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Article

A study on the improvement of corrosion fatigue strength of Al7075-T6 alloy by ultrasonic nanocrystal surface modification technology

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Abstract: Aluminum alloys are extensively used in civil aircraft due to their lightweight, high strength, and excellent formability. However, their susceptibility to corrosion and corrosion fatigue poses a significant maintenance challenge in aviation environments. This study explores the effectiveness of ultrasonic nanocrystal surface modification (UNSM) technology in enhancing the corrosion fatigue strength of Al7075-T6 alloy. Specimens were subjected to controlled corrosion conditions and treated with UNSM either before or after corrosion exposure. Corrosion fatigue tests revealed that UNSM treatment significantly increased fatigue life—by over 140 times compared to untreated corroded specimens—by inducing deep compressive residual stress, increasing surface hardness, and refining surface structure. These results highlight UNSM's potential to delay crack initiation and propagation in corrosive environments, offering a promising surface enhancement strategy for aircraft aluminum alloys.

Keywords: corrosion fatigue, Al7075-T6 alloy, ultrasonic nanocrystal surface modification (UNSM), compressive residual stress, fatigue life enhancement

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1. Introduction

Aluminum alloys have long been fundamental materials in the aerospace industry due to their exceptional strength-to-weight ratio, corrosion resistance, and manufacturability. In particular, high strength 7000 series aluminum alloys—such as Al7075, Al7050, and Al7475—are widely employed in critical aircraft structures including fuselage panels, wings, landing gears, and fuel systems [1,2]. Among them, Al7075-T6 stands out for its superior mechanical properties but is notably susceptible to corrosion fatigue in aggressive environments, particularly where chloride ions are present [3].

Corrosion fatigue, defined as the synergistic interaction between cyclic loading and corrosive attack, can significantly compromise structural integrity and service life. It remains a major concern for aircraft manufacturers and maintenance operations seeking to uphold airworthiness and safety standards. To counteract corrosion fatigue, efforts have traditionally focused on the development of corrosion-resistant alloys, application of protective coatings, and environmental control strategies. However, surface modification technologies are gaining attention for their ability to impart beneficial compressive residual stress and improve surface integrity [3-5].

One such method, Ultrasonic Nanocrystal Surface Modification (UNSM), has demonstrated promise in rejuvenating fatigue performance through severe plastic deformation, nanocrystallization of surface layers, and reduction of crack initiation sites. Previous studies indicate that UNSM treatment can elevate the fatigue life of corroded Al7075 specimens by over an order of magnitude, largely attributed to its ability to suppress crack propagation and enhance surface hardness [5,6].

In this study, the applicability of UNSM treatment is evaluated via corrosion fatigue testing of Al7075-T6 specimens subjected to both pre and post corrosion treatment scenarios. This dual approach aims to elucidate the role of compressive stress in mitigating corrosion fatigue damage and validate the potential of UNSM as a reliable surface enhancement technique for aircraft grade aluminum alloys.

2. Materials and methods

2.1. Material

The aluminum alloy used in this study is Al7075-T6, selected for its high strength and widespread application in aircraft structures. The alloy's chemical composition and mechanical properties are summarized in Tables 1 and 2. This material meets the requirements of Aerospace Material Specification (AMS) 4045 standard, which is the specification for Al7075-T6 alloys used in aerospace applications.

Table 1. Chemical compositions of Al7075-T6 (wt%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.091	0.112	1.68	0.009	2.598	0.208	5.364	0.02	Balance

Table 2. Mechanical properties of Al7075-T6

Ultimate tensile strength	Tensile yield strength	Elongation
579.8 N/mm^2	485.9 N/mm^2	14.6 %

2.2. Specimen

Corrosion fatigue specimens were machined into an hourglass shape to concentrate stress in a central notch. The minimum diameter at the stress-concentrated region is 3 mm, with surface roughness controlled to Ra 0.1 μm. Runout tolerance was maintained below 0.005 mm to ensure consistency in loading conditions. The specimens were manufactured in accordance with the "International Organization for Standardization (ISO) 1143: Metallic materials - Rotating bar bending fatigue testing" standard.

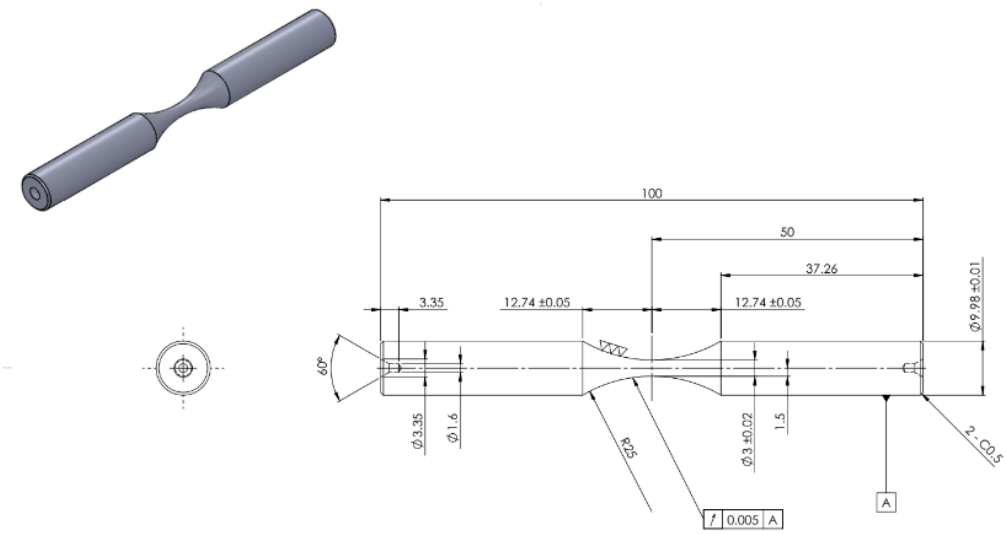


Figure 1. Illustrates the detailed geometry of the specimen.

2.3. Corrosion condition

Corrosion conditions followed standardized protocols per American Society for Testing and Materials (ASTM) G69-97 and ASTM G31-21 [7,8]. Specimens were immersed for 12 hours in a test solution comprising 58.5 ± 0.1 g of NaCl and 9 ± 1 mL of 30 % hydrogen peroxide per liter of deionized water. This accelerated corrosion environment simulated aggressive service conditions commonly encountered in aviation. Figure 2 compares pre and post corrosion appearances of the specimen surfaces.

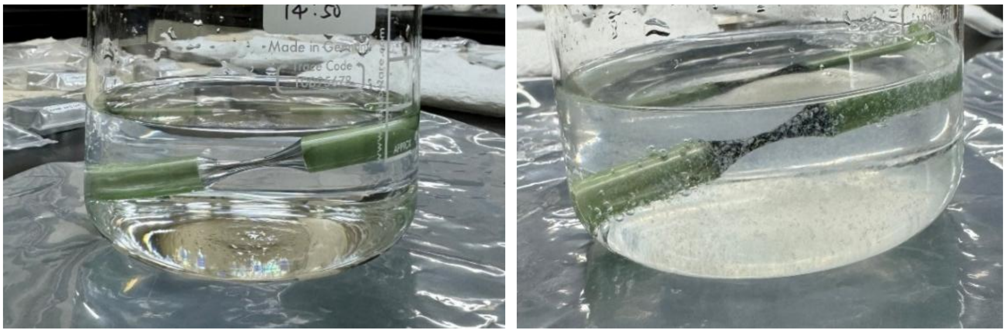
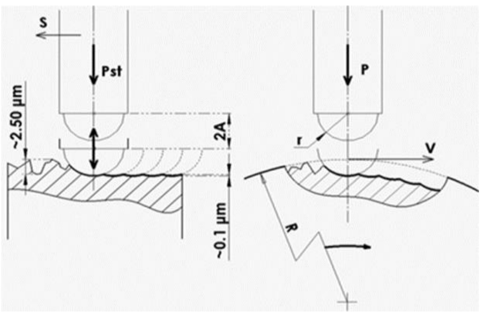


Figure 2. Appearance of the specimen before and after corrosion.

2.4. UNSM technology

The main concept and mechanism of UNSM technology are shown in Figure 3. A tungsten carbide ball attached to an ultrasonic device that strikes the surface of a work-piece 20,000 or more times per second with 1,000 to 100,000 shots per square millimeter. These strikes, which can be described as micro cold-forging, bring severe plastic deformation (SPD) and elastic deformation to surface layers and thus generate nano-crystalline structure. This nano-structural modification of the surface layer can improve both the strength (hardness) and ductility (toughness) of the work-piece simultaneously according to the well-known Hall-Petch theory [9,10]. This process also improves surface integrity, increases surface hardness, produces micro-dimples, and induces compressive residual stress in surface layers [11,12]. The UNSM effects and their anticipated benefits are summarized in Table 3 [13-15]. The UNSM treatment conditions applied to the specimens for the corrosion fatigue test in this study are as shown in Table 4. The UNSM conditions in Table 4 refer to the UNSM conditions of the previously studied Al6061-T6 alloy [16], and the static load was increased considering Al7075-T6, which has higher strength and fatigue resistance than Al6061-T6.



Remark:

S : feed rate [mm/rev]
P_{st} : static load [N]
A : peak-to-peak amplitude [µm]
P : dynamic load [N]
V : spindle speed [rpm]
R : specimen radius [mm]
r : tip radius [mm]
F : frequency [Hz]

Figure 3. Mechanism of UNSM.

Table 3. The effects of UNSM treatment and their anticipated benefits

Effects of UNSM treatment	Anticipated benefits
Deep compressive residual stresses (Greater than 1,000 MPa into depths of more than 2,000 μm)	- Improved Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) endurance limit - Improved rolling contact fatigue strength - Improved stress corrosion cracking resistance
Micro dimples surface (Area: 1-2 μm^2, Depth: submicron, Pattern pitch: few μm)	- Reduced surface roughness - Decreased friction coefficient - Reduced wear rate
Increased hardness (into depths of more than 1,500 μm)	- Reduced wear rate - Improved LCF and HCF endurance limit
Nano-crystalline structure (Grain sizes of 50-200 nm into depths of 100 μm)	- Increased tensile strength and hardness - Increased fatigue strength - Increased wear resistance

Table 4. UNSM treatment conditions for corrosion fatigue specimens

Frequency	Amplitude	Static load	Spindle speed	Feed rate	Tip diameter
20 kHz	30 μm	50 N	50 rpm	0.07 mm/rev	2.4 mm

The surface hardness of Al7075-T6 was initially 170 Hv and increased to a maximum of 198 Hv after UNSM treatment. The surface hardness of the UNSM-treated specimens increased by up to 16 % compared to the untreated specimens. In addition, the surface compressive residual stress increased from an initial -24 MPa to -458 MPa after UNSM treatment.

2.5. Fatigue test

Corrosion fatigue tests were conducted on a four-specimen rotary bending fatigue tester (YRB200, Yamamoto, Japan) at 3,150 rpm, with a stress ratio R = -1. Bending stress ranged from 120 to 300 MPa, corresponding to a fatigue life threshold of 10^7 cycles over approximately 2.2 days. Three specimen groups were tested:

I. C (Corroded only) : 8 EA
II. CU (Corroded, then UNSM treated) : 6 EA
III. UC (UNSM treated, then corroded) : 3 EA

This classification enabled comparative analysis of UNSM effects on corrosion fatigue resistance.

3. Results

Previous studies by R. Zhang et al. [5] and A. Sharma [17] investigated the corrosion fatigue behavior of Al7075-T6 alloy in conjunction with UNSM. These studies reported a substantial decrease in fatigue life following corrosion exposure, whereas UNSM-treated specimens exhibited up to a 20-fold improvement. The enhancement was primarily attributed to the formation of compressive residual stress, which suppresses fatigue crack propagation. In this study, UNSM treatment was performed after forced corrosion with reference to previously studied corrosion times to confirm the corrosion fatigue delay after UNSM application [5]. In addition, the corrosion fatigue tendency when corrosion occurred prior UNSM treatment was also confirmed. The test results are shown in Figure 4.

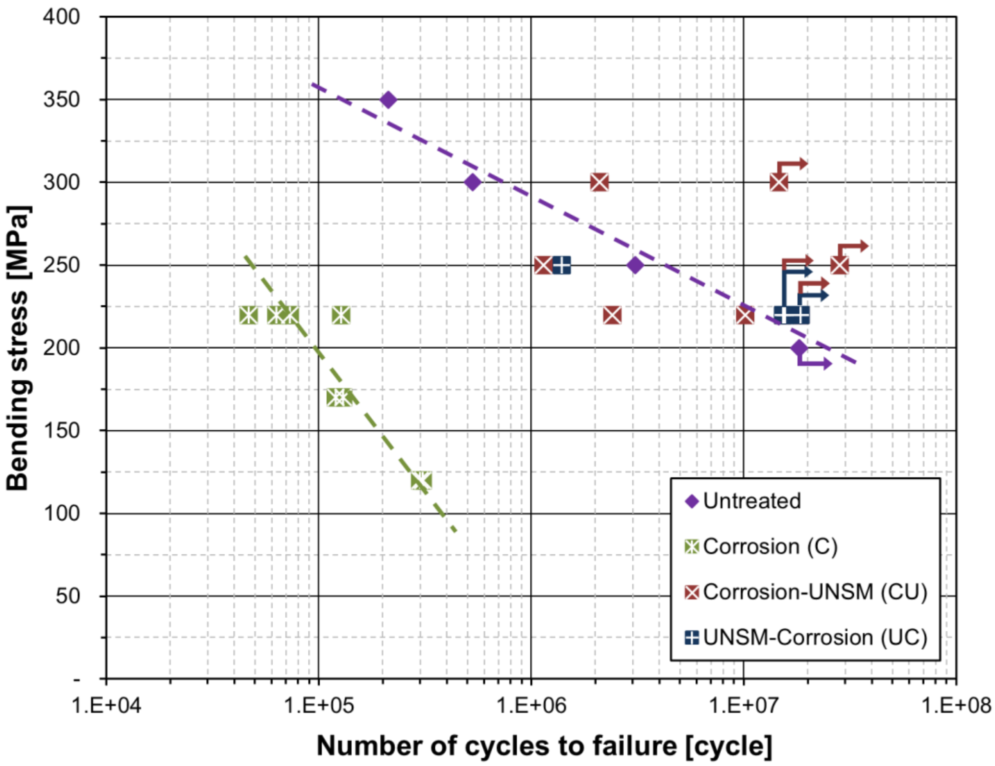
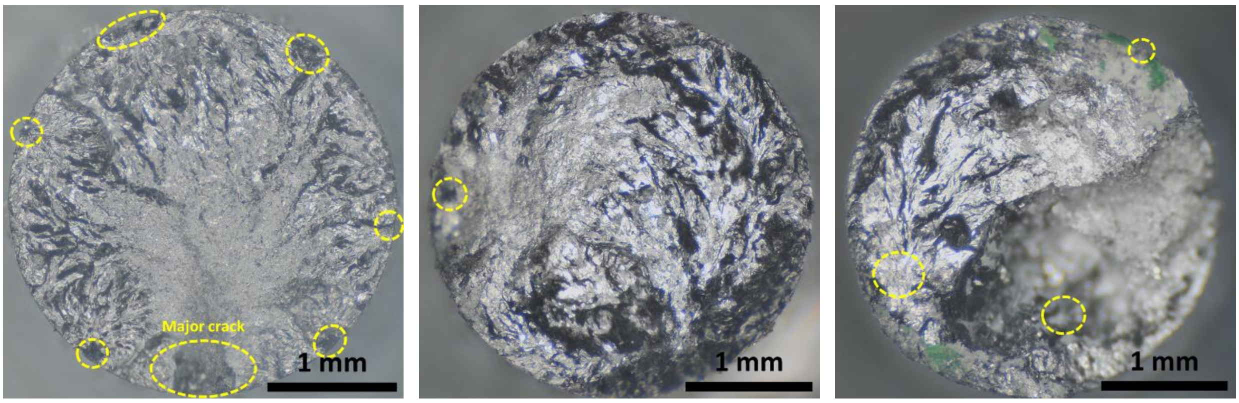


Figure 4. Corrosion fatigue test results of Al7075-T6 (one marker is data from one sample).

According to the experimental results presented in Figure 4, all the C specimens failed at bending stresses ranging from 120 to 220 MPa, with a fatigue life of up to 3.1×10^5 cycles. In contrast, the fatigue life of the untreated, non-corroded specimens was up to 1.8×10^7 cycles, and these specimens did not fail. Corrosion is a significant factor in fatigue degradation. Based on these results, the corrosion fatigue limit of the C specimens is expected to fall below the 120 MPa stress range.

Both UNSM-treated groups showed dramatic improvements in fatigue performance relative to the corroded group. The CU specimens achieved a fatigue life of up to 2.8×10^7 cycles from 220 to 300 MPa range, while the UC specimens exhibited a fatigue life of up to 1.8×10^7 cycles from 220 to 250 MPa range. At equivalent stress levels, the fatigue life of the CU and UC specimens significantly increased compared to the C specimens.

These results underscore the role of surface-induced compressive residual stresses in delaying corrosion crack initiation and propagation. While compressive residual stresses are widely known to affect fatigue life under non-corrosive conditions, they also appear to have an impact in corrosive environments.



(a) C specimen (b) CU specimen (c) UC specimen

Figure 5. Optical micrographs showing the fatigue fracture surfaces of 7075-T6 alloy at a bending stress of 220 MPa (fatigue life: (a) 7.2×10^4 cycles; (b) 1.0×10^7 cycles; (c) 1.5×10^7 cycles).

Figure 5 shows optical micrographs of the fatigue fracture surface of a 7075-T6 alloy at a bending stress level of 220 MPa. Figure 5(a) confirms that fatigue crack initiation was distributed across the specimen surface. Fatigue cracks propagated through major cracks. The height difference between the fracture surfaces of the specimens is relatively small. Figures 5(b) and 5(c) show that cracks initiated from corrosion pits or defects within the specimen rather than from the surface. In both specimens, the height difference between the fracture surfaces is relatively large, and the number of cracks originating from the surface is smaller than that of the C specimen. In both specimens, the UNSM treatment pattern still exists on the outer surface of the fracture site. This may indicate the presence of compressive residual stresses that enhance fatigue properties.

4. Concluding Remarks

UNSM treatment was applied to Al7075-T6 alloy specimens to enhance fatigue life under corrosive conditions. The technology is versatile and can be applied either before or after corrosion exposure. While the mechanisms behind improved corrosion fatigue performance require further investigation, the introduction of compressive residual stresses via UNSM treatment is a likely contributing factor. To elucidate the relationship between corrosion fatigue resistance and surface modification, future studies will perform detailed fracture surface analyses to identify fatigue crack initiation sites and propagation trends. These findings will guide deeper exploration into the correlation between fatigue life extension and residual stress profiles induced by UNSM processing.

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