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Performance Evaluation and Durability Analysis of 52100 Bearings under Varying Heat Treatment Conditions in Aerospace Applications

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Abstract – This study investigates the performance and longevity of two types of bearings—the motor bearing and the input module bearing—fabricated from 52100 (100 Cr6) bearing steel, following a 500-hour flight operation. Case evaluations, including hardness testing and vibration analysis, were conducted after the bearings underwent various heat treatments, specifically at temperatures of 600°C and 700°C. The findings revealed that the input module bearing heat-treated at 600°C experienced increased vibration levels, which, while initially within acceptable limits, resulted in the bearing becoming inactive after 900 hours due to the cumulative effects of the operational environment. In contrast, the bearing treated at 700°C exhibited the highest vibration levels, correlating with excessive iron contamination in the oil, suggesting a requirement for further thermal processing. Additionally, the analysis indicated that vibration and torque values remained stable at 600°C but deteriorated significantly at 700°C. These results underscore the critical influence of heat treatment and operational conditions on bearing performance. Consequently, this research emphasizes the necessity for optimized heat treatment processes and routine maintenance protocols to enhance bearing reliability in high-stress and elevated temperature environments, particularly in aerospace applications. This work provides valuable insights into the factors impacting bearing failure and offers a foundation for future studies aimed at improving bearing technology and maintenance practices.

Keywords – Bearings, Heat Treatment, Vibration Analysis, Aerospace Applications, Durability.

I. INTRODUCTION

Bearings are critical components in helicopter engines, functioning as supports that enable smooth rotation and movement of various engine components. In these high-stress environments, bearings are subjected to extreme loads, temperatures, and speeds, which can significantly impact their performance and longevity. The reliability of bearings directly influences the overall efficiency and safety of helicopter operations, as failures can lead to costly repairs, operational downtime, and, in severe cases, catastrophic incidents. Selecting the appropriate bearing material and employing suitable heat treatment processes is essential in enhancing their wear resistance and fatigue life, thereby ensuring that helicopter engines remain operational under the demanding conditions they face [1, 2].

In helicopter engines, bearings are subjected to unique operational conditions, including high rotational speeds, varying loads, and challenging environmental factors such as temperature fluctuations and lubrication issues. According to Hwang et al. [3], the performance of the bearings directly impacts engine efficiency and reliability, making their design and material selection crucial for operational safety.

Heat treatment processes, such as carburizing, normalizing, and quenching, are employed to improve the mechanical properties of bearing steels, enhancing features like hardness, toughness, and fatigue resistance. Hu et al. [4] detailed that carburizing, which introduces carbon into the surface of low-carbon steels, significantly improves wear resistance, making it a preferred method for components subjected to high surface pressure. The literature indicates that the optimization of heat treatment parameters is vital for maximizing the performance of bearings. Studies by Chen et al. [5] highlighted the importance of precise temperature control and cooling rates during the quenching process to prevent undesirable microstructural changes that can lead to premature failure. Additionally, normalizing processes can refine the grain structure of bearing materials, which subsequently enhances their overall mechanical properties and service life. Specific studies have focused on the T700 helicopter engine, which is used in various military and civilian applications. Research conducted by Gomez et al. [6] examined the bearings within the T700 engine, emphasizing the need for tailored heat treatment processes to cope with the engine's operational demands. Their findings suggested that implementing a combination of carburizing followed by quenching resulted in significant improvements in fatigue life and operational reliability compared to standard treatment methods. Given the critical nature of helicopter bearing applications, integrating predictive maintenance strategies with heat treatment processes has gained attention. Kuo et al. [7] suggested that continuous monitoring of bearing conditions, including vibration analysis and temperature readings, can provide insights into their performance and predict potential failures before they occur. This method aligns with the increasing trend toward condition-based maintenance, aiming to enhance the lifecycle management of helicopter engines. The studies reaffirm that the quality and longevity of bearings used in helicopter engines are heavily influenced by their material selection and the implementation of effective heat treatment techniques. Furthermore, the exploration of predictive maintenance in conjunction with advanced heat treatment processes holds promise for extending the operational life of critical components such as those in the T700 helicopter engine. As ongoing research continues to address these challenges, future advancements may lead to even more reliable bearing technologies that meet the rigorous demands of helicopter operations [8, 9].

This paper analyzes the effects of heat treatment techniques on the service life of bearings used in helicopter engines, employing predictive maintenance strategies to optimize performance and durability. Bearings are essential components in various industrial applications, and their reliability is critical for enhancing production efficiency and cost-effectiveness. Heat treatment enhances the mechanical properties of bearing steels, potentially extending their fatigue life, but requires careful optimization of treatment parameters to understand its implications on longevity. The study utilizes predictive maintenance techniques to monitor and assess the performance of bearings after heat treatment, aiming to prevent costly breakdowns and ensure operational continuity. A case analysis of common heat treatment methods, such as carburizing, normalizing, and quenching, is conducted to investigate their specific impacts on bearing lifespan, focusing on key material attributes like fatigue resistance, hardness, and toughness. Ultimately, this research seeks to propose optimal heat treatment conditions that enhance bearing durability and reduce failure rates, thereby allowing industrial facilities to improve maintenance strategies, lower costs, and maximize equipment uptime. The findings provide valuable insights for bearing manufacturers and users, contributing to advancements in the field and promoting better performance and reduced maintenance costs.

II. MATERIALS AND METHOD

This study adopts a short methodology to investigate the effects of heat treatment techniques on the service life of bearings used in turbine engines, particularly focusing on the T700 engine. The study involves the selection and application of various heat treatment processes, including carburizing, normalizing, and quenching, on bearing steel samples. Each treatment is executed under a range of parameters, such as temperature, duration, and atmosphere, to systematically assess their influence on critical material properties, including hardness, fatigue resistance, and toughness. A case experimental setups was designed to test the selected bearing materials, aiming to identify optimal heat treatment conditions that enhance performance and longevity.

Furthermore, the study integrates predictive maintenance techniques to evaluate the performance of bearings after heat treatment, particularly in the context of turbine engine operations. Techniques such as condition monitoring, vibration analysis, and temperature tracking is employed to collect real-time data on the operational performance of bearings within simulated working environments, akin to the T700 engine's operational framework. This data facilitates a thorough analysis of how various heat treatment conditions impact the longevity and reliability of bearings, thereby identifying best practices for maintenance strategies. By correlating performance metrics with heat treatment parameters, the research aims to address existing knowledge gaps and provide valuable insights for manufacturers and maintenance engineers, ultimately enhancing the effective utilization of bearings in turbine engines and improving overall operational efficiency in industrial applications. The power transmission system and bearing functions discussed in this study are shown in Fig. 1.

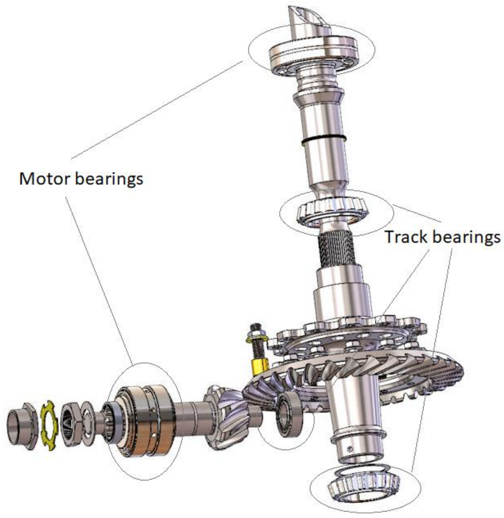

Fig. 1 Powertrain for helicopter engine [10]

A. Material

In this study, the primary components analyzed are the input module bearing and the motor bearing, both critical due to their operational conditions characterized by high torque, stress, and elevated temperatures. These two bearings are seen in Fig. 2. The input module bearing, composed of an inner ring, outer ring, retainers, and grooved races, operates efficiently under reduced torque and stress conditions, as it is designed to facilitate rotation with minimal resistance. Two input module bearings are utilized, functioning within a gearbox that converts the 20,900 RPM from the engine into motion transmitted to the main module via the input shaft. Additionally, this system incorporates a freewheeling unit, which activates during situations such as engine failure or when rotor speeds exceed engine speeds, allowing continued motion without engine input until the rotor speed falls below the engine speed, at which point the engine is re-engaged. The motor bearing, consisting of two inner rings, an outer ring, a retainer, and a cage, is mounted at the rear of the compressor in the T700 engine. This bearing allows the forward movement of the compressor while preventing vertical displacement, operating at a speed of 4,400 RPM and subjected to temperatures reaching approximately 1,575°F. It is noteworthy that this bearing is among the most frequently prone to failure within the motor's assembly.

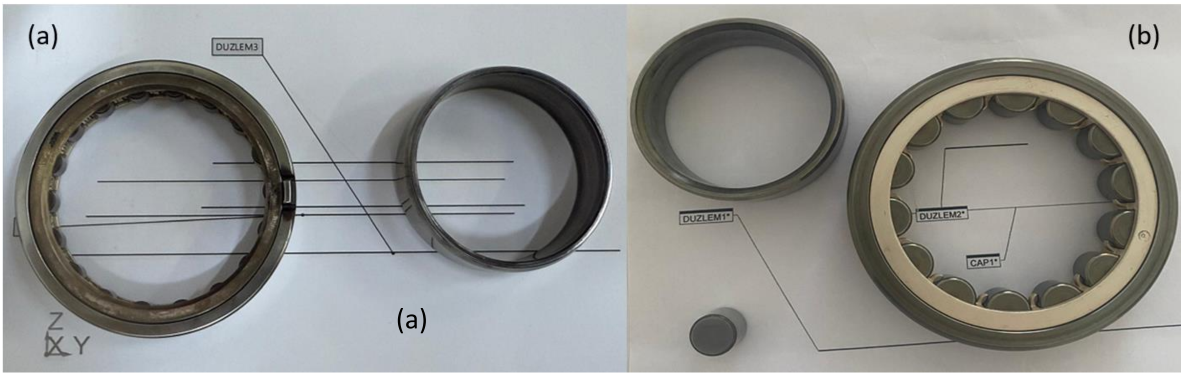

Fig. 2 Bearings a) motor bearing b) track bearing

B. Method

Both bearings utilized in this study are fabricated from 52100 (100 Cr6) bearing steel. After undergoing 500 hours of flight operation, these bearings were subjected to heat treatment and subsequently underwent a series of checks before installation on the aircraft.

The hardness of the high-temperature motor bearing was measured at 58.8 HRC, while the transmission bearing exposed to high torque exhibited a hardness value of 61.3 HRC (See Fig. 3). These hardness values fall within the permissible limits as defined by the relevant technical publication (NAVAIR-01-1A-503).

Fig. 3 Bearing hardness test

Due to the differing operational conditions of the two bearings, their hardness and wall thickness varied. In this context, the bearings underwent distinct heat treatment processes during manufacturing. After 500 hours of operational use, the motor bearing was subjected to heat treatments at temperatures of 850°C, 800°C, and 750°C, while the high-torque input module bearing was heat-treated at 500°C, 600°C, and 700°C, followed by air cooling.

After the respective heat treatment procedures, both bearings were connected to an analyzer testing device to simulate operational conditions within the aircraft. The assessment focused on determining whether the bearings operated smoothly or emitted vibrations or noise at high RPMs.

Fig. 4 Bearing vibration test

The Coordinate Measurement Machine (CMM) is a sophisticated measurement device capable of performing measurements in Cartesian coordinates is shown in Fig. 5. With a probing head that can rotate 360 degrees and move along the X, Y, and Z axes, this machine achieves measurement precision within 1 micron or less.

Fig. 5 Bearing cage and diameter tests

Both bearings were mounted within a specifically designed test rig that simulates the torque, temperature, vibration, and pressure conditions expected during flight. Throughout the testing process, periodic measurements of vibration, temperature, pressure, and torque were recorded and tabulated to evaluate the operational status and wear rates of the bearings.

III. RESULTS

Following the completion of 500 flight hours for both the motor and input module bearings, necessary inspections were conducted, and vibration, torque, temperature, and pressure data were collected and recorded using a test brake system. Subsequently, these bearings were reinstalled onto the aircraft, where assessments were made during routine maintenance or in the event of any malfunctions. The condition of the motor bearing subjected to heat treatment at 750°C is illustrated in Figure 5 and detailed in Table 1.

Table 1. Lifetime monitoring for Motor bearing baked at 750°C

Maintenance	Fault	Bearing status
500 Hour Routine Maintenance	-	Active
700 Hour Essential Maintenance	Engine Power Loss	Active
1000 Hour Routine Maintenance	Engine Power Loss	Active
1100 Hour Essential Maintenance	Aircraft Hard Landing	Expired

The heat treatment test temperatures established for the tracking bearing were lower than those for the motor bearing due to its operational conditions, which involve relatively lower heating temperatures. The condition of the input module bearing heat-treated at 600°C is presented in Table 2.

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Table 2. Lifetime monitoring for Tracking bearing baked at 600°C

Maintenance	Fault	Bearing status
500 Hour Routine Maintenance	-	Active
700 Hour Essential Maintenance	Tail Blade Wire Snagging	Active
900 Hour Essential Maintenance	Aircraft Vibration	Expired

Results should be clear and concise. The most important features and trends in the results should be described but should not interpreted in detail.

IV. DISCUSSION

Upon examining the test data for the input module bearing heat-treated at 600°C, it was observed that, compared to the 500°C bearing, the vibration levels increased but remained within acceptable limits. However, due to the presence of vibrations during the aircraft's test flights, the bearing became inactive after 900 hours of operation. It was noted that the highest vibration values were observed in the bearing treated at 700°C, with the analysis report of the oil sample taken from within the bearing indicating excessively high levels of iron (FE), suggesting that further heat treatment was necessary. Consequently, it was concluded that the bearing heat-treated at 700°C would likely fail after 800 hours of usage.

The variable temperature effects on the tracking bearing's vibration and torque values are presented in Figure 6.

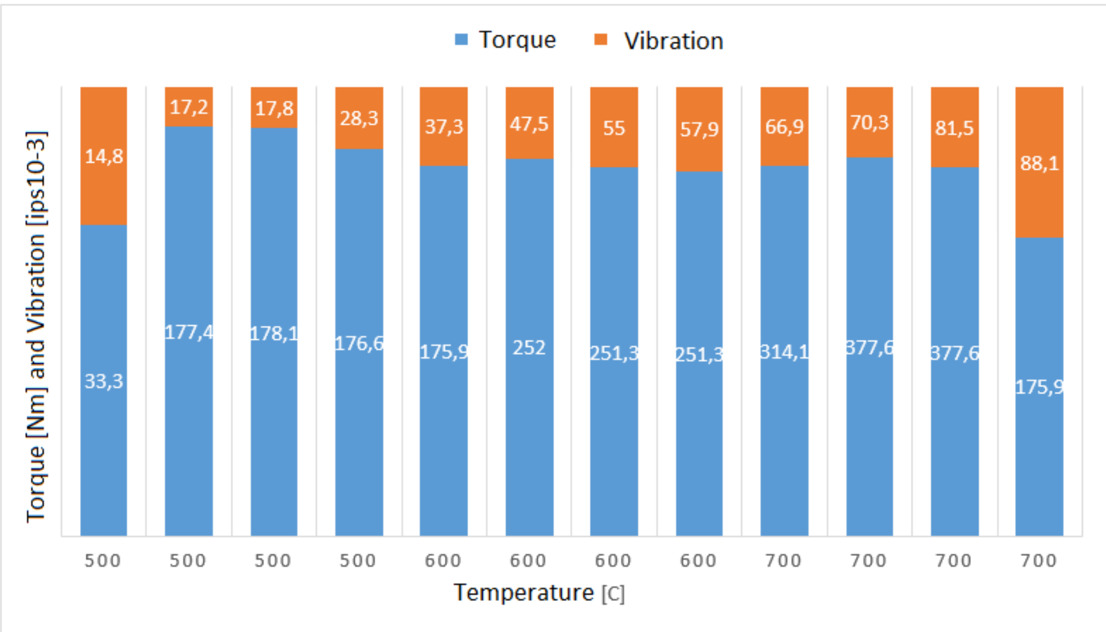

Fig. 6 Tracking bearing Torque and Vibration results

It is evident that while the torque and vibration values exhibited stable variation at 600°C, there was a noticeable decrease in torque and an increase in vibration at 700°C. Therefore, it can be concluded that the primary reason for the bearing's failure beyond this temperature is attributed to the heightened levels of vibration experienced.

V. CONCLUSION

The main conclusions of the study should be summarized in a short Conclusions section. This study systematically evaluated the performance and durability of motor and input module bearings manufactured from 52100 (100 Cr6) bearing steel under various operational and thermal conditions. Following 500 flight hours, comprehensive testing revealed that the input module bearing heat-treated at 600°C exhibited increased vibration levels, yet remained within acceptable limits until it became inactive after 900 hours due to consistent vibrations during test flights. Conversely, the input module bearing heat-treated at 700°C displayed the highest vibration levels, indicating a potential failure threshold at 800 hours, exacerbated by excessively high iron content in the lubricant, which necessitated further thermal processing. The analysis of the tracking bearing showed stable torque and vibration values at 600°C, but significant deterioration at 700°C, highlighting the critical impact of thermal treatment on bearing performance. Overall, these findings underscore the importance of optimizing heat treatment parameters and conducting regular maintenance to enhance the reliability and longevity of bearings under high-stress and high-temperature conditions in aerospace applications.

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