed here with an ATEQ F620 differential pressure system shown in Figure 16, which uses a reference volume to test the part. This helps to compensate for any variations in ambient pressure or temperature, as these occur on both sides simultaneously. Only a leak in the test piece will cause our transducer membrane to move.

Figure 16. ATEQ F620

The second advantage of this method is that accuracy does not decrease with test pressure, as the transducer measures the pressure differences between the two circuits, unlike traditional pressure decay technology, which measures pressure drops relative to atmospheric pressure.

As shown in Figure 17, representing the principle of leak measurement, the test sample 3 and the reference sample 5 are subjected to identical pressure. A differential sensor 4 measures the pressure variation between the test sample 3 and the reference sample 5. In some applications, the reference sample can be replaced with a cap.

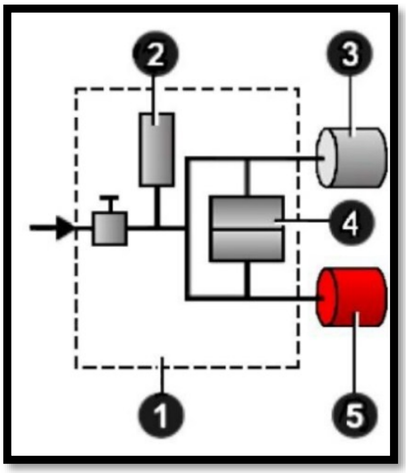


Figure 17. Leak measurement principle

The leak test is performed underwater with air at a pressure of 10 bar for 120 seconds. The result of the leak test is determined by two factors:

- the leak rate must not exceed 0.5 cc/minute;
- there must be no visible air leaks.

This method directly validated the functional sealing of the joint, complementing the structural information from microscopic and CT analyses.

Tensile pull-out testing

Tensile pull-out testing evaluates the mechanical strength of a joint by applying a controlled axial load until failure occurs. It provides quantitative data on the maximum force the joint can withstand, as well as the mode of failure–cohesive (material fracture) or adhesive (bond separation). In thermoplastic welding, cohesive failure is typically desired as it indicates that the weld is stronger than the base material.

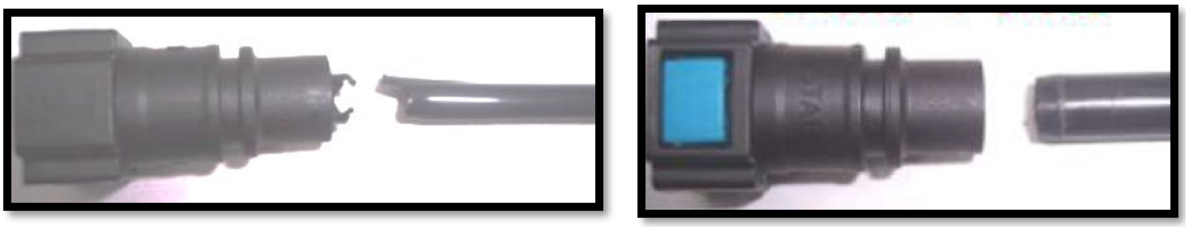
The pull-off test was performed on an Instron 3369 tensile testing machine with a cell force of 5000 N, shown in Figure 18.

Figure 18. Instron 3369 tensile testing machine

The tests are performed at ambient temperature (23 °C) at a speed of 100 mm/minute. The samples have a tube length of 110 mm.

The pull-off test result is conditioned by two factors:

- the force value must exceed 300 N;
- the break must be cohesive and not adhesive – which means that the break must occur in the tube material and not at the weld (Figure 19).



a) Cohesive break *b)* Adhesive break

Figure 19. Break types in the tensile pull-out test

This method ensured that, beyond sealing performance, the welded joints possessed adequate structural integrity for their intended service conditions.

RESULTS AND DISCUSSION

Defect types observed

The inspection methods revealed several recurring defect categories in Spin Welded (SW) joints:

- Flash/Burr formation – observed externally (Figure 7 and Figure 8), often resulting from excessive welding displacement or high energy input.
- Incomplete fusion – detected primarily by X-ray CT scans (Figure 13 and Figure 14), linked to insufficient welding time, low axial pressure, or improper displacement to the "zero" point.
- Interface cracks – observed under microscopy, attributed to residual stresses from rapid cooling or contamination in the weld zone.
- Porosity and voids – small cavities detected by CT scanning, often related to material moisture content or gas entrapment during the welding process.

These defects can have different functional impacts: for example, burrs may not immediately compromise sealing but can interfere with assembly or cause stress concentration, while incomplete fusion directly compromises both sealing and strength.

Comparative evaluation of inspection methods

Given that no single inspection technique could identify all defect types, the study implemented a multi-method approach. Table 1 summarizes the characteristics of each method, based on their application in this study.

Based on these results, a comparative chart of the performance of SW joint inspection methods was created. This chart shown in Figure 20 allows for easier visualization in order to choose inspection methods that optimize the relationship between cost efficiency, analysis speed, and defect detection coverage.

Table 1. Comparative evaluation of inspection methods used for SW joint quality assessment

Method	**Principle**	**Defects Detected**	**Advantages**	**Limitations**	**Relative Time/Cost**
Visual External Inspection	Direct optical observation of external surfaces	Flash, burrs, surface irregularities	Very fast, no equipment needed	Cannot detect internal defects	Low
Bright Field Microscopy	Light transmitted through prepared cross-section	Incomplete fusion, cracks, positioning errors	Good image clarity, relatively fast	Destructive, limited to examined section	Medium
X-ray Computed Tomography (CT)	3D reconstruction from multiple X-ray projections	Incomplete fusion, voids, cracks (360° coverage)	Comprehensive, non-destructive	High cost, long acquisition time	High
Polarized Light Microscopy	Polarized illumination highlights birefringence/stress	Fusion zone thickness, subtle unbonded areas	Precise thickness measurement	Destructive, limited area coverage	Medium
Leak Testing	Pressurization and detection of pressure loss or bubbles	Loss of sealing integrity	Direct functional validation	No information on defect morphology	Low–Medium
Tensile Pull-out Testing	Axial force applied until failure	Insufficient mechanical strength, failure mode	Quantitative strength data, functional relevance	Destructive, no defect location info	Medium

Method selection for production use

While X-ray CT was the only method capable of providing complete internal mapping of the weld, its high cost and long acquisition time make it impractical for 100% production inspection. For regular manufacturing quality control, the combination of bright field microscopy (for structural assessment) and functional tests – leak testing and tensile pull-out testing – offers a practical compromise between detection capability, cost, and cycle time.

In practice, the study recommends:

- Full CT analysis during process validation or troubleshooting;
- Microscopy + functional tests for ongoing production quality assurance;
- Visual inspection as an immediate, low-cost screening method.

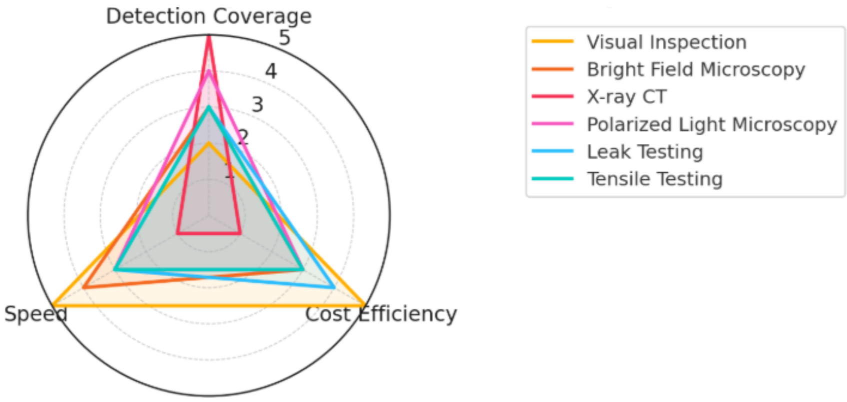


Figure 20. Comparative performance of inspection methods for SW joints

CONCLUSIONS AND PERSPECTIVES

This study systematically investigated defect detection and characterization in Spin Welded (SW) thermoplastic tube–connector assemblies used in automotive fluid transfer systems. By combining visual inspection, optical microscopy, X-ray computed tomography, polarized light microscopy, leak testing, and tensile testing, a comprehensive evaluation methodology was developed to assess both structural integrity and functional performance.

The findings highlight that:

- Defects such as flash formation, incomplete fusion, interface cracks, and porosity can occur under a variety of process deviations, even when external appearance is within acceptable limits.
- Critical process parameters–including welding time, total displacement, displacement to the zero point, and energy input–are strongly correlated with defect occurrence.
- While X-ray CT is the only method providing complete 360° internal mapping of the weld, its cost and time requirements limit its use to process validation and troubleshooting. For routine production, the combination of bright field microscopy and functional tests offers an optimal balance between defect detection capability, resource requirements, and inspection speed.

By understanding how and where defects occur in SW joints, manufacturers can improve quality assurance strategies and reduce the risk of non-conforming parts reaching the customer.

The results of this study provide a robust diagnostic framework that can be directly leveraged for process optimization. In particular, the correlations established between defect types and specific process parameters form a quantitative basis for tuning welding conditions to minimize defect occurrence.

To achieve these perspectives, the next stage of research can focus on:

- Refining process parameter windows using statistical capability analysis and Six Sigma methodologies;
- Implementing optimized tolerance limits for key variables such as welding time, displacement, and energy input;
- Evaluating the effect of optimized parameters on defect reduction and overall process stability in serial production.

Ultimately, the integration of defect analysis with parameter optimization is expected to significantly enhance weld quality, improve production efficiency, and ensure compliance with stringent automotive safety requirements.

REFERENCES

[1] Kalas, Vinayak & Roos, Laurens-Jan. (2016). Welding of thermoplastic composites. 10.13140/RG.2.1.4101.0803. https://www.researchgate.net/publication/303938951

[2] Wikipedia. (accessed on 21 October 2024) Spin welding of polymers. Wikipedia.

[3] Wikipedia. (accessed on 21 October 2024) Testing of advanced thermoplastic composite welds.) Wikipedia.

[4] Tintatu, A., Bidaud, P., Badulescu, C., Le Grognec, P., Adrien, J., Bonnard, G., Maire, E., Bindi, H., Coguenanff, C. (2023). Robust water diffusion modeling in a structural polymer joint based on experimental X-ray tomographic data at the micrometer scale. *Polymer Degradation and Stability, Volume 218, 110594, ISSN 0141-3910*

[5] Tintatu, A., Bidaud, P., Badulescu, C., Le Grognec, P., Adrien, J., Maire, E., Bindi, H., Coguenanff, C. (2023). Understanding of water uptake mechanisms in an epoxy joint characterized by pore-type defects. *The Journal of Adhesion*, *Volume 100(1), Issues 1–33*

[6] Tintatu, A., Badulescu, (2024). Analysis of porosity evolution in a bonded assembly under tensile-shear stress by X-ray mictrotomography. *Scientific Bulletin Automotive, Volume 33*

[7] Joining Innovation with Expertise - TWI. (accessed on 12 February 2025) Failure Investigation of Welded Moulded Plastic Components – TWI.

[8] Buffiere, J.Y., Maire, E., Adrien, J., Masse, J.-P., Boller, E. (2010). *In Situ* Experiments with X ray Tomography: an Attractive Tool for Experimental Mechanics. *Exp Mech* 50, 289–305, https://doi.org/10.1007/s11340-010-9333-7

[9] A.C. Kak, M. Slaney. (2001). Principles of Computerized Tomographic Imaging, SIAM.