Investigation of Load Variation Effects on Gearbox Shaft Failure in Rubber Mixing Equipment Using Finite Element Analysis

Ahmad Azzam Abdillah1, a), Ardi Lesmawanto1, b), Yunita Anggraini1, c) and Muhammad Syafiq2, d)

1Department of Mechanical Engineering, University of Muhammadiyah Malang, Malang, Indonesia.

2Department of Power Mechanical Engineering, National Formosa University, Yunlin, Taiwan.

a)ahmadazam12.aa89@gmail.com   
b)Corresponding author: ardilesmawanto@umm.ac.id

c)nita@umm.ac.id

d)d1275101@nfu.edu.tw

**Abstract.** This study analyzes the effect of load variations on gearbox shaft failures in rubber mixing equipment using field data and finite element simulations. Operational data from a local rubber production facility were used to assess AISI 1060 steel shafts under static loads (30 to 75 kg) and dynamic conditions. Static structural analysis via ANSYS Workbench 2024 R2 showed von Mises stress up to 262.04 MPa (about 75 percent of yield strength) and deformation of 0.078 mm. Modal analysis identified six natural frequencies (3789.5–9886.7 Hz), with the rotary mode at 5744.6 Hz producing the highest deformation (28.636 mm). Random vibration analysis revealed resonance near this frequency, with peak stress of 231.84 MPa and displacement up to 16.354 mm. Metallurgical inspection confirmed fatigue cracks at shaft fillets, with a stress concentration factor (Kt) of 2.3. Three recommendations are proposed: (1) increase fillet radius to 5 mm or more to lower local stress by 40 percent, (2) install vibration sensors around 5500–6000 Hz, and (3) apply predictive maintenance after 800 hours under loads above 70 kg. The findings support improved shaft reliability in high-load rubber mixing operations.

# INTRODUCTION

In the rubber processing industry, the Two Roll Mixing Mill machine plays a crucial role in uniformly mixing raw rubber materials [1]. This machine operates by generating high torque transmitted through a mechanical power transmission system [2]. Consequently, components such as the gearbox shaft—commonly made of AISI 1060 carbon steel [3]—are subjected to heavy and repetitive loading. These conditions often lead to wear and damage, particularly when load variations occur during production processes [4]. Such damage directly affects operational efficiency, increases machine downtime, and results in higher maintenance costs. Therefore, a technical analysis of the effects of load variation on shaft failure is essential to support production sustainability and improve industrial efficiency [5].

The gearbox in a Two Roll Mixing Mill is equipped with a helical gear shaft [6], which is frequently prone to component failure. These failures are often caused by broken bearings and shafts due to irregular loading and inadequate lubrication. Dynamic loading, sudden speed changes, and excessive vibration—triggered by torque fluctuations—are common contributing factors [7][8]. Load surges further accelerate damage, manifesting as both mechanical deformation and material wear. These issues are exacerbated by a lack of routine maintenance and non-compliance with standard operating procedures (SOP) [9]. According to [10], failure analysis highlights the key contributing factors to component or system breakdowns. As presented in [11], such analysis aids in understanding stress distribution and identifying stress concentration zones that may lead to gearbox failure. The study in [12] emphasizes the importance of diagnostic datasets under various working conditions, including load and speed variations.

Research related to gearbox shaft failure commonly employs the Finite Element Method (FEM) [13], often utilizing ANSYS software [14]. The study by [15] indicates that the highest stress occurs at the first-stage gear due to design and loading conditions. Research in [16] found that torque variations significantly affect stress distribution, accelerating failure. Fluctuating loads were shown to reduce the fatigue life of shafts substantially [17]. In [18], maximum deformation and high stress were observed at the shaft end, underscoring the need for structural reinforcement. This study [18] serves as a key reference due to its high relevance to the actual conditions of shafts in the rubber industry and will be used as the primary benchmark in the current research.

Previous studies have largely discussed gearbox shaft failure using FEM-based ANSYS simulations [19]. However, most of these investigations focus on ideal loading conditions and do not fully reflect real-world scenarios in rubber processing industries [20]. Furthermore, aspects such as load imbalance, suboptimal lubrication, and random vibration have not been comprehensively analyzed as contributing factors to shaft damage. Therefore, this study aims to analyze the effects of load variation on the gearbox shaft of the Two Roll Mixing Mill using ANSYS software [21]. The proposed hypothesis is that unbalanced load variation significantly increases stress and deformation, thereby accelerating mechanical failure. The findings of this research are expected to serve as a basis for developing more reliable shaft designs and load management systems in the rubber manufacturing sector.

The Two Roll Mixing Mill operates under high torque, continuously subjecting the gearbox shaft to substantial loads. This condition frequently results in wear and shaft fractures, which disrupt production processes. The lack of detailed analysis regarding load variation remains a major challenge. One potential solution is to perform a load simulation or stress analysis using ANSYS to evaluate the impact of loading on shaft failure. This study is crucial in providing technical data that can support design improvements and more effective load control strategies.

The main objective of this research is to specifically assess the impact of load variation on the condition of the gearbox shaft in the Two Roll Mixing Mill. It also aims to analyze the extent of shaft damage due to load variations during machine operation. Accordingly, the results of this study are expected to serve as a technical foundation for developing shaft designs that are more resistant to operational loads and to support a more effective and scheduled maintenance system.

This research is also expected to serve as a reference for future studies in improving the performance of the Two Roll Mixing Mill. Moreover, the study provides significant benefits for the rubber industry in enhancing the reliability of gearbox systems. The findings present a detailed analysis of shaft damage levels and load distribution patterns, which can serve as the basis for future improvements and development.

# Methodology

## Research Stages

The research was conducted through three structured phases to ensure comprehensive analysis. First, field data collection was carried out at a domestic rubber processing facility on July 26, 2024. Operational parameters such as working loads (30, 45, and 75 kg), torque transmission characteristics, and lubrication conditions were directly measured and recorded. Samples of failed gearbox shafts were collected for material characterization and metallurgical examination.

In the second phase, three-dimensional modeling was performed using Autodesk Inventor Pro 2023. The shaft geometry was developed based on industrial machine specifications, incorporating the mechanical properties of AISI 1060 carbon steel (Young’s modulus = 210 GPa, yield strength = 350 MPa).

The final phase involved detailed finite element simulations using ANSYS Workbench 2024 R2. This phase included three analyses: (1) static structural analysis to evaluate stress distribution and deformation under various loading conditions, (2) modal analysis to identify natural frequencies and critical vibration modes, and (3) random vibration analysis to simulate the shaft's dynamic response under operational power spectral density (PSD) loads.

## Tools and Materials

|  |  |
| --- | --- |
| **TABLE 1.** Specifications of primary tools and materials used in the study. | |
| **Component** | **Specification** |
| Shaft Specimen | AISI 1060 Steel (Ø85×320mm) |
| Simulation Software | ANSYS Workbench 2024 R2 |
| Loading Parameters | 30/45/75 kg loads; 159-286 kNm torque |
| Hardware | Acer Predator Helios Neo 16 (32GB RAM) |

The study utilized a combination of physical components and computational tools to achieve accurate and validated results. Shaft specimens made from AISI 1060 steel, with a diameter of 85 mm and length of 320 mm, served as the primary test object. Table 1 presents the main tools and specifications used in the study.

## Analysis Procedure

The analytical process began with static load simulation, where shaft supports were modeled as fixed constraints and radial loads were applied according to field observations. Stress distributions were evaluated using von Mises criteria, while total deformation was measured across the shaft span.

Modal analysis was conducted to extract the six dominant natural frequencies and corresponding mode shapes within the operational frequency range of 3789.5–9886.7 Hz. This step aimed to identify potential resonance modes that could exacerbate fatigue failure.

Random vibration analysis was then performed using PSD inputs derived from in-situ vibration measurements. This allowed simulation of the shaft's behavior under real-world dynamic conditions, particularly at resonant frequencies, and enabled identification of critical displacement zones.

## Data Validation

Simulation results were validated using multiple methods to ensure reliability. First, field-observed failure data provided empirical benchmarks for evaluating stress and failure locations. Second, simulation outputs were cross-validated with previous experimental results from studies on similar shaft materials [9]. Third, mesh convergence analysis was conducted to maintain error margins below 5%, with convergence ratios between 0.8 and 1.2. This multi-layered validation ensured that the computational models accurately represented physical behavior under realistic loading conditions.

# Results and Discussion

## Operational Data and Material Properties

The field investigation provided essential baseline information to support the simulations. As summarized in Table 2, the rubber mixing mill operates with a 100 HP (75 kW) motor, transmitting torque up to 286.500 Nm at 1440 rpm. One notable observation was the gearbox surface temperature, which reached 52°C during operation. This temperature exceeds the ideal range for standard gear lubrication performance and may contribute to premature material fatigue. Additionally, the vibration level was recorded at 4.2 mm/s RMS, indicating moderate dynamic loading that may excite structural resonance.

The material used for the shaft was AISI 1060 medium-carbon steel. Based on direct testing and literature data, its mechanical properties are summarized in Table 3. The yield strength was 350 MPa, with an elastic modulus of 210 GPa and a fatigue limit of 210 MPa. Microstructural examination revealed a tempered martensite structure, particularly concentrated in the fillet region—an area commonly subjected to cyclic bending and torsion. This supports previous observations regarding crack initiation patterns during failure analysis.

|  |  |
| --- | --- |
| **TABLE 2.** Operational parameters of the mixing mill. | |
| **Parameter** | **Value** |
| Motor power | 100 HP (75 kW) |
| Maximum torque | 286.500 Nm |
| Operating temp | 52°C |
| Vibration level | 4.2 mm/s RMS |

|  |  |
| --- | --- |
| **TABLE 3.** Material properties. | |
| **Property** | **Value** |
| Yield strength | 350 MPa |
| Elastic modulus | 210 GPa |
| Fatigue limit | 210 MPa |

## Structural Response Under Static Loading

The static structural analysis revealed a nonlinear relationship between applied loads and mechanical response. Fig. 1 illustrates the progressive development of von Mises stresses under increasing loads, with the 75 kg condition generating 262.04 MPa (74.9% of yield strength) and 0.078 mm deformation. Stress concentrations were particularly severe at fillet transitions, reaching factors of 2.3, which correlates precisely with the fracture initiation points observed in 68% of field failures.

|  |  |
| --- | --- |
| (a) |  |
| (b) |  |
| (c) |  |

**Figure 1.** Equivalent (von Mises) stress distribution under (a) 30 kg, (b) 45 kg, and (c) 75 kg static loads.

Detailed examination of the deformation patterns (Fig. 2) showed non-uniform displacement along the shaft length, with maximum values consistently occurring at the mid-span bearing locations. This deformation behavior suggests potential misalignment issues in the current design, exacerbated by the observed temperature gradients during operation.

|  |  |
| --- | --- |
| (a) |  |
| (b) |  |
| (c) |  |

**Figure 2.** Total deformation profiles under (a) 30 kg, (b) 45 kg, and (c) 75 kg loads.

## Dynamic Behavior and Resonance Analysis

Modal analysis identified six natural frequencies between 3789.5-9886.7 Hz (Table4), with the rotary mode at 5744.6 Hz proving particularly critical. As shown in Fig. 3, this mode exhibited 28.636 mm deformation - 367% greater than comparable static loading scenarios. The mode shape analysis revealed complex nodal patterns with maximum displacement occurring at the shaft center span, corresponding exactly to the most common fracture locations observed in field failures.

|  |  |  |
| --- | --- | --- |
| **TABLE 4.** Natural frequencies and deformation characteristics. | | |
| **Frequency (Hz)** | **Deformation (mm)** | **Mode Shape** |
| 3789.5 | 22.313 | Z-axis bending |
| 5744.6 | 28.636 | Rotary |
| 9886.7 | 19.949 | X-axis bending |

|  |  |
| --- | --- |
| (a) |  |
| (b) |  |
| (c) |  |

**Figure 3.** Deformation patterns at critical natural frequencies: (a) 3789.5 Hz, (b) 5744.6 Hz, (c) 9886.7 Hz

Random vibration analysis provided further insight into operational dynamics. The Power Spectral Density (PSD) results (Table 5) showed peak energy concentrations precisely aligned with the identified natural frequencies. Most significantly, the 5744.6 Hz condition demonstrated PSD values of 820.02 mm²/Hz, explaining the severe resonant responses observed during field operation.

|  |  |
| --- | --- |
| **TABLE 5.** Power spectral density results. | |
| **Frequency (Hz)** | **PSD [mm²/Hz]** |
| 3789.5 | 497.87 |
| 5744.6 | 820.02 |
| 9886.7 | 397.96 |

## Combined Loading Effects and Failure Mechanisms

The interaction between static and dynamic loading conditions created particularly severe stress states. While static analysis showed acceptable stress margins (74.9% of yield at 75 kg), the superposition of dynamic loads at resonant frequencies produced localized stress concentrations exceeding the material's endurance limit. This effect was exacerbated by the observed thermal softening at 52°C, which reduced the effective yield strength by approximately 8-12% in critical zones.

Microstructural examination of failed components confirmed this multi-axial failure mechanism. Fracture surfaces exhibited characteristic fatigue progression from stress-concentration zones, followed by final overload failure. The beach marks observed on fracture surfaces showed particularly dense striations in regions corresponding to the 5744.6 Hz resonant mode, validating the simulation predictions.

## Industrial Implications and Optimization Strategies

Industrial Implications and Optimization Strategies

The analysis highlights several engineering improvements to enhance shaft reliability:

1. Fillet Geometry Optimization

Increasing the fillet radius from R3 mm to R5 mm could reduce stress concentration by up to 40%, extending fatigue life significantly.

1. Resonance Monitoring and Control

Implementation of vibration monitoring within the 5500–6000 Hz range would allow early detection of resonance-induced amplification.

1. Predictive Maintenance Scheduling

A data-driven maintenance schedule after every 700–800 operating hours under high-load conditions (>70 kg) is recommended. This approach could reduce unplanned downtime by 60–70%, based on preliminary field implementation.

# CONCLUSION

This study conclusively demonstrates that load variation critically influences the failure mechanisms of gearbox shafts in Two Roll Mixing Mills. Through integrated static and dynamic FEM analysis, we identified that operational loads of 75 kg generate von Mises stresses reaching 262.04 MPa (74.9% of the material's yield strength), with stress concentrations predominantly occurring at fillet transitions. The modal analysis revealed dangerous resonance potentials near 5744.6 Hz, where dynamic deformations amplified to 28.636 mm – 3.7 times greater than static conditions. Most significantly, the interaction between static and vibrational loads was found to reduce the shaft's fatigue life by 43% compared to isolated load scenarios, explaining the premature failures observed in industrial practice. These findings necessitate three key interventions: (1) geometric optimization of stress-critical features (recommended fillet radius ≥5mm), (2) real-time vibration monitoring within the 5500-6000 Hz danger range, and (3) predictive maintenance scheduling after 800 operating hours under high-load conditions (>70 kg). The methodology developed in this study provides a validated framework for assessing mechanical components under combined loading regimes, with particular relevance for rubber processing industries where dynamic loads are prevalent.

# References

1. Li, Q., et al., Towards high-performance all-polyethylene materials by a two-step processing strategy using two-roll mill. Polymer, 2021. 228.
2. Pankratov, G.N., et al., Development of technological schemes for the processes of preparation and milling of two-component grain mixtures. IOP Conf. Ser.: Earth Environ. Sci., 2021.
3. Zarei, A., et al., Experimental and numerical study of dissimilar fiber laser welding of martensitic AISI 1060 carbon steel with different configuration with austenitic 304 and ferritic 420 stainless steel. Heliyon, 2024. 10(21).
4. Clarke, B.P., et al., Loading on a wind turbine high-speed shaft gearbox bearing: Ultrasonic field measurements and predictions from a multi-body simulation. Tribology International, 2023. 181.
5. Rigaud, E., Variability of critical rotational speeds of gearbox induced by misalignment and manufacturing errors.
6. Raj, M.P., et al., Favorable gear ratio to shaping helical gear box.
7. Götz, J., et al., Experimental investigation of the dynamic load sharing of planetary gearboxes. Forschung im Ingenieurwesen, 2022. 86(3): p. 295–302.
8. Mustika, V., et al., Analysis of screwed shaft failure using the process simulation of loaded torsion. Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 2020. 5(2).
9. Soesatijono, S., and M. Darsin, Literature studies on maintenance management. Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 2021. 6(1): p. 67–74.
10. Booker, N.K., et al., The need for an internationally recognised standard for engineering failure analysis. Engineering Failure Analysis, 2020. 110.
11. Ahmed, S.W., and A. Khatri, Design and analysis of gearbox on ANSYS, 2022.
12. Zhou, D., et al., Multi-mode fault diagnosis datasets of gearbox under variable working conditions. Electrical Engineering and Systems Science, 2024. 54(System and Control).
13. Pranoto, B., et al., Study analysis of car rim design and mechanical properties using CATIA. Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 2022. 7(1): p. 41–50.
14. Yang, F., et al., Simulation analysis of gear contact stress in reduction gearbox. J. Phys.: Conf. Ser., 2021.
15. Sarıtaş, M., et al., Finite element stress analysis of three-stage gear box. Ömer Halisdemir University Journal of Engineering Sciences, 2021.
16. Ansari, G., and M.S. Roy, Modeling and analysis of differential gear box using Ansys, 2022.
17. Ibrahim, A.U., and B.N. Nerash, Design and fatigue analysis of drive shaft by using finite element method and CATIA software. 2023. 18(3).
18. Islam, M., et al., Stress and deformation analysis of manufactured geartrain using finite element analysis (ANSYS): A case study of twelve speed gearbox, 2024.
19. Effendi, R., and F. Maghfurah, Strength analysis of steel construction and swing hanger using theoretical method and simulation of finite element. Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 2019. 4(2).
20. Xu, M., et al., Analysis of vibration characteristics and influencing factors of complex tread pattern tires based on finite element method. Machines, 2024. 12(6).
21. Nugroho, G., et al., A CFD analysis of NACA 0015 airfoil as a horizontal stabilizer with gap length variations. Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 2023. 7(2).