Fatigue Properties of Aluminum Alloy (A6061-T6) with Ultrasonic Nano-crystal Surface Modification

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General knowledge

Good effectiveness on **light weight**

Good **thermal conductivity** and non-magnetism

Good **corrosion resistance**, a low density and a **high specific strength**

100% **recyclable**

Good **ductility** and **low melting point**

Good usage to the transportation fields (ex: Aircraft, Vehicle, Railroad etc.)

**Keyword**: UNSM, Fatigue strength, VHCF (Very High Cycle Fatigue)
**Introduction to UNSM Technology**

- **$P_{st}$**: Static Load
- **$A$**: Amplitude
- **$V$**: Speed,
- **$S$**: Feed (mm/rev)
- **$D$**: Specimen Diameter
- **$f$**: Frequency (kHz)

The total force $P_t$ can be calculated as:

$$P_t = P_{st} + p \sin 2\pi ft$$

(2.5~5 times of static load)

![Model of UNSM](image)
UNSM Device

Fig. 2 Configuration of the UNSM device

Fig. 3 Distribution of stress and amplitude of the UNSM device
Comparison among UNSM and established technologies

Table 1 Results of various established technologies on mechanical properties

<table>
<thead>
<tr>
<th>Tech.</th>
<th>SP</th>
<th>LSP</th>
<th>LPB, DR</th>
<th>USP</th>
<th>UNSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy source</td>
<td>Powder Injection</td>
<td>Laser Heat</td>
<td>Static Load</td>
<td>Ultrasonic Dynamic Load</td>
<td>Static Load + Ultrasonic Dynamic Load</td>
</tr>
<tr>
<td>Compressive Residual Stress/Depth</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Hardness &amp; Depth</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Nano Structure</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Surface Topology (Dimple)</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 4 Comparison of “case” depths by cold work and fatigue strength for different mechanical surface treatments

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## Experimental procedure

### Table 2  Chemical composition of A6061-T6 Alloy.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (Wt. %)</td>
<td>0.6</td>
<td>0.24</td>
<td>0.33</td>
<td>0.12</td>
<td>1.0</td>
<td>0.21</td>
<td>0.01</td>
<td>0.02</td>
<td>Remainder</td>
</tr>
</tbody>
</table>

### Table 3  Mechanical properties of A6061-T6 Alloy.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
<th>Young’s Modulus (GPa)</th>
<th>Vickers Hardness (Hv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6061-T6</td>
<td>276</td>
<td>310</td>
<td>20</td>
<td>68.9</td>
<td>117</td>
</tr>
</tbody>
</table>
Experimental procedure

Fig. 5 Fatigue specimen (dimension : mm)

\[ \sigma = \frac{9.81 \times 32 \times W \times L \times K_t}{\pi d^3} \]

W : weight (Kgf)
L : distance between the loading point and the critical section of the specimen (L=46.5mm)
K_t : stress concentration factor (K_t = 1.08)
d : diameter of the critical section of the specimen
Experimental procedure

Very High Cycle Fatigue (VHCF) test machine (Giga Cycle Fatigue)

(a) Motor
(b) Spindle
(c) Specimen
(d) Photo sensor & Micro switch
(e) Bearing & Spring
(f) Weight
(g) Counter

Fig. 6 Dual-spindle rotating bending fatigue testing machine
Fig. 7  Distribution of hardness ‘before’ and ‘after’ UNSM treatment

40% increase compared with before UNSM specimens

Element: A6061-T6
- ▲ before UNSM
- ■ after UNSM (1.5Kgf)
- ◇ after UNSM (3.0Kgf)

Original hardness
Fig. 8 The variation of surface treatments between ‘before’ and ‘after’ UNSM
Surface roughness

The results of roughness test

(a) ‘before’ specimen
(b) ‘after’ specimen

Roughness

<table>
<thead>
<tr>
<th>Roughness</th>
<th>A6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before UNSM</td>
</tr>
<tr>
<td>(R_a(\mu m))</td>
<td>1.48</td>
</tr>
<tr>
<td>(R_{\text{max}}(\mu m))</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 4 Comparison of surface roughness ‘before’ and ‘after’ UNSM treatment.
Fig. 10  *S-N Curve*
Observations of fracture surface (before UNSM)

(a) Low magnification ($\times 100$) of crack initiation site ($\sigma_a = 150\text{MPa}$, $N_f = 2.02 \times 10^7$)

(b) Enlarged photo of crack initiation site at high magnification ($\times 1000$)
Observations of fracture surface (before UNSM)

(c) A fracture surface indicates many crack initiation site at \((\sigma_a = 250\text{MPa}, N_f = 1.59 \times 10^6)\)

(d) Enlarged surface crack initiation site (X 500)
Observations of fracture surface (before UNSM, striation)

(e) \( (\sigma_a = 250\text{MPa}, \ N_f = 1.59 \times 10^6) \)

(f) An example of ductile striation
Observations of fracture surface (after UNSM, striation)

(g) Surface structure changed by UNSM treatment (68.9 ~ 172 μm)

(h) Magnification (×3000) of crack initiation site
\(\sigma_a = 250\text{MPa}, N_f = 1.14 \times 10^7\)
SEM & EDS analysis

Al-Mg-Si compounds were analyzed by EDS

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>7.25</td>
<td>11.58</td>
</tr>
<tr>
<td>O K</td>
<td>45.88</td>
<td>55.04</td>
</tr>
<tr>
<td>Mg K</td>
<td>0.67</td>
<td>0.53</td>
</tr>
<tr>
<td>Al K</td>
<td>45.74</td>
<td>32.53</td>
</tr>
<tr>
<td>Si K</td>
<td>0.46</td>
<td>0.31</td>
</tr>
<tr>
<td>Totals</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
XRD experimental procedure

- Cutting
  - Size 1cm X 1cm
- Pretreatment
  - HBF₄ + H₂O
- AC etching
  - 30°C, 40~80s
  - 20Hz ~ 60Hz
  - 200mA / Cm²
- Washing
  - For 60s by using distilled water
- Drying
  - 250°C sintering
  - By using furance

Fig. 11 Diagram of A6061-T6 specimen etching process

Fig. 12 XRD equipment
Fig. 13  Schematic illustration of X-ray diffraction profile

Table 4  Conditions of X-ray diffraction

<table>
<thead>
<tr>
<th>X-ray target</th>
<th>Cu-Kα</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction plane</td>
<td>(311)</td>
</tr>
<tr>
<td>Filter</td>
<td>Ni</td>
</tr>
<tr>
<td>Voltage</td>
<td>40kV</td>
</tr>
<tr>
<td>Current</td>
<td>20mA</td>
</tr>
</tbody>
</table>
Texture observation

(a) Observation of the micro structure of ‘before UNSM’

(b) ‘after UNSM’ 1.5Kgf

(c) ‘after UNSM’ 3.0Kgf
XRD experiment results

(a) diagram shows specimen for ‘after UNSM’ 1.5Kgf

(b) diagram shows specimen for ‘after UNSM’ 3.0Kgf

Fig. 14 2θ-sin²ψ diagram for (311) diffraction plane in A6061-T6
### Table 5 Compressive residual stresses of measured positions

<table>
<thead>
<tr>
<th>specimen</th>
<th>Position</th>
<th>Compressive residual stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (surface)</td>
<td>-198 ± 4.3</td>
<td></td>
</tr>
<tr>
<td>2 (100 μm)</td>
<td>-188 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>3 (200 μm)</td>
<td>-140.6 ± 3.7</td>
<td></td>
</tr>
<tr>
<td>4 (300 μm)</td>
<td>-88 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>5 (400 μm)</td>
<td>-97 ± 6.7</td>
<td></td>
</tr>
</tbody>
</table>

#### Fig. 15 Relation between distance from specimen surface and compressive residual stress

- **-88 MPa**
- **-141.9 MPa**

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Fig. 16  Pole figure analysis of ‘after UNSM’ 3.0Kgf  
(position 1: analysis in deep from the surface)
Fig. 17 Pole figure analysis of ‘after UNSM’ 3.0Kgf (position 2: analysis in 100μm deep from the surface)
(a) Analysis of stereo graphic projection pole figure(200μm)

(b) 2.5D for pole figure analysis of specimen(200μm)

Fig. 18 Pole figure analysis of ‘after UNSM' 3.0Kgf
(position 3: analysis in 200μm deep from the surface)
Fig. 19  Pole figure analysis of ‘after UNSM’ 3.0Kgf  
(position 4: analysis in 300μm deep from the surface)
Fig. 20  Pole figure analysis of ‘after UNSM’ 3.0Kgf  
(position 5: analysis in deep 400μm from the surface)
Conclusions

1. The UNSM treatment increased the fatigue strength about 50%.

2. 40% surface hardness was improved by UNSM treatment. The surface roughness also decreased 3.4 ~ 8.7 times with the treatment.

3. UNSM treatment changed surface structure of A6061-T6 material as nano-size of it about 69~172 μm depth from surface by severe plastic deformation (SPD).

4. The maximum -198 MPa was measured for compressive residual stress in ‘after UNSM’ 1.5Kgf treatment condition by using X-RAY diffraction, and this compressive residual stress (CRD) would be caused by increase in fatigue strength of Al material, and, the creation of texture could be confirmed through pole figure analysis since there was no change in slope according to depth in ‘after UNSM’ 3.0Kgf residual stress distribution.

SPD layer which has low roughness hardened surface with compressive residual stress (CRD) improves fatigue strength and mechanical properties.
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References


Thank You!