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Optimization of spin welding parameters for reliable automotive fluid transfer assemblies

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Abstract. Ensuring the integrity of thermoplastic tube–connector joints is essential for the reliability and safety of automotive fluid transfer systems. This work focuses on defining and optimizing spin welding parameters to minimize defect occurrence and guarantee consistent joint quality. A Design of Experiments (DOE) approach was applied on a Mecasonic 72 horizontal welding machine, testing 20 parameter sets across 200 assemblies. Results showed that only 25% of the initial parameter sets fulfilled all acceptance criteria, underlining the narrowness of the unoptimized process window. To address this, Taguchi's loss function was combined with statistical capability studies (Cp, Cpk) performed on 100 production samples, leading to optimized parameter ranges with tolerance intervals reduced by nearly 40%. The optimized process demonstrated high robustness, with capability indices significantly above automotive requirements (Cpk ≥ 1.67). Validation through tensile pull-out tests, leak testing, and light microscopy confirmed the elimination of defects such as incomplete fusion, excessive flash, and cracks. The proposed framework provides a reliable methodology for achieving defect-free spin-welded joints, offering both statistical rigor and industrial feasibility for large-scale automotive production.
Keywords: Spin Welding, thermoplastic welding, process optimization, Design of Experiments, statistical process control, automotive fluid transfer.

INTRODUCTION

The use of thermoplastic tubing for fluid transfer systems in the automotive industry has become increasingly prevalent due to its lightweight properties, chemical resistance, and flexibility in design and manufacturing. These systems are widely employed in critical applications such as fuel delivery, brake assistance, vapor recovery, AdBlue transfer, and cooling/heating loops. In such applications, especially those located in the engine compartment, joint integrity is safety-critical, as failures may result in leakage, loss of functionality, or hazardous operating conditions.

Among the joining methods available, Spin Welding (SW) has emerged as a robust solid-state process capable of ensuring high tensile strength, sealing integrity, and full process traceability. The process relies on frictional heating generated by the rotational motion between a connector and a thermoplastic tube under axial pressure, followed by consolidation during cooling. Compared with conventional insertion or O-ring based assemblies, SW offers superior robustness against high pressures (up to 10 bar) and thermal variations in automotive environments [1-3].

A limitation of SW is that the weld interface is located internally, making direct optical inspection impractical. In a previous study [1], we addressed this challenge by investigating defect detection and characterization in spin-welded assemblies. Using a combination of microscopy, X-ray computed tomography [4], leak testing, and mechanical pull-out tests, common defect types were identified –

including flash formation, incomplete fusion, porosity, and interface cracks – and their correlation with deviations in welding parameters was established [1].

While this work provided the necessary diagnostic framework, it also revealed that process optimization is essential to minimizing or eliminating defect occurrence.

Building on these findings, the present study focuses on optimizing process parameters for spin-welded assemblies used in automotive fluid transfer systems. Using a Design of Experiments (DOE) approach [5], followed by process capability studies [6], we establish optimized parameter windows for production. Furthermore, a simplified validation methodology is proposed for series production, combining tensile and leak testing with basic microscopy, thus balancing accuracy, cost, and industrial feasibility.

The objectives of this article are therefore threefold:

- To define and validate an initial process window for spin welding using DOE.
- To optimize process parameters and tolerance limits through statistical capability analysis.
- To propose a simplified characterization method suitable for large-scale automotive production.

Through this approach, we aim to demonstrate that defect minimization in SW assemblies can be systematically achieved by combining parameter optimization with targeted quality assurance techniques, thus increasing process robustness in safety-critical automotive applications.

EXPERIMENTAL FRAMEWORK AND INITIAL PROCESS WINDOW

The assemblies investigated in this study consist of multilayer polyamide tubes joined with injection-molded thermoplastic connectors. The multilayer tube used here consists, from the outside to the inside, of a layer of polyamide 12 (PA12), a layer of adhesive, a layer of ethylen vinyl Alcohol (EVOH) and a layer of polyamid 6 (PA6) [1]. The assembly is made between components manufactured from the same family of polymers. The connectors were specifically designed with a cylindrical joining zone, ensuring full circumferential contact with the tube during the welding process (Figure 1).

Spin welding is the chosen joining process for these components. In SW, the connector is rotated at high speed while the tube remains stationary under axial force. Frictional heating at the interface softens the material, enabling intermolecular diffusion. Once the target displacement and heat input are reached, rotation is stopped and axial pressure is maintained to consolidate the joint.

A properly executed weld between the tube and connector is characterized by a continuous circumferential joint with no gaps, cracks, or incomplete fusion in the weld area marked in red in Figure 1. The weld is considered incorrect if the weld is not complete between the outer surface of the tube and the connector in the weld area marked in red over a length of ~6 mm. The presence of a uniform burr of material at the tube-connector interface indicates adequate flow and consolidation, while excessive burrs or irregular accumulations indicate an energy imbalance. Functionally, a solid weld must withstand axial pull-out forces and high internal pressures without leakage.

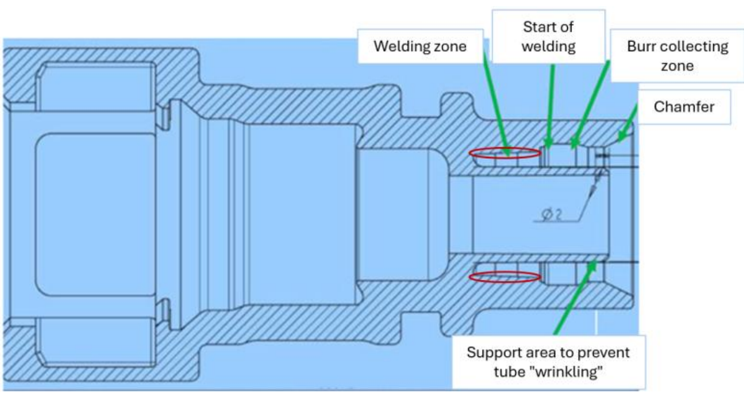


Figure 1. Representation of the spin weld area in a longitudinal section in the connector

The experimental investigations were performed on a Mecasonic 72 horizontal spin welding machine (Figure 2), equipped with a brushless electric motor and a pneumatic cylinder. The connectors were mounted in titanium holders to minimize deformation, while process control and data acquisition were managed by Mecawin software, enabling precise parameter adjustment and full traceability.

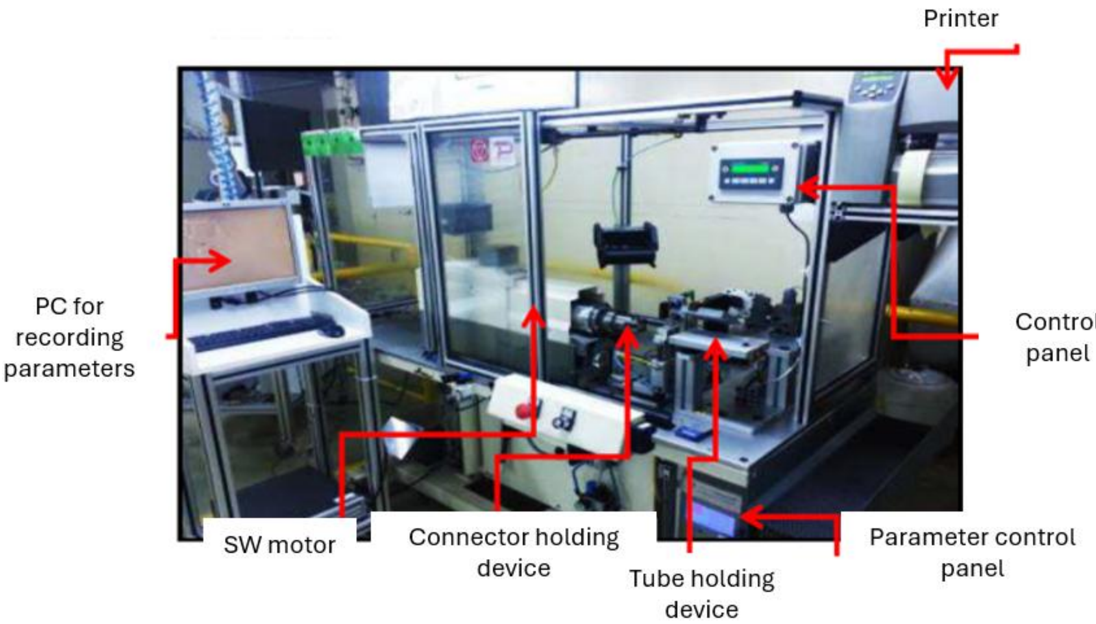


Figure 2. Mecasonic 72 spin welding machine

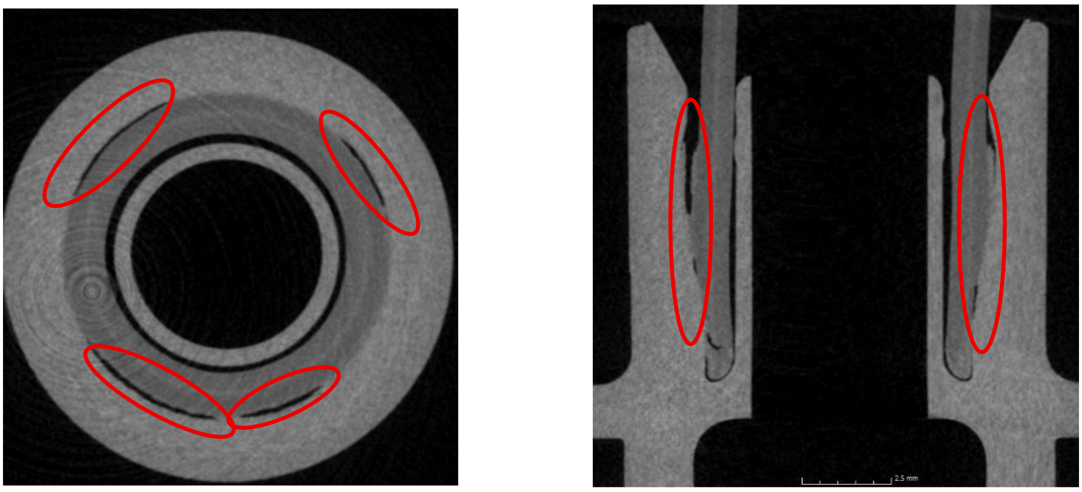
The Design of Experiments (DOE) methodology was applied to establish the initial process window. Twenty different parameter sets were tested, each on 10 assemblies, for a total of 200 samples. The analysis focused on five main process variables: welding time, total displacement, displacement to the "zero" point, welding displacement, and energy input.

Acceptance criteria included external appearance, microscopic evaluation, sealing integrity, and tensile pull-out strength. Results showed that only 25% of the parameter sets produced assemblies fulfilling all requirements, confirming that the unoptimized process window is narrow and prone to generating non-conforming parts.

One of the most frequent rejection causes was excessive flash or molten material accumulation at the tube exit, symptomatic of excessive energy input. Conversely, insufficient heat input caused irregular fusion or discontinuities at the weld interface. Microscopic analysis (bright field imaging at 5×–30× magnification) offered further insight into weld morphology. While it could confirm uniformity and continuity at localized cross-sections, this destructive method could only evaluate selected regions of the circumference, leaving undetected zones where discontinuities might occur.

To overcome this limitation, X-ray microtomography (CT) was employed [7], providing non-destructive, three-dimensional visualization of the entire weld circumference. CT scanning revealed defects that were missed by both visual inspection and microscopy, most critically incomplete circumferential fusion (Figure 3). These defects, though not always visible externally, represent a severe risk for leakage in service.

The decisive advantage of CT was its ability to map the weld zone continuously over 360°, highlighting that some samples apparently conforming by visual and microscopic criteria were in fact defective. This finding demonstrated that parameter optimization was indispensable: without it, defective parts could be produced undetected by conventional inspection methods. Interested readers can find more details about these analyses in our previous article [1].



a. Transverse section b. Longitudinal section

Figure 3. Example of incomplete circumferential fusion in assembley detected by CT scan

PROCESS OPTIMIZATION AND CAPABILITY STUDY

From Mecawin parameters to relevant variables

The Mecawin software used with the Mecasonic 72 spin welding machine provides an extensive set of controllable and monitored parameters (Figure 4).

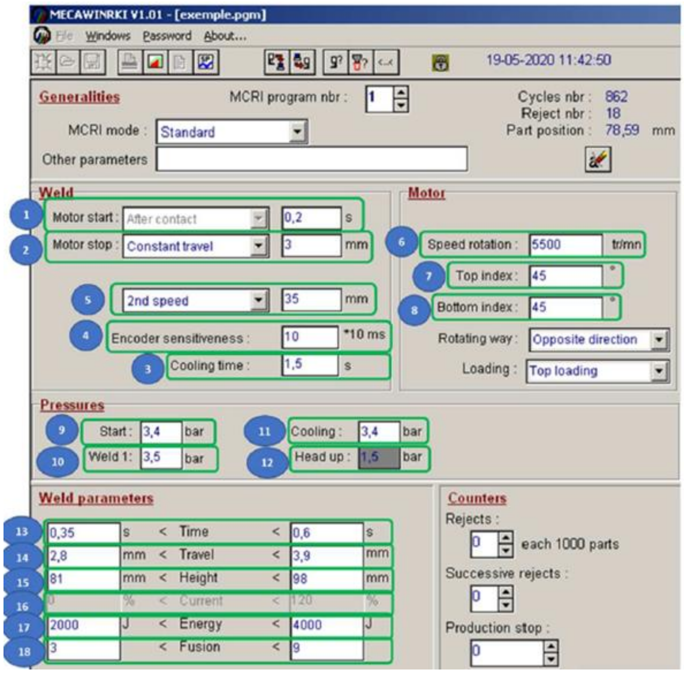


Figure 4. Mecawin process parameter interface – Relevant parameters: 1. The gap between the point where the two components come into contact and the start of the rotational movement; 2. The point at which the rotational movement stops; 3. Cooling time; 4. Parameter on which the accuracy of the weld starting 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; [1]

The set of parameters include rotational speed, axial force, welding time, displacements, energy input, and auxiliary cycle settings. While this list is comprehensive, practical investigations have shown that only a subset of variables decisively influence weld integrity:

- Welding time
- Total translation
- Zero-point translation (initial contact reference)
- Welding distance (effective material flow distance)
- Energy input

These parameters were therefore selected as the focus of the optimization study, while the remaining ones were kept constant at nominal values.

Defining initial parameters

In automotive safety-critical assemblies, it is insufficient to remain merely "within specification." To formalize this principle, the Taguchi quality loss function [8] was applied (Figure 5). According to Taguchi, any deviation from the nominal target produces incremental quality loss, even if the part is technically compliant.

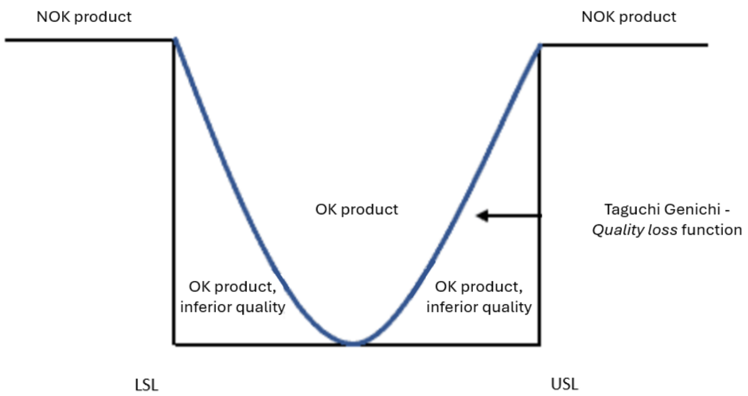


Figure 5. Taguchi quality loss function applied to spin welding parameters

This has been the guiding principle in interpreting the DOE results. Out of 20 parameter sets tested (200 assemblies), only 25% met all customer acceptance criteria. However, applying the Taguchi principle meant that even within this subset, not all sets were equally safe. From five apparently conforming sets, three were retained as robust candidates to define the initial process window, as illustrated in Figure 6. In this way, theoretically, the risk of a NOK part being delivered to the customer is eliminated because even parts that fall outside the control limits still fall within the limits imposed by the customer.

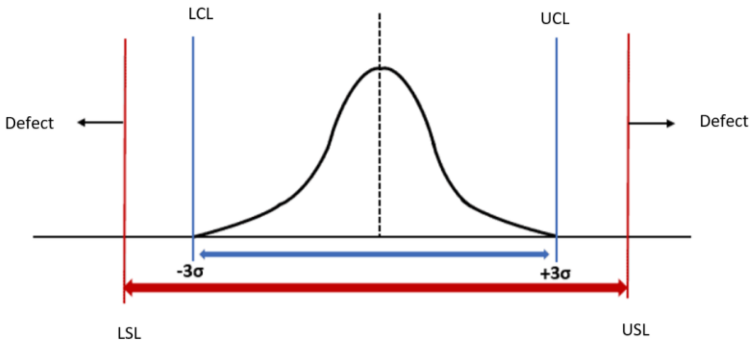


Figure 6. Initial process control limits defined

The retained sets corresponded to three parameter conditions – slightly sub-nominal (N−1) – Table 1, nominal (N) – Table 2, and slightly supra-nominal (N+1) – Table 3. Acceptance criteria were divided into two categories:

- Product characteristics: sample number, external appearance, appearance of the weld zone, leak test result and tensile pull-out strength.
- Key process characteristics: welding time, total displacement, zero-point displacement, welding displacement and energy input.

Table 1. *N-1* result set

	Sample number	1	2	3	4	5	6	7	8	9	10
Product characteristics	External appearance	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Appearance of the weld zone	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Leak test result	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Tensile pull-out strength [N]	863.791	879.601	872.616	857.526	861.527	880.616	859.673	859.149	863.272	873.568
Key process characteristics	Welding time [s]	0.61	0.62	0.62	0.61	0.61	0.62	0.62	0.62	0.61	0.62
	Total translation [mm]	83.02	83.02	83.02	83.03	83.03	83.01	83.03	83.02	83.02	83.02
	Translation to point 0 [mm]	78.81	78.81	78.81	78.80	78.81	78.80	78.80	78.81	78.81	78.81
	Welding distance [mm]	4.23	4.21	4.21	4.23	4.22	4.21	4.23	4.21	4.21	4.21
	Energy input [J]	2238	2247	2245	2231	2248	2243	2236	2239	2249	2232
Error message		No errors									

Table 2. *N* result set

	Sample number	1	2	3	4	5	6	7	8	9	10
Product characteristics	External appearance	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Appearance of the weld zone	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Leak test result	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Tensile pull-out strength [N]	866.191	851.075	843.71	871.209	875.179	840.845	880.727	883.977	861.728	879.192
Key process characteristics	Welding time [s]	0.67	0.68	0.68	0.68	0.68	0.67	0.68	0.68	0.68	0.67
	Total translation [mm]	83.24	83.23	83.24	83.23	83.22	83.23	83.24	83.25	83.23	83.24
	Translation to point 0 [mm]	78.80	78.80	78.81	78.81	78.80	78.80	78.81	78.81	78.80	78.81
	Welding displacement [mm]	4.44	4.43	4.43	4.42	4.42	4.43	4.43	4.44	4.43	4.43
	Energy input [J]	2387	2395	2400	2406	2399	2401	2405	2400	2397	2395
Error message		No errors									

Table 3. *N+1* result set

	Sample number	1	2	3	4	5	6	7	8	9	10
Product characteristics	External appearance	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Appearance of the weld zone	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Leak test result	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Tensile pull-out strength [N]	806.917	832.003	832.773	828.702	802.461	817.662	829.359	827.954	825.411	851.352
Key process characteristics	Welding time [s]	0.77	0.77	0.77	0.78	0.78	0.78	0.77	0.77	0.78	0.78
	Total translation [mm]	83.51	83.49	83.50	83.50	83.50	83.49	83.49	83.50	83.50	83.50
	Translation to point 0 [mm]	78.81	78.80	78.81	78.81	78.80	78.80	78.80	78.81	78.80	78.81
	Welding displacement [mm]	4.70	4.69	4.69	4.69	4.70	4.69	4.69	4.69	4.70	4.69
	Energy input [J]	2690	2703	2709	2753	2761	2748	2705	2699	2761	2753
Error message		No errors									

Based on the comparative analysis of these three sets, Table 4 defined the preliminary control limits for each key process variable. Rather than adopting the broad customer specification ranges, the study introduced narrower limits (LCL/UCL) derived from the performance of the three conforming sets. This adjustment effectively excluded borderline regions where hidden defects had been identified.

This decision effectively reduced the process window by ~40%, eliminating borderline regions where hidden defects were detected.

Table 4. Initial process parameter ranges

Process parameter		Data
Welding time [s]	LCL	0.61
	UCL	0.78
Total translation [mm]	LCL	83.01
	UCL	83.51
Translation to point 0 [mm]	LCL	78.80
	UCL	78.81
Welding distance [mm]	LCL	4.21
	UCL	4.7
Energy input [J]	LCL	2232
	UCL	2761

Optimized process parameters

Once the initial "responsible" process window had been defined from DOE results, the next step was to verify its robustness under real production conditions. For this purpose, a capability study was performed on 100 assemblies, produced using tubes and connectors originating from different material batches. This ensured that the natural variability of raw materials was reflected in the process evaluation.

The statistical analysis focused primarily on welding displacement, a representative parameter that directly reflects material flow and heat generation. Data were analyzed using Minitab statistical software, producing both simple capability indices and a comprehensive Six Pack analysis.

The capability histogram (Figure 7) showed that all 100 measured values were within tolerance limits, with the process mean slightly shifted toward the lower specification limit (LSL). Even with this small offset, capability indices were excellent: Cp = 3.25 and Cpk = 2.96, far exceeding the minimum requirement of Cpk ≥ 1.67 imposed for safety-critical automotive parts. This indicated that the natural spread of the process was more than three times smaller than the tolerance window, confirming a very low probability of nonconforming assemblies.

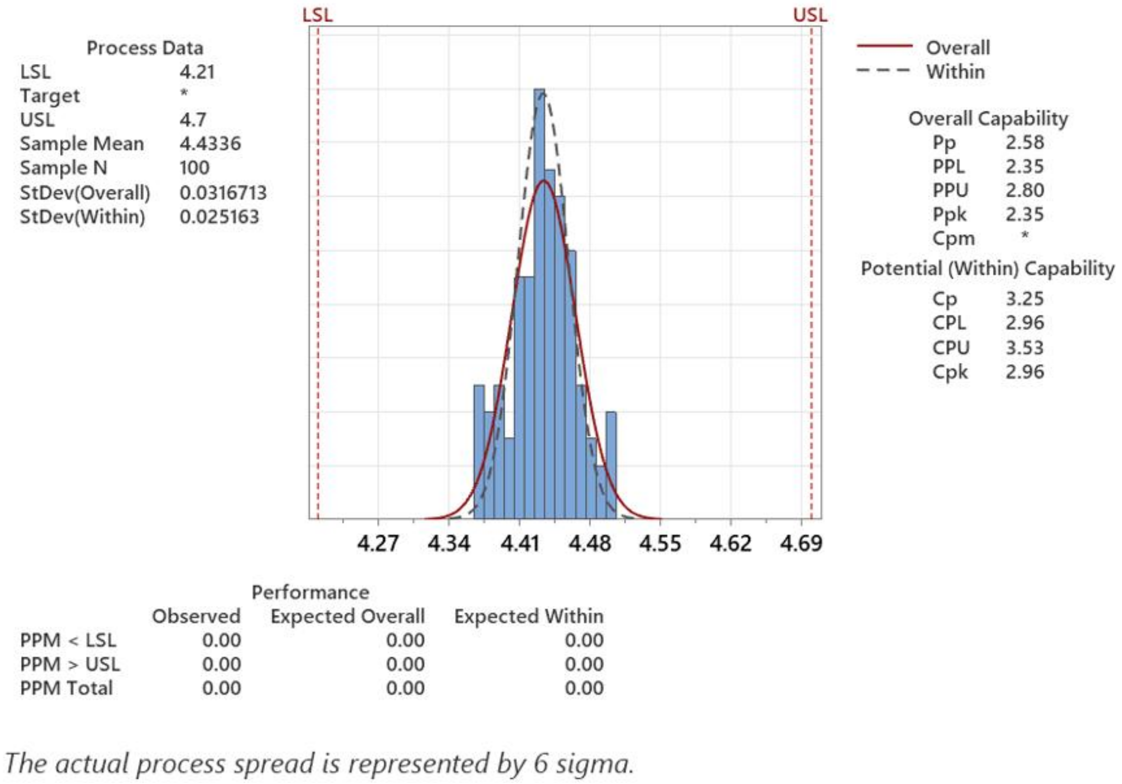


Figure 7. Process Capability histogram and Cp/Cpk indices for welding displacement

The Six Pack analysis (Figure 8) provided further confirmation of process stability. Individual and moving range charts demonstrated statistical control with no out-of-control points. The "last 25 observations” plot indicated random, well-distributed data around the mean. The normal probability plot confirmed approximate normality, while the capability histogram again emphasized that process values were comfortably inside the tightened specification limits. Importantly, the Six Pack allowed recalculation of practical control limits: the upper control limit (UCL) was changed from 4.70 mm to 4.55 mm, and the lower control limit (LCL) from 4.21 mm to 4.30 mm. This narrowing ensured centering of the process well away from risky boundary regions.

Although Figures 8 and 9 illustrate only the case of welding displacement, the same capability study was systematically performed for all other key process variables:

- Welding time,
- Total displacement,
- Zero-point displacement,
- Welding energy.

For each of these parameters, Cp/Cpk indices confirmed that the process was statistically capable, and Six Pack analyses validated stability and approximate normality. In every case, tolerance ranges were tightened following the same logic as for welding displacement, progressively reducing the acceptance intervals while keeping the process centered.

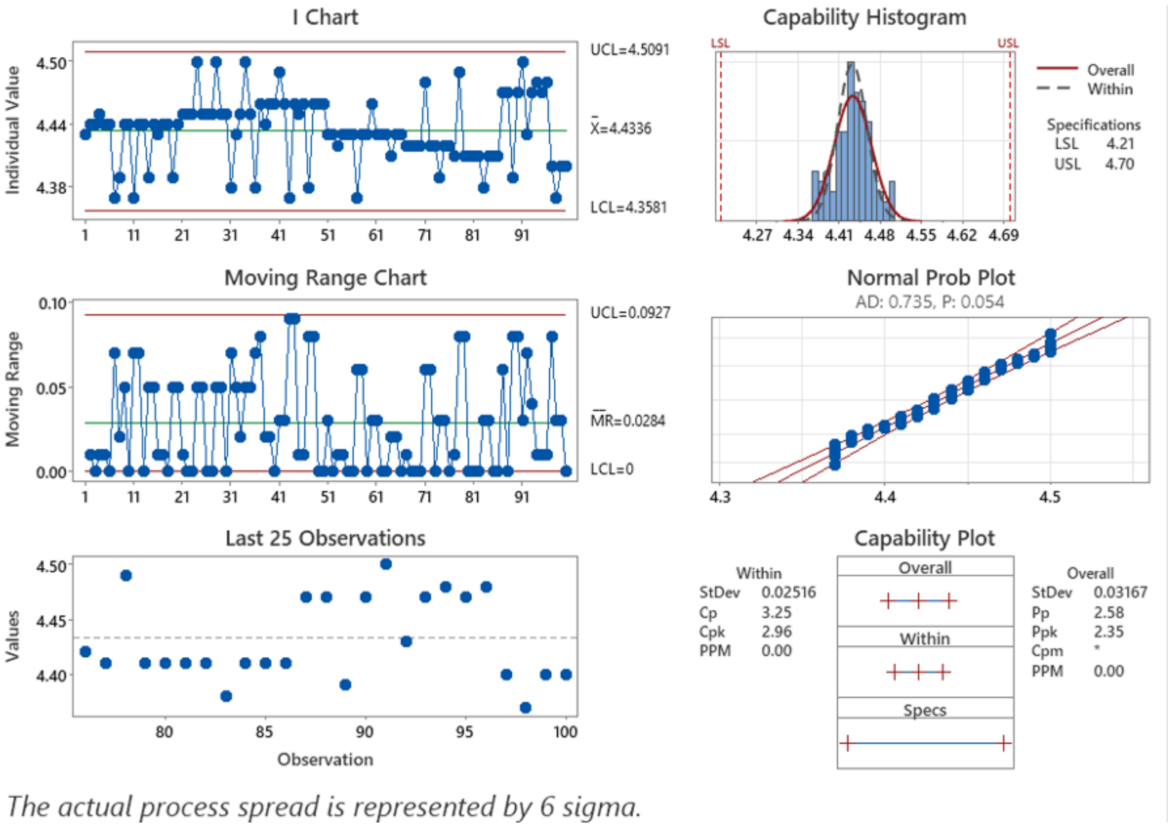


Figure 8. Process Capability Six Pack report for welding displacement

The results of this statistical evaluation were documented in Tables 5 and 6, which highlight how the process window was tightened step by step.

Table 5 shows the parameters optimized after the capability study. Based on Cp/Cpk values, the control limits for each key process variable (welding time, total displacement, zero-point displacement, welding displacement, and energy input) were further narrowed and centered. For example, the welding distance limits were tightened from 4.21–4.70 mm to 4.30–4.55 mm, ensuring process centering far from risky margins.

Table 5. Optimized process parameter ranges

Process parameter		Data
Welding time [s]	LCL	0.63
	UCL	0.75
Total translation [mm]	LCL	83.10
	UCL	83.36
Translation to point 0 [mm]	LCL	78.80
	UCL	78.81
Welding distance [mm]	LCL	4.3
	UCL	4.55
Energy input [J]	LCL	2250
	UCL	2625

In Table 6, a comparison is made between the initial and optimized limits. This table quantified the degree of refinement, making explicit the reduction of tolerance ranges for each parameter. Such documentation is crucial for quality monitoring, providing clear baseline thresholds to detect drift or decide when re-validation is necessary.

The outcome of this sequential tightening was a robust, statistically validated process window, significantly more reliable than the initial customer specification. Importantly, this refinement minimized the risk of borderline assemblies – parts that might pass functional tests but fail under service conditions.

Table 6. Initial parameters/optimized parameters comparison

Process parameter	Data
Welding time [%]	-29.4
Total translation [%]	-48.0
Translation to point 0 [%]	NA
Welding distance [%]	-49.0
Energy input [%]	-29.1

Finally, confirmation of the final optimization of these parameters was achieved through simplified inspection methods—such as tensile testing, leak testing, and bright field microscopy—and through X-ray microtomography (CT) as the decisive reference method.Its contribution was twofold:

- CT revealed the hidden defects (particularly incomplete circumferential fusion) that forced the narrowing of the initial window.
- CT later confirmed that assemblies produced under the optimized ranges (Table 6) were free of such defects, even when natural batch-to-batch variability was included.

Thus, CT validation was essential for identifying the problem and for proving that the solution was effective.

PRACTICAL VALIDATION IN SERIES PRODUCTION

Once the process parameters had been optimized and statistically validated, the next step was to confirm their robustness under real production conditions. For large-scale industrial application, quality assurance must balance technical accuracy with cost and time efficiency. While CT scanning provided the most complete defect characterization, its high cost and long acquisition time make it impractical for routine series inspections. Therefore, a simplified validation methodology was established, relying on three complementary techniques in addition to the visual inspection mentioned above: tensile testing, leak testing, and bright field microscopy.

Tensile Pre-Leak Testing

The first step in validation was the tensile pull-out test (Figure 9), to ensure mechanical integrity of the joint. Assemblies were subjected to an axial force of 300 N, representative of the maximum stresses encountered in automotive fluid transfer systems during assembly and service. The pull-off test was performed on an Instron 3369 tensile testing machine with a 5000 N load cell. The tests are performed at ambient temperature of 23˚C at a speed of 100 mm/minute until breakage. The samples have a tube length of 110 mm. Passing this test with a cohesive failure (i.e., a failure in the material of the components and not in the weld area) and not an adhesive failure (i.e., in the weld area) confirmed that the weld provided sufficient structural anchorage between the tube and the connector.

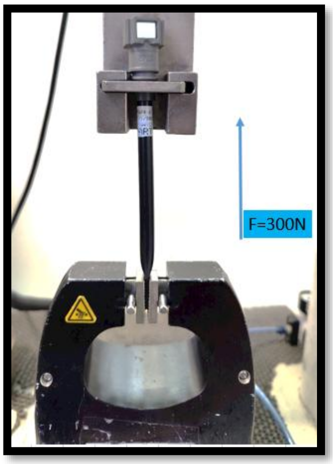


Figura 9. Tensile pull-out test of spin-welded assemblies

The results demonstrated that assemblies produced within the optimized parameter window consistently withstood the 300 N load without failure. This provided a first confirmation that the narrowing of limits translated into improved mechanical robustness.

Leak Testing Under Pressure

Following the tensile check, assemblies were subjected to a leak test at 10 bar by immersing them in water and applying internal air pressure. This method simulated real service conditions, where the assemblies are exposed to high internal pressures of fuel, AdBlue, or cooling fluids [9].

All samples tested under the optimized process parameters successfully passed the leak test, showing no bubble formation during the test period. This confirmed the sealing capability of the joints and validated that incomplete fusion defects, which had previously been identified only by CT, were now effectively eliminated.

Microscopic Bright Field Examination

To complement mechanical and functional tests, bright field microscopy was applied to selected cross-sections of welded assemblies. This method, while destructive, is simpler and faster than CT scanning, making it suitable for occasional validation during production runs.

The samples for this test are cut using a Presi Mecatome T202 (Figure 10) cutting machine equipped with a Presi UTW Ø200 cutting wheel operating at 400 rpm. This produces a clean and controlled cut through the welded area, suitable for microscopy.

a. Presi Mecatome T202

b. Sectioned sample

Figure 10. Longitudinal sectioning of samples

The cut analysis surface is then polished using a Minitech 250 SP1 - Presi machine (Figure 11) equipped with an abrasive disc at a speed of 300 rpm. Polishing is carried out in four stages, gradually reducing the size of the abrasive grains to obtain a flat, reflective surface without marks:

– M P600 abrasive disc;

– M P1200 abrasive disc;

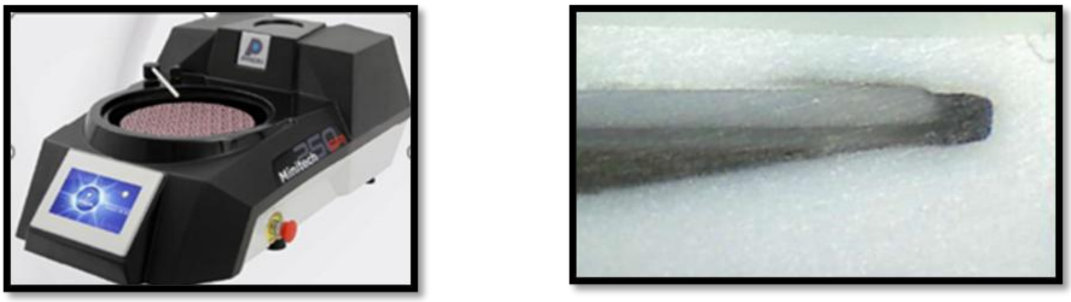
– M P2300 abrasive disc;

– RAM cloth + alumina (final polishing).

With this preparation protocol, bright field observations can be performed in this study at 5× to 30× magnification, as needed.

The combined use of visual inspection, tensile testing, leak testing, and bright field microscopy offered a practical yet reliable validation methodology for production environments. While less comprehensive than CT scanning, this combination effectively ensured that assemblies produced with optimized parameters met both mechanical and sealing requirements. Moreover, by integrating microscopic checks at controlled intervals, the method provided sufficient sensitivity to detect potential deviations in process performance.

Through this validation stage, it was confirmed that the optimized parameter window (Table 6) is statistically robust and practically reliable in series production. The simplified validation method thus offers an industrially feasible alternative to CT, maintaining high confidence in joint integrity while significantly reducing inspection time and cost.



a. Minitech 250 SP1 - Presi b. Surface prepared for microscopic analysis

Figure 11. Polishing of samples

CONCLUSIONS AND PERSPECTIVES

This study has shown that achieving defect-free spin-welded assemblies in automotive fluid transfer systems requires both precise joining equipment and a carefully optimized and statistically validated process window. The experimental and statistical investigations carried out here demonstrated that welding time, displacement, and energy input are the most critical parameters influencing joint quality.

Initial DOE results confirmed that wide parameter ranges permitted by client specifications were insufficient to guarantee reliability. While many assemblies passed visual, microscopic, and functional tests, X-ray microtomography (CT) revealed incomplete circumferential fusion in certain cases – defects that would remain undetected in a production environment. This finding provided the rationale for systematically narrowing the process window and applying stricter statistical control.

By combining Taguchi's loss function with capability studies on 100 assemblies from different material batches, the process window was reduced by nearly 40% compared with the initial specification. Statistical indices (Cp and Cpk well above 1.67) confirmed that the optimized process was not only capable but also robust across material variability. The sequential refinement of parameters was documented, from DOE-based selection to optimized limits, ensuring that production variability remained far from regions prone to defects.

A further outcome of this study was the development of a practical validation strategy for industrial deployment. While CT scans remain the most reliable diagnostic tool, their cost and duration preclude routine use. Instead, a combination of tensile pull-out testing, leak testing under pressure, and bright field microscopy in addition to the visual inspection provided an efficient yet reliable alternative for monitoring series production. Assemblies produced under optimized conditions consistently demonstrated mechanical robustness, leak-tightness, and structural continuity of the weld interface.

The perspectives opened by this work extend beyond the immediate application. The methodology presented here – integrating DOE, advanced defect detection, statistical capability analysis, and pragmatic validation techniques – can be transferred to other thermoplastic joining processes facing similar challenges. In particular, industries dealing with safety-critical fluid systems can adopt this framework to enhance process robustness, reduce hidden defect risks, and establish reliable, cost-effective quality control strategies.

In conclusion, the study has achieved three major contributions:

- Established the limits of conventional inspection methods and highlighted the decisive role of computed tomography in identifying hidden defects in the spin welds of the studied assembly;
- Defined and statistically validated an optimized process window, narrowing parameter ranges to ensure robustness and reproducibility;
- Proposed a simplified but effective validation methodology for series production, enabling industrial implementation without compromising safety.

By integrating defect detection, parameter optimization, and practical validation, this research provides a comprehensive framework for ensuring the long-term integrity of spin-welded assemblies in automotive fluid transfer systems. Future work will focus on extending this methodology to other thermoplastic materials and geometries, and on exploring in-line non-destructive evaluation methods that could further reduce reliance on destructive sampling while maintaining defect detection capability.

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