

APPLICATION OF FAILURE MODES AND EFFECTS ANALYSIS (FMEA) FOR QUALITY IMPROVEMENT IN SPUR GEAR MANUFACTURING PROCESS: A CASE STUDY

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Abstract

The spur gear industry in Pakistan is beset with serious operating problems, especially the failure of the gears during manufacturing without notice, resulting in substantial rejection rates, expensive rework, and unreliable product quality. Failure Mode and Effects Analysis (FMEA) has been used widely in various industries, including automotive and mechanical assembly industries, but there is limited empirical literature on the systematic use of FMEA in the micro level manufacturing stages of spur gear production in a developing industrial environment. The present study proposes comprehensive PFMEA (Process FMEA) case study to overcome this, using the Delphi technique to combine experts' knowledge and systematically identify, categorize and quantify operational risks of each of eight manufacturing processes for Waseem Brothers Gear Industry, Gujranwala, Pakistan. Potential failures were assessed by Severity (S), Occurrence (O), and Detection (D) rankings and Risk Prioritization Numbers (RPNs) were calculated. Before intervention, the most important risk factors identified were: gear cutting (RPN = 240), heat treatment (RPN = 140) and raw material storage corrosion (RPN = 75). All the RPN values after implementing the targeted corrective actions were kept below the threshold of 70, which was achieved by optimizing the lubrication regimes, controlled thermal dwelling parameters, ventilated storage covers and high-performance tool sharpening. The proposed framework offers some practical and cost-effective ways for spur gear manufacturers to mitigate risk in their operations to maximize operational efficiency and improve quality management.

1. INTRODUCTION

The manufacturing industries of spur gears in developing countries like Pakistan are facing severe quality requirements and continuous productivity and efficiency constraints. An important reason for revenue loss and production

delays is the unexpected failure during manufacture leading to high scrap rate, long rework, delivery delays and reduced mechanical reliability[1]. The failures may be due to a variety of causes, including poor design, material defects, poor process control, or lack of preventive

maintenance [2]. Furthermore, the challenges are compounded by the absence of a systematic procedure to identify, evaluate and reduce risks[3]. FMEA and other Total Quality Management (TQM) methods can play a significant role in increasing the productivity of industries in the manufacture of spur gears. FMEA can be used to analyze the possible failure modes, their effects, and the risk at any stage of the manufacturing process[4]. It is a proactive, structured engineering technique to be used in the identification of potential failure modes, a review of the systemic causes and effects of failures, and a prioritization of actions to reduce risk. Process FMEA (PFMEA) is an application of FMEA to manufacturing processes that determines a Risk Priority Number (RPN) for each failure mode by multiplying three numeric values: Severity (S), Occurrence (O), and Detection (D).

$$RPN = S \times O \times D \quad \text{Eq.1}$$

Previous research has shown that FMEA is applicable to a variety of industrial applications. Aized et. al used PFMEA to improve and optimize the production of leaf springs, they found that there were significant reductions in high RPN failure modes[4]. To prevent the occurrence of fatigue failure, Fonte et al. did investigation of crankshaft failure [5], and Feili et al. introduced expert opinion to FMEA in order to improve automobile production system for side door hinge [6]. Muzakkir et al. used FMEA to assess the reliability of journal bearings[7] and Suryoputro et al. utilized Fuzzy FMEA to manage forklift operation risks[8]. Moreover, the implementation of FMEA into other practices such as Total Quality Management (TQM), Six Sigma (DMAIC) and Lean processes has been proven to enhance process stability, cycle times and operational cost savings, regularly[9-11]. Peeters et al. have built hybrid models of Fault Tree Analysis (FTA) and FMEA for optimization of the maintenance of a complex system[12]. Moreover, the life of steel cord belts and joints was the subject of investigation in another paper. A related field, Joseph used FMEA to analyze the most likely failure modes in steel cord belts and joints,

recommending specific solutions to improve the useful life of these parts[13]. At the broader level, manufacturing industries can improve their overall productivity with process streamlining, waste reduction and process control to shorter lead time and sustained operational efficiency. Although FMEA has been widely used in the structural reliability and automotive applications and in general mechanical systems, there is a lack of literature on the application of empirical, step-by-step process FMEA directly in spur gear manufacturing processes in small-scale industrial environments. Spur gear fabrication involves tightly coupled mechanical and thermal operations—including sawing, turning, facing, boring, gear cutting (shaping), deburring, and heat treatment—each presenting distinct micro-structural and dimensional risk factors. Existing studies rarely provide quantitative pre- and post-intervention evaluations across these specific manufacturing steps in regional SME environments.

To address this gap, this study formulates the following primary research question: How can a structured Process FMEA framework, combined with expert-consensus techniques, systematically identify, prioritize, and eliminate critical process-induced defects in spur gear manufacturing to reduce high-risk RPN scores below acceptable operational thresholds without requiring prohibitive capital investment? To answer this question, this research implements Process FMEA in a spur gear manufacturing organization to identify potential failures and their effects across all production operations, calculate initial RPN scores, apply targeted recommended actions, and recalculate RPN scores to evaluate process improvements.

2. CASE STUDY

The present study was carried out in Waseem Brothers Gear Industry, which is a leading small to medium scale manufacturing unit of spur gears in Civil Lines of Gujranwala, Punjab, Pakistan. The research centers on defect mechanisms in the entire spur gear manufacturing process, specifically in the production and quality control areas. Technical data were methodically collected

by conducting literature review, direct field study, structured survey and multi-round expert consultations on the shop floor.

The Delphi technique was incorporated in the Process FMEA (PFMEA) evaluation system to overcome the challenges of coordinating tasks between different departments and the scheduling problem between production managers and quality assurance engineers and senior machinists. A questionnaire was designed to assess the failure modes, root causes, operational effects and associated rating metrics (S, O, D). Each failure mode was independently evaluated in successive rounds by experts. Summed scores were regrouped after each round until the scores were agreed upon by experts. The expert scoring was evaluated statistically, showing very high convergence with a minimum standard deviation of the scores from expert evaluation of $\sigma \leq 0.42$, which guaranteed a solid and unbiased risk assessment.

3.METHODOLOGY

Waseem Brothers Gear Industry has implemented a PFMEA system as shown in Figure 1 in a systematic manner. The manufacturing process flow examined in this study includes eight

successive primary manufacturing processes: Sawing, Turning, Facing, Boring, Grooving, Gear Cutting, Deburring and Heat Treatment as shown in Figure 2. Each of these operations is evaluated according to a set of standardized criteria for Severity (S), Occurrence (O) and Detection (D) on a scale of 1 to 10, then risk is assessed within each operation. The severity (S) of a failure mode depends on how much it affects the performance or safety of the system and ranges from 1 (no discernible effect) to 10 (critical safety hazard that occurs unexpectedly); as given in Table 1. Process Occurrence (O) ranges from 1 to 10, corresponding to extremely rare events (less than 1 failure for every 3,600 units) to almost inevitable events (more than 100 failures for every 3,600 units), as shown in Table 2. Detection (D) evaluates the ability of existing process control to detect defects before they reach the customer, with 1 being certain automated defect detection, and 10 being no process control at all that would catch escapes that go to the customer as described in Table 3. The Risk Priority Number can be obtained by multiplying the three parameters as stated in Eq. (1) above.

Table 1: Process Severity Rating Criteria (S)

Rank	Effect	Severity
10	Hazardous Without Warning	Failure of spur gear assembly or failure in critical process that can endanger the safety of passenger and cause fatal accident without prediction.
9	Hazardous with Warning	Failure of spur gear assembly or failure in critical process that can endanger the safety of passenger and cause fatal accident with predictability.
8	Very High	Failure that causes 100% loss of primary performance and function of spur gear assembly that lead to serious accident or failure that can disturb production line.
7	High	Failure in a process that can reduce performance and function of spur gear assembly and lead to serious accidents. A portion of product must be reworked.

6	Moderate	Failure that can reduce performance and function of a spur gear assembly. A small portion of product have to be reworked.
5	Low	Affected spur gear are usable or operable but at a reached level of performance or function. Product can be reworked without any material loss.
4	Very Low	Lead to multitudes of warranty claims against spur gear assembly.
3	Minor	Lead to warranty claims against spur gear assembly with respect to fit and finish.
2	Very Minor	Noise is use or operation. Defect noticed by very limited users
1	None	No visible effect or effect can be ignored

Table 2: Process Occurrence Rating Criteria (O)

Rank	Evaluation	Process Occurrence
1	Almost never occurs	0 per 3600 pieces
2		1 per 3600 pieces
3	Low incidence rate	2 per 3600 pieces
4		3 per 3600 pieces
5	Moderate incidence rate	4 per 3600 pieces
6		5 per 3600 pieces
7	High incidence rate	Grater then 10 per 3600 pieces
8		Grater then 20 per 3600 pieces
9	Frequently occur	Grater then 50 per 3600 pieces
10		Grater then 100 per 3600 pieces

Table 3: Process Detection Rating Criteria (D)

Rank	Detection
10	Failure cannot be detected before delivery to customer. No process controls available to detect failure.
9	Failure is likely to be flowed out to customer. Process controls currently in place cannot detect failure.
8	Extremely difficult to be detected failure before shipping. Process control currently in place will probably not detect failure.
7	Failure is detectable by periodic sampling inspection. Difficult to detect failure by current process control. Failure can be detected by periodic sampling inspection.
6	Failure can be detected by regularly conducted sampling inspection or 100% visual inspection. Process controls currently in place may overlook failure
5	Failure can be detected by 100% final inspection (manual). Process controls currently in place may detect failure.

4	Failure can be detected by 100% final inspection through checking fixture or gauge. Failure can be detected in the subsequent process.
3	Failure can be detected in the subsequent process. Process controls currently in place can detect failure (monitor Trends by using statistical process control in addition to 100% inspection and so on)
2	Failure can be detected within the process. Process control such as QA devise and so on in place for 100% inspection with automatic error detection failure
1	Detection is easy and no attention is required. Process control system such a QA devices and son on is in place for 100% inspection with automatic error detection and removal features.

The operational risk is ranked in order of importance based on the decision boundaries, as defined in Table 4. Mandatory corrective action plans are triggered for failure modes exhibiting $RPN > 70$ or Severity rankings $S \geq 8$. Once the

process interventions are put in place, the RPN scores are recalculated after the interventions to quantitatively confirm the effectiveness of the risk reduction.

Table 4: Risk Priority Number Rating Thresholds (RPN)

Sr#	RPN	Response
10 9	401-1000	Top priority Immediate measures required
8 7	250-400	High priority Implement measures
6 5	101-249	Moderate priority Monitor the occurrence of a failure mode and implement measures accordingly
4 3	11-100	Low priority Implement measures where time and resources allow
2 1	1-10	Accept as a remaining risk No further measures required

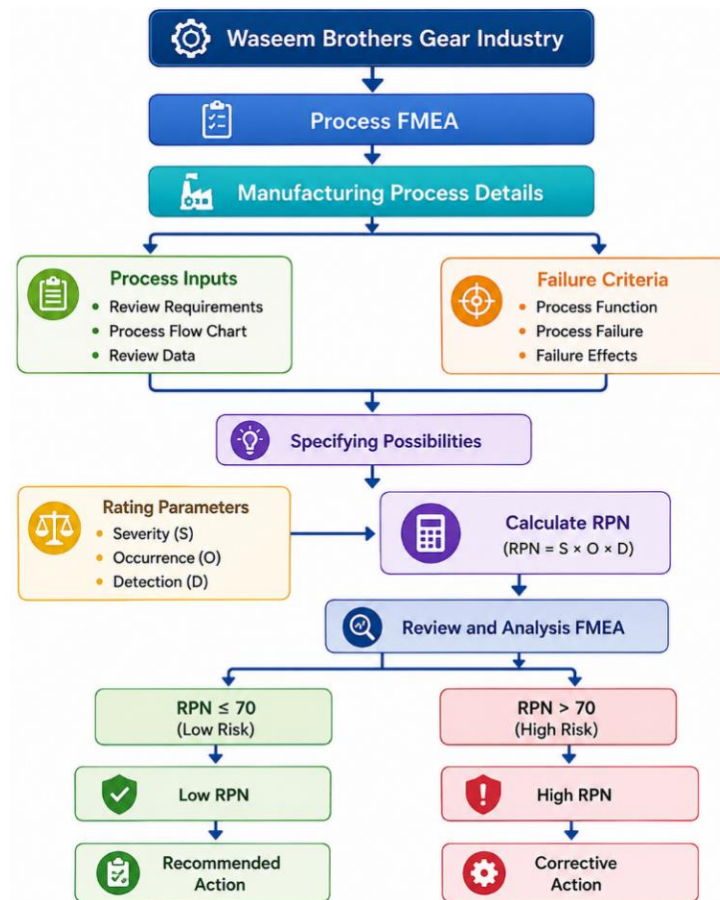


Figure 2: Tree representation of FMEA Methodology

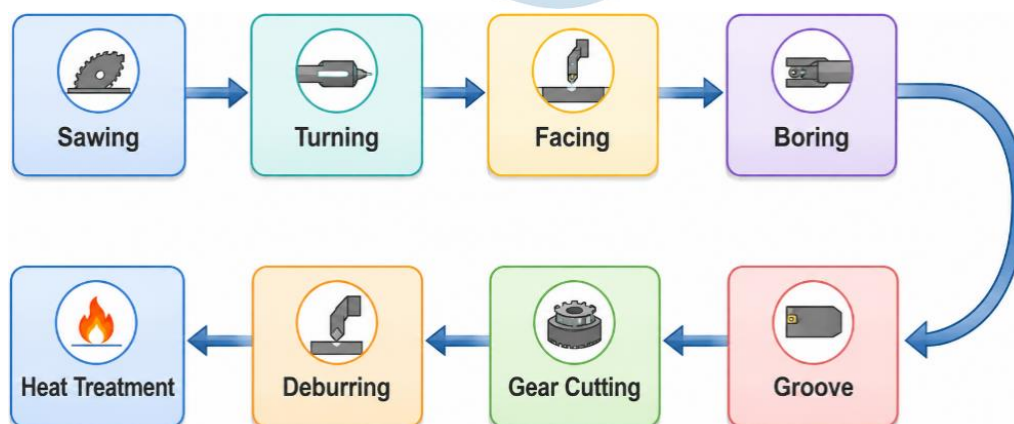


Figure 1: Manufacturing Process Flow Chart of Spur Gear

3.1 Baseline Rejection Analysis

At Waseem Brothers Gear Industry, the baseline production and rejection of quality data was captured during 12 months of monitoring. One hundred and twenty-one point one-three (12.13%)

per cent of the spur gears were rejected in a total of 4,476 produced. Of the spur gears manufactured a total of 543 were found to be defective, representing 12.13% per year rejection.

Table 5 shows the monthly rejection summary for all major manufacturing processes.

Table 5: Baseline manufacturing rejection data for spur gear production (Jan–Dec) [WU7]

Month	No of Gear	Rejection	Per . %	Corrosion Defect	Facing	Turning	Gear Cutting	Drilling	Deburring	Heat Treatment
Jan-21	365	43	11.78	8	1	4 16	2		3	9
Feb.	481	56	11.64	9	0	5	26	3	4	12
March	420	49	11.66	8	1	4 24	0		0	12
April	500	60	12	9	1	5	28	2	3	14
May	440	54	12.27	6	0	5 25	2		3	13
June	255	30	11.76	3	0	3	15	0	1	8
July	326	52	15.95	6	1	4 17	1		3	10
Aug.	354	48	13.55	7	1	3	13	2	2	10
Sep.	240	30	12.5	5	0	3 14	1		1	7
Oct.	312	36	11.53	6	1	3	16	1	0	9
Nov.	451	43	9.53	9	1	5 9	2		3	13
Dec.	332	42	12.65	7	0	4	19	1	1	10
Total	4476	543	12.13	83	7	48	222	16	24	127

3.2 Analysis of Defect Mechanisms

The physical defects observed in the different manufacturing processes are fully described in Figure 3 (a–l). High ambient humidity levels and unventilated storage conditions caused raw material storage corrosion (Figures 3a, 3b) that accounted for 83 rejected units (15.29% of total rejections). Inconsistent operator skills and dull cutting inserts contributed to non-conformities in turning and boring operations (Figures 3c–3g), as dimensional tolerances became larger than engineering specifications. This was especially true for boring operations, where bore enlargement

reached its most extreme form; a standard bore size growing from 22 mm to a defective size of 24 mm as shown in Figures 3f and 3g.

The hobbing and shaping operations resulted in the single highest share of rejects in the form of gear surface pitting, with 222 being rejected, representing 40.88% of total defect rejection rates across the production. The defect rejection rate which had the single highest number of rejects in the production line was the "gear surface pitting" defect, during the hobbing and shaping process, with 40.88% of the total defect rejection rate. The causes of this phenomenon of localized surface

pitting and distortion of the tooth profiles mostly were found to be due to the severe contact fatigue and lack of fluid lubrication and excessive wear of the cutting tool. In addition, the surface of the gear teeth was affected by the presence of micro-cracks caused by improper use of manual deburring tools, resulting in local notch effects and stress concentration zones around the edges

of the gear teeth, leading to micro-cracks. Lastly, heat treatment thermal distortion (Figure 3l) resulted from insufficient thermal dwelling time and quenching parameters, resulting in incorrect case hardness and tooth cracking in the area, and leading to 127 rejected units, accounting for 23.39% of the total rejection.

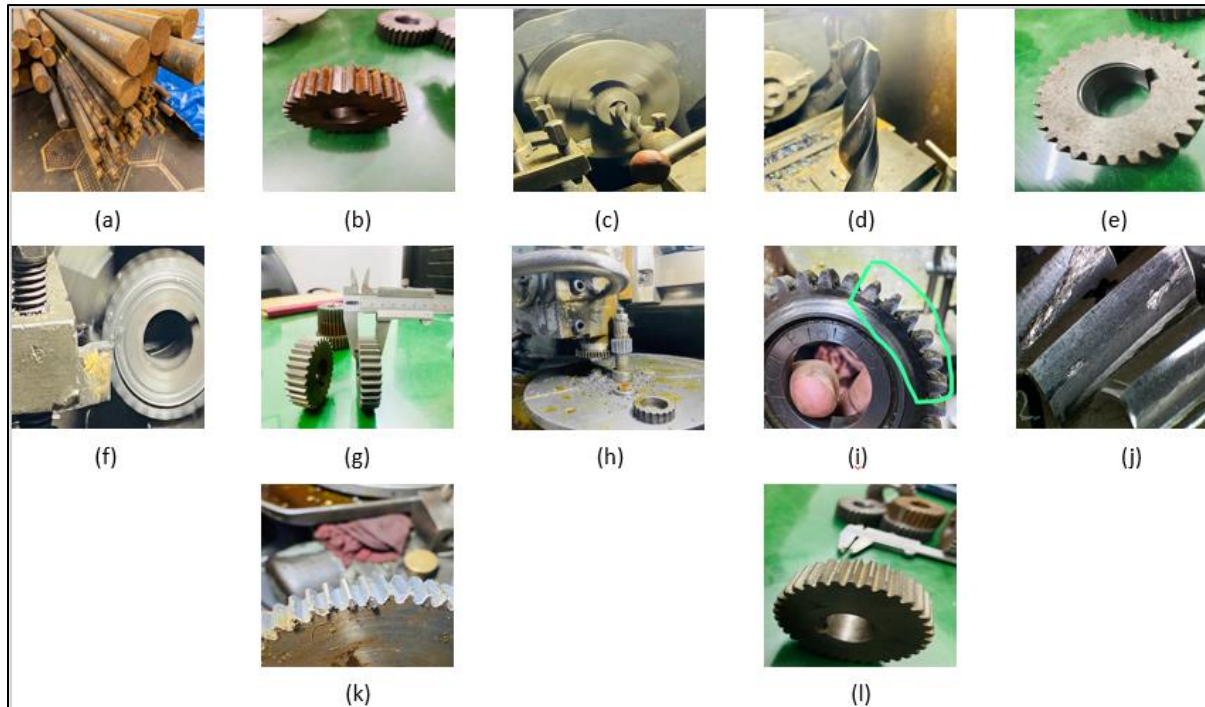


Figure 2 Pictorial Proofs of Failures (a, b): Corrosion due to improper material storage, (c, d, e): Oversized Drilling, (f,g): Oversized Truning, (h,i,j): Pitting due to improper lubrication, (k): Formation of Sharp Edges in Deburring, (i): Over Heat Treatment Fault

4. RESULTS AND DISCUSSION

4.1. Baseline Risk Priority Assessment

The potential failure modes, along with their associated causes, operational effects, and baseline Risk Priority Number (RPN) calculations are summarized in Table 6 and visually depicted in Figure 5. The baseline analysis shows that the highest critical risk is found at the gear cutting operation with the highest RPN of 240 for the entire spur gear manufacturing line. This operation is controlled with the application of high performance cutting fluid lubrication between hobbing/shaping tool and work piece in order to reduce pitting failure and tooth profile

distortion, and mandatory cutting tool replacement is applied. The heat treatment process was the second highest operational risk with a baseline RPN of 140. The control measures for heat treatment include the correct voltage settings in the furnace, the controlled immersion duration in the quench and the optimization of the fixture arrangement to avoid physical contact between the adjacent gears during thermal cycling (Figure 5). A third primary risk factor was corrosion of raw materials during storage (RPN = 75); this risk was mitigated by improving the storage facility ventilation and by mandating protective plastic covering over raw bar stock after

the completion of the raw material quality control inspection.

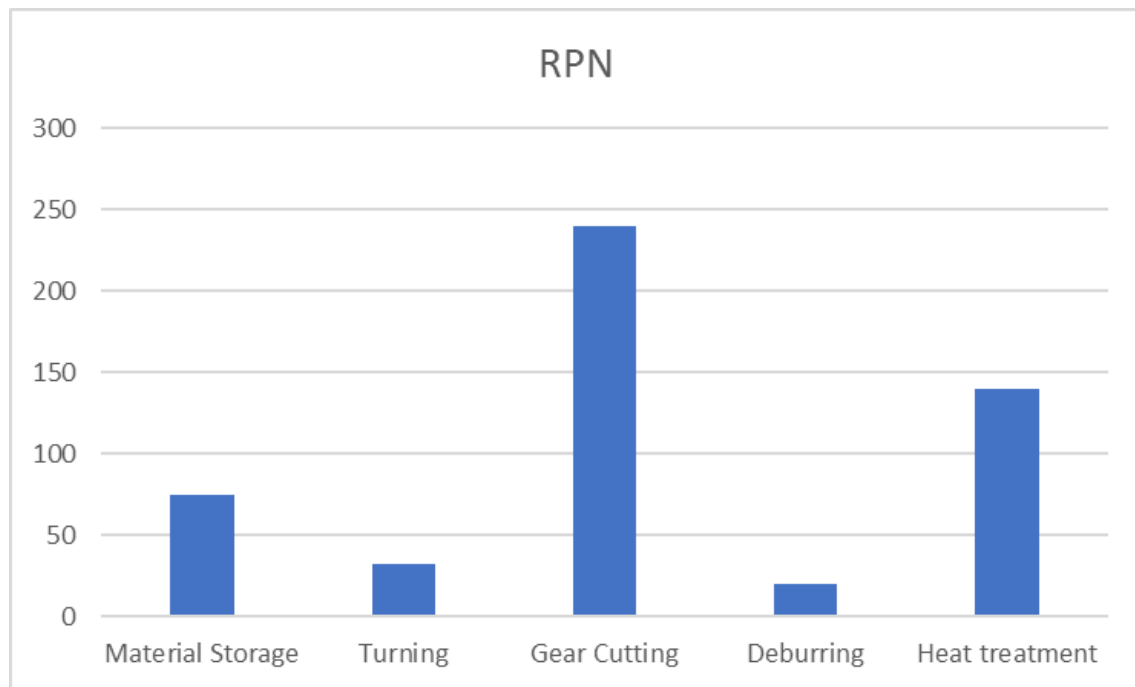


Figure 4: Graphical Representation of RPN's of Different Manufacturing Operations

4.2. Technical Discussion of Failure Mechanisms and Mitigation Dynamics

The four primary operational domains of interest are considered below to establish a comprehensive engineering foundation for the quality non-conformities observed

4.2.1. Tribological Mechanics and Micro-Pitting in Gear Cutting Operations

Gear tooth surface pitting (RPN = 240 → 80) is fundamentally a surface-initiated contact fatigue phenomenon, where the high cyclic Hertzian contact stress, σ_H , is generated during tooth meshing.

$$\sigma_H = \sqrt{\frac{F_N}{\pi w} \cdot \frac{\frac{1}{\rho_1} + \frac{1}{\rho_2}}{\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}}} \quad \text{Eq.2}$$

where F_N is the normal applied load, w is the active face width, $\rho_{1,2}$ are the radii of curvature at the contact point, $E_{1,2}$ is the Elastic Moduli, and $\nu_{1,2}$ represent the Poisson's ratios of the mating

materials. In a situation of poor fluid lubrication, elasto-hydrodynamic lubrication (EHL) film parameter falls below unity ($\lambda < 1.0$) and the lubrication regime of the contact changes from full-film to boundary lubrication. Under high shear forces, micro-cracks are formed along the pitch line due to asperity contact. Involute deviations from the tooth geometry occur in the teeth of the worn cutting tool, directing the pressure to the pitch line. The high-viscosity extreme-pressure (EP) cutting lubricants restore the fluid film parameter ($\lambda > 2.0$), which physically separates mating asperities. Concurrently, the replacement of tools according to the regulations prevents their degradation to the highest possible degree and ensures that the shear stresses caused by the friction are limited and that the occurrence of defects is reduced from $O = 6$ to $O = 2$.

4.2.2. Metallurgical Kinetics and Phase Transformations in Heat Treatment

The variations in hardness and thermal distortion (RPN = 140 → 45) are due to uncontrolled cooling gradients in the quenching part of the heat

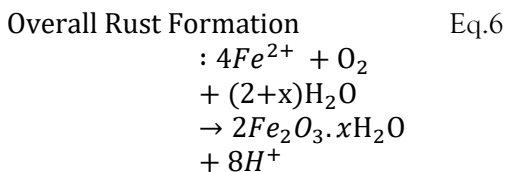
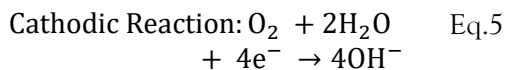
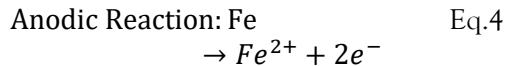
treatment. If spur gears are rapidly cooled, phase transformation from austenite (γ) to martensite (α) will be accompanied by a characteristic volumetric expansion of about 4% :



Steep thermal gradients develop at the tooth thickness (t) if there is variation in thermal dwelling times or furnace temperature profiles. Additionally, due to the contact of gears within the quench bath, localized "quenching shadows" are formed, which leads to large cooling rate differences ($\dot{T}_{\text{surface}} \gg \dot{T}_{\text{shadow}}$). This differential transformation results in a greater amount of residual tensile stress, causing dimensional distortion, localized micro-cracking and also non-uniform case depth. Uniform thermal mass distribution ($\dot{T}=\text{const.}$) is achieved with standardized dwell times, calibrated furnace thermocouples and isolated fixturing. This achieves a stabilization of the martensitic phase distribution and lowers the stress concentration in the structure from $O = 4$ to $O = 1$ and the number of occurrences.

4.2.3. Electrochemical Corrosion Kinetics in Bar Stock Storage

The mechanisms of rust and oxidation (RPN = 75 $\rightarrow$ 25) of raw materials are electrochemical corrosion processes that occur in the atmosphere. When the relative humidity (RH) in the storage area is higher than 60%, a thin layer of water forms on the steel bar surface, which is the case in unventilated areas, an active galvanic micro-cell is formed.



This forms an iron oxide film on the surface that will act as an abrasive contaminant in the turning and facing process and lead to tool wear and surface roughness non-conformancies on the gear blanks. Passive airflow ventilation keeps moisture condensation below the critical RH. Combining these two techniques, ventilation and protective polymer sheeting, provides a physical barrier to the corrosive airborne species reducing anodic dissolution and decreasing occurrence from $O = 3$ to $O = 1$.

4.2.4. Machining Mechanics and Stress Concentration in Primary/Secondary Operations

Turning & Boring Dynamics (RPN = 32): Tool deflection and excessive feed force (F_f) caused thermal expansion of cutting insert under excessive feed force (F_f) are the dimensional non-conformities governed. The use of calibrated measuring tools and fixed 3 jaws clamping makes it possible to reduce deflection and chatter vibrations. Micro-Cracks (RPN = 20): Aggressive abrasive tools can cause micro notching of gear tooth edges when deburring the gears by hand. Geometric notch theory, predicts that the stress concentration factor (K_t) increases rapidly as the notch root radius (r) decreases:

$$K_t = 1 + 2\sqrt{\frac{a}{r}} \quad \text{Eq.7}$$

Where "a" is the notch depth. To ensure smooth edge chamfer radii ($r \rightarrow \infty$), formal training of operators and mandatory re-sharpening of tools after 25–30 cycles remove the stress risers which might otherwise lead to service-life fatigue cracks.

4.3. Post-Intervention Risk Assessment

The RPN values for both turning (RPN = 32) and deburring (RPN = 20) were below the critical action value (RPN $\leq$ 70) even before process standardization was implemented, but additional reduction of operational risk was obtained by process standardization. After all corrective actions were implemented, post-intervention RPN values were recalculated (Table 7 and Figure 5). The overall effectiveness of the PFMEA framework was demonstrated by all process steps showing significant risk reduction with all

processes operating within acceptable quality limits.

Table 6: Calculation of RPN using severity, occurrences, and detection rankings

Operation Description	Potential Failure	Effect	Cause	Severity	Occurrences	Detection	RPN
Material Storage	Corrosion and rust due to high humidity	Reduced level of performance or function	High humidity storage, no proper ventilation	5	3	5	75
Turning	Turning of some pieces are oversize & some are undersize	Difficult in assembly due to oversize, Subsequent operation problem	Operator fault, Tool sharpness issue, Improper mounting	8	2	2	32
Gear Cutting	Surface pitting and fatigue failure of the gear tooth	Loss of performance or function, large portion of product have to be reworked	Operator fault, Gear cutting tool issue, improper lubrication,	8	6	5	240
Deburring	Sharp edges become areas where internal stresses concentrate	Quality issues or gear tooth damage	Operator fault, using of improper tool for deburring operation	5	2	2	20
Heat treatment	Hardness greater or less than required	Function problem, Gear tooth crack,	Temperature time problem, conveyor speed	7	4	5	140

By standardizing the process, the operational risk was lowered further, as was the baseline RPN value for turning (RPN = 32) and deburring (RPN = 20), which were already lower than the critical action threshold (RPN≤70). To overcome the dimensional variations, calibrated precision measuring instruments, standard layout marking tool and formal operator training on rigid chuck clamping technique were adopted for turning operation. In deburring operations, defects were reduced by setting up regular schedules of tool inspection for re-sharpening or replacement of the

tool (after every 25 to 30 processed units) and educating the operators about the classification of edge-chamfers. The post-intervention RPN values were then computed after the corrective actions listed in the table below were implemented (Table 7 and Figure 6). The reduction of all the risks associated with the various steps of the process allowed all the operations to be conducted within acceptable quality ranges and the overall effectiveness of the PFMEA framework was validated.

Table 7:Recalculation of RPN after applying recommended actions

Operation Description	Potential Failure	Effect	Cause	Recommended action	Severity	Occurrences	Detection	RPN
Material Storage	Corrosion and rust due to high humidity	Reduced level of performance or function	High humidity storage, no proper ventilation	Giving Proper ventilation to material storage area, covering the material by plastic sheets	5	1	5	25
Turning	---	---	---	---	---	---	---	---
Gear Cutting	Surface pitting and fatigue failure of the gear tooth	Loss of performance or function, large portion of product have to be reworked	Operator fault, Gear cutting tool issue, improper lubricant,	Use proper lubricant and sharp gear cutting tool use	8	2	5	80
Deburring	---	---	---	---	---	---	---	---
Heat treatment	Hardness greater or less than required	Function problem, Gear tooth crack,	Temperature time problem, conveyor speed	Parameter inspection, hardness test, thermocouple	7	1	5	45

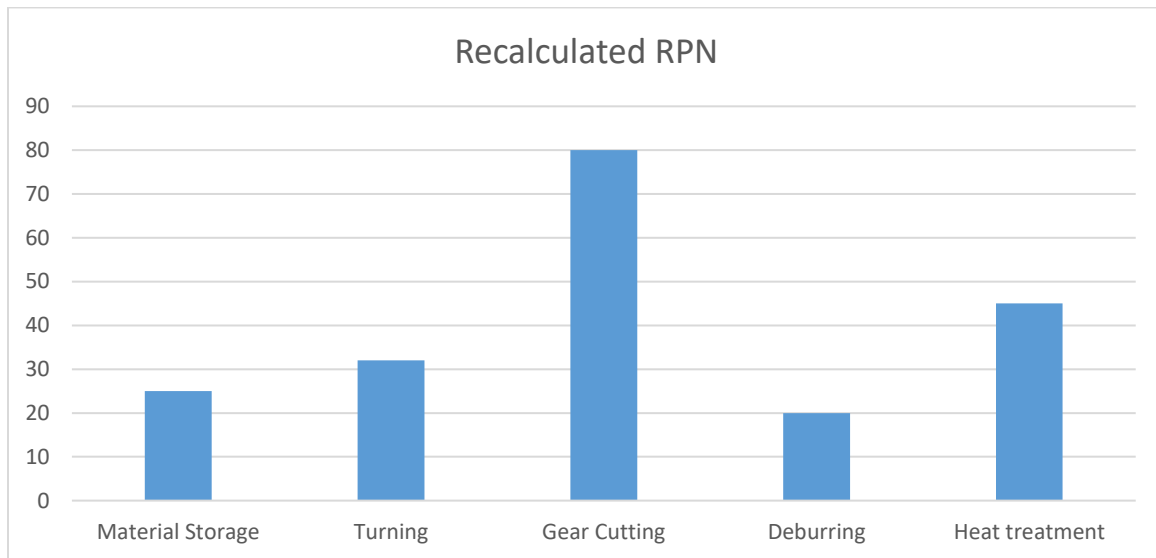


Figure 3: Graphical Representation of re-calculated RPN against different manufacturing processes in gear manufacturing

5. CONCLUSION

The study showed that Process Failure Mode and Effects Analysis (PFMEA) could be applied effectively to improve the quality control and reliability in the manufacturing process of spur gears. Initial evaluations showed that the 10 highest operational risks (RPNs) were: gear cutting (RPN = 240), heat treatment (RPN = 140), and material storage corrosion (RPN = 75). Incorporating specific engineering solutions to the problems, including high concentration fluid lubrication, planned cutting tool maintenance, controlled heat treatment cycles by thermocouple, and enhanced storage ventilation by covering cutting tool boxes, all operational risks were lowered to acceptable levels during all essential processes. Further quality improvements on the shop-floor were achieved by additional process improvements for turning and deburring. The expert-led PFMEA framework, overall, was able to help the facility to keep the manufacturing rejections to a minimum, which helped the facility meet the strict industrial quality standards and improve customer satisfaction and their competitive market share in the market.

6. FUTURE SCOPE OF WORK

The present research on improving the manufacturing process of spur gears using Failure Mode and Effects Analysis (FMEA) opens up several avenues for future exploration and development. Some potential areas for future research and application include: In the current study, the manufacturing of spur gears was taken as the target industry.

The use of FMEA, however, can be expanded to other manufacturing industries; like automotive, aerospace, and machinery, to improve the reliability and quality of a range of components and products. Advanced technologies like artificial intelligence (AI), machine learning (ML), and data analytics could be integrated with FMEA for future research. The technologies can aid in automating the FMEA process, process large databases of data and offer real-time information for ongoing improvement in manufacturing processes. Although the current research was oriented on failures that occurred during the manufacturing process, future studies should be expanded to incorporate failures that occur due to other factors, including design, material selection, assembly, and maintenance. This extensive review will help to understand failure modes and their impact more comprehensively and improve the

product's performance and durability. The use of FMEA in conjunction with other quality control and process improvement tools, such as Six Sigma or Lean Manufacturing, could be considered. Combining FMEA with these methodologies could provide a more holistic approach to optimize the manufacturing process of spur gears, identify potential failure modes, and implement preventive measures effectively.

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