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Effect of radiographic film quality on SMAW weld defect detection in SA 240 Gr 316L pressure vessels

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Abstract

Ensuring the structural integrity of pressure vessels requires accurate detection of welding defects, as these vessels must withstand high internal and external pressures. Radiographic testing is a critical method for evaluating weld quality, but its accuracy depends on film quality, exposure conditions, and radiographic techniques. This study evaluates the effect of radiographic film quality on the accuracy of SMAW weld defect identification in SA 240 Gr 316L pressure vessels. Two radiographic techniques (Internal Source and Panoramic) were compared at different Source-to-Film Distances (SFD) using an Ir-192 radiation source (58 Ci and 59 Ci) and Fuji Xd film as the imaging medium. Exposure times were determined using the Practical Exposure Chart for Ir-192, resulting in 3 minutes 25 seconds at 40 inches SFD and 1 minute at 12 inches SFD. Radiographic evaluation was performed following ASME Section V standards to assess film density, defect detection accuracy, and film sensitivity. Results show that the Panoramic Technique yielded film density values between 2.50 and 2.88, while the Internal Source Technique produced values between 2.78 and 3.15. The film sensitivity was measured at 1.66%, with defect identification including 42 mm and 10 mm slag inclusion defects and 8 mm porosity within the weld. Certain defects required repair and re-inspection based on ASME acceptance criteria. These findings highlight the importance of radiographic parameters on defect detection accuracy for reliable weld integrity assessment in pressure vessels.

Keywords:
Pressure vessels, exposure time, Fuji XD film, panorama, gamma ray radiography.

1 Introduction

A pressure vessel is a closed container designed to contain fluids, either liquids or gases, that have pressure characteristics that are different from the ambient pressure. Pressure vessels have special specifications because they must be able to withstand the pressure of the contained fluid, plus the load due to the weight of the vessel itself and various other external loads [1].

The pressure that arises due to internal pressure produced on the fluid contained therein, for example, compressed gas or reactions in the vessel and external atmospheric pressure which is an important consideration in testing pressure vessels [2].

According to [3] The selection of welding joint quality is also a special concern in the manufacture of pressure vessels, this is done to prevent defects or the inability of the welded joint to withstand the workload expected by consumers. In various cases, the failure of a type of construction often occurs due to the failure of the connection with the welding joint method [4],

Based on the study conducted[5]which states an incident where the inner tank DC01Ek experienced a failure in the circular weld (C-weld) caused by corrosion cracking, this occurred when the connection was carried out without referring to the standards used as guidelines in the manufacture and testing of pressure vessels.

Non-destructive testing is an important tool to ensure and control weld quality and the possibility of defects that can affect the strength and safety of pressure vessel structures [6]. NDT can be defined as an examination that aims to identify defects in materials without damaging or destroying the object or specimen being tested [7].

This testing is generally carried out to ensure that the quality of the product and materials used are still safe and have not exceeded the damage tolerance limit [8]This study uses one of the Non-Destructive Tests, the Radiography Test, because this method provides a clear Figure of the defect in the material, including its shape, size, and location.

Radiography testing is an inspection method using a radiation source (X-rays or gamma rays) as a medium to detect welding defects that occur on the surface or below the surface, with film as a recorder of the resulting image [9]. According to research by [10]A film is exposed to light for a certain time, the length of the exposure time is influenced by the thickness of the object to be examined, the distance of the object from the radiation source, the activity of the radiation source, and the quality of the film used during testing.

Apte et al. in their research showed that the radiation exposure produced by the radiation source will penetrate the test object and experience attenuation in the test object, so that the attenuated radiation can be recorded by the film attached to the back of the test object [11]. The research is relevant by (Oglat et al.), after the film washing process is complete, the film can be evaluated to determine the presence of defects in the test object by looking at the difference in the level of darkness or density on the film [12].

Radiographic techniques are often chosen to determine the condition of a construction or installation because this technique will depict (imaging) the condition of the inspected material. This technique is widely used in the fabrication world, especially in boiler construction joints, pressure vessels, and piping [13]. This method plays a very important role in determining the limits of acceptance and rejection of welding results on a material. This method uses a radiation source to identify the presence of cracks, porosity, foreign body infiltration (slag inclusion), and other imperfections because the indication of defects can be seen clearly, and the ability to detect defects on the surface and below the surface, so it can be applied to various types of materials [14].

Based on research by Liu et al., the main challenge is its accuracy in detecting the smallest defects, especially in materials with varying thicknesses [15]. In this case, it is often difficult to ensure the quality of perfect welding joints considering that variations in material thickness can affect the examination results. The results of research conducted by Budhu et al., showed that the challenges that often occur in interpreting the results of radiographic films resulted in errors in detecting the type of defect [16]. Soltes et al. identified that the challenge of radiographic testing lies in the unstable or insufficiently powerful radiation source which can produce a blurred image (sensitivity) on the film in identifying certain types of defects such as slag inclusion and porosity, which is still a challenge in industrial practice [17].

This test aims to analyze defects in vessel welding joints and address gaps by evaluating the effectiveness of the single-wall viewing method with the inside source technique and the panoramic technique in detecting welding defects at various exposure distances. In addition, the acceptance standard for radiographic results referring to the level of blackness (density) of the film after the digitization process using a positive film scanner needs to be further analyzed to ensure that the method used has met the applicable safety standards by international regulations and guidelines. The density of the radiographic film according to the standard used by ASME secV in the range between min2.0-max4.0 [18].

This analysis includes the identification of the shape and type of defects in the weld joints detected using gamma radiography. Radiographic testing by varying the two techniques of internal and panoramic radiation is expected to provide deeper insight into the best method to improve the accuracy of detecting defects in welding in the pressure vessel industry, and can contribute to the development of more accurate and efficient NDT methodologies in the industry.

2 Research methods

This study was conducted on the results of SMAW welding on the circumferential seam and longitudinal seam joints on the shell vessel. The welding results were tested using the Non-Destructive Test (NDT) method, namely the Radiography Test. By utilizing the radiography test, clear information can be obtained regarding the presence of defects in the welding results, thus allowing for a more detailed evaluation.

2.1 Determination of variables

The distance from the radiation source to the film and the exposure time are two important factors in influencing the quality of the radiographic results. Variations on the two lighting techniques with the first lighting using the panoramic technique with a distance of 40 inches from the source to the film and the second using the Internal Source Technique with a distance of 12 inches from the source to the film.

Determination of exposure time is based on the thickness of the material and the type of defect to be detected according to the ASME Section V standard which provides specific guidelines for setting exposure times appropriate to material thickness and defect type. These two variables must be controlled by these standards to ensure accurate results and meet the applicable acceptance criteria in radiographic testing.

2.2 Equipment and materials

The equipment used in the testing process is shown in Table 1.The following materials were used for the study as shown in Table 2.

Table 1 Radiography Test Equipment

No	Equipment	Specification
1	Gamma Ray	(Iridium -192)
2	Source Tube	3/4"
3	Lead screen/Plate	PB 0.125
4	Survey Meter	ND-2000A
5	Penetration Meter (IQI)	ASTM
6	Movie Viewer	View-lite 0417
7	Densitometer	Digit-x

Table 2 Radiographic Test Materials

No	Material	Specification
1	Type of Material	SA 240Gr 316L
2	Material Thickness	10mm
3	Weld thickness	5mm
4	Welding Methods	SMAW (Shielded Metal Arc Welding)
5	SFD (Source Film Distance)	1016mm (40inch) and 305mm (12inch)
6	Radiation Sources	Iridium-192
7	Activity	59Ci and 57Ci
8	Source Size	(3x3.5mm)
9	IQI (Image Quality Indicator)	ASTM 1B
10	Radiography Techniques	*Single Wall Single Viewing (SWSV)*
11	Screen Type	Lead 0.125 mm
12	Type of Film	FUJI XD

2.3 Testing procedure

The radiographic testing procedure consists of several key steps to ensure accurate defect detection and compliance with safety standards. The first step is the preparation of the test object's surface. Before placing the radiographic equipment, the weld surface of all butt joint welds must be thoroughly cleaned of spatter, scale, slag, and other contaminants to prevent interference with image quality.

Next, the specimen is marked to provide a clear identity. Proper labeling is essential to avoid data misidentification, particularly in cases where defects are detected and subsequent repairs are required. The Image Quality Indicator (IQI) is then determined based on plate thickness measurements and standards outlined in ASME Section V. The IQI ensures that the radiographic image meets the required sensitivity for defect detection.

Before installing the radiographic film at the welding location, it is positioned between lead plates (lead screens). This placement helps absorb excess radiation, ensuring proper exposure and preventing unnecessary radiation scattering that could degrade image clarity. The film is then installed at the marked welding location, as shown in Fig. 1, using a retaining device or clip to maintain stability and prevent movement that could blur the radiographic image.

Fig. 1. Radiography Test Shooting Preparation Process

Following film placement, the radiation tube, source tube, and radiation igniter are prepared. It is crucial to position the radiation tube behind the installed radiographic film to prevent direct exposure. Direct radiation exposure would result in film overexposure or burning, rendering it unusable for defect analysis. A survey meter is then used to determine a safe distance from the radiation source during imaging. This step ensures that operators and surrounding personnel are adequately protected from radiation exposure.

Once safety measures are in place, the radiographic film is exposed to radiation for a specified duration (exposure time), as illustrated in Fig. 2. After the exposure period ends, the source tube is closed, and the radiation tube is turned off to secure the surrounding environment from radiation hazards.

After exposure, the film undergoes a series of processing steps, including developing, rinsing, fixing, washing, and drying. These steps are critical for obtaining a clear and accurate radiographic image [19]. Finally, once the film is processed, it is analyzed using a film viewer. This step allows for the identification and evaluation of any defects present in the tested material, ensuring that the weld meets the required quality standards.

Fig. 2. Film Mounting to Test Object

In radiographic testing, film quality is a very important aspect in determining the accuracy of defect evaluation results [20]. The selection of film for radiography of test objects depends primarily on the thickness and type of material being tested, as well as the range of source intensities (Ci) available at the gamma-ray source [21]. The selection of film also takes into account the desired quality of the radiographic film and the duration of exposure. If high radiographic quality is required, then a slow film (film with finer grains) is used; conversely, to reduce the exposure time, a fast film (film with large grains) is used [22]. Fine-grained films often produce more optimal images.

2.4 SWSV shooting method with variations of the techniques

1. Panoramic technique

Based on the illustration of radiographic irradiation shown in **Error! Reference source not found.**. The panoramic technique allows evaluation of the weld quality on pipes or large components without the need to repeatedly move the radiation source or film [23].

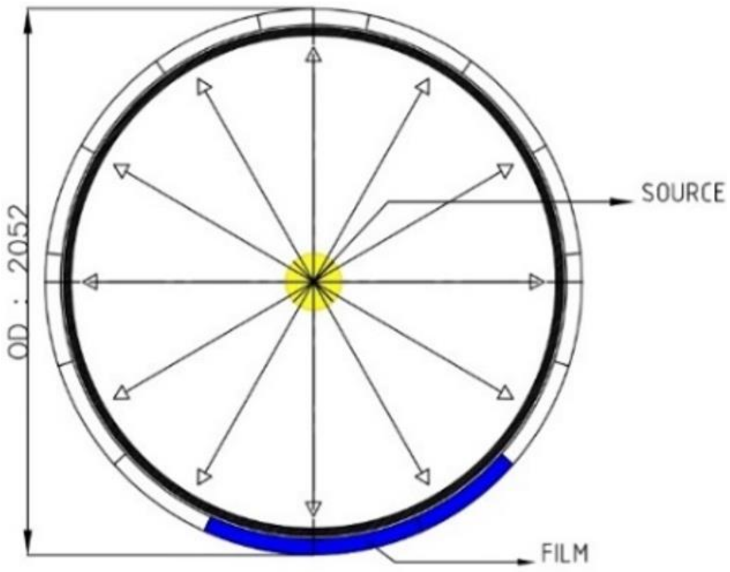

Fig. 3 Panoramic Shooting Sketch Technique

2. Internal source techniques

Internal source irradiation techniques, such as in Fig. 4 placing the radiation source inside the component being tested, eliminating the need to move or reposition it, reducing the potential for errors, and increasing inspection efficiency.

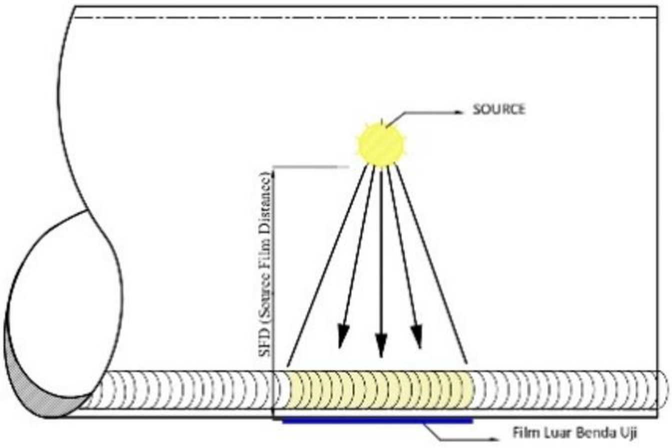

Fig. 4. Internal Source Technique Shooting Sketch

2.5 Determining parameters

1. Calculating Weld Thickness

TW (Exposure Time) = Material Thickness + Thickness $face\ and\ root\ reinforcement = 10 + 5 = 15mm$

2. Determining the minimum SFD

Effective source (F) $=\sqrt{3^2 \times 5^2} = 3{,}461$

Minimum SFD $=\frac{F \times TW}{UG} +$ TW $=\frac{3{,}461\times 15}{0{,}51} + 15 = 116{,}8mm$

The SFD used on the radiography machine is 1016mm for panoramic technique and 305mm for (internal source technique), the minimum distance for taking radiographic images on this material is by the minimum SFD calculation.

3. Penetrameter Determination (IQI)

Based on the TW=15mm calculation, IQI uses Wire Type 8 Set 1B on the Source Side. Choosing the right IQI is important in photographing welded products. because it is related to the sensitivity of a radiographic film. Sensitivity is a measure of the quality of a film related to the smallest details and defects that can be observed.

4. Geometric unsharpness calculation

Based on the geometric unsharpness requirements for the equations in film classification to determine the limit value for each material thickness can be determined, as shown in the following ASME sec. V standards.

Test specimen thickness in inches & (mm)	Unsharpness Factor /Ug, (inches) & (mm)
Under 2 (50 mm)	0.020 (0.51)
2-3 (50-75mm)	0.030 (0.76)
3-4 (75-100)	0.040 (1.02)
Greater than 4 (100)	0.70 .78)

Table 3 Geometric Unsharpness

Test specimen thickness in inches & (mm)	Unsharpness Factor /Ug, (inches) & (mm)
Under 2 (50 mm)	0.020 (0.51)
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Greater than 4 (100)	0.71 .78)

Unsharpness factor (Ug) on

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3-4 (75-100)	0.040 (1.02)
Greater than 4 (100)	0.72 .78)

In setting the desired image quality in radiographic testing based on material thickness, then the test object that has a thickness below 50mm, the resulting image will be relatively sharper because gamma ray radiation can penetrate thinner materials more easily, therefore a smaller unsharpness of 0.51mm is needed to ensure that internal defect details can be detected properly without the image becoming faded.

3 Results and discussion

From the results of radiographic testing on pressure vessel joints with a diameter of 2023mm made of Stainless Steel SA240 Gr 316L with a material thickness of 10mm.

3.1 Exposure Time

In the study, it was found that longer exposure times in Radiographic tests did not always improve the accuracy of detecting welded joint defects in vessels, which is in line with research findings [24], which identified that overexposure can obscure the details of small defects. These results are also relevant to international standards such as ISO 17636-2 and ASTM E94, which recommend setting the proper exposure time according to the material thickness and the type of defect to be detected (Fig. 5). This study informs that in the Single Wall Single Viewing (SWSV) method, setting the proper exposure time, together with other variables such as the distance of the radiation source to the film, is very important to avoid the loss of details due to overexposure and to improve the sensitivity of defect detection in pressure vessel welding. These findings provide practical guidance to improve the effectiveness of radiographic testing in industry and improve inspection procedures according to applicable standards.

$$Exp,Time = \frac{EFxD^2}{\mathrm{I}} \qquad \frac{T1}{T2} = \frac{D1^2}{D2^2}$$

It is known: Twelding = $15\ mm^2$, Activity Source 1= $59\ Ci$, and,2 = $58\ Ci$, IQI = Set B number 8 Source Side, and EF= 195 Ciminet (from the Grafix ExpCart Ir 192 table)
Expiry time 1 = $195\ Ci \times (1^2) \div 59Ci\ = 3{,}3 menit$

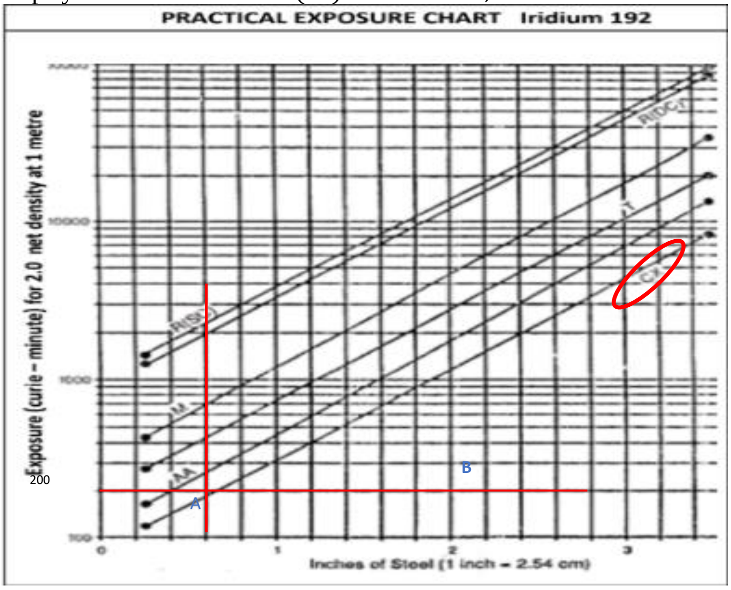

Fig. 1 Practical Exposure Chart Iridium192

If Actual SFD 40 Inch (101.6 cm)
T2 = $(1{,}016^2)\ \times 3{,}3 = 3{,}406\ menit$ =3 minutes 25 seconds
Expiry date2195 $Ci \times (1^2) \div 57Ci\ = 3{,}4\ minutes$

If the Actual SFD is 12 Inch (30.5 cm)
T2= $(0{,}3048^2) \times\ 3{,}4 =\ 0{,}325\ minute\ =\ 20\ seconds.$

3.2 Sensitivity level (EPS)

The sensitivity level is good because, on the IQI B wire with the smallest diameter measuring 6, all six wires are visible from the smallest to the largest.

$$\text{EPS} = \frac{Smallest\ wire\ diameter}{Material\ thickness}\ 100\% = \frac{0{,}25}{15}\ \times\ 100\% = 1{,}66\%$$

In industries that follow the ASME Section V standard, the equivalent sensitivity accepted for radiographic testing is set at a maximum of 2%. This means that the higher the sensitivity, the smaller the defects that can be detected. This is especially important in industries that involve high-risk materials, such as pipe or pressure vessel welds. Found that the increase in sensitivity is influenced by the setting of radiographic parameters such as Exposure time, radiation source energy, (Source-to-Detector Distance, SFD).

3.3 Radiographic results (Geometric Unsharpness)

By using a densitometer to measure the results of radiographic film irradiation, it will be seen that there is a difference in the absorption of radiation by the material. High density variations, such as 14.26% (in the panoramic technique) in Table 7 shows the number of defects in the welded joints, while in a density variation of 12.57% in (internal source technique) indicates the presence of a single defect; a high-density variation difference indicates non-uniformity in the weld joint, which could be caused by internal defects such as porosity, lack of fusion, or cracks.

Factors that influence differences in radiation absorption when a source emits radiation that penetrates a material include differences in density, thickness, and absorption characteristics that are influenced by differences in composition [6].

1. Ug (panoramic)= $(F \times t) \div\ (SFD - t) = (3{,}461 \times 15) \div (1016 - 15) = 51{,}915 \div\ 1001 = 0{,}052$mm (Actually)
2. Ug (internal source technique) = $(F \times t) \div\ (SFD - t) = (3{,}461 \times 15) \div\ (305 - 15) = 51{,}915 \div\ 290\ = 0{,}179$mm (Actually)

The geometric unsharpness of the radiographic results should not exceed 0.02 inches for material thicknesses below 2 inches/0.51 mm.

3.4 Density

1. Obtained in the panoramic technique,

$\varDelta$D = $DO_{max}\ -\ DO_{min}$ =2.88-2.50=0.38
Average Density = $\text{DO}_{\text{rata-rata}} = \frac{Overall\ Average}{\text{number of film}} = \frac{58.685}{22} = 2{,}667$
Density Variation (%)= $\frac{\varDelta DO}{DO_{Average}} \times\ 1 = \frac{0.38}{2.667} \times 100 =\ 14{,}26\%$

2. On (internal source technique)

$\varDelta$D= $DO_{max}\ -\ DO_{min} =\ 3{,}15\ - 2{,}78\ = 0{,}37$
Density Variation (%)= $\frac{\varDelta DO}{DO_{Average}}\ \times\ 100\ = \frac{0.37}{2.943} \times\ 100\ = 12{,}57\%$

3.5 Internal source engineering test data analysis

The results of the radiographic film irradiation data on the shell vessel joints identified welding defects, which are displayed on Table 4. Acceptance criteria for welding defects, there are porosity defects with a thickness of 10 mm, then the maximum permitted is 2.5 mm. If it exceeds a diameter of 2.5 mm, it can cause leakage at the joint, therefore, it is necessary to carry out re-welding repairs with a welding sample grinding procedure until welding defects are found and re-radiography is carried out [25]. The results of the radiographic testing of the internal source technique Fig. 6.

Table 4 NDT welding inspection results with internal source technique.

Join No Shell	Position Film	Film Density D=2.0-4.0	Internal Welding	Evaluation	
				Acc	Reputation
1 B LW	0-1	2.82 – 3.10		Acc	
	1-2	2.78 – 2.96		Acc	
	2-3	2.80 – 3.06		Acc	
	3-4	2.86 – 3.10		Acc	
	4-5	2.80 – 3.15	Porosity: 1mm	Acc	

Radiographic test data using the Internal Source Technique showing the presence of Internal Porosity defects. Result value density on Fig. 6. obtained between 2.80min-3.15max, with the presence of Internal Porosity defects. However, the size of the detected defect (1mm) is still within the Acceptance Criteria for Defects (ACC) limits so that no re-welding or repair is necessary. The density level will vary on the amount of radiation reaching the film through the tested object, with dark areas indicating more exposure, while light areas indicating less exposure.

Fig. 6. Film Specimen No. 4-5 Joint No. 1B (LW) (internal source technique)

3.6 Panoramic technique test data analysis

The results of the panoramic technique test data can be seen; several welding defects were identified. Table 5 with 21 Radiographic Test Film specimens. Based on the results of the radiographic test on Table 5, the panoramic technique produces density values between 2.50min-2.88max, while the internal source technique has a range of 2.78min – 3.15max in Table 4.

Both techniques produce density values that are within the range that meets the ASME Section V, T-274 standard, which is between 2.0 min and 4.0 max. Although both techniques meet the acceptance criteria, the internal source technique tends to produce slightly higher densities, potentially increasing the sensitivity of the test by up to 1.66%. Higher sensitivity allows for more accurate defect detection. However, if the density is too high, this can cause the image to be too dark, making small defects difficult to see. On the other hand, panoramic techniques with lower densities provide a clearer image and the details of defects remain well visible.

Table 5. NDT welding inspection results with a panoramic radiography test method

Specimen Name	Position Film	Film Density D=2.0-4.0	Internal Welding	Evaluation	
				Acc	Reputation
1 A CW	0-1	2.64-2.88		Acc	
	1-2	2.60-2.80	Porosity: 1mm	Acc	
	2-3	2.60-2.80	Slag inclusion: 10mm		*Rejected*
	3-4	2.60-2.80		Acc	
	4-5	2.60-2.80	Porosity: 8mm		*Rejected*
	5-6	2.60-2.80		Acc	
	6-7	2.60-2.80		Acc	
	7-8	2.60-2.80	Porosity: 2mm	Acc	
	8-9	2.69-2.70	Porosity: 1mm	Acc	
	9-10	2-60-2.70		Acc	
	10-11	2-60-2.70		Acc	
	11-12	2-60-2.70		Acc	
	12-13	2-60-2.70		Acc	
	13-14	2.51-2.69		Acc	
	14-15	2.50-2.70	Porosity: 2mm	Acc	
	15-16	2.50-2.70	Slag inclusion: 18mm		*Rejected*
	16-17	2.50-2.75		Acc	
	17-18	2.50-2.70		Acc	
	18-19	2.50-2.70	Porosity: 1mm	Acc	
	19-20	2.50-2.70		Acc	
	20-21	2.50-2.70	Porosity: 2mm	Acc	
	21-0	2.50-2.70		Acc	

In the panoramic test specimen, the welding results on the Butt Joint Shell specimen films number 2-3, 4-5, and 7-8 show the results of the radiographic test film on Fig. 7 And Fig. 8..Fig. shows the density value obtained was 2.60min-2.80max, indicating ideal radiation exposure quality and by standards, allowing clear detection of Slag Inclusion defects along (10mm) of SMAW welding results. Fig. 8 shows a density value of 2.60min-2.80max, referring to a fairly good density range in detecting radiographic film images, an Internal Porosity defect of (8mm) was obtained.

Fig. 7 Film Specimen No 2-3

However, not all specimens that have defects can be categorized as rejects, because the determination of acceptance and rejection is based on the standard used, namely ASME Sec VIII Div.1. In the research results, the majority of defects that occur in the specimen are porosity-type defects (hollow volume), which are usually caused by water vapor in the metal, inappropriate shielding gas, excessive welding speed, the electrode used is still damp, and welding cooling is too fast [26].

Fig. 8. Film specimen no 4-5

From this test, the analysis value is obtained that if the density is too high, the cause is too high source activity, too long development time, and misuse of radiographic techniques. Too low density (<2.0) makes the film look pale, the details are less clear. If the density is too high (>4.0) the film is too dark, so small defects are difficult to detect.

The use of radiographic testing in welding inspection offers several benefits. Mechanically, welding defects can be observed and measured with high clarity, allowing for precise evaluation of the weld quality [27]. This method is capable of identifying both surface and subsurface defects, ensuring a comprehensive assessment of the material's integrity. Additionally, radiographic testing provides consistent test data that can be acquired and stored for further analysis and documentation.

However, radiographic testing also has several disadvantages. The process poses potential hazards to operators and individuals in the surrounding area, necessitating strict safety precautions to limit exposure and secure the testing environment. Moreover, this method is less effective in determining the depth of defects in thick materials, requiring integration with ultrasonic testing for a more thorough inspection [28]. Furthermore, conducting radiographic testing requires experienced and certified personnel to ensure accurate interpretation of results and compliance with safety regulations.

4 Conclusion

This study shows that radiographic film quality significantly affects the accuracy of SMAW weld defect detection in SA 240 Gr 316L pressure vessels. Radiographic evaluations using both the Panoramic and Internal Source Techniques revealed variations in film density, with the Internal Source Technique achieving slightly higher density values (2.78–3.15) than the Panoramic Technique (2.50–2.88). A sensitivity level of 1.66% was achieved, allowing for the identification of slag inclusions (42 mm and 10 mm) and porosity defects (8 mm). Defects exceeding ASME Section V acceptance criteria required re-welding and re-evaluation. Several factors influencing radiographic quality were identified, including radiation source activity, exposure duration, and film processing conditions. Optimizing these parameters is essential for ensuring reliable defect detection and maintaining pressure vessel integrity. Future research could focus on advanced image processing techniques or digital radiography.

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