Performance Assessment and Failure Mechanisms of Roller Bearings Using Dual Material Comparison

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***Abstract*:** This study presented the performance and failure mechanisms of roller bearings for structural steel and AISI 52100 alloy steel under various operating conditions. It emphasizes how material properties affect stress, deformation, and thermal performance according to simulations carried out in ANSYS Workbench. Results clearly present that AISI 52100 alloy steel exhibits better strength against stress, dimensional stability, and thermal efficiency compared with structural steel. Key factors contributing to the bearing's failure included high tightening axial force, vibration, and temperature, with spalling and wear as the dominant modes of failure. The improvement in performance further came through dimensional changes reducing stress and deformation. The whole research highlights the need for attention to material selection and axial force control while designing roller bearings to be reliable and efficient. Findings of the present study may thus advocate for the use of AISI 52100 alloy steel in applications requiring high performance and durability. Future studies might look at advanced materials and optimized designs to further advance bearing reliability under demanding conditions.

Keywords: Roller bearings, AISI 52100 alloy steel, structural steel, stress analysis, deformation, thermal performance, failure mechanisms, axial tightening force, spalling, wear, ANSYS Workbench, material comparison, dimensional modifications.

I. INTRODUCTION

Roller bearings are an integral part of mechanical systems, providing frictionless rotational motion between moving parts under load. They are highly important for achieving efficiency, reliability, and longevity in machinery and equipment applications; be it industrial, automotive, or aerospace [1]. Roller bearings directly affect the overall operational stability of a mechanical system due to their ability to tolerate various loads, vibrations, and different thermal conditions without failure. Poor bearing performance can lead to increased wear, energy loss, and even catastrophic system failures, and for this reason, it necessitates usage of robust materials and designs. Notably, the need for understanding and optimization in roller bearings marks an essential step for promoting efficiency in mechanical systems and reducing maintenance costs [2].

Overloads or improper distribution of loads are among the causes of roller bearing failures. The bearings are designed to work within specified load limits, and conditions above such limits may result in surface fatigue, material deformation, or even fracture [3]. Static overloads are likely to bring about indentations or cracks on bearing surfaces, whereas dynamic overloads could result in rolling contact fatigue with spalling and pitting. Even within acceptable load ranges, improper load alignment can induce uneven stress distribution, thereby increasing wear and reducing bearing lifespan. Vibrations cause significant roller bearing impacts, which may lead to premature wear and structural damage. Such vibrations may build up micro-movements within the bearing, thus causing fretting corrosion and damaging surfaces. Among the causes of dynamic instability, resonant vibrations or irregular frequency loads can cause misalignment, along with localized stresses on the bearing components [4]. Additionally, excessive vibration accelerates the breakdown of lubrication films, which results in increased friction and heat generation, which finally leads to bearing failure.

Roller bearings suffer considerably under both high and low operating temperatures. The former causes the lubricant to break down in viscosity and effectiveness, thereby increasing friction and abrasive wear. Substantial heat exposure may also result in thermal expansion where clearances within the bearing are altered, which might lead to seizure [5]. It follows that low temperatures render the lubrication fluid less workable, thereby raising resistance and the possibility of embrittlement of materials, which would crack under stress. The three influences of load, vibration, and temperature combine to increase the probability of bearing failure. For instance, high loads

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create frictional heat, and vibrations tend to churn the lubricant, reducing its ability to counteract thermal effects. These factors working together accelerate material fatigue and lubrication breakdown, so bearings need to be designed with such conditions in mind. Understanding these failure mechanisms and resolving them are necessary to increase the reliability and performance of bearings in demanding applications.

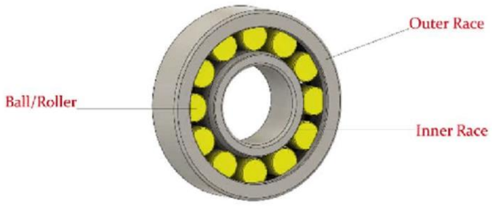


Figure 1 Roller-bearing structure [6]

Figure 1 represents roller bearing which is a popular kind of rolling-element bearing used to minimize friction between moving parts. It has an inner race (the inner ring which rotates with the shaft), and then there is an outer race (the stationary outer ring), to which balls or rollers (yellow) are placed between the two races to bring about smooth rotating with minimal friction.

A. Rationale for comparing two different materials.

Critical in understanding the impact of material properties on bearing performance under different operating conditions is a comparison of two different materials in roller bearings. Mechanical, thermal, and tribological properties differ across various types of materials, thus showing how each is likely to respond to stresses like load and vibration at temperatures. The differences are studied, and this study identify a material that is better than the other in durability, efficiency, and wear resistance, thereby allowing optimization of bearing designs for specific applications. Such a comparison also enables the identification of the trade-off between performance, cost, and manufacturing feasibility [7]. One might have very good mechanical strength and handle high loads in some material, whereas other material could perform better at elevated temperatures for enhanced thermal stability. Thirdly, some may offer better lubrication compatibility or even more robust resistance to vibration-induced fatigue. The comparison of these materials under the same controlled experimental conditions brings them nearer to understanding relative strengths and weaknesses and helps make more informed decisions when selecting materials for demanding environments.

Material comparison also assists in addressing the changing requirements of the industry for sustainable and high-performance components [8]. Increasing the demand for lightweight and energy-efficient designs would necessitate comparisons between traditional materials and alternative advanced materials. Such rationale guarantees that selection based on theoretical property values is further reinforced by evidence based on experience and practice, a guarantee for reliability and performance optimization in actual applications.

B. Types of rolling bearings

Ball Bearings: These are deep groove ball bearings, designed for significant capabilities in both radial and axial loads with good high speed and low friction characteristics. They are well suited for electric motors and gearboxes. Angular contact ball bearings are manufactured for application with combined axial and radial loads, for loads in one direction, and have a common application for high precision applications including machine tools and pumps. Self-aligning ball bearings are suitable for offsetting angular misalignment in shafts [9]. Systems with such alignment deviation can operate reliably. Here, there are versatile solution variants for mechanical applications.

Roller Bearings: Cylindrical roller bearings are designed particularly for radial loads with high-speed applications, used in gearboxes and compressors. The spherical roller bearings can withstand heavy radial and axial loads; they are more commonly used in demanding conditions such as mining and construction equipment. Tapered roller bearings efficiently bear radial loads along with axial loads, used in automotive and industrial applications [10]. Compact in construction and of high load-carrying capacity, needle roller bearings are often used for transmissions and steering systems to provide efficient performance in space-constrained applications.

Thrust Bearings: Ball thrust bearings are designed to take axial loads in low-speed operations with smooth operation and the reliability of turntables or swivels [11]. Roller thrust bearings, however, are designed with a higher load carrying capacity and are often used in heavy machinery and turbines where high performance through substantial force is required.

Specialized Bearings: Precision bearings are designed to operate with high accuracy and speed; they are ideal in demanding applications such as aerospace and robotics. Magnetic bearings are appropriate for high-speed and clean environments, as they do not have physical contact and work through magnetic fields [12]. Hybrid bearings have steel races and use ceramic rolling elements that result in reduced friction and higher durability and thus offer longer operational lifetimes, making them suitable for the high-performance and specialty applications.

II. LITERATURE REVIEW

The significance of rolling bearing problem detection for increasing production efficiency and lowering accident rates in intricate mechanical systems was underlined by **Hakim, M. et al. (2023) [13].** Large volumes of monitoring data did, however, provide a barrier to the fault diagnostic methods that are now in use. A potential method for identifying intelligent bearing problems, deep learning is currently one of the most explored topics in the industry. Giving a thorough overview of Deep Learning (DL) based on bearing fault diagnosis is the goal of this study. Convolutional neural networks, recurrent neural networks, autoencoders, and generative adversarial networks are the most popular deep learning algorithms for identifying bearing flaws. It summarizes, categorizes, and explains a number of works on the topic while talking about various transfer learning designs and pertinent theories. The applications and issues in the field of study are also addressed.

According to **Kumar, N., & Satapathy, R. K. (2023) [14],** bearing failures in crucial aerospace applications persisted in spite of in-depth research and improvements in materials and production techniques. Instead of using a comprehensive and holistic approach, the material and processing components of bearing—which are frequently secondary—become the main focus of the study. As a result, in contrast to traditional failure analysis, this study critically investigates possible problems with functionality, operation, high DN (diameter × rpm) scenarios, slide, skid, and fatigue distress, and atypical assembly configurations that result in opposing inputs to the rolling parts. In aeroengine bearings when both races revolve, a contra-rotating bearing can lessen the impact of conflicting inputs. It covers both traditional and cutting-edge ideas. Additionally, a short on common and atypical bearing materials is provided. A number of methods for diagnosing faults and tracking bearing health are described. To enhance design, material selection, manufacture, and analysis, bearing life testing is required. The aerospace sector chooses B1.0 life, even though Weibull analysis is more commonly used to predict the B10 life of bearings across industries. A synopsis of potential future developments is also provided. In order to prolong life and reduce failures, this study attempts to provide an application viewpoint on aerospace bearings.

According to **Pan, C. et al. (2023) [15],** roller bearings are a common part of contemporary technology. Small friction, low starting torque, good rotation accuracy, low power loss, and high efficiency are some of its benefits. Research on the construction and operation of novel roller bearings is helpful in enhancing bearing performance. As a result, the latest work needs to be analyzed and summarized. Goal: A summary of recent research on roller bearings yields some useful findings that can be used to forecast future advancements in the field and serve as a reference for future research in related areas. Methods: This study compiles the typical patents pertaining to roller bearings, such as needle rollers, spherical, cylindrical, and tapered roller bearings.

These roller bearings' benefits and drawbacks are examined. Analysis is done on how these bearings' unique construction affects their performance. Results: The studies of the patents pertaining to roller bearings provide a summary of the current issues. It is anticipated that new roller bearing patents will be created in the future. In conclusion, the precision and dependability of the entire apparatus are increased by optimizing the roller bearing construction. The roller bearing structure must be continuously improved in accordance with the real working conditions, with a particular focus on bearing structure simplification. There will be an increasing number of new bearings developed in the future.

According to **Li, J., Luo, W., & Bai, M. (2024) [16],** rolling bearings are essential parts that are prone to malfunctions while rotating machinery is in use. Thus, it is crucial to correctly diagnose the condition of rolling bearings. With a focus on three main areas—data pre-processing, fault feature extraction, and fault feature identification—this work thoroughly examines traditional techniques for rolling bearing problem diagnosis based on vibration signals. Examined in detail are the fundamental ideas, salient characteristics, challenges of application, and appropriate situations for different algorithms. Additionally, the Case Western Reserve University bearing dataset is used to study and evaluate various defect identification techniques. Future development paths are also expected based on the state of the bearing defect diagnosis study at the moment. It is anticipated that this study will be a useful resource for future research aiming to deepen their comprehension and advance rolling bearing defect diagnosis technology.

According to **Peng, B. et al. (2022) [17],** a rolling bearing failure can result in catastrophic accidents or the shutdown of mechanical equipment, which can have a devastating effect on society and generate enormous financial losses. These studies and industry pioneers give rolling bearing fault diagnostics a lot of attention, making it a significant topic. Publications on this subject are becoming more numerous. However, a thorough analysis of previous research from the viewpoints of vibration signal-based problem detection and fault type recognition in rolling bearings is lacking. As a result, this study uses vibration signals to identify fault types and detect recent faults. It starts by giving a general review of rolling bearing failure diagnosis and common defect kinds. The current techniques for diagnosing faults are then divided into two categories: fault detection techniques and fault type recognition techniques. Each of these is reviewed and described independently. To provide people interested in this topic additional direction, a synopsis of current datasets, limitations and difficulties of current approaches, and future directions are finally provided. All things considered, this review investigates and evaluates the techniques for identifying rolling bearing issues and offers thorough recommendations for those working in this area.

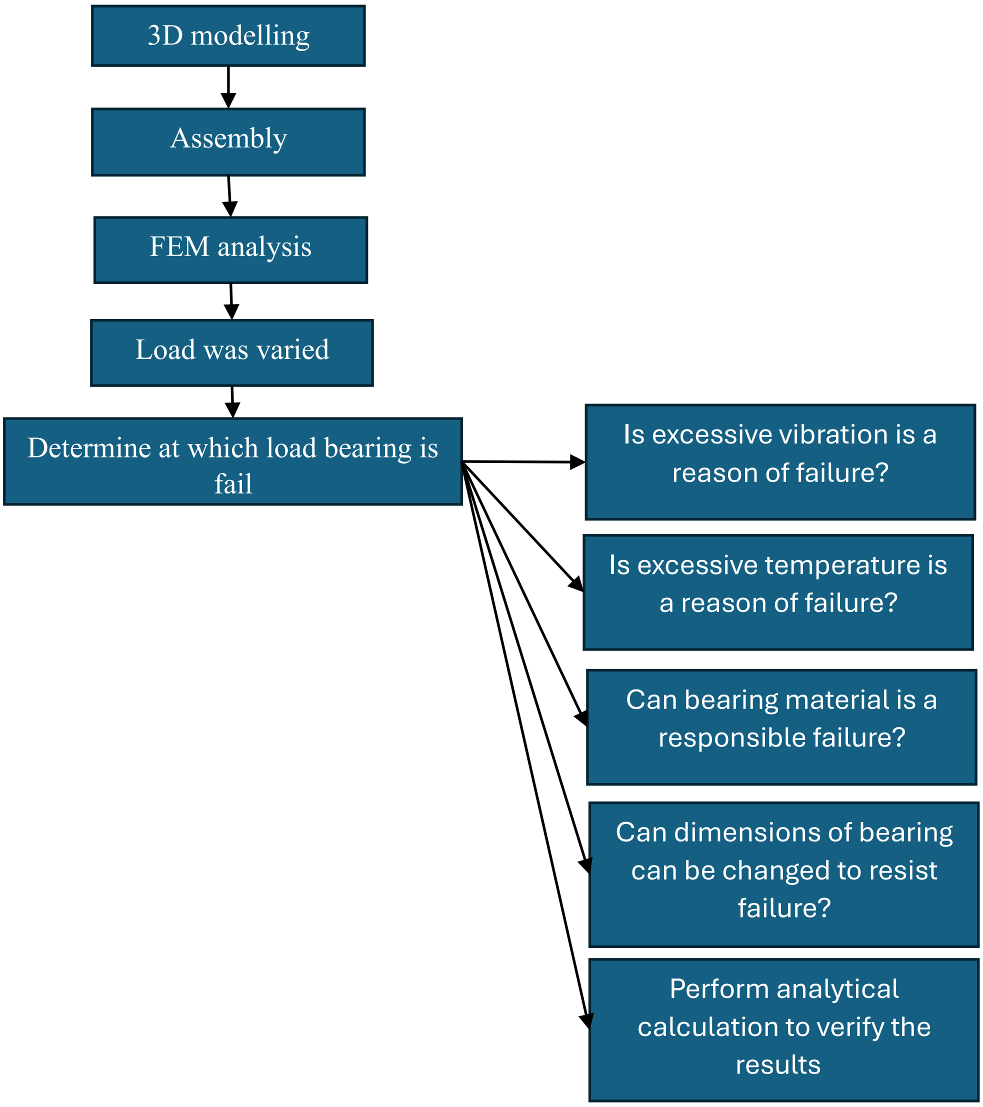
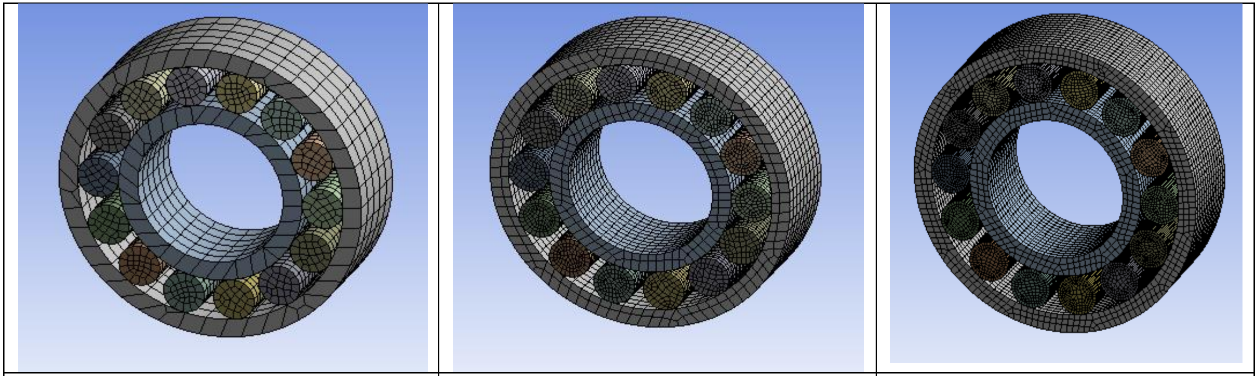


Figure 2 Flow chart of methodology adopted

III. METHODOLOGY

A. Meshing

After modeling, the roller bearing is meshed in ANSYS Workbench with SOLID186 3D hexahedral 20node element which exhibits quadratic displacement behavior along with three degrees of freedom per node. The model is discretized into nodes and elements, then subjected to coarse, medium, and fine meshes for the determination of contact stress dependency on the denseness of the mesh. Its results show that contact stress values are independent of the number of nodes and elements, thereby providing reliable results with optimized mesh configurations.

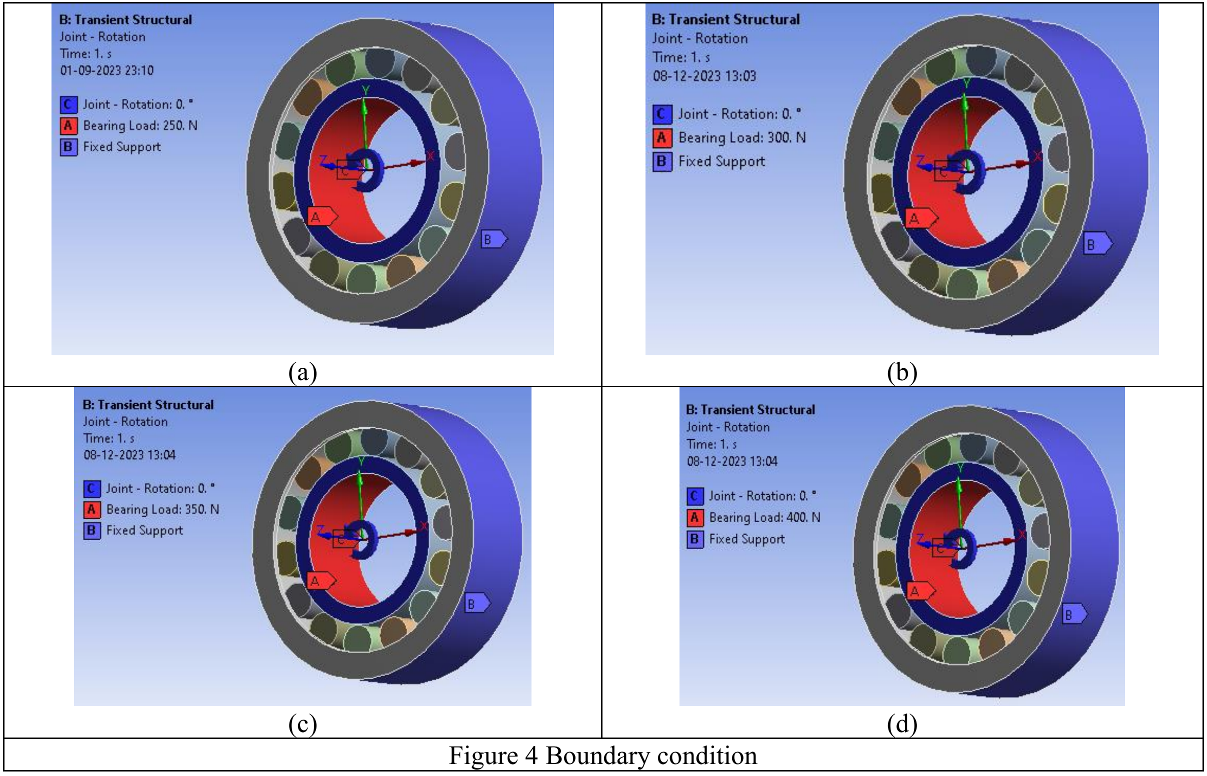


(a) Coarse mesh (b) Medium mesh (c) Fine mesh

Figure 3 Mesh model

B. Boundary condition

After meshing, boundary conditions were applied to the model simulating real-life circumstances as per Fig. 3.6. A body-to-ground revolute joint was applied on the inner face of the bearing, and a body-to-ground planar joint on the faces of the rolls. Transient analysis was carried out in the Mechanical APDL solver to determine the roller bearing's response under design constraints. The yield strength and tensile strength were considered as the critical material properties to determine when the material loses its elasticity and its maximum stress capacity. With the specified loading conditions, the simulation was performed to assess performance.



(a) (b) (c) (d)

Figure 4 Boundary condition

The study assumes the bearing's outer race is connected to a rigid frame, a common scenario where frame rigidity and elastic loads do not affect bearing properties. Real-world cases with compliant frames or excessive loads causing deformation and shaft misalignment require specialized analyses, which are beyond this study's scope.

C. Material properties

Material properties are important aspects of achieving accurate simulations, which may affect deformation strength and stiffness. Key properties that were used in this analysis for structural steel include Young's modulus, which is 200 GPa; Poisson's ratio, 0.3; and density, 7850 kg/m³, to ensure precision. Roller bearings use materials such as metals or composites to be durable under specific conditions.

Table 1. Properties of materials

Material Property	Structural Steel
Material Type	Structural Steel
Young's Modulus	2×10^{11} Pa^2
Density	7850 kg/m^3
Poisson's Ratio	0.30
Bulk Modulus	1.6667×10^{11} Pa
Shear Modulus	7.6923×10^{10} Pa
Tensile Strength	2.5×10^{8} Pa
Ultimate Shear Strength	4.6×10^{8} Pa

IV. RESULTS AND DISCUSSION

Convergence analysis ensures accurate radial bearing stiffness estimation with minimal computational time through grid independence testing. This involves refining the mesh, running simulations, and comparing results to ensure output remains consistent across finer grids. The process continues until results show negligible differences, confirming grid independence.

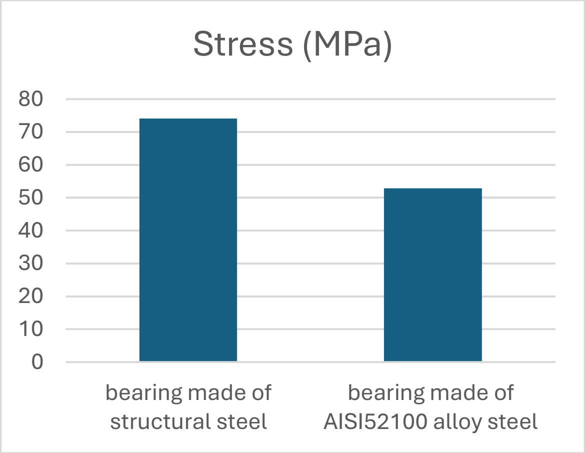


Figure 4 Stress comparison

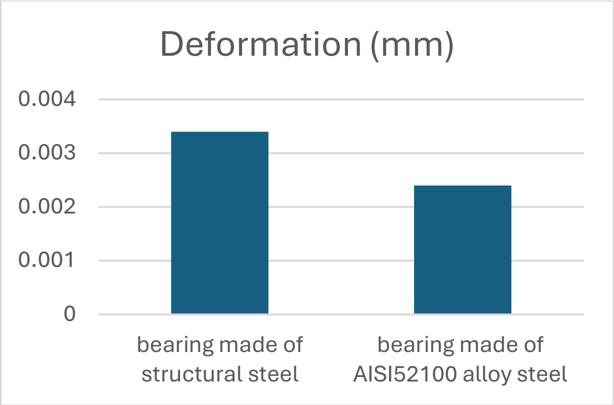


Figure 5 Deformation comparison

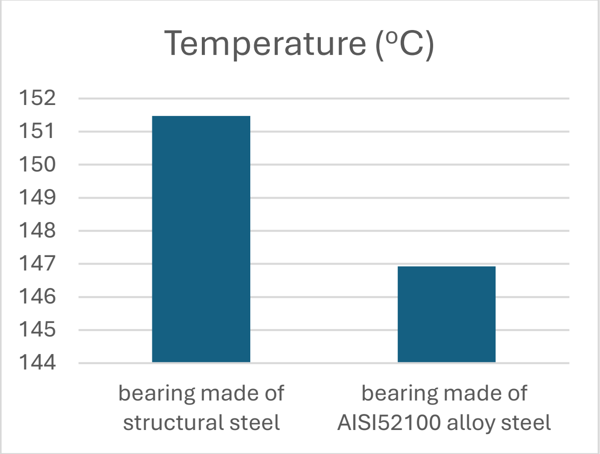


Figure 6 Temperature comparison

Figure 4 shows stress comparison that the bearings made of structural steel experience relatively higher stress at around 70 MPa compared to AISI 52100 alloy steel at an approximate value of 50 MPa. The implication is that AISI 52100 alloy steel has a better resistance to load-induced stress and hence less prone to failure. Figure 5 shows deformation results reveal that bearings of structural steel experience greater deformation than those of AISI 52100 alloy steel, namely ~0.0035 and ~0.0025 mm, respectively. Lesser deformation means superior rigidity and more resistance toward shape distortion under load by the latter. Figure 6 shows a temperature chart indicating higher temperatures for structural steel bearings (~151°C) than those AISI 52100 alloy steel bearings do (~146°C) underscores that during operation, AISI 52100 alloy steel heats more and dissipates heat better, resulting in the improvement of thermal stability and working. When thickness of inner and outer race is increased and structural steel is replaced with AISI52100 alloy steel under same loading conditions, stress is reduced to 52.91 MPa which is below the calculated stress 68.93 N/mm^2, hence in this case, our design is also safe.

The table compares stress, deformation, and temperature for structural steel and AISI52100 alloy steel bearings, reduced stress and deformation with dimension modification, where both are lower with respect to AISI52100 alloy steel showing lower stress and deformation but higher sensitivity towards temperature changes.

Table 2 Comparison table

Bearing material	Stress, MPa	Deformation, mm	Temperature, °C
Without modification in dimension			
Structural steel	79.37	0.0037	151.47
AISI52100 alloy steel	37.04	0.0017	146.93
With modification in dimension			
Structural steel	74.08	0.0034	148.74
AISI52100 alloy steel	52.91	0.0024	121.05

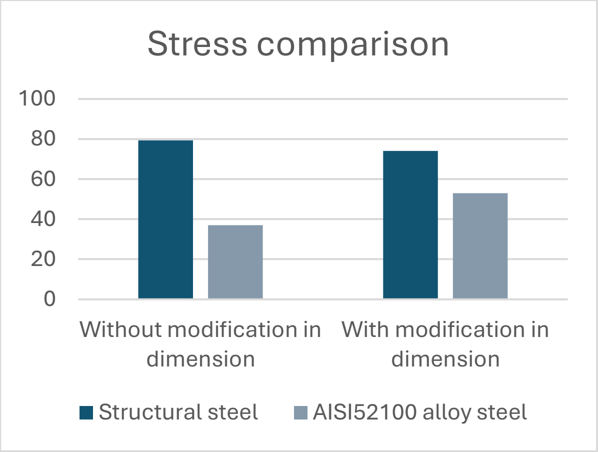


Figure 7 Stress comparison

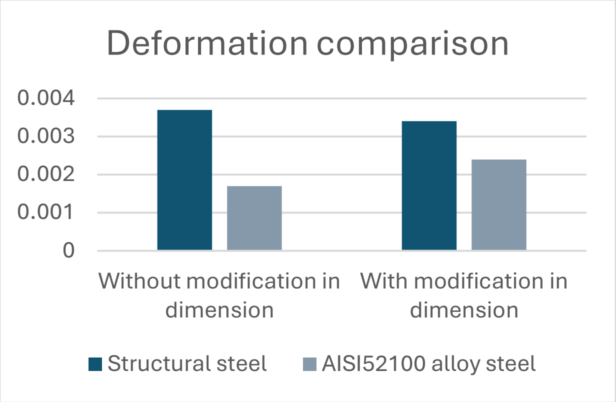


Figure 8 Deformation Comparison

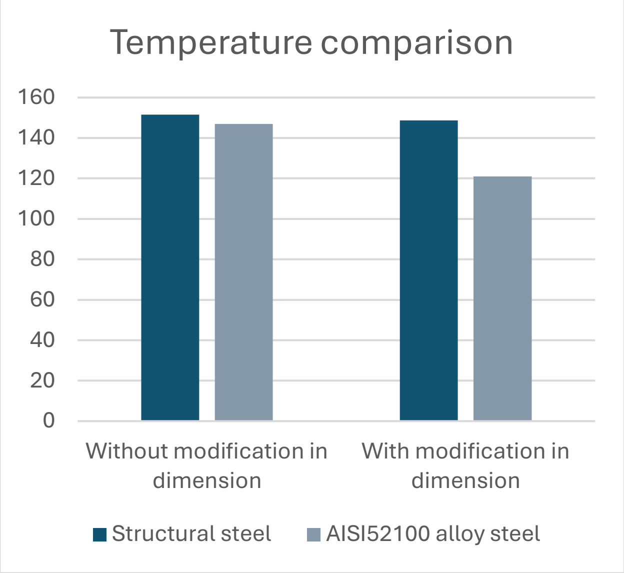


Figure 9 Temperature comparison

Figure 7 shows stress comparison results demonstrate higher stresses in structural steel bearings than in those made of AISI 52100 alloy steel for the two conditions, viz. without and with dimensional modification. Figure 8 dimensional modifications decrease stress in both materials, however, AISI 52100 alloy steel always shows lower stress, implying better material performance underload. Structural steel bearings deform more than AISI 52100 alloy steel bearings. Annealing reduces deformation slightly in both materials but still indicates better resistance to deformation by the AISI 52100 alloy steel, this time with a view to maintaining dimension stability under load. Figure 9 temperature comparison shows that structural steel bearings reached a little bit higher temperature than AISI 52100 alloy steel bearings. Dimensional alteration shows that there is a minor diminution of the temperature for both materials, while AISI 52100 alloy steel again becomes a little better stable towards thermal stability and thus is more compatible to high temperatures.

A. Discussion on failure analysis

The failure is mostly found in centrifugal pumps with cylindrical roller bearings, excessive vibration and temperature lead to fatigue spalling and wear in the outer and inner ring raceways, rollers, and cages. High local contact stress, caused by an excessive tightening axial force from the lock nut, was the main cause of this type of failure. Analysis by ANSYS showed deformation, increased cylindricity and taper distortion of the inner ring raceway with increased tightening torque as such 338-372 Nm with high local stress that comes with contact fatigue and wear. Such failure is prevented if axial force in tightening stays within the scope established at minimizing deformation, vibrations, and temperature-induced stress.

V. CONCLUSION

Structural steel and AISI 52100 alloy steel roller bearings have been subject to a comprehensive study involving performance and failure mechanisms under various conditions. Experimental outcomes show that due to stress resistance, deformation stability, and thermal performance, AISI 52100 alloy steel outperformed structural steel. Dimensional modifications further reduce stress and deformation in the two materials, but it always showed superior performance of the AISI 52100 alloy steel. High tightening axial forces, vibration, and temperature were found to be the most significant factors of bearing failure, with spalling and wear as the most frequent failure modes.

The research thus highlights the material selection and axial force control to determine bearing design capable of being reliable and long-lasting. The results suggest that in conditions where strength is required, bearing application will be made of the AISI 52100 alloy steel since it is able to handle high stress and maintain structural integrity under extreme stress. Further research can be conducted on advanced materials as well as optimum design strategies to further improve the performance of critical applications bearings.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose

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