Analysis of causes of piping welding defects in steam gas power plants with FMEA and AHP method

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Abstract. *High welding intensity is an integral part of the construction process of a Steam Gas Power Plant (PLTGU). The existence of weld defects has a significant potential for rework, additional construction costs, and delays in project completion. In the fabrication of pipe joints by welding in the PLTGU additional construction project with a capacity of 650 MW in Muara Tawar, welded joints were found to be rejected at 22.44%. This study aimed to analyze and determine the leading causes of rejected weld defects at the welded joint using the methods used, namely FMEA and AHP. Based on the Pareto diagram, it is known that two types of welding defects dominantly occur in welded joints which will then become the priority for repairs carried out by the contractor, namely porosity and cluster porosity. Based on the FMEA method, it is known that two groups of Risk Priority Number (RPN) values differ quite a lot, namely the group with low RPN values (1-140) and the group.*

Keywords: AHP, FMEA, welding, weld defect.

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1. Introduction

Developments in population, economics, and technological developments make the demand for electricity supply continue to increase. According to the International Energy Agency (IEA), by 2020, the world's total final electricity consumption will reach 22,315 TWh, 4.0% higher than in 2019. This increases the share of electricity in total final energy consumption from 19% in 2018 to 24% by 2040. Electricity demand is expected to be particularly strong in developing countries. Meanwhile, in Indonesia, in the next five years (2020-2024), the construction of power generation infrastructure is planned to reach a total capacity of 27.28 GW. In this power station, the piping system is an important part that is used to convey water, water vapor, chemical solutions, fuel oil, lubricating oil, air, and gas from one piece of equipment to another, where some of them experience high pressure and temperature during operation

High welding intensity is an integral part of the PLTGU construction process. The existence of weld defects has a significant potential for rework, additional construction costs, and delays in project completion. In the additional construction project of PLTGU with a capacity of 650 MW in Muara Tawar (Muara Tawar Combine Cycle Power Plant Block 2, 3 & 4 Add-On Project), it was found that quite many welded joints were rejected from the radiographic test results because they had weld defects that did not meet the acceptable acceptance requirements defined by the standard. This research was conducted to reduce these weld defects to meet the project owner's expectations for the reliability of the piping system in accordance with predetermined acceptance criteria (Trimarjoko et al., 2019).

Due to its weaknesses, according to (Aprianto et al., 2021) in their research, risk factors were evaluated using Failure Mode and Effect Analysis (FMEA). FMEA is a method that can determine problem priorities (Aini, 2021; Rozak et al., 2020). In addition, this method analyzes the risk of severity, detection, and occurrence (Qin et al., 2020; Hernadewita et al., 2022). Besides requiring priority from the root of the problem, decisions are also made related to the most significant factor, namely the Analytical Hierarchy Process (AHP) (Wang et al., 2018). AHP is a method for making a decision, designed and carried out by selecting several alternatives, which are evaluated with multiple criteria (Wahid et al., 2022; Sequeira & Adlemo, 2021). Damage to the piping system can cause the operational failure of the unit (electrical energy generation station). Apart from damage to the material due to high pressure and temperature, corrosion, and other damage, it can also be caused by leaking welded joints in the piping components due to poor quality welds (Tešić, 2020;

Berrekia et al., 2019). This study aimed to analyze and determine the main causal factors for porosity or cluster porosity in pipe welded joints.

2. Method

The primary data obtained comes from observation and individual interview results. Observations were made by observing the construction work environment, work tools, work materials, work documents, and workforce. While individual interviews were conducted by holding a question and answer session with the site QA/QC manager, welding inspector, supervisor, and QA/QC inspector who supervised the piping welding work. Meanwhile, other primary data sources were obtained from the results of the Focus Group Discussion (FGD) (Aprianto et al., 2022), which was conducted by holding an official discussion forum led by the facilitator or moderator involving 13 participants who were directly involved in welding, experienced, competent and including those certified by national and international institutions (authorize) consisting of welders, supervisors, QA/QC inspectors, welding inspectors, level II radiographic technicians, and QA/QC managers. While secondary data is obtained from the work contract book between the owner and the contractor, all procedures and technical reports related to welding, and all agreed international standards. The stages of problem solving are as follows:

1. The initial stage is carried out by analyzing all weld defects that are rejected (reject) based on radiographic test reports and then determining the welding defects that are a priority for improvement (critical to quality) by looking at the percentage using a Pareto diagram (Setiawan & Setiawan, 2020)
2. To identify and collect data on all the causes of the dominant (failure mode) weld defects based on their management aspects/elements, which are known through individual interviews with each pipe welding production supervisor.
3. Conduct field observations to prove all information obtained from individual interviews.
4. Confirm the data collected both from the summary of the results of individual interviews and the results of observations involving welders, the pipe welding production supervisory team, and the radiography team in the Focus Group Discussion (FGD) forum to provide a mutually agreed assessment of all causes failure with the FMEA method (Mutlu & Altuntas, 2019). The steps taken are as follows:
    a. Identify all failure modes.
    b. Determining each parameter of each rating on the severity, occurrence, and detection criteria obtained through an agreement with the QA/QC manager of the contractor.
    c. Provide an assessment for each value of severity (S), occurrence (O), and detection (D) for each failure mode from the results of an agreement with the supervisory team, welder, and radiography team.

5. Determining the weight of the S, O, and D criteria through discussions with the QA/QC Manager and the supervisory team from the contractor. At this stage, the AHP method is carried out with the following steps (Yu & Liu, 2021):
    a. Setting criteria or creating a hierarchy
    b. It is done with a discussion of questions and answers with the QA/QC department of the contractor's piping division.
    c. Weighting of the criteria by measuring the consistency of the criteria weight

    It is done with a discussion of questions and answers with the QA/QC department of the contractor's piping division.

$$\mathrm{CI} = (\lambda\mathrm{max} - \mathrm{n})/\mathrm{n} \tag{1}$$

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RC} \tag{2}$$

$$\text{New RPN} = (W_S \text{ x } S) + (W_O \text{ x } O) + (W_D \text{ x } D) \tag{3}$$

6. Confirm RPN calculation.
7. Identify the root cause of the problem (Figure 1)

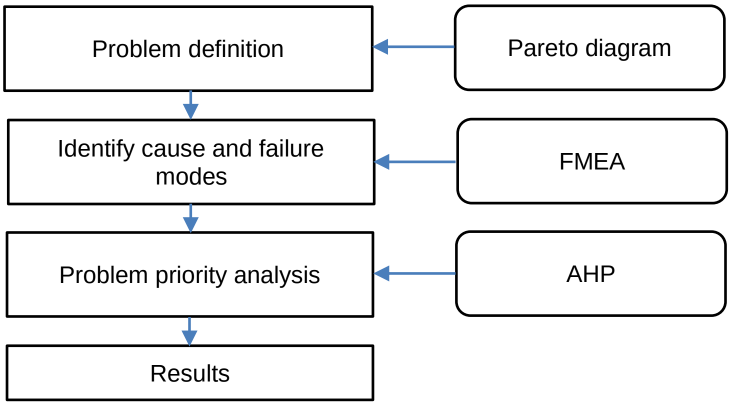

Figure 1 Stages of Problem-Solving.

3. Results and Discussion

Analysis with Pareto Charts

The initial stage was carried out by analyzing defects with the most significant percentage using a Pareto chart, as shown in Figure 2.

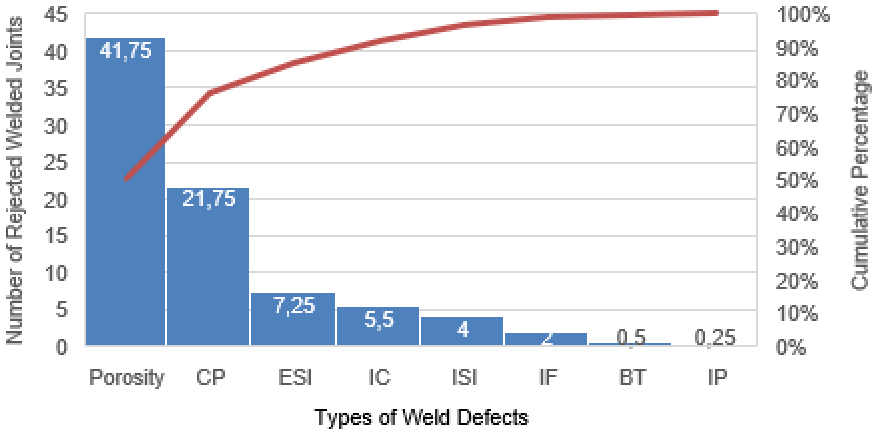

Figure 2 Pareto Diagram of Weld Defects in HRSG Block 2.1.

Based on the Pareto diagram, eight types of defects are rejected because their size and density exceed the tolerance limit of the acceptable standard. It can be seen that porosity is the most dominant weld defect in welded joints, there are 41.75% of welded joints are rejected due to porosity, where the cumulative percentage of total rejected welded joints is 50.30%, while in second place there are 21.75% of welded joints which was rejected due to cluster porosity with a cumulative percentage of the total rejected welded joints being 76.50%. Because the characteristics of cluster porosity are almost the same as porosity, cluster porosity is also decided as a priority for improvement or is considered critical to quality, so further analysis must be carried out by identifying the causative factors.

Results of Observations on Welding

In this study, observations were made on 40 pipe-welded joints used as objects of observation, as evidenced by the results of individual interviews. All of the welded joints were then subjected to radiographic tests. The results of the radiographic tests showed that there were welded joints that did not have porosity defects at all, had porosity defects but were still acceptable, and had porosity defects that were rejected because their dimensions exceeded the tolerance limits set by the ASME BPVC Section I and ASME B31.1. The radiographic test results are depicted in Figure 3.

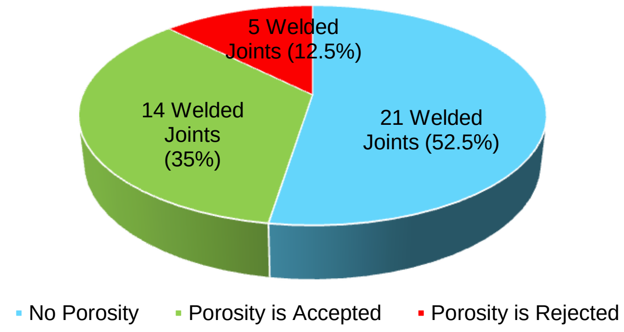

Figure 3 Radiographic Test Results.

Subsequent observations and measurements were carried out by comparison of the set current value by the welder in the welding machine to the range of electric current values determined by the Welding Procedure Specification (WPS) to know the level of understanding of the welder to WPS that must be used or in other words; this comparison will show the ability of the welder to determine the suitable range of electric current values according to the WPS that must be used. The results of these measurements and comparisons are depicted in Figure 4

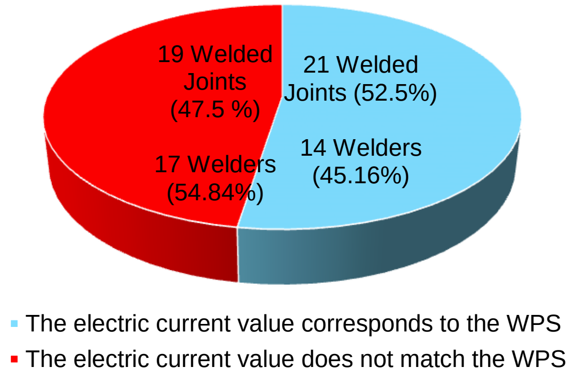

Figure 4 Comparison of Electric Current in Settings and WPS.

Based on the observations, it was found that four welders had adjusted the electric current value correctly but had also adjusted the electric current incorrectly. Welders like this were categorized as unstable welders. The number of unstable welders is depicted in Figure 5.

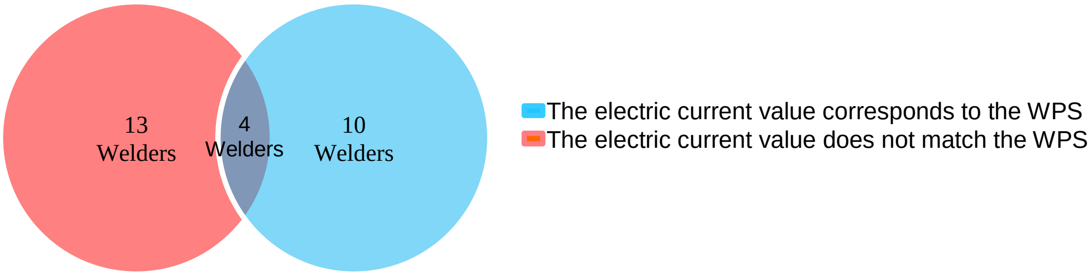

Figure 5 Comparison of Electric Current in Settings and WPS - Labile Welders.

In this study, observations, measurements and comparisons were also made on the set current value by the welder in the welding machine to the output current value of the welding machine to know the performance of the welding machine, including the level of accuracy (deviation) from the electric current indicator contained in the welding machine or even the possibility of damage to the welding machine. According to the international standard IEC 60974-1, the level of accuracy for voltage and electric current on an indicator between 100% and 25% of the maximum setting (maximum setting) is 10% of the actual voltage and electric current. The results of the measurements and comparisons are depicted in Figure 6

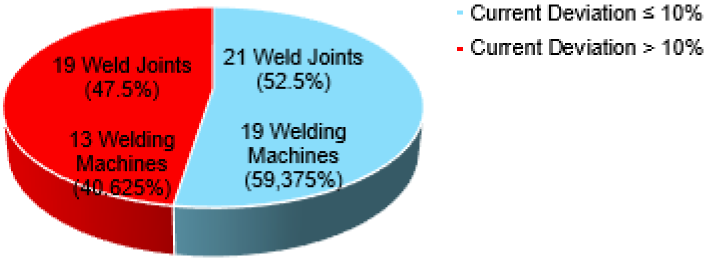

Figure 6 Comparison of Welding Machines Based on the Deviation of Electric Current.

Based on the 19 welding joints mentioned above, several welding machines had produced an electric current deviation smaller than 10% but at other times produced an electric current deviation of greater than 10%, as was the case with the 21 welding joints above. The number of such welding machines is illustrated in Figure 7

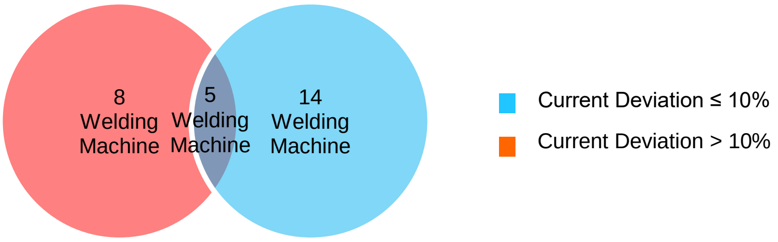

Figure 7 Comparison of Welding Machines Based on the Deviation of Electric Current - Abnormal Welding Machines

Using a scatter diagram shows that for the SMAW process, setting the electric current at intervals of 50 – 220 amperes WPS most often results in an electric current deviation greater than 10%, which amounts to 57.14%, as shown in Figure 8.

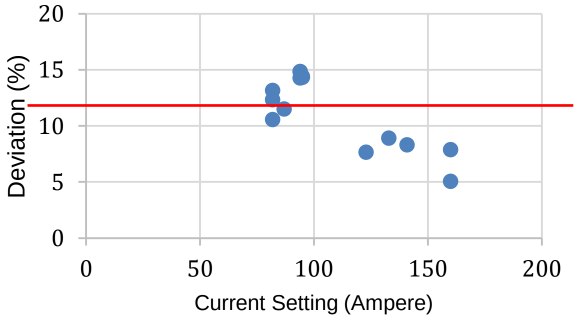

Figure 8 Deviation of the SMAW Process for Each Current Setting at 50 – 220 Amperes WPS.

Using a scatter diagram shows that for the GTAW process, setting the electric current at intervals of 80 – 150 amperes WPS most often results in an electric current deviation of greater than 10% where the amount reaches 50%, as shown in Figure 9.

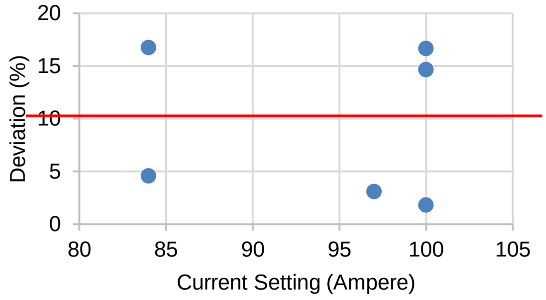

Figure 9 Deviation of the GTAW Process for Each Current Setting at 80 – 150 Amperes WPS.

In this study, measurements and comparisons were also made on wind speed around the work area using an anemometer to determine its effect on the appearance of porosity. The results of the measurements and comparisons are depicted in Figure 10 and Figure 11.

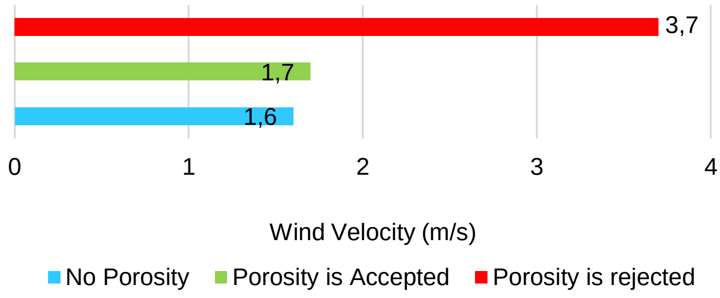

Figure 10 Comparison of Porosity Based on Wind Velocity in the GTAW Process.

Based on Figure 10, the wind velocity from 0.0 – 1.6 m/s is the range of wind velocity meeting values where the weld results can be without porosity defects, have porosity defects with the accepted dimensions, and can also have porosity defects whose dimensions are rejected.

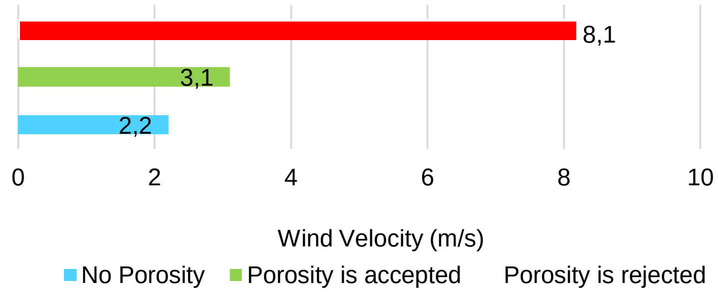

Figure 11 Comparison of Porosity Based on Wind Speed in the SMAW Process.

Based on Figure 11 the wind velocity from 1.0 – 2.2 m/s is the range of wind velocity intersection values where the weld can be without porosity defects, has porosity defects but dimensions are acceptable, and can also have porosity defects whose dimensions are rejected. Based on the explanation above, it can be concluded that wind speed is not the only cause of porosity in the weld results, either with the GTAW or SMAW processes.

Analysis with Failure Mode and Effect Analysis (FMEA)

After obtaining the type of weld defect that is a priority with the Pareto diagram, the next step is to assign weights with the FMEA method, which is a structured procedure in which there are three criteria in this method, namely Severity, Occurrence, and Detection, which are used to obtain a high-Risk Priority Number (RPN) value and ultimately used to identify and analyze potential failures and prevent as many failure modes as possible so that later repairs can be made. Following are the results of the FMEA analysis, which can be seen in Table 1.

Table 1 FMEA Analysis Results

CTQ	Welding Process	Failure Cause	S	Failure Effect	O	Preventive measure	D	RPN
Porosity and Cluster Porosity	The electric current in the welding machine is unstable because the genset as a source of electric power is under a high load.	Genset are also used as a power source for electrical equipment for other construction work.	7	Interfere with the performance of the welding machine.	7	Providing a particular genset for the electric power source of the welding machine.	8	392

CTQ	Welding Process	Failure Cause	S	Failure Effect	O	Preventive measure	D	RPN
	The performance of the welding machine has decreased, or the welding machine has been damaged.	- Due to the age factor - Due to lack of maintenance resulting in damage.	7	The flow of electric current fluctuates, or the output current becomes unstable, or the set current value does not match the output current value.	7	Repair the welding machine or replace it with a new one.	8	392
	The tents (shelters) are broken, and the design is not good.	The design is not sturdy, and the shelter material is not good.	8	Wind enters the welding area.	7	Repair damaged shelters and modify them (tents must cover or block wind movement from axial & radial directions.	6	336
	High wind speed.	The sea breeze is moving fast.	7	Air enters the welding pool.	7	Stop welding for a moment when the wind is blowing hard	6	294

Analysis with Analytical Hierarchy Process (AHP)

1. Hierarchical arrangement

After obtaining the severity (S), occurrence (O), and detection (D) values of each failure mode, the S, O, and D criteria are then weighted using AHP. This weighting is done to see the possibility of hidden risks from two or more different failure modes but with the same RPN or, in other words, to find the highest RPN value.

A hierarchy of potential causes of porosity weld defects in the welding process was developed after an interview with the QA/QC department of the contractor's piping division. The hierarchical arrangement of the causes of porosity weld defects is shown in Figure 12

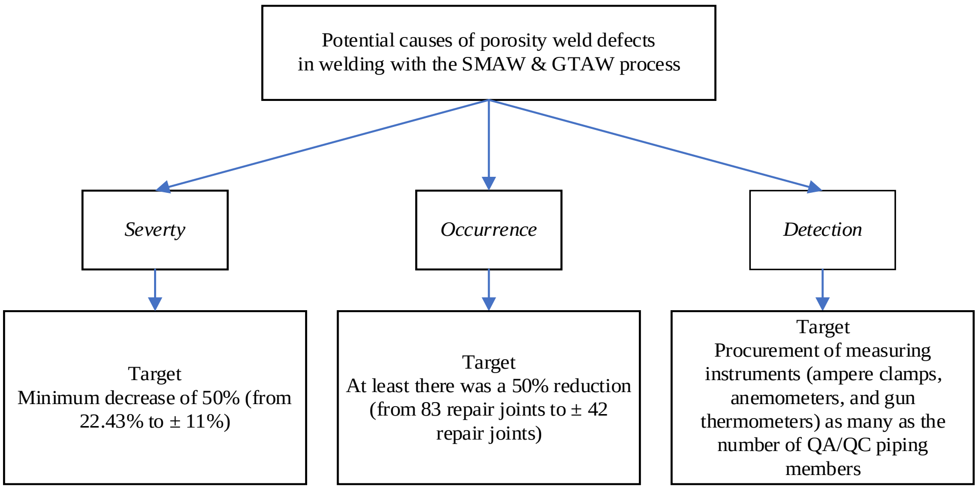

Figure 12 Hierarchy of Porosity Weld Defect Causes.

2. The weighting of the criteria/ calculation of the AHP weight

Discussions were held with informants who were quite experienced, certified, and directly involved in the supervisory function of pipe joint welding work to determine each criterion's weight. The discussion begins by asking questions about the weight of each criterion and comparisons between these criteria. The following is the result of the weighting of the criteria provided by the informants, as shown in Table 2.

Table 2 Discussion Results of Criteria Weight

Criteria	Weighting Assessment	Criteria
Severity	3	Occurance
Severity	1/3	Detection
Occurance	1/5	Detection

Based on Table 2, the informants argue that severity is slightly more critical than occurrence; this means that the severity of the porosity weld defects is slightly more important than the number of defective weld joints. According to the informant, the detection ability of the supervisor and the measuring instrument used is slightly more critical than the severity and more critical than the number of defective welding joints; this is following the actual situation that the company management does not provide supervisors with electrical measuring instruments, namely ampere clamps.

3. Compilation of consistent weight criteria

The next step is to create a pairwise comparison matrix, namely pairwise comparisons between criteria accompanied by the total weight values for each criterion, as shown in Table 3.

Table 3 Pairwise Comparison Between Criteria

Criteria	Severity	Occurance	Detection
Severity	1	3	1/3
Occurance	1/3	1	1/5
Detection	3	5	1
Total	4,33	9	1,53

4. Normalize each criterion value to get the eigen vector value

Normalization is done by dividing each criterion weight value by the sum of the criterion weights in each column and then calculating the average criterion weight value in each row to get the eigenvector value. The results of the calculation of the normalization of the comparison matrix for each criterion value are shown in Table 4

Table 4 Normalization of Pairwise Comparison Matrix

Criteria	Severity	Occurance	Detection	Eugen Vector
Severity	0,23	0,33	0,22	0,26
Occurance	0,08	0,11	0,13	0,11
Detection	0,69	0,56	0,65	0,63
Total	1,00	1,00	1,00	1,00

5. Calculating the consistency ratio

To find out the consistency of pairwise comparisons between criteria, a consistency test was then carried out with equations 1 and 2. The Random Consistency Index value with matrix size 3 was 0.58. The following is the calculation of the Random Consistency Index test.

$$\lambda \max = (4.33 \times 0.26) + (9 \times 0.11) + (1.53 \times 0.63)$$

$$\lambda \max = 3.0797$$

$$CI = \frac{(3.0797 - 3)}{3} = 0.027$$

$$CR = \frac{0.027}{0.58} = 0.047$$

Based on the calculation results, the Consistency Ratio (CR) value is 0.047. Because the CR value is ≤ 10%, the pairwise comparison matrix between criteria is considered consistent or justifiable.

6. Confirm RPN calculation

To validate or overcome the weakness of FMEA due to the similarity of values on the severity, occurrence, and detection criteria weights, a new RPN calculation is performed by adding up the eigenvector multiplication results with each failure mode value weight with equation 3. WS, WO, and WD, respectively, are the weight of the average/relative criteria of the severity, occurrence, and detection criteria. The results of the new RPN calculation for each failure mode value are presented in Table 5.

Table 5 The Result of FMEA and AHP Analysis

No	Failure Mode	Failure Cause	S	Failure Effect	O	Prevent Measure	D	RPN FMEA	RPN AHP	Rank FMEA	Rank AHP
1	The electric current in the welding machine is unstable because the generator as a source of electric power is under a high load.	Generators are also used as a power source for electrical equipment for other construction work.	7	Interfere with the performance of the welding machine.	7	Providing a particular generator for the electric power source of the welding machine.	8	392	7,63	1	1
	The performance of the welding machine has been decreased, or the welding machine has been damaged.	- Due to the age factor - Due to lack of maintenance resulting in damage.	7	The flow of electric current fluctuates, or the output current becomes unstable, or the set current value does not match the output current value.	7	Repair the welding machine or replace it with a new one.	8	392	7,63	1	1
2	The tents (shelters) are broken, and the design is not good.	The design is not sturdy, and the shelter material is not good.	8	Wind enters the welding area.	7	Repair damaged shelters and modify them (tents must cover or block wind movement from axial & radial directions.	6	336	6,63	2	2
3	High wind speed.	The sea breeze is moving fast.	7	Air enters the welding pool.	7	Stop welding for a moment when the wind is blowing hard, and use the correct protective awning.	6	294	6,37	3	3
4	Damage to the current and voltage indicators on the welding machine.	Due to the age factor.	7	The current and voltage values shown by the indicator do not match the output.	7	Replace the welding machine indicators with new ones.	5	245	5,74	**4**	**5**
		Haven't recalibrated yet.				Periodic and consistent routine calibration is required.	5	245	5,74	**4**	**5**
	Difficult accessibility to read WPS or welding procedures.	- Welding position or location is far from the information board - The information board is not wide enough to contain all WPS & welding procedures	7	The welder does not comply with the essential and supplementary essential variable provisions in the WPS.	7	Provide soft copies of WPS and welding procedures to welders to store on their smartphones so that they are more easily accessible	5	245	5,74	**4**	**5**
	Lack of understanding of welding	No free time to study it or for lack of	7	There are stages of preliminary	7	Explain the welding procedure.	5	245	5,74	**4**	**5**

No	Failure Mode	Failure Cause	S	Failure Effect	O	Prevent Measure	D	RPN FMEA	RPN AHP	Rank FMEA	Rank AHP
	procedures.	interest.		work that the welder skips.							
5	The electrode is heated or dried by direct burning using a heating torch.	The oven has not been brought to the field, and the dryer is damaged.	6	The flux becomes brittle, peels off easily, and impurities (CO2 layer) form on the surface of the flux.	1	Drying the electrode to a higher temperature must use an oven instead of a dryer; further drying using a dryer.	7	42	6,08	**8**	**4**

Based on Table 5, the failure modes for rank 1 (first highest RPN) from FMEA and FMEA-AHP calculations are precisely the same; namely, the performance of the welding machine has decreased, or the welding machine has been damaged, and the electric current in the welding machine is unstable because the genset as a power source of electricity is under high load. Likewise, the failure mode for rank 2 (second highest RPN) from FMEA and FMEA-AHP calculations is precisely the same; namely, the shelter is damaged, and the design is not good, and so is the failure mode for rank 3 (third highest RPN) from the calculation FMEA and FMEA-AHP are also precisely the same; namely high-velocity speeds. However, the failure mode for the fourth rank (fourth highest RPN) from FMEA and FMEA-AHP calculations differs.

After obtaining the highest RPN value from the results of the FMEA-AHP calculation, it is known that the failure mode that has the most potential to cause the weld joint to be rejected is when the performance of the welding machine has decreased or the welding machine has been damaged and the electric current in the welding machine is unstable due to the genset as a source of electric power is under a high load, but the contractor also wants to repair the second highest failure mode, namely damaged shelters and bad design.

Identify the Root Cause of the Problem

After identifying the three potential failure modes, which are the primary targets for improvement, identification, and analysis of the root causes of the failure modes is carried out as shown in Figure 13, Figure 14 and Figure 15. This identification is carried out by conducting FGDs involving the supervisory team (QA/ QC manager, welding inspector, piping inspector, and QA/QC inspector), including welders directly involved in pipe joint welding work in HRSG Block 2.1.

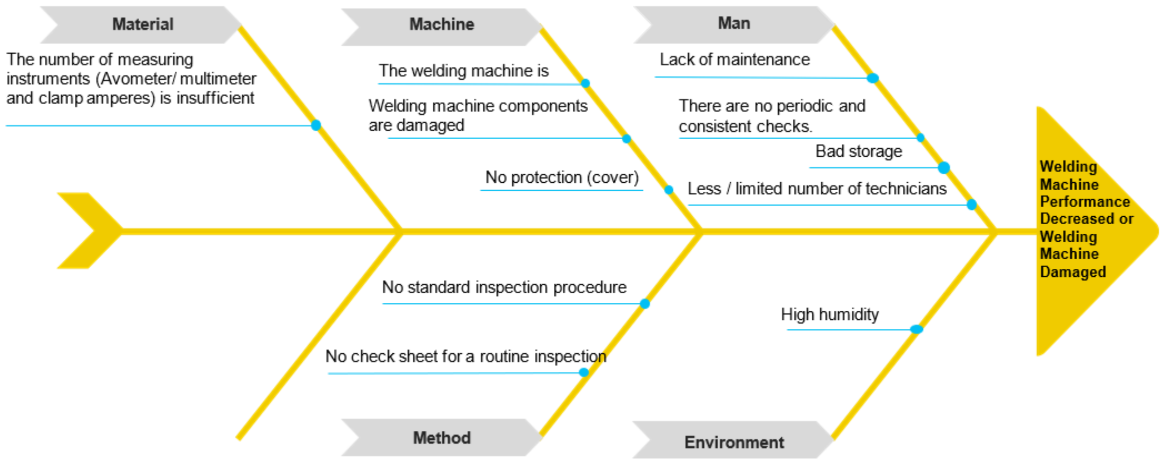

Figure 13 Welding Machine Performance Decreased or Welding Machine Damaged.

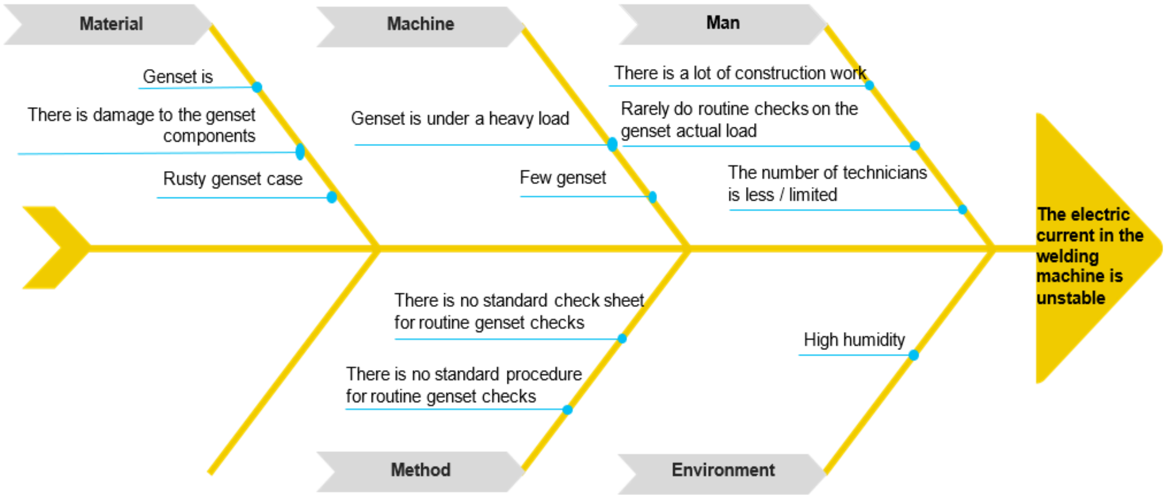

Figure 14 The Electric Current in the Welding Machine is Unstable.

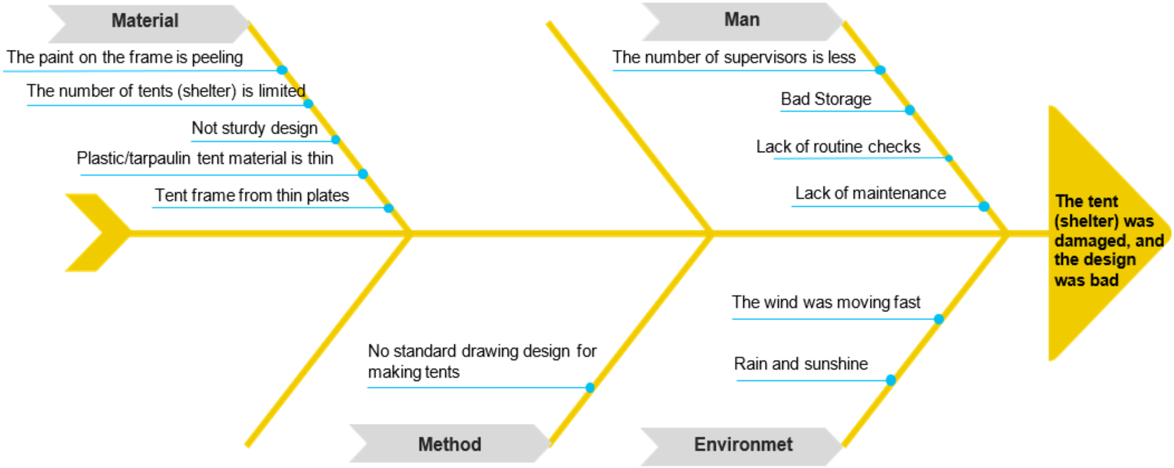

Figure 15 The Tent (Shelter) was Damaged, and the Design was Bad.

4. Conclusions and Suggestion

Based on the problem-solving analysis, it can be concluded that the failure mode or the most dominant factor causing the occurrence of rejected porosity defects is the failure mode which has an RPN value of 392 from the analysis results with FMEA or which has an RPN value of 6.63 from the analysis results with AHP. This failure mode is the performance of the welding machine has been decreased or the welding machine has been damaged, and the electric current in the welding machine is unstable because the genset that functions as a source of electric power is under a high load. So it can be concluded that there are three failure modes which are the primary targets for improvement, namely the performance of the welding machine has been decreased or the welding machine has been damaged, the electric current in the welding machine is unstable because the genset that functions as a source of electric power is under a high load, and the tent is damaged or the design is not good.

Although this study found three failure modes or the main causes of porosity and cluster porosity in the welds produced by GTAW and SMAW processes, this research did not include humidity and ambient temperature measurements around the welding area. High humidity or low ambient temperature contains water vapour in the air or wind and water vapour which is also often the cause of porosity and cluster porosity; therefore, further research involving these two factors needs to be carried out in the future.

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