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The Effect Of Ultrasonic Testing Variables On The Evaluation Of Weld Quality

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ

المجادلة :11

الإهداء

بكل الحب والامتنان، أهدي هذا البحث المتواضع إلى من كانت لهم البصمة الأعمق في مسيرتي العلمية والحياتية. . . إلى والديّ العزيزين، منبع الحكمة والدعم، اللذين قدّما لي كل ما أملك من قوة وإصرار، وكانا لي المرفأ الآمن في لحظات التعب والقلق، فلهما مني كل الشكر والدعاء. وإلى أساتذتي الأفاضل الذين لم يبخلوا بعلمهم وتوجيهاتهم، فكانوا النور الذي أضاء لي طريق المعرفة، أخص بالذكر مشرف البحث الذي منحني من وقته وجهده ما ساعدني على تجاوز العقبات بكل ثقة. كما أهدي هذا العمل إلى كل من ساندني بكلمة، بدعاء، بابتسامة، في رحلة لم تكن سهلة، لكنها كانت مليئة بالتحديات التي صقلتني وعلّمتني. وأخيرًا، إلى نفسي التي اجتهدت وصبرت وثابرت حتى وصلت، أهدي هذا الجهد المتواضع ليكون شاهدًا على أن لا شيء مستحيل بالإرادة والإيمان.

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Fig.1 Sonatest Ultrasonic Flow detector D20+

Abstract

This Study Investigates The Influence Of Key Ultrasonic Testing (Ut) Variables—Specifically Probe Angle And Frequency—On The Detection And Characterization Of Weld Defects. Using Combinations Of 60° And 70° Probe Angles With 2 Mhz And 4 Mhz Frequencies, Common Weld Defects Including Porosity, Cracks, Slag Inclusions, Lack Of Fusion, And Lack Of Penetration Were Analyzed For Signal Response (Gain). The Results Revealed That Lower Frequency Probes (2 Mhz) Consistently Produced Higher Gain Readings, Indicating Superior Defect Detectability. Additionally, A 70° Probe Angle Frequently Enhanced Signal Response Due To Improved Alignment With Defect Geometries. Among The Defects Studied, Lack Of Fusion Exhibited The Highest Gain At 60°/2 Mhz, Highlighting The Importance Of Tailoring Ut Parameters To Defect Orientation And Type. These Findings Underscore The Critical Role Of Optimized Ut Settings In Ensuring Accurate Weld Quality Evaluation And Suggest That Strategic Selection Of Probe Characteristics Can Significantly Enhance Flaw Detection Capabilities.

INTRODUTION

Ultrasonic Testing

Ultrasonic Testing (UT) Uses High Frequency Sound Waves (Typically In The Range Between 0.5 And 15 Mhz) To Conduct Examinations And Make Measurements. Besides Its Wide Use In Engineering Applications (Such As Flaw Detection/Evaluation, [1]

Dimensional Measurements, Material Characterization, Etc.), Ultrasonics Are Also Used In The Medical Field (Such As Sonography, Therapeutic Ultrasound, Etc.).[2]

In General, Ultrasonic Testing Is Based On The Capture And Quantification Of Either The Reflected Waves (Pulse-Echo) Or The Transmitted Waves (Through-Transmission). Each Of The Two Types Is Used In Certain Applications, But Generally, Pulse Echo Systems Are More Useful Since They Require One-Sided Access To The Object Being Inspected. [3]

Ultrasonic Testing (UT) Is One Of The Most Important Non-Destructive Testing Techniques, Relying On The Transmission Of High-Frequency Sound Waves (1 To 10 Megahertz) Through A Material And Analyzing The Reflected Waves To Detect Defects And Determine Metal Properties[4]. It Is Widely Used To Ensure The Safety Of Facilities And The Quality Of Products. This Technique Can Identify Various Defects, Including Cracks, Porosity, And Lack Of Fusion In Welds, Providing Valuable Information About The Weld Quality And Integrity Of Offshore Components[5]

Previous Studies

radiographic testing involving X-ray or gamma rays to generate weld joint images that reveal internal defects(Zuo, F.; Liu, J.; Zhao, X.; Chen, L.; Wang, L. An X-ray-based automatic welding defect detection method for special equipment system. IEEE/ASME Trans. Mechatron. 2023, 29, 2241–2252) [8], magnetic particle testing, which observes the behaviour of applied magnetic particles to detect surface and near-surface defects (Reddy, K.A. Non-destructive testing, evaluation of stainless steel materials. Mater. Today Proc. 2017, 4, 7302–7312) [9], and liquid penetrant testing, which involves the usage of penetrating fluid that seeps into cracks or pores and further examining the area under UV light after removal of the fluid.(Block, S.B.; Da Silva, R.D.; Lazzaretti, A.E.; Minetto, R. LoHi-WELD: A novel industrial dataset for weld defect detection and classification, a deep learning study, and future perspectives. IEEE Access 2024, 12, 77442–77453) [10]

1. X-Ray Testing

Method Of Conducting Metal Inspection:

1. Sample Preparation: Thoroughly Clean The Metal Surface To Remove Grease And Dirt. Secure The Sample In An Appropriate Position For X-Ray Exposure.

2. 2. Placing The X-Ray Device And Radiation Source: Use A Device That Generates X-Rays (X-Ray Tube) Or Gamma Rays (Such As Iridium-192 Or Cobalt-60).

fig.2 X-Ray Testing

Direct The Radiation Towards The Part To Be Examined.

3. Placing The X-Ray Detector (Film Or Digital Detector): Behind The Sample, Place A Detector (Such As A Film Strip Or Digital Imaging Device) To Capture The Radiation After It Passes Through The Metal. The Varying Degrees Of Radiation Passing Through The Metal, Based On Density, Form An Image Revealing Defects.[11]

4. Operating The Device: Expose The Sample To Radiation For A Specific Period Based On The Metal Thickness And Device Type. Then Develop The Films Or Display The Digital Images On The Screen.

5. Analyzing The Results: The Inspection Technician Analyzes The Image And Looks For Evidence Of Cracks, Cavities, Or Other Defects.

Advantages Of X-Ray Testing:

- Precisely Detects Internal Defects Without Sample Damage.
- Used On A Wide Range Of Metals And Materials.
- High Accuracy For Small Defects.

Disadvantages:

- Requires High Safety Precautions Due To Radiation.
- Equipment And Testing Costs May Be High.
- Difficulty In Inspecting Very Thick Metals.

3. Magnetic Particle Inspection (MPI)

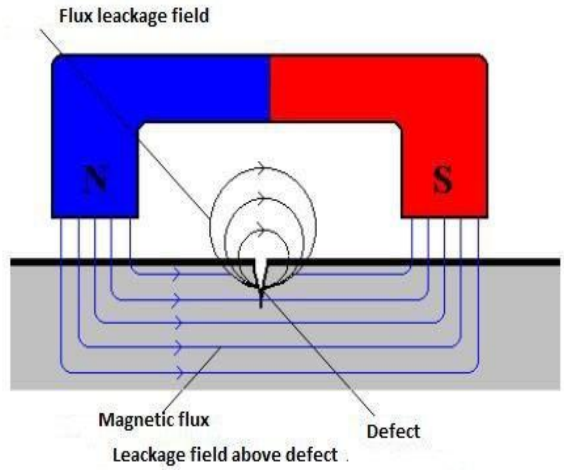
Also Known As Magnetic Particle Testing, Is A Non-Destructive Testing Method Used To Detect Surface And Near-Surface Defects In Magnetized Materials Only, Such As Iron And Steel.

fig.3(MPI)test

Principle Of The Inspection:

The Inspection Is Based On The Principle That Defects In The Material Affect The Flow Of The Magnetic Field, Causing Some Of It To Leak Outside The Surface. By Applying Fine Magnetic Particles (Such As Iron Powder) On The Surface, They Gather At The Location Of The Defect, Making It Clearly Visible.[12]

Steps For Conducting The Inspection:



1. Surface Preparation: Thoroughly Clean The Surface From Oils, Rust, Paint, Or Any Debris That Could Hinder Detection. Chemical Cleaners Or Grinding Processes Can Be Used.

2. Magnetizing The Piece: Passing An Electric Current Through Or Around The Piece To Generate A Magnetic Field. There Are Two Methods:

- Direct Current (DC): Provides Better Results For Near-Surface Defects.
- Alternating Current (AC): More Effective In Displaying Surface Defects.

3. Applying The Magnetic Particles:

- Dry Powder: Sprinkled Directly On The Surface.
- Wet Particles: Suspended In Liquid And Poured Or Sprayed On The Surface. The Particles Can Be Colored Or Fluorescent (Visible Under Ultraviolet Light).

4. Observation And Detection: If A Defect (Such As A Crack) Is Present, It Will Cause A Leakage In The Magnetic Field, Attracting Particles To It And Displaying It As A Line Or Accumulation. When Using Fluorescent Particles, The Inspection Is Carried Out In A Dark Room Using UV Light.

5. Removing The Particles And Cleaning The Piece.

6. Interpreting And Documenting The Results.

Advantages Of The Inspection:

- Quick And Easy.
- Low Cost.
- High Accuracy In Detecting Surface Defects.

Disadvantages:

- Suitable Only For Magnetizable Materials (Iron And Steel).
- Does Not Detect Deep Or Internal Defects.

4. Eddy Current Testing (ECT)

Is A Type Of Non-Destructive Testing (NDT) Used To Detect Surface And Subsurface Defects, And Evaluate The Electrical Conductivity Properties Of Materials, Such As Metals.[13]

Principle Of Operation:

- An Alternating Electric Current Is Passed Through A Copper Coil Within A Probe.
- This Current Generates A Varying Magnetic Field.
- When The Probe Approaches A Conductive Material, The Magnetic Field Induces Small Circular Electrical Currents Within The Material, Known As "Eddy Currents."

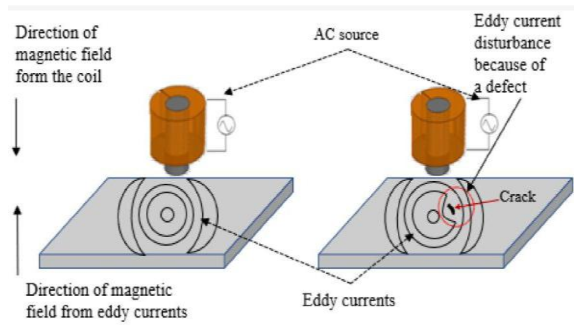


fig.4(ECT)test

- These Currents, In Turn, Generate An Opposing Magnetic Field.
- Any Flaw Or Change On The Material Surface (Such As A Crack, Thickness Variation, Corrosion) Will Affect The Behavior Of These Currents.
- These Changes Are Measured By The Probe And Analyzed Using An Electronic Device, Indicating The Presence Of Defects.

Applications Of Eddy Current Testing:

- Detecting Surface Cracks.
- Measuring Coating Thickness Or Material Thickness.
- Detecting Corrosion Or Subsurface Voids.
- Differentiating Materials And Metals Based On Their Properties.
- Inspecting Heat Exchanger Tubes, Aircraft Components, And Metal Structures.

Advantages Of Eddy Current Testing:

- Non-Contact Inspection.
- Very Fast And Effective.
- Suitable For Small Or Complex Areas.
- Can Be Used On Coatings Or Layers.

Disadvantages:

- Works Only On Electrically Conductive Materials.
- Results Can Be Affected By Changes In Thickness Or Distance Between The Probe And The Surface.
- Requires Precise Calibration And High Expertise.
- Less Sensitive To Very Deep Defects.

5. **Liquid Penetrant Testing**

Also Known As PT (Penetrant Testing), Is A Non-Destructive Testing Method Used To Detect Surface Defects Such As Cracks, Pores, Small Holes, Or Any Open Voids On The Surface Of Materials.[14]

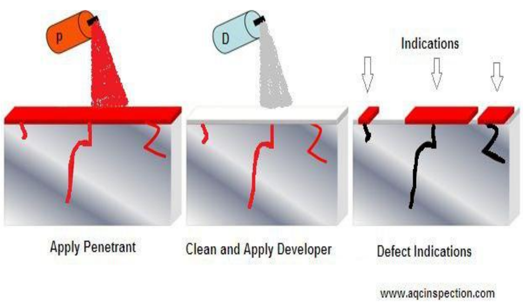
fig.5(LPT)test

Working Principle:

It Relies On Capillary Action, Where A Low Surface Tension Colored Liquid Penetrates Into The Tiny Defects On The Surface. After Removing The Excess Liquid And Applying A Developer, The Defect Becomes Clearly Visible.

Steps For Conducting The Inspection:

1. Pre-Cleaning: Remove Any Oils, Greases, Rust, Dust, Or Coatings. The Surface Must Be Dry And Free From Any Debris.



2. Penetrant Application: Spray Or Apply A Colored Liquid (Usually Red Or Fluorescent) On The Surface. Leave It For A Specific Time (10-30 Minutes Depending On The Type Of Liquid) To Penetrate Into Any Surface Defect.3. Excess Penetrant Removal: Gently Wipe The Surface To Remove The Liquid Without Pulling Out What Entered The Defects. Special Materials Or Water Are Used Based On The Type Of Liquid.

4. Developer Application: Apply A Fine White Powder Or Liquid That Absorbs The Remaining Liquid Inside The Defect And Pulls It To The Surface. Defects Appear As Colored Indications (Usually Red On A White Background).

5. Inspection:

- Under Normal Light If The Dye Is Visible (Visible Dye).
- Using UV Light If The Dye Is Fluorescent (Fluorescent Dye) In A Darkroom.

Advantages Of Liquid Penetrant Testing:

- Simple And Easy To Use.
- Cost-Effective.
- Detects Very Minute Defects.
- Can Be Used On Most Solid Materials (Metals, Ceramics, Plastics).

Disadvantages:

- Only Detects Open Surface Defects.
- Requires A Completely Clean And Dry Surface.
- Not Suitable For Rough Or Porous Surfaces.

Examples Of Liquid Penetrant Testing Applications:

- Weld Inspection: To Detect Micro Cracks Or Defects Resulting From Rapid Cooling.
- Mechanical Part Inspection: Such As Columns, Blades, Gears To Detect Corrosion Or Stress-Induced Cracks.
- Aviation And Automotive Industries: For Inspecting Minute Cracks In Aluminum That Are Not Visible To The Naked Eye.

Important Considerations During The Inspection:

- The Ideal Inspection Temperature Should Be Between 10°C And 50°C.
- Liquid Penetrant Testing Should Not Be Used On Very Rough Or Non-Metallic Porous Surfaces Such As Concrete.
- Dwell Time Of The Liquid Is Crucial Because It Affects The Detection Accuracy.

1. Background and Importance of Weld Inspection

Welding is an essential fabrication process used extensively across industries such as aerospace, automotive, construction, and energy generation. It ensures structural integrity and continuity in metallic components, providing both mechanical strength and leak-proof joints. However, welds are also susceptible to various types of discontinuities and defects—including porosity, cracks, slag inclusions, lack of fusion, and lack of penetration—which can severely compromise the performance and safety of components if undetected or improperly characterized.[15]

To mitigate these risks, nondestructive testing (NDT) techniques have been developed and refined, among which ultrasonic testing (UT) stands out for its high sensitivity, penetration depth, and real-time inspection capability. Ultrasonic methods, especially when coupled with advancements like phased array technology and digital signal processing, have become crucial tools in both manufacturing quality control and structural health monitoring.

This research contributes to the growing body of work on ultrasonic weld inspection by providing a comparative evaluation of different weld defects based on probe angle, frequency, and resulting signal amplitude. The results serve to further clarify the interaction between ultrasonic waves and defect morphology, orientation, and material boundaries.

2. Ultrasonic Testing: Principles and Practices

Ultrasonic testing employs high-frequency sound waves—typically in the range of 0.5 to 10 MHz—that propagate through a material. When these waves encounter a boundary such as a crack or an inclusion, part of the wave is reflected back and captured by a transducer. The time of flight, amplitude, and phase of these echoes provide information about the presence, size, and nature of discontinuities.[16]

Conventional UT employs single-element transducers, while advanced methods such as Time-of-Flight Diffraction (TOFD) and Phased Array Ultrasonic Testing (PAUT) enable detailed characterization and sizing of flaws with higher precision and spatial resolution (Charlesworth & Temple, 2001). PAUT, in particular, allows the steering, focusing, and scanning of the ultrasonic beam electronically, which improves defect detection probability and coverage (Schmid et al., 2012).

3. Wave Propagation and Scattering in Welded Materials

The propagation of ultrasonic waves in welded joints is complex due to anisotropy, inhomogeneity, and geometric discontinuities. Welds often contain dendritic microstructures and residual stresses that cause beam distortion and scattering (Ogilvy, 1991; Tsinopoulos et al., 2000).

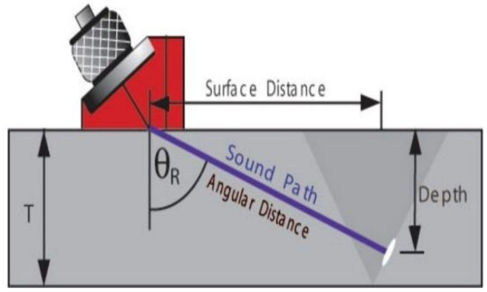


Fig.6

These effects become more pronounced at higher frequencies or with angled beam techniques, which are necessary for detecting planar flaws such as lack of fusion and cracks.[17]

Lighthill's (1978) theoretical formulations on wave propagation in fluids provide the foundational physics, while works like Rose (1999) and Hirao & Ogi (2003) expand the theory to wave behavior in solids, including mode conversion and guided wave phenomena. These concepts are critical to interpreting the behavior observed in this study, where different probe angles and frequencies yield varying

4. Types of Weld Defects and Their Ultrasonic Characteristics

Each weld defect has unique ultrasonic signatures:

Porosity comprises gas-filled voids, generally resulting in low-amplitude, diffuse backscatter due to their spherical shape and acoustic impedance mismatch (Cho et al., 2000).

Cracks present as sharp, planar reflectors and often generate strong, consistent echoes depending on their orientation relative to the probe beam (Lord & Thompson, 1978; Sohn et al., 2004).

Slag inclusions are solid foreign materials trapped in the weld, often producing erratic, anisotropic reflections due to their irregular geometry (Fellinger et al., 1995).

Lack of fusion,and lack of penetration are both examples of planar discontinuities at the weld boundary and root, respectively. They are often the most critical dueto their potential to grow under fatigue loading (Berthold, 1989).Accurate detection of these flaws requires optimal selection of probe parameters—such as frequency and angle—which is central to the present study.

6. Motivation and Objectives of the Study

revious research has evaluated UT parameters for specific applications, but a systematic comparison across multiple defect types under consistent conditions is still limited. For example, Hatchell (2004) compared UT techniques broadly, while Yashiro et al. (2002) examined quantitative evaluation of welding flaws without fully isolating the effects of frequency and angle.

This study addresses the gap by analyzing how probe angle (60° and 70°) and frequency (2 MHz and 4 MHz) affect signal amplitude for each defect type. The amplitude of reflected signals, measured in decibels (dB), provides a basis for assessing flaw detectability and probe sensitivity. The goals are:

To determine the most sensitive probe configuration for each defect type.

To examine how flaw morphology interacts with wave frequency and incidence angle.

To support the development of guidelines for optimized UT inspection of welds.

6. Methodology OverviewA

series of ultrasonic tests were conducted on welded samples containing known defects—porosity, crack, slag inclusion, lack of fusion, and lack of penetration. Each defect was examined using combinations of two probe angles (60° and 70°) and two frequencies (2 MHz and 4 MHz). The amplitude of the reflected ultrasonic signals was recorded and analyzed.

The defect length was also varied across samples to evaluate its correlation with signal amplitude. These measurements allowed for a comparative assessment of how each parameter influenced the detection sensitivity of the ultrasonic probe.

7. Literature Context and Theoretical Support

A . Probe Angle and Beam

SteeringThe angle of incidence plays a key role in the interaction of ultrasonic waves with defects, particularly for planar flaws. At certain angles, energy transmission into the flaw is maximized, resulting in higher echo amplitudes (Kim et al., 2018). This principle underlies angled beam techniques, which are especially effective for locating lack of fusion defects at weld toes (Biernacki et al., 2007).

Studies by Cawley & Alleyne (1996) and Zhang & Lee (2012) support the use of guided and steered waves for flaw localization in large and complex structures. The present work builds upon these insights by applying angled beam probes to multiple defect types.

B . Frequency Effects and Resolution

Frequency selection involves a trade-off between resolution and penetration. Lower frequencies (e.g., 2 MHz) offer deeper penetration but lower sensitivity to small defects, whereas higher frequencies (e.g., 4 MHz) provide better resolution but suffer from increased attenuation and scattering (Silk, 1984; Maev, 2008).

Moles & Mukherjee (2002) and Dutta et al. (2016) have used simulation and neural network techniques to optimize frequency selection for weld flaw classification. These methodologies align with the empirical approach taken in this study.

C . Signal Processing and Interpretation

The interpretation of ultrasonic signals is influenced by various processing techniques, such as envelope detection, frequency filtering, and wavelet analysis (Wang & Yuan, 2007). While this study uses raw amplitude values, future work could incorporate signal processing to enhance defect characterization.

The use of neural networks and advanced algorithms for defect classification, as discussed by Dutta et al. (2016), highlights the trend toward intelligent inspection systems—an area where this study provides foundational data.:

Advantages And Disadvantages

The Primary Advantages And Disadvantages When Compared To Other NDT Methods Are:

Advantages

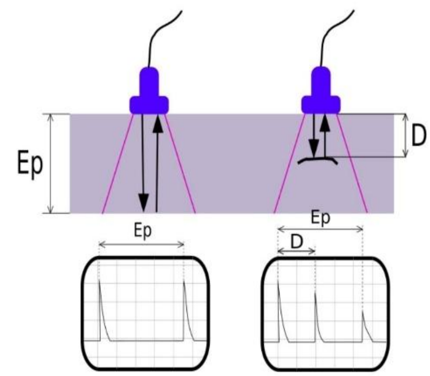
- It Is Sensitive To Both Surface And Subsurface Discontinuities.
- The Depth Of Penetration For Flaw Detection Or Measurement Is Superior To Other NDT Methods.
- Only Single-Sided Access Is Needed When The Pulse-Echo Technique Is Used.
- It Is Highly Accurate In Determining The Reflector Position And Estimating Its Size And Shape.
- Minimal Part Preparation Is Required.
- It Provides Instantaneous Results.
- Detailed Images Can Be Produced With Automated Systems.
- It Is Nonhazardous To Operators Or Nearby Personnel And Does Not Affect The Material Being Tested.
- It Has Other Uses, Such As Thickness Measurement, In Addition To Flaw Detection.
- Its Equipment Can Be Highly Portable Or Highly Automated.

Disadvantages

- Surface Must Be Accessible To Transmit Ultrasound.
- Skill And Training Is More Extensive Than With Some Other Methods.
- It Normally Requires A Coupling Medium To Promote The Transfer Of Sound Energy Into The Test Specimen.
- Materials That Are Rough, Irregular In Shape, Very Small, Exceptionally Thin Or Not Homogeneous Are Difficult To Inspect.
- Cast Iron And Other Coarse Grained Materials Are Difficult To Inspect Due To Low Sound Transmission And High Signal Noise.
- Linear Defects Oriented Parallel To The Sound Beam May Go Undetected.
- Reference Standards Are Required For Both Equipment Calibration And The Characterization Of Flaws.

Ultrasonic Testing (UT)

Basic Principles



A Typical Pulse-Echo UT Inspection System Consists Of Several Functional Units, Such As The Pulser/Receiver, Transducer, And A Display Device. A Pulser/Receiver Is An Electronic Device That Can Produce High Voltage Electrical Pulses. Driven By The Pulser, The Transducer Generates High Frequency Ultrasonic Energy. The Sound Energy Is Introduced And Propagates Through The Materials In The Form Of Waves. When There Is A Discontinuity (Such As A Crack) In The Wave Path, Part Of The Energy Will Be Reflected Back From The Flaw Surface. The Reflected Wave Signal Is Transformed Into An Electrical Signal By The Transducer And Is Displayed On A Screen. Knowing The Velocity Of The Waves, Travel Time Can Be Directly Related To The Distance That The Signal Traveled. From The Signal, Information About The Reflector Location, Size, Orientation And Other Features Can Sometimes Be Gained.[18]

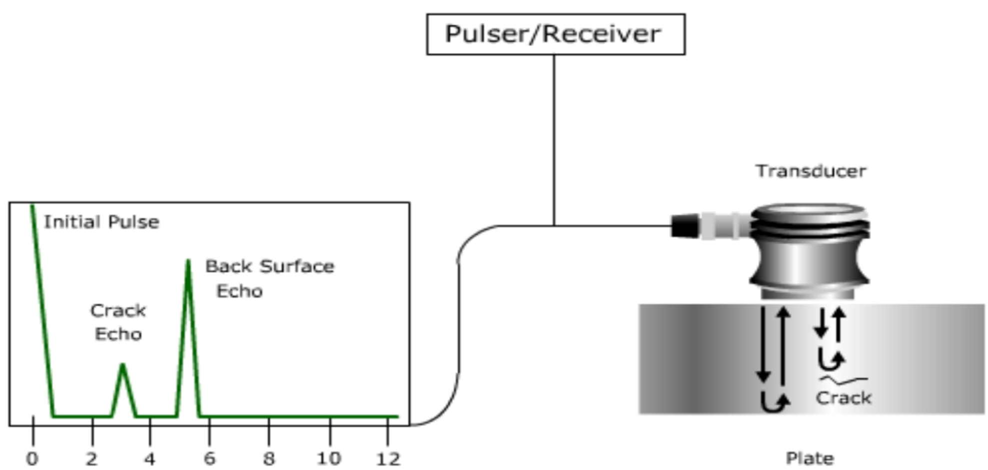


Figure 7 Shows The Basic Principle Of Ultrasound.

The Factors Influencing Ultrasonic Inspection

The Impact Of Ultrasonic Testing Variables On Evaluating Weld Quality Significantly Depends On Several Key Factors Related To How The Tests Are Conducted And The Techniques Used.

Some Variables That Can Affect The Results Include:

1. Device Setup And Frequency Used

The Frequency And Wavelength Ratio Of Defects:

The Choice Of Frequency Depends On The Size And Type Of Defects To Be Detected. High-Frequency Waves Produce A Small Wavelength, Providing Higher Accuracy In Detecting Minute Defects Such As Small Cracks Or Slight Variations In The Metal Structure. On The Other Hand, Low-Frequency Waves Can Penetrate Thicker Sections But May Compromise Accuracy In Determining The Defect Location And Size.[19]

Physically, The Wavelength Used Should Be Suitable For The Defect Dimensions; A Defect With A Size Less Than Half The Wavelength May Not Be Clearly Distinguished.

Technical Settings Of The Device:

- Gain: Proper Gain Adjustment Is Essential To Amplify The Reflected Signal Without Amplifying Noise.
- Time Window: Defining A Suitable Time Period For Signal Reception Is Critical To Separate Useful Signals From Wave Reflections From External Surfaces Or Minor Defects.
- Frequency Filters: They Can Be Used To Isolate The Desired Frequency Signals And Eliminate Interference From Various Noise Sources.

Angle Of Incidence:

The Angle At Which The Wave Enters The Material Is A Key Factor In Determining Its Reflection And Refraction Paths When Encountering Defects.

Improper Entry Angles May Lead To Unexpected Wave Refractions Or Scatterings, Making Them Difficult To Analyze, Resulting In Unreliable Outcomes. [20]

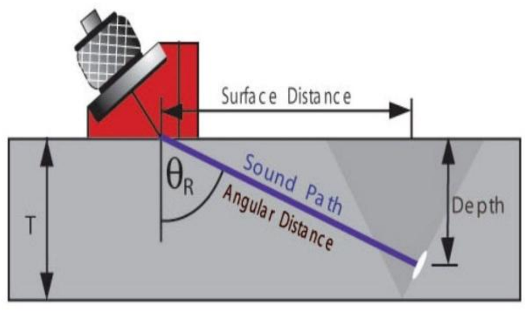


fig.8 angle of wave

Relying On Multiple Techniques Such As Double Or Multiple Angle Inspections Can Enhance The Precision Of Defect Detection.

Couplants:

- A Coupling Medium (Such As Oil Or Gel) Must Be Used To Ensure Wave Transmission Without Significant Energy Loss.
- The Quality Of The Coupling Medium In Terms Of Viscosity And Homogeneity Can Affect The Intensity And Regularity Of The Transmitted And Received Signals.[21]

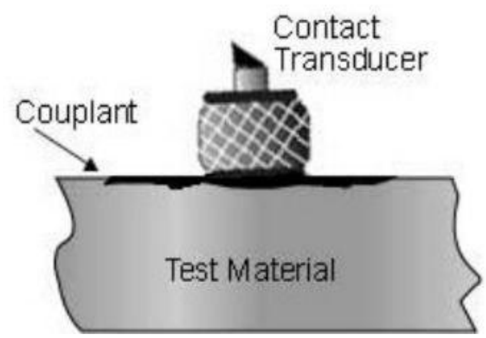


Fig.9 Couplants

- The Presence Of Air Bubbles Or Uneven Distribution Of The Medium May Cause Unwanted Reflections Leading To Misinterpretations.

3. Material's Physical And Mechanical Properties

Physical Constants:

Density And Elastic Modulus: The Material's Density And Modulus Of Elasticity Affect The Speed Of Sound Waves Transmission, Hence Impacting The Accuracy Of Arrival Times And Reflections.

Absorption And Wave Scattering: Some Materials Absorb Acoustic Energy Or Scatter Waves Due To Their Granular Structure Or Inherent Fine Defects Within The Metal.

Distortions And Variations Within The Weld:

In Welding Areas, There May Be Changes In Mechanical Properties Due To Rapid Cooling Or Thermal Effects. The Presence Of Mixed Metal Regions Or Areas Containing Impurities, Such As Voids Or Cracks, Can Alter The Wave Path And Influence Reflection Strength.[20]

4. Welding Process And Sample Quality

Welding Process Techniques:

Welding Operations (Such As Arc Welding, Gas Welding, And Laser Welding) Differ In Their Impact On The Final Sample Structure In Terms Of Temperature And Cooling Rates, Resulting In Variations In The Metal Structure In The Weld Area.

The Degree Of Control In The Welding Process – Whether Mechanical Or Manual – Can Affect The Welding Quality And The Uniformity Of Properties Within The Welded Zone.

Sample Preparation And Surface Preparation:

Sample Surfaces Must Be Clean And Free From Contamination And Rust To Ensure Perfect Contact With The Coupling Medium. Any Surface Preparation Flaws May Result In Unexpected Wave Scatterings Affecting The Final Interpretation Of Received Signals.

5. Device Calibration And Operational Expertise

Periodic Calibration:

Ensure The Use Of Regularly Calibrated Devices To Ensure Measurement Accuracy; Minor Deviations In Calibration Can Lead To Significant Errors When Analyzing Results. Using Standard Samples Or Known As "Calibration Wedges" To Calibrate The Device Before Starting Tests Is A Fundamental Step.

Operational Experience And Proficiency:

Understanding Technical Practices And Analyzing Signal Waveform Requires Specialized Expertise; The Operator's Experience Can Determine Whether Interferences Are Due To Equipment Issues Or Actual Defects In Welding.

6. Environmental Conditions And External Influences

Temperature And Ambient Environment:

Atmospheric Conditions Such As Temperature And Humidity Affect Material Properties And Device Performance, As Temperature Changes Can Alter Wave Propagation Speed.[21]

Vibration And Interference:

During Testing In Industrial Settings, Vibrations From Heavy Equipment Or Machine Movement Can Interfere With The Signals Received.

A Stable Testing Environment Must Be Provided, Or Measures Must Be Taken To Compensate For These Interferences (Such As Mechanical Barriers Or Insulation).

Evaluating Welding Quality Using Ultrasonic Testing Is Not Just About Device Performance; It Involves The Integration Of Several Factors And Their Harmonization. This Requires:

Choosing Appropriate Device Settings And Frequencies That Align With The Nature Of The Defect And Weld Size. Ensuring The Quality Of The Couplant And Correct Angles For Wave Introduction.

A Precise Understanding Of The Studied Material's Properties And The Impact Of Internal Distortions On Wave Transmission.

Emphasizing Careful Sample Preparation And Continuous Operator Training. Processing Signals Using Advanced Digital Techniques And Accurately Analyzing Patterns.

Monitoring Environmental Conditions To Ensure Result Stability And Achieve Precise Device Calibration. In This Manner, A More Accurate And Reliable Assessment Of Welding Quality Can Be Achieved Using Ultrasonic Testing Techniques, Contributing To Improving Manufacturing Processes And Reducing Potential Defects In The Final Products.

Variables Used In The Research

1. Ultrasonic Wave Frequency.

A. High Frequencies (5-10 Mhz):

Detection Precision And Detectable Flaw Size:

- High Precision: High Frequencies Allow For Very Precise Measurements Due To The Short Wavelength, Enabling The Accurate Detection Of Small Defects.
- Small And Fine Defects: These Frequencies Can Detect Flaws Such As Fine Cracks, Small Irregularities In The Metallic Structure, And Others Related To Variations In The Metal Structure.

Limitations And Challenges:

- Sensitivity To Thin And Uneven Surfaces: High Frequencies Require A Uniform Surface; Deviations Or Variations In The Material On The Surface May Cause Signal Dispersion Or Data Distortion.
- Limited Penetration In Thick Materials: Despite The High Precision, The Penetration Capability May Be Limited In Thick Materials; As Sample Thickness Increases, Energy Disperses More, Reducing The Effectiveness Of Detecting Defects Within The Weld Depth.

B. Low Frequencies (1-2 Mhz):

Penetration And Application In Thick Materials: Capability

- Deep Penetration: With Longer Wavelengths, Low-Frequency Waves Can Penetrate Thick Materials Better, Making Them Suitable For Detecting Flaws In Deep Welds And Thick Parts.
- Detection Of Relatively Large Flaws: These Frequencies Can Identify Larger Flaws Such As Significant Voids, Lack Of Fusion, And Large Cracks In Thick Materials.

Limitations And Challenges:

- Low Detection Precision: Very Small Flaws Can Be Challenging To Detect Using Low Frequencies, Possibly Requiring Additional Techniques
- Flaw Location And Size Determination: It May Be Difficult To Pinpoint The Precise Location And Size Of A Flaw When Using Low Frequencies, Necessitating Assisting Techniques For Determination.

In Summary

The Decision To Use High Or Low Frequency Should Be Based On The Following Considerations:
Detection Accuracy: High Frequency Provides Better Detail For Small Defects.
Penetration Capability: Low Frequency Allows For Inspecting Thick Materials And Detecting Larger Defects.
Sample Properties And Application: Surface Evaluation, Thickness, And Expected Defects Should Be Assessed To Achieve The Best Balance Between Accuracy And Penetration.

2. Transmission And Reception Angles

The Choice Of The Best Angle For Detecting Metal Defects Using Ultrasonic Waves Depends On The Type Of Defect (Surface Or Internal) And Its Orientation Relative To The Metal Surface. Here Is Some Important Information About Selecting The Appropriate Angle:

A. Optimal Angles Based On Defect Type:

Internal Defects:

- 0-Degree Angle (0°): Used To Directly Send A Longitudinal Wave Vertically Into The Surface. Suitable For Detecting Deep Internal Defects (Such As Voids Or Impurities) And Effective When Defects Are Parallel To The Metal Surface.

Inclined Or Non-Vertical Defects:

- 45° To 70° Angle: Shear Waves Are Used To Penetrate The Metal At An Inclined Angle, Ideal For Detecting Cracks Or Non-Vertical Voids. Common In Weld Inspections As Defects Are Often Inclined Relative To The Surface.

Surface Defects:

- 70° Angle Or Higher: Surface Waves Are Used To Detect Defects Very Close To The Surface, Effective For Detecting Fine Cracks And Surface Defects.

B. Defects Related To Welds:

- Angles Between 45° And 60° Are Most Common For Inspecting Welds Where Defects (Such As Intergranular Cracks Or Incomplete Penetration) Are Inclined Relative To The Metal Surface.

C. Other Considerations For Angle Selection:

- Metal Thickness: Low Angles (0°) Are Used In Thin Metals To Avoid Multiple Reflections, While Inclined Angles (45° To 70°) Are Preferred In Thick Metals To Improve Access To Defects.
- Defect Orientation: Defects Perpendicular To The Wave Direction Show Stronger Reflections, So The Angle That Makes The Wave Collide Vertically With The Defect Is Chosen.

Wave Type:

- Longitudinal Waves: Used With Low Angles (0°) To Detect Internal Defects.
- Shear Waves: Used With Inclined Angles (45° To 70°) To Detect Inclined Defects.
- Surface Waves: Used With Sharp Angles To Detect Surface Defects.

In Summary:

- 0° Angle: For Deep Internal Defects Parallel To The Surface.
- 45° To 70° Angle: For Inclined Defects, Especially In Welds.
- 70° Angle Or Higher: For Surface Defects.

Selecting The Appropriate Angle Depends On The Inspection Design And Analysis Of Defect Orientation And Nature To Ensure The Best Sensitivity For Detection.

Factors Affecting The Speed Of Ultrasonic Waves:

1. Material Density:

Definition: Density Is The Mass Per Unit Volume Of A Material (Often In Units Of Kg/M^3).

Impact: As The Material Density Increases, The Mass Of The Particles Increases, Making It Difficult For Sound Waves To Travel Quickly Since The Particles Need More Time To Transfer Energy To Each Other.

Result: Generally, Increasing Density => Decreasing Speed Of Sound, But This Is Also Related To Elasticity, Meaning That The Relationship Is Not Always Linear.

2. Material Elasticity:

Definition: Elasticity Refers To The Material's Ability To Return To Its Original Shape After Deformation. It Is Often Measured By The Young's Modulus Or The Bulk Modulus.

Impact: More Elastic Materials Transmit Sound Faster Because They Respond More Quickly To The Applied Forces And Efficiently Transmit Vibrations.

Result: Increase In Elasticity => Increase In Speed Of Sound.

Important Note: In Some Materials Like Metals, Despite High Density, High Elasticity Gives A High Speed Of Sound (E.G., Steel).

3. Temperature:

Definition: Temperature Affects The Movement And Speed Of Particles.

Impact In Gases: With Increasing Temperature, The Energy Of Particles Increases, Moving Faster, Facilitating The Transmission Of Sound Waves.

Result In Gases: Higher Temperature => Higher Speed Of Sound.

In Solids And Liquids: The Impact Is Less Pronounced, And The Result May Vary Depending On The Nature Of The Material, As Heat Can Reduce Molecular Cohesion.

4. Medium Type:

Gases: Sound Is Slower Because Particles Are Dispersed, And The Distance Between Collisions Is Large (E.G., Air).

Liquids: Faster Than Gases As Particles Are More Closely Packed, Allowing Vibrations To Travel More Quickly (E.G., Water).

Solids: Sound Travels As Fast As Possible Because Particles Are Tightly Bonded, Accelerating Wave Transmission (E.G., Iron Or Glass).

Example:

Speed Of Sound In Air (At 20°C): Approximately 343 M/S

In Water: Approximately 1480 M/S

In Steel: Approximately 5000 M/S

The Importance Of Calibrating Devices

1. Device Calibration:

Regular Calibration: Devices Should Be Calibrated Periodically Using Approved Standards To Ensure That Readings Remain Accurate Despite Exposure To Environmental Changes.[22]

Calibration In Similar Conditions: It Is Preferable To Calibrate Under The Same Pressure And Temperature Conditions In Which The Tests Will Be Conducted, Or Adjust Readings Based On Differences.

Recording Calibration Data: Accurate Records Of Calibration Processes Must Be Kept To Monitor Any Changes Or Deviations In The Device's Performance Over Time.

2. Use Of Reference Materials:

Selecting Materials With Known And Stable Properties: Reference Materials With Reliable Mechanical, Thermal, Or Chemical Properties Should Be Used Under Various Test Conditions.

System Performance Verification: Reference Material Can Be Used To Test The Device And The System's Performance As A Whole Before Commencing Actual Sample Testing.

Comparison With Theoretical Results: Reference Materials Help Verify The Alignment Of Measurement Results With Expected Values, Boosting Confidence In Result Accuracy.

3. Adjusting Test Procedures:

Compensating For Pressure And Temperature Effects: Protocols Should Be Adjusted To Include Compensatory Steps To Calculate Changes That May Occur In The Material Or Device Due To Pressure Or Temperature Variations.

Thermal And Pressure Stabilization: Pre-Conditioning The Sample And Device In Test Ambient Conditions Is Preferable To Reduce Result Variations.

Standardizing Test Speed And Exposure Time: To Ensure Consistency, The Time Samples Are Exposed To Heat Or Pressure Should Be Standardized Before And During Testing.

Using Thermal Barriers Or Insulating Pressures: In Some Cases, Thermal Barriers Or Protective Covers Can Be Used To Shield Sensitive Components From Sudden Temperature Or Pressure Changes.

Properties Of Metal Suitable For Defect Detection:

Ultrasonic Waves Are Effective In Detecting Defects In Most Metals, But Their Effectiveness Depends On The Metal Properties Such As Density, Homogeneity, And Elasticity[23]. The Best Types Of Metals For Detection Using Ultrasonic Waves Are Those Characterized By:

1. High Homogeneity:

Homogeneous Metals Like Carbon Steel And Stainless Steel Provide Smooth Wave Propagation, Making It Easier To Detect Defects.

2. Moderate Density And Elasticity:

Metals With Moderate Density And Elasticity Such As Aluminum And Titanium Are Ideal As Waves Propagate Easily With Precise Reflections In The Presence Of Defects.

3. Low Acoustic Scattering:

Fine-Grained Metals Like Copper And Processed Aluminum Reduce Wave Scattering, Enhancing Detection Accuracy.

4. Good Wave Reflection Capability:

Metals With Good Reflective Surfaces Within The Material, Such As Bronze And High-Performance Alloys, Show Clear Reflections In The Presence Of Defects.

Types Of Metals Suitable For Detection:

1. Steel: Widely Used In Industries For Its Homogeneity And Ease Of Wave Propagation, Suitable For Detecting Internal Cracks, Voids, And Impurities.

2. Aluminum: Lightweight And Easily Inspected With Ultrasonic Waves, Suitable For Detecting Small Defects, Especially In The Aerospace Industry.

3. Titanium: Used In Medical And Aerospace Industries, Its Flexible Properties Facilitate The Detection Of Internal Defects.

4. Copper And Alloys: Suitable For Detecting Internal And Surface Defects, Used In Pipes And Electrical Industries.

5. Nickel And Alloys: Used In Heat And Corrosion-Resistant Applications, Demonstrating Good Performance In Defect Detection.

Metals Less Efficient For Ultrasonic Inspection:

Coarse-Grained Metals Like Cast Iron Scatter Waves Due To Large Grain Size, Reducing Detection Accuracy.

Porous Metals Like Some Aluminum Alloys Have Pores That Interfere With Wave Propagation.

Here's The English Translation Of The Arabic Text You Provided:

"In Addition To That, There Are Other Factors That Can Affect The Efficiency Of Ultrasonic Inspection For Metals. For Example, The Shape And Size Of Defects Can Lead To Variations In The Strength Of The Reflected Signal And The Ease Of Their Detection. Also, The Surface Roughness Of The Metal Can Cause Additional Scattering Of The Waves, Reducing The Sensitivity Of The Inspection.

Furthermore, The Frequency Of The Ultrasonic Waves Used Plays A Crucial Role. Higher Frequencies Can Provide Better Accuracy In Detecting Small Defects, But They May Penetrate Materials Less Effectively, Especially Those With A Coarse Structure. Conversely, Lower Frequencies Can Penetrate Materials Better But May Be Less Sensitive To Fine Defects[24].

Therefore, When Conducting An Ultrasonic Inspection, It Is Essential To Consider The Properties Of The Material, The Types Of Potential Defects, And To Choose The Appropriate Frequency And Technique To Achieve The Best Possible Results. In Some Cases, It May Be Necessary To Use Complementary Inspection Techniques To Ensure Comprehensive Detection Of Any Existing Defects[25

Types Of Internal Welding Defects:

Internal Defects In Welding Are Issues That Occur Inside The Welded Joint, Affecting Its Strength And Quality[26]. Some Of The Most Important Types Of These Defects Include:

1. Porosity:

Occurs Due To Trapped Gases Inside The Molten Metal During The Cooling Process.

May Appear As Small Or Large Bubbles Distributed Within The Material.

Causes Include Metal Contamination With Grease Or Oils, Moisture In Base Materials Or Fillers, And High Cooling Rates.

2. Cracks:

Can Be Longitudinal, Transverse, Or In The Form Of Small Cracks Within The Material.

Arise From Thermal Stresses Or Structural Changes During Cooling.

Types Include Hot Cracks (At High Temperatures) And Cold Cracks (After Cooling).

3. Lack Of Fusion:

Failure To Fuse The Filler Material With The Base Metal Or Between Different Layers Of The Weld.

Causes Include Low Welding Current, Incorrect Electrode Angle, And High Welding Speed.

4. Incomplete Penetration:

Insufficient Penetration Of The Weld Through The Base Material Thickness.

Causes Include Inadequate Welding Current And Improper Gap Between Parts.

5. Inclusions:

Entrapment Of Foreign Materials Like Slag Or Metal Oxides Within The Weld.

Causes Include Insufficient Cleaning Between Layers And The Use Of Low-Quality Welding Materials.

6. Cavity:

Voids Within The Weld Due To Uneven Contraction During Cooling.

May Vary In Size Depending On The Degree Of Contraction.

7. Structural Discontinuities:

Include Areas With Irregular Formation Or Weaknesses In The Weld.

Causes Include Incorrect Welding Techniques And Improper Joint Design.

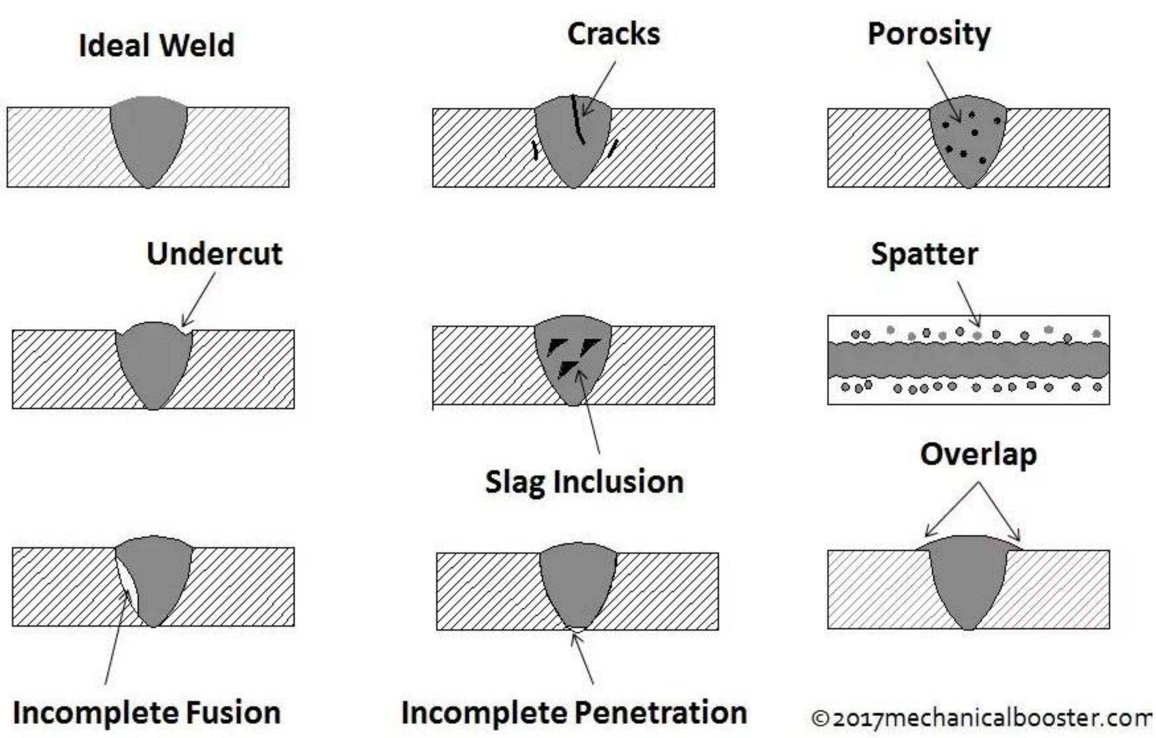
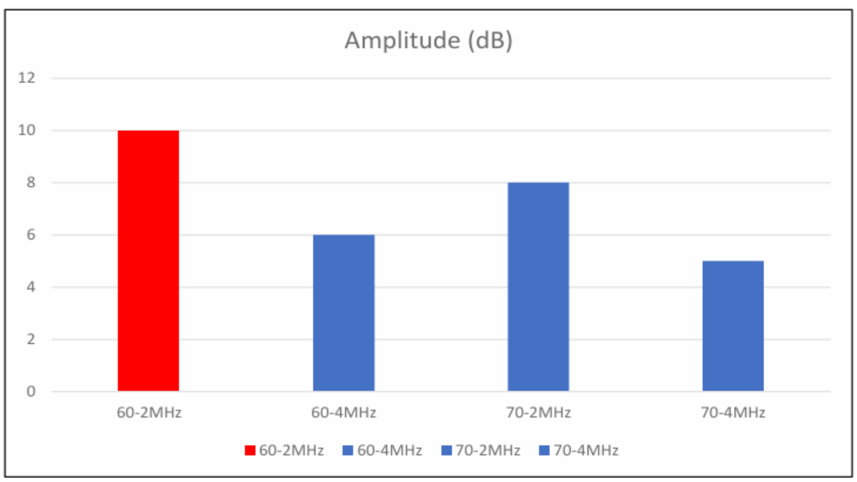


Figure 9 Types Of Internal Welding Defects

Calculations

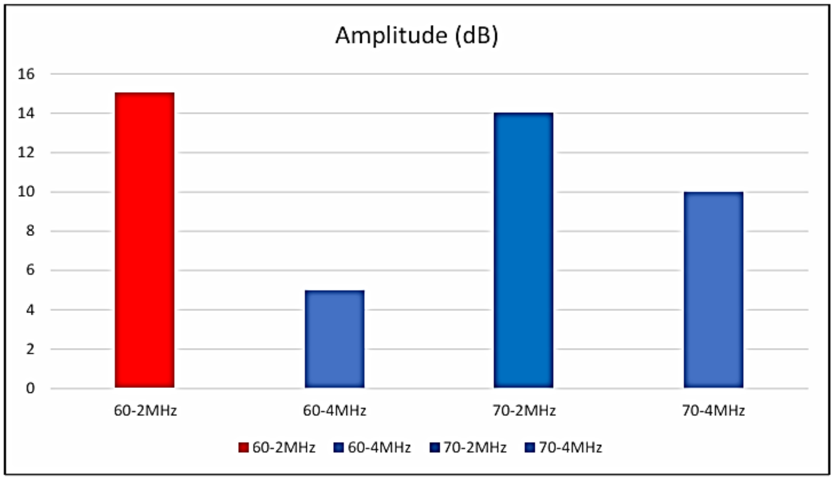
Fig.10 different angles and frequencies


fig.11 Samples used in the experiment



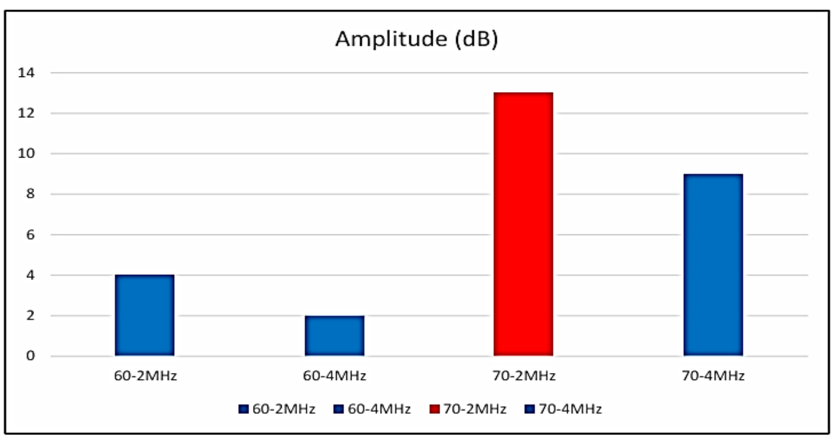
Defect type	Probe Angle	Probe Frequence	Defect Length	Defect Gain
Porosity	60 Degree	2 MHz	10 mm	0 dB
	60 Degree	4 MHz	10 mm	-4 dB
	70 Degree	2 MHz	08 mm	-2 dB
	70 Degree	4 MHz	08 mm	-5 dB

Fig.12



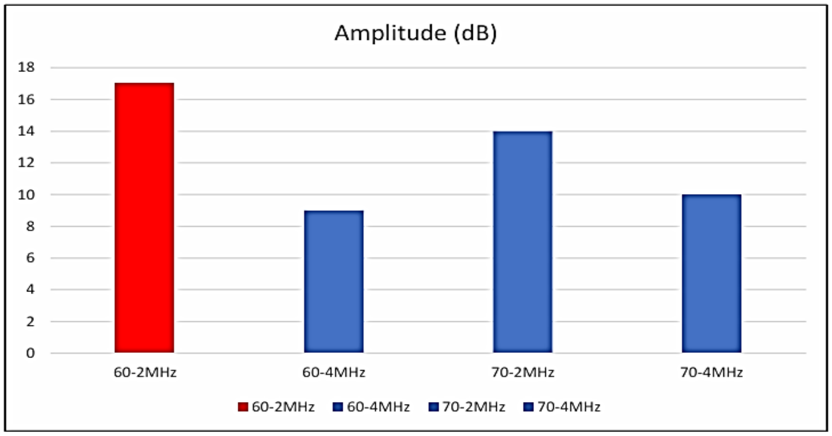
Defect type	Probe Angle	Probe Frequence	Defect Length	Defect Gain
Crack	60 Degree	2 MHz	16 mm	5 dB
	60 Degree	4 MHz	16 mm	-5 dB
	70 Degree	2 MHz	14 mm	4 dB
	70 Degree	4 MHz	14 mm	0 dB

fig.13



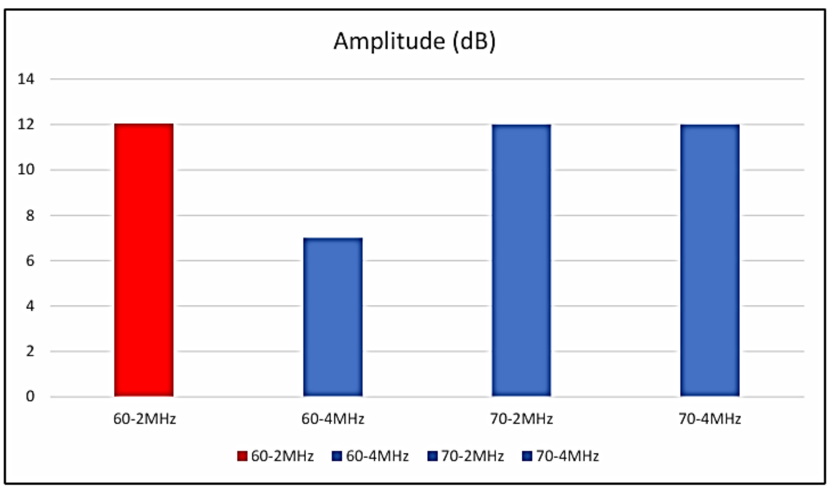
Defect type	Probe Angle	Probe Frequence	Defect Length	Defect Gain
Slag	60 Degree	2 MHz	10 mm	-6 dB
	60 Degree	4 MHz	08 mm	-8 dB
	70 Degree	2 MHz	10 mm	3 dB
	70 Degree	4 MHz	10 mm	-1 dB

Fig.14



Defect type	Probe Angle	Probe Frequence	Defect Length	Defect Gain
Lack of Fusion	60 Degree	2 MHz	15 mm	7 dB
	60 Degree	4 MHz	15 mm	-1 dB
	70 Degree	2 MHz	15 mm	4 dB
	70 Degree	4 MHz	15 mm	0 dB

Fig.15



Defect type	Probe Angle	Probe Frequence	Defect Length	Defect Gain
Lack of Penetration	60 Degree	2 MHz	20 mm	2 dB
	60 Degree	4 MHz	20 mm	-3 dB
	70 Degree	2 MHz	15 mm	2 dB
	70 Degree	4 MHz	15 mm	2 dB

Fig.16

Discussion

The Experimental Data Offers Valuable Insights Into How Ultrasonic Testing (Ut) Parameters—Specifically Probe Angle, Frequency, And The Resulting Gain—Affect The Detectability And Characterization Of Common Weld Defects. The Types Of Defects Examined Include Porosity, Cracks, Slag Inclusions, Lack Of Fusion, And Lack Of Penetration. For Each Defect Type, Measurements Were Taken Using Two Probe Angles (60° And 70°) And Two Frequencies (2 Mhz And 4 Mhz), While Defect Lengths Varied Across Categories.

Effect Of Probe Angle And Frequency

Across All Defect Types, Two Consistent Trends Emerge:

Lower Frequencies (2 Mhz) Tend To Produce Higher Gain (Amplitude) Readings Compared To 4 Mhz For The Same Probe Angle And Defect Type.

A 70° Probe Angle Often Enhances The Signal Response Compared To The 60° Angle, Especially When Paired With The 2 Mhz Frequency.

These Trends Align With The Physics Of Ultrasonic Wave Propagation: Lower Frequencies Penetrate Deeper And Scatter Less, Yielding Stronger Signals For Larger Or More Deeply Embedded Flaws. However, They Offer Lower Resolution. Higher Frequencies, While More Sensitive To Small Defects, Are Also More Susceptible To Attenuation, Particularly In Coarse-Grained Weld Metal, Which Could Explain The Generally Lower Gain Values.

Defect-Specific Observations

The results are displayed in bar charts showing Amplitude (dB) for various combinations of probe angle (60 and 70 degrees) and probe frequency (2 MHz and 4 MHz), along with corresponding tables detailing Defect Length and Defect Gain. This discussion will systematically analyze the amplitude variations for each defect type, considering the influence of probe angle and frequency.

1. Porosity

The bar chart for Porosity shows the amplitude in dB for different probe angle and frequency combinations. The accompanying table provides details on defect length and defect gain (fig.12).

A. 60 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 10 dB. The defect length is 10 mm with a defect gain of 0 dB (fig.12).
- At 4 MHz, the amplitude drops significantly to around 6 dB. The defect length remains 10 mm, but the defect gain is -4 dB. This indicates that for a 60-degree probe, a higher frequency (4 MHz) leads to a lower detected amplitude for porosity, potentially due to increased scattering or attenuation at higher frequencies when interacting with porous structures. The negative defect gain at 4 MHz further supports the idea of reduced signal strength (fig.12).

B. 70 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 8 dB. The defect length is 8 mm with a defect gain of -2 dB (fig.12).
- At 4 MHz, the amplitude is around 5 dB. The defect length is 8 mm, and the defect gain is -5 dB. Similar to the 60-degree probe, the 70-degree probe also shows a decrease in amplitude when moving from 2 MHz to 4 MHz, suggesting a consistent trend of higher frequency leading to lower amplitude for porosity detection. The smaller defect length (8mm) compared to the 60-degree scenario (10mm) for the 70-degree probe might also influence the amplitude, but the trend of amplitude reduction with increasing frequency remains evident (fig.12).

2. Crack

The bar chart for Crack illustrates the amplitude response to different probe parameters. The corresponding table provides defect characteristics (fig.13).

A. **60 Degree Probe Angle:**

- At 2 MHz, the amplitude is notably high, approximately 15 dB. The defect length is 16 mm with a defect gain of 5 dB. This suggests that a 60-degree probe at 2 MHz is highly effective in detecting cracks, yielding a strong amplitude response and a positive defect gain.
- At 4 MHz, the amplitude drops significantly to around 5 dB. The defect length remains 16 mm, but the defect gain is -5 dB. This drastic reduction in amplitude at 4 MHz, coupled with a negative defect gain, indicates that for cracks, higher frequencies with a 60-degree probe might be less effective in producing a strong reflected signal, possibly due to the interaction of the shorter wavelength with the crack geometry (fig.13).

B. **70 Degree Probe Angle:**

- At 2 MHz, the amplitude is approximately 14 dB. The defect length is 14 mm with a defect gain of 4 dB. This shows a strong response, comparable to the 60-degree, 2 MHz combination, indicating good detectability.
- At 4 MHz, the amplitude is around 10 dB. The defect length is 14 mm, and the defect gain is 0 dB. While there's a reduction in amplitude compared to 2 MHz at the same angle, the drop is not as severe as observed with the 60-degree probe. A 0 dB defect gain suggests that the signal is neither amplified nor attenuated relative to a reference, implying a reasonable detection capability even at 4 MHz for a 70-degree probe for cracks (fig.13).

3. Slag

The bar chart for Slag presents the amplitude results for various probe settings. The detailed defect information is in the accompanying table.

A. **60 Degree Probe Angle:**

- At 2 MHz, the amplitude is approximately 4 dB. The defect length is 10 mm with a defect gain of -6 dB. This suggests a relatively low amplitude response and significant signal attenuation (fig.14).

- At 4 MHz, the amplitude is even lower, around 2 dB. The defect length is 8 mm, and the defect gain is -8 dB. This indicates that for slag, a 60-degree probe generally struggles to produce a strong signal, and the performance further degrades with increasing frequency. The combination of lower amplitudes and negative defect gains points to challenging detection for slag using this probe angle and frequency range (fig.14).

B. 70 Degree Probe Angle:

- At 2 MHz, the amplitude significantly increases to approximately 13 dB. The defect length is 10 mm with a defect gain of 3 dB. This is a remarkable improvement compared to the 60-degree probe, suggesting that a 70-degree probe at 2 MHz is much more effective in detecting slag. The positive defect gain confirms a stronger signal (fig.14).

- At 4 MHz, the amplitude is around 9 dB. The defect length is 10 mm, and the defect gain is -1 dB. While there's a decrease in amplitude compared to 2 MHz at 70 degrees, it is still a considerably better response than any of the 60-degree probe combinations. The slight negative defect gain suggests some attenuation, but the overall detectability remains much higher. This highlights the importance of probe angle for effective slag detection (fig.14).

4. Lack of Fusion

The bar chart for Lack of Fusion displays the amplitude readings. The table provides details on defect length and gain.

60 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 17 dB. The defect length is 15 mm with a defect gain of 7 dB. This represents a very strong signal, indicating high detectability for lack of fusion using a 60-degree, 2 MHz probe. The high positive defect gain further reinforces this (fig.15).

- At 4 MHz, the amplitude drops significantly to around 7 dB. The defect length remains 15 mm, but the defect gain is -1 dB. This substantial reduction in amplitude and the negative defect gain suggest that increasing the frequency to

4 MHz with a 60-degree probe makes it less effective for detecting lack of fusion, similar to the trend observed with cracks (fig.15).

70 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 15 dB. The defect length is 15 mm with a defect gain of 4 dB. This also shows a strong amplitude, although slightly lower than the 60-degree, 2 MHz combination (fig.13).
- At 4 MHz, the amplitude is around 8 dB. The defect length is 15 mm, and the defect gain is 0 dB. Similar to the 60-degree probe, there's a decrease in amplitude at 4 MHz, but the overall response is still relatively good, with a 0 dB defect gain indicating no net attenuation (fig.15).

5. Lack of Penetration

The bar chart for Lack of Penetration shows the amplitude results. The associated table provides defect specifics (fig.16).

60 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 4 dB. The defect length is 20 mm with a defect gain of 2 dB. This indicates a relatively modest amplitude, but with a positive defect gain (fig.16).
- At 4 MHz, the amplitude is around 2 dB. The defect length remains 20 mm, but the defect gain is -3 dB. The amplitude decreases at higher frequency, and the defect gain becomes negative, suggesting reduced detectability (fig.16).

70 Degree Probe Angle:

- At 2 MHz, the amplitude is approximately 3 dB. The defect length is 15 mm with a defect gain of 2 dB. The amplitude is similar to the 60-degree, 2 MHz combination, with a positive defect gain (fig.16).
- At 4 MHz, the amplitude is also around 3 dB. The defect length is 15 mm, and the defect gain is 2 dB. Interestingly, for lack of penetration with a 70-degree probe, the amplitude and defect gain remain consistent when changing the frequency from 2 MHz to 4 MHz. This suggests that for this specific defect and

probe angle, the frequency has less impact on the detected amplitude compared to other defect types. The smaller defect length (15mm) for the 70-degree probe scenarios compared to the 60-degree scenarios (20mm) might contribute to the observed amplitude (fig.16).

General Observations and Analysis:

Across the different defect types, several trends emerge regarding the influence of probe angle and frequency on amplitude.

1.**Frequency Impact**: For most defect types (Porosity, Crack, Slag, Lack of Fusion), increasing the probe frequency from 2 MHz to 4 MHz generally leads to a decrease in the detected amplitude. This can be attributed to several factors inherent to ultrasonic wave propagation:

- Attenuation: Higher frequency ultrasonic waves experience greater attenuation as they travel through the material. This means more energy is lost due to absorption and scattering, resulting in a weaker signal returning from the defect.
- Scattering: For defects with complex geometries or distributed features (like porosity or some types of slag), higher frequency waves, with their shorter wavelengths, are more prone to scattering. This diffuses the energy, leading to a weaker reflected signal back to the transducer.
- Resolution vs. Penetration: Higher frequencies offer better resolution, allowing for the detection of smaller defects or finer details within a defect. However, this often comes at the cost of penetration depth. If the defect is deeper or the material is highly attenuative, a higher frequency might not reach the defect with sufficient energy or return a detectable signal.

2.Probe Angle Impact: The probe angle significantly influences the amplitude, particularly for certain defect types.

- Slag: The most striking example is Slag, where a 70-degree probe angle at 2 MHz yields a significantly higher amplitude (around 13 dB) compared to the 60-degree probe at 2 MHz (around 4 dB). This suggests that the orientation of the ultrasonic beam relative to the slag defect is crucial for effective detection. Slag inclusions can have various shapes and orientations, and a different probe angle might provide better geometric alignment for reflection (fig.14).

- Crack and Lack of Fusion: For these planar or volumetric defects, both 60-degree and 70-degree probes at 2 MHz generally show strong amplitudes, indicating good detectability from multiple angles. However, there are nuances; for cracks, 60-degree, 2 MHz showed the highest amplitude (fig.13).

- Lack of Penetration: For lack of penetration, the amplitude response was relatively consistent across both probe angles and frequencies for the 70-degree probe. This might indicate that the nature of lack of penetration, being a discontinuity along the weld root, allows for effective detection regardless of minor variations in probe angle within this range (fig.16).

3.Defect Gain: The defect gain values provide further insight into the signal strength relative to a reference. Positive defect gain indicates amplification or a strong signal, while negative gain indicates attenuation. The trends in defect gain generally align with the observed amplitude trends:

- Stronger signals (higher amplitudes) are typically associated with positive or less negative defect gains (e.g., Crack at 60-2MHz with 5 dB gain, Lack of Fusion at 60-2MHz with 7 dB gain) (fig.13and 15).

- Weaker signals (lower amplitudes) are usually accompanied by more negative defect gains (e.g., Slag at 60-4MHz with -8 dB gain, Porosity at 70-4MHz with -5 dB gain) (fig.12 and 14).

4.Defect Length: While the defect length is provided in the tables, its direct correlation with amplitude is not always straightforward in this dataset. For instance, for Porosity, the defect length was 10mm for 60-degree probes and 8mm for 70-degree probes, but the amplitudes varied significantly with frequency. Similarly, for Lack of Penetration, the defect length was 20mm for 60-degree probes and 15mm for 70-degree probes, yet the amplitudes were in a similar range. This suggests that while defect size is a factor, the interaction of the ultrasonic wave with the defect's *type*, *geometry*, and *orientation* relative to the probe angle and frequency plays a more dominant role in determining the reflected amplitude (fig.12)

Conclusion

The Results Clearly Demonstrate That Ultrasonic Testing Variables—Especially Probe Angle And Frequency—Have A Pronounced Effect On The Evaluation Of Weld Quality. Lower Frequency Probes (2 Mhz) Consistently Resulted In Higher Gain Amplitudes, Suggesting Superior Performance In Detecting Larger And More Deeply Embedded Defects. Additionally, A 70° Probe Angle Often Provided Better Interaction With Defect Geometries, Particularly For Slag And Lack Of Fusion.

Each Defect Type Exhibits Unique Acoustic Characteristics, Influencing How Ultrasonic Waves Interact With Them. Therefore, Selecting The Optimal Testing Parameters Is Critical For Accurate Flaw Identification And Classification. For Comprehensive Weld Inspection, Practitioners Should Consider Using Multiple Probe Settings To Maximize Detection Sensitivity And Reliability.

Future Work Could Explore The Integration Of Phased Array Ultrasonic Testing (Paut) To Dynamically Vary Angle And Focus Depth, Providing A More Flexible And Detailed Inspection Regime. Moreover, Correlating These Ultrasonic Results With Radiographic Or Destructive Testing Outcomes Could Further Validate And Calibrate The Findings.

Recommendations

Based On The Findings Of This Study, The Following Recommendations Are Proposed To Enhance The Effectiveness And Accuracy Of Ultrasonic Testing In Weld Inspection:

1. Utilize Lower Frequency Probes For General Weld Inspection

Probes Operating At 2 Mhz Offer Better Penetration And Higher Signal Gain, Making Them More Suitable For Detecting Larger Or Subsurface Weld Defects, Particularly Porosity, Cracks, And Lack Of Fusion.

2. Employ Multiple Probe Angles For Comprehensive Coverage

Combining 60° And 70° Angles Allows For Improved Interaction With Various Defect Orientations, Especially Slag And Fusion-Related Anomalies. This Approach Minimizes The Chances Of Missing Defects Due To Beam Misalignment.

3. Avoid Exclusive Use Of High Frequencies In Coarse-Grained Welds

While 4 Mhz Probes Provide Higher Resolution, Their Increased Attenuation Reduces Detection Sensitivity In Thicker Or Rougher Weld Materials. They Should Be Used Selectively For Fine Or Near-Surface Defect Characterization.

4. Incorporate Advanced Techniques Where Applicable

Consider The Use Of Phased Array Ultrasonic Testing (Paut) Or Time-Of-Flight Diffraction (Tofd) For More Detailed Imaging And Depth Profiling, Particularly In Critical Applications Where Weld Integrity Is Paramount.

5. Calibrate Equipment Based On Known Defect Samples

To Enhance Interpretation Accuracy, Calibration Should Be Done Using Reference Blocks Containing Artificial Or Known Defects Similar In Size And Type To Those Expected In The Welds Under Inspection.

6. Integrate Results With Other Ndt Methods For Validation

Where Possible, Supplement Ultrasonic Inspection With Radiographic Testing Or Metallographic Validation To Confirm Findings And Improve Overall Defect Assessment Reliability.

7. By Adopting These Practices, Industries Can Achieve More Reliable And Precise Weld Evaluations, Leading To Improved Structural Safety And Reduced Maintenance Costs.

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