

Article

Analysis of Cracking of 7075 Aluminum Alloy High-Lock Nuts

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Abstract: A 7075 aluminum alloy high-lock nut developed multiple cracks after 3 years of exposure to atmospheric conditions. To identify the root cause of the cracking, a comprehensive analysis was conducted, including chemical composition, macro- and micro-fracture analyses, microstructural analysis, mechanical performance verification, and residual stress testing. The results indicated that stress corrosion was the cause of the fractures. After assembly, the crimping part of the high-lock nuts exhibited significant residual tensile stress and stress concentration, which led to stress corrosion in the industrial atmospheric environment. A comparison of the residual tensile stress in high-lock nuts with wall thicknesses of 0.75 mm, 1.00 mm, and 1.25 mm revealed that the residual tensile stress at the crimping part decreased as the wall thickness increased. Additionally, stress corrosion testing demonstrated that high-lock nuts with a wall thickness of 1.25 mm did not undergo stress corrosion within 30 days.

Keywords: 7075 aluminum alloy; high-lock nut; stress corrosion; residual stress; wall thickness



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1. Introduction

Aluminum alloy 7075 was first used in the aerospace industry and is still widely used today as a high-strength alloy. As an aluminum–zinc–magnesium–copper alloy, 7075 is characterized by its high specific strength and low density, making it ideal for demanding applications in aerospace [1], mold processing [2], mechanical equipment [3] and fixtures, etc. Its superior mechanical properties, particularly in terms of strength and stress corrosion resistance, have cemented its role in the production of critical aerospace components such as wing beams, spacer frames, and high-lock nuts, where structural integrity is paramount.

Common fracture modes of aluminum alloys include fatigue fracture, large stress overload fracture, stress corrosion fracture [4,5], etc. Different fracture modes have corresponding fracture characteristics [6]. Extensive research has been conducted to investigate the cracking mechanisms of high-strength aluminum alloys, particularly those associated with fatigue, stress overload, and stress corrosion cracking (SCC). Several studies have specifically focused on the cracking behavior of high-strength aluminum alloys, including the mechanisms of crack initiation and propagation under different loading conditions. Branco [7] observed that 4% and 8% pre-strain deformation in 7050-T6 aluminum alloy resulted in the formation of a substantial number of dislocations. These dislocations accumulated near slip bands and grain boundaries, which facilitated the initiation of fatigue cracks and progressively reduced the low-cycle fatigue life of the alloy. Similarly, Azadi et al. [8] studied the low-cycle fatigue behavior of A356-T0 and A356-T6 alloys at both room temperature and elevated temperatures. They discovered that the heat-treated alloy at elevated temperatures exhibited the longest fatigue life. Additionally, they noted a correlation between the distance of striations on the fracture surface and the fatigue life; specifically, as the transverse width of the striations increased, the fatigue life decreased. Pao and Holtz [9] studied the fatigue crack growth behavior of 7075 aluminum alloys

under different aging conditions, environments, and load ratios. They found that fatigue crack growth rates increase in more aggressive environments (vacuum < air < NaCl), with hydrogen embrittlement as a key mechanism, and that higher stress ratios further accelerate crack growth. In addition, the impact of aging conditions and environmental factors on the crack growth behavior of aluminum alloys has been widely studied using techniques such as electron microscopy and fatigue testing under controlled environments. Rafiq A. Siddiqui et al. [10] investigated how aging temperature and duration impacted the fatigue properties of 6063 aluminum alloys. Their research indicated that the vacancy diffusion mechanism was crucial in the formation of Guinier–Preston (GP) zones, where a fine quasi-stable phase is precipitated due to uniform nucleation during the dissolution process. This phase was structurally similar to the primary matrix, with coherence between the two, which disrupted the lattice regularity and increased the alloy's fatigue defects. Schwarzenböck et al. [11] performed SCC tests on 7085 aluminum alloy in humid air and determined that crack initiation was driven by hydrogen embrittlement rather than an anodic reaction.

Additionally, the SCC behavior of aluminum alloys under corrosive environments has been extensively studied. Fujii et al. [12] demonstrated that corrosion pitting in NaCl solution initiates along planes of concentrated stress and strain. Euesden et al. [13] used in situ observation techniques to reveal that surface-connected gas pores combined with Mg-based intermetallic compounds often initiate SCC in 7xxx alloys. Currently, the methods to enhance the stress corrosion resistance of aluminum alloys include compositional optimization, heat treatment, and surface modification. Wang et al. [14] demonstrated that trace Ag additions refine grain boundaries and stabilize precipitates, reducing SCC susceptibility. Reda et al. [15] revealed that retrogression and reaging (RRA) enhance SCC resistance by promoting coarse grain boundary precipitates that act as hydrogen traps, reducing segregation at grain boundaries. Liu et al. [16] showed that optimized heat treatments enhance corrosion resistance and mechanical properties by improving precipitate distribution in 7075 aluminum alloys. Bao et al. [17] found that advanced shot peening techniques, particularly laser peening, induce deep compressive stress layers, effectively suppressing SCC initiation and propagation. Sun et al. [18] introduced a novel electromagnetic shocking treatment (EST), which modifies grain boundary microstructure and improves SCC resistance by promoting grain boundary wetting, phase transformation, and grain bridging.

In the aerospace sector, 7075 aluminum alloy is often employed in the fabrication of components subjected to high stress and corrosion, such as high-lock nuts used in aircraft assemblies. Specifically, after 3 years of service, high-lock nuts made from 7075 aluminum alloy with MJ6 × 1 specifications were found to have developed cracks. Processing technology for the undercutting—CNC lathe—milling hexagonal—tapping—crimping—surface treatment (yellow anodized)—after about 3 years of use, showed that the cracking phenomenon exists in many portions of nuts. This study aimed to investigate the root cause of cracking in 7075 aluminum alloy high-lock nuts by conducting macro- and micro-fracture analysis, microstructural examination, and mechanical property validation. The findings from this study will provide a foundation for improving the design and manufacturing processes of high-lock nuts, thereby enhancing the reliability in aerospace applications.

2. Materials and Methods

2.1. Aluminum Alloy High-Lock Nuts

The high-lock nuts used in this study were made from 7075 aluminum alloy, with a chemical composition conforming to the AMS-QQ-A-225/9 standard [19]. The primary alloying elements include zinc, magnesium, and copper. The production process of the high-lock nuts strictly follows industry standards and includes the following stages: cutting, CNC turning, hexagonal milling, threading, crimping, and surface treatment. The surface treatment involves applying a yellow chromate conversion coating to enhance corrosion resistance. The structure of the high-lock nut is divided into two parts: the process part

and the working part, connected by a break-off groove. During installation, the process part, equipped with a wrench structure, helps tighten the nut until the specified torque is reached, causing the break-off groove to fracture and detach the process part, thus completing the assembly. This separation not only reduces the weight of the fastener but also ensures proper preload, providing high resistance to loosening. The nuts studied have a standard size of $MJ6 \times 1$, with a height of 14 mm, an outer diameter of 10 mm, a nominal inner diameter of 6 mm, a wall thickness of 0.75 mm, and a thread pitch of 1 mm. The tightening torque is 5.1 N·m, with an applied loading of 8.5 kN, and the nuts are subjected to continuous tensile load after assembly.

Vickers hardness tests were conducted on the longitudinal cross-section of the cracked nut using an FV-800 Vickers hardness tester FT (Yokohama, Japan). The methodology employed was in accordance with the ASTM E92 standard [20], utilizing a test load of 49 N and a dwell time of 15 s, with a measurement error within a range of $\pm 5\%$. The measured hardness values in the transverse direction were 154 HV, 157 HV, and 152 HV, with an average of 154 HV, and those in the longitudinal direction were 151 HV, 153 HV, and 156 HV, with an average of 153 HV. According to ASTM A370 standard [21], this equates to approximately 502 MPa, which meets the required material specification of ≥ 469 MPa.

2.2. Microstructure Characterization

The microstructure of the failed high-lock nuts was analyzed using several advanced microscopy techniques. The fracture morphology and microstructural abnormalities were examined using an EVO18 scanning electron microscope (SEM) ZEISS (Jena, Germany). The SEM was also equipped with an energy-dispersive X-ray spectroscopy (EDS) system for elemental analysis, specifically to detect the presence of corrosive elements on the fracture surface. Additionally, a Spectra 300 transmission electron microscope (TEM) FEI (Waltham, MA, USA) was employed to further investigate the distribution of second-phase particles within the grains and along the grain boundaries. The samples were taken from the longitudinal core of the cracked nuts and prepared using ion thinning techniques.

2.3. Residual Stress Testing

Residual stress measurements were conducted using the Xstress 3000 X-ray residual stress analyzer Stresstech (Finland, Europe). This instrument determines residual stress by measuring the strain in the material through X-ray diffraction of the crystal planes. The analysis focused on the circumferential region of the nut, with particular attention to the crimping part before and after installation. Residual stress testing was conducted at three crimping positions around the nut circumference, separated by 120° . The specific test locations are illustrated in Figure 1.

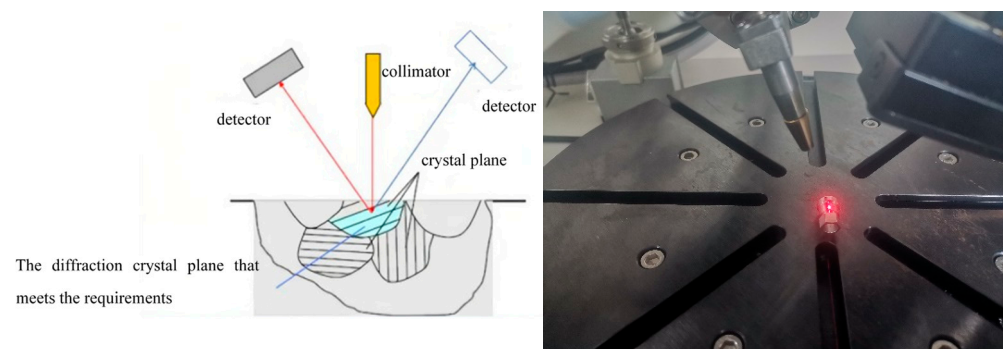


Figure 1. Principle and process of X-ray residual stress measurement.

2.4. Stress Corrosion Testing

Stress corrosion testing of the aluminum alloy high-lock nuts was conducted according to the ASTM G44 standard [22], utilizing an alternate immersion method. The test subjects included 100 high-lock nuts for each of the three wall thicknesses: 0.75 mm, 1.0 mm, and

1.25 mm. The alternate immersion process involved submerging the nuts in a 3.5 wt% NaCl solution with a pH of 6.5 for 10 min, followed by air drying for 50 min. This cycle was repeated for 30 days. After the test period, the numbers of high-lock nuts exhibiting stress corrosion cracking (SCC) were compared to evaluate the influence of wall thickness on the SCC resistance of the nuts.

3. Failure Analysis of High-Lock Nuts

3.1. Macroscopic Appearance of Cracked Nuts

A macroscopic examination was performed on the cracked 7075 aluminum alloy high-lock nuts. As shown in Figure 2, the cracks were located within the deformation zone of the nut's locking structure and extending axially. The surface exhibited partial damage to the yellow oxide film, which appeared to have been caused during disassembly. No significant plastic deformation was observed near the fracture, and the fracture surface exhibited an intergranular pattern.

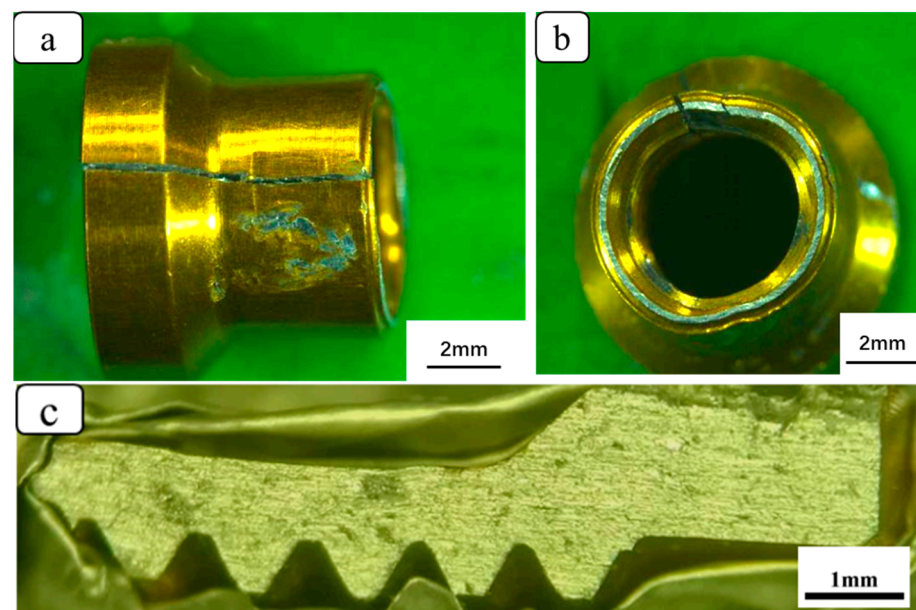


Figure 2. Macroscopic appearance of the cracked high-lock nut: (a) macroscopic physical appearance of the cracked nut; (b) macroscopic appearance from the right-hand side; (c) macroscopic fracture surface morphology.

3.2. Chemical Composition

To analyze the chemical composition of the cracked nuts, samples were extracted from the fissured exterior. The composition was determined using an OPTIMA7000DV inductively coupled plasma (ICP) spectrometer PE (Waltham, MA, USA). As shown in Table 1, the chemical composition of the cracked nuts was in accordance with the specifications for 7075 aluminum alloy as outlined in AMS-QQ-A-225/9.

Table 1. Chemical composition of cracked nuts (wt/%).

Ingredient	Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	Al
Split nuts	5.58	2.42	1.58	0.25	0.36	0.31	0.20	0.16	Remainder
Standardized requirements	5.1~6.1	2.1~2.9	1.2~2.0	0.18~0.28	≤0.50	≤0.40	≤0.30	≤0.20	Remainder

3.3. Microscopic Fracture Morphology

The fracture morphology was observed using an EVO18 scanning electron microscope (SEM) ZEISS (Jena, Germany). For detailed analysis, the fracture was segmented into three distinct regions, labeled A, B, and C, as illustrated in Figure 3. The surface was relatively rough, exhibiting intergranular features. Most of the fracture surface exhibited no evidence of corrosion products, with only a limited region in the vicinity of the notch displaying corrosion products and striations. Additionally, no evidence of metallurgical defects, such as porosity or inclusions, was observed.

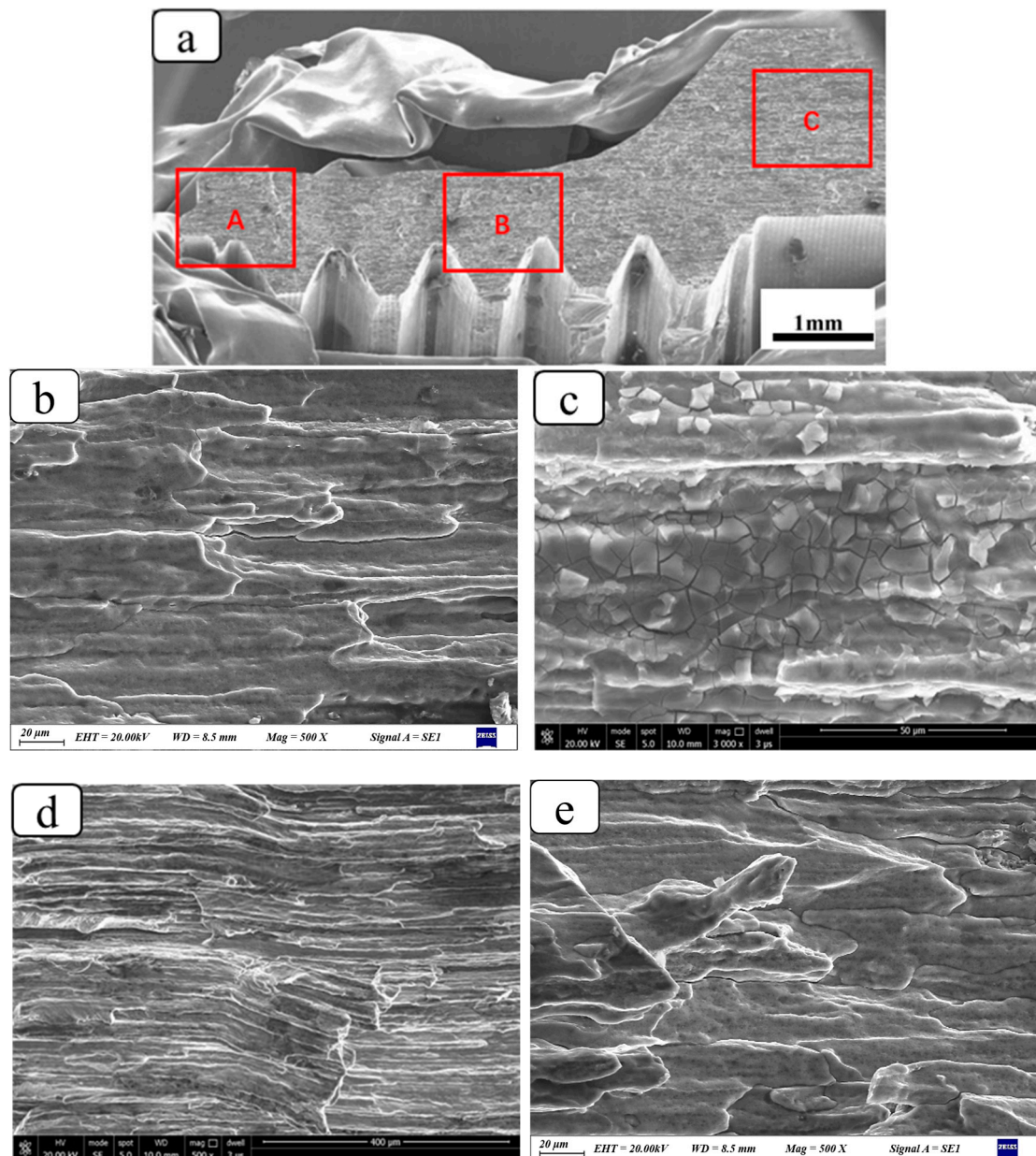


Figure 3. Microscopic morphology of the fracture surface: (a) macroscopic fracture surface morphology; (b) morphology of zone A; (c) striations in zone A; (d) morphology of zone B; (e) morphology of zone C.

A micro-area compositional analysis of the original crack fracture was conducted using an energy dispersive spectroscope (EDS) attached to the scanning electron microscope (SEM). The elemental composition is provided in Table 2. In addition to the elements

characteristic of the 7075 aluminum alloy, the fracture surface also contains corrosive elements, such as chlorine (Cl) and sulfur (S), with a higher content of oxygen (O).

Table 2. EDS analysis results of the original fracture surface of the cracked nut.

Element	O	Mg	Al	S	Cl	Fe	Co	Ni	Zn
Content	35.96	9.88	44.03	1.89	1.40	0.30	0.21	0.20	6.13

3.4. Microstructure Analysis

Microstructure analysis was performed on samples extracted from the cracked area in both the longitudinal and transverse directions. The samples were prepared with the ASTM E3 standard [23], while the corrosion procedure followed the ASTM E407 standard [24]. The etching solution consisted of 2 mL HF, 5 mL HNO₃, 3 mL HCl, and 190 mL H₂O. After etching, the crack morphology and microstructure were observed using an Imager A1m optical microscope ZEISS (Jena, Germany), as illustrated in Figure 4. The fracture presents an intergranular morphology, displaying secondary cracks and branched ends. The cross-sectional grains are equiaxed and uniform, while the longitudinal section displays an elongated fibrous morphology. The microstructure did not exhibit the typical overburn characteristics, such as thickened grain boundaries, triangular grain boundaries, or intragranular remelting spheres, which are typical in aluminum alloys.

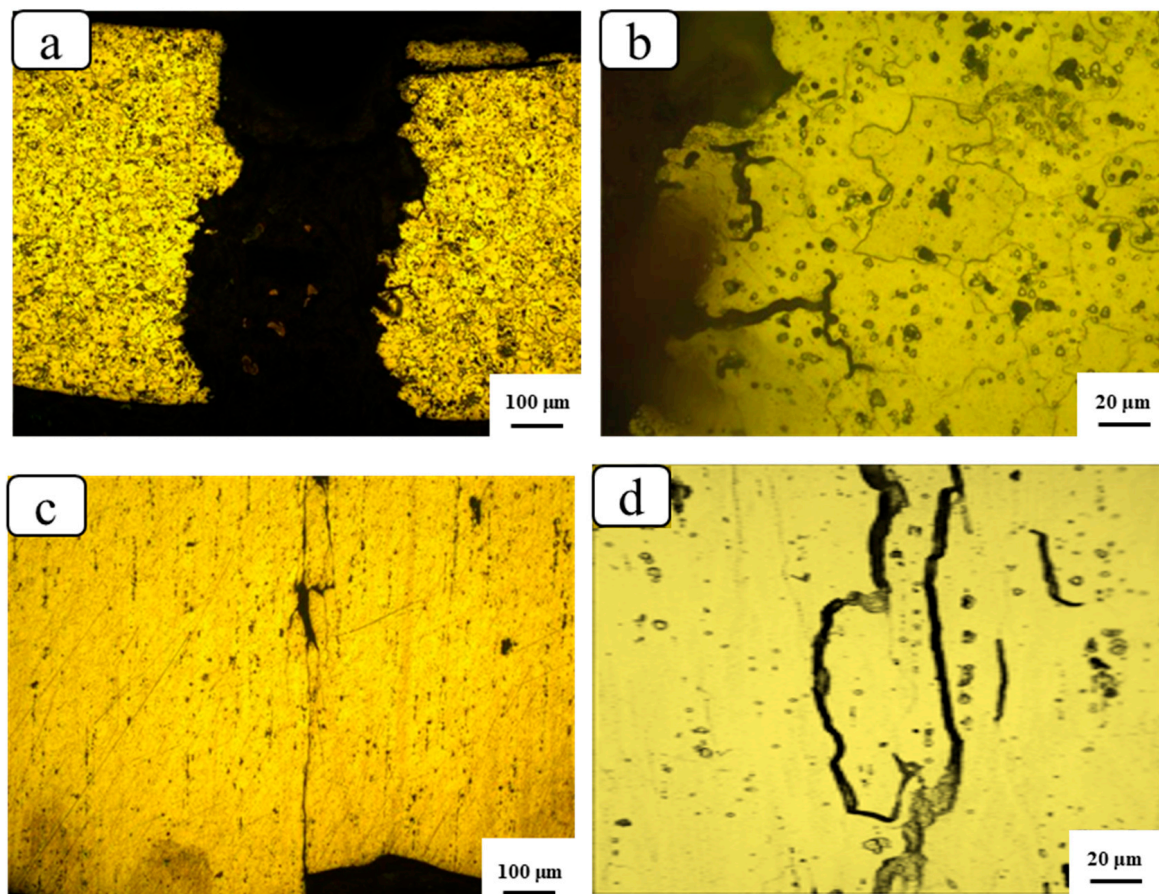


Figure 4. Crack morphology and microstructural characteristics: (a) crack cross-section at 100 $\times$; (b) intergranular secondary crack at 500 $\times$; (c) longitudinal section of crack at 100 $\times$; (d) intergranular secondary crack at 500 $\times$.

3.5. Analysis of Intragranular and Grain Boundary Precipitates

Samples from the longitudinal center of the cracked nut were subjected to ion thinning, and their morphology was examined using a Spectra 300 transmission electron microscope (TEM) FEI (Waltham, MA, USA). The analysis revealed a significant presence of finely dispersed precipitates within the grains, which contribute to the material's strengthening. At the grain boundaries, the precipitates were distributed in a discontinuous chain-like pattern, which enhances the resistance of the base material to stress corrosion, as shown in Figure 5.

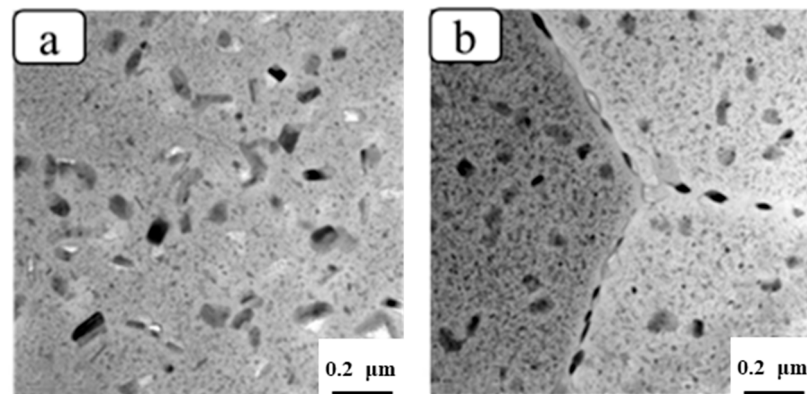


Figure 5. Grain boundary and intragrain precipitates: (a) intragrain precipitates; (b) grain boundary precipitates.

3.6. Residual Stress Analysis

Residual stress analysis was conducted on three unused nuts from the same production batch as the failed nuts to compare the residual stresses at the crimping part before and after installation. An Xstress-3000 X-ray residual stress analyzer Stresstech (Finland, Europe) was employed to ascertain the residual stress at the crimping part of the unused nuts, with a measurement error within a range of $\pm 10\%$. Subsequently, residual stresses were measured in the circumferential direction at the crimping part of the nuts, following the same installation procedure as that used for the failed nuts. The specific test results are presented in Figure 6 and Table 3. X-ray diffraction (XRD) is used to measure residual stress, and the calculation formula is derived based on elastic mechanics according to Bragg's law. Elastic mechanics studies homogeneous, continuous, and isotropic media. The grain size of 7xxx series aluminum alloys is relatively small and lacks preferred orientation, so the fitting curve of $\sin^2\Psi$ versus strain is well linear. Measuring stress in the range of $0\text{--}45^\circ$ does not affect the measurement accuracy and can improve testing efficiency. Following the installation procedure, the residual stresses in the circumferential direction at the crimping part of the nuts were found to be tensile and at a relatively high level.

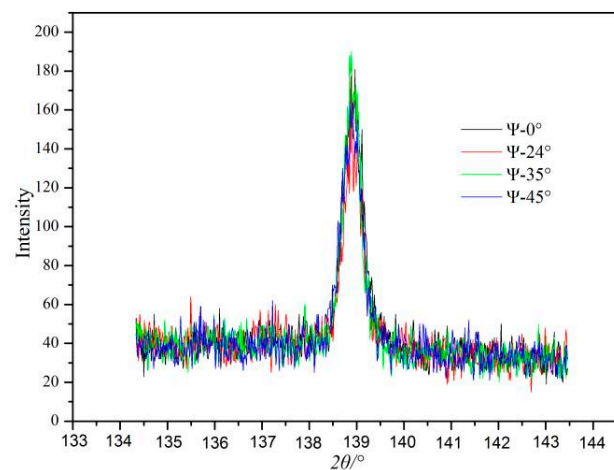


Figure 6. Maximum intensity of X-ray diffraction peaks determined from Ψ .

Table 3. Residual stress test results.

Serial Number	Crimping Position						Average Residual Stress/MPa	
	Crimping 1		Crimping 2		Crimping 3		Not Installed	After Installation
	Not Installed	After Installation	Not Installed	After Installation	Not Installed	After Installation	Not Installed	After Installation
Nut #1	131	268	125	275	107	237	121	260
Nut #2	90	301	113	286	88	282	97	290
Nut #3	79	242	111	331	80	231	90	268

3.7. Oxide Film Layer

The cracked nut was treated with yellow anodizing and acetyl alcohol lubrication on the high-pressure surface before crimping. After service, the oxide film on the crimping part was damaged. Unused nuts from the same batch were examined with an EVO18 scanning electron microscope to evaluate the integrity of the crimping and other surface areas. As can be seen from Figure 7, there are multiple micro-cracks in parallel distribution on the surface oxide film at the crimping part of the high-lock nut, while the oxide film at the non-crimping part is complete without cracking.

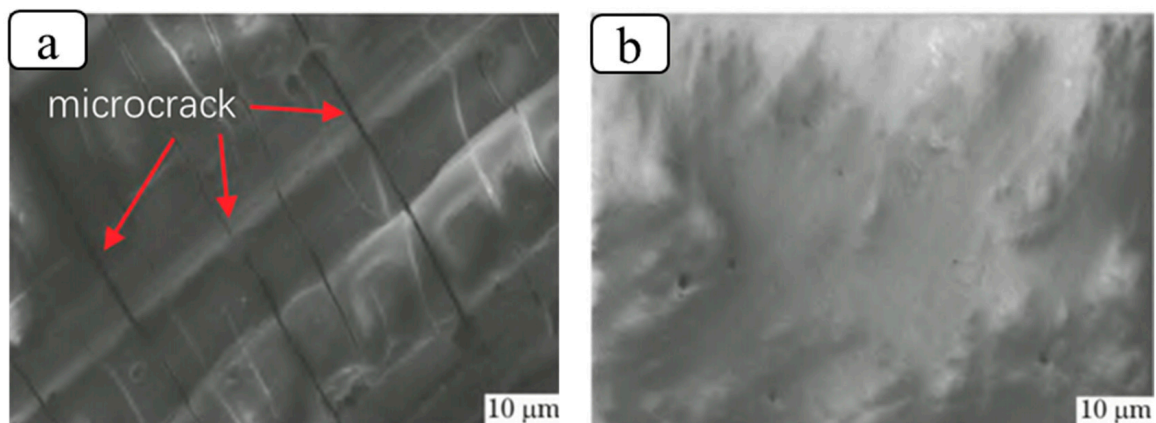


Figure 7. Oxide film morphology on surface of the same batch of unused high-lock nuts: (a) at crimping position; (b) at non-crimping position.

4. Failure Mode Analysis

The hardness and chemical composition of the failed high-lock nut met the specified product standards. Macroscopic examination revealed a fracture surface with an intergranular appearance and no significant macroscopic plastic deformation. Microscopic analysis showed intergranular cracking morphology, a small number of locally visible crazing patterns. EDS analysis of the surface identified the presence of corrosive elements such as Cl and S, along with a higher content of O. The other detected elements are consistent with the composition of 7075 aluminum alloy matrix. Metallurgical examination revealed that the fracture exhibited intergranular characteristics, with secondary cracks and branched crack end morphology. No typical signs of overheating in the aluminum alloy microstructure were detected, ruling out overheating as the cause of intergranular fracture. Transmission electron microscopy (TEM) analysis of the failed nut indicated that the second-phase particles were extensively dispersed within the grains and discontinuously chain-like along the grain boundaries. Residual stress analysis of nuts from the same batch, before and after installation, indicated that the circumferential residual stress at the crimping part was tensile. After installation, the tensile stress significantly increased, reaching close to three times the pre-installation level, as shown in Table 3.

The fracture observed in the 7075 aluminum alloy high-lock nut exhibited typical characteristics of stress corrosion cracking (SCC), including intergranular fracture, the presence of corrosion products, and striations on the fracture surface. Research indicates that [4,25,26] SCC requires tensile stress, the presence of specific corrosive media in the environment, and materials with stress corrosion sensitivity. The aircraft operational environment is complex, and with industrialization, Cl^- ions are commonly present in the atmosphere, providing the necessary corrosive medium for nut cracking. Additionally, sulfur in the environment can also promote stress corrosion cracking by enhancing material embrittlement [27,28]. In the assembly process, friction between the bolt and nut inevitably damages the oxide film on the thread surface, exposing the material directly to the corrosive environment. Microstructural analysis reveals that the intragranular precipitates are diffusely distributed, which strengthens the material matrix, while the intergranular precipitates are distributed intermittently, forming a chain-like pattern. Research shows that the coarse, discontinuous MgZn_2 phase (or its isomorphic AlZnMgCu phase) at the grain boundaries can act as a trap for hydrogen, effectively improving the stress corrosion sensibility of the material [29,30]. Residual stresses, particularly tensile stresses, play a crucial role in exacerbating stress corrosion.

The manufacturing process of high-lock nuts includes a crimping treatment after tapping, during which the threads undergo plastic deformation through extrusion to enhance anti-loosening performance. This step is a significant source of residual stresses due to the extensive deformation involved. The relatively small crimping area is particularly susceptible to stress concentration, which exacerbates the risk of SCC.

5. Residual Stress and Its Impact on Stress Corrosion

Stress corrosion cracking is a phenomenon in which cracks are produced on the surface or inside the material and continue to expand under the combined effect of tensile load and a corrosive environment [31–33]. The formation of stress corrosion cracking needs to have three conditions at the same time: tensile stress, corrosive media, and material stress corrosion sensitivity. The process of stress corrosion cracking is usually divided into two stages: crack initiation and crack expansion [34]. In the crack initiation stage, the applied tensile stress and the residual stress within the material together prompt the material surface or internal micro-defects or weaknesses to develop into macro-cracks. In the crack expansion stage, the cracks continue to expand under the action of the corrosive medium, which ultimately leads to material failure [35].

Residual stress refers to the material in the manufacturing or processing process, due to plastic deformation, phase transformation, welding, and other processes generated by the internal stress; this stress still exists in the material after the external force is lifted [36].

The presence of residual stress can affect the material's susceptibility to stress corrosion. When the residual tensile stress exists within the material, this stress superimposed on the applied tensile stress will reduce the stress threshold for crack initiation, making it possible for stress corrosion cracking to occur at lower stress levels. Therefore, reducing the residual tensile stress within the material can offset part of the effect of the applied tensile stress to a certain extent, increase the stress threshold for crack initiation, and thus improve the stress corrosion resistance of the material [37].

In the crack expansion stage, the magnitude of the residual stress also has an important effect on the crack expansion rate [38]. A large residual tensile stress accelerates the crack expansion, causing the crack to expand to a critical size in a short time, leading to material failure [6]. Smaller residual tensile stresses can slow down the crack expansion rate and prolong the service life of the material. Therefore, reducing the residual stress can effectively improve the stress corrosion resistance of the material and delay the failure time of the material [39,40].

In contrast, if the residual stress within the material is large, especially for parts subjected to high stress such as high-lock nuts, the increase in residual stress will significantly reduce the stress threshold for crack initiation. This means that stress corrosion cracking can occur at lower applied stresses in the material. In addition, larger residual stresses accelerate crack propagation and further reduce the stress corrosion resistance of the material. Therefore, controlling and reducing the level of residual stress constitute one of the important measures to improve the stress corrosion resistance of key components such as high-lock nuts.

In summary, stress corrosion cracking is a complex process that is affected by a variety of factors. By reducing the residual stress, the stress corrosion resistance of the material can be effectively improved, and its service life can be extended. This is of great significance to ensure the safety and reliability of key components such as high-lock nuts.

The primary source of residual stresses in high-lock nuts is the manufacturing and installation processes. The production of aluminum alloy high-lock nuts frequently employs a three-point crimping method, with crimping locations and root cracking at the crimping position, as illustrated in Figure 8. An excessive degree of extrusion or the presence of thin walls in the nut can result in the concentration of stress at the root, leading to the formation of cracks at the crimping position. These cracks serve as initiation points for stress corrosion.

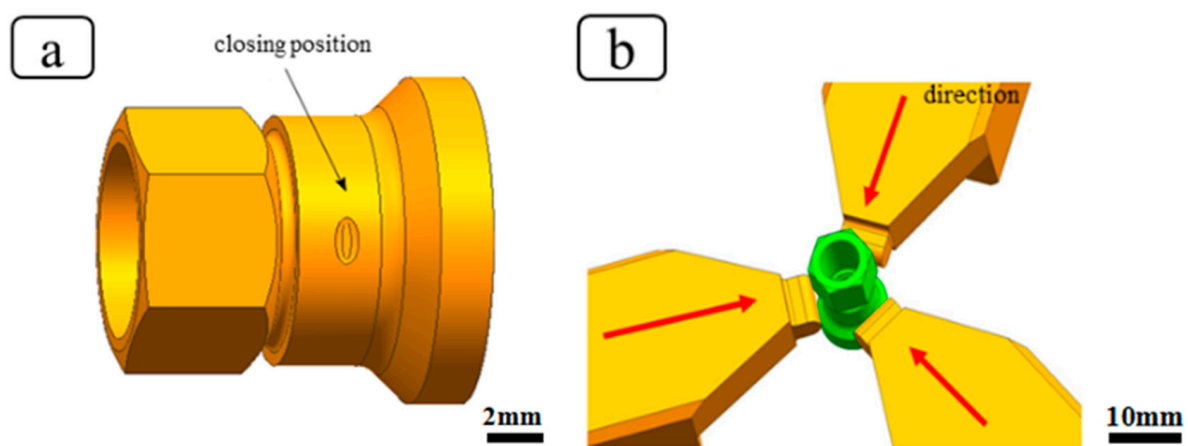


Figure 8. High-lock nut crimping schematic diagram: (a) crimping position; (b) crimping schematic diagram.

5.1. Influence of Nut Wall Thickness on Residual Stress

The standard does not impose a mandatory requirement for the wall thickness of nuts but provides reference values. To investigate the effect of wall thicknesses on residual stresses at the crimping position, specimens with wall thicknesses of 0.75 mm, 1.0 mm, and

1.25 mm were selected. These specimens were prepared following the same manufacturing process as the failed nuts. After assembly, residual stress measurements were conducted using an X-ray residual stress analyzer; specific test data are presented in Table 4. For identical crimping parameters, the residual stresses at the crimping position of the assembled high-lock nuts were consistently tensile. It was observed that the residual tensile stress decreased with increasing wall thickness.

Table 4. Residual stress data for different wall thicknesses.

Wall Thickness	Measured Value/MPa			Average Residual Stress/MPa
	Crimping 1	Crimping 2	Crimping 3	
0.75 mm	253	269	281	268
1.00 mm	210	228	215	218
1.25 mm	157	136	141	145

5.2. Stress Corrosion Testing Verification

In accordance with the ASTM G44 test method, stress corrosion verification was undertaken in a constant humidity and temperature stress corrosion testing machine. The test environment was a solution of 3.5 wt% NaCl at room temperature with a pH value of 6.5. Three groups of high-lock nuts with different wall thicknesses were assembled and subjected to an alternating immersion process. The nuts were immersed in the solution for 10 min and then air-dried for 50 min, and the time taken for stress corrosion cracks to appear was recorded. The specific results are detailed in Table 5. The probability of stress corrosion cracks appearing within 30 days for nuts with a wall thickness of 0.75 mm was approximately 15%. For the nuts with a wall thickness of 1.0 mm, the probability was approximately 10%. Nuts with a wall thickness of 1.25 mm exhibited no significant corrosion cracking within the 30-day observation period.

Table 5. Stress corrosion test results.

Wall Thickness/mm	Number of Specimens with Stress Corrosion Cracks After 30 Days for 100 Products/Pieces
0.75	15
1.00	10
1.25	0

6. Conclusions

(1) The cracking observed in the 7075 aluminum alloy high-lock nuts during service is attributable to stress corrosion. The relatively thin wall thickness (0.75 mm) necessitates a crimping deformation to ensure sufficient locking torque, leading to stress concentration and significant residual tensile stresses. During assembly and subsequent service, the application of additional assembly stresses and operational loads further exacerbate the residual tensile stresses in the circumferential direction, ultimately resulting in stress corrosion cracking under the combined influence of these factors.

(2) To mitigate the risk of stress corrosion cracking in standard 7075 aluminum alloy high-lock nuts, it is recommended that the dimensions of the nut's wall thickness be optimized (for example, to 1.25 mm). The objective of this adjustment is to reduce residual tensile stress levels in the crimping position, thereby enhancing the reliability and quality of nut performance over the course of its service life.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy. But the raw data cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest: Author Shuai Wang was employed by the company China Academy of Launch Vehicle Technology. Authors Qianwang Gao, Yongchun Xu and Yanwei Xu were employed by the company Aerospace Precision Production Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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