Improving Quality on Tire Curing Process by Using Six Sigma and Failure Mode and Effects Analysis (FMEA) Method - A Case Study in Leading Tire Manufacturer

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Abstract*—Tires are one component of transportation that play a very important role. Because tires on vehicle have direct contact with the road surface and affect safety. Truck Bus Bias Tire Manufacturer increased production during the pandemic of Covid-19. Tire production process requires production parameters that are in accordance with the specifications. Undercure is the highest type of defect occurred during the period of 2018-2020 (10.992 ppm). This research uses the Six Sigma method and Failure Mode and Effect Analysis. This method is a continuous improvement system that can be applied to solve a problem. Improvement will be made to the curing machine that contributes to the highest undercure defect and to the machine components that have the highest risk priority number. Defect of undercure was caused by a deviation from one of the curing process specifications. The deviation was caused by a failure in the pneumatic system, namely no lubrication in the pneumatic system (63.81%). Improvements made were the installation of an air lubricator on the curing machine. The improvements process uses the Six Sigma and FMEA which causes a decrease in undercure defects from an average of 372 ppm to an average of 235 ppm. Preventive maintenance is done to maintain standard curing specifications on the machine components with the highest risk priority number.

***Keywords*—six sigma, FMEA, DMAIC, tire, defect**

I. Introduction

Tires are one component of transportation that play a very important role. Because tires have direct contact with the road surface and affect safety. Therefore, to reduce the risk of road accident, tire companies can create good quality products and promote safety. Companies can create or produce tires with good quality. In order to do that, there are several things that need to be considered such as production parameters should be in accordance with the specifications, raw materials to production machines should be in normal conditions or ready to operate.

Truck Bus Bias Tire Manufacturer is one of the largest tire exporters from Indonesia. In the Covid-19 pandemic there was an increase in the number of tire production on the truck bus bias tire as shown in Fig. 1.

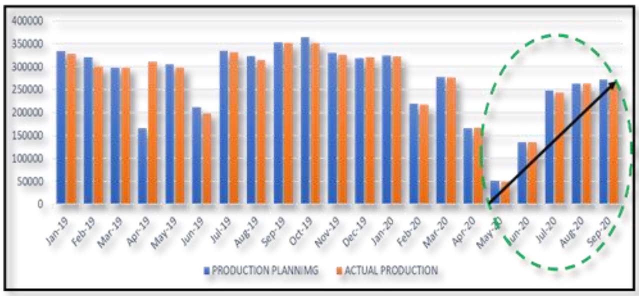

Fig. 1. Tires production of truck bus bias plant (Jan 2019 – Sep 2020)

Broadly speaking, the tire production process starts from the compounding stage at the Plant Mixing Center. Then the compound will be distributed to the Tread Extruder, Topping Calender, Bead Gromed to make tire forming components. Furthermore, these components will be assembled in the building to form a semi-finished tire called greentire. The finished greentire is then perforated to remove the wind trapped in the tire component layers and then enters the curing process to form greentire into a tire. Finished tires are then selected in the Final Inspection section. Tires that are in accordance with the standards can be distributed to consumers while those that do not fit the standard will be separated.

Curing is the process of vulcanizing greentire into a tire. The machine used for this process is curing machine. Curing machines use a certain pressure and temperature to process greentire into tires. Pressure and temperature are regulated in several stages of the curing process depending on the type of the machine. In general, the type of curing machine is divided into two namely platen and dome. The difference between the two machines lies in the method of heating the tire mold. The platen curing machine uses a hollow plate that is fed with the steam to heat the mold. While the dome mold curing machine is heated by entering the steam directly without intermediate media in a closed dome. Curing process indicators must comply with specified specifications, this is to avoid defects. Defect of undercure is the highest defect during the period of 2018-2020 and the total defect of undercure in 3 years (2018-2020) is 10.992 ppm as shown in Fig. 2

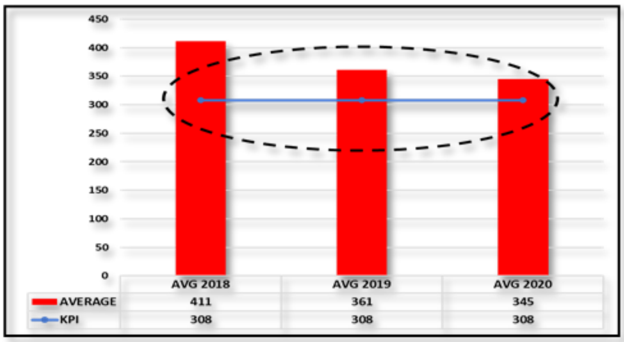

Fig. 2. The average of Undercure Key Performance Indicator

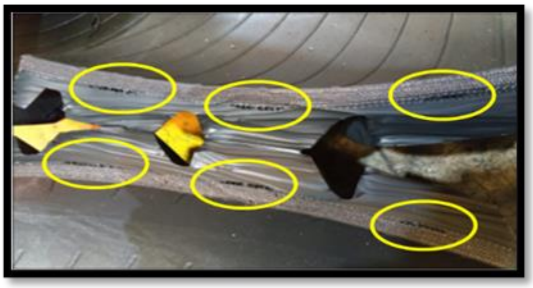

Fig. 3. Defect of undercure

Fig. 3. Shows the average number of undercure defects in 3 years. Most of the undercure defect exceeded the target of key performance indicator. This is the background of researchers to improve quality on tire curing process. The analysis will be carried out using the Six Sigma method and Failure Mode and Effects Analysis (FMEA). DMAIC stages (Define, Measure, Analyze, Improve and Control) are implemented to reduce defects in the tire curing process. This method focuses on improving the quality (reducing waste) by helping the organization produce a product or service that is better, faster, and cheaper.

II. Literature Review

A. *Quality*

Quality is defined as all features and characteristics of goods and services that are able to meet visible or disguised needs. Quality is the keyword in all industrial competition, every company must be able to produce a product with good quality and meet consumer needs [1].

1) *Check Sheet*

Check sheet is a data collection sheet that is used to facilitate and simplify data recording. The aim is to ensure that data is collected correctly and accurately, for process control and problem solving. The inspection sheet can be used to determine the distribution of the production process to find out the number of defective products, the location of defects, and the causes of defects [2].

2) *Flow Chart*

A flowchart shows a series of symbols to describe the sequence of steps in an operation or process. This chart serves as a problem-solving tool to detect and analyze areas or process steps that may have a potential problem by documenting and explaining operations, so it is very useful for finding and improving quality into processes [3].

3) *Histogram*

Histogram is a bar chart that is used to show variations in data. In the context of quality management, a histogram is a graphical device that shows the distribution and pattern of data from a process. If the collected data shows that the process is stable and predictable, then a histogram can be used to show the capability of the process. Although a group of data has the same quality standards, if the distribution of data is widened to the left or to the right, it can be said that the quality of the production in that group is less, conversely, the narrower the distribution of data on the left and right of the middle value, the production results can be said to be of higher quality, because it is closer to the predetermined specifications [2].

4) *Scatter Diagram*

Scatter diagrams are used to express the correlation or relationship between one factor and another characteristic or cause and effect. If the two variables are correlated, the coordinate points will fall along the line or curve. The better the correlation, the tighter the points approach the line [2].

5) *Control Chart*

Control chart is a map that is used to change the process over time. Through this description, it can be detected whether the process is running well (stable) or not. The map is used to evaluate whether a process is under statistical quality control or not. The main characteristic of the control chart is the existence of a pair of control limits (upper and lower limits), the data collected will be able to detect trends in the actual process conditions [2].

6) *Paretto Chart*

The Pareto chart is a chart containing both a bar chart and a line chart. Bar charts show data classifications and values, while line charts represent cumulative data totals. The principle of the Pareto diagram is in accordance with Pareto law which states that a group always has the smallest percentage (20%)

of value or has the greatest impact (80%). The Pareto chart identifies 20% of the causes of vital problems to achieving 80% of overall improvement [2].

7) *Fishbone Diagram*

A cause-and-effect diagram or often called a fishbone diagram is a tool for identifying various potential causes of an effect or problem and analyzing the problem through a brainstorming session. The problem will be broken down into a number of related categories including humans, materials, machines, procedures, policies, and so on. Each category has reasons that need to be elaborated through a brainstorming session [2].

B. *Six Sigma*

Six Sigma is a methodology for improvement process and a statistical concept that seeks to determine variations in a process. Variation in a process leads to opportunities for error which can create a risk of product defects. Poor customer satisfaction is caused by defects in actual products in process or services. The Six Sigma method increases customer satisfaction and ultimately reduces process costs by reducing variations and opportunities for errors [4].

Six Sigma - DMAIC (Define, Measure, Analyze, Improve, Control) consists of five main stages:

1) *Define*

Formally defines the target of process improvement that is consistent with customer demand or needs and the company's strategy [5].

2) *Measure*

Measures the performance of the process at the moment (baseline measurements) so that it can be compared with the target set. Mapping processes and collecting data relating to key performance indicators (KPI) [5].

Measuring the current process [6]

a. Checking the adequacy of the data to be measured.

b. Documentation of current performance and effectiveness.

c. Perform a comparison test of defective products with products according to specifications.

3) *Analyze*

Analyze the causal relationships of various factors studied to find out the dominant factors that need to be controlled [5].

Analyzing measurement results, determining the causes of process failure and possible solutions for process improvement [6]:

a. Identify the root causes of process failures.

b. Identify the difference between the current performance and the target set.

c. Estimation of the resources needed to achieve the target.

d. Identify possible obstacles.

4) *Improve*

Optimize the process using analyzes such as Design of Experiments (DOE) and others to find out and control the optimum conditions of the process [5].

Improving processes, implementing changes which eliminate imperfections [6].

5) *Control*

Control the process continuously to improve process capability towards Six Sigma targets [5].

Controlling the improved process, monitoring the results in a continuous way [6]:

a. Documentation of standardization improvement plans and monitoring process.

b. Confirmation of improved procedures.

c. Transferring of ownership of the corresponding team after completion of the project.

C. *Failure Mode and Effect Analysis*

Failure Mode and Effects Analysis can identify potential failures and confirm important and significant characteristics to be addressed with design changes, processes, or inclusion in a process control plan. FMEA evaluates the adequacy of the proposed control data for improvement and the need to mitigate risks with changes to the design verification plan or manufacturing control plan [7].

FMEA determines the priority of failure mode risks through the risk priority number (RPN) which is the product of occurrence (O), severity (S) and detection (D) of a failure [8].

$$RPN = O \times S \times D \quad (1)$$

This value is the product of the multiplication of the severity, incidence rate, and detection rate. The RPN determines the priority of failure. The RPN value is used to rank potential process failures [9].

Data processing using the FMEA method is carried out through several stages [10]:

1) Identify potential failure modes and their effects in order to obtain the severity. Severity is done to analyze risk by calculating how big or how intent is the events that affect the output process[10].

TABLE I
SEVERITY RATING [11]

EFFECTS	RATING	DESCRIPTION
Dangerous without warning	10	A system failure that has a very dangerous effect
Dangerous and there is a warning	9	A system failure that produces harmful effects
Very High	8	The system does not operate
High	7	The system operates but cannot run fully
Moderate	6	The system is operating and safe but has decreased performance so that it affects output
Low	5	Experience a gradual decline in performance
Very Low	4	Little effect on system performance
Small	3	Little effect on system performance
Very Small	2	Negligible effect on system performance
None	1	There is no effect

2) Identify potential failure causes to see the failure rate (Occurrence) on the assembly line. Occurrence is the probability that a particular cause or mechanism appears, shown in Table 2 [12].

TABLE II
OCCURRENCE RATING [12]

RATING	PROBABILITY of OCCURANCE
10	More than 50 per 7200 hours of use
9	36-50 per 7200 hours of use
8	31-35 per 7200 hours of use
7	26-30 per 7200 hours of use
6	21-25 per 7200 hours of use
5	16-20 per 7200 hours of use
4	11-15 per 7200 hours of use
3	5-10 per 7200 hours of use
2	Less than 5 per 7200 hours of use
1	Never at all

3) Identifying controls that have been carried out by the company in order to determine the level of existing detection. Probability on detection is one type of assessment to identify the cause or mechanism of risk, where each rating has its own criteria that can be seen in Table 3 [12].

TABLE III
DETECTION RATING [12]

RATING	DETECTION DESIGN CONTROL
10	Cannot be detected
9	Very low and very difficult odds to be detected
8	Very low chance and difficult to detected
7	Very low chance to detected
6	Low chance to detected
5	Medium chances to detected
4	Pretty high chance to detected
3	High chance to detected
2	Very high chance to detected
1	Definitely detected

III. RESULT AND DISCUSSION

A. *Define*

Determining what the problem is and what is needed to obtain a solution. At this stage several things are done, namely: knowing the sigma level of the research object. The level of sigma undercure defect in 3 years was between 4.8 - 4.9, in 2020 the level of sigma under cure defect is 4.87 as shown in Fig. 4.

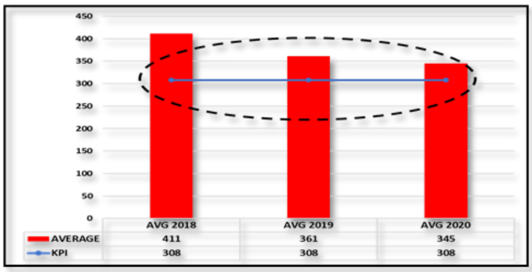

Fig. 4. The average key performance indicator of undercure

Identification of any deviations from the specifications caused by changes in the variables that affect production will be carried out. Green tire that has entered the vulcanization process cannot be reprocessed, so if there is a specification deviation the resulting product will be scrapped.

TABLE IV
FAILURE MODE OF UNDERCURE DEFECT

SUB SYSTEM	FAILURE MODE
Internal Temperature	Internal Temperature Out Spesification
External Temperature	External Temperature Out Spesification
Internal Pressure	Internal Pressure Out Spesification
Shaping Pressure	Shaping Pressure Out Spesification

B. *Measure*

Determine the current performance process and what data will be analyzed. In the research, the data of machine contributing to undercure defect and the data of machine damage that resulted in undercure defect for the 2018-2020 period are needed for initial analysis of repairs as shown in Fig. 5.

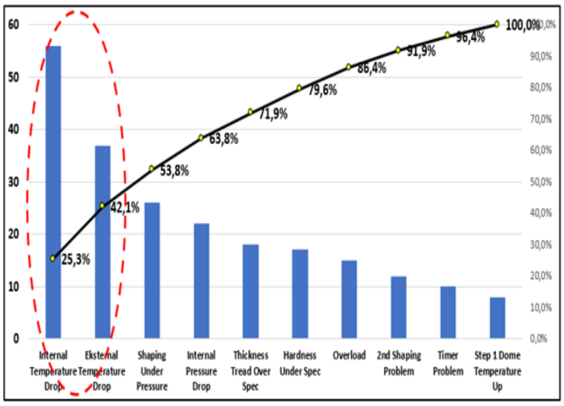

Fig. 5. The cause of undercure defect

Internal and external temperature drop are the highest cause of defect of undercure during the periods of 2018-2020. The cause of the undercure defect will be analyzed at a later stage to find out the root of the problem.

FMEA determines the priority of failure mode risks through the risk priority number (RPN) which is the product of occurrence (O), severity (S) and detection (D) as shown in Table 5.

TABLE V
SEVERITY, OCCURANCE AND DETECTION OF UNDERCURE DEFECT

FAILURE MODE	NO	PARTS	CAUSE OF FAILURE MODE	S	O	D
Internal Pressure Out Spesification	1	Leaky Seal Solenoid Valve	No Lubrication	5	6	8
	2	Piston Solenoid Valve Jammed	No Lubrication	6	6	8
	3	Piston Valve leaky or Jammed	No Lubrication	7	5	7
	4	Check Valve Leaky or Clog	Corrotion	6	4	5
Internal Temperature Out Spesification	5	Leaky Seal Solenoid Valve	No Lubrication	5	6	8
	6	Piston Solenoid Valve Jammed	No Lubrication	6	6	8
	7	Piston Valve leaky or Jammed	No Lubrication	7	5	7
	8	Check Valve Leaky or Clog	Corrotion	6	4	5
External Temperature Out Spesification	9	Leaky Seal Solenoid Valve	No Lubrication	5	6	8
	10	Piston Solenoid Valve Jammed	No Lubrication	6	6	8
	11	Control Valve Leaky	No Lubrication	7	6	6
	12	Leaky Regulator Valve	No Lubrication	6	5	7
	13	Platen Leaky or Clog	Corrotion	7	4	5
	14	Leaky Rames Packing	Packing Scrape	7	6	6
	15	Leaky Seal Dome	Seal Scrape	6	4	4
	16	Leaky Head Cykinder	Corotion	7	5	5
Shaping Pressure Under Pressure	17	Leaky Seal Solenoid Valve	No Lubrication	5	6	8
	18	Piston Solenoid Valve Jammed	No Lubrication	6	6	8
	19	Membrane Shaping Crack	Over Utilitation	6	6	6
	20	Disc Ring Leaky	Ring Scrape	6	7	6
	21	Check Valve Leaky or Clog	Corrotion	6	4	5
	22	Leaky Regulator Valve	No Lubrication	6	5	7
	23	Leaky Seal Piston Top Ring	Seal Scrape	6	7	7

C. *Analyze*

Analyze is carried out to get an understanding of why a problem occurs and where opportunities for improvement exitst. There are four factors that can be analyzed, namely man, machine, material and method as shown in Fig. 6.

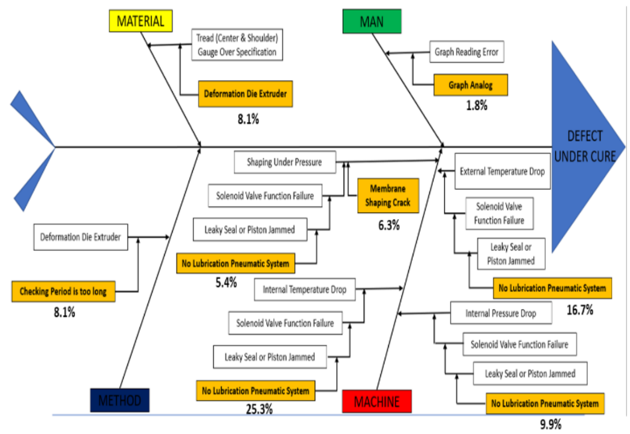

Fig. 6. Fishbone diagram of undercure defect

The root causes of undercut defects are no pneumatic lubrication system, membrane forming cracks, graphic reading errors and deformation die extruder. This project will analyze the causes of the vulcanization process, namely the curing machine. The system on the curing machine will be analyzed more to get the risk priority number (RPN).

TABLE VI
RISK PRIORITY NUMBER DEFECT UNDER CURE

FAILURE MODE	NO	PARTS	CAUSE OF FAILURE MODE	S	O	D	RPN
Internal Pressure Out Spesification	1	Leaky Seal Solenoid Valve	No Lubrication	5	6	8	240
	2	Piston Solenoid Valve Jammed	No Lubrication	6	6	8	288
	3	Piston Valve leaky or Jammed	No Lubrication	7	5	7	245
	4	Check Valve Leaky or Clog	Corrotion	6	4	5	120
Internal Temperature Out Spesification	5	Leaky Seal Solenoid Valve	No Lubrication	5	6	8	240
	6	Piston Solenoid Valve Jammed	No Lubrication	6	6	8	288
	7	Piston Valve leaky or Jammed	No Lubrication	7	5	7	245
	8	Check Valve Leaky or Clog	Corrotion	6	4	5	120
External Temperature Out Spesification	9	Leaky Seal Solenoid Valve	No Lubrication	5	6	8	240
	10	Piston Solenoid Valve Jammed	No Lubrication	6	6	8	288
	11	Control Valve Leaky	No Lubrication	7	6	6	252
	12	Leaky Regulator Valve	No Lubrication	6	5	7	210
	13	Platen Leaky or Clog	Corrotion	7	4	5	140
	14	Leaky Rames Packing	Packing Scrape	7	6	6	252
	15	Leaky Seal Dome	Seal Scrape	6	4	4	96
	16	Leaky Head Cykinder	Corotion	7	5	5	175
Shaping Pressure Under Pressure	17	Leaky Seal Solenoid Valve	No Lubrication	5	6	8	240
	18	Piston Solenoid Valve Jammed	No Lubrication	6	6	8	288
	19	Membrane Shaping Crack	Over Utilitation	6	6	6	216
	20	Disc Ring Leaky	Ring Scrape	6	7	6	252
	21	Check Valve Leaky or Clog	Corrotion	6	4	5	120
	22	Leaky Regulator Valve	No Lubrication	6	5	7	210
	23	Leaky Seal Piston Top Ring	Seal Scrape	6	7	7	294

D. *Improve*

The results showed that some priority actions were taken, namely the failure mode in the form of no lubrication pneumatic system (63.81%) as shown in Fig. 7. A part from being seen from the highest cumulative RPN score, repairs to these failures were also carried out by considering realistic actions in terms of time and cost.

No lubrication pneumatic system is one of the root problems that cause damage to the control system so that the tire vulcanization parameters are not accordance with specifications. To prevent damage to the pneumatic system, an air lubricator will be installed. Pneumatic lubricant will be injected into the airways flowing the oil to provide lubrication to the internal working parts of the pneumatic tools and to other devices such as cylinders and drive valves as shown in Fig. 8.

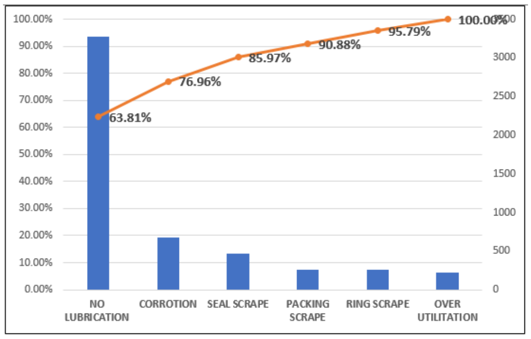

Fig. 7. RPN Cause of undercure defect failure

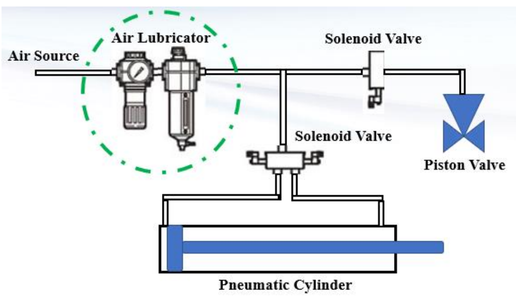

Fig. 8. Modification of air lubricator in pneumatic system

E. *Control*

This is the last stage in the six-sigma approach, where at this stage an organizational process or product improvement and ongoing performance monitoring are carried out. At this stage, a new level of performance is ensured in standard conditions which are then documented and published which is useful as a corrective step for the next improvement process. The data of undercure defect after improving the curing machine shown in Figure. In June the defect still exceeded the key performance indicator value. However, this value has decreased compared to May 2020. The monitoring results on July 2020 – November 2020 of undercure defect was below the key performance indicator value as shown in Fig. 9. Based on the results of the RPN calculation after modification as shown Table 7, the RPN no lubrication decreased below 200.

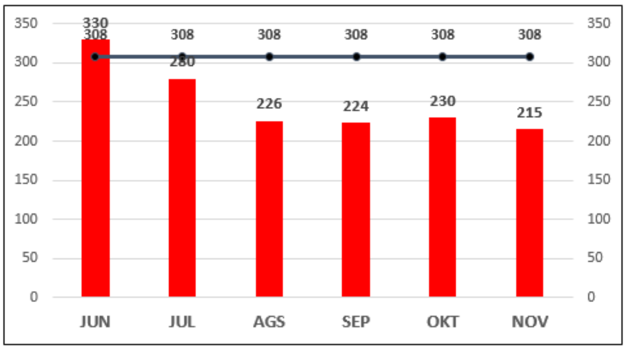

Fig. 9. Undercure defect after improvement

TABLE VII
RISK PRIORITY NUMBER OF UNDERCURE DEFECT AFTER IMPROVEMENT

FAILURE MODE	NO	PARTS	CAUSE OF FAILURE MODE	S	O	D	RPN
Internal Pressure Out Spesification	1	Leaky Seal Solenoid Valve	No Lubrication	4	5	8	160
	2	Piston Solenoid Valve Jammed	No Lubrication	5	5	8	200
	3	Piston Valve leaky or Jammed	No Lubrication	6	4	7	168
	4	Check Valve Leaky or Clog	Corrotion	6	4	5	120
Internal Temperature Out Spesification	5	Leaky Seal Solenoid Valve	No Lubrication	4	5	8	160
	6	Piston Solenoid Valve Jammed	No Lubrication	5	5	8	200
	7	Piston Valve leaky or Jammed	No Lubrication	6	4	7	168
	8	Check Valve Leaky or Clog	Corrotion	6	4	5	120
External Temperature Out Spesification	9	Leaky Seal Solenoid Valve	No Lubrication	4	5	8	160
	10	Piston Solenoid Valve Jammed	No Lubrication	5	5	8	200
	11	Control Valve Leaky	No Lubrication	6	4	7	168
	12	Leaky Regulator Valve	No Lubrication	5	5	7	175
	13	Platen Leaky or Clog	Corrotion	7	4	5	140
	14	Leaky Rames Packing	Packing Scrape	7	6	6	252
	15	Leaky Seal Dome	Seal Scrape	6	4	4	96
	16	Leaky Head Cykinder	Corotion	7	5	5	175
Shaping Pressure Under Pressure	17	Leaky Seal Solenoid Valve	No Lubrication	4	5	8	160
	18	Piston Solenoid Valve Jammed	No Lubrication	5	5	8	200
	19	Membrane Shaping Crack	Over Utilitation	6	6	6	216
	20	Disc Ring Leaky	Ring Scrape	6	7	6	252
	21	Check Valve Leaky or Clog	Corrotion	6	4	5	120
	22	Leaky Regulator Valve	No Lubrication	5	5	7	175
	23	Leaky Seal Piston Top Ring	Seal Scrape	6	7	7	294

Controlling the improved process, monitoring the results in a continuous way. Documentation of standardization improvement plans and monitoring process. Confirmation of improved procedures and transferring ownership of the corresponding team after completion of the project.

IV. Conclusion and Recomendation

A. *Conclusion*

To improve the quality in the curing process is done by reducing defects and maintaining process specifications according to the standards and preventing specifications deviation as much as possible. In this project, the machine is the most important factor in order to keep the process specifications up to the standard. Potential failure is prevented by modifying the highest damage. Based on the RPN value, no lubrication pneumatic system has the highest RPN value. This is the basis for the modification to install an air lubricator in the pneumatic system. Monitoring during the five months of July 2020- November 2020 making the undercure defects decrease or below the key performance indicator value. The average undercure defect per month is 235 ppm with a key performance indicator value of 308 ppm. In June 2020 undercure defects were still above the key performance indicator value because the improvement process was not comprehensive on the curing machine.

B. *Recomendation*

This recommendation is addressed to tire practitioners and manufacturers regarding the prevention of undercure defects in truck bus bias tires. Preventive maintenance is maintained to avoid repeated failures. This is done to reduce failure and control the results of these modifications. The monitoring step is carried out to see if there is a disturbance or not in the system after modification. In addition to monitoring, other systems can be modified so that the potential for failure is reduced.
Air lubricator in the pneumatic system is carried out by preventive maintenance so that the equipment is actually functioning. Besides that, other equipment such as the solenoid valve and piston valve are guaranteed to function. The leaky seal piston top ring has the highest RPN value of 294; this part needs preventive maintenance or improvement.

The next suggestion is to measure the service life of spare parts, such as seals, packing and lubricating oil so that part replacement can be done before the damage occurs and no system is disturbed and the curing process specifications remain up to the standard.

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