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Analysis of Ovality Deviation of Bending Superheater Tube Boiler Fabrication Process with Six Sigma Method in Manufacturing Company

Rina Sandora[1,] and Syirva Maulidya[2]
[1)] Piping Engineering Study Program, Department of Ship Mechanical Engineering, Shipbuilding Institute of Polytechnic Surabaya.
[2)]Design and manufacturing engineering Study Program, Department of Ship Mechanical Engineering, Shipbuilding Institute of Polytechnic Surabaya.
Email : rinasandora@ppns.ac.id[1], syirvamaulidya@student.ppns.ac.id[2]

Abstract - Quality control in fabrication is critical to the success of the production process. In this study, key factors in production quality control were identified by analyzing the influence on the tube bending process in fabrication work. Ovality deviations occur during the tube bending process that exceeds 9 percent. 30 boiler superheater tube elements had to go through the repair process. The causes of tube bending deviations were analyzed using the Six Sigma approach with the DMAIC (Define, Measure, Analyze, Improve, and Control) methodology. The causes of failure were analyzed using FMEA, and the highest RPN of 320 was obtained due to design planning and manufacturing of bending dies that are by the OD tube and the placement of clamp die and pressure die distances that are not too far apart. In addition, an RPN value of 294 was obtained due to the bending speed being too high. The recommendation for the next project is to consider using a C-Frame machine with better control to make it easier for operators to adjust the pressure, temperature, and speed of a good machine to better maintain ovality.

Keyword : Quality Control, Six Sigma, Superheater Tube Boiler, Failure Mode and Effect Analysis (FMEA)

I. INTRODUCTION

Progress in the industrial sector in Indonesia has increased every year. Research is needed on how to realize a product with the best quality that is expected to be used efficiently and effectively in the long term.

Quality control in fabrication is an absolute requirement for the success of a production process. This study aims to determine the things that need to be considered in controlling the quality of production by analyzing the things that hinder the bending process in fabrication work. So that the fabrication work can take place properly without disturbing the delivery schedule and preventing excessive production costs.

One of the manufacturing companies runs production with the fabrication process. One of the products produced is a boiler superheater tube for the needs of an industrial company. Fabrication was carried out in November 2022-January 2023. This manufacturing company is a fabrication service company, especially for pressure part products. With most employees who have decades of competence in their fields, this company has succeeded in becoming a trusted partner of large industrial companies in Indonesia.

During fabrication, there was a discrepancy in tube ovality from the customer specification. During a dimensional inspection by QC after the bending process, tube ovality of more than 9 percent was found. 30-element superheater tube boiler that has been produced must go through the repair process first in various ways. After that, the new tube ovality is obtained by the standard.

Based on the above problems, the company needs an improvement in product quality control, so that in this study is focused on reducing the level of non-conformity in the bending tube process which will be analyzed using a Six Sigma approach with the DMAIC (Define, Measure, Analyze, Improve & Control) stages, namely by measuring the defect rate of a product or DPMO (Defect Per Million Opportunities) and sigma value.

Six Sigma is the right method to prove the success of achieving quality improvement. With levels of numbers that show the current level of production quality to achieve targets for a company regarding product quality. So that with the Six Sigma method, an improvement proposal is obtained for the company to prevent the possibility of product discrepancies with standards again in the future to save time, effort, and costs, and the company can produce the best quality products.

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II. RESEARCH METHODOLOGY

According to (Montgomery, 1990) quality control is a process control activity to measure product quality characteristics, compare them with existing specifications or requirements, and take appropriate remedial action if there is a difference between actual appearance and predetermined standards.

2.1 Quality Control

Control is an activity carried out to ensure that production and operation activities are carried out according to what has been planned so that if there is a deviation, the deviation can be corrected and the specified expectations can be achieved (Buffa, 1999). Meanwhile, quality according to Assauri (1999) is the invoices contained in an item or result that causes the item or result to be by the purpose for which the item or result is needed. So quality control is a tool for management to maintain, improve, and maintain quality by reducing the number of defective products to provide benefits and satisfy customer desires (Mizuno, 1994). Quality can be interpreted as a product that has the maximum ability to include durability, reliability or progress, strength, ease of packaging, and when the product is damaged it is easy to repair or reparate it according to Luthfia (Razalie, 2019). According to Gasperz opinion in (Anjayani, 2011) is a way of continuously improving performance at the operation or process level, from any functional area of an organization, using available resources and existing capital.

2.2 Six Sigma

The Six Sigma method is one of the tools commonly used in product quality control. This method has the concept of setting quality standards to reach 3.4 deviations per one million possibilities. The Six Sigma method is divided into several stages to achieve product quality improvement. The use of the Six Sigma method can be used to determine the causes and factors that affect deviation to reduce defective production (Salomon, Ahmad, & Limanjaya, 2017).

The Six Sigma method is a method or way to achieve operating performance of 3.4 defects for every one million activities or opportunities. Six Sigma also provides proven benefits, which include cost reduction, productivity improvement, market share growth, defect reduction, and production or service development (Pande, 2002). So that using the Six Sigma method can provide suggestions for improvements (improve) to the company to reduce the level of defects in the product. (Gasperz, 2002).

2.3 DMAIC

Six Sigma DMAIC is often described as a methodology for solving problems (De Mast & Lokkerbol, 2012), (R. Krishnan & Prasath, 2013). Six Sigma requires tools that are used systematically (Naeem et al., 2016). The methods and techniques used in the Six Sigma DMAIC analysis can be seen in Table 1 (Thanhdat et al., 2016), (B. R. Krishnan & Prasath, 2014) and (Girmanová et al., 2017).

Table 1. Six Sigma DMAIC Methods and Techniques

Project Phase	Description	Tools and Technique
Define	1. Define the target of the improvement activity 2. Define the current state 3. Define the problem and identify defects	Project charter, stakeholder analysis, process flowchart, SIPOC diagram, CTQ definitions, Voice of the customer gathering, DMAIC Work breakdown structure
Measure	1. Data collection 2. Identifying possible causes of defects 3. Measuring the validity and reliability of the existing system	Process flowchart, Data collection plan, benchmarking, measurement system analysis, Voice of Customer gathering, process sigma calculation
Analyze	1. Analyze the system to identify measures to eliminate the gaps that arise 2. Perform identification based on the data owned 3. Identify the relationship between variables owned	Histogram, Pareto chart, time series/run chart, scatter plot, regression analysis, Cause and effect/fishbone diagram, 5 whys, process map review and analysis, statical analysis
Improve	1. Assess the causes of the biggest problems 2. Improve the system	Brainstorming, mistake proofing, design of experiment, QFD/House of Quality, Failure Modes and Effects Analysis (FMEA), Simulation Software
Control	Control the new system	Process sigma calculation, Control chart, Control plan

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2.4 SIPOC Diagram

The SIPOC diagram is a tool used in the Six Sigma methodology, which is a visual image that describes how the process can provide services to customers. According to Anthony, Vinodh, & Gijo (2015: 83) in a book entitled Lean Six Sigma for Small and Medium Sized Entreprises. SIPOC (Supplier, Input, Process, Output, Customer) is a process improvisation tool that provides a key summary of inputs and outputs from one or in a continuous format.

The SIPOC diagram is a tool used by Six Sigma teams to identify all relevant elements in a process improvement before the process is carried out. This diagram helps in explaining a project that is complex and unclear in scope. In the DMAIC phase, this SIPOC diagram is found in the Measure phase. The explanation of the parts of the SIPOC diagram according to (Soemohadiwidjojo, 2017) is as follows:

1. Supplier - a person or group that provides information, raw materials, or other resources, to the process.
2. Input - something that feeds into the process
3. Process - a set of steps that process the input and add value to the input.
4. Output - the result of the process (product) or the final process.
5. Customer - the person group or process that receives the output.

2.5 DPMO (Defect Per Million Opportunity)

In the six sigma method, mismatches or offgrades are errors and mistakes made by customers. Output quality is measured in DPMO or the rate of offgrade per million opportunities. DPMO is a measure of failure in a Six Sigma quality improvement program that indicates failures per million opportunities. The target of Six Sigma quality control. Motorola is 3.4 DPMO, but is interpreted as follows: in a single product unit, there is an average chance of failure of a CTQ (chance of not meeting customer desires) is only 3.4 failures out of one million parts of the product (Gaspersz, 2002). DPMO calculation according to (Breyfogle, 2003) :

$$DPU = \frac{D}{U} \quad (1)$$

$$DPO = \frac{D}{O} = \frac{D}{U \times O} \quad (2)$$

$$DPMO = DPO \times 1.000.000 \quad (3)$$

Description:
DPU = Number of Defects per Unit
DPMO = Number of Defects per Opportunity
DPMO = Number of Defects per Million Opportunities
U = Number of Units
O = Number of Opportunities that will Result in Defects (Opportunity)
D = Number of Defects

Table 2 is a sigma level that can be used as a measure of performance targets in an industrial system. According to (Gasperz, 2002) the higher the sigma target achieved, the better the performance of the industrial system. So that 6-sigma is better than 4-sigma and 3-sigma. Sigma levels can be seen in Table 1.

Table 2. Sigma Performance Table

Sigma Level	Defects Per Million Opportunities
1	690,000
2	308,537
3	66,807
4	6,210
5	233
6	3,4

Source: P*and*e, P & Larry (2002:10) in (Ulinnuha, 2019)

2.6 FMEA (Failure Mode and Effect Analysis)

According to Hanif (in Hariani, 2017), FMEA is an engineering technique used to determine, identify, and eliminate known failures, problems, errors, and the like from a system, design, process, and/or service before it reaches consumers. From the definition of FMEA above, which refers more to quality, it can be concluded that FMEA is a method used to identify and analyze a failure and its consequences to avoid the failure. FMEA is an engineering technique used to define, identify, and eliminate known failures, problems, errors, and the like from a system, design, process, and/or service before it reaches the consumer (Stamatis, 1995).

By analyzing what is done we can find the effects or impacts that are likely to make mistakes in a product or the production process. With this FMEA method, it is possible to analyze problems that arise in a product that will be made or a process that will be carried out. Then, because the problem that has the potential to arise has been formulated, it can later be determined how to prevent it.

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According to Nurkertamanda and Wulandari (in Hariani, 2017) explained that RPN is an indicator of criticality to determine the corrective action by the failure mode. The RPN calculation is obtained with the following equation:

$$RPN = Severity \times Occurrence \times Detection \quad (4)$$

RPN is used by many FMEA procedures to assess risk using the following three criteria:

a. Severity (S) - is the first step to analyzing risk, namely calculating how the impact or intensity of the event affects the output of the process. Severity grouping according to its rank level can be seen in Table 3.

Table 3. Severity

Rank	Class	Criteria
1	Negligible severity	We don't have to think about how this will impact the performance of the product. The end user will probably not notice this defect.
2	Mild Severity	The consequences are only mild. End users will not notice any change in performance. Repairs can be done during regular maintenance.
3		
4	Moderate severity	End-users will experience performance degradation, but it is still within tolerance limits. Repairs are inexpensive and can be completed in a short period.
5		
6		
7	High severity	End users will experience unacceptable adverse consequences that are beyond tolerance. Repairs are very expensive.
8		
9	Potential safety problems	The consequences are extremely dangerous and affect the safety of the user. Contrary to the law.
10		

Source: Hariani, 2017

b. Occurrence O - Is the likelihood that the cause will occur and result in some form of failure during use. Shows the value of the frequency of a problem that occurs. Grouping occurrence according to the level of ranking can be seen in Table 4.

Table 4. Occurrence

Rank	Class	Criteria
1	Remote	1 dari 100000
2	*Low*	10 dari 100000
3		50 dari 100000
4	*Moderate*	100 dari 100000
5		200 dari 100000
6		500 dari 100000
7	*High*	1000 dari 100000
8		2000 dari 100000
9	*Very High*	5000 dari 100000
10		10000 dari 100000

Source: Hariani, 2017

c. Detection D - This is a control tool used to detect potential causes. Identify methods that are applied to prevent or detect modes of failure. Grouping detection according to its rank level can be seen as in Table 5.

Table 5. Detection

Rank	Class	Criteria
1	Preventive methods are very effective. There is no chance that the cause may arise.	Almost definitely
2	The possibility of the cause occurring is very low.	Very high
3		
4	The possibility of causes occurring is moderate. Prevention methods are not yet effective. Causes are still recurring	Moderate-high
5		Moderate
6		Weak
7	The probability of causes occurring is still high. Prevention methods are still not effective. Causes are still recurring	Very weak
8		A few
9	The probability of the cause occurring is very high. Prevention methods are not effective. Causes always recur.	Very few
10		Almost impossible

Furthermore, the RPN results obtained from several respondents were calculated on average. The average result will show indicators to measure the risk of failure mode. The average value becomes the final value written in the RPN table. Then the calculation of the critical value of RPN is carried out. RPNs that are more than the critical value of RPN determine the priority scale level of repairs that must be made first. The calculation is done with the following equation:

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$$A \quad v = \frac{T \quad l\, v}{N \quad o \; r} \tag{5}$$

$$R \quad C \quad v = \frac{T \quad v \quad R}{N \quad o \; R} \tag{6}$$

2.7 Bending

Bending is one of the forming processes commonly used to make everyday items such as car components, aircraft, and household appliances. The bending process is done by bending the workpiece until it changes shape which causes stretching of the metal around the straight line area (in this case the neutral axis). As we know a sheet plate with a wave shape has a higher stiffness than a flat sheet plate (Schmid, 2008).

III. RESULT AND DISCUSSION

3.1 *Define*

According to Montgomery (2009:52), defining is the first step taken to improve the Six Sigma method. The purpose of the define step is to determine the problem, research objectives, and scope of the process. After that, it will be determined what is Critical To Quality (CTQ) for the customer or what is considered problematic by the customer. The identification of potential CTQ is formulated in Table 6.

Table 6. CTQ on superheater tube boiler fabrication

No.	CTQ (Critical to Quality)
1	Dimensions and Tolerances
2	Material Characteristics a. Consideration for using other material specifications b. Material condition checking
3	Bending Method a. Careful planning b. Bending speed c. Bentonite sand filling method d. Use of mandrell ball e. Training of bending operators f. Consideration of new machine purchase
4	Inspection and Testing

The next stage is the creation of a SIPOC diagram which is used to illustrate the flow of the production process in the manufacture of boiler element tube superheater products. This diagram serves to find out the flow that occurs in the production process starting from suppliers, inputs, processes, outputs, and customers. The SIPOC diagram can be seen in Table 7.

Table 7. SIPOC Diagram

SIPOC Diagram					
	Supplier	Input	Process	Output	Customer
Phase	1. Raw Material (Tube Boiler) Supplier (Company Workshop Warehouse)	1. Boiler Superheater Tube Technical Specifications: a. Material Specifications b. Equipment and Production Implementation Methods c. Quality Control and Testing in the Field d. Measurement e. Technical payment 2. Materials a. Tube SA 213 T22 b. Pipe SA 213 TP304	1. Fabrication: Marking, Bending, Layout, Fit Up, Welding, PWHT 2. Quality Inspection and Testing as per Standards: Radiography Test for Buttweld, Hardness Test, NDE for Welding, Hydrotest	1. 30 Fabricated Boiler Tube Superheater Element 2. Manufacturing Data Report	1. Production Department in a Manufacturing Company 2. Customer Who Will Use the Boiler

3.2 *Measure*

According to Harahap (Masdalifah, 2019) three main things must be done, namely:

1. Select or determine CTQ quality characteristics,
2. Develop a data collection plan,
3. Performance baseline measurement at the sigma output level. Calculation of DPMO (Defect per Million Opportunity) level and achievement of sigma capability level.

This measurement is carried out by observation during the production process on 30 *elements of the boiler tube superheater* (all products in this fabrication project). The results of the calculation of proportions, p, UCL, and LCL are in Table 8.

Table 8. Calculation Results of Proportion, $\bar{p}$, UCL, and LCL

NO	NG	Total Check	Proportion	$\bar{p}$	UCL	LCL
1	19	37	0,513514	0,403604	0,645576	0,161632
2	17	37	0,459459	0,403604	0,645576	0,161632
3	13	37	0,351351	0,403604	0,645576	0,161632
4	20	37	0,540541	0,403604	0,645576	0,161632
5	14	37	0,378378	0,403604	0,645576	0,161632
6	15	37	0,405405	0,403604	0,645576	0,161632
7	18	37	0,486486	0,403604	0,645576	0,161632
8	16	37	0,432432	0,403604	0,645576	0,161632
9	16	37	0,432432	0,403604	0,645576	0,161632
10	14	37	0,378378	0,403604	0,645576	0,161632
11	12	37	0,324324	0,403604	0,645576	0,161632
12	15	37	0,405405	0,403604	0,645576	0,161632
13	14	37	0,378378	0,403604	0,645576	0,161632
14	13	37	0,351351	0,403604	0,645576	0,161632
15	11	37	0,297297	0,403604	0,645576	0,161632

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16	14	37	0,378378	0,403604	0,645576	0,161632
17	19	37	0,513514	0,403604	0,645576	0,161632
18	11	37	0,297297	0,403604	0,645576	0,161632
19	17	37	0,459459	0,403604	0,645576	0,161632
20	13	37	0,351351	0,403604	0,645576	0,161632
21	15	37	0,405405	0,403604	0,645576	0,161632
22	16	37	0,432432	0,403604	0,645576	0,161632
23	18	37	0,486486	0,403604	0,645576	0,161632
24	13	37	0,351351	0,403604	0,645576	0,161632
25	16	37	0,432432	0,403604	0,645576	0,161632
26	14	37	0,378378	0,403604	0,645576	0,161632
27	13	37	0,351351	0,403604	0,645576	0,161632
28	15	37	0,405405	0,403604	0,645576	0,161632
29	13	37	0,351351	0,403604	0,645576	0,161632
30	14	37	0,378378	0,403604	0,645576	0,161632
Total	448	1110				
Average	15	37				

Based on Table 8, a P control map graph is created to make it easier to find data that is outside the control limit. Making P control maps is assisted using Minitab *software*. Control map graph P fabrication *tube boiler superheater* can be seen in Figure 1.

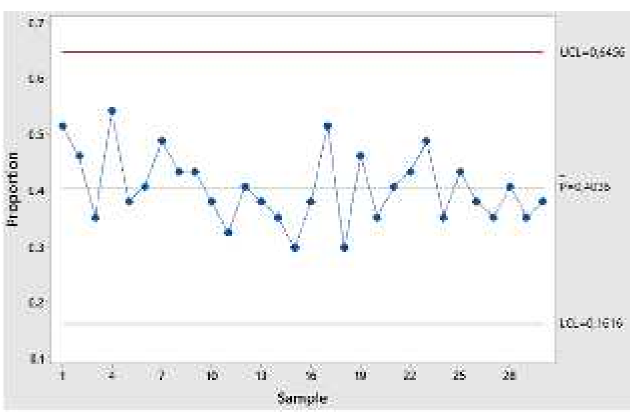

Figure 1. P-Control Map Graph

Figure 1 indicates that the average number of deviations in one element is 0.4036 with the same control limit. This is because the number of *samples* in each *element* inspected has the same value. There is no plot that is out of control, it shows that the P value in the production of *boiler tube superheaters* is still statistically controlled.

Furthermore, DPMO calculations are carried out to measure the sigma level using the DPMO conversion table of the Six Sigma assessment. Data calculation in Table 9.

Table 9. Data Calculation and Sigma Value Conversion

Value Data Calculation	Value
Amount of Boiler Tube Superheater Elements	30
D (Number of defective products that occur)	448
U (Number of product units)	1110
DPU Ovality	0,403604
DPO Ovality	0,004036
DPMO Ovality	40.360,36
Sigma Value	3,25

The calculation of the DPMO Ovality value gets a result of 40,360, then converted to a sigma table obtained a value of 3.25, which means that the production ability has a capability of 3.25 out of 6 sigma. The higher the sigma target achieved, the better the performance of the industrial system.

3.3 *Analysis*

The analysis was performed with Failure Mode and Effect Analysis (FMEA). FMEA is a method for identifying potential failures for good process planning to predict, reduce, or avoid error rates and predict damage or adverse effects caused by the production process. Based on the FTA diagram made earlier, it is known the cause of bending deviations that occur during the boiler tube superheater fabrication process. The weighting in the FMEA table contains Severity, Occurrence, and Detection values which are used to obtain RPN values to provide a risk rating for each cause of failure.

Table 10. Data Calculation and Sigma Value Conversion

Failure Mode	Causes of failure	S	O	D	RPN
Ovality deviation > 9%	*The bending speed* is too high	7	7	6	294
	No bentonite sand-filling method is carried out	8	6	5	240
	Not using mandrell ball	6	6	5	180
	OD *Dies* bending is not by the OD *tube* to be bending	8	8	5	320
	The distance between the *clamp* die and *the pressure die* is too far	8	8	5	320
	The pressure die is not level	6	6	5	180

Based on Table 10 determination of severity, occurrence, and detection values is carried out by the Quality Control Staff, Quality Control Supervisor,

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Production Supervisor, and Production Manager by distributing FMEA questionnaires. From each respondent's answer, it is accumulated and calculated on average using Equation 4. It can be known that the highest RPN value obtained is 320 for ovality deviation, with the cause of failure OD Dies bending does not match the OD tube to be bent and the distance between the clamp die and pressure dies is too far.

The RPN Ovality assessment for severity OD Dies bending does not match the OD tube to be bent to get a severity value of 8, interpreted as very high. If such causes occur, then the influence on ovality deviations in bending products is very high. While the assessment of occurrence gets a value of 8 is interpreted as high. If such causes occur frequently, then the probability of deviations caused by such failure modes is about 1 in 50 events. While the assessment of detection gets a value of 5 is interpreted as medium. The ability of the control device to carry out deviation detection is classified as moderate.

After performing the FMEA analysis stage and calculating RPN, the next step is to calculate the critical value of RPN above the critical value. The calculation of the critical value for ovality deviation in equation 5 is as follows:

$$R \quad C \quad V = \frac{R \quad T \quad V}{N \quad o \quad R}$$

$$R \quad C \quad V = \frac{294 + 240 + 180 + 320 + 320 + 180}{6}$$

$$R \quad C \quad V = 255{,}67$$

From the calculation above, a critical value of 255.67 is obtained using Equation 5. 3 factors cause failure that have a more critical RPN value of 294, two RPNs with a value of 320. Failure factors that have an RPN value greater than the critical value will be prioritized for further corrective action.

3.4 *Improve*

Improve is the stage of providing improvement proposals, the results of repair proposals obtained the quality of superheater tube boiler element products.

The proposed improvements are sorted from the causes of failure that have an RPN value above the critical RPN value. Proposed improvements to reduce the causes of ovality and wall thickness deviations in tube boiler superheater products can be seen in Table 11.

Table 11. Proposed Improvements to Bending Tube

Causes of Failure	RPN	Proposed Improvement Action	Things to Expect
Bending speed too high	294	Decreasing the machine speed during the pipe-bending process	Diameter dimensions maintained by standards and customer specifications
No bentonite sand-filling method performed	240	Filling the tube with sand before the bending process to engineer the product to be rigid	Solid objects will make it easier for operators to maintain tube dimensions
Not using mandrell ball	180	Considering the use of a mandrel ball if no bentonite sand filling is done	Improve dimensional accuracy to be more consistent and by specified specifications
The OD of the bending die does not match the OD of the tube to be bent.	320	Design planning and manufacturing of bending dies that match the OD of the tube	A well-designed mold can help improve tube shape and ensure good structural integrity.
The distance between the clamp die and the pressure die is too far	320	Spacing of clamp die and pressure die that is not too far apart	Allows for even stress distribution during bending
Pressure die not level	180	Equivalent pressure die adjustment	Reduces the possibility of defects in the bent tube

3.5 *Control*

The *Control* stage is the final stage of identification in the *Six Sigma* method. Repair trials were carried out using several improvement suggestions to test tube quality improvements. Trials are carried out in consideration of suggestions for improvement obtained from the company. The bending experiment in this study uses several variations of the planned method so that the data obtained can be processed with the specified method. The optimal combination obtained will then be experimented to validate the combination. The validation test can be found in Table 12.

Table 12. Bending Tube Improvement Method

Label	A	B	C	D	E	F
Trial 1	✔	-	-	-	-	✔
Trial 2	✔	✔	-	-	-	✔
Trial 3	✔	✔	✔	✔	-	✔

Description:

A. Decreasing the engine speed during the pipe bending process.

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B. Filling the tube with sand before the bending process to engineer the product to be solid
C. Pellets will be spaced not too far from the clamp die and pressure die
D. Equal adjustment of pressure die
E. Consideration of hot bend execution in the bending process
F. Evaluation of the bending method such as modification of the bending tool (change of dies with a very tight radius). Inspection of material conditions and consultation with experts.

In the first bending trial, bending results with very high ovality deviations are shown in Table 13.

Table 13. Trial Improvement Bending Tube 1

		1		
	Process	COLD	COLD	COLD
Bending	Radius	R 50	R 50	R 50
	Degree	180	180	180
	Max	38,9	38,9	38,5
Roundness/	Min	32,4	31,2	32,0
Ovality	*Ovality*	17,11%	20,26%	17,11%
	Max. Req (%)	9,00%	9,00%	9,00%

In the first bending trial, *bending* was obtained with ovality deviations but not as high as in experiment 1, namely in Table 14.

Table 14. Trial Improvement Bending Tube 2

		2		
	Process	COLD	COLD	COLD
Bending	Radius	R 50	R 50	R 50
	Degree	180	180	180
	Max	38,2	38,4	38,3
Roundness/	Min	34,3	33,2	33,3
Ovality	*Ovality*	10,26%	13,68%	13,16%
	Max. Req (%)	9,00%	9,00%	9,00%

Bending results with fairly good ovality deviations with 2 points not exceeding the tolerance limit are shown in Table 15.

Table 15. Trial Improvement Bending Tube 3

		2		
	Process	COLD	COLD	COLD
Bending	Radius	R 50	R 50	R 50
	Degree	180	180	180
	Max	38,40	38,15	38,25
Roundness/	Min	35,65	35,55	34,80
Ovality	*Ovality*	7,24%	6,84%	9,08%
	Max. Req (%)	9,00%	9,00%	9,00%

From the results of the experiment, it can be identified if the third experiment is the best combination compared to other experiments. Of the three bending points, both points have two good ovalities. It can be concluded that the decrease in machine speed, the sand filling method, without the implementation of hot bends, the laying of the distance between the clamp die and pressure die is not too far, and the equivalent adjustment of the pressure die can affect the ovality of the bending tube results for the better.

IV. CONCLUSION

Based on the results of the analysis that has been carried out and discussed, the following conclusions are obtained:

1. From the analysis obtained using the FMEA method, the recommended corrective action plan according to the results of the analysis of the RPN value that exceeds the critical value with values of 294 and 320 for ovality inequality is:
   a. Speed drop during operation of the bending machine
   b. Planning the design and manufacture of bending die molds by OD tube
   c. Laying the distance between the clamp die and pressure die is not too far
2. The combination of variable process temperature, engine speed, and pressure as a preventive measure to reduce ovality and wall thickness deviations in bending tubes is:
   a. Temperature 600°C with a heating torch and consideration of hot bend method. After that cold bend with a C-Frame machine can also be further customized according to material specifications and customer application needs.
   b. Machine speed with a relatively small tube diameter (38mm) and a large bending radius (50mm), the recommended machine speed is 1 degree per second.
   c. The pressure applied during bending must be stable, which can be achieved by: Planning the design and manufacture of bending dies whose OD matches the OD of the tube, placing the clamp die and pressure die not too far apart, and adjusting the pressure die equivalent to the clamp die.

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