RELIABILITY ENHANCEMENT OF STEEL ROLLING MILL USING FAULT TREE ANALYSIS

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This work investigates the failure data analysis of steel rolling mill used for producing Thermo Mechanically Treated (TMT) rod. Initially, a cost model is developed to analyze the failure costs and thereby quality tools such as brainstorming and Fault Tree Analysis (FTA) is used to identify the root cause of the breakdowns and alternative technical solutions to the root cause are found in order to improve the reliability of the system. The overall annual cost assessment due to breakdowns has been made, by considering the component cost, replacement cost, and cost incurred due to a loss of production, annual rework and rejection cost. A framework is developed for evaluation of failure modes and improvement of reliability by appropriate design modifications in order to reduce the downtime and cost due to downtime. Remedial measures such as the introduction of the rotary shearing machine are suggested, in order to increase the reliability level and production rate of the mill.

Keywords: Steel Rolling Mill, TMT rod, Reliability, Fault Tree Analysis.

1. Introduction

In today's competitive world, the reliability of equipment is extremely important to maintain quality and to meet delivery deadlines [1-2]. This is achieved by using proper maintenance strategies and design changes for unreliable subsystems and components of a complex system. It is significant to develop a strategy for maintenance, replacement and design changes related to those subsystems and components [2]. An analysis of downtime along with causes is essential to identify the unreliable components and subsystems [3].

Reliability analysis is one of the main tools to ensure agreed delivery deadlines which in turn to maintain certain indefinable factors such as customer goodwill and company reputation [1]. Downtime often leads to both tangible and intangible losses. These losses may be due to some unreliable systems/components, thus an effective strategy for maintenance, replacement, and introduction of new systems needs to be framed out [2]. A system is constituted by a number of subsystems designed to achieve a common specific result with an

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acceptable level of reliability. The type of subsystem's failure and its frequency has a direct effect on the system's reliability [4-5]. Thus, it becomes very important to locate the critical elements and analyze their reliability. Furthermore, in many situations, it is easier and less expensive to test components/subsystems rather than the entire system.

In this study, the problem is based on excessive downtime of rolling mill stands in a steel rolling mill. In each mill stand, rollers were used for the rolling the ingots to produce TMT rods. The general outline and the working principle are presumed to be self-explanatory from Fig. 1. Rejects, rework and downtime leads to wastage and additional costs to the products, profit margin drops down and thus the product becomes less competitive in the market. So, the company has to reduce production rate forcibly, which ultimately increases the cost of production.

This study was carried out to analyze downtime, find out the main cause and locate the critical components/subsystems based on their frequency of failure, develop models to predict the reliability of the system and expected costs associated with currently unreliable subsystem and to explore the design options available and estimate the cost-benefit by considering the design change. Brainstorming and Fault Tree Analysis (FTA) is used to identify the root cause of the breakdowns. Fault Tree Analysis (FTA) is an established technique in risk management associated with identified hazards specific to focused fields. It is a comprehensive, structured and logical analysis method aimed at identifying and assessing hazards of complex systems [6-8]. In the following sections, a framework was developed for evaluation of failure modes and improvement of reliability by appropriate design modifications in order to reduce the downtime and cost due to downtime. Remedial measures such as the introduction of the rotary shearing machine are suggested, in order to increase the reliability level and production rate.

1.1 TMT rod manufacturing process

TMT rod is manufactured in a process in which the ribbed rod is heat-treated in three stages during the production process itself which are produced by the rolling process. Initially, the raw material (i.e. ingots) is heated up to 1300oC in reheating furnace and fed into rolling stands, due to the rolling process, the cross-section of ingot will be decreasing correspondingly whereas the length will be increased since it passes through rolls in roughing stand, intermediate stand, continuous stand and finishing stand. Finally, it passes through TMT box and reaches the cooling bed, before reaching to cooling bed; the rod will be cut by shearing machine for standard size. The bar is rapidly cooled/ quenched in high-pressure water spray system as it emerges from the finishing stand of the rolling mill. Thus, the hot rolled TMT rod undergoes thermomechanical treatment in three successive stages namely, quenching, self-tempering, and atmospheric cooling, during the process. The following Fig. 1 illustrates the TMT rod making process.

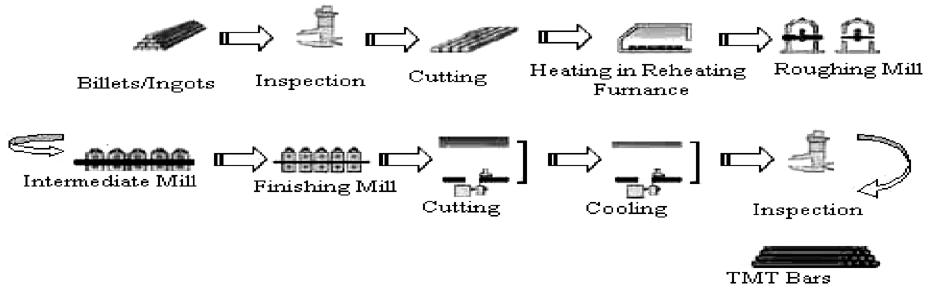

Fig. 1 Manufacturing process of TMT rod [9]

2. Methodology

The following are the basic steps involved in this case study in order to investigate and to improve the productivity of the steel rolling mill.

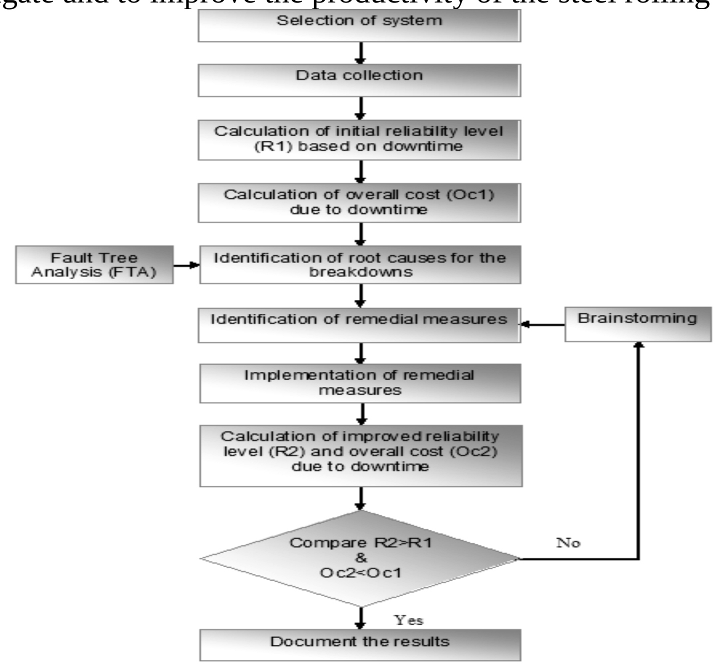

Fig. 2 Framework of Methodology

i. Selection of the system
ii. Data Collection
iii. Reliability analysis and cost analysis
iv. Identification of root causes for the failures
v. Identification of remedial measures
vi. Implementation of remedial measures

Based on the above steps a generic framework has been developed for the evaluation of failures modes and reliability improvements

2.1 Selection of the System

To implement Reliability Centered Maintenance (RCM) in a steel rolling mill, system selection for the study is very much important for improving reliability level of a system because it requires an immense investment of time and resources, so the selection of system has to be made properly [11]. Downtime analysis and Pareto analysis of the system, based on breakdown data will be useful for identifying the system for which the reliability level has to be improved [12-13].

Initially, data collection was made by using check sheet, in which failure data and frequency of failures were collected. Based on the failure data the present failure rate and reliability level were calculated. Then based on the breakdown analysis, the systems with less reliability level were selected to improve its reliability level and to reduce its failure rate. The failure data has been collected by using production report. It was observed that the breakdowns were more steel rolling mill since it was newly erected. Thus by using the following equations, reliability and cost analysis were made.

$$f(t) = F \,/\, \text{total no. of working hours} \quad (1)$$

$$R(t) = 1 - f(t) \quad (2)$$

Thus by using the above equations and breakdown data, the failure rate and reliability level for each section of the rolling mill were identified and tabulated in Table 1.

From the above results, the reliability level of the continuous stand and furnace section were very less. Hence initially these two sections were selected for the investigation and the cost incurred due to breakdowns in the continuous stand and furnace sections were more, and it was identified using cost model as shown below.

Table 1

Reliability Level of Each Section

Sl. No.	Sections	Failure rate, f(t)	Reliability level, R(t)
1	Furnace	0.298	0.701
2	Roughing mill	0.271	0.728
3	Intermediate mill	0.197	0.802
4	Continuous mill	0.329	0.670
5	Finishing mill	0.174	0.826
6	Pinch and shear roll	0.112	0.887
7	Quenching section	0.104	0.896
8	Cooling bed	0.108	0.891

$$O_c = X_1 + X_2 + X_3 \quad (3)$$

Where,

$X_1 = N_r * C_r$, $X_2 = F\,(MTTR * N * L_r)$, $X_3 = F\,(MTTR * P_r * C_p)$

The above equation, Equation (3) comprises of three terms such as, the first term (X_1) provides the rejection cost, second term (X_2) provides the cost of fixing the breakdown and third term (X_3) deals with the cost incurred due to ideal time of the machines (i.e., since process involves in continuous sequences of operations, breakdown in a particular machine will lead to ideal time of other machines because they cannot process without completing the previous activities). Thus the sum of all three terms gives the overall cost due to that breakdown.

3. Root Cause Investigation

Based on the reliability analysis, continuous mill and furnace sections were taken for the investigation. Pareto analysis is a classical tool used for prioritizing the vital few breakdowns that have to be addressed in those sections. A Pareto chart is a graphical representation that displays data in order of priority [3, 6, and 14]. It is a powerful tool for identifying the relative importance of causes, most of which arise from only a few of the processes, hence the 80:20 rule (i.e., 80 percent of the problems occurs to due to 20 percent of the causes). Pareto Analysis is used to focus problem-solving activities so that areas creating most of the issues and difficulties are addressed first.

Based on the data collected, Pareto analysis for the continuous mill and furnace section has been made in order to prioritize the vital few breakdowns. Fig. 3 shows the Pareto chart for the continuous mill.

The continuous mill exists between the intermediate mill and finishing mill and it consists of seven rolling stand which performs rolling process. Thus from above Pareto chart, breakdowns in the fourth stand (C_4) and second stand (C_2) guide boxes of the continuous mill are the critical elements of the system. The photograph of the guide box used in the continuous mill section is shown in Fig. 4.

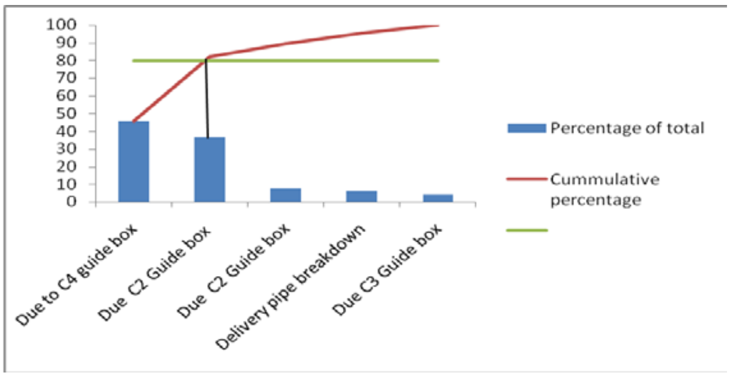

Fig. 3 Pareto Chart for Continuous section

Fig. 4 Photograph of guide box used in continuous mill

Similarly, Fig. 5 shows the Pareto analysis of furnace section, based on that vital few elements were identified as material low heat, ejector breakdown, and gasifier breakdown. Root causes for the critical elements have been investigated as follows.

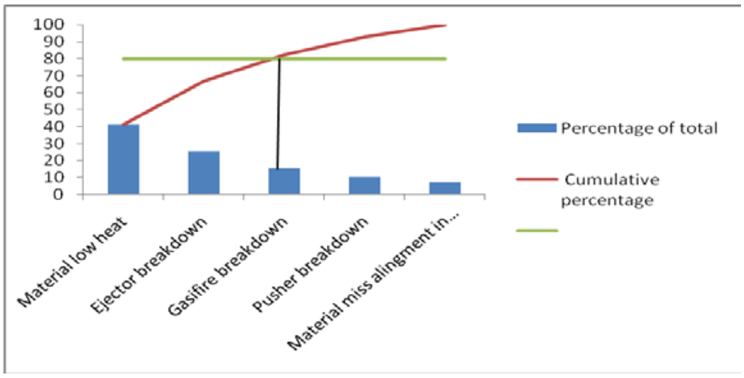

Fig. 5 Pareto Chart for Furnace section

Based on the Pareto analysis and cost models the overall breakdown cost for the critical elements are identified and tabulated in Table 2. The overall cost calculated below is for twelve months of failure data.

Table 2

Overall Cost of Critical Breakdowns

Sl. No.	Critical elements	Overall cost (USD)
1	Breakdown due to C_4 Guide Box	3220.59 USD
2	Breakdown due to C_2 Guide Box	2156.11 USD
3	Breakdown due to furnace failure	1395.17 USD

The overall breakdowns cost in the continuous mill and furnace sections were calculated to be 5376.70 USD and 1395.17 USD per year respectively. Since the breakdown cost is very high, these sections were selected for the investigation and the root causes for those breakdowns are identified by using Fault Tree Analysis as shown in the following section.

Fault Tree Analysis begins with clearly defining the top event, which is an undesired event to evaluate. The various combinations of events that can lead to the occurrence of the top event are then determined. The various levels in the fault tree depict how the propagation of lower-level events causes the top event to occur. Logic operators known as gates determine how events are generated. In the construction of a fault tree, various symbols are used to represent events and gates. When building a fault tree, perform the following steps [15-19]:

(i) Identify the top event.
(ii) Identify the first-level events.
(iii) Link these first-level events to the top event using gates.
(iv) Identify the second-level events.
(v) Link these second-level events to the top event using gates.
(vi) Continue to repeat these steps as they are necessary for all subsequent levels of events.

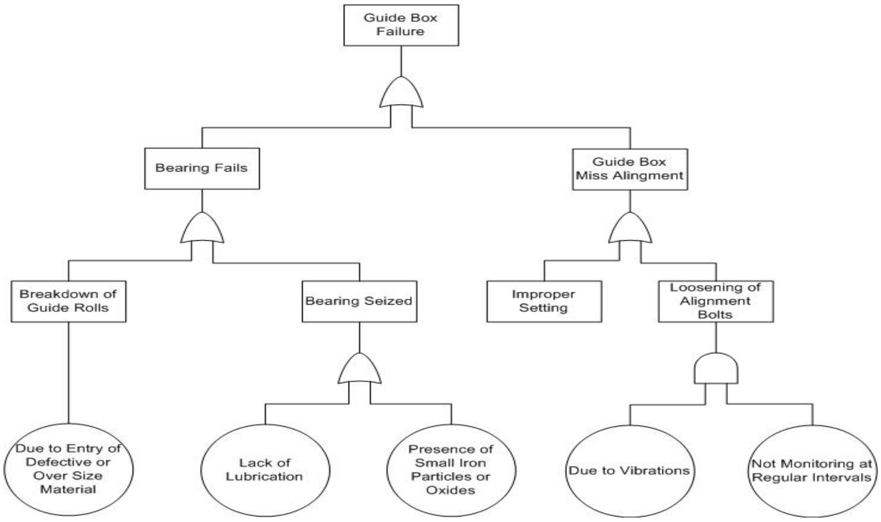

Fig. 6 Fault Tree Analysis for Guide Box Failure

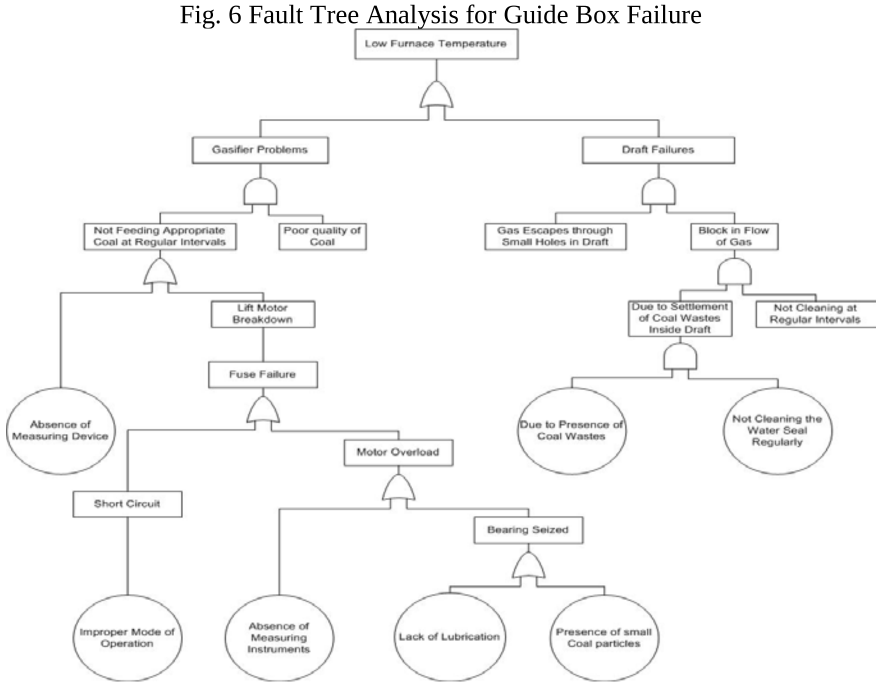

Fig. 7 Fault Tree Analysis for low furnace temperature

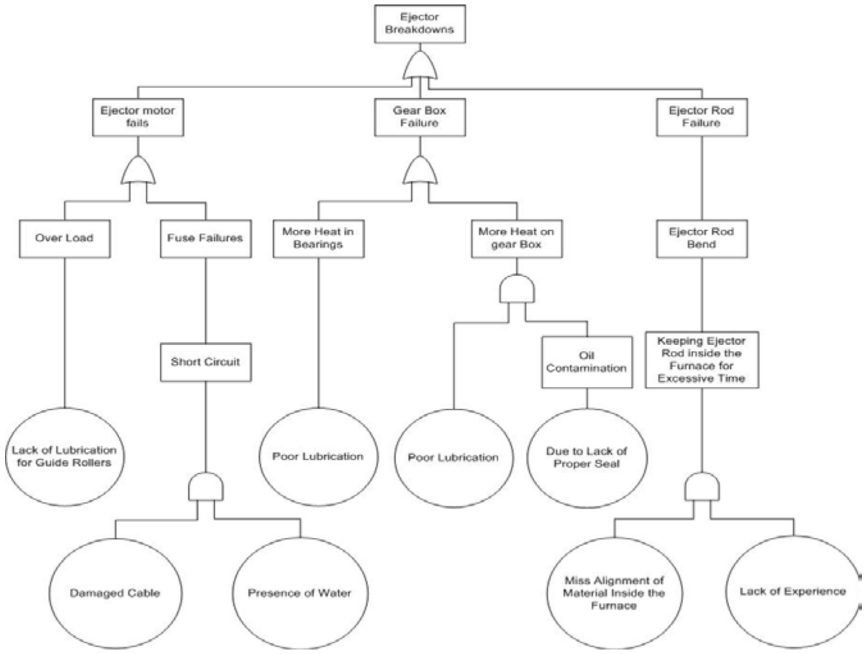

Fig. 8 Fault Tree Analysis for Ejector Breakdowns

From Fig. 6, Fig. 7 and Fig. 8 the Fault Tree Analysis (FTA) of vital few elements, for which the root causes for the various failures which affect the reliability level of the system were identified. Based on the investigation, some of the root causes which lead to process failure of the selected systems are presented below.


Fig. 9 Material split

Fig. 9 shows the defect called front end split material. This is one of the major reasons for the process breakdown due to guide box of the continuous mill. When this split material enters to the rolling stand passage, it will be interrupted and it might not be processed since the gap between the rolls would be less as per the requirement, hence it would not allow the split material to pass through it and that leads to the breakdown. To fix this problem it requires more time and resources, further other rolling mill stands will be idle until fixing this problem.

Fig. 10 Material low heat

Fig. 10 shows the defect called material low heat, this was identified as a failure and it might affect the production process. The material shown in the figure is called ingots, which will be raw material for TMT rods. These ingots have to be maintained at an optimal temperature that is suitable for the process. Temperature drop in furnace leads to this kind of defect. Similarly, the time spent by the raw material inside the furnace is also vital; hence it requires the experienced and skilled operator to operate the ejector, which is used to eject the ingots out from the furnace.

Fig. 11 Coal waste interruptions

Fig. 11 shows the breakdowns that caused by low furnace temperature due to coal waste jam in the draft. Due to this, the gas escapes through the gaps in the draft, which leads to reduced efficiency of the furnace.

Fig. 12 Damaged cable of ejector motor

Fig. 12 shows the damaged cable of the ejector motor. The ejector motor's cable was on the ground near to the track of ejector hence movement of ejector system cause damage to the cable. The ejector rod is used to eject the material outside the furnace hence water is passed over the ejector rod to cool it. Due to presence of water and damaged cable, ejector motor fails frequently.

After identifying the root causes, remedial measures are identified by using techniques such brainstorming and freewheeling etc. thus by following this technique, many alternative solutions were suggested for which best solutions was selected and implemented. During brainstorming session, suggestions from various stages of employees were collected. Hence in order to reduce particular breakdown i.e breakdown due material split, the suggestion to implement new shearing machine in front of the continuous stand was selected based on the cost-benefit analysis. Thus after implementing the shearing machine, the breakdown due to that reason was reduced and hence production rate of the system was increased.

4. Implementation

Following the brainstorming technique, many alternative solutions were suggested form which better solutions were selected and implemented. Based on the cost-benefit analysis and other factors such as compatibility with other systems, some of the remedial measures are implemented and hence reliability level of the system was improved. In order to reduce particular breakdown i.e. breakdown due material spilled, the suggestion to implement new shearing machine in front of the continuous stand was selected based on the cost-benefit analysis. The details of suggestions provided for the issues addressed in the steel rolling mill were listed in Table 3.

The defect, material split was overcome by introducing a shearing machine. These defects are caused due to excess pressure in the previous rolling mill, and thus the material coming out from the mill will have this defect. In order to overcome this problem, a shearing machine with oscillating guide box mechanism was introduced. The oscillating guide box will direct the raw material into the shearing machine before entering into the continuous mill, due to this, the material split would be removed from the front end and rear end. The shear force applied to the raw material results in the formation of sharp edge that then leads to the smooth entry of the raw material to next rolling stand without any interruption. Fig. 13 shows the shearing machine which was implemented in the continuous strand.

Fig. 13 Implementation of shearing machine

Table 3

Suggestions of Remedial Measures

Sl. No.	Breakdown	Failure Mode	Cause for Failure	Remedial measures
1.	Material oversize	Increase in gap between rollers	Wear of rolls	Time-based monitoring,
			Loosening of handles	checking at regular intervals
		Settlement of scales/chips on the material	Lack of water circulation in the runway	Suggested to Implement proper water circulation system in order to remove scales and chips.
2.	Guide box failure	Failure of guide rolls	Lack of lubrication	Lubricate at regular interval of time
			Presence of iron oxides in bearings of guide box	Provide proper bearing seal
			Settlement of oxides in roll groves	Provide proper water circulation system
			Material split due to contact with previous guide box	Implement shearing machine in front of continuous stand
		Vibration	Loosening of alignment bolts.	Monitor and fix the bolts at regular intervals.
3.	Furnace breakdowns	Low heat	Poor quality of coal and not feeding appropriate amount of coal	Suggested to implement measuring device
			Gas Leakage in draft	Suggested to fix the gap and clean the water seal and draft regularly to avoid coal sludge settlement
		Lift motor fuse failure	Overloading	Lubricate motor bearing at regular intervals
			Short circuit due to improper mode operation for stopping	Implemented braking system and suggested to provide proper training to the operator
4.	Ejector breakdown	Ejector motor failure	Short circuit due to damaged cable. because of cable lying on the track caused the damage and presence of water to cool ejector rod caused a short circuit	Separate channel is provided in order to prevent cable water
		Gearbox failures	More heat dissipation	Lubricate regularly and provide proper seal to prevent oil from contamination

Similarly, in furnace section, some of the remedial measures are also implemented. Fig. 14 b depicts the tampered cable of ejector motor in the furnace section. The tampered cable of ejector motor and water, which is used for cooling the ejector rods, had contact with each other, due to this the ejector motor fails frequently. The reason for cable damage is identified as the cable resting on the ground and it lies near to the track of ejector. Hence, when ejector moves on the track it damages the cable. In order to prevent cable damage and to protect the cable from water, a new system was developed as shown in Figure 14 b. In this system, the cables were attached to a separate column over the ejector. This setup will allow the cable to elongate and shrink automatically as per the requirement.

a. Before

b. After

Fig. 14 New Channel for Ejector Motor Cable

5. Results and Discussions

Initially, when the system was taken to study, the reliability level was very low. In order to improve reliability level, the breakdowns needed to be reduced. Thus, root causes for the breakdowns are investigated and some of the remedial measures for the root causes are identified. The remedial measures which are identified are implemented to the system. Thus, by implementing the remedial measures reliability level has been improved.

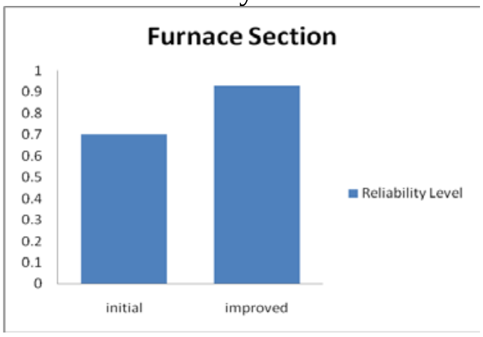

Fig. 15 Improved Reliability Level of Furnace Section

Fig. 16 Improved Reliability Level of Continuous Section

Fig. 15 shows the comparison chart of the reliability level for furnace section. After the implementation of some of the suggested remedial measures, the reliability level in furnace section was improved by 20%. Similarly, same procedure followed to improve reliability level in the continuous stand and hence through this work, the reliability level of the continuous stand was improved by 15%. Fig. 15 shows the comparison of initial and improved reliability level of the continuous mill.

Table 4 shows the comparison of improved reliability level with an initial reliability level of the system. The reliability level of furnace section and continuous mill were increased by 17% and 15% respectively. Similarly, by implementing other remedial measures, the overall reliability level of the plant could be improved.

Table 4

Reliability level comparison table

Sl. No.	Sections	Initial Reliability Level	Improved Reliability Level
1	Furnace section	0.701	0.87
2	Continuous section	0.670	0.82

4. Conclusion

Based on the failure data analysis conducted in the TMT rod manufacturing steel rolling mill, the following conclusions were drawn;

(i) A framework was developed in order to implement reliability based investigation for steel rolling mill.

(ii) Based on the reliability analysis, it was so evident that the failure rate of continuous stands and furnace section are more.

(iii) The reliability level of furnace section and continuous mill were increased by 17% and 15% respectively.

Similarly, by implementing other remedial measures, the overall reliability level of the plant could be improved.

Nomenclature

MTTR	:	Mean Time to Repair
L_r	:	Labour Cost per Hour
N	:	No. of Labours
F	:	frequency of occurrence
N_r	:	No of pieces rejected
P_r	:	Production rate
C_p	:	Cost per TMT rod.
C_r	:	Rejection cost of TMT rod
$f(t)$	:	Failure rate.
$R(t)$	:	Reliability Level.
O_c	:	Overall cost due to particular failure

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