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# Review of Phased Array Ultrasonic Testing of Weld Joints

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## ABSTRACT

Welding is a prevalent joining technique used on metals in industrial manufacturing. It is very important to detect welding defects that may occur without damaging the welding constructions. The conventional ultrasonic inspection is the most widely used non-destructive test method for the detection of weld defects. Phased Array Ultrasonic Testing (PAUT) is a significant method within the category of ultrasonic non-destructive testing methods because ultrasonic phased arrays offer significant technical advantages over conventional ultrasonic methods such as improved sensitivity, accurate characterization and faster inspection. The aim of this article is to provide a comprehensive review on analysing defects in welded joints by utilizing PAUT. Different studies in the literature related to the non-destructive testing of weld joints by PAUT have been reviewed. Various examples of how the type, depth, and size of welding defects are detected in a highly effective manner have been provided. As a result, it was concluded that phased array ultrasonic testing is a highly efficient technique compared to conventional ultrasonic methods for detecting welding defects.

**Keywords:** Phased Array Ultrasonic Testing (PAUT), Ultrasonic Testing (UT), Evaluation of Weld Imperfections or Defects

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# Kaynaklı Birleştirmelerde Phased Array Ultrasonik Tekniğinin Kullanımı Hakkında Derleme


## ÖZ

Endüstriyel imalatlarda metallerin birleştirilmesi amacıyla en yaygın kullanılan birleştirme tekniği, kaynaktır. Kaynaklı imalatların kaynak bölgelerinde oluşabilecek kaynak kusurlarının, önceden tespit edilmesi en önemli mühendislik süreçlerinden birisidir. Konstrüksiyona zarar vermeden kaynak kusurlarının tespit edilmesi amacıyla en yaygın kullanılan tahribatsız muayene yöntemi ise ultrasonik muayene tekniğidir (UT). Son yıllarda ultrasonik muayene teknikleri arasında hacimsel kaynak kusurlarının tespitinde en yaygın kullanılan tekniklerden birisi de phased array ultrasonik tekniğidir (PAUT). Bu tekniğin geleneksel ultrasonik muayeneye tekniklerine göre tercih edilmesinin başlıca sebepleri şunlardır: Daha ileri seviyede geliştirilmiş kusur tespit hassasiyeti, kusurların daha doğru ve net tespit edilebilmesi, çok daha geniş bir bölgenin daha hızlı bir şekilde muayene taramasının yapılabilmesi. Bu makalenin amacı kaynaklı konstrüksiyonlarda meydana gelebilecek hacimsel kaynak kusurlarının PAUT ile tespiti hakkında kapsamlı bir inceleme yapmaktır. Çeşitli literatür çalışmaları incelenerek, PAUT analizlerinin nasıl yapıldığı ile ilgili bilgi vermektir. Bu tekniğin geleneksel ultrasonik yöntemlere göre kaynak kusur türlerinin tespit edilmesinde, hataların boyutu, şekli ve derinliği ile ilgili bilgilerin elde edilmesinde ne kadar hassas, etkin ve verimli olduğunu göstermektir. Sonuç olarak, kaynak kusurlarının hacimsel tespitinde phased array ultrasonik muayenesinin, geleneksel ultrasonik tekniklere göre çok daha verimli, hızlı ve doğru analiz yapılabilmesi imkânını sağlayan bir teknik olduğu değerlendirilmiştir.


**Anahtar Kelimeler:** Ultrasonik Muayene (UT), Phased Array Ultrasonik Muayene (PAUT), Kaynak Kusurlarının Değerlendirilmesi

## 1 Introduction

Non-Destructive Testing (NDT) includes a group of analysis methods that assess the properties of a material, structure, or component without causing any damage to its functionality or serviceability (Nilsson et al., 2023). NDT method is designed to identify the type, quantity, shape, position, and dimensions of defects in the specimen, covering both surface and internal defects (Zhao, 2021). NDT is important in inspection procedures within the industrial sector, as the precision of defect information measured is critical for ensuring the safety of factory operations (Hampson et al., 2022). Currently, industrial applications employ NDT techniques to identify fractures and defects in various materials (Selim et al., 2020). The American Society of Non-destructive Testing describes NDT as “the examination of an object using technology that does not affect the object's future usefulness”, specifically the examination of specimens without damaging the structure (Jodhani et al., 2023).

NDT is an approach that uses physical principles to ascertain the properties of materials, thus helping identify and evaluate potentially dangerous defects or faults (Hu et al., 2012). NDT methods are defined by ISO 9712 as a discipline based on physical principles and engineering. ISO 9712 classifies NDT procedures into multiple tests, which include: acoustic emission testing (AT), eddy current testing (ET), infrared thermographic testing (TT), leak testing (LT), magnetic particle testing (MT), penetrant testing (PT), radiographic testing (RT), computed tomography (CT), strain gauge testing (ST), ultrasonic testing (UT), and visual testing (VT) (Segovia Ramírez et al., 2023). Ultrasonic testing is a commonly used non-destructive technique for analysing weld joint (H. Zhou et al., 2018). Testing evaluates materials, components, or defects in the welded joint without damaging the material (Deepak et al., 2021). Ultrasonic testing is commonly used to inspect welding results and mentions specific standards such as BS EN ISO 17640 and BS EN ISO 19285 (Mohseni et al., 2021). It introduces two distinct types of defects in welded joints: (1) external defects, which are easy to identify and occur on the material's surface, and (2) internal defects, which occur inside the welded joint. It then discusses the importance of pursuing advanced non-destructive testing technologies to effectively identify internal defects in welds, which is indeed an important topic in modern industrial manufacturing (Zeng et al., 2020).

Non-destructive ultrasonic testing uses high-frequency mechanical waves to create images of the internal structure of a component. In the last decade, there has been a significant increase in the utilization of ultrasonic phased arrays in ultrasonic non-destructive testing for the standardized examination of components (Singh et al., 2020). Phased array ultrasonic testing (PAUT) is a modern non-destructive testing (NDT) method that utilizes the Ultrasonic Testing (UT) technique (Mirmahdi, Khamedi, et al., 2023). PAUT has been the preferred method for inspecting thick welded sections in joints, tubes, and pressure vessels since its emergence (Mohseni et al., 2021).

This manuscript aims to serve as a reference for researchers engaged in non-destructive testing processes, particularly Ultrasonic testing. It discusses the types of weld joint defects identified through phased array ultrasonic testing analysis.

## 2 Importance of non-destructive testing of welded joints

Welding is a commonly used method for production and joining in industrial manufacturing. However, welding is also the joining technique most commonly linked to defects or imperfections. These can include cracks, porosity, lack of fusion, incomplete penetration, and spatter. Such issues may result from careless or inexperienced welders, poor welding conditions, incorrect materials, improper welding procedures, or an unfavorable environment.

Welding defects can cause catastrophic failures under stress, especially in important structures like bridges or airplanes. Welding defects can weaken the welded joints. Therefore, welded joints must be inspected before, during, and after the welding process to ensure the quality and reliability of the welds.

The most important techniques for inspecting weld regions are non-destructive testing (NDT) methods. NDT enables the detection of imperfections in weld regions, ensuring the product's safety before it enters service and preventing catastrophic failures. NDT is an essential quality control measure, helping to maintain high welding standards and reducing the risk of poor welds. Compared to destructive testing, NDT methods are more cost-effective, as they allow for weld assessment without damaging or scrapping the work-piece. This enables timely repairs and prevents defects from spreading.

## 3 Ultrasonic Testing

Ultrasonic testing (UT) is a type of acoustic inspection that falls under non-destructive testing. It is used to find defects in structures by using different methods and classifying the defects. Since 1975, this technique has been proven effective at detecting defects because it is simple and highly sensitive (Jodhani et al., 2023).

Ultrasonic Testing (UT) uses high-frequency sound waves to check the condition of an object and find defects on its surface, below the surface, or inside. The sound waves used are higher than the range of human hearing. The choice of frequency depends on the material being tested and the type of information needed (Inês Silva et al., 2023). UT works by sending ultrasound waves into the object, and the receiver detects the resulting wave response (Mirmahdi, Afshari, et al., 2023). The high-frequency sound waves are directed towards the specimen region or areas where fractures are expected to structure. The defects in the material can be identified by analysing the changes in the receiver wave response (Kong et al., 2020). The frequency range of the ultrasonic signal is between 1 MHz and 20 MHz, which impacts the sensitivity and resolution of measurements. Increased frequencies enable more precise identification of small defects. However, they also reduce penetration depth due to surface scattering (Selim et al., 2020).

UT is a widely used method for testing industrial components. (Chabot et al., 2020). It is usually carried out using either single-element transducers or ultrasonic arrays, which are transducers that consist of many independently connected elements (Javadi et al., 2020). An ultrasonic array transducer consists of numerous piezoelectric elements stimulated with carefully timed pulses to generate wave beams that sweep across different specimen areas. This causes the wave fronts of the delayed signals to combine and create Huygens' interference patterns (Xu & Zhou, 2014). An array offers the advantage of enhanced image quality due to its ability to manipulate the direction and focus of ultrasound by adjusting the time delay between firing the elements of the array (Singh et al., 2020).

Ultrasonic arrays are increasingly being adopted as a standard technology across various industries due to their ability to implement advanced detection and imaging techniques (Ménard et al., 2020). An ultrasonic array is a transducer with several interconnected parts (Drinkwater & Wilcox, 2006). The phased array beams can be electrically scanned, guided, swept, and focused during the defect identification. Ultrasonic beam steering optimizes the selected beam angle by directing it perpendicular to the displayed defect (Szávai et al., 2016).

# 4 Phased Array Ultrasonic Testing (PAUT)

Ultrasonic inspection has been used since World War II to check the safety and quality of industrial equipment. In the 1960s, phased array ultrasonic testing (PAUT) was developed, using transducers with multiple emission sources. PAUT is mainly used in the media industry, but in the 1980s, it began being applied to assess industrial equipment (Payão Filho et al., 2022). Phased array ultrasonic testing has become more popular in recent years because it offers better imaging, greater flexibility, and the ability to perform fast and multiple inspections (Sumana & Kumar, 2020). PAUT is an advanced type of non-destructive testing employed to evaluate defects, including weld joints (Jayasudha & Lalithakumari, 2022). PAUT has developed popularity in numerous NDE applications because of its superior array flexibility compared to single-element transducers (Sweeney et al., 2023). Considering the advancement of UT technology, PAUT has taken the role of traditional ultrasonic methods and NDT testing in a wide range of evaluation applications, particularly in assessing post-welding (Huggett et al., 2017).

Ultrasonic phased arrays have effectively detected defects, measured thickness, and analysed welding inspections (Feng & Qian, 2020). The latter offers several advantages when comparing systems that use single-element transducers to those that use ultrasonic arrays (Phased Array Ultrasonic Testing). Firstly, it provides higher and faster inspection flexibility, allowing for scanning complex geometric components. Secondly, it enables synthetic scanning and focusing aperture. Lastly, it allows scanning at various angles and positions while keeping the transducer stationary (Javadi et al., 2020). Another advantage of the Phased array ultrasonic testing technology is its ability to achieve deflection, focussing, and scanning, resulting in improved detection of material defects (Gao et al., 2024). Conventional phased array ultrasonic testing employs multi-element probes and a hardware delay law to concentrate the beam on specific specimen locations (Chabot et al., 2020). PAUT has the characteristics of a compact transducer and high inspection precision due to proper time-delayed pulses of array elements (Li et al., 2019). Phased arrays have many piezoelectric transducers, arranged in a linear or matrix fashion (Duernberger et al., 2022). Figure 1 illustrates the process of weld testing using the phased array ultrasonic testing. The equipment primarily includes a probe array, encoder, and acquisition unit. During the testing process, the probe comprises a sequence of piezoelectric transducers connected to the evaluated structure. These transducers are provided with gel or water. The test can be positioned on or near the base metal component, and the probe must be systematically traversed along the weld. Figure 1 illustrates the X direction, also known as the Scan-direction, which refers to the direction in which the probe moves (Bouzenad et al., 2022).

## 4.1 PAUT Inspection of Weld Imperfections

Bouzenad et al. (2022) conducted a study on PAUT testing and presented a simulation validation. They tested three different situations using ultrasonic testing, including numerical modelling to simulate real defects like holes or artificial voids. In the final case, they performed in-situ testing to examine natural defects. The specimen is a V-butt welded joint connecting two carbon steel pipes, each with a thickness of 7.62 mm and a circumference of 300 mm, as shown in Figure 2. The results show that to best detect defects, scanning should be done on both sides of the weld beam using the 1/PAUT method, with the welding probe positioned at different distances of the welding probe, specifically $Y_{Offset}$..

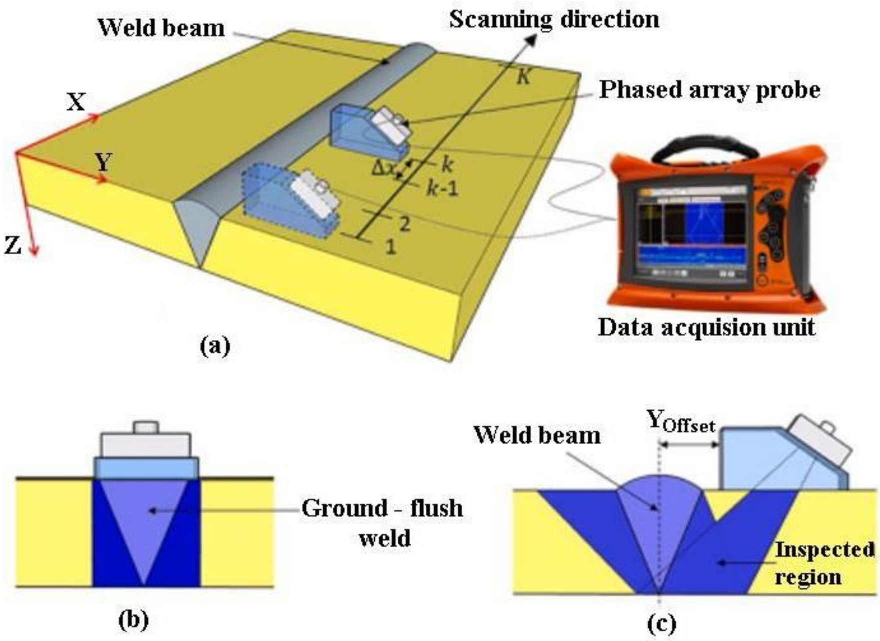



**Figure 1:** The lateral weld beam experimental setup (a), the B-scan for a ground-flush weld (b), and the S-scan for a regular weld (c) comprise the weld beam PAUT inspection process (Bouzenad et al., 2022)

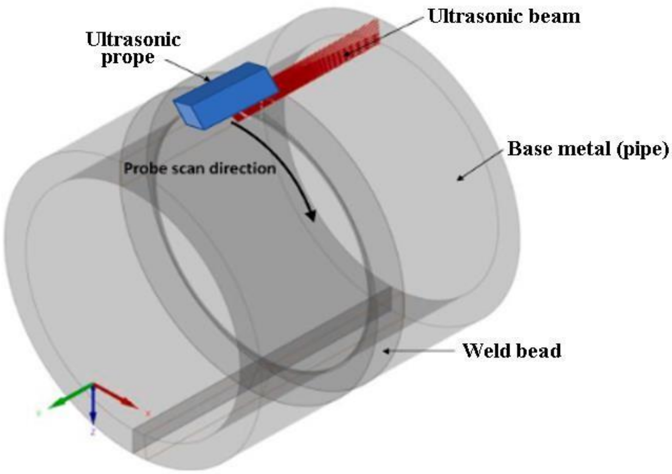



**Figure 2:** An example of the specimen (pipe) in 3D design (Bouzenad et al., 2022)

Phased array ultrasonic testing (PAUT) has proven to be a powerful tool for assessing the quality of joints. It provides clear images that help differentiate between bonded and de-bonded areas, using different colours and intensities. Upadhyay et al. (2019) studied the PAUT inspection of an explosively welded stainless steel and aluminium joint. They created A-scan, B-scan, and C-scan images from all sections of the plate. The C-scans showed the bonded and de-bonded areas in different colours and intensities. The results confirmed that more than 70% of the SS-Al joint was bonded.

PAUT offers clear advantages over traditional ultrasonic testing (UT) for detecting critical flaws. Ali et al. (2023) studied the challenges of using PAUT to identify defects in friction stir welded Al 6061-O plates. They estimated three defect parameters: (a) defect length, (b) defect height, and (c) defect position using PAUT. The quality of the results depends on several key factors that affect the probability of detection (POD). PAUT has been shown to have a higher probability of detection, but it is important to choose the right probe, scanning method, and defect orientation to get consistent results. The study also found that PAUT can effectively detect lack of fusion (LoF) defects.

Analysing the location and size of defects in weld region is crucial, so welding defects should be defined in three dimensions. The 3D PAUT technique is used for this purpose. Provencal and Laperrière (2022) studied a method that simultaneously identifies weld geometry and defects, while reconstructing both the surface of the welded joint and the defects. Welding defects can include lack of fusion (LoF), slag, incomplete root penetration, root fusion issues, cracks, and porosity. Figure 3 shows the data used in the segmentation model. The initial column displays the S-scan input column, the second column shows the identified weld imperfections, and the final column labels the weld geometry class.

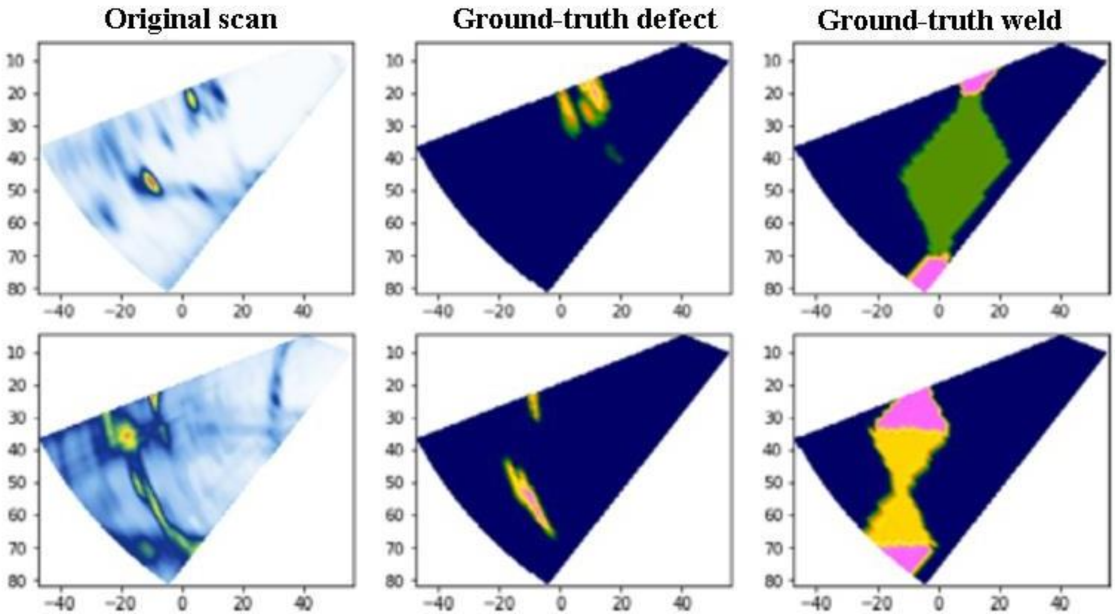



**Figure 3:** Sample input and ground-truth data. Weld geometry (final column): base material (blue), incomplete reflection (pink), single V (green), double V (yellow) (Provencal & Laperrière, 2022)

One of the major problems in welded joints is lack of penetration, especially at the weld root. PAUT is effective in accurately detecting lack of penetration in the weld region. Mandache et al. (2012) conducted a study to identify penetration defects in butt joint friction stir (FS) welds. Figure 4 shows the results of the PAUT analysis on these joints. The study found that PAUT could detect reflections caused by defects up to about 160 mm, but not beyond 179 mm from the initial welding point. Although there were signs between the cursors at 217 and 235 mm in subsequent results, these indications did not surpass the background noise level in the signal. Therefore, they cannot be attributed to discontinuities in the weld.

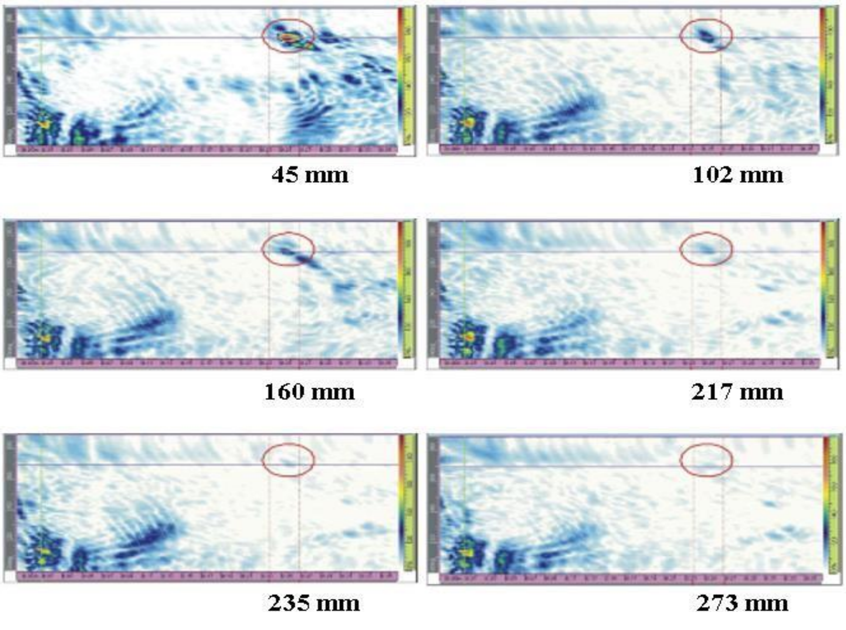



**Figure 4:** Phased array ultrasonic sectorial scans are varying distances from butt weld start (Mandache et al., 2012)

Numerous studies have been conducted on applying phased arrays in welding joints, specifically in V-groove weld designs. One of these studies is the work titled "Application research on ultrasonic phased array detection algorithm for austenitic stainless steel with V-groove weld" conducted by Li et al. (2024). The analysis uses a central frequency of 10 MHz with 32 array elements with respective element spacing of 0.6 mm and 0.5 mm. Figure 5 shows the phased array detection results, indicating the exact location of the defect. Additionally, the image clarity and correction are significantly improved, as shown in the comparison image before and after applying the focusing law correction.

The success of phased array ultrasonic testing for weld defects like vertical cracks, lack of fusion, and lack of penetration depends on whether a dual element matrix probe or a single linear array probe is used. Fu et al. (2019) studied vertical defects in electron beam butt joints using a performance probe. They tested the defects with a 2.5 MHz 64-element dual element matrix probe and a 2.25 MHz 64-element single linear array probe. Figure 6 shows the lack of penetration in the EBW test sample was determined using the PAUT of dual element matrix array probe at 2.5 MHz and single linear array probe at 2.25 MHz. The results show that the outcomes obtained with both types of probes are of acceptable quality.

PAUT also provides very good results in inspecting weld regions on circular surfaces (pipes). Zhou et al. (2018) studied PAUT for detecting and measuring circumferential surface cracks in welded steel pipes. Figure 7 shows the results from standard A-scan data and sectorial scan data obtained using phased array ultrasound on a welded pipe sample.

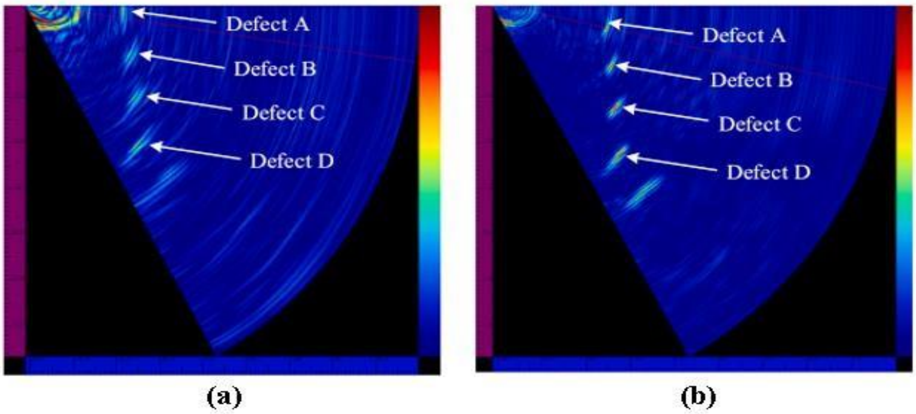



**Figure 5:** Sector testing results (a) before and (b) after correction of focusing law (Li et al., 2024)

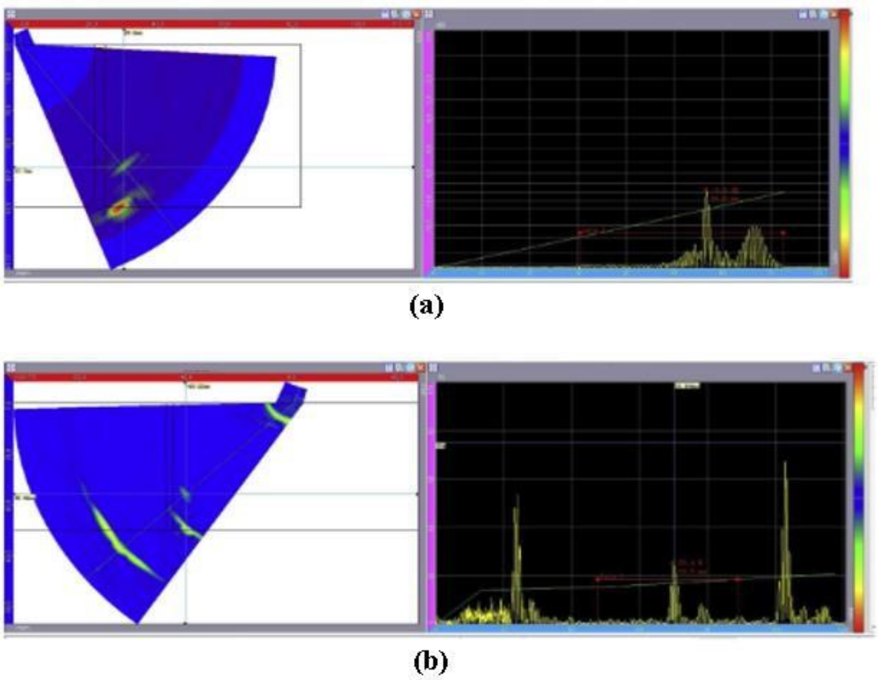



**Figure 6:** The lack of penetration in the EBW test sample was determined using the PAUT (a) dual element matrix array probe at 2.5 MHz and (b) single linear array probe at 2.25 MHz (Fu et al., 2019)

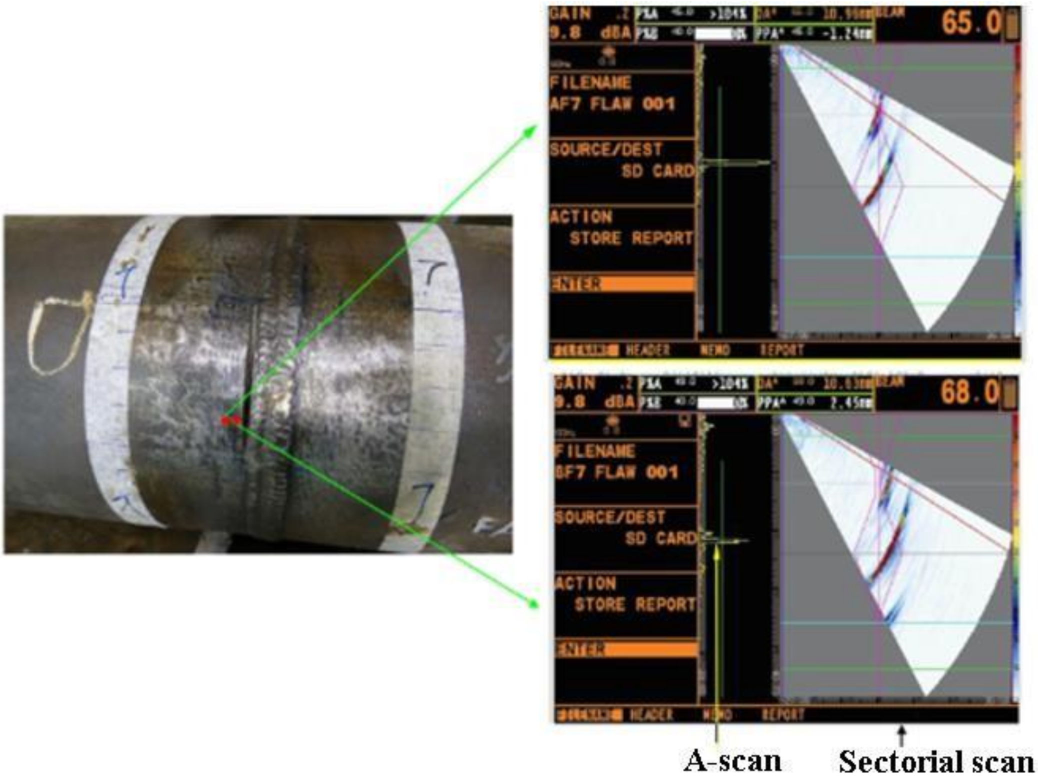



**Figure 7:** Typical A-scan and sectorial scan measurements taken at various points along the welded pipes ( Zhou et al., 2018)

PAUT signals have been improved with the support of artificial intelligence (AI), making it easier to detect small weld defects, such as microcracks. Kim & Lee (2024) studied AI for phased-array ultrasonic testing, using training data sets and neural networks to help differentiate between normal and defect signals. They analysed 20 welded joint samples using OmniPC software to extract A-scan signals. Figure 8 shows a comparison between the S-scan image from the OmniPC program and the S-scan image from the study's method. Although the colours differ, the two results are similar and can be easily compared. Figure 9 shows the B-scan and C-scan results, which share the same X-axis during scanning, with both normal and defective signals shown at the same time.

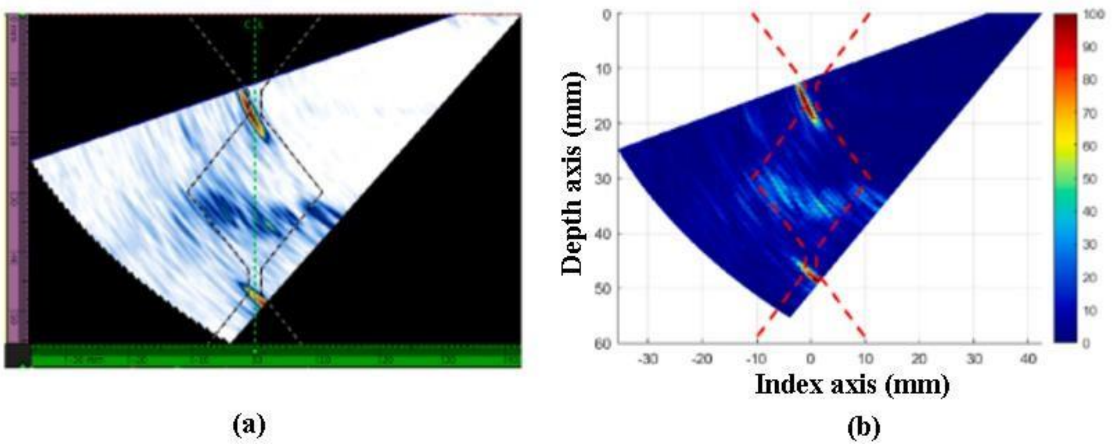



**Figure 8:** The outcomes of (a) the OmniPC program and (b) the coordinate transformation technique on S-scan images (Kim & Lee, 2024)

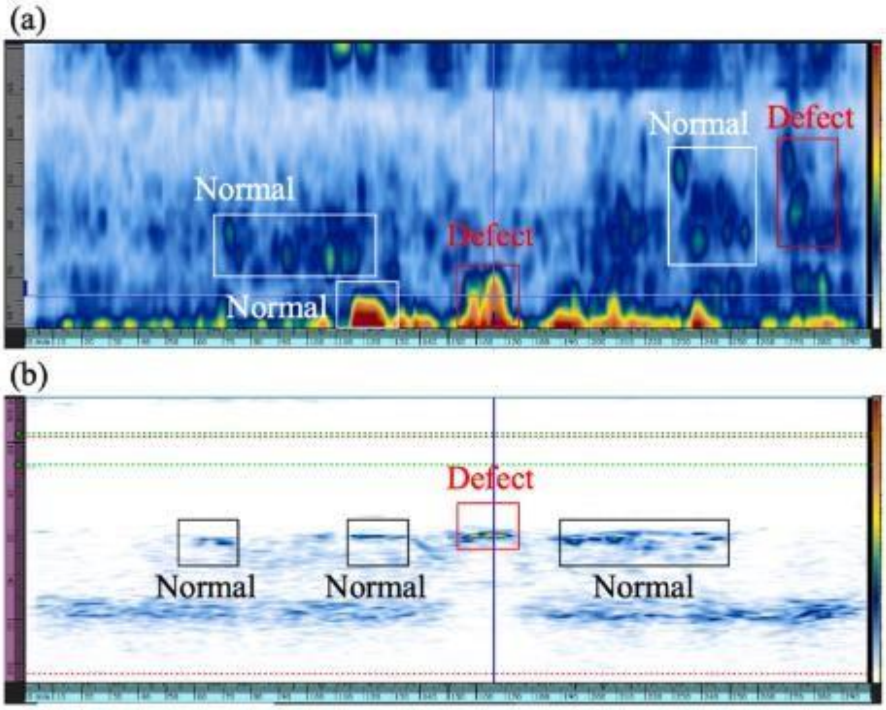



**Figure 9:** (a) C-scan and (b) B-scan images (Kim & Lee, 2024)

Some researchers have focused on the comparison between the detection capabilities and characterization of flaws in welded joints using phased array ultrasonic testing (PAUT) and radiographic testing (RT). One of these researchers, Harara & Altahan (2018), studied and compared phased array ultrasonic testing (PAUT) and radiographic testing (RT) to examine welded joints on steel plates. In this study, four specimens, each 35 mm thick, were analysed using both PAUT and RT methods to detect any faults in the welded connections. It has been concluded that, when a suitable PAUT procedure is applied, using the PAUT technique instead of RT is much more advantageous, as it is faster and poses no health risks to humans. Figure 10 shows images of welded joints assessed using both radiographic and PAUT methods. The radiograph indicates slag infiltration but no fractures. In contrast, the PAUT image clearly shows three indications and provides detailed information about the type, location, and size of each defect in the welded joint.

Phased array ultrasonic testing (PAUT) is commonly used to detect defects in welds created by different welding methods. In particular, the study by Deepesh et al. (2019) investigated the friction welding of tube-to-tube plates using an external tool (FWTPET) to develop an effective PAUT method for detecting and characterizing defects. This technique introduces a new method for connecting the tube to the tube plate and requires a detailed investigation to identify and characterize any defects in the weld. Figure 11 shows the results of the PAUT analysis, revealing internal defects. It was found that the defect alters the reflection pattern on the edge of the tube.

Figure 12 displays PAUT images showing void and ring tunnel defects. Once an indication is detected, the size and location of the de-bonding defect can be assessed by analysing the A-scan signals. Specifically, the severity and position of the defect can be estimated by examining the defect signal’s amplitude and the reduction in the edge amplitude.

Figure 13 shows macrographs of the FWTPET specimen, illustrating de-bonding on the root side, a ring tunnel defect, a cavity, and excessive flash. In the case of ring tunnel defects, there is a noticeable decrease in the edge signal. It can be concluded that digital radiography and phased array ultrasonic testing provide more significant results.

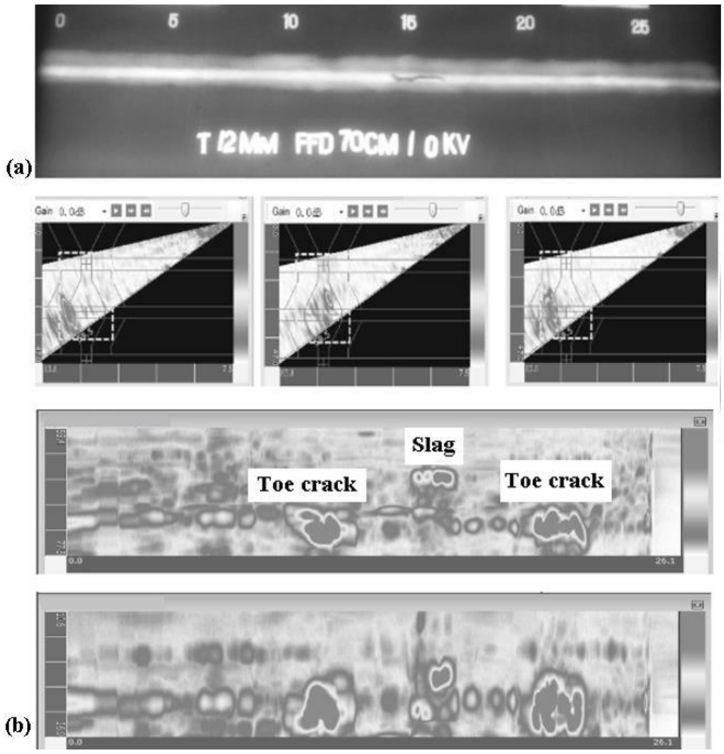
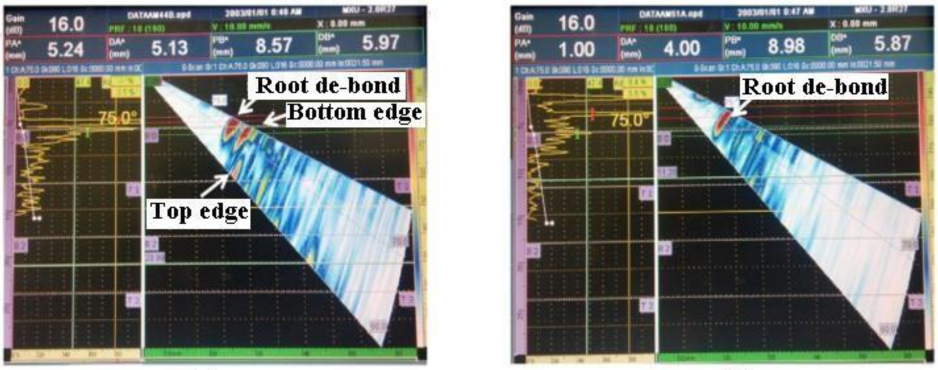
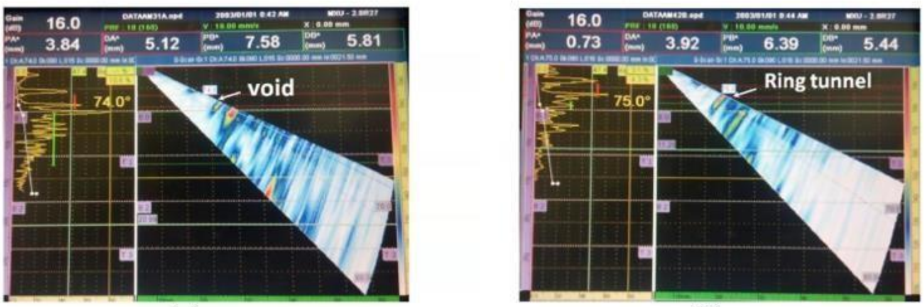



**Figure 10:** The second welded joint's testing results from (a) RT and (b) PAUT, as well as the indications of faults found by each of the two inspection methods (Harara & Altahan, 2018)




(a) (b)

**Figure 11:** Image from PAUT displaying root de-bonding defects (Deepesh et al., 2019)




(a) (b)

**Figure 12:** PAUT image showing (a) void (b) ring tunnel (Deepesh et al., 2019)

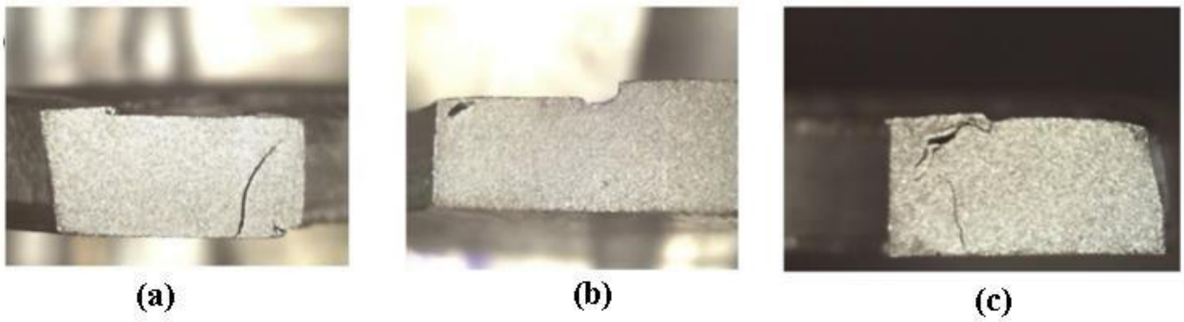



**Figure 13:** FWTPET specimen macrographs illustrating (a) de-bonding on the root side, (b) a ring tunnel, and (c) a cavity and excessive flash (Deepesh et al., 2019)

PAUT can be used to detect imperfections in welds from various welding techniques. Kumar et al. focused on PAUT analysis to examine defects in welded joints made using the shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) welding methods. In this study, welded samples of SS 316LN and Alloy 800, containing artificial defects such as lack of fusion, were created using metal arc welding. Figures 14 and 15 show the S-scan results of the GTAW and SMAW weld samples from both the SS 316LN side and the Alloy 800 side, respectively. In these diagrams, Defect 1, Defect 2, and Defect 3 are identified for each welding technique, with each having different depth values. The size and depth of the defects depend on the scanning direction and the orientation of the defects. The S-scan method enables precise detection of defects on both sides of the weld.

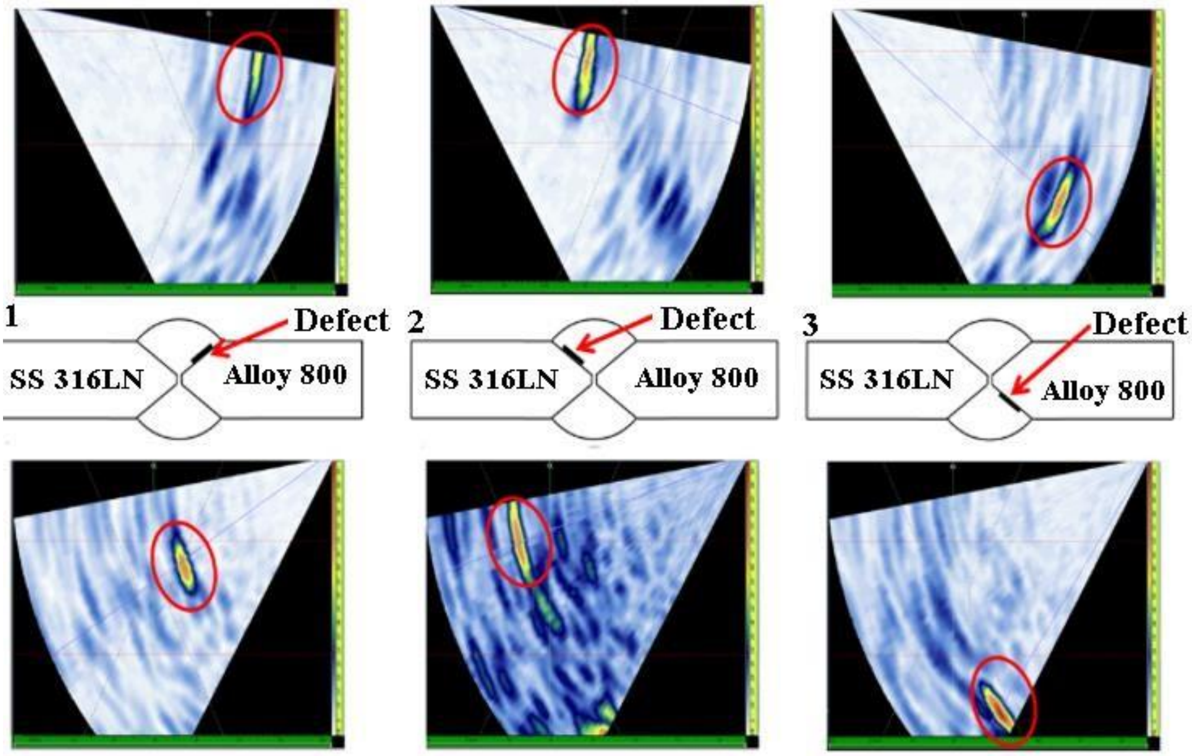



**Figure 14:** The GTAW weld sample was scanned (S-scan) from the SS 316LN side (top) and the Alloy 800 side (bottom) (Kumar et al, 2022)

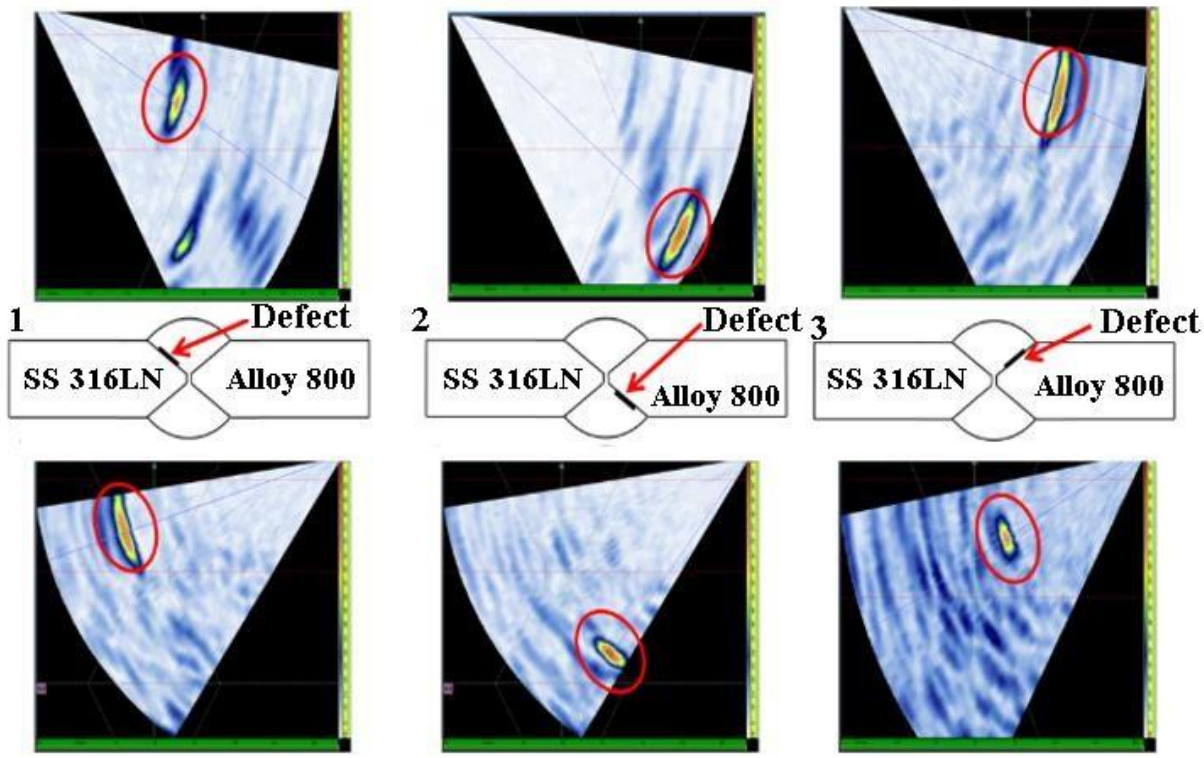



**Figure 15:** The SMAW weld sample was scanned (S-scan) from the SS 316LN side (top) and the Alloy 800 side (bottom) (Kumar et al, 2022)

## 5 Conclusions

This study comprehensively reviewed recent progress in non-destructive testing of weld joints using phased array ultrasonic testing (PAUT), which is an efficient method for detecting internal weld defects. It was also concluded that the main advantages of PAUT over conventional ultrasonic testing include improved inspection times and efficiency, increased reliability of measurements, and the ability of phased array probes to capture hundreds of signals simultaneously, which allows for faster flaw identification and weld quality assessments. Based on these observations, the following conclusions were drawn:

(a) The PAUT technique is widely recognized for its ability to detect both bonded and de-bonded areas in different material joints, making it highly effective for examining welded specimens.
(b) To detect and characterize defects in welded joints, the phased array ultrasonic testing (PAUT) procedure must involve simultaneous sectoral scanning of both sides of the weld axis, using an encoder and phased array probes.
(c) The PAUT analysis shows a high probability of detection, but some factors need careful attention. Inconsistent results can arise from parameters such as probe selection, operator skill, scanning method, and defect orientation.
(d) The PAUT technique is effectively used to detect defects in joints made by various welding methods.

## 6 Declarations

### 6.1 Study Limitations

Phased Array Ultrasonic Testing (PAUT) is an important method within ultrasonic non-destructive testing, effectively detecting defects, measuring thickness, and analysing welds. This review considers imperfections or defects in welded joints using the PAUT.

### 6.2 Competing Interests

There is no conflict of interest in this study.

### 6.3 Authors' Contributions

**Desi GUSTIANI:** Contributed to the process of developing, arranging, and presenting data for an article. The responsibility for doing a comprehensive literature review as part of the research process and responsible for authoring the full main manuscript.

**Hüseyin UZUN:** Contributed to the process of identifying concepts, supervising, and reviewing. In addition, responsible for analysing and interpreting the findings of the article.

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