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Fracture and Failure Analysis of Wheel Bolt on Main Landing Gear CN235 220M Aircraft

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Abstrak

Baut roda pesawat CN235 220M merupakan salah satu jenis baut yang krusial untuk menjaga tekanan udara di dalam ban. Komponen ini diketahui mengalami fraktur saat beroperasi. Penelitian ini bertujuan untuk melakukan analisis forensik terhadap mekanisme dan penyebab kegagalan material melalui pengamatan morfologi mikro dan makro, uji komposisi kimia, analisis mikrostruktur, dan uji kekerasan pada baut yang mengalami fraktur, termasuk analisis FEA. Analisis FEA menunjukkan hasil yang memuaskan, yang mengonfirmasi keakuratan lokasi fraktur prematur. Hasil mikromorfologi menunjukkan adanya ujung retakan pada zona inisiasi, yang menjadi titik konsentrasi tegangan. Selain itu, teramati adanya guratan-guratan yang disebabkan oleh pembebanan siklik. Analisis EDS menunjukkan adanya kandungan oksigen yang tinggi pada zona inisiasi, yang mengindikasikan adanya retakan yang disebabkan oleh korosi. Seiring berlanjutnya pembebanan siklik, secara bertahap area penampang baut terkikis hingga kelelahan material menyebabkan fraktur akhir. Rekomendasi yang dapat diambil seperti mengendalikan faktor lingkungan menggunakan penghambat karat, mengendalikan kelembaban, menerapkan strategi pemeriksaan dan pemeliharaan yang tepat, meningkatkan perilaku mengemudi pilot, dan mengevaluasi kembali desain baut dan sifat material dapat membantu meningkatkan kinerja dan mengurangi risiko kegagalan.

Kata kunci: *CN235 220M; baut roda; kelelahan; matalografi; scanning electron microscope; analisis kegagalan*

Abstract

The wheel bolt of the CN235 220M aircraft is a type of fastener crucial for maintaining air pressure within the tire. It was discovered that this component fractured during operation. This study aims to conduct forensic analysis on the mechanism and causes of material failure through micro and macro morphological observations, chemical composition tests, microstructural analysis, and hardness testing on the fractured bolt, including FEA analysis. The FEA analysis shows satisfactory results, confirming the accuracy of the premature fracture location. Micro-morphology results showed a crack tip in the initiation zone, which became a stress concentration point. Additionally, striations caused by cyclic loading were observed. EDS analysis revealed a high oxygen content in the initiation zone, indicating a corrosion-assisted crack. As cyclic loading continued, it gradually eroded the bolt's cross-sectional area until the material's fatigue led to final fracture. Recommendations can be taken such as controlling environmental factors using rust inhibitors, controlling humidity, implementing appropriate inspection and maintenance strategies, improve pilot driving behavior, and re-evaluating bolt design and material properties may help enhance performance and reduce failure risk.

Keywords: *CN235 220M; wheel bolt; fatigue; metallography; scanning electron microscope; failure analysis*

1. Introduction

The integrity and reliability of the main landing gear (MLG) components are vital for the safety of flight operations. Among these components, the wheel bolt plays a crucial role in maintaining air pressure within the tire and ensuring structural stability during various phases of flight, especially during takeoff and landing. The CN235 is a light transport aircraft owned by the Indonesian Air Force, averaging 400 flight hours annually. Thus, the reliability of its MLG system is critical, making the performance analysis of the wheel bolt essential. The CN235 220M aircraft's wheel bolt was found fractured at the shank during use. The bolt in question is an M15 x 80 double hex flange bolt. It operates at temperatures ranging from 10°C to 200°C, with a torque of 28 ft lbs [1-3]. The sudden fracture of the wheel bolt in the CN235 MLG prompted a thorough investigation into the material properties and failure mechanisms involved. Understanding these aspects is crucial to prevent future failures and ensure the continued safety and reliability of the aircraft.

Numerous researches have been investigated the fatigue and fracture modelling of the bolts, such as Abdelrahman et al. analyzed failure of fatigue failed on galvanized steel bolt [4]. Molaei et al. introduced a comparative analysis of classical methods for crack propagation of the connecting bolts [5]. Shafie et al. developed advanced numerical tools for progressive damage simulation in turbine tube bolts [6]. Fu et al. introduced computational approaches for fracture prediction on a bolt [7]. He et al. explored advanced material characterization on bolt [8]. While our work extends the material insights by applying them to numerical simulations and life estimation methodologies in order to provide a comprehensive of damage mechanism. This study will contribute to the broader field of materials science and engineering, providing insights into the behavior of critical aircraft components under operational stress. The knowledge gained will not only enhance the safety and performance of the CN235 but also aid in the development of more durable materials and structures for future aircraft designs.

2. Material and Method

2.1. Experimental section

To analyze the failure of the CN235 wheel bolt, several experimental tests were applied to understand the material properties and failure mechanisms. First, a spectrophotometric test was conducted to analyze the chemical composition of the bolt material. This process involved sample preparation by cutting and polishing the surface of a bolt before measuring it using a Bruker Q2 ION spectrophotometer. Sequentially, macro observations were performed to identify visible surface damage, such as crack patterns or discoloration. Detailed observations were made using Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) with a Thermo Scientific Quanta 650.

In the next stage, microstructural analysis of the base material was performed using metallography. The bolt sample was cut and polished to achieve a smooth, reflective surface. Etching was done using a solution of 95ml ethyl alcohol 96% + HNO_3 5ml for 1 minute. Finally, micro Vickers hardness testing was conducted to measure the material's hardness using an FM 800 Tester. Five points were measured at 1 mm intervals with a 1 kgf load along the bolt shaft to observe changes in hardness values.

2.2. Numerical investigation

To estimate the stress field on the component, static load simulation was performed using open source finite element analysis. This process involved modeling the bolt geometry, determining material properties. In this study a mix of high-quality quadratid elements (second order tetrahedrons), boundary layer refinement, gradual mesh transition and fine meshing near the contact surface were used to ensure better stress acuracy. Adaptive meshing was also applied to refine mesh in high stress regions. Applying preload and applied load on shear force element with the magnitude was based on the aircraft weight and operational force, thus the load was equal to 56.8 Mpa. The symmetric boundary condition was used to simplify the model and was fixed or restrained in all directions because the bolt head is rigidly supported, and simulating to calculate stress distribution. The simulation results were then validated with experimental data to identify critical locations susceptible to failure. Based on this analysis, recommendations for improving material lifespan, such as design modifications or using stronger materials, can be provided.

3. Results and Discussion

Here are the results from a series of observations and tests conducted to investigate the factors contributing to failure and to prevent future accidents. The spectrophotometric results confirm the bolt material as AISI H13, consistent with standard aerospace-grade selections for high-stress applications detailed composition is shown in the Table 1.

Table 1. Chemical composition of bolt materials using Spectrophotometric analysis.

No.	65/24-S184 (%)	Standard deviation	Standard AISI H13
C	0.412	0.019	0.32-0.45
Si	0.874	0.018	0.80-1.20
Mn	0.318	0.0047	0.20-0.50
P	0.017	0.0001	<0.03
S	0.016	0.0002	<0.03
Cr	5.141	0.098	4.75-5.50
Mo	1.278	0.028	1.10-1.75
Ni	0.067	0.005	0.3
Cu	0.056	0.0087	0.25
Al	0.0061	0.0015	-
Co	0.006	0.001	-
Mg	<0.0050	0.0001	-
Nb	<0.0050	0.0013	-
Ti	<0.0030	0.00008	-
V	0.321	0.013	0.80-1.20
W	<0.100	0.003	-
Fe	91.5	0.139	Balance

Visual inspection of the fracture surface of the failed bolt was conducted. Figure 1 shows a macrograph of the fractured bolt. Macroscopically, a crack tip is observed in the crack initiation zone. The crack then grew gradually until the effective cross-sectional area reached a critical point, resulting in an instantaneous final fracture. The fracture surface exhibited a flat and wavy profile, indicating that crack propagation occurred due to shear lips and a mixed-mode fracture. Additionally, the surface roughness changed from smooth to coarse in the direction of crack propagation, suggesting that the material had experienced cyclic loading and a transformation in the fracture mode [3].

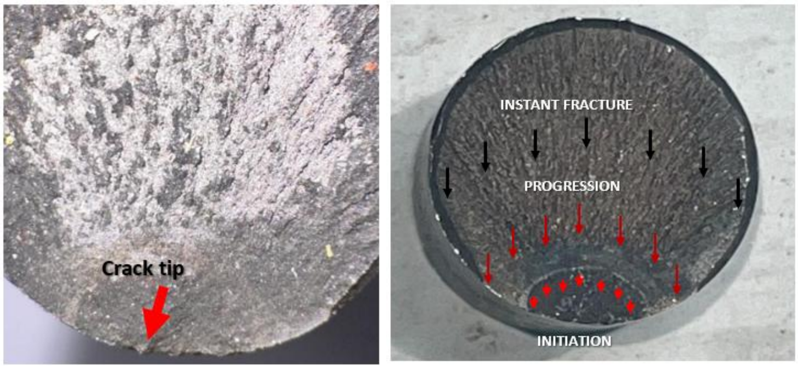


Figure 1. Macrograph of fractured bolt

Figure 2 shows metallographic analysis of the CN235 wheel bolt observed with SEM at high magnification. SEM observations revealed a martensitic microstructure with carbides precipitating at the grain boundaries and within the grains. Martensite appeared as needle-like or plate-like structures with rough surfaces and high contrast. The carbides were fine particles evenly distributed throughout the matrix.

Based on spectrophotometric analysis, the carbon content was found to be 0.4%, classifying the material as hypoeutectoid steel. Martensite forms in hypoeutectoid steel subjected to quenching (rapid cooling) and is subsequently tempered, causing carbide precipitation within the martensite. This structure provides an optimal combination of hardness, strength, toughness, and wear resistance, making the material highly suitable for aviation applications. The homogeneity in carbide distribution also indicates good material quality and well-controlled manufacturing processes.

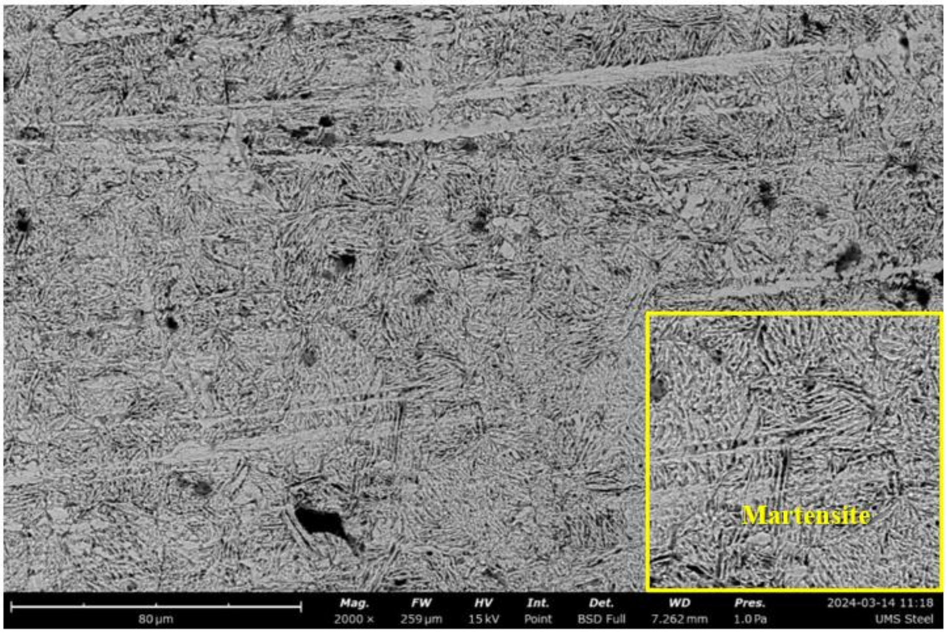


Figure 2. SEM image of bolt's microstructure

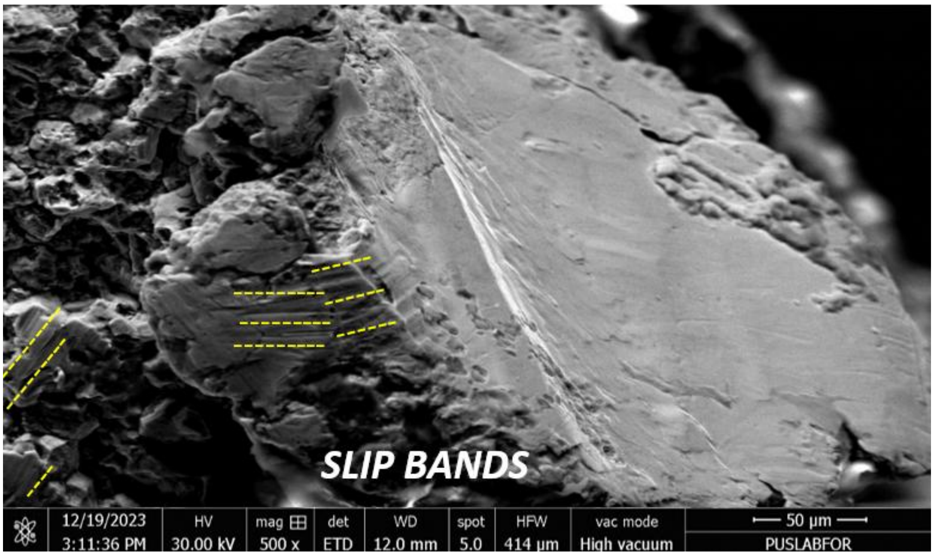


Figure 3. Slip bands appearance on the fracture surface

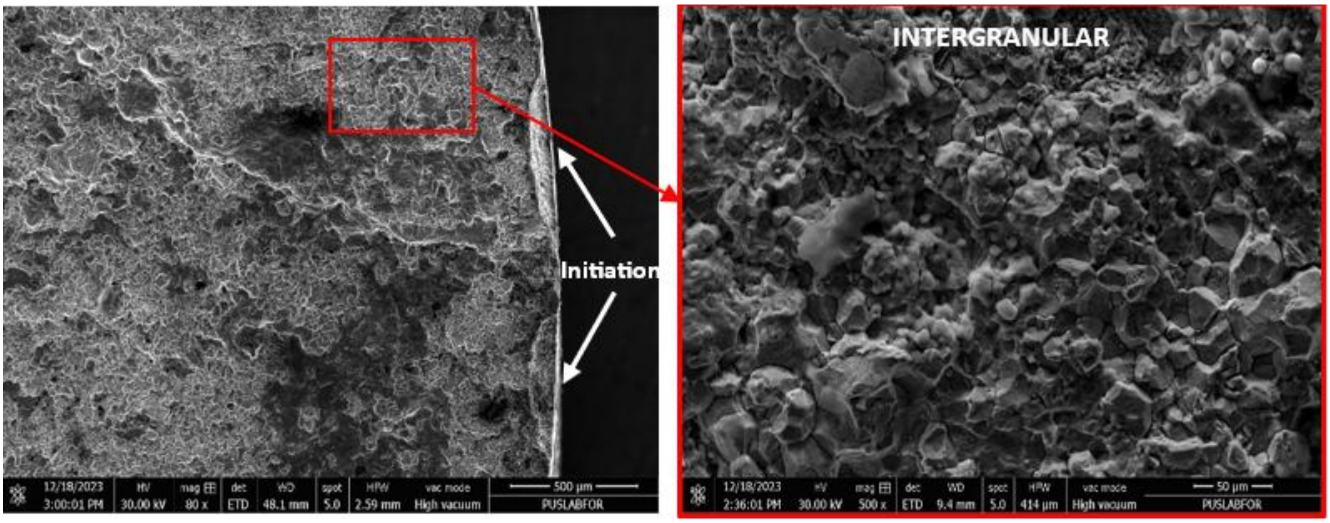
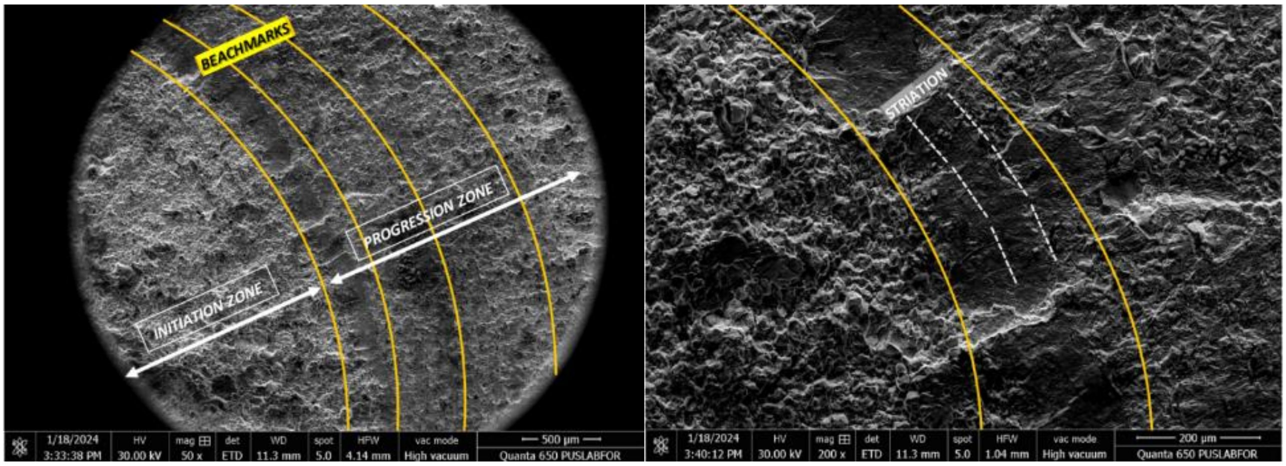


Figure 4. Initiation zone at the fractured surface

Figure 3 shows SEM observations that revealed slip bands and an initiation zone on the outer surface of the component. Cyclic slip forms at stress amplitudes below the yield limit. Slips tend to occur on the material surface due to less restriction on their movement. Slip occurs from localized irreversible deformation caused by concentrated cyclic loading. The newly exposed material surface becomes covered by an oxide layer, leading to strain hardening. Consequently, subsequent slips accumulate and form microcracks that can continue to grow under further cyclic loading.

In the initiation zone, cracks were observed propagating through grain boundaries. Figure 4 indicates grain boundary weakness due to corrosion, which accelerates crack growth. At higher magnification (200x), striations were observed, implying single-cycle stress on the fatigue crack. Striation patterns (Figure 5) are perpendicular to the direction of crack propagation. The variation in striation pitch indicates non-uniform loading cycles.



(a) (b)

Figure 5. SEM images of bolt's (a) fractured surface; and (b) higher magnification showing striation step

The initiation and propagation zones were analyzed using EDS. Figure 6 shows a higher oxygen content (17.6%) in the initiation zone. This supports the hypothesis that corrosion played a significant role in the failure mechanism and concludes that the failure occurred due to corrosion-assisted fatigue cracking. Corrosion fatigue can occur under cyclic loading in a corrosive environment because slip bands facilitate anodic dissolution, which then grows into a crack initiation zone. The fatigue behavior of a material can drastically change in the presence of oxygen and moisture in the air. Similar findings have been consistent with others, showing that the combination of cyclic loads and a corrosive environment accelerates fatigue [14-16]. Table 2 indicates the micro Vickers hardness test results, which showed an increase in hardness near the fracture area, no longer complying with the standard. These results validate the occurrence of cyclic hardening due to cyclic loading in the stress concentration area.

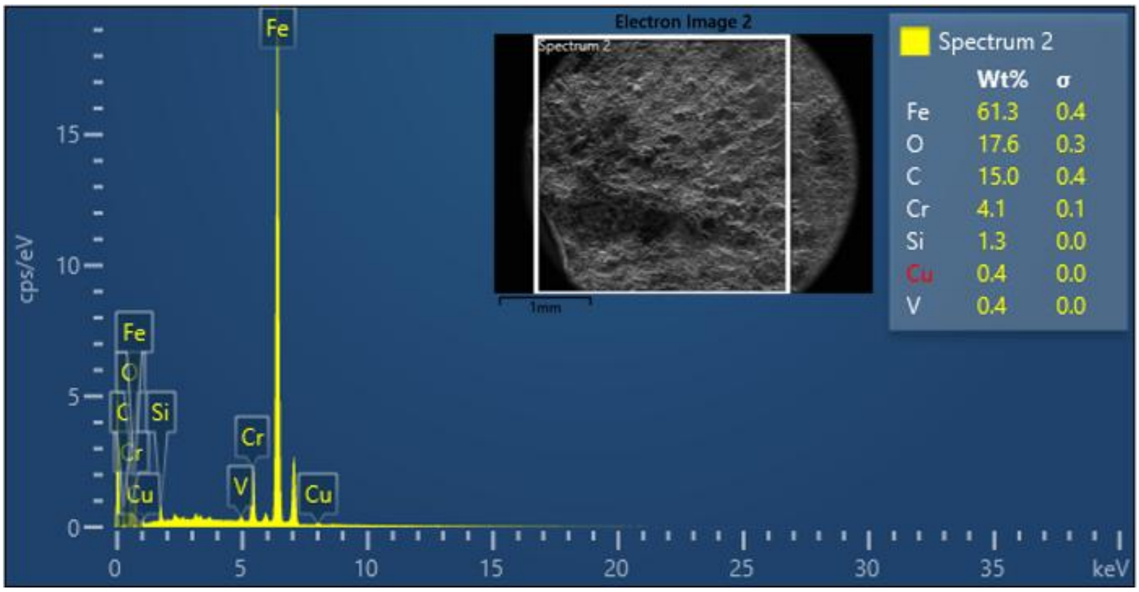
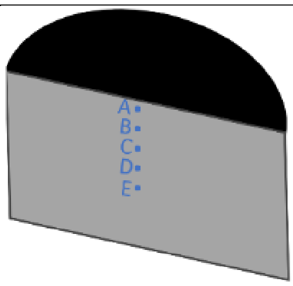


Figure 6. EDS results of the fractured surface

Table 2. The results of the micro Vickers hardness test and the indentations.



	d1	d2	HVN
Point A	61.24	57.5	526.1
Point B	58.57	58.57	523.6
Point C	64.28	56.12	511.6
Point D	62.35	60.18	494
Point E	61.77	61.77	481.3

Figure 7 shows finite element analysis of the wheel bolt. The load applied to the bolt accommodates the overall weight, which is uniformly distributed on the aircraft's wheels, and tolerates the spike load that occurs during the landing process. The maximum shear stress and equivalent (Von-Mises) stress analysis results with static loading showed values of 50.9 MPa and 93.2 MPa, respectively, with a maximum elastic strain of 0.0075 concentrated at the fatigue failure initiation zone. Ideally, the maximum stress would undergo infinite cycles based on the available SN curve of the material. Thus, premature failure is discussed. This validates that the critical location has the highest potential to become a fatigue failure initiation zone. Additionally, the results show that the bolt design concentrates stress in the shank area, making it stronger than the threads.

Visual observations and load simulations indicate that the failure location in this case is a critical point with a high potential for failure initiation. As the wheel rotates, the CN235 wheel bolt operates under cyclic loading. Static loads from

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the aircraft's weight, dynamic loads during taxiing, and shock loads during landing create high local stress in the stress concentration area (critical point). This stress contributes to cumulative damage, beginning with the formation of microcracks (slip bands) on the outer surface of the bolt. Slip bands then nucleate into the initiation zone as loading continues until fracture [9-11].

During aircraft operation, crack growth from the initiation zone is vulnerable to external influences. Observations showed high oxygen content and intergranular fracture patterns in the initiation zone. This indicates accelerated crack growth due to intergranular corrosion. Crack growth in the initiation zone continues to reduce the effective area, increasing stress in the remaining area. Consequently, material fatigue occurs and culminates in the final fracture [12-15].

The type of failure observed is fatigue failure with fracture propagation. Recommendations to prevent similar failures include reducing loading cycles and controlling environmental factors, such as using rust inhibitors, controlling humidity, or implementing appropriate inspection and maintenance strategies. Taking action to improve the most effective pilot driving behavior such as mooth and consistent throttle application ensures proper acceleration, inadequate rudder input or overcorrection can lead to asymmetric thrust or aerodynamic drag, proper flare technique results in a smooth landing, while immediate deployment of reverse thrust and brakes ensures rapid deceleration without undue stress on the airframe, and poor control during landing can lead to a hard landing and tailstrike. Additionally, re-evaluating bolt design (Figure 7) and material properties may help enhance performance and reduce failure risk.

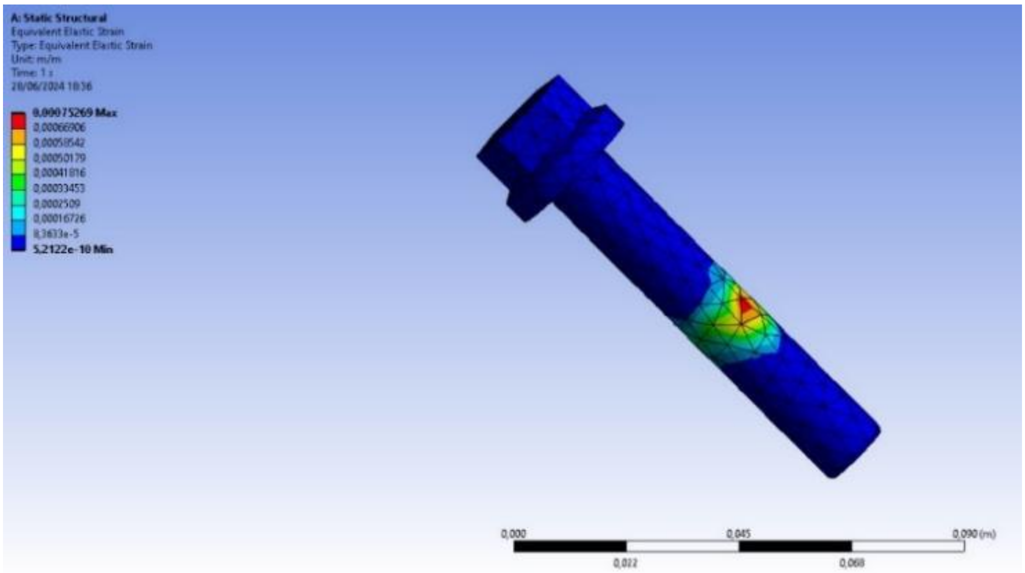

Figure 7. Von-Mises stress of studied bolt using finite element analysis

4. Conclusions

The forensic analysis of the fractured CN235 220M wheel bolt revealed that the primary cause of failure was corrosion-assisted fatigue cracking. Macroscopic and microscopic observations indicated that the crack initiation began in a high-stress concentration area with localized slip bands and developed into a fracture as the crack propagated. SEM analysis and EDS testing confirmed the presence of corrosion products in the initiation zone, contributing to the accelerated crack growth. Moreover, hardness testing showed cyclic hardening in the fracture area, validating the occurrence of fatigue. Stress analysis confirmed that the initiation zone experienced the highest local stress concentration. To prevent such failures in the future, the study recommends improving bolt design, considering the fatigue resistance of the materials used, improve the most effective pilot driving behavior, and implementing rust inhibitors and regular inspections to detect early signs of corrosion. These measures will enhance the durability and reliability of the CN235 wheel bolt, contributing to safer and more efficient flight operations.

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