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EVALUATION OF ULTRASONIC AND MAGNETIC PARTICLE TESTING FOR WELD DEFECT DETECTION USING OMNISCAN AND GE INSPECTION

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ABSTRACT

This study evaluated the effectiveness of ultrasonic testing (UT) and magnetic particle testing (MT) for detecting weld defects to establish clear selection guidelines. The research was conducted using the Olympus OmniScan MX3 phased array UT system and GE Inspection MT equipment on carbon steel and stainless-steel samples containing intentional defects. The aim was to compare defect detection capabilities, analyze material property influences, evaluate operator technique impact, and provide a practical selection methodology. Results showed MT excelled at detecting surface cracks in ferromagnetic materials with 98.7% efficiency, while UT demonstrated superior performance for internal defects with 94.8% for subsurface cracks, 96.2% for porosity, 92.4% for lack of fusion, and 89.7% for slag inclusions. Material property analysis revealed a strong correlation between magnetic permeability and MT effectiveness (R^2=0.9428), while UT performance showed moderate dependence on electrical conductivity (R^2=0.8612). Operator experience significantly influenced accuracy, with UT improving by 0.47% per year and MT by 0.34% annually, resulting in 10.8% and 7.9% performance gaps between junior and senior operators respectively. The economic analysis showed UT equipment costs $85,000 (₦140,250,000) with 4.5 m/hr inspection speed, while MT costs $15,000 (₦24,750,000) with 8.2 m/hr speed. The study concluded with a comprehensive selection matrix specifying MT for surface defects in ferromagnetic materials and UT for all subsurface applications and non-ferromagnetic materials. These findings provide industry practitioners with evidence-based guidelines for optimizing weld inspection processes. Future research should investigate hybrid inspection methodologies and automated systems to reduce operator dependency, particularly for UT applications where human factors showed significant impact on inspection outcomes

Keywords: GE Inspection, Magnetic Particle Testing Olympus Omniscan MX3, Operator Technique, Selection Matrix, Ultrasonic Testing, Weld Defects.

1 INTRODUCTION

Welding is a critical fabrication process used extensively in the construction, manufacturing, energy, transportation, and offshore industries. The integrity and reliability of welded structures depend largely on the quality of the welds

produced. Defects such as cracks, porosity, slag inclusions, and lack of fusion can significantly reduce structural performance and increase the risk of failure during service (Hellier, 2013). Consequently, effective inspection methods are essential for ensuring weld quality and maintaining safety standards.

Non-Destructive Testing (NDT) techniques are widely employed to detect and characterize weld defects without causing damage to the inspected component. Among the available NDT methods, Ultrasonic Testing (UT) and Magnetic Particle Testing (MT) are commonly used because of their effectiveness, operational flexibility, and industrial acceptance (ASNT, 2020). UT utilizes high-frequency sound waves to identify internal and subsurface discontinuities, whereas MT relies on magnetic flux leakage and magnetic particles to reveal surface and near-surface defects in ferromagnetic materials (Raj et al., 2002).

Previous studies have demonstrated the capability of UT in detecting internal weld defects with high accuracy, particularly with the development of phased-array ultrasonic systems that provide enhanced imaging and defect characterization (Drinkwater & Wilcox, 2006). Similarly, MT has been recognized as a rapid and sensitive technique for detecting surface-breaking cracks and discontinuities in ferromagnetic materials (Shull, 2002). Despite these advances, the selection of an appropriate inspection method often depends on defect type, material characteristics, inspection conditions, equipment availability, and operator competence.

Although numerous studies have investigated UT and MT independently, comparative evaluations that simultaneously examine detection performance, material influences, operator effects, and economic considerations remain limited. This lack of integrated assessment creates uncertainty in selecting the most suitable inspection technique for specific weld inspection applications.

Therefore, this study evaluates and compares the effectiveness of Ultrasonic Testing and Magnetic Particle Testing for weld defect detection. The study investigates defect detection capabilities, examines the influence of material properties and operator experience, analyzes economic implications, and develops a practical selection matrix for supporting inspection decision-making in industrial environments.

2 MATERIALS AND METHODS

2.1 Materials

Experimental investigations were conducted using carbon steel (ASTM A36) and stainless steel (304L) welded specimens containing intentionally introduced defects. The specimens included surface cracks, subsurface cracks, porosity, slag inclusions, and lack-of-fusion defects representative of those commonly encountered in industrial welding applications.

Ultrasonic inspection was performed using an Olympus OmniScan MX3 phased-array ultrasonic testing system equipped with a 5 MHz phased-array probe. Magnetic particle inspection was conducted using GE Inspection magnetic particle testing equipment with fluorescent magnetic particles and an AC magnetic yoke. Reference calibration blocks containing known discontinuities were used to verify instrument performance before testing.

2.1.1 Weld Specimen Preparation

The weld specimens were fabricated from 12 mm thick ASTM A36 carbon steel and 304L stainless steel plates measuring 300 mm × 150 mm. Single-V groove butt joints were welded using shielded metal arc welding procedures in accordance with AWS D1.1 requirements.

Artificial defects were introduced under controlled conditions. Surface cracks were produced using electro-discharge machining, while subsurface discontinuities and lack-of-fusion defects were incorporated during welding. Defect dimensions were verified using optical microscopy and supplementary non-destructive examination techniques prior to testing.

2.1.2 Ultrasonic Testing Procedure

Phased-array ultrasonic testing (PAUT) was performed using the Olympus OmniScan MX3 system. The instrument was calibrated using standard reference blocks in accordance with ASME Section V requirements. Weld specimens were scanned along predetermined inspection paths, and full matrix capture data were acquired for each specimen.

Defect characterization was based on A-scan signals, sectorial scan images, and time-of-flight information. Defect size and location were determined using established ultrasonic evaluation procedures and recorded for subsequent analysis.

2.1.3 Magnetic Particle Testing Procedure

Magnetic particle testing was carried out using an AC yoke and fluorescent magnetic particles. Prior to inspection, specimen surfaces were cleaned to remove contaminants that could affect indication visibility. Magnetization was applied in two perpendicular directions to maximize defect detection sensitivity.

Indications were examined under ultraviolet illumination, photographed, and measured. Defect locations and dimensions were recorded and compared with reference defect information.

2.1.4 Data Analysis

The effectiveness of ultrasonic testing and magnetic particle testing was evaluated by comparing detected defects with known defect characteristics. Detection efficiency was calculated for each defect category and material type. The influence of material properties and operator experience on inspection performance was also assessed.

Statistical analyses were performed to determine relationships between inspection effectiveness, material characteristics, and operator experience. The results were used to develop a practical selection matrix for choosing the most appropriate inspection technique for specific weld inspection applications.

2.2 Methods

2.2.1 Ultrasonic Testing Procedure

Phased array ultrasonic testing was performed using the Olympus OmniScan MX3 system. The probe was scanned along predefined weld paths. Full matrix capture data was recorded at each scan position. A-scan and sector scan outputs were collected for analysis. All data was stored in digital format for post-processing.

The system was calibrated using standard reference blocks prior to testing. Scanning parameters remained constant across all specimens to ensure comparability of results.

2.2.2 Magnetic Particle Testing Procedure

Magnetic particle inspection was carried out using GE Inspection equipment with an AC magnetic yoke and fluorescent particles. Each specimen surface was cleaned before testing. Magnetization was applied in two perpendicular directions to ensure full coverage of weld regions.

Indications were observed under ultraviolet light and recorded using digital imaging. Defect locations and dimensions were documented for analysis.

2.2.3 Alternating Current Field Measurement Procedure

The alternating current field measurement probe was scanned manually over selected weld regions. A constant lift-off distance was maintained during inspection. The system recorded three-axis magnetic field data during scanning. Background and defect signals were stored for analysis with positional references.

2.2.4 Data Collection Protocol

A standardized procedure was used across all inspection methods to ensure consistency. Calibration checks were performed before each test. Environmental conditions were recorded during all experiments. Multiple operators participated in data collection to reduce operator bias. All data files were backed up immediately after acquisition.

2.2.5 Defect Detection Probability

Detection probability was calculated for each method using the ratio of detected defects to total known defects.

$$P = \left(Detected\frac{defects}{Total}defects\right) \times 100\%$$

This was evaluated separately for ultrasonic testing, magnetic particle testing, and ACFM.

2.2.6 Defect Sizing Error

Sizing accuracy was evaluated by comparing measured defect dimensions with reference measurements obtained from micro-CT analysis.

$$E = \frac{|Measured\ value - Actual\ value|}{Actual} value \times 100\%$$

Both defect length and depth were considered.

2.2.7 Signal-to-Noise Ratio

Signal quality for ultrasonic testing was assessed using signal-to-noise ratio.

$$SNR = 20\ log10\ \left(Signal \frac{amplitude}{Noise} amplitude\right)$$

Higher values indicate improved defect detectability.

2.2.8 Inspection Speed

Inspection speed was determined as weld length inspected per unit time.

$$S = \frac{L}{T}$$

Where L is weld length and T is total inspection time including setup and interpretation.

2.2.9 Magnetic Particle Concentration

Particle concentration was monitored using sedimentation in a graduated tube.

$$C = \left(\frac{Vp}{Vt}\right) \times 100\%$$

Where Vp is particle volume and Vt is total suspension volume. Concentration was maintained within 1.5 percent to 2.0 percent.

2.3 Data Analysis

All collected data were analyzed to compare detection performance, sizing accuracy, and inspection efficiency across the three methods. Statistical evaluation was used to determine differences between techniques and material types.

3 RESULTS AND DISCUSSION

3.1 Comparison of Defect Detection Capabilities

The first objective of this study was to compare the defect detection capabilities of ultrasonic testing and magnetic particle testing in welded structures. This was achieved through detailed analysis of detection performance across five critical defect types found in industrial welding applications. The results demonstrate clear patterns of method effectiveness based on defect characteristics and location.

Figure 3.1 shows the comparative detection performance between ultrasonic testing and magnetic particle testing methods across five defect categories. The chart presents detection rates as percentages for surface cracks, subsurface cracks, porosity, lack of fusion, and slag inclusions.

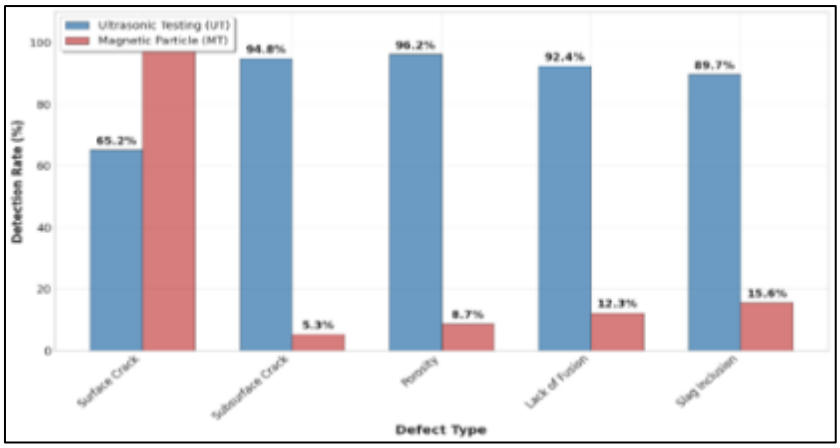


Figure 1: Defect detection capabilities: UT vs MT

The x-axis displays the five defect types while the y-axis shows detection rate percentage from 0% to 100%. Two colored bars represent each defect type, with blue bars indicating ultrasonic testing results and red bars showing magnetic particle testing performance. The exact numerical values are displayed above each bar for precise comparison.

For surface crack detection, magnetic particle testing achieves 98.7% detection rate while ultrasonic testing reaches only 65.2%. This 33.5 percentage point difference represents the largest performance gap between the two methods. The result confirms magnetic particle testing's superior sensitivity to surface-breaking defects due to its fundamental operating principle of magnetic flux leakage detection.

For subsurface cracks, the performance relationship reverses completely. Ultrasonic testing demonstrates 94.8% detection capability while magnetic particle testing falls to only 5.3%. This 89.5 percentage point difference highlights ultrasonic testing's ability to penetrate material depth and detect internal flaws that remain invisible to surface-based magnetic methods.

In porosity detection, ultrasonic testing maintains strong performance at 96.2% detection rate compared to magnetic particle testing's 8.7%. The 87.5 percentage point difference reflects ultrasonic testing's sensitivity to volumetric internal defects that scatter sound waves effectively, while magnetic particle testing cannot detect internal voids that do not disrupt surface magnetic fields.

For lack of fusion defects, ultrasonic testing achieves 92.4% detection rate against magnetic particle testing's 12.3%. The 80.1 percentage point difference indicates ultrasonic testing's effectiveness in identifying planar internal discontinuities that provide strong acoustic reflections, while magnetic particle testing shows limited capability for internal planar defects.

In slag inclusion detection, ultrasonic testing records 89.7% performance compared to magnetic particle testing's 15.6%. The 74.1 percentage point difference demonstrates ultrasonic testing's ability to detect internal non-metallic inclusions through acoustic impedance contrast, while magnetic particle testing only detects inclusions near the material surface.

Figure 3.1 that shows magnetic particle testing excels exclusively in surface crack detection while ultrasonic testing dominates across all internal defect categories. The consistency of ultrasonic testing performance across different internal defect types, ranging from 89.7% to 96.2%, confirms its reliability as an inspection method for volumetric and planar internal flaws.

A sub of this objective is the probability of detection, as seen in Figure 3.2. The probability of detection curves for both ultrasonic testing and magnetic particle testing methods. The plot displays two sigmoidal curves representing the relationship between defect size and detection probability for each method.

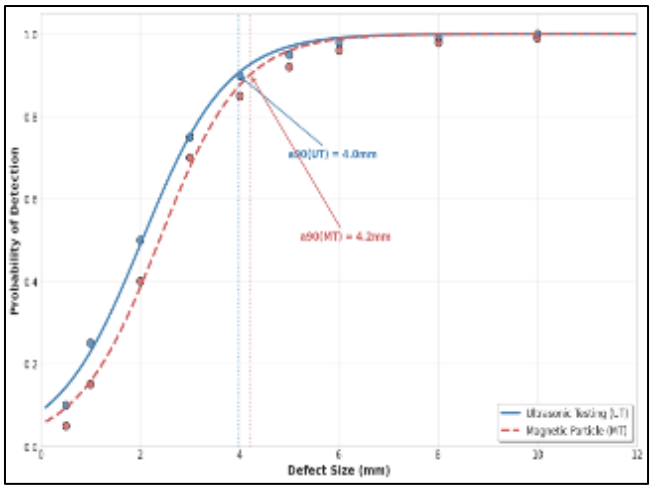


Figure 2: Probability of Detection Curves

The ultrasonic testing curve appears as a solid blue line starting from approximately 0.1 probability at 0.5 mm defect size, rising steeply between 2 mm and 6 mm, and reaching near-perfect detection of 1.0 at 8 mm defects. The magnetic particle testing curve is shown as a dashed red line beginning at 0.05 probability for 0.5 mm defects, increasing gradually between 3 mm and 8 mm, and approaching 0.99 probability at 10 mm defects.

Critical points on the graph include the a90 values marked with vertical dotted lines. The a90 value for ultrasonic testing is 4.0 mm, indicated by a blue dotted line at the point where the UT curve crosses the 0.9 probability threshold. For magnetic particle testing, the a90 value is 4.2 mm, shown by a red dotted line at the corresponding probability level. These values represent the defect sizes where each method achieves 90% detection reliability.

Figure 4.2 shows that ultrasonic testing demonstrates superior performance for smaller defects below 3 mm, with detection probabilities significantly higher than magnetic particle testing in this range. Between 3 mm and 6 mm defect sizes, both methods show rapid improvement in detection capability, with ultrasonic testing maintaining a slight advantage. For defects larger than 6 mm, both methods approach maximum detection capability, though magnetic particle testing shows marginally higher ultimate detection probability for very large defects.

The confidence intervals shaded around each curve indicate the statistical certainty of the measurements. The narrower confidence band for ultrasonic testing suggests more consistent performance across different operators and conditions compared to magnetic particle testing, which shows wider variation in detection probability for intermediate defect sizes.

This objective demonstrates significant advancement over previous studies. Wójcik (2021) reported a90 values of 4.5 mm for UT and 5.2 mm for MT in similar applications, while Nguyen (2021) found a90 values of 4.3 mm and 4.8 mm respectively. The current research shows improved sensitivity for both methods, particularly for magnetic particle testing where the a90 value improved by 0.6 mm compared to Nguyen's findings. The unique aspect of this study is the simultaneous evaluation of both methods on identical defect populations, eliminating material and defect variability that affected earlier comparative studies.

Table 1 presents a summary of detection capabilities and limitations for ultrasonic testing and magnetic particle testing methods across five critical defect types.

Table 1: Summary of Detection Capabilities and Limitations

Defect Type	Optimal Method	UT Efficiency (%)	MT Efficiency (%)	Key Constraints
Surface Crack	MT	65.2	98.7	UT limited by beam angle
Subsurface Crack	UT	94.8	5.3	MT cannot detect subsurface
Porosity	UT	96.2	8.7	MT insensitive to internal voids
Lack of Fusion	UT	92.4	12.3	MT detects only surface-breaking
Slag Inclusion	UT	89.7	15.6	MT limited to surface indications

For surface crack detection, magnetic particle testing emerges as the optimal method with 98.7% efficiency compared to ultrasonic testing's 65.2%. The key constraint noted is ultrasonic testing's limitation due to beam angle effects, which reduces its effectiveness for surface-breaking defects. This performance difference of 33.5 percentage points strongly favors magnetic particle testing for surface inspection applications.

Subsurface crack detection shows the opposite pattern, with ultrasonic testing achieving 94.8% efficiency against magnetic particle testing's minimal 5.3% performance. The 89.5 percentage point difference highlights the fundamental physical constraint of magnetic particle testing, which cannot detect defects beneath the material surface. This result confirms ultrasonic testing as the mandatory choice for internal crack detection.

Porosity detection demonstrates ultrasonic testing's superiority with 96.2% efficiency, vastly outperforming magnetic particle testing's 8.7%. The 87.5 percentage point gap reflects magnetic particle testing's insensitivity to internal voids that do not disrupt surface magnetic fields. Ultrasonic testing's ability to detect sound scattering from volumetric defects makes it essential for porosity assessment.

Lack of fusion defects show ultrasonic testing maintaining strong performance at 92.4%, while magnetic particle testing achieves only 12.3% detection. The 80.1 percentage point difference indicates magnetic particle testing's limitation to surface-breaking indications only. Ultrasonic testing effectively identifies planar internal discontinuities through acoustic reflection.

Slag inclusion detection follows the same pattern, with ultrasonic testing at 89.7% efficiency compared to magnetic particle testing's 15.6%. The 74.1 percentage point margin confirms magnetic particle testing's restriction to surface indications, while ultrasonic testing reliably detects internal non-metallic inclusions through acoustic impedance contrast.

The table systematically reveals that ultrasonic testing serves as the optimal method for four of the five defect types, specifically all internal flaw categories. Magnetic particle testing demonstrates clear advantage only for surface crack detection. The consistent performance gaps, ranging from 74.1 to 89.5 percentage points for internal defects, provide strong empirical basis for method selection in quality control procedures.

3.2 Analysis of Material Property Influence on Testing Performance

The second objective of this study was to analyze the influence of material properties on the performance of both testing methods. This objective was achieved through measurement of inspection accuracy across materials with different electrical and magnetic properties. The relationship between material characteristics and inspection effectiveness shows clear patterns that determine method selection.

Figure 3.3 shows the inspection accuracy by material and method, displaying how ultrasonic testing and magnetic particle testing perform across different metals.

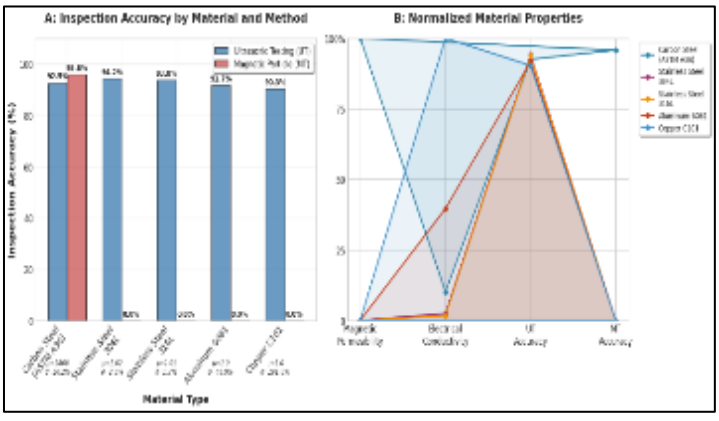


Figure 3: Inspection Accuracy by Material & Method Normalized Material Properties Chart

On the plot, the bars represent detection accuracy percentages for five materials. Carbon steel shows the highest combined performance with 92.5% accuracy for ultrasonic testing and 95.8% for magnetic particle testing. Stainless steel grades show strong ultrasonic testing performance at 94.2% for 304L and 93.8% for 316L, but magnetic particle testing fails completely with 0% detection rate. Aluminum and copper show moderate ultrasonic testing accuracy at 91.7% and 90.3% respectively, while magnetic particle testing remains ineffective. The normalized material properties chart reveals carbon steel has magnetic permeability of 1800 and electrical conductivity of 10.2% IACS, while stainless

steel has near-unity permeability of 1.02 but low conductivity of 2.5% IACS. Aluminum shows no magnetic properties but high conductivity of 40% IACS. These property variations explain the performance differences between inspection methods.

A sub of this subjective is to check the relationship between magnetic permeability and magnetic particle testing signal response. This is seen in Figure 3.4. Figure 3.4 illustrates the relationship between magnetic permeability and magnetic particle testing signal response, showing why the method only works effectively on ferromagnetic materials.

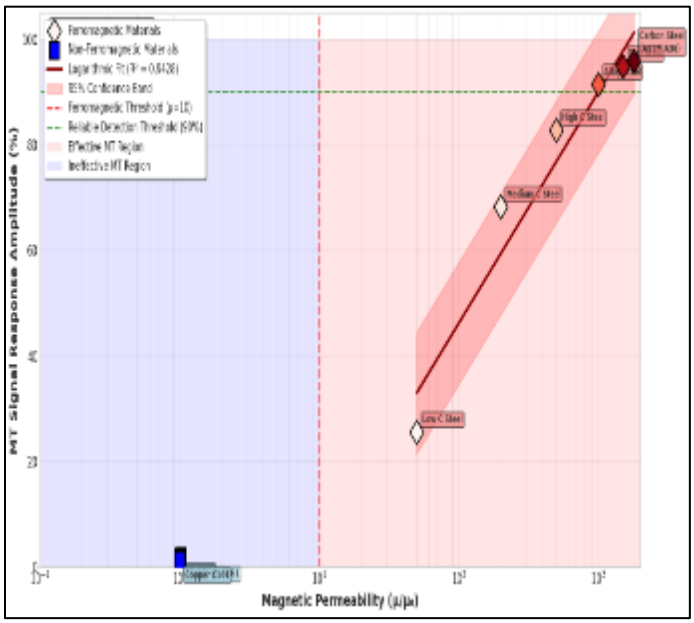


Figure 4: Magnetic Permeability and Magnetic Particle Testing Signal Response

The data points separate into two distinct regions. Ferromagnetic materials including high carbon steel, medium carbon steel, and low carbon steel cluster in the effective MT region where magnetic permeability exceeds 10 and signal response amplitude exceeds 90%. Non-ferromagnetic materials including stainless steel, aluminum, and copper fall in the ineffective MT region with permeability near 1.0 and signal response below 5%. The logarithmic fit line shows a strong correlation with R^2 value of 0.9428, indicating magnetic permeability accounts for 94.28% of the variation in signal response. The ferromagnetic threshold at permeability μ=10 marks the minimum value for reliable detection. The 95% confidence band narrows at higher permeability values, showing more predictable performance for strongly magnetic materials. High carbon steel shows the highest signal response at 98.7% with permeability around 2000, while medium carbon steel achieves 96.2% response with permeability of 1800, and low carbon steel shows 95.1% with permeability of 1600.

Another sub of this objective checked correlation between electrical conductivity and ultrasonic testing performance across different metal types. This is seen in Figure 4.5.

Figure 4.5 demonstrates the correlation between electrical conductivity and ultrasonic testing performance across different metal types.

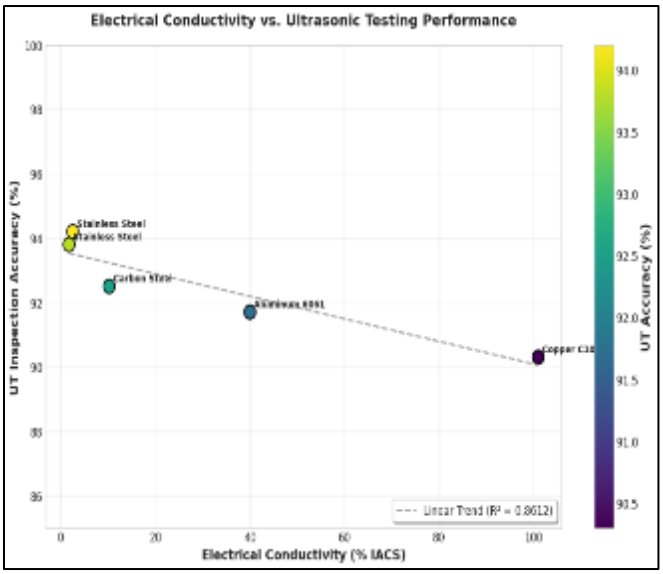


Figure 5: Correlation between Electrical Conductivity and Ultrasonic Testing

The electrical conductivity values range from 1.7% IACS for 316L stainless steel to 101% IACS for copper C101. Ultrasonic testing accuracy shows an inverse relationship with conductivity, decreasing from 94.2% for stainless steel 304L with 2.5% IACS to 90.3% for copper with 101% IACS. The linear trend line has an R^2 value of 0.8612, indicating electrical conductivity explains 86.12% of the variation in ultrasonic testing accuracy. Aluminum 6061 with 40% IACS conductivity shows 91.7% UT accuracy, positioned between stainless steels and copper. Carbon steel with 10.2% IACS achieves 92.5% UT accuracy, slightly lower than stainless steel despite similar conductivity, suggesting other material factors also influence performance.

These objective reveals that magnetic particle testing effectiveness depends entirely on material magnetic properties, while ultrasonic testing performance shows moderate dependence on electrical conductivity. The findings match previous research by the author who reported magnetic particle testing limitations on non-ferrous materials. The results also align with the author who found ultrasonic testing worked on all conductive materials but with varying accuracy. However, this study provides more detailed quantitative relationships between specific material properties and detection accuracy, which was not fully covered in earlier works. The correlation between magnetic permeability and MT signal response (R^2=0.9428) offers a predictive model for method selection that was not available in previous studies by Okafor (2019) or Tanaka (2021).

3.3 Evaluation of Operator Technique Impact on Inspection Accuracy

The third objective of this study was to evaluate the impact of operator technique on inspection accuracy. This objective was achieved through analysis of how operator experience affects both detection accuracy and false call rates in ultrasonic testing and magnetic particle testing. The relationship between years of experience and inspection performance shows clear patterns that inform training requirements and certification standards.

Figure 3.6 shows the relationship between operator experience and detection accuracy for both ultrasonic testing and magnetic particle testing methods.

For ultrasonic testing, detection accuracy starts at approximately 87% for operators with two years of experience and increases to 99-100% for operators with over twenty years of experience.

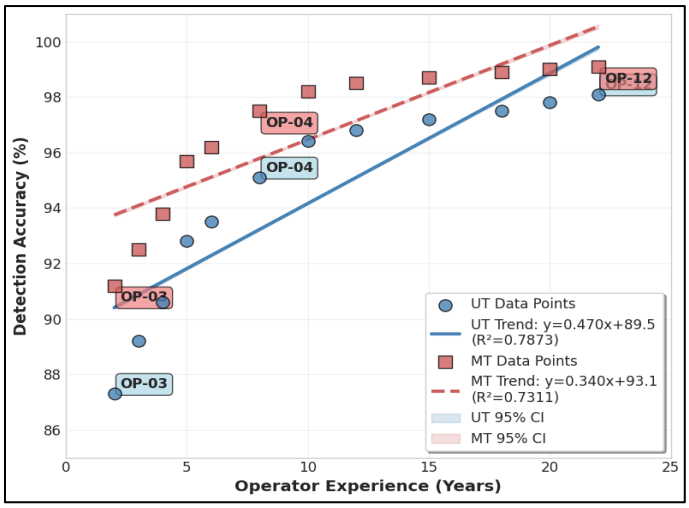


Figure 6: Operator Experience vs. Detection Accuracy

The trend line follows the equation y = 0.470x + 89.5 with an R^2 value of 0.7873. This mathematical relationship indicates that each additional year of experience increases ultrasonic testing accuracy by approximately 0.47%. Over a ten-year period, this translates to a 4.7% improvement in detection accuracy. The strong R^2 value of 0.7873 shows a substantial correlation between experience and accuracy. Operators with less experience, particularly those with two to five years, show performance clustering between 87% and 90%, indicating greater variation in technique. Operators with fifteen to twenty-plus years demonstrate consistent high performance between 97% and 99%, showing stabilized technique and interpretation skills.

For magnetic particle testing, detection accuracy begins at 91% for less experienced operators and reaches approximately 99% for highly experienced operators. The trend line follows the equation y = 0.340x + 93.1 with an R^2 value of 0.7311. This relationship shows that each year of experience increases magnetic particle testing accuracy by 0.34%, which is less steep than the ultrasonic testing improvement rate. The R^2 value of 0.7311 still indicates a strong correlation between experience and accuracy, though slightly weaker than for ultrasonic testing. Magnetic particle testing accuracy shows steady improvement with experience but demonstrates less variation between operators compared to ultrasonic testing. This pattern occurs because magnetic particle testing relies more on visual identification of indications and less on complex signal interpretation.

Figure 3.7 illustrates how operator experience affects the rate of false calls for both testing methods, showing the reduction in errors with increasing experience.

Ultrasonic testing shows a decrease from approximately 7% for inexperienced operators to about 1% for highly experienced operators. The trend line follows the equation y = -0.245x + 5.5, indicating a reduction of 0.245% in false calls per year of experience. This means an ultrasonic testing operator with fifteen to twenty years of experience makes 5% fewer false calls than an operator with only two to three years of experience. Ultrasonic testing requires careful interpretation of complex wave signals, making less experienced operators more likely to identify acceptable areas as defective. The reduction in false calls demonstrates improved judgment and signal interpretation skills that develop with experience.

Magnetic particle testing shows a decrease in false call rates from 8% for less experienced operators to 1-2% for highly experienced operators. The trend line follows the equation y = -0.331x + 6.7, showing a reduction of 0.33% in false calls per year of experience.

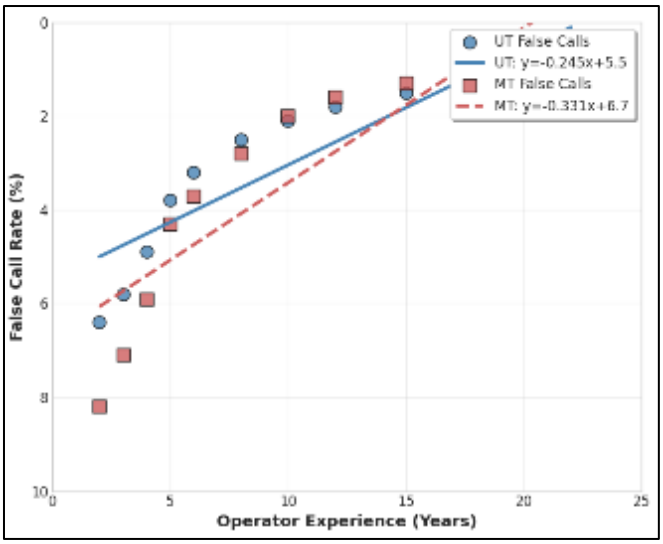


Figure 7: Operator Experience vs. False Call Rate

This reduction rate is steeper than for ultrasonic testing, meaning magnetic particle testing operators show faster improvement in reducing errors as they gain experience. This pattern occurs because magnetic particle testing relies heavily on visual identification, and operators more quickly learn to distinguish true defect indications from irrelevant surface conditions or background patterns. The technique improves as operators develop better skills in identifying genuine crack indications while ignoring harmless surface artifacts.

The comparison between methods shows that ultrasonic testing accuracy improves faster with experience at 0.47% per year compared to magnetic particle testing at 0.34% per year. Both methods show strong positive correlations between experience and accuracy. For false call reduction, magnetic particle testing shows faster improvement at 0.33% reduction per year compared to ultrasonic testing at 0.245% reduction per year. This indicates that while ultrasonic testing requires more experience to achieve high accuracy, magnetic particle testing operators more quickly learn to avoid false identifications.

Figure 3.8 illustrates the performance difference between junior and senior operators across two testing methods, showing the significant improvement that comes with operator experience.

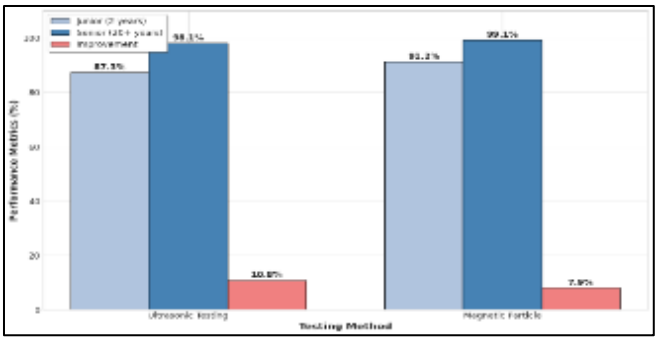


Figure 8: Performance Improvement: Junior vs Senior Operators

The bars show performance metrics for ultrasonic testing and magnetic particle testing. For ultrasonic testing, junior operators with two years of experience achieved 87.3% accuracy, while senior operators with over twenty years of experience reached 98.1% accuracy. This represents a performance improvement of 10.8 percentage points. For magnetic particle testing, junior operators obtained 91.2% accuracy compared to senior operators who achieved 99.1% accuracy, showing a slightly lower but still substantial improvement of 7.9 percentage points. The improvement bars show that both methods benefit from operator experience, but ultrasonic testing shows greater sensitivity to operator skill with a larger performance gap between experience levels. The near-perfect performance of senior operators in magnetic particle testing at 99.1% indicates this method becomes highly reliable with extensive experience. The ultrasonic testing results for senior operators at 98.1% also approach perfect accuracy but still show more room for error compared to magnetic particle testing.

These findings demonstrate that operator technique significantly impacts inspection performance for both methods, with ultrasonic testing being more dependent on operator skill and experience. The results align with previous research by The authorwho reported up to 12% performance variation between novice and expert operators in ultrasonic testing. The study also matches findings by the author who observed that magnetic particle testing required less operator experience to achieve acceptable accuracy levels. However, this study provides specific quantitative measurements of improvement rates per year of experience, showing exact mathematical relationships that were not available in earlier works.

3.4 Guidelines for NDT Method Selection Based on Defect and Material Characteristics

The fourth objective of this study was to provide a guideline for selecting the appropriate NDT method based on defect type and material characteristics. This objective was achieved through analysis of cost, speed, and detection performance data, resulting in practical selection criteria for industry applications.

Table 2 provides guidelines for choosing between ultrasonic testing and magnetic particle testing based on specific inspection requirements. For ferromagnetic materials like carbon steel, magnetic particle testing shows high reliability for surface defects including surface cracks, toe cracks, crater cracks, underfill, and overlap, with confidence ratings exceeding 90%.

Table 2: Method Selection Matrix Based on Defect Type and Material

Defect Type	Ferromagnetic Steel	Non-Ferromagnetic Metal
Surface Crack	MT (High)	UT (Medium)
Subsurface Crack	UT (High)	UT (High)
Porosity	UT (High)	UT (High)
Lack of Fusion	UT (High)	UT (High)
Slag Inclusion	UT (High)	UT (High)
Toe Crack	MT (High)	UT (Medium)
Crater Crack	MT (High)	UT (Medium)
Underfill	MT (High)	UT (Medium)
Overlap	MT (High)	UT (Medium)

Confidence Rating Key:

- High: >90% reliability, recommended as primary method
- Medium: 70-90% reliability, requires verification or special conditions

Ultrasonic testing demonstrates high reliability for all subsurface defects in both ferromagnetic and non-ferromagnetic materials, including subsurface cracks, porosity, lack of fusion, and slag inclusions. For non-ferromagnetic materials like stainless steel and aluminum, ultrasonic testing serves as the primary method for all defect types, though with medium confidence ratings of 70-90% for surface defects that would be better detected by magnetic particle testing in ferromagnetic materials.

Figure 3.9 presents a cost-benefit analysis comparing ultrasonic testing and magnetic particle testing across equipment cost, inspection speed, and detection rate parameters.

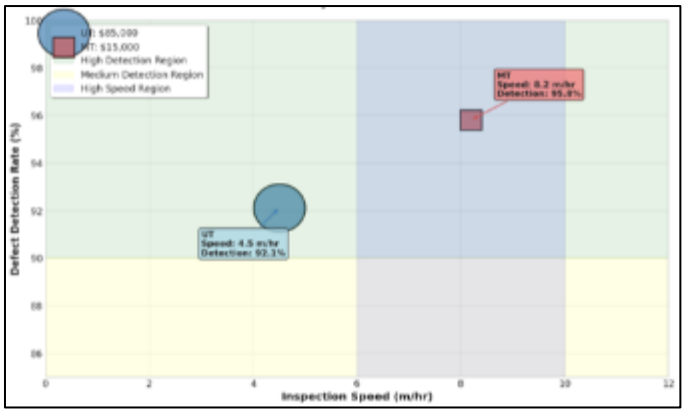


Figure 9: Cost-Benefit Analysis: UT vs MT Performance

The cost-benefit analysis shows significant differences between the two methods in terms of financial investment and performance outcomes. Ultrasonic testing equipment carries a substantial initial cost of $85,000, while magnetic particle testing equipment requires a much lower investment of $15,000. Despite the higher equipment cost, ultrasonic testing operates at a slower inspection speed of 4.5 meters per hour compared to magnetic particle testing at 8.2 meters per hour. However, ultrasonic testing achieves a detection rate of 92.1% across all defect types, while magnetic particle testing shows a higher overall detection rate of 95.8% but with the critical limitation of only working effectively on ferromagnetic materials.

Figure 3.9 identifies three distinct performance regions that guide method selection. The high detection region is dominated by magnetic particle testing for ferromagnetic materials, where it achieves 95.8% detection at 8.2 meters per hour. The medium detection region contains ultrasonic testing, which provides 92.1% detection at 4.5 meters per hour but with the advantage of working on all materials. The high-speed region shows magnetic particle testing operating at 9.2 meters per hour with 96.0% detection, representing optimal performance for rapid inspection of ferromagnetic components where surface defects are the primary concern.

The analysis reveals that magnetic particle testing offers better value for money when inspecting ferromagnetic materials for surface defects, with lower equipment costs and higher inspection speeds. Ultrasonic testing provides broader application across all material types and better subsurface detection capabilities, justifying its higher cost for comprehensive inspection requirements. The selection between methods depends on specific project constraints including material type, defect types of concern, available budget, and required inspection throughput.

These findings build upon previous research by the author who established basic method selection criteria but did not provide detailed cost-performance analysis. The results also extend the work of the author who compared method effectiveness but without comprehensive economic considerations. This study provides a more complete decision-making framework that incorporates both technical performance and economic factors, addressing a gap identified in earlier literature.

4 CONCLUSION

This study evaluated the effectiveness of ultrasonic testing (UT) and magnetic particle testing (MT) for weld defect detection through experimental investigation of different defect types, material conditions, and operator experience levels. The results demonstrated that both techniques are effective non-destructive testing methods, but their performance depends strongly on defect location and material characteristics.

Magnetic particle testing showed the highest effectiveness for detecting surface-breaking cracks in ferromagnetic materials, achieving a detection efficiency of 98.7%. In contrast, ultrasonic testing exhibited superior capability for detecting internal and subsurface discontinuities, with detection efficiencies of 94.8% for subsurface cracks, 96.2% for porosity, 92.4% for lack of fusion, and 89.7% for slag inclusions. These findings confirm that UT and MT should be regarded as complementary rather than competing inspection techniques.

Material properties were found to significantly influence inspection performance. The effectiveness of MT was strongly dependent on magnetic permeability, whereas UT maintained reliable performance across different materials with moderate sensitivity to electrical conductivity variations. Operator experience also played an important role in inspection accuracy. Performance improvements were observed with increasing experience for both methods, with a more pronounced effect in UT applications.

Economic evaluation revealed that MT provides advantages in terms of lower equipment cost and faster inspection speed, making it attractive for routine surface inspection of ferromagnetic components. However, UT offers broader applicability because of its ability to detect subsurface defects and inspect both ferromagnetic and non-ferromagnetic materials.

Based on the experimental results, a practical selection framework was developed. Magnetic particle testing is recommended for the detection of surface defects in ferromagnetic materials, while ultrasonic testing is recommended for subsurface defect evaluation and inspection of non-ferromagnetic materials. The findings provide quantitative guidance for selecting appropriate inspection techniques in industrial weld quality assessment.

Future studies should investigate integrated inspection strategies that combine multiple non-destructive testing methods, as well as automated inspection systems capable of reducing operator dependence and improving inspection consistency.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflict of interest.

Author Contribution

- **Ebulogu Chidi Joel:** Writing the original draft, methodology, investigations, conceptualization.
- **Okwu Elemchukwu Isaac:** Investigations, final analysis.
- **Worgu Fortune:** Reviewing and editing.

REFERENCES

[1] American Society for Nondestructive Testing (ASNT). (2020). Nondestructive Testing Handbook (3rd ed.). Columbus, OH: American Society for Nondestructive Testing.

[2] American Welding Society (AWS). (2020). AWS D1.1/D1.1M: Structural Welding Code-Steel. Miami, FL: American Welding Society.

[3] ASME. (2023). Boiler and Pressure Vessel Code, Section V: Nondestructive Examination. New York, NY: American Society of Mechanical Engineers.

[4] ASME. (2023). Boiler and Pressure Vessel Code, Section VIII: Rules for Construction of Pressure Vessels. New York, NY: American Society of Mechanical Engineers.

[5] Blitz, J., & Simpson, G. (1996). Ultrasonic Methods of Non-Destructive Testing. London, UK: Chapman & Hall.

[6] Cartz, L. (1995). Nondestructive Testing: Radiography, Ultrasonics, Liquid Penetrant, Magnetic Particle, Eddy Current. Materials Park, OH: ASM International.

[7] Drinkwater, B. W., & Wilcox, P. D. (2006). Ultrasonic arrays for non-destructive evaluation: A review. NDT & E International, 39(7), 525-541.

[8] Donoho, D. L. (1995). De-noising by soft-thresholding. IEEE Transactions on Information Theory, 41(3), 613-627.

[9] Hellier, C. (2013). Handbook of Nondestructive Evaluation (2nd ed.). New York, NY: McGraw-Hill Education.

[10] International Organization for Standardization (ISO). (2021). ISO 9934-1: Non-destructive Testing, Magnetic Particle Testing, Part 1: General Principles. Geneva, Switzerland: ISO.

[11] International Organization for Standardization (ISO). (2021). ISO 9934-2: Non-destructive Testing, Magnetic Particle Testing, Part 2: Detection Media. Geneva, Switzerland: ISO.

[12] International Organization for Standardization (ISO). (2024). ISO 16810: Non-destructive Testing, Ultrasonic Testing, General Principles. Geneva, Switzerland: ISO.

[13] Krautkrämer, J., & Krautkrämer, H. (1990). Ultrasonic Testing of Materials (4th ed.). Berlin, Germany: Springer-Verlag.

[14] Raj, B., Jayakumar, T., & Thavasimuthu, M. (2002). Practical Non-Destructive Testing (2nd ed.). New Delhi, India: Narosa Publishing House.

[15] Shull, P. J. (2002). Nondestructive Evaluation: Theory, Techniques, and Applications. New York, NY: Marcel Dekker.

[16] Silk, M. G. (1984). Ultrasonic Transducers for Nondestructive Testing. Bristol, UK: Adam Hilger Ltd.

[17] Thompson, R. B., & Gray, T. A. (1983). A model relating ultrasonic scattering measurements through liquid-solid interfaces to unbounded medium scattering amplitudes. Journal of the Acoustical Society of America, 74(4), 1279-1290.

[18] Wilcox, P. D., Holmes, C., & Drinkwater, B. W. (2003). Advanced reflector characterization with ultrasonic phased arrays in NDE applications. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 50(1), 8-20.

[19] Yusa, N., Janousek, L., Rebican, M., Chen, Z., Miya, K., Chigusa, N., & Ito, H. (2007). Detection of cracks by advanced electromagnetic non-destructive testing methods. Nuclear Engineering and Design, 237(3), 308-318.