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Probability of Defect Detection in Different Welding Processes by using Radiography Testing

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Abstract: This study aims to evaluate the probability of detecting defects in different welding processes using radiographic testing as a non-destructive evaluation method. The research examines the effectiveness of radiography in identifying welding defects through an extensive literature review covering welding techniques, radiographic inspection methods, and factors influencing defect detection probability. The experimental work involved preparing welded specimens using three welding processes gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), and brazing on 5 mm thick stainless steel SS316 and brass plates with suitable filler materials. The fabricated specimens were subjected to radiographic inspection and assessed by trained radiographers for defect identification. The results showed that defect detection probability varies with the welding process, with GTAW providing the highest detection rate, followed by SMAW and brazing. The findings confirm that radiographic testing is an effective technique for detecting welding defects and that optimizing radiographic parameters according to the welding method can further improve detection efficiency. The study also discusses the significance of these results for advancements in welding technology and radiographic testing practices.

Keywords: Radiographic Testing, Welding Defects, Gas Tungsten Arc Welding (GTAW), Shielded Metal Arc Welding (SMAW), Brazing.

I. INTRODUCTION

Welding, as a method of joining metals, has a long and significant history that traces back to ancient civilizations. Archaeological discoveries reveal that welded metal objects existed during the Bronze Age, which lasted from approximately 3000 BCE to 1200 BCE. During this period, blacksmiths commonly used forge welding, a technique in which metal pieces were heated until red-hot and then hammered together to create a strong joint. This method enabled the production of various tools and weapons. Another joining technique practiced during the Bronze Age was brazing, where a filler metal was heated until molten and allowed to flow into the gap between two metal pieces. Although brazing produced durable joints, it was generally weaker than welded joints and required greater skill. In addition, blacksmiths of that era developed essential metalworking tools such as hammers, tongs, and anvils, which improved the shaping and handling of metals during welding operations. These traditional tools continue to play an important role in modern welding practices.

The Bronze Age marked an important period of advancement and experimentation in metalworking, during which humans discovered innovative methods for shaping and joining metals. Although welding methods at that time were relatively simple compared to later developments, they established the basic principles that contributed to the evolution of modern welding techniques. In ancient civilizations such as Egypt and Mesopotamia, brazing was widely used for joining gold and silver ornaments. This process involved heating metal pieces and applying a filler alloy with a lower melting point, which melted and flowed into the joint to create a strong connection between the metals.

During the Iron Age, which extended from approximately 1200 BCE to 500 CE, more advanced welding methods were introduced, enabling stronger and more accurate metal joining. One significant development was fire welding, a process similar to forge welding but using direct flame heating to provide better control over temperature. This technique made it possible to join metals, particularly high-carbon steels, that were previously difficult to weld. Another important innovation was pressure welding, where heated metal pieces were hammered together under force to form durable bonds. The process could be repeated several times to manufacture more intricate metal structures. Overall, the Iron Age represented a major phase of progress in welding technology, and many of the techniques developed during this period formed the basis for modern welding practices that are still refined and applied today.

The modern era of welding has been characterized by continuous technological advancements and the development of innovative welding techniques. In the mid-1800s, French engineers Edmond Fouché and Charles Picard introduced gas welding, which used a hydrogen-oxygen flame to heat and melt metals. In 1881, French scientist Auguste de Méritens invented arc welding, a process that utilized an electric arc for faster and more accurate metal joining. During the late 1800s and early 1900s, Elihu Thomson developed resistance welding, where electric current and pressure were applied to join metals. The 1920s witnessed the development of gas metal arc welding (GMAW or MIG welding), which employed a continuously fed wire electrode and shielding gas, while the 1930s saw the emergence of gas tungsten arc welding (GTAW or TIG welding), known for producing strong and precise welds using a tungsten electrode and shielding gas. In the 1940s, submerged arc welding (SAW) was introduced, using a wire electrode and granular flux to protect the weld area. The 1950s brought electron beam welding (EBW), which used high-energy electron beams for highly accurate welding, followed by laser welding in the 1960s, enabling rapid and precise metal joining through high-powered laser beams. After the 1960s, welding technology advanced rapidly with the introduction of automation, robotics, and computerized welding systems, significantly improving efficiency, precision, and process control. Laser welding became more widely adopted during the 1980s, while the 1990s introduced friction stir welding, a solid-state process particularly effective for aluminum and lightweight materials. In recent decades, further innovations such as high-definition plasma arc cutting, hybrid laser-arc welding, and metal 3D printing have expanded the capabilities of welding technology. The development of advanced materials, including high-strength alloys and composites, has also contributed to the evolution of modern welding techniques, making welding processes increasingly accurate, versatile, and efficient.

Welding terminology consists of specialized terms used to describe welding processes, equipment, materials, and techniques within the welding industry. A weld is formed by joining metals through heating and fusion, where the base metal refers to the material being joined and the filler metal is added to improve joint strength and properties. Important terms include weld pool, weld bead, and weld joint, which describe the molten metal, deposited weld material, and the connection area between metals. Welding operations also involve concepts such as welding position, welding process, electric arc, flux, shielding gas, and welding electrode, all of which play vital roles in producing quality welds. Safety and quality assurance are supported by equipment like welding helmets, documents such as welding procedure specifications (WPS), and professionals like welding inspectors. In addition, non-destructive testing (NDT) methods, including radiography and ultrasonic testing, are widely used to detect weld defects without damaging the material.

II. LITERATURE SURVEY

F. Zuo, J. Liu, M. Fu, J. Lu and H. Liu et al. Weld defect detection is an important research topic in the field of industrial non-destructive testing. However, this is a challenging task, as X-ray images typically exhibit low contrast and defects often have varying shapes and sizes, making existing methods unable to accurately capture the location information of weld defects. To address these challenges, this paper develops a new framework to effective detect different types of defects from low quality X-ray images. Firstly, an adaptive contrast enhancement method is designed to effectively generate optimized X-ray images, which is beneficial for the feature extraction process. Secondly, an adaptive feature pyramid network equipped with deformable convolution is proposed to fit defects with varying shapes and sizes, effectively improving the generalization performance of the model. In practical applications, we adopt the pipeline weld X-ray defect dataset in northern China and demonstrate the effectiveness of the method [1].

Tusongjiang.Kari, A. Yimamu, Y. Zhou and X. Ma et al. To effectively enhance the accuracy and efficiency of weld defect detection, this paper proposes a YOLOv5-based method for detecting and classifying weld defects, enabling precise identification and categorization of weld failures. The research is structured as follows: First, to mitigate the impact of noise, low contrast, and uneven illumination on image recognition, preprocessing techniques including image filtering and enhancement are applied to the original images. Then, a convolutional neural network-based weld defect recognition model is developed using the YOLOv5 algorithm. Finally, the model's detection accuracy and stability are comprehensively evaluated using a dataset of real weld images. Experimental results demonstrate that the proposed model achieves accurate and reliable weld defect detection and identification, providing an effective approach for ensuring the safety and reliability of welded structures [2].

F. Zuo, J. Liu, W. Yu, Y. Ren, L. Wang and Z. Zhao et al. Automatic welding technology has been widely applied in the field of industrial production. In promoting high-quality intelligent manufacturing processes for the consumer market, precise detection of welding defects is a key link in enhancing product reliability. Considering the high demand for domain knowledge in welding defect inspection tasks, existing methods have shortcomings in fine-grained recognition. To overcome these weaknesses, this article proposes a dual-expert detection method for automatic welding defect inspection, inspired by the human multi-expert complementary evaluation process. The method process is mainly reflected in the following aspects. Firstly, a high-precision robot welding defect inspection system that integrates application platform based data collection, model training, and deployment has been effectively implemented. Then, diverse detection experts are constructed using complementary regression paradigms to obtain predictions from multiple perspectives. Finally, a dual-expert fusion scheme based on probabilistic ensembling is designed to fully integrate prediction information and obtain refined results. In the experiment, a database rich in diverse types of welding defects is applied for training and systematic testing, and multiple sets of refined indicators are evaluated. In addition, we also discussed edge deployment, failure case analysis, and the application of in consumer PCB defect detection. These practical application results indicate that the proposed method can achieve product level implementation, effectively reducing the threshold for industrial testing and enabling end-users to gain benefits [3].

Z. Shen and J. Sun et al. This paper proposed two novel method of real-time online detection of welding seam defects for canisters based on computer vision. In the proposed approaches, the region of welding seam is aligned after a preprocessing procedure to the acquired images. The first method is named as column gray-level accumulation inspection (CAI). In this method, an original curve is shaped by implementing the accumulating operation, followed by being exerted the mean value smoothing operation. Then a modified first difference method is used for the curve in order to segment the defects of the image of welding seam. The second method, named as frame difference testing (FDT), is also proposed for defect detecting. Finally, an information fusion approach based on D-S evidence theory that combines the CAI and FDT methods is used to reduce the rate of false alarm and improves the reliability of defect detection. Experimental results show that the proposed method can detect the welding seam defects with 90 percent accuracy and it can meet the requirement of real-time on-line continuous detection [4].

III. METHODOLOGY

Radiography testing is a non-destructive testing (NDT) technique that uses X-rays, gamma rays, or other forms of electromagnetic radiation to examine the internal structure of materials and detect defects without causing damage. Due to their short wavelengths, X-rays and gamma rays can penetrate metals such as carbon steel and stainless steel, making them highly effective for industrial inspection. In this project, X-ray radiography was used to identify defects in welded metal components. The development of radiographic testing began with Wilhelm Conrad Rontgen's discovery of X-rays in 1895 and Marie Curie's discovery of the radioactive element radium in 1898.

The principle of radiographic testing involves placing the test specimen between a radiation source and a film or electronic detector. As radiation passes through the material, variations in thickness and density affect the amount of radiation absorbed. Dense and thicker regions absorb more radiation, while defects such as cracks or voids allow more radiation to pass through, producing darker areas on the radiographic image. The method is highly effective for detecting internal flaws, although defect visibility depends on factors such as radiation energy, material thickness, and the orientation of the defect. Since radiographic testing involves radioactive sources, strict safety regulations and local rules must be followed during inspection procedures.

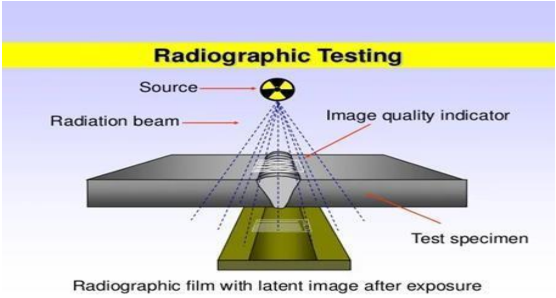
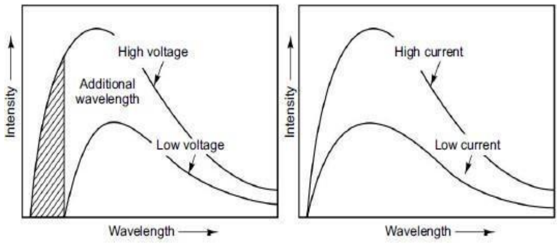


Fig. 1: Radiographic Testing

The intensity and characteristics of X-rays are greatly affected by the tube voltage and current in an X-ray tube. Increasing the voltage between the electrodes produces X-rays with shorter wavelengths and significantly increases the intensity of the X-ray beam, which is proportional to the square of the voltage (I=KV2)(I=KV^2)(I=KV2). Similarly, increasing the tube current, which is the flow of electrons between the cathode and anode, also increases the intensity of the X-rays. This tube current should not be confused with the filament current, which is responsible for heating the filament to release electrons.



(a) Effect of change in voltage

(b) Effect of change in tube current

Fig. 2: Effect of Change in Tube & Current

When penetrating radiation such as X-rays or gamma rays passes through a material, it interacts with the matter in a complex way, resulting in the reduction of radiation intensity, known as attenuation. This attenuation occurs mainly through two processes: absorption, where the radiation energy is absorbed by the material, and scattering, where the radiation changes direction after interacting with particles in the material.

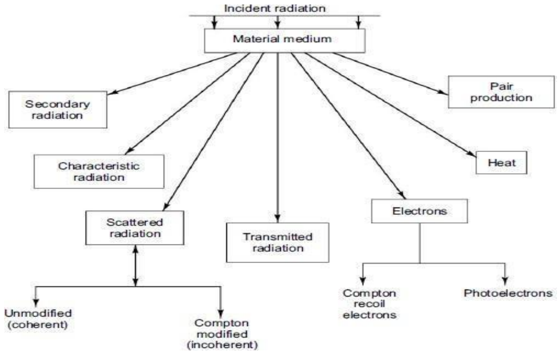


Fig. 3: Complex Interaction

Industrial radiography uses high-energy X-rays and gamma rays for inspection purposes, making radiation safety extremely important because excessive exposure can harm the human body. Improper handling of radiation may cause somatic and genetic effects, which may appear after a long period except in cases of severe exposure. To ensure radiation safety, the Government of India established the Radiation Protection Rules, 1971 under the Atomic Energy Act, 1962, which define safe working conditions and permissible radiation dose limits for workers. These rules require regular monitoring of radiation workers, maintaining exposure within prescribed limits, identifying causes of excessive exposure, and keeping cumulative exposure records throughout a worker's career. Radiation protection mainly focuses on measuring exposure levels and minimizing unnecessary exposure. Radiation hazards are classified into external and internal hazards. External hazards occur due to exposure to X-rays, gamma rays, or radioactive contamination, with X-rays and gamma rays being the most penetrating and harmful. Internal hazards occur when radioactive substances enter the body through breathing, swallowing, or skin cuts, where the severity depends on the amount absorbed, duration of retention, and type of radioactive material.

TIG welding, also known as Gas Tungsten Arc Welding (GTAW), is an arc welding process that uses a non-consumable tungsten electrode to generate heat and join metal components. It is widely preferred for welding Stainless Steel 316 because it produces precise, high-quality welds with excellent surface finish and minimal distortion, especially in thin sections. The welding process begins with proper cleaning and preparation of the metal surfaces to remove contaminants such as oil, rust, and dirt. During setup, the tungsten electrode is connected to the TIG torch and power supply, which creates a high-frequency current to ionize the argon shielding gas and form the welding arc. The intense heat generated by the arc melts the metal, and a filler rod may be manually added to strengthen the joint. Argon gas is continuously supplied to protect the molten weld pool from atmospheric contamination. After welding, the joint is allowed to cool gradually to reduce stress and distortion, and finally the weld surface is ground and polished to achieve a smooth finish and improved appearance.

Fig. 4: POD v/s Size of defect

Fig. 5: SS316 after TIG welding

Shielded Metal Arc Welding (SMAW), commonly known as stick welding, is a welding process that uses a consumable flux-coated electrode to create an electric arc for melting and joining metals. As the electrode melts, the flux coating forms a protective shield around the weld, preventing atmospheric contamination. SMAW is a versatile and widely used welding technique suitable for welding steel, stainless steel, cast iron, and certain non-ferrous metals, making it popular in construction, repair, maintenance, shipbuilding, automotive repair, and petrochemical industries.

Fig. 6: SS316 after Arc welding

Common applications include welding pipelines, structural steel, pressure vessels, storage tanks, and heavy equipment. Although TIG and SMAW welding follow similar procedures, they differ mainly in cleanliness requirements, electrode type, and filler metal application. TIG welding requires a higher level of surface cleanliness and uses a non-consumable tungsten electrode with manually added filler metal, whereas SMAW uses a consumable coated electrode such as SS309L, where the filler material is automatically supplied as the electrode melts during welding.

IV. RESULT ANALYSIS

After completing TIG welding and arc welding on Stainless Steel 316, along with brazing on brass components, the welded specimens were examined using X-ray radiography testing to determine the probability of defect detection in different welding processes. Film-based X-ray radiography was employed, in which X-ray radiation was passed through the welded joints while a radiographic film placed on the opposite side captured the transmitted image. The developed film images were then analyzed to identify welding defects such as porosity, cracks, and incomplete fusion. The resulting radiographic images for each welding process were used to evaluate and compare the effectiveness of defect detection.

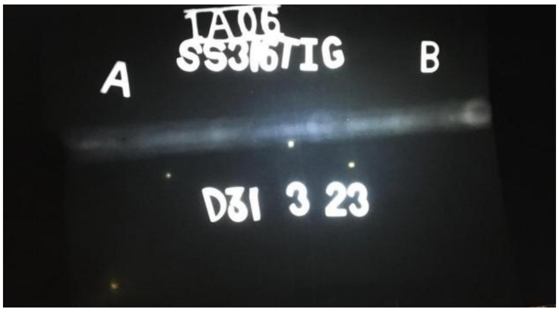


Fig. 7: X-ray film of TIG welding

The X-ray film of TIG welding consists of defects such as under fill, Hi-lo (Misalignment), incomplete penetration, Excess weld metal.

POD = (Number of Defects Detected / Total Number of Defects) x 100%

POD = (4/5)*100 % = 0.8*100 % = 80

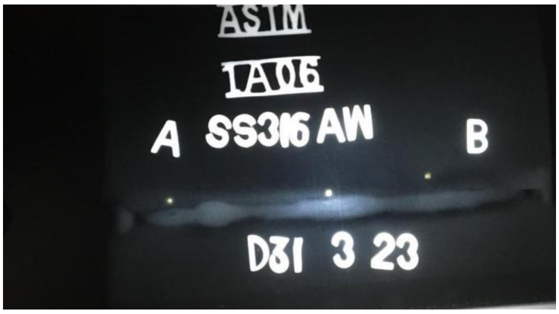


Fig. 8: X-ray film of Arc welding

The X-ray film of Arc welding consists of defects such as Lack of fusion, Undercut,

Excess weld metal, Incomplete penetration.

POD = (Number of Defects Detected / Total Number of Defects) x 100%

POD = (4/6)*100 % = 0.67*100 % = 67%

Fig. 9: X-ray film of Brazing

X-ray film of Brazing consists of defects such as Lack of penetration and root cavity.

POD = (Number of Defects Detected / Total Number of Defects) x 100 %

POD = (2/3)* 100 % = 0.67*100 % = 67 %

V. CONCLUSION

In conclusion, the study demonstrates that radiography testing is an effective non-destructive testing technique for assessing weld quality and detecting defects in welded joints. The results showed that TIG welding achieved the highest defect detection rate, followed by SMAW and brazing, indicating that TIG welding is the most reliable process for identifying weld defects through radiographic inspection. The study also revealed that the probability of defect detection is strongly influenced by the size and type of defect, with larger defects being easier to identify than smaller ones and certain defect types showing greater detectability. These findings provide useful insights for improving welding quality by optimizing welding and radiographic testing parameters to minimize defects and enhance inspection accuracy. Furthermore, the study highlights the need for future research to investigate other non-destructive testing methods and compare their effectiveness with radiography testing.

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