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Evaluación de la integridad de soldaduras en secciones huecas: sensibilidad, y factores humanos
Assessing weld integrity of hollow structures: sensitivity and human factors

Alejandro Martínez Gordon; Fernando Israel Olmedo; Tomás Prieto Gómez; Alberto Leal Matilla

Departamento de Tecnología de la Edificación. E.T.S de Edificación. Universidad Politécnica de Madrid.
alejandro.mgordon@upm.es

Resumen—**Este trabajo evalúa un caso de estudio enfocado en la fabricación y control de calidad de elementos tubulares metálicos destinados a la edificación, centrándose en la detección de defectos para prevenir corrosión y fallos inesperados en servicio. A lo largo de 15 lotes de producción, se emplearon métodos como inspección visual, corrientes inducidas, análisis mecánicos y prueba de fugas. Los defectos se concentraron especialmente en la soldadura TIG, fusión incompleta (más común) y grietas, con tamaño medio de 4.523 ± 1.5 mm. Las pruebas de fugas detectaron fallas transversales de hasta 0.127 mm, superando el límite de 0.508 mm de las corrientes inducidas. Por su parte, los análisis mecánicos confirmaron cumplimiento con las especificaciones del fabricante en todo momento, presentando un límite elástico promedio de 958 ± 21 MPa, una ductilidad de 7 ± 1 % y una dureza HRC de 30 ± 2. Por tanto, se recomienda enfatizar la capacitación de operadores y habilitar mantenimientos preventivos que fortalezcan la calidad para productos destinados a la edificación.**

Palabras clave— Incoloy 825; defectos, ensayos no-destructivos; soldadura TIG; control de calidad.

Abstract— **This paper focused on the manufacturing and quality control of tubular metal elements destined for building practices, centered on early defect detection to prevent corrosion and unexpected in-service failures. Throughout 15 production batches, methods such as visual inspection, eddy current testing, mechanical analysis, and pressure leak testing were employed. Defects were particularly located in the TIG welding, incomplete fusion (the most common), and cracks, with an average size of 4.523 ± 1.5 mm. Leak testing detected transverse flaws as small as 0.127 mm, exceeding the eddy current limit of 0.508 mm. Furthermore, mechanical analyses confirmed compliance with the manufacturer's specifications at all times, presenting an average yield strength of 958 ± 21 MPa, a ductility of 7 ± 1% and an HRC hardness of 30 ± 2. Therefore, as corrective measures, more emphasize in operator training as well as enabling preventive maintenance would increase the quality of products intended for these constructive elements.**

Index Terms— Incoloy 825, defects, non-destructive-testing, TIG welding, quality control.

I. INTRODUCTION

THE manufacture and quality assurance of welded hollow metallic elements destined for building practices (e.g., structural tubing, protective casings, service ducts and conduit sleeves) demands sensitive, reliable inspection methods and robust maintenance to avoid in-service leakage, corrosion and premature failure. These hollow elements serve a wide range of roles in the built environment: they act as structural members, protective envelopes for services, conduits for utilities, and barriers against environmental aggressors. Given that these components often perform critical functions—bearing load, protecting electrical or mechanical services, or preventing ingress of moisture and contaminants—the integrity of their weld zones is fundamental to both performance and safety. Failure to detect small weld discontinuities can lead to costly remedial works, accelerated corrosion, and in extreme cases, structural compromise (Olson & Davis, 2006).

Professors at Departamento de Tecnología de la Edificación at Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, (Spain).

TIG welding, shown in Fig 1, is the dominant method for fabricating tubular components and fittings used in construction. While modern welding techniques and qualified welding procedures produce joints with acceptable bulk mechanical properties, localized defects are inevitable in any production environment (Olson & Davis, 2006), (Deepak, Bupesh Raja, & Srikanth, 2021). Typical discontinuities found in welded tubular members include lack-of-fusion or lack-of-penetration, porosity, slag inclusion, undercut, and cracking. Among these, incomplete fusion and small through-wall perforations are particularly insidious in thin-walled tubes because they can be difficult to detect visually yet permit fluid ingress or create corrosion initiation sites (Meola, Squillace, Minutolo, & Morace, 2004). Crack-type defects, while less frequent, are the most likely to produce catastrophic consequences if left unaddressed, particularly under cyclic loading or in aggressive environments (Ong, Eng, & Noroozi, 2016).

Given this context, non-destructive testing (NDT) forms the backbone of an effective quality assurance regime. NDT methods differ in the physical principle exploited, whether electromagnetic, acoustic, optical, or hydraulic, and how they are applied (Groysman, 2019). Surface and near-surface techniques such as visual inspection or eddy-current scanning offer rapid, low-setup inspection of weld seams and can flag areas of probable lack-of-fusion, surface cracks, or significant material thinning (Ahmad & J. Bond, 2018). Volumetric methods like ultrasonic testing (UT) and radiographic testing (RT) are better suited to detect internal flaws and provide information on flaw depth and orientation, but usually require more operator skill and setup (Meyendorf, Ida, Singh, & Vrana, 2025). On the other hand, leak or pressure testing (hydrostatic or pneumatic) it is highly sensitive to even very small through-thickness perforations and therefore particularly relevant when the tubular element must act as a fluid barrier or protective enclosure (Ahmad & J. Bond, 2018).

Mechanical testing—tensile tests, hardness measurements, and metallographic cross-sections—remains an indispensable complement to NDT because it verifies the metallurgical integrity and mechanical properties of the base material and weld metal (Meola, Squillace, Minutolo, & Morace, 2004). However, they are unable to act as a substitute for sensitive NDT methods that screen every item for localized discontinuities. Consequently, a hybrid approach that includes rapid in process screening, targeted inspection, destructive verification on representative samples, combined with a final leak testing required, delivers the best balance between cost, throughput and safety assurance (Santos, Monteiro, & Santos, 2023).

Corrective maintenance and repair strategies are equally important in optimizing quality control. The act of detecting a defect is only the start: effective follow-through requires clear, documented repair procedures, re-inspection protocols, and traceable records that link weld parameters, inspection results and repair activities. Repairs must be validated by the same or more sensitive inspection techniques used for acceptance to confirm defect remediation. When well-executed, corrective maintenance minimizes site rework, reduces exposure to moisture and contaminants, and lowers the probability of latent field failures (Quintana, Leung, & Rene Villalobos, 2009).

Human factors materially influence the overall reliability of inspection regimes. The sensitivity and repeatability of any NDT method are closely tied to operator competence, procedural fidelity, and the existence of independent verification or escalation pathways.

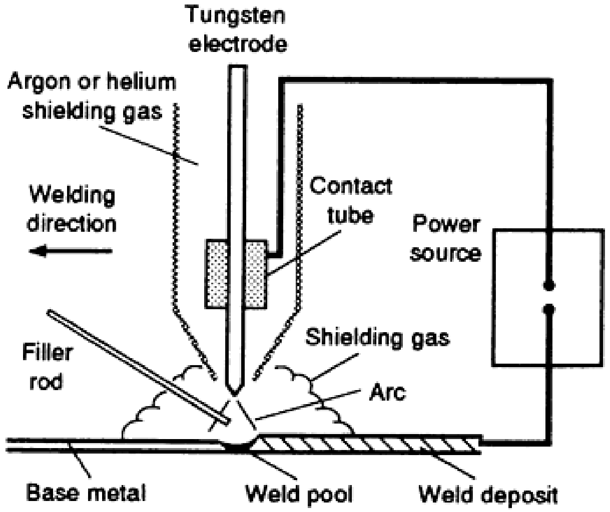


Fig. 1. Schematic of a TIG welding process.

In practice, false negatives often arise not from method limitations but from inconsistent scanning technique, poor equipment calibration, inadequate procedure, or production pressures that limit inspection time. Focused training, certified technician programs, standard operating procedures, digital recording of inspection data, and “stop-the-line” authority for inspectors are therefore essential interventions to reduce human-error driven risk (Quintana, Leung, & Rene Villalobos, 2009).

This study presents a focused case study that quantifies defect types and sizes encountered in welded tubular production, destined for building practices, evaluating the comparative detection limits and practical trade-offs of eddy-current scanning and pressure/leak testing, and examining how corrective maintenance and human oversight influence manufacturing quality and downstream lifecycle risk. The findings were used to propose corrective measures intended to make welded tubular elements more reliable, durable and safe in service.

II. MATERIALS AND METHODS

A. *Methodology*

To achieve the proposed objectives, the following stages were devised: determining manufacturing defects, verifying compliance with specifications, and finally, determining the effectiveness of the techniques implemented in this case study to detect discontinuities, as seen in Fig 2.

A series of tubular samples were obtained from a strip of commercial Incoloy 825® alloy (UNS08825) with dimensions of 22 x 0.750 mm, as well as a chemical composition in accordance with ASTM B-704, and a density of 8.14 g/ml, as reported by the manufacturer Special Metals (Germany).

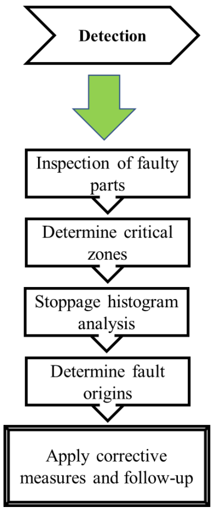


Fig. 2. Flow chart of stages and steps implemented.

A total of twenty-five pieces rejected by the manufacturer and six tubular samples measuring 130 mm were used to study the defects present in those pieces and to perform quality control tests for welded tubes (two per test) by means of macro lens inspection. In addition, forty-five tubular samples measuring 251 mm, three from each of the fifteen batches used by the company during this project, were employed to verify the hardness of the components.

Furthermore, forty-five tubular specimens measuring 203 mm, three from each of the fifteen batches, were prepared to evaluate the mechanical properties through tensile tests. Lastly, five tubular samples also measuring 203 mm were used to compare the effectiveness of discontinuity detection between leakage tests and eddy current tests. All tubular samples presented a hollow structure with an outer diameter of 6.35 mm and an inner diameter of 0.889 mm (wall thickness).

Plant staff was interviewed and reports of failed production runs collected. To identify critical areas as well as the geometry and location of the most common defects, defective parts were inspected using a MEIJI TECHNO® EMZ-13TR macrolens and Motic Images 2.0 ML software. Based on this information, a failure histogram was generated from early 2014 to late 2015, classifying defect types and their causes. Quality control tests such as flattening, flaring, and flange formation were also evaluated, and corrective measures were established to ensure product integrity and operational continuity.

Subsequently, compliance with mechanical specifications was verified through tensile and hardness tests. Fifteen production batches were studied, from which tubular specimens were extracted for tensile tests using a Tinius Olsen® 50ST universal testing machine at constant strain rate, reporting elasticity modulus, tensile strength, and yield strength. In addition, forty-five tubular samples were analyzed with a Mitutoyo HR-500 durometer to determine hardness (HRC).

Finally, the sensitivity of eddy current testing and leakage tests for defect detection was evaluated. Incoloy 825® samples with controlled laser-drilled holes were prepared and tested with a PRÜFTECHNIK device calibrated at 100 kHz and with a nitrogen-based leakage system under different pressures. Pressure drops and associated times were recorded to assess detection effectiveness.

III. RESULTS AND DISCUSSION

This section outlines the results from the conducted activities, focusing on: (1) identifying manufacturing defects in the tubular components, (2) verifying compliance of key properties with company specifications, and (3) comparing eddy current and leakage testing to assess their efficacy in detecting discontinuities.

Using the information gathered from interviews and reports, a failure histogram covering the manufacturing period was constructed, and a concise analysis of defective parts allowed identification of failure causes, recurrent defects, critical zones and the implementation of corrective measures to mitigate these faults. The study began with an evaluation of the failure reports, followed by interviews with plant personnel to identify the likely origins of these failures and strategies to mitigate or eliminate them. This combined information resulted in a histogram, as shown in Figure 3.1, which records the frequency of interruptions observed during the manufacture of the tubular components between January and August 2014-2015.

Fig 4 instead shows three of the most frequent causes of interruptions, which were operator errors (15 events), activation of the eddy current equipment alarm (12 events), and failures in the welding station (7 events). Operator errors were traced to instances in which operators introduced process modifications that were not specified or performed tasks without the proper training.

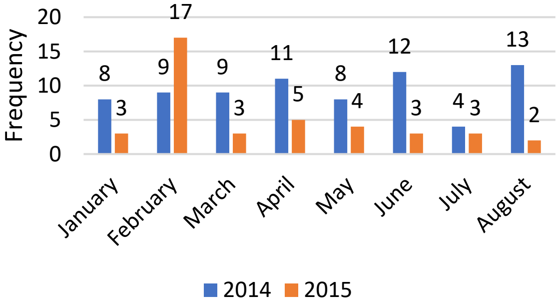


Fig. 3. Histogram of manufacturing interruptions.

Negligence, parameter variation and lack of training were identified as the main constituents of operator error, as seen in Fig 5. Better-trained operators on the first shift experienced limited interruptions, while the probability of an operator error increased by approximately 40% during the second shift. Alongside the shift analysis, a registry of defects was executed and is illustrated in Fig 6.

Approximately 80% of defects occurring during manufacture are due to poor welding, typically resulting from misadjusted welding rollers or mechanical vibrations that cause the electrode to jump and interrupt continuous welding. Less frequent defects include excessive penetration, cracks and holes. These defective parts were further analyzed using a MEIJI TECHNO® EMZ-13TR macrolens and the Motic Images 2.0 ML software. Quality control tests for flattening, flaring and flange formation were also evaluated to determine whether the welded tubing met ASTM B-751 requirements. Representative images and the ensuing analysis follow.

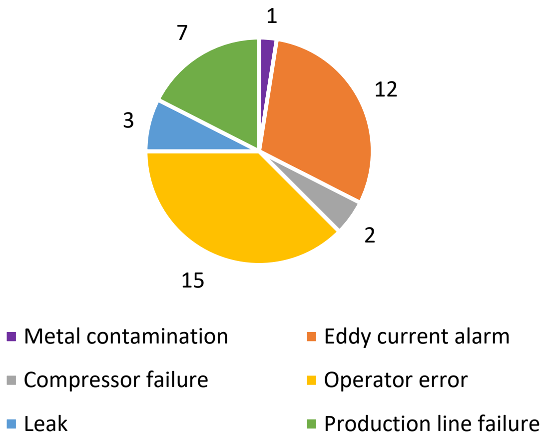
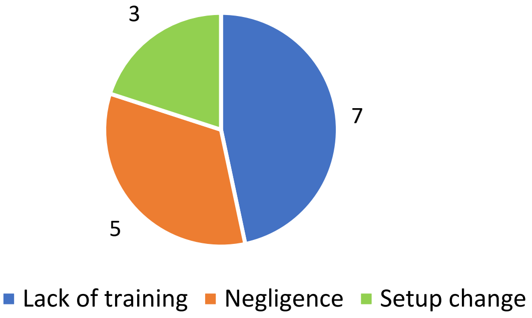


Fig. 4. Manufacturing issue.



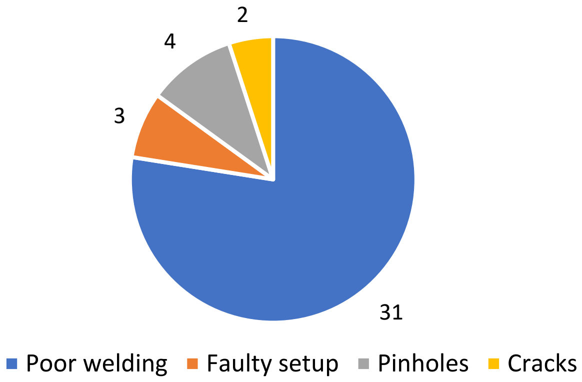


Fig. 6. Discontinuities in tubular components.

Excessive penetration was detected reaching where a depth of more than 4 mm. This type of defect typically occurs when weld penetration exceeds the total thickness of the base metal. Typical causes include high currents, insufficient preheating or excessively low welding speed (Olson & Davis, 2006). Notably, excessive penetration is relatively uncommon in this tubular manufacture—below 10%—despite the reduction in welding speed associated with the teardrop redesign.

Moreover, cracks were also noticed in various forms and locations along the welded joint. The transverse cracks are common in single-pass welds and usually originate from stresses that accumulate during cooling (Ahmad & J. Bond, 2018). Transverse cracks may be considered as "hot cracks"—intergranular separations triggered by hot brittleness or localized planar contraction—or transgranular separations resulting from stresses that exceed material strength. Typically originating in the weld bead and sometimes propagating into the heat-affected zone, these cracks are known among the most damaging defects in welded products (Olson & Davis, 2006).

Lastly, the presence of holes and poor welding was also visualized during this period. Holes are small orifices usually located near the weld bead, whereas poor welding is the interruption in weld continuity caused by machine vibrations or improper roller adjustment that produces irregularities in the bead (Olson & Davis, 2006), (Semiatin, 2006). Poor welding remained as the most common defect in pipe or tubular manufacturing, generating unexpected additional costs in production.

In summary, defects in this type of product are typically confined to the weld zone: cracks are the most harmful but relatively rare, while poor welding are the most likely to occur. Defects evaluated displayed variable geometry and sizing, and the average defect size was determined to be 4.523 ± 1.5 mm. To verify whether weld quality met standards, welded tube quality control tests were performed—specifically flaring, and flange formation—and inspected under macroscopic magnification in accordance with company requirements.

The flaring employed a tool to expand the tube diameter, and the piece was inspected under the macrolens for signs of cracking. In this case an absence of irregularities in both frontal and lateral views indicated acceptable weld quality for all samples. Similarly, flange formation testing revealed compliant and non-compliant samples. The non-compliant sample showed cracking in the weld area, suggesting a need for corrective actions such as increased welding current or reduced welding speed to improve penetration and weld quality. These mechanical-quality tests were implemented to probe weld ductility in multiple directions and ensure that only high-quality welded products progress in the sensor cable manufacturing cycle.

With the collected information, corrective measures were proposed for effective manufacturing. A revised preventive maintenance plan was introduced to complement the existing semiannual week-long upkeeping.

The new maintenance initiative, as seen in Table 1, implemented at the beginning of March 2015, contributed to an approximately 40% reduction in production interruptions during March–August 2015 compared to March–August 2014, thus improving operational continuity and reducing economic losses. Samples were submitted for testing to verify product condition and mechanical property status before allowing the final product to proceed in the chain line. Tensile tests and hardness measurements were conducted to characterize the mechanical response of the tubular product and to compare results with a five-year study performed by the manufacturer. A representative stress–strain curve for Incoloy 825® is shown in Fig 7.

TABLE I.
PRODUCTION STOPPAGE REGISTRY

Year	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
2014	8	9	9	11	8	12	4	13
2015	3	17	3	5	4	3	3	2

Avg/month	**Total Faults**
9,25	74
5	40

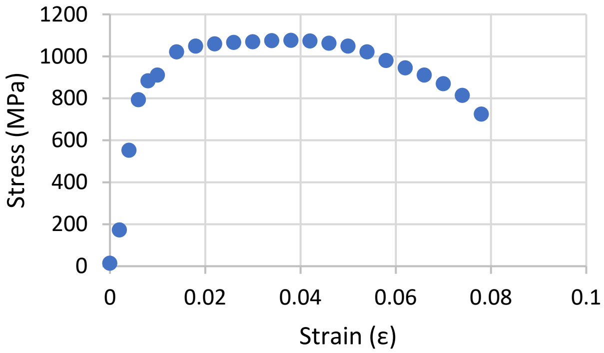


Fig. 6. Stress-strain curve for Incoloy 825®.

The characteristic stress–strain curve displays an elastic region associated with the modulus of elasticity (Young's modulus), a yield stress (σ_y), and a tensile strength representing the maximum stress of the curve, followed by a decline and eventual fracture. The nickel–iron–chromium alloy Incoloy 825® contains molybdenum and copper additions and can only be hardened by cold work. Cold working instead increases the dislocation density, causing dislocations to entangle, which limits dislocation motion. As dislocation density increases, the resistance to dislocation movement increases, and this is reflected in tensile tests by a reduction in ductility but an increase in yield strength and ultimate tensile strength (Semiatin, 2006). Characteristic parameters extracted from the engineering stress–strain curves of the 15 batches were compared with reference values.

This comparison determined that values remained within the ranges as those previously registered by the manufacturer, with the exception of ductility where average and maximum values decreased due to the amount of cold work applied. As anticipated, yield and ultimate tensile strength increased, consistent with a higher dislocation density limiting dislocation motion. Consequently, the batches used throughout this project comply with company requirements. Fundamental mechanical tests like tensile and hardness evaluations provide vital information on product design characteristics, allowing engineers to implement corrections or adjustments when necessary.

Having characterized manufacturing defects and mechanical properties, the sensitivity of eddy current testing and leakage testing for defect detection was then determined. Eddy current inspection was carried out at the end of welding station using the PRÜFTECHNIK device consisting of a minimally configured single-channel unit were signal interpretation is limited to a binary detection approach (yes/no). The system also supported a wide range of coils and probes that facilitated inspection.

The eddy current unit detected only one (0.508 mm) of the four prepared samples —0.127, 0.254, 0.381, 0.508 mm. Interviews revealed that, with the current calibration, the equipment can detect most defects. Eddy currents form in the metallic surface in direct proportion to excitation frequency while penetration depth decreases with increasing frequency (E. Farag, Toyserkani, & Khamesee, 2022). Selecting an inspection frequency represents a compromise as ASTM B-751 (ASM International, 2021) specifies a maximum frequency of 100 kHz for this type of products. Penetration must be sufficient to reach the depth of the defect in order to be properly detected, but as frequency decreases sensitivity typically diminishes, so an inspection frequency sufficiently high to achieve sensitivity yet compatible with the required penetration depth must be chosen. When deep defects must be detected, very low frequencies are used at the expense of sensitivity, which reduces the capability to detect small defects (Olson & Davis, 2006).

Eddy current testing is an extremely versatile, fast technique that yields immediate results with minimal preparation. On the other hand, leakage testing by pressure loss, once executed, the results were compared with eddy current testing capabilities to determine the superior detection method (Haeng Hur, Sik Choi, & Hyun Lee, 2010). In this case, Analysis focused on the gauge located farthest from the defect given its longer reaction time to pressure changes in time, implementing pressured nitrogen gas at 7 and 14 MPa.

Higher testing pressures enabled rapid detection of leaks compared to current setup at 7 MPa. These outcomes also indicated that analog gauges are inadequate for sensitive leak detection—operators can at best detect changes of about 0.3 MPa using analog meters (Lower detection capabilities). Notably, the leakage method detected defects in all four prepared samples at both 7 and 14 MPa when using nitrogen and analog gauges. It was possible to detect defects down 0.127 mm with a pressure drop of 0.7 MPa in less than one hour of testing in several scenarios. The leakage test required more time and expertise when comparing experimental setups and results are not immediate; detection of a leak at 7 MPa can take a minimum of about 10 minutes under practical conditions. Moreover, interpretation of results and preparation demands are greater than for eddy current testing.

Although both NDT's techniques can detect the average defect size encountered in manufacturing, only pressure leakage testing detected all holes in the prepared samples, reflecting its higher sensitivity relative to eddy currents, which are constrained by variables that cannot be eliminated in any inspection scenario (Bin Fazle, Islam, & Kumar Prodhan, 2022). Sensitivity of the leakage test can be further enhanced by using a lower molecular weight test gas such as helium, by extending testing time and by employing higher-sensitivity pressure gauges; such corrective measures can permit detection of defects down to 0.00254 mm.

Consequently, leakage testing emerges as a superior technique for detecting very small through-wall defects. Despite this, eddy current testing maintains a crucial role on the manufacturer's production line because it enables rapid detection of a large majority of defects during early manufacturing stages. As such, this technique will deliver immediate results requiring minimal preparation, positioning itself as a key in-process inspection tool while leakage testing serves as a robust backup verification method to ensure final product compliance with quality requirements.

Furthermore, a closer look at the temporal distribution of failures clarifies the operational context: the marked drop in interruptions between 2014 and 2015 (Table I) reflects a combination of design changes, procedural improvements and a revised maintenance cadence rather than a single isolated action. The teardrop redesign provided greater mechanical clearance and lowered stoppage risk, while simultaneous process controls and the newly instituted preventive maintenance acted synergistically to stabilize production. The decision to trade welding speed for weld quality exemplifies an engineering-economic compromise: slower welding reduced throughput but yielded higher weld penetration and fewer defects, thus lowering rework and scrap rates (Olson & Davis, 2006). From a cost-benefit perspective, the net effect favored the manufacturer: translating into fewer interruptions and reduced defective product rates, lowering overall operational costs despite the marginal decline in hourly output.

Moreover, workforce shifts emerged as a meaningful contributor to defects. The concentration of operator errors in later shifts points to issues such as uneven training, inconsistent handover practices and reduced supervision. Addressing these issues requires targeted interventions, such as, implementing standardized shift handover checklists, expanding training for night-shift personnel and introducing practical competency assessments. These corrective measures in the production network are low-cost but carry high-impact, aligning workforce capability with technical process requirements and reducing the incidence of operator-induced interruptions (Quintana, Leung, & Rene Villalobos, 2009).

On the materials side, tensile and hardness testing revealed responses consistent with cold work hardening: increased yield and ultimate tensile strengths accompanied by reduced ductility. While higher strength can be advantageous, reduced ductility can elevate the risk of brittle-like failures under certain service conditions. Therefore, manufacturing departments should monitor work-hardening levels and, if necessary, introduce controlled annealing steps or adjust forming processes to ensure that final product toughness remains appropriate for the intended service demands (Semiatin, 2006). Microstructural characterization—absent from the current dataset—would provide valuable confirmation: optical microscopy and scanning electron microscopy of weld zones and heat-affected zones would reveal whether defects originate from localized microstructural features such as porosity, inclusions or microcracks that then act as stress concentrators. Such insights would directly inform welding parameter optimization geometric limitations (Safari, Mostaan, & Derakhshan, 2018).

Statistically, average values aligned with the manufacturer's values for yield (883 vs 800 MPa), ultimate strength (958 vs 900 MPa) and hardness (30 vs 32 HRC), while ductility exhibited a downward shift in mean values (7 vs 10%). Notably, strength increased, indicating that the cold work performed on this new batch of samples strengthened previously weak specimens; however, ductility distribution merit monitoring, since rare low-ductility outliers can have disproportionate effects on reliability and field performance. Given the complementary advantages of eddy current and leakage testing, a pragmatic quality assurance strategy is recommended: implementing eddy current inspection as a rapid in-line screening method to identify and correct surface defects immediately and deploy leakage testing selectively as a high-sensitivity verification step for critical batches or periodic samples. Enhancing leakage detection by using helium as a tracer gas, increasing test duration where feasible, and adopting digital high-precision pressure gauges will improve detection thresholds and enable automated data capture and analysis.

The revised preventive maintenance plan implemented in March 2015—adding a targeted one-day stop three months after the general semi-annual service, addressing common wear points such as polishers, forming stations, adjustment rollers and the coolant tank of the welding production line. These short, focused stops for cleaning, lubrication and alignment checks are cost-effective measures to prevent mechanical drift and maintain welding stability. When combined with a computerized maintenance management system (CMMS) that records interventions, tracks component lifetimes and triggers scheduled actions; these measures reduce unplanned downtime and promote continuous improvement (Quintana, Leung, & Rene Villalobos, 2009).

Limitations of this work should be acknowledged. The eddy current unit lacked an oscilloscope that would enable detailed waveform analysis and potentially improve sensitivity through signal processing. The leakage tests relied on analog gauges that constrained temporal resolution; substituting digital high-precision gauges would allow finer pressure-drop detection thresholds and automated logging. The binary nature of the eddy current results limited interpretative depth, and microstructural characterization was not performed, which would otherwise help attribute observed mechanical behavior to localized microstructural phenomena.

Taken together, these findings support a cohesive operational recommendation to maintain and preserve weld integrity, institutionalize a one-day preventive maintenance interval between major servicing or upkeeping, expand operator training programs and shift handover protocols, and implement a layered inspection program combining eddy current screening with selective leakage verification using upgraded instrumentation. This integrated path maximizes defect detection, preserves mechanical-property conformance, and improves overall product reliability. As such, NDT's remains indispensable in contemporary manufacturing.

When deployed as complementary tools rather than singular solutions, eddy current and leakage testing provide robust assurance against defects. Coupling optimized process design, disciplined maintenance and targeted skills development creates a resilient production system able to deliver consistently high-quality products and to meet both industrial and safety-critical expectations. To measure the effectiveness of these recommendations, clear metrics, such as, reduction in interruptions, defect-per-million rates, rework hours saved and mean time between failures must be defined and review quarterly to ensure continuous improvement or whether to implement more corrective measures. With measurable targets and periodic inspections, the plant can sustain gains while adapting to future product or process changes (Civera & Surace, 2022).

IV. CONCLUSIONS

The present study demonstrates that manufacturing defects in the hollow tubular products are predominantly confined to the weld region; among the variety of observed flaws, cracks represent the most structurally harmful class but with low occurrence rates, whereas incomplete welds or poor welding points are the most common anomaly. Quantitative examination of defective parts established that defects exhibit variable geometry and orientation and that the mean defect size measured in this study is 4.523 ± 1.5 mm. This spatial and dimensional characterization has practical significance because it defines the target detection envelope for NDT methods and informs acceptance criteria and sampling strategies for production control. Mechanical-quality tests—including flaring and flange formation—function effectively as ductility screens for the welded zone, exercising the joint in multiple directions and preventing propagation of low-ductility welds further down the production line.

Fundamental mechanical testing revealed behaviour consistent with cold-work strengthening. As cold work accumulates, dislocation density increases and mobility becomes constrained, producing higher yield and ultimate tensile strengths but a commensurate reduction in ductility. These shifts remain within range of previously reported values by the manufacturer's historical dataset.

The comparative study of eddy current inspection and pressure-loss leakage testing clarifies the complementary roles of both methods. Eddy current testing proved to be a fast, flexible, and minimally preparatory as a screening tool capable of rapidly scanning surfaces or near-surface anomalies; however, its sensitivity is constrained by probe geometry, excitation frequency and available instrumentation. With the calibration and equipment used in this work, only the largest laser-drilled discontinuity (0.508 mm) was consistently detected, while the practical detection threshold reported by operators was approximately 0.635 mm. As mentioned previously, eddy current penetration depth decreases with frequency, and ASTM guidance limits inspection frequency for this wall thickness to 100 kHz; consequently, field implementation requires a frequency-selection compromise tailored to defect depth and size, and benefits substantially from the addition of oscilloscope-grade signal capture and signal-processing algorithms to improve inspection.

Leakage testing, implemented as a pressure-loss method using nitrogen and analog gauges, required more experimental setup and operator skill but delivered markedly higher sensitivity: all artificially introduced holes were detected at both 7 MPa and 14 MPa, and defects down to 0.127 mm produced measurable pressure drops within practical test durations. The sensitivity advantage of leakage methods can be further enhanced by replacing nitrogen with lower-molecular-weight tracer gases (helium), increasing test duration if production allows, and employing digital high-precision pressure gauges with automated logging. Under these improvements, smaller discontinuities would also be detected (sub-micrometre), thus, unveiling leakage testing as an excellent high-sensitivity verification technique for final acceptance of critical batches.

Operational interventions implemented during the project produced measurable benefits. A redesign of the product cross-section from circular to a teardrop profile improved weld penetration and reduced certain defect modes by lowering welding travel speed from ~244 m/h to ~226 m/h.

Introducing a targeted preventive maintenance interval (a one-day stop) that focuses on polishers, forming stations, roller adjustments and the coolant system yielded an approximate 40% reduction in unplanned interruptions during the monitored production window. These findings illustrate how modest engineering and maintenance policy changes can produce outsized reliability improvements when combined with process and human factors controls.

Human factors were of high importance during the entire study, as operator-induced errors remained the most frequent cause of interruptions, concentrated disproportionately in later shifts. Mitigations that are practical and low cost—standardized shift-handover checklists, competency-based training for night shifts, routine parameter audits and strengthened supervisory feedback loops—are therefore recommended as high-impact measures to reduce the primary source of interruptions.

In terms of NDT inspection, in-line eddy current inspection should be retained as a rapid first-pass screening mechanism to detect obvious surface and near-surface defects, enabling immediate corrective action during production. Selective leakage testing should serve as a high-sensitivity verification step for critical production lots or periodic samples intended to validate process capability. This dual strategy leverages the speed of eddy currents and the sensitivity of pressure-loss testing while controlling cost and throughput impact. Instrumentation upgrades—most notably adding oscilloscope-grade acquisition to the eddy current system, replacing analog gauges with digital acquisition devices, adopting helium for leakage testing or adding a mass spectrometer leak detection for highest sensitivity—will considerably enhance detection limits and traceability.

Microstructural and fractographic analyses (optical microscopy, SEM, energy-dispersive X-ray analysis) were not performed here but would provide decisive evidence linking defect formation to microstructural causes such as porosity, inclusions, or localized brittle phases in the heat-affected zone. Future investigations should therefore combine high-resolution microscopy, weld-parameter mapping, and controlled thermal-mechanical trials to identify robust parameter windows that minimize crack nucleation while preserving required mechanical properties.

Lastly, the integration of targeted product design adjustments, disciplined preventive maintenance, focused workforce development and a dual-tiered NDT regime represents a coherent path toward sustained quality improvement for hollow tubular products. Such an integrated approach yields tangible reductions in interruptions and defective output while preserving the manufacturing throughput necessary for commercial viability. For research and industry practitioners, the practical implication is clear: pairing rapid in-line screening with selective, high-sensitivity verification—supported by upgraded instrumentation and data capture—delivers the most effective balance of defect detection, cost control and production continuity.

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