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Investigation of The Fatigue Behavior of Gyrocopter Propellers Produced From 6061 T6 Aluminium Alloy

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Abstract

In the aviation sector, the production of propeller-driven aircraft is being accelerated due to the increase in passenger numbers, the possibility of transportation for shorter distances, and the reduction in costs in aircraft designs. Gyrocopter vehicles, which have recently begun to be used in aviation, have significant potential in the near future. The demand for these air vehicles in the aviation sector is growing due to their ability to operate in relatively short ranges, their low operational and maintenance costs. Generally, the systems that most significantly reduce costs in these aircraft are propellers. The technological advancements in material science have facilitated innovative solutions in the design and manufacturing of propellers from a wide range of materials. The combination of nanotechnology and materials science has been achieved alongside ongoing innovations in these two evolving technologies. In this study, samples of propellers produced from 6061 T6 Aluminium Alloy, were produced with a special extrusion model and were then subjected to fatigue, tensile, and hardness tests. The mechanical standards of the produced propellers were examined to determine whether the desired flight configurations could be achieved.

1. Introduction

Fatigue behavior in aviation materials is a critical concern, as aircraft components are subject to cyclic stresses during operation, leading to progressive structural degradation over time. In recent studies, researchers have emphasized the importance of understanding fatigue mechanisms in materials such as aluminum alloys, composites, and titanium alloys, which are commonly used in the aerospace industry. These materials are tested under repeated loading conditions to simulate real-world scenarios, enabling the prediction of their lifespan and the optimization of maintenance schedules. Findings show that fatigue behavior is influenced by factors such as microstructure, crack initiation, and propagation, as well as the presence of stress concentrators, all of which can significantly reduce the performance and safety of aircraft components. Thus, advancements in fatigue analysis contribute to the development of more resilient materials and improved safety measures in aviation (Kansoy & Tekin, 2023; Gürbüz & Taşkın, 2023; Uzun et al., 2024;).

6061 aluminum alloy is widely used in aerospace, automotive, and structural applications due to its favorable combination of strength, corrosion resistance, and ease of fabrication. Its fatigue behavior, however, is a critical factor in determining its reliability in cyclic loading conditions. Fatigue occurs when materials are subjected to repeated stresses below their ultimate tensile strength, leading to crack initiation and propagation over time. For 6061 aluminum alloy, the fatigue life is influenced by its microstructure, surface finish, and environmental factors, including corrosion and temperature. The material's response to cyclic loading is also affected by heat treatments such as T6, which enhance its mechanical properties. Numerous studies have investigated the fatigue characteristics of 6061 aluminum under various conditions, focusing on crack growth rates, fatigue strength, and the role of defects and surface imperfections. These investigations are crucial for optimizing the use of 6061 aluminum in safety-critical components, ensuring both longevity and performance under fatigue-inducing conditions (Chen et al., 2018; Johnson & Miller, 2020).

Gyrocopter propellers are essential components that contribute significantly to the efficient operation and flight stability of gyrocopters. These air vehicles feature an unpowered rotor for lift and a powered propeller for thrust, with the propeller playing a crucial role in generating the forward propulsive force. The performance of the gyrocopter propellers directly impacts the aircraft's stability maneuverability and performance in various mission legs during the flight (Czyż et al., 2021). Recent numerical computational studies have focused on the aerodynamics of gyrocopters, particularly examining the the autorotating rotors under various conditions. These studies have shed light on the intricate interactions between the fuselage, empennage and propellers in gyrocopters, highlighting the importance of understanding the dynamics and aerodynamic characteristics of the gyrocopter propellers. This understanding is vital for optimizing the propeller design and for enhancing the overall performance of the gyrocopters in diverse flight scenarios.

6061-T6 aluminum alloy, part of the 6xxx series, is widely utilized in engineering fields such as automotive, aircraft and shipbuilding due to its advantageous properties (Abioye et al., 2021). This alloy is commonly used in the production of structural components like wings, fuselages in aircraft, wheel spacers, rims in automobiles, and ship frames (Abioye et al., 2021). Its popularity is attributed to its high strength, corrosion resistance, cost-effectiveness, formability, and weldability (Lee & Liu, 2014). The 6061-T6 alloy is favored for its mechanical strength, low density, and corrosion resistance (Irizalp & Saklakoğlu, 2018). Studies have investigated the mechanical properties of 6061-T6 aluminum alloy, including its laser welded joints, showcasing its versatility and significance in engineering applications (Nie et al., 2020). The unique properties of the AA 6061-T6 aluminum alloy make it a preferred material for a wide range of structural and engineering applications.

In this study, propellers were manufactured from 6000 series aluminum using the extrusion method, and their mechanical properties were investigated. The mechanical standards of the produced propellers were examined to determine whether the desired flight configurations could be achieved.

2. Materials and Methods

In this study, aluminium propellers were produced using the hot extrusion method, with Aluminum 6061 alloy chosen for its numerous benefits. The production process consisted of five main steps: Billet Preparation and Heating, Extrusion Pressing, Cooling, Cutting, and Heat Treatment. The cutting process was applied to propeller blades for the gyrocopter, set at a diameter of 9 inches (22.86 cm). Billets underwent heating to facilitate the passage of aluminum material through the die, with temperatures ranging from 350 °C - 500 °C. Initially, billets were heated to around 250°C using recycled exhaust gases before reaching approximately 450°C in the main heating section. Temperature accuracy was ensured through thermocouple measurements directly contacting the billet surface. Maintaining billet temperatures within the optimal range of 350 °C - 500 °C was crucial for enhancing product quality.

The 3D design of the rotor blade was created using AutoCAD software, with its lateral area calculated as 39.60 cm² (0.00396 m²). The length of the aluminum billet, post-cutting, was determined to be 5 meters with a radius of 11.43 cm, resulting in a lateral area of 410.43 cm² and 0.04 m². Employing the extrusion ratio formula yielded a ratio of 10:1. The extrusion process operated at a ram speed of 0.4 meters per second, exerting a force of 950 MPa on the aluminum billet. Upon completion of the extrusion process, the aluminum billet formed the foundational structure of the propeller.

At the end of the extrusion the aerophyll structure reached a temperature of approximately 310 °C. In order to maintain the desired quality, temperatures during the process were kept below 50 °C. High-quality surface finish and proper hardening of the aerophyll structure according to the specified shape were ensured through rapid heating and controlled cooling.

After cooling with water to below 50 °C, the aerophyll structure underwent finalization of propeller shaping through a cutting operation. To enhance corrosion resistance against anticipated high humidity and environmental conditions during gyrocopter usage, the propeller underwent an anodizing process. Surface sanding was conducted using sandpaper to eliminate imperfections prior to anodizing. Anodizing of the propeller blades was carried out using sulfuric acid at 18 °C, with voltage set at 15 volts and current at 1200 Amperes. To economize on anodizing costs for the aluminum propeller blades, preference was given to a horizontal anodizing bath. Following 30 minutes of anodizing, the blades underwent inspection in a detection bath and were subsequently immersed in pure water at 90 °C for 45 minutes. This process resulted in the formation of a 5-micron thick anodized coating on the blades. A 4.1-meter cutting operation was conducted on the extrusion-produced propeller, reinforced with a steel shaft, to prevent breakage and enhance rigidity against flight forces, ensuring minimal deflection during flight.

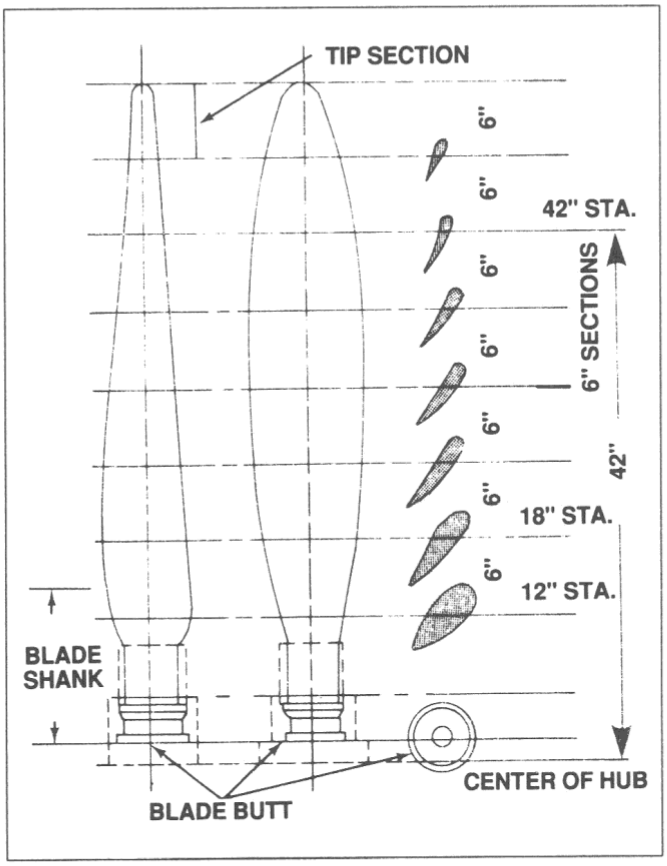

Figure 1. Representation of the nine station areas from which samples were taken for testing. (De Remer, D., 2017).

Samples, extracted from extrusion-manufactured propeller, were produced using the Lasermark 4000 laser cutting machine at GÜRBÜZ TREYLER A.Ş facility. Laser cutting was employed to ensure flawless and error-free sample production, with the process completed successfully using 4 kW voltage in 15 minutes. Utilization of the laser-cutting also facilitated a production free of any post-porcessing, such as chip removal or sanding. Following the completion of the cutting process, the samples were removed after 1 hour, given the high power and temperature during cutting. The samples were horizontally cut from the propeller blade to ensure homogeneous distribution, with sample specimens extracted from different segments (root, mid and tip) of the propeller blade.

In order to demonstrate homogeneity in propeller production, nine samples were obtained, as depicted in Figure 1, based on propeller stations. This process was conducted progressively from the hub to the tip of the blade.

The NACA 8H/12 airfoil structure was selected due to its high efficiency in lightweight constructions, despite its inadequacy for achieving high lift ratios, which are essential for helicopters and civilian aircraft.

Nine samples derived from the propeller blades underwent fatigue tests at the Margem Laboratory of Karabük University. The fatigue tests were conducted using the MTS Landmark dynamic test machine in accordance with TS EN ISO 13674-1 standards, at a temperature of 26°C and 35% humidity. Initially, the required loads for the samples were determined within a range of minimum 0.55 kN to maximum 2.5 kN. Subsequently, load values were set at 0.55 kN, 1 kN, 1.35 kN, 1.5 kN, 2 kN, and 2.5 kN. Fatigue tests were performed under a total of six different dynamic loads, comprising seven main and two spare tests. The total duration of the tests for these samples was 170 hours.

In order to achieve the desired accuracy in the tensile test results, three test specimens were extracted, and the tensile tests of these prepared specimens were conducted using the Zwick Roell Z250 model tensile testing machine at the laboratory of BERDAN CIVATA company. All tensile tests were conducted at 23°C and 39% humidity with a test speed of 0.33 mm/s. The testing process was carried out in accordance with TS EN ISO 6892-1 METHOD B standards.

The hardness measurements of the samples produced from the propeller blades were performed using the Galileo digital hardness measurement device in the quality laboratory of BERDAN CIVATA company. To ensure high accuracy in hardness measurement results, three measurements were taken at equal intervals along a line passing through the center of each sample, dividing the sample into two equal parts.

3. Result and Discussion

The raw data obtained from the experiments conducted on nine samples within the load range of 0.55 kN to 2.50 kN are presented in Table 1 and Figure 2.

Table 1. Fatigue test data

Dynamic Load	Cycle
± 0.55 kN	10 x 10^6
± 1.0 kN	10 x 10^6
± 1.35 kN	1132865
± 1.5 kN	393122
± 2.0 kN	103487
± 2.50 kN	13905

Sample dimensions were logged into AUTOCAD for drawing and for calculation of the sample areas. Through this computational process, the sample area was determined to be 30,510 mm². Utilizing this calculation, the stress/strain curve was derived using the unitary transformation MPa = Newton/mm². Figure 3 illustrates the stress/strain curve.

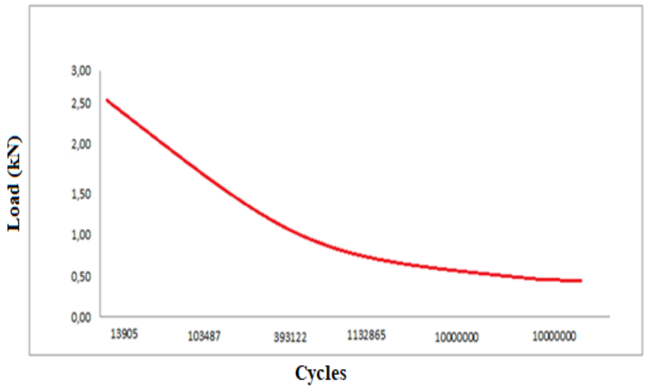

Figure 2. Load/Cycles graphic.

As depicted in Figure 3, experiments conducted under dynamic loading from 2.5 kN to 0.55 kN demonstrate a logarithmic increase in cycle count. This increase remains constant beyond 10x10^6 cycles, indicating the onset of infinite fatigue life.

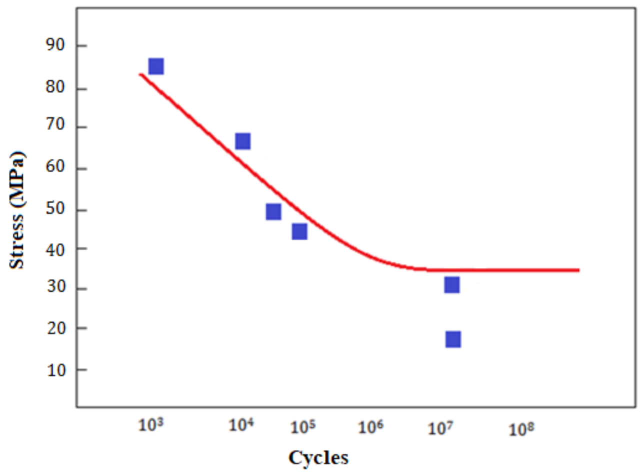

Figure 3. Stress/ Cycle Graph.

The fatigue graph shown in Figure 4 reveals two significant regions known as the ultimate strength and fatigue limit which shown by X signs. Tensile strength is defined as the stress level required to cause damage in a single cycle. In Zone I and Zone III region, our material is subjected to high stresses.

The graph in Figure 4 illustrates the maximum strength level of the propeller blades to be approximately 81 MPa. Stress levels at and above this threshold result in significant damage to the material. Therefore, the maximum stress level that can be tolerated by the propeller blades is determined to be 81 MPa.

Figure 4 illustrates the fatigue strength of the propeller blades. The limit shown on 10^6 cycles signifies that the material can endure an infinite number of cycles without experiencing damage. The approximate value of stress is 30 MPa, indicating that the propeller blades will operate for an extended duration under stress levels below this threshold. This value indicates nearly infinite fatigue life, regardless of other factors. In the fatigue limit region, shown as Zone I in Figure 5, the samples undergo a high number of cycles. Therefore, he fatigues limit region is also named as the high-cycle fatigue value.

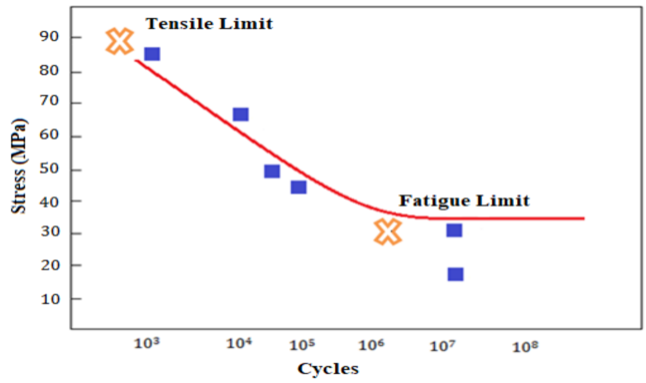

Figure 4. The representation of the tensile limit and fatigue limit on the fatigue graph.

Figure 5 illustrates the initiation of damage starting at a maximum of 81 MPa. Zone I exhibits rapid damage formation, ultimately resulting in propeller fracture. Zone I, also known as the rapid damage occurrence range, spans from 81 MPa to 65 MPa in the graphical representation. Prolonged operation of the propeller within this range is deemed abnormal due to potential adverse consequences.

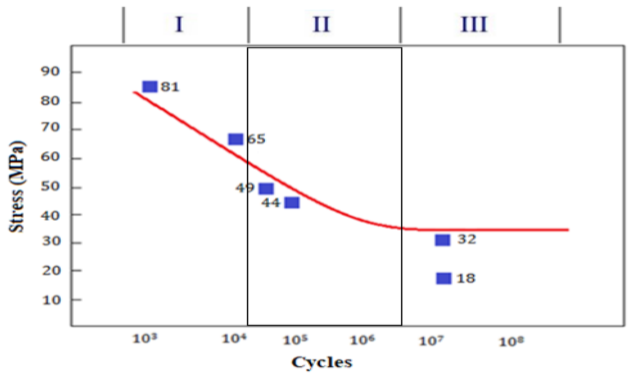

Figure 5. Representation of high and low-cycle fatigue limits.

High-cycle fatigue, prolongs propeller usage due to reduced pressure exertion and ranging from 65 Mpa to 32 Mpa. Within this range, damage formation slows down, which enables longer term use however the damage is not prevented entirely. Eventually, despite increased propeller usage, damage-related issues will impede further operation.

The stress value required for the propeller to achieve extended fatigue life is evident in Figures 3 and 4. Zone III, representing infinite fatigue life for the sample, ranges below 32 MPa. At this stress level or lower, it is established that the fatigue life is infinite regardless of external factors. Therefore in this fatigue range, the propeller's fatigue life can also be assumed to be infinite. Although, in time, some damage may still occur, however, without it leading to any fractures or cracks.

The fatigue test graphs depict the propeller's fatigue life under various pressure levels experienced during operation, expressed in MPa. These graphs establish the maximum and minimum pressure thresholds that the propeller should endure throughout its operational life.

These pressure ranges offer valuable insights into the operational configurations of the propellers, revealing the requisite pressure levels for prolonged usage without experiencing fatigue damage.

The analysis of aluminum's tensile and yield strength results from Material's study indicates no issues with the propeller's usability (Material, 2020). It can withstand flight-induced tensile forces such as fatigue strength, without any concerns.

Figure 6 presents the tensile test graph of the propeller sample specimens. Prepared samples were attached to the test device, where tests were conducted at a constant ambient temperature of 23°C and a pulling speed of 15 mm/min. The samples, with dimensions of 50 mm in length and a cross-sectional area of 30,510 mm² before testing, exhibited a length change of 56.763 mm post-test.

Subsequently, the test data (recorded in the form of, the modulus of elasticity, percentage elongation, maximum tensile strength, yield strength, and ultimate tensile strength of the material) were analyzed by using an ORIGIN software.

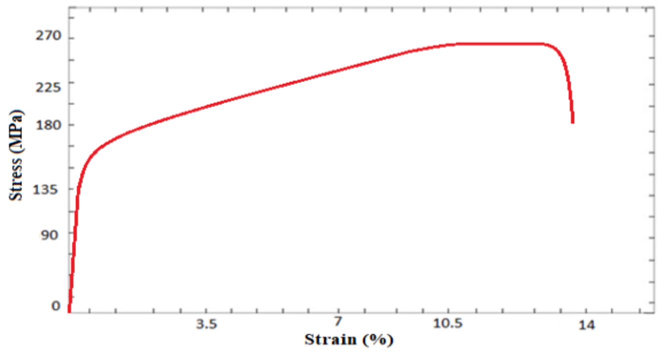

Figure 6. Stress-strain graphic.

Upon examining the stress-strain graph presented in Figure 6, it is observed that the stress increases logarithmically, reaching maximum tensile strength with a slight increase in pressure, followed by fracture of the samples.

All samples have reached the same tensile strength and fracture limit. The yield and ultimate tensile strengths are separately shown in Table 2 (Robert, 2018).

Table 2. Tensile strength results.

Sample Code	Yield Strength 0.02% (MPa)	Yield Strength 0.05% (MPa)	Tensile Strength (MPa)
A.1	250	253	264
6061-T4	110-140	130-160	180-230
6061-T6	215-290	240 -275	260 -310

Figure 6 displays the permanent yield values at 0.2% and 0.5% elongation of the samples. In the tensile test study utilizing the 6061-T6 aluminium alloy, the absence of a distinct yield point necessitated defining the stress value corresponding to plastic elongation of 0.2% and 0.5% as the yield strength.

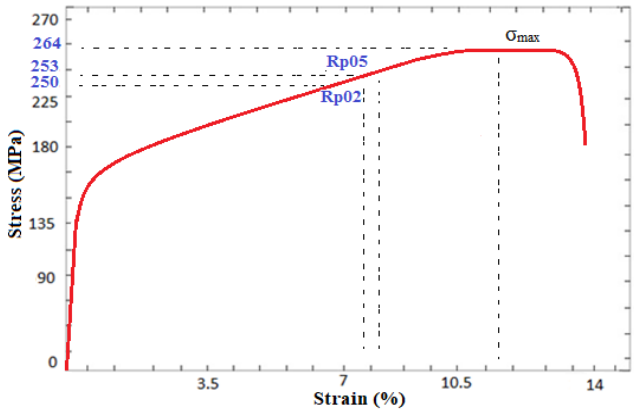

Figure 7. Representation of yield and tensile strength on the graph.

Table 2 illustrates that the yield strengths at 0.2% and 0.5% elongation of the produced samples fall within the previously determined limits of the 6061-T6 aluminum alloy. Additionally, the tensile strength of the sample, measured at 264 MPa, lies within the boundaries of the aluminum 6061-T6 temper. Both mechanical property values exceed those of the T4 temper.

In Figure 7, illustrates the σ_{max} value which is the maximum tensile strength attainable by the sample. The terms Rp02 and Rp05 signify the yield strength at 0.2% and 0.5% elongation, respectively.

When comparing the tensile test data presented in Table 3 with the data for aluminum 6061-T6, it can be seen that the sample with a 13% elongation falls within the standard limits. The elasticity modulus of 85 GPa for the sample is notably higher than the standard values, indicating minimal deformation under the stress applied. This property is desirable for propeller systems and will positively impact their utilization.

Table 3. The results of tensile strength.

Sample Code	Elongation (%)	Elastic Modulus (GPa)	Strength (kN)
A.1	13%	85	9.105
6061-T6	12-25%	68.3	-

All the data obtained from the tensile tests conducted on the samples are provided in Tables 2 and 3. Examination of the data in these tables reveals that the tensile strength is 264 MPa, the elasticity modulus is 85 GPa, and the maximum force strength is 9.105 kN.

Propellers made from 6061-T6 material have similar tensile and fatigue strength to T6 and T4 specimens (Sunström, 2018). Compared to 6063-T5 alloy, our samples exhibit higher fatigue and tensile strength. The propeller shows no damage under dynamic loads, indicating infinite fatigue life. Successful production of propeller blades with infinite fatigue life is evident. Tensile test analysis confirms that the propeller's strengths fall within established ranges in similar studies.

Comparing the stress-strain characteristics of 6061-T6 and 6063-T5 aluminum, the stress value of the produced propeller is very close to that of previously obtained 6061-T6 aluminum stress values. These findings indicate that the gyrocopter propeller provides the necessary tensile strength for flight. The tensile and yield values of the propeller do not pose any obstacles in terms of flight configurations (Chawla, 2013).

These three mechanical properties play a critical role in the flight configurations of the propeller. Their measurements are within the required standard range for aluminum, ensuring compliance with aviation safety standards. Deviation from these standard ranges could lead to dislocations during use, posing risks to aviation safety. The inclusion of these values within the desired range demonstrates that the manufactured propeller meets all required flight standards. Thus, propeller blades flying within the specified value range will not exhibit any dislocations, damage, or deterioration. Longer service life is offered by propellers that do not manifest damage or defects during use. Therefore, it has been demonstrated that manufactured propellers can have a high service life when used within the desired strength range.

Table 4. Hardness test results.

Sample Code	Rockwell (HRB)	Brinell (HB)	Vickers (HV)
1	51	90	95
2	52	90	95
3	52	90	95

The average hardness value of the samples following the hardness test is 90 HB, which closely aligns with the standard measurements of aluminum 6061-T6. Through the conducted heat treatments, the hardness value has been maintained at the indicated level. This preservation is due to the undesirability of excessive hardness in the flight configuration of the propeller. Consequently, the hardness value of the produced propeller resembles that of previously manufactured aluminum 6061-T6 in terms of hardness. This value signifies a moderate-soft hardness conducive to flight safety. Given that propeller blades must execute various movements during flight, excessive hardness is undesirable. Hence, the resultant moderate-soft value is deemed suitable for flight safety.

4. Conclusion

In conclusion, it has been demonstrated that the 6061-T6 aluminum alloy propeller blades possess mechanical properties that align with and exceed the rigorous standards required for aviation applications. The fatigue life was confirmed to endure significant cyclic loading, with the potential for infinite fatigue life under certain stress conditions, ensuring long-term durability in flight operations. The tensile strength was validated to meet industry standards, indicating that the material can withstand operational stresses without compromising structural integrity. Additionally, the hardness measurements were found to strike an optimal balance between strength and ductility, contributing to the propeller's resilience and safety. These findings affirm that the 6061-T6 aluminum alloy is suitable for the manufacture of propeller blades, ensuring compliance with aviation safety standards and offering the potential for an extended service life under the specified operational conditions.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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