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Small Surface Fatigue Crack Behaviors of Cr-Mo Steel AISI4137

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Abstract: Costs are increasing due to the addition of alloying elements such as V, W, and Mo to prevent damage to Cr-Mo steel for fastening bolts, but field tests have shown that it is not an appropriate solution for improving physical properties through heat treatment. In this study, the characteristics of fatigue cracks using Cr-Mo steel for fastening bolts before and after UNSM (ultrasonic nanocrystal surface modification) treatment were studied using fracture mechanics and fracture analysis methods. Specifically, using untreated and UNSM-treated materials: (1) the characteristics of small surface fatigue cracks existing on the surface, and (2) the surface fatigue cracks in the depth direction were observed and analyzed. The microstructure of Cr-Mo steel was refined by severe plastic deformation (SPD) from the surface to a depth of about 100 μm according to the static load of UNSM, and the fatigue limit increased by 30% as a large compressive residual stress was formed. Additionally, like the untreated materials, fisheye cracks did not occur in UNSM-treated materials, even when inclusions were present, and all specimens fractured while forming surface cracks. Accordingly, one or more of the multiple small surface fatigue cracks (MSFC) grew and developed into a major crack that determines the fatigue life, and a major ridge was formed among the many micro-ridges in the internal direction. In other words, this major crack grew and developed a major ridge in the internal direction, determining the lifespan of the test specimen.

Keywords: ultrasonic nanocrystal surface modification (UNSM); compressive residual stress; multiple small surface fatigue cracks; ridge; Cr-Mo steel



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1. Introduction

Recently, mechanical materials are increasingly being used at high speeds and under high loads. As a result, metal materials crack due to continuous repeated loading, leading to rapid destruction. Therefore, the demand for metallic materials with improved fatigue strength and fatigue life, reliability, and infinite life is increasing. Accordingly, surface treatment methods that can obtain the necessary properties by improving the surface properties of high-strength materials are becoming very important [1–6].

Surface treatment methods include surface hardening methods such as carburizing, nitriding, and carbonitriding, as well as shot peening, UNSM (ultrasonic nanocrystal surface modification), roller burnishing, and deep rolling. These methods generate compressive residual stress on the surface, delaying the occurrence of fatigue cracks and improving the fatigue life of parts [7–12].

Methods such as adding alloy elements and improving heat treatment methods are increasing costs due to the addition of elements such as V, W, and Mo. Furthermore, due to

the limitations of improving physical properties through heat treatment, it has been proven through field tests that these methods cannot be an appropriate solution to the damage of Cr-Mo steel, a material for fastening bolts [13–16].

Therefore, research is being conducted to improve mechanical properties by refining the structure to a certain depth by causing plastic deformation on the surface of the material. Among these studies, many studies have been attempted recently on UNSM technology, which induces plastic deformation on the material surface using ultrasonic vibration energy. In addition, this UNSM technology is a method of improving the physical properties from the surface of the material to a certain depth. It can simultaneously improve surface roughness and harden the surface of the part and is an eco-friendly technology that does not generate processing chips.

In this study, the behavior of MSFC using Cr-Mo steel for bolting before and after UNSM (ultrasonic nanocrystal surface modification) treatment was studied and analyzed to using fracture mechanics and fracture analysis methods. Specifically:

- (1) Observation and analysis of the characteristics of multiple small surface fatigue cracks on the surface.
- (2) Observation and analysis of the multiple small surface fatigue cracks in the depth direction.

2. Test Specimen Processing and Fatigue Tester

2.1. UNSM Technology

UNSM technology applies ultrasonic vibration energy to apply more than 20,000 hits per second (about 1000 to 10,000 times/mm²) to the metal surface using a ball with very large static and dynamic loads, transforming the surface into a micronized structure. As a result, the microstructure of the surface layer is reformed into a nanocrystalline structure. At the same time, it is a technology that forms very large and deep compressive residual stresses [4–10].

Figure 1a shows the processing system of UNSM, which consists of a generator that generates ultrasonic frequencies, an air compressor that applies a static load, a transducer that generates mechanical ultrasonic waves, a booster that amplifies the generated ultrasonic waves, a horn that transmits the amplified ultrasonic waves, and a ball tip that ultimately delivers the ultrasonic vibration energy to the workpiece.

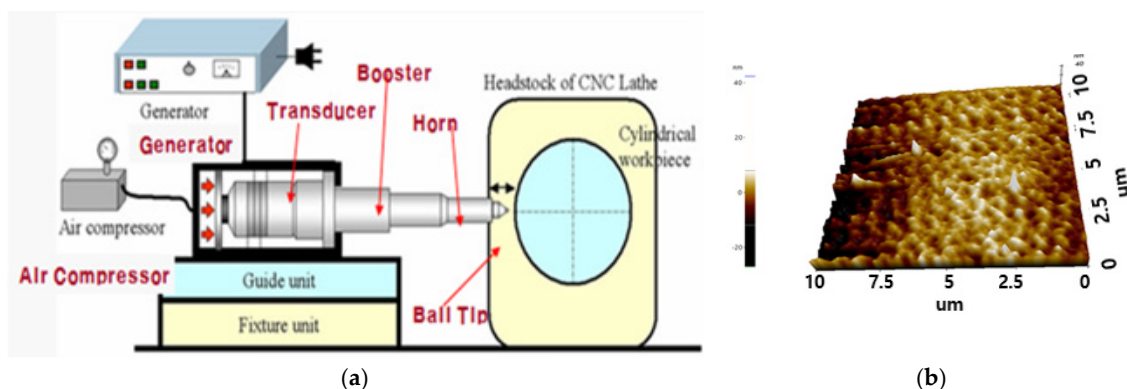


Figure 1. (a) UNSM system, (b) the traces of 3D (x, y, z) surfaces using an atomic force microscope (AFM) after UNSM treatment.

Figure 1b also shows the traces of 3D forging using an atomic force microscope (Bruker, AFM, Scanning Probe Microscope, NX20, Billerica, MA, USA). When UNSM treatment is applied to the surface in this way, it exhibits characteristics such as formation of micro-dimples on the surface, improvement of surface roughness, increase in surface hardness,

nanoization of crystals, and the formation of deep and large compressive residual stress. Therefore, in fields such as VHCF (very high cycle fatigue) and SCC (stress corrosion cracking), the increase in durability and fatigue strength is very large, the tribology characteristics are improved, and wear resistance is greatly improved by reducing the coefficient of friction [6–10].

2.2. Fatigue Test Specimen and Fatigue Tester

The shape and dimensions of the fatigue specimen are shown in Figure 2A. The Cr-Mo material used in this study was provided as a test specimen suitable for the standard fatigue tester specified by the Research Group for Statistical Aspects of Materials Strength [13–15]. The minimum diameter of the test piece is 3 mm, the radius of curvature of the rounded part is 7 mm, the total length is 100 mm, and the stress concentration coefficient is $K_t = 1.02$.

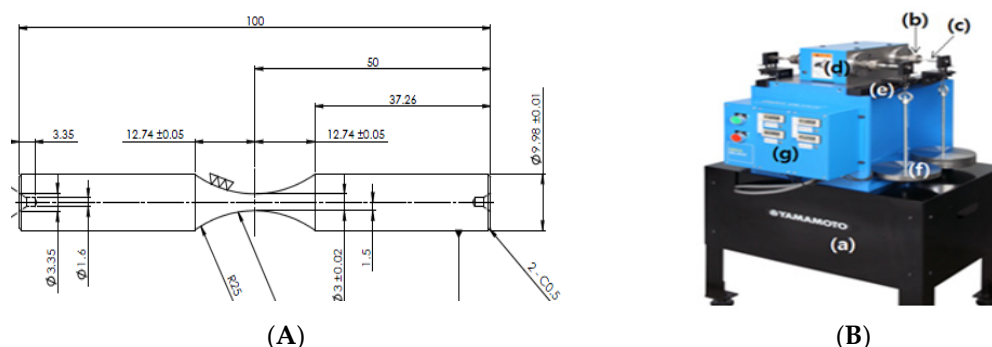


Figure 2. (A). Configuration of fatigue specimen (unit; mm) and (B) cantilever-type rotary bending fatigue testing machine. (a) motor, (b) spindle, (c) specimens, (d) sensor, (e) bearing and spring, (f) weight, (g) counter.

For the test specimen, abrasive paper ranging from No. 100 to No. 2000 was used, and the surface was mirror-polished depending on the purpose. The fatigue life of the specimen at room temperature was tested in air under the conditions of a frequency of 53 Hz and a stress ratio of $R = -1$ using a cantilever rotary bending fatigue tester (YRB200, Yamamoto, Nagaoka, Japan) that simultaneously uses four specimens, as shown in Figure 2B.

2.3. Material of Test Specimen and UNSM Effects

The test specimen used in this study was a Cr-Mo steel AISI4137, which is widely used as a high-strength fastening bolt. Its chemical composition is shown in Table 1. It is a Cr-Mo steel with 1.01% Cr and 0.20% Mo, and both JIS and KS standards are SCM435 steel. The heat treatment method involved maintaining austenite at 855 °C for 30 min, then oil cooling it at 500 °C for 60 min, and then air cooling it to temper it.

Table 1. Chemical composition of Cr-Mo steel (wt%).

Composition	C	Si	Mn	Cr	Mo	V	Ni
Cr-Mo steel AISI4137	0.36	0.19	0.66	1.01	0.20	-	0.02

Table 2 shows the mechanical properties of the test specimens of Cr-Mo steel before and after UNSM treatment (static load 70 N). In other words, there is little change in mechanical properties, such as tensile strength, before and after UNSM treatment. However, the elongation and reduction in area of UNSM-treated material increased by 65.3% and 22%, respectively, showing the effective effect of UNSM. In other words, it was implied that the microstructure on the surface of Cr-Mo steel was modified by UNSM treatment.

Table 2. Mechanical properties of Cr-Mo steel.

Specimen AISI4137	Tensile Strength (MPa)	Yield Stress (MPa)	Elongation (%)	Reduction in Area (%)
Before UNSM	991	902	17.0	67.3
After UNSM	993	904	28.1	82.1

The UNSM treatment conditions used in this study are shown in Table 3, and the test specimens were subjected to elaborate surface treatment. To verify the effectiveness of UNSM, various experiments were conducted using high-strength bolts. The test specimen was subjected to a frequency of 20 kHz on the ball tip using UNSM technology and subjected to static loads (Pst) of 40 N, 70 N, and 100 N.

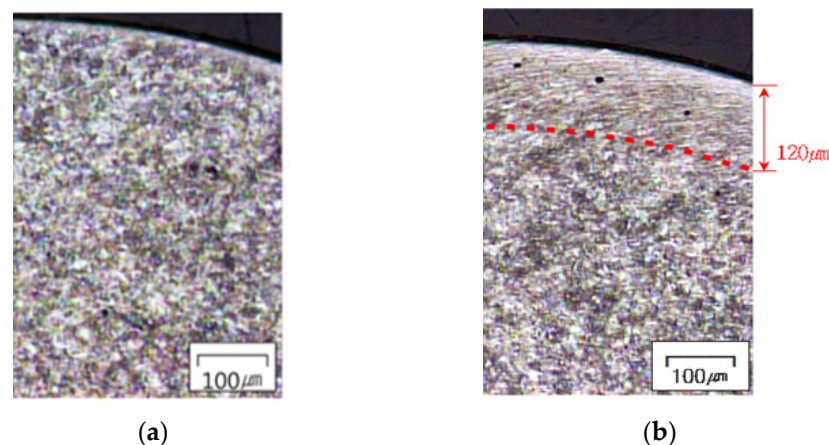
Table 3. UNSM conditions.

Frequency (KHz)	Generator Power Level (%)	Static Load (Pst, N)	Feed Rate (mm/rev.)	Speed (rpm)	Tip Diameter, (mm)
20	30	40, 70, 100	0.04	120	2.38

2.4. Surface Observation Using an Optical Microscope and an Atomic Force Microscope

After UNSM treatment, the ultra-fine structure (nano-microstructure) caused by the UNSM treatment can be observed from the surface to about 80 to 120 μm in the depth direction, as shown in Figure 3a,b. Figure 3c shows the traces in a relatively micro area of 3D ($x = 10 \mu\text{m}$, $y = 10 \mu\text{m}$, $z = 400 \text{ nm}$) forging, and Figure 3d also shows the traces in a relatively micro area of 2D ($x = 0.6 \mu\text{m}$, $y = 0.16 \mu\text{m}$) forging using an atomic force microscope (AFM, Scanning Probe Microscope, NX20, USA). When UNSM treatment is applied to the surface in this way, it exhibits characteristics such as the formation of micro-dimples (c, d) on the surface, improvement of surface roughness (Figure 4b), increase in surface hardness (Figure 5a), nanoization of crystals, and the formation of deep and large compressive residual stress (Figure 5b).

It has been reported that the micronized structure under the influence of plastic deformation by ultrasonic energy causes synergistic effects in hardness, compressive residual stress, wear, and fatigue characteristics in the plastically deformed area [10–12]. Furthermore, according to the Hall–Petch equation, as the crystal grain size decreases, yield strength and hardness increase.

**Figure 3.** Cont.

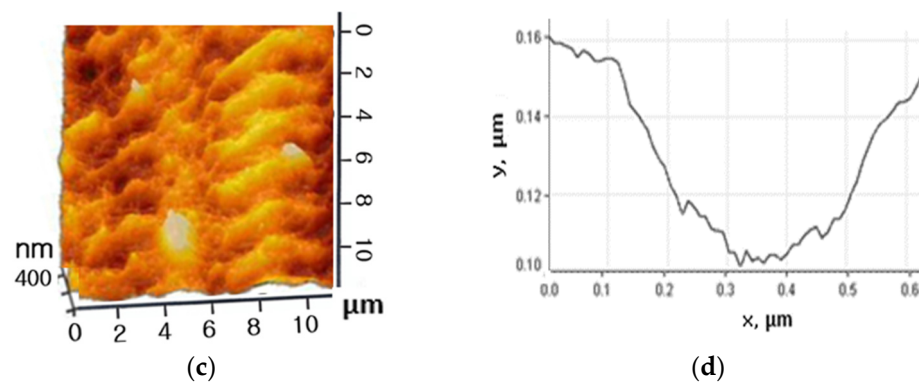


Figure 3. Photos of changes in microstructure “before and after UNSM” observed at $100\times$ magnification during UNSM treatment. (a) before UNSM, (b) after UNSM 100N. (c) The traces of 3D ($x = 10\ \mu\text{m}$, $y = 10\ \mu\text{m}$, $z = 400\ \text{nm}$) forging and (d) the traces of 2D ($x = 0.6\ \mu\text{m}$, $y = 0.16\ \mu\text{m}$) forging using an atomic force microscope after UNSM 100N treatment.

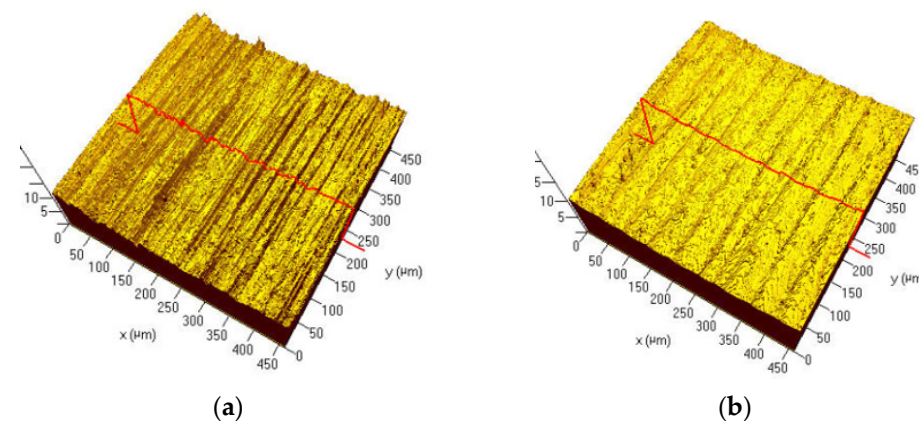


Figure 4. Enlarged images of the surface condition of the specimen before (a) and after (b) UNSM treatment in 3D traces in a relatively large area ($x = 450\ \mu\text{m}$, $y = 450\ \mu\text{m}$, $z = 10\ \mu\text{m}$) using an atomic force microscope (AFM).

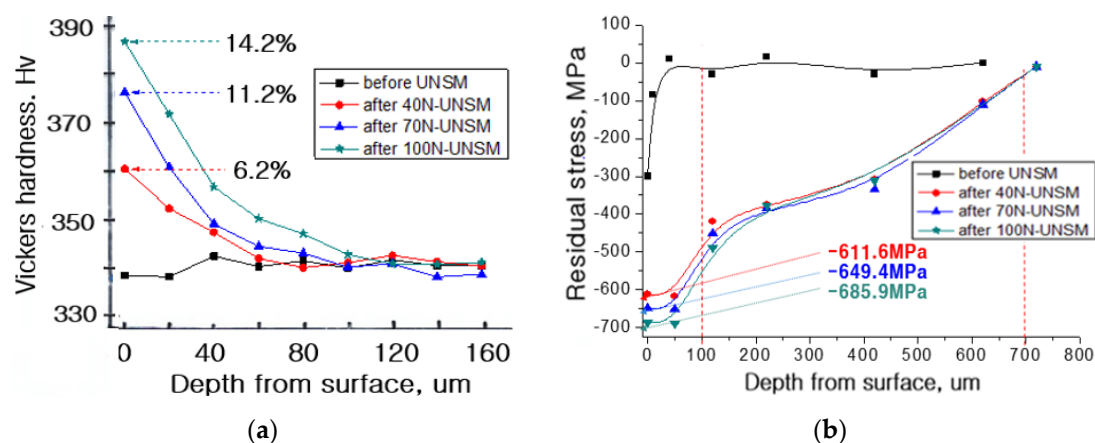


Figure 5. (a). Distribution of micro Vickers hardness from surface before and after UNSM treatment of AISI4137. (b) shows data comparing the change in compressive residual stress of AISI4137 along the depth direction.

3. Test Results and Discussion

3.1. Surface Observation of Test Specimen According to UNSM Treatment

Figure 4 shows an enlarged view of the surface condition of the specimen before (a) and after (b) UNSM treatment in 3D traces in a relatively large area ($x = 450\ \mu\text{m}$, $y = 450\ \mu\text{m}$, $z = 10\ \mu\text{m}$) through an AFM.

In this example, the surface condition of the specimen before UNSM treatment (Figure 4a) showed many three-dimensional processing traces and irregular scratches, but the surface condition of the specimen after UNSM treatment (Figure 4b) was well organized. The traces and scratches of this high level of machining have disappeared, revealing a very regular and well-organized surface in 3D. The refined crystal structure (Figure 3) affected by severe plastic deformation (SPD) caused by UNSM treatment is expected to increase tribological properties and fatigue strength by increasing hardness and forming compressive residual stress [1–7].

3.2. Changes in Surface Hardness and Compressive Residual Stress

Figure 5a shows that when three static loads of 40 N, 70 N, and 100 N were applied to Cr-Mo steel AISI4137 with UNSM treatment, the hardness value increased to a high level on the surface and then gradually decreased in the depth direction. The effect of surface treatment tended to disappear at a depth of about 100 μm .

The surface hardness increased by about 6.2~14.2% due to UNSM treatment up to about 100 μm . After that point, the hardness values before and after UNSM treatment were similar. This change in hardness seems to approximate the depth of change in the microscopic structure and compressive residual stress from the surface to the depth due to the influence of UNSM treatment.

Figure 5b presents data comparing the change in compressive residual stress along the depth direction of Cr-Mo steel. Compressive residual stress is the most important factor in improving durability and wear resistance. This residual stress was measured at every 20 μm depth using an X-ray residual stress measuring device (RIKAGU, Japan) under the conditions shown in Table 4. At this time, electrolytic polishing was used to remove a depth of 20 μm .

Table 4. Conditions of X-ray diffraction.

X-Ray Target	Cu-K α
Diffraction plane	(311)
Filter	Ni
Voltage	40 kv
Current	20 mA

As shown in Figure 5b, the compressive residual stress of the surface of Cr-Mo steel before UNSM treatment is about -300 MPa. However, the effective depth of this compressive residual stress is very small and is formed only on the surface. The depth is so thin that it has virtually no effect on the mechanical properties.

After UNSM treatment of Cr-Mo steel, compressive residual stress (-600 ~ -700 MPa) was formed. Additionally, the effective depth was measured to be about 430 μm , and zero stress, which is the boundary layer of residual stress, was reached at a depth of 700 μm . In this way, unlike untreated materials, UNSM-treated materials generate and form large compressive residual stress from the surface to a certain depth, which is expected to be the main reason for improving the wear resistance of UNSM-treated materials, improving fatigue life, and delaying the occurrence of fatigue cracks [4,11].

The increase in hardness of the untreated and treated materials almost disappeared at 100 μm from the surface. The compressive residual stress of the untreated material also disappeared at this depth.

However, the UNSM-treated material was examined, with a red dotted line in the picture indicating a surface depth of 100 μm . This showed that a residual stress of -500 to

–580 MPa exists at 100 μm . In this way, it appears that the microstructural change from the surface to a depth of 100 μm and the formation of compressive residual stress maintain a deep relationship due to the influence of UNSM treatment. Another red dotted line (at a surface depth of 700 μm) showed that the compressive residual stress that had formed significantly was almost eliminated.

3.3. Changes in Fatigue Properties

3.3.1. S-N Diagram and Macroscopic Fractured Fatigue Characteristics

Figure 6a shows the S-N diagram data for SCM435 published by Sakai and Tanaka et al. in VHCF-3, indicated by a blue square ■ and a green line as “Ground” [13–15]. The results of this study are marked in red • and are shown simultaneously with the “Ground” data in Figure 6a. The test specimen used in this study was provided by the Research Group for Statistical Aspects of Materials Strength and was heat treated in the same manner as the “Ground” material before being used in the fatigue test. The results of “Ground” and the results of the untreated material in this study were in excellent agreement. As seen in Figure 6a, the results of the fatigue test are the same even when the study location and the researchers are different. In this study, fatigue characteristics before and after UNSM treatment were studied using the “Ground” material and the verified AISI4137 specimen.

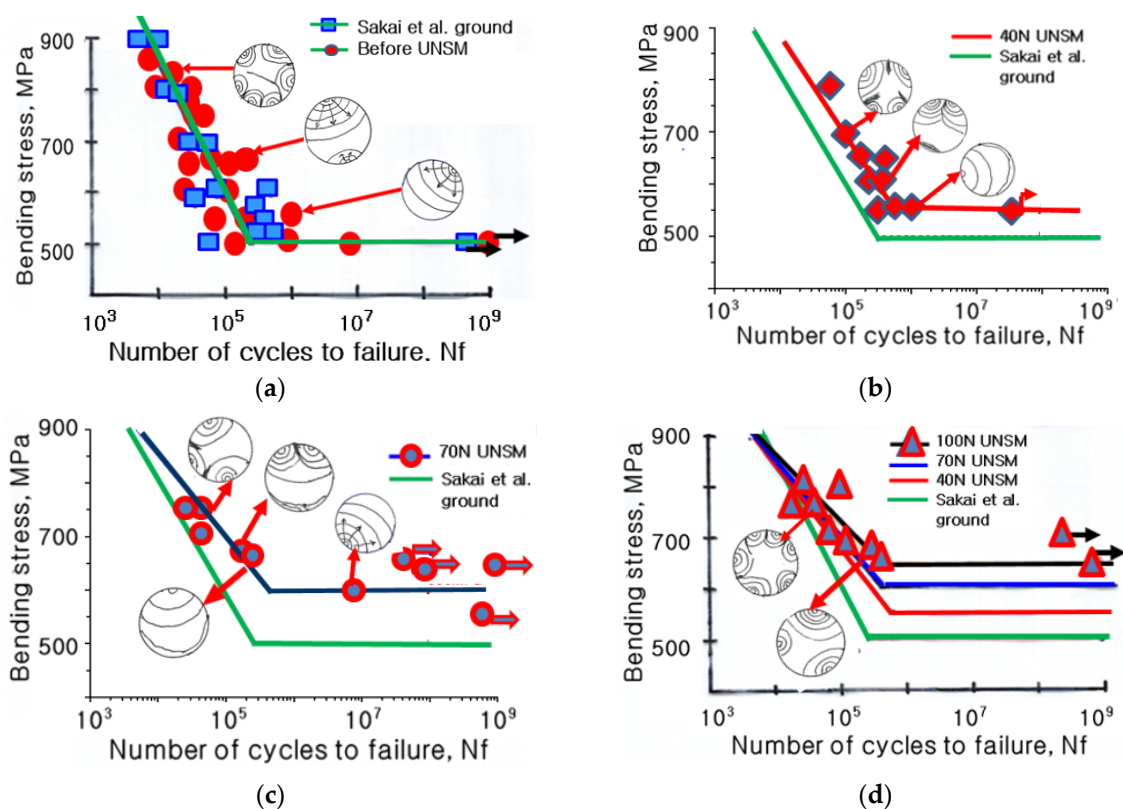


Figure 6. (a) shows the S-N diagram of Sakai’s SCM435 [13] as “Ground” with square marks and the results of this study with circular marks and compares them at the same time. (b) The S-N data for AISI4137 material treated with UNSM under a static load of 40N was compared to the “Ground” data (green line) in the diamond marks and the red line. (c) The S-N data for Cr-Mo steel treated with UNSM under a static load of 70 N was compared to the “Ground” data (green line) in the circular marks and the black line. (d) shows a simultaneous comparison of all S-N diagram data for Cr-Mo steel before and after UNSM treatment.

In Figure 6a, the macroscopic fracture characteristics were sketched and compared to the S-N data for the untreated Cr-Mo steel at three stress levels. At the 550 MPa level, one surface crack occurred, grew, and fractured at a fatigue life of 1.1×10^6 . At the 650 MPa

level, two surface cracks occurred, grew, coalesced, and fractured at 2.3×10^5 . Additionally, at the 840 MPa level, six surface fatigue cracks occurred, grew, and fractured at 1.5×10^4 .

The characteristics at the three stress levels above show that as the fatigue life increases, the number of surface fatigue cracks that occur decreases. In the short-life region, the number of surface fatigue cracks increases, showing a tendency to grow, coalesce, and fracture.

In Figure 6b, the S-N data for Cr-Mo steel treated with UNSM under a static load of 40N is compared to the “Ground” material data (green line), and the red ♦ shape and the red line are shown. In this case, the 10^9 cycle fatigue limit was 550 MPa, which was approximately 10% higher than the 500 MPa of the untreated material.

In Figure 6b, the macroscopic fracture characteristics of Cr-Mo steel treated with UNSM at 40 N were sketched and compared at three stress levels. At the 550 MPa level, one surface fatigue crack occurred, grew, and fractured at a life of 9.9×10^5 . At the 600 MPa level, two surface fatigue cracks occurred, grew, coalesced, and fractured at 3.5×10^4 . Additionally, at the 700 MPa level, four surface fatigue cracks occurred, grew, fractured at 9.7×10^4 , and coalesced, and three ridges were formed on surface.

The characteristics of the three stress levels of Cr-Mo steel treated with UNSM-40N above show that the number of surface fatigue cracks occurring decreases as the fatigue life increases. In addition, in the short-life region, the number of surface fatigue cracks increased, and the tendency for occurrence, growth, coalescence, and fracture was similar to that of the untreated material.

In Figure 6c, the S-N data of Cr-Mo steel treated with UNSM under a static load of 70 N is shown by comparing the “Ground” material data indicated by the green line with the data indicated by • and the black line. In other words, the fatigue limit was 600 MPa, which was about 20% higher than the 500 MPa of the untreated material.

In Figure 6c, the macroscopic fracture characteristics of Cr-Mo steel treated with UNSM-70N were sketched and compared at four stress levels. At the 600 MPa level, one surface crack occurred, grew, and fractured at a life of 7.6×10^6 . At the 670 MPa level, one surface fatigue crack (Figure 7) occurred, grew, and fractured at 2.3×10^5 . At the 675 MPa level, two surface fatigue cracks occurred, grew, coalesced, and fractured at 1.7×10^5 . Finally, at the 750 MPa level, three surface fatigue cracks occurred, grew, and fractured at 5.37×10^4 .

The characteristics of the above four stress levels are that when the fatigue life is long, the number of surface fatigue cracks generated decreases, and in the short-life region, the number of surface cracks increases, and the tendency for occurrence, growth, coalescence, and fracture is similar to that of the untreated material and the UNSM-40N material.

Figure 6d shows a comparison of all S-N diagram data of Cr-Mo steel before and after UNSM. In Figure 6d, the S-N data obtained by the fatigue test of UNSM-treated AISI4137 material with a static load of 100N is shown in the ‘▲’ shape, and the fatigue limit was shown at about 650 MPa. In other words, the fatigue limit increased by about 30% compared to the untreated material and increased by about 10% compared to the 600 MPa of the UNSM-70N material. The fatigue limit and lifespan extension effects of this UNSM treatment are similar to other research results [3–9]. In addition, it can be seen that the effect of UNSM treatment is weakened in areas where fatigue life is lower than 5×10^4 . However, in the VHCF area, as the effect of UNSM treatment increases, the fatigue limit and life extension effect increase.

In the Cr-Mo steel used in this experiment, fisheye cracks, which are caused by inclusions inside the surface and are characteristic of VHCF fatigue, were not observed at all. In this experiment, one or multiple small surface cracks occurred on the surface of the specimen, and growth, coalescence, and fractured surfaces were observed.

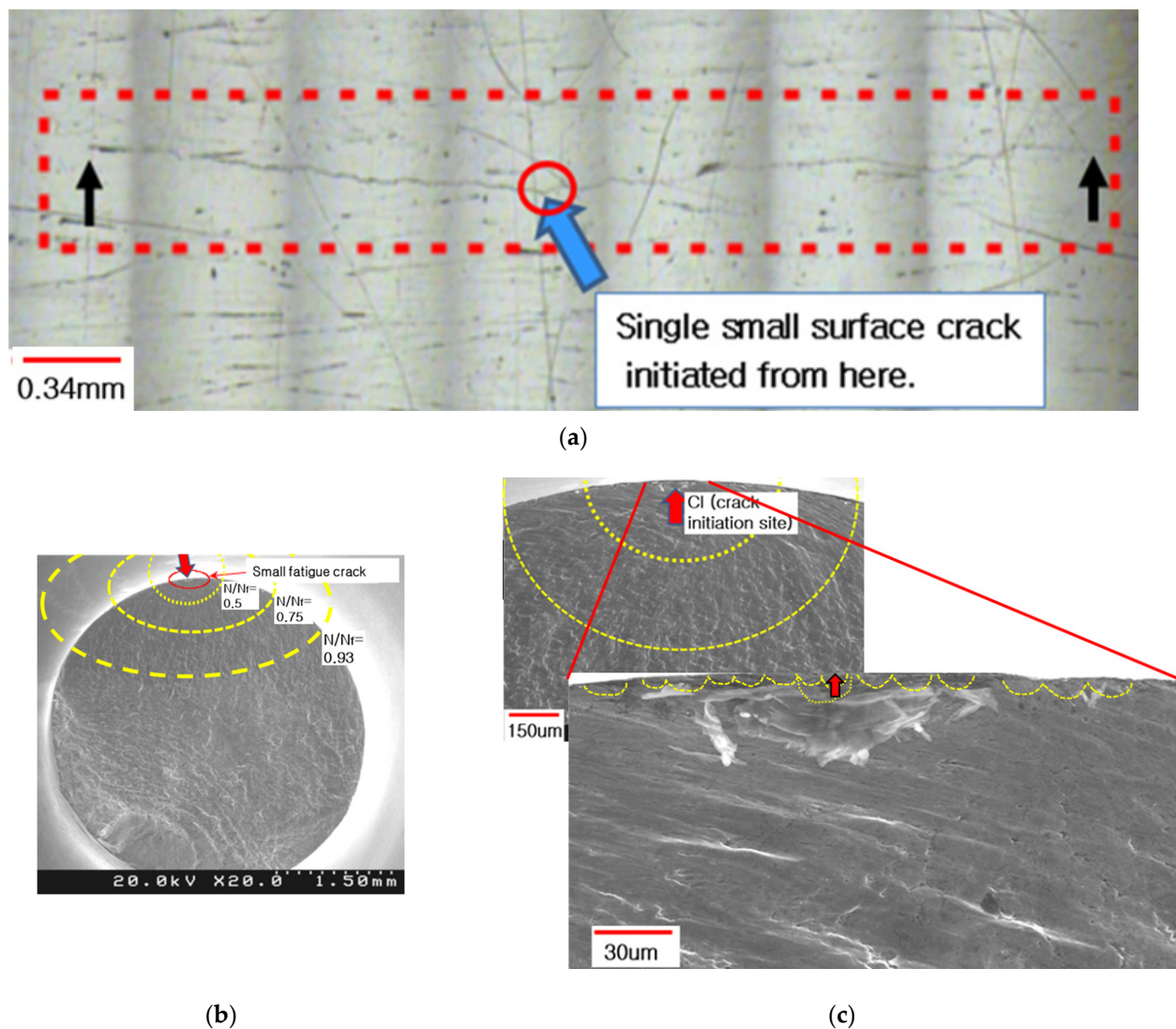


Figure 7. (a) A photo taken by mosaic picture of a small surface fatigue crack obtained by replica film under UNSM-70N treatment at 670 MPa, $N = 2.14 \times 10^5$ ($N/N_f = 93\%$, $N_f = 2.3 \times 10^5$). The small surface fatigue cracks grew and coalesced to become the major crack that determined fatigue life. (b,c) were SEM photos taken of the fracture surface. As shown by the arrow in (a), a small surface fatigue crack occurs as a single crack, and the growth process is sketched with dotted line in (b). (c) is a photo taken at $100\times$ of the origin of the surface crack initiation site of (b).

The factors that have a significant impact on the improvement of fatigue life include the decrease in surface roughness after UNSM treatment. However, the main factors are the nanoization of crystal grains near the surface of the test specimen, the formation of compressive residual stress, and the increase in surface hardness.

3.3.2. Observation and Analysis of the Characteristics of Multiple Small Surface Fatigue Cracks on the Surface

Figure 7 is a test specimen obtained by grinding and buffing after UNSM-70N treatment. During this fatigue test, replicas were collected at intervals of 5 to 8% of the expected rupture life of the fatigue test using the replication method to determine the major crack after fatigue rupture [17–20]. An example of the growth behavior of the major crack is shown in Figure 7. The black arrows point to both ends of the surface fatigue crack in Figure 7a. The length in the picture, 208 mm, was actually measured as 3.54 mm.

However, this is a photo taken at $100\times$ magnification by backtracking using the replica method to show that when $N = 2.14 \times 10^5$ is used, a small surface fatigue crack occurs on the surface at a life ratio of 93% and grows slowly. Figure 7 shows the fracture at a fracture life of $N_f = 2.3 \times 10^5$ under a bending stress of 670 MPa. The area indicated by the circle and blue arrow in the picture corresponds to the CI (crack initiation site) in Figure 10 and is the origin of the major crack.

3.3.3. Observation and Analysis of the Characteristics of Numerous Small Surface Fatigue Cracks in the Depth Direction

Case of Untreated Material

Figure 7b is an SEM image of the fracture surface of the same specimen shown in Figure 7a, taken at $20\times$ magnification. The arrow in Figure 7b points to the CI in Figure 7a, and the process of this small surface fatigue crack occurring on the surface and growing, coalescing, and breaking is shown by the yellow dotted line.

In Figure 7b, the fatigue crack is sketched in a breaking inward state, and one red line indicates the location of a small surface crack initiation. Additionally, the three yellow dotted lines show the growth behavior of the small surface fatigue crack at 50%, 75%, and 93% (the same life ratio as in Figure 7a), depending on the lifespan ratio. This figure is based on the reference in Figure 11a [21].

Figure 7c is a $100\times$ enlarged photograph of the origin of the small surface fatigue crack in Figure 7b, and the growth of the surface cracks in the inner direction are indicated by dotted lines. This case is identical to the sketched characteristics of the macroscopic fracture surface in Figure 6c, initially growing into a semicircular shape and gradually changing into an ellipse. The SEM (scanning electron microscope) photographs used in this study were taken at various magnifications using FE-SEM (S-4300, Hitachi, Tokyo, Japan) equipment.

Figure 7c is a $100\times$ magnified SEM photo of the CI part where the crack occurred. The surface crack length of 220 μm indicated by the red solid line ($500\times$ magnification) in this photo was formed as follows: from left to right, the yellow micro-surface fatigue cracks have lengths of 16.6 μm , 9.3 μm , 16.6 μm , 10.3 μm , 12.4 μm , 12.9 μm , 9.8 μm , 10.3 μm , 13.4 μm , 15.5 μm , 14.5 μm , 15.5 μm , 19.7 μm , and 17.1 μm , respectively. In other words, as the 14 micro-surface fatigue cracks occurred, grew, and coalesced on the surface, they became the major crack and proceeded with the process of growth and coalescence with adjacent cracks. Even in the internal direction of this major crack, each crack grows and coalesces, as shown by the yellow dotted line in Figure 7, forming multiple micro-ridges, as indicated by the arrows in Figure 8b.

Case of UNSM-Treated Material

Figure 8a is an SEM photograph taken at $20\times$ magnification of the fracture surface of UNSM-100N-treated material (675 MPa, $N_f = 3.1 \times 10^5$). As shown by the three arrows in the picture, the process of small surface fatigue cracks occurring and growing, coalescing, and breaking inward is sketched with yellow dotted lines. S1 and S3 grew like a single crack, but the process of S2 merging with the adjacent S3 crack was sketched with a red line. However, the red dotted lines are partially unexposed due to S3 on the fracture surface. In the process of growing this surface fatigue crack and merging with adjacent cracks, ridges were formed on the surface, as shown in the picture, depending on the spacing of the crack tips.

In Figure 8a, the fatigue crack (S1) is sketched in a breaking inward state, and one red line indicates the location of a small surface crack initiation. Additionally, the three yellow dotted lines show the growth behavior of small surface fatigue cracks at 75%, 87%, and 92% depending on the lifespan ratio. This figure is also based on the reference in Figure 11a.

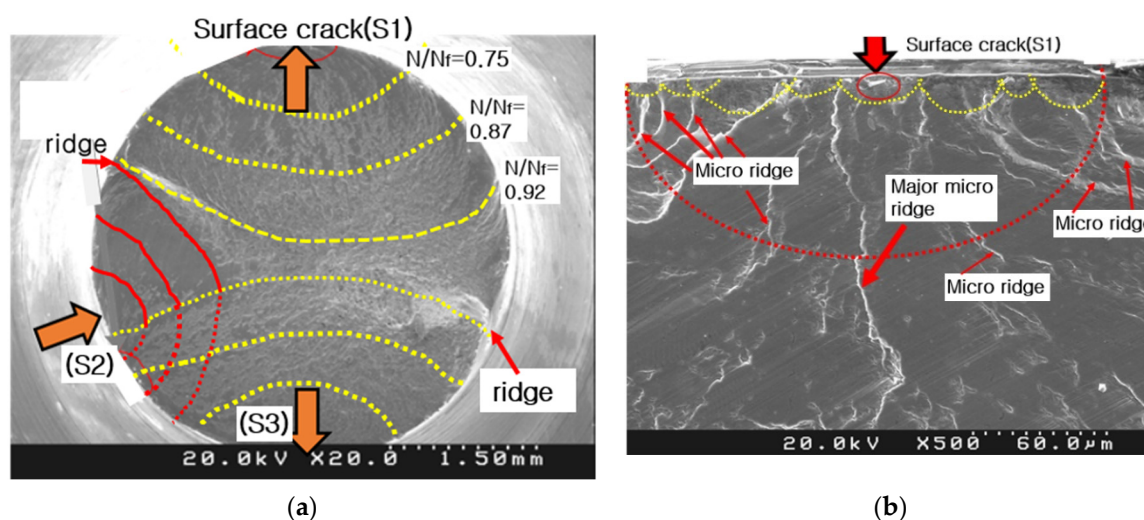


Figure 8. (a) is an SEM photograph taken at $20\times$ magnification of the fractured surface of UNSM-100N-treated material at 675 MPa and $N_f = 3.1 \times 10^5$. The three arrows in the picture sketch the process of surface crack formation, growth, coalescence, and fracture with dotted lines. (b) is a photograph taken at $500\times$ magnification of the origin of S1, and inclusions are indicated by small red circles at the origin of the surface crack. It can be seen that the surface grows and coalesces with adjacent micro-cracks. Additionally, micro-cracks inside the material form micro-ridges, and the process of increasing depth in the inner direction is repeated.

Figure 8b is a photograph taken at $500\times$ magnification of the origin of surface crack S1. Surface crack S1, indicated by a red oval, is enlarged inward, and the occurrence and growth of multiple small surface fatigue cracks is indicated by eight yellow dotted lines. In other words, even small surface fatigue cracks that look like single cracks in the replica data of Figure 7a are actually the result of repeated growth and coalescence of multiple micro-surface fatigue cracks on the surface, as shown in Figure 10B. In addition, it was possible to simultaneously observe the process of growth and coalescence in the depth direction, as seen with the yellow micro-crack in Figure 8b. This process increases the crack length on the surface, forms a micro-ridge in the depth direction, and increases the depth in the internal direction [22–24].

In other words, it was confirmed that the surface grew and coalesced with the adjacent micro-surface crack, and that the process of increasing depth while forming a micro-ridge was repeated in the depth direction of the micro-crack. In addition, inclusions are indicated by small red ovals at the origin of these surface cracks.

In the SEM photo in Figure 8b, the surface crack length of 214.8 μm in the red dotted line of S1 was formed as follows: from left to right, eight yellow micro fatigue cracks measuring 15.6 μm , 26.4 μm , 48 μm , 26.4 μm , 38.4 μm , 37.2 μm , 16.8 μm , and 33.6 μm are formed, forming major cracks on the surface and undergoing growth and coalescence processes. In the inner direction of this major crack, each crack grows and coalesces as shown by the yellow dotted line, forming multiple micro-ridges as indicated by the arrows in Figure 8b. The occurrence, growth, and coalescence behavior of these micro-surface fatigue cracks are shown in Figures 8b and 9b, and are in good agreement with the surface behavior shown in Figure 10.

Figure 9a is an SEM photograph taken at $20\times$ magnification of the fracture surface of UNSM-100N-treated material (800 MPa, $N_f = 2.6 \times 10^4$). As shown by the five arrows in the figure, many small surface fatigue cracks occurred in the high load and short lifespan area and grew, coalesced, and fractured inward, sketched with dotted lines.

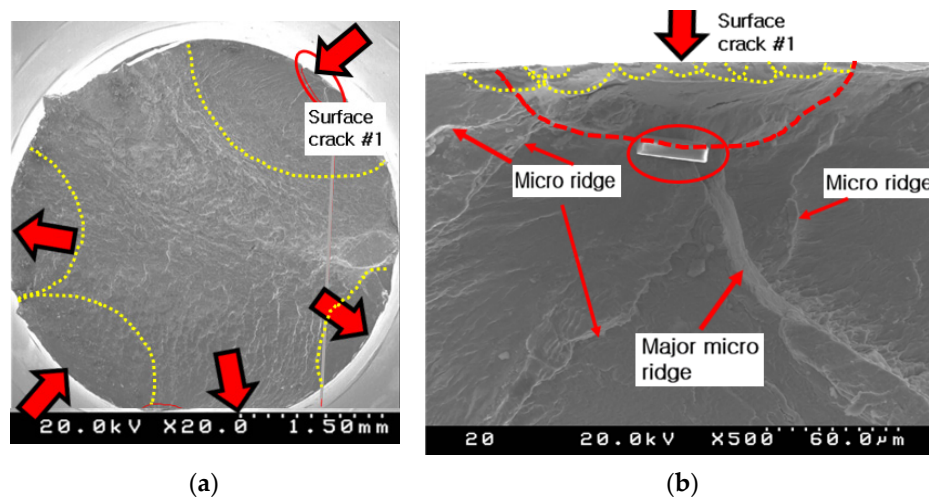


Figure 9. (a) is an SEM photograph taken at 20× magnification of the fracture surface at 800 MPa and $N_f = 2.6 \times 10^4$ in UNSM-100N-treated material. (b) is a photograph taken at 500× magnification of the origin of surface crack S1. Inclusions are indicated by a red circle at the origin of the small surface fatigue crack.

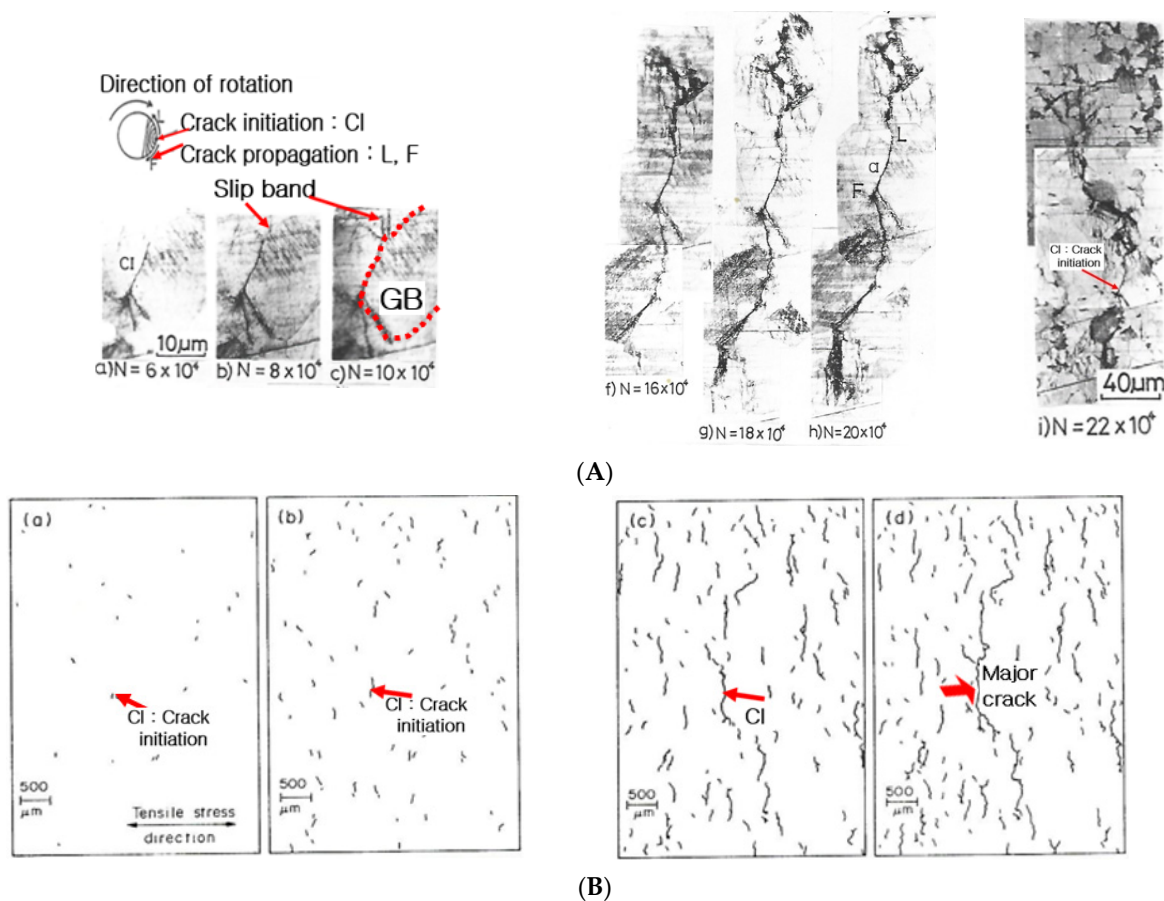


Figure 10. (A) At the grain boundary (GB), which is vulnerable to tensile stress, a persistent slip band (PSB) appears, as shown in the figure, and gradually develops into a major crack that determines the life of the specimen (mild steel, 220 MPa, $N_f = 4.8 \times 10^5$). The crack grows both on the surface (Figure (a–c,f–i)) and in the depth (Figures 8b and 9b) direction. (B) These data visualize the behavior of micro-surface fatigue cracks in a photograph connected using the mosaic method on tracing paper. The state in which many fatigue cracks appear on the surface and coalesce is shown in Figure 10B. Among these many micro-surface cracks, one is a major crack and determines the fatigue life of the specimen (mild steel, 333 MPa, $N_f = 1.17 \times 10^5$), $N/N_f = 0.17$ (a), 0.43 (b), 0.85 (c), and 0.97 (d) [17–20].

Figure 9b is a photograph taken at $500\times$ magnification of the origin of surface crack S1, and the red dotted line shows that nine surface fatigue cracks, indicated by ovals, have grown inward. Even within this dotted line, many small surface cracks, as shown in Figure 8b, occurred and grew as they coalesced. Many micro-ridges (Figure 9b) were formed in the depth direction, and among them, a major micro-ridge was formed. Therefore, among the many surface fatigue cracks, at least one is the major crack, which determines the fatigue life of the specimen. Among the many micro-ridges, a major ridge is formed in the internal direction and develops in the inner direction of the major crack, determining the fatigue life. In addition, inclusions are indicated by red circles at the origin of this surface crack.

If the observation results of the fracture surface above are summarized in relation to the references [17–21], they are as shown in Figure 11a, and the following points can be analyzed:

(1) When bending stress is applied, a persistent slip band (PSB) is created at the grain boundary (GB), which is vulnerable to tensile stress, as shown in Figure 10A(a–c). The PSB gradually slips in the surface (Figure 10) and depth (Figures 8b and 9b) directions. It grows and develops into a major crack that determines the lifespan of the test piece.

(2) Figure 10B shows the occurrence, growth, and coalescence of micro-surface fatigue cracks on the surface shown in Figure 10A. They are sketched on tracing paper by connecting many optical photos (as in the example of Figure 10A(i)). This is part of the data visualized using a mosaic method. As shown in Figure 10A,B, growth and coalescence with another adjacent micro fatigue crack continue. Many small ridges (Figures 8b and 9b) are generated in the depth direction, and the major ridge grows along the depth direction of the major crack, which determines the lifespan.

(3) In this way, many small surface fatigue cracks appear on the surface, as shown in Figures 8b and 9b, and the combined state is shown in Figure 10B. Among these many surface fatigue cracks, one or more become a major crack, determining the fatigue life of the test specimen.

(4) In particular, if internal inclusions exist near the surface, resistance to repeated slip motion is generated, resulting in micro-surface fatigue cracks on the surface, such as in Figure 8a (S1) and Figure 10A(a) (CI). Also, if inclusions do not exist, the PSB resists repetitive motion at the grain boundary, where impurities exist, resulting in micro-surface fatigue cracks that become major cracks.

(5) The surface crack length of $214.8\text{ }\mu\text{m}$ in the red dotted line of S1 in Figure 8b was traced for its life in Figure 11c. This corresponds to a lifespan rate of approximately 65%. In addition, the average length of eight micro-surface fatigue cracks within the red dotted line is $30.3\text{ }\mu\text{m}$, so the lifespan was traced in Figure 11a. This corresponds to a lifespan rate of approximately 35%.

(6) If you trace the lifespan of the dotted line on S1 in Figure 8a in Figure 11a, it corresponds to 75%, 87%, and 92%, respectively. It can be seen that the crack propagation speed gradually increases.

(7) Figure 11c is a sketch of the shape of micro-surface fatigue cracks and micro-ridges in the depth direction by rotating Figure 8b by 90 degrees. Additionally, Figure 11b is a sketch tracing the morphology of micro-surface fatigue cracks at a stage (about 32%) prior to the eight yellow dashed lines in Figure 11c, which corresponds to a life fraction of about 40%.

(8) The fatigue life of Cr-Mo steel was improved after UNSM treatment. What is unique about Cr-Mo steel is that inclusions were found inside the crack occurrence location, as shown in Figures 8b and 9b. In other studies, inclusions were located at the center of

fish-eye crack occurrence. However, in this Cr-Mo steel, surface fatigue cracks occurred, grew, and fractured in both UNSM-treated and untreated materials.

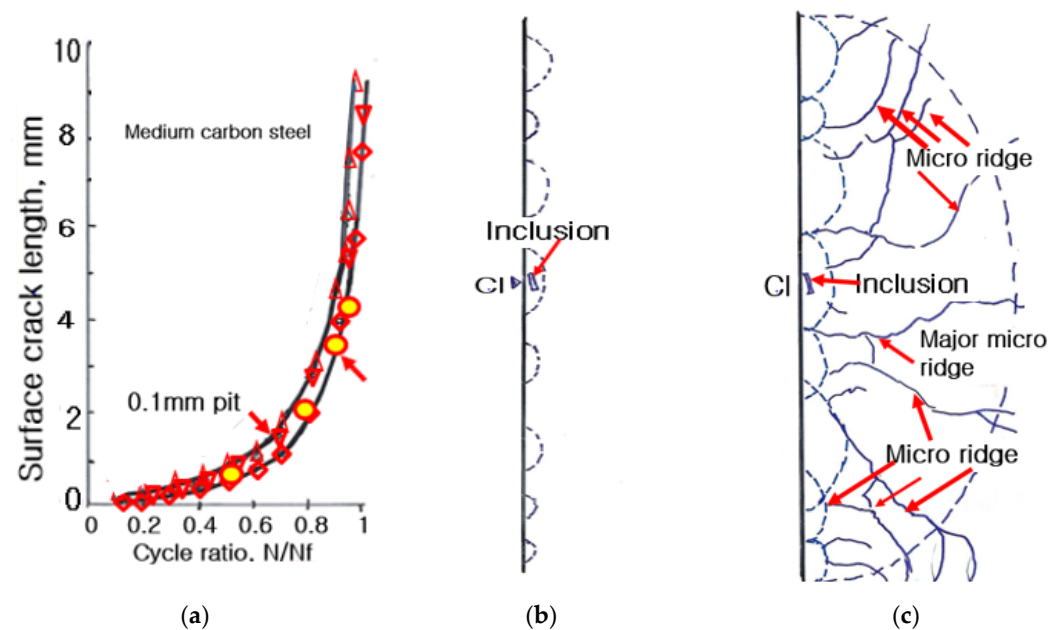


Figure 11. (a) Comparison curve according to the growth and cycle ratio of the surface fatigue crack length on a small circular artificial notch material with a surface and depth of 0.1 mm in medium carbon steel [21]. (b) is a sketch tracing the morphology of micro-surface fatigue cracks at a stage (cycle ratio about 32%) prior to the eight dashed lines in (c). (c) is a sketch of the shape of micro surface fatigue cracks and micro-ridges in the depth direction by rotating Figure 8b by 90 degrees, which corresponds to cycle ratio about 40%.

4. Conclusions

In this study, Cr-Mo steel AISI4137, which is used for high-strength fastening bolts, was studied. The following results were obtained through fracture mechanics and fracture analysis as follows: (1) the occurrence, growth, and coalescence behavior of numerous small surface fatigue cracks on the surface were observed and analyzed, and (2) the growth characteristics of fatigue cracks in the depth direction were analyzed.

As the static load of the UNSM treatment increased, the structure of Cr-Mo steel was refined by severe plastic deformation from the surface to a depth of about 100 μm . The surface hardness also increased as a large compressive residual stress was formed. Additionally, the fatigue limit increased by 30% in the VHCF area, and the fatigue life was greatly improved.

In the Cr-Mo steel, fish-eye cracks did not occur, even if inclusions existed on the fracture surface. In the UNSM-treated material, like the untreated material, all surface cracks occurred and fractured as they grew.

Accordingly, one or more of the many micro-surface fatigue cracks grew and developed into a major crack, which determined the fatigue life. Among the many micro-ridges in the internal direction, a major ridge was formed inside the major crack. In other words, this major crack grew and coalesced on the surface and developed a major ridge in the inner direction, which determined the lifespan of the test specimen.

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