Fatigue characteristics of nano-structured tool steel under load variation by ultrasonic cold forging treatment

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1. Introduction

Recently, the use of high strength steels (HSS) for automotive applications has been drastically increased not only to enhance the safety and durability of vehicles, but also lighten the weight for a high degree of fuel efficiency. In the side trimming operation in the production of HSS, knife breakage and burr frequently occur. In addition, such breakage and bad quality of strip cutting face are affected by yield as well as by reduced productivity and reliability on production line [1-5]. This study examined the variation of mechanical properties of nano-structured surface by ultrasonic cold forged tool steel (SKD-61). Same ultrasonic cold forging treatment (UCFT) process was applied to produce the trimming knife. Their effectiveness and reliability of the UCFT were successfully verified through the field test by trimming process in cold rolling line of POSCO.

2. Ultrasonic Cold Forging Treatment (UCFT)

2.1 Principles and application of UCFT

UCFT uses ultrasonic vibratory energy as a source, and several tens of thousands of strikes per second to the material surface as constant pressure is applied. These strikes cause severe plastic deformation to surface layers and induce a nano-crystal structure. Model of the UCFT is shown in Fig.1. In this figure, $P_{st}$ is the static load, $P$ is the amplitude of dynamic load, $S$ is the feed of main shaft of the ultrasonic vibratory device, $S_s$ is the moving distance of the ball between two striking points. In ultrasonic cold forging, total energy ($P_t$) acting on the workpiece from the ultrasonic vibratory device is the sum of the static energy ($P_{st}$) pushing ultrasonic vibratory device with constant pressure and the dynamic energy occurred through the ultrasonic vibration as eq. (1). Strength of the dynamic energy is 2.5 to 5 times larger than the static energy.
Fig.2 shows configuration of the UCFT device. It consists of several components such as the ultrasonic generator (a) generating electric ultrasonic frequency, the air compressor (b) pushing ultrasonic generator unit with constant pressure, the piezo-transducer ([c], Pb(Zr,Ti)O$_3$), the booster (d) amplifying the ultrasonic vibration, the horn (e) transmitting the ultrasonic vibration and ball tip ([f], tungsten carbide).

2.2 Effect of the UCFT on mechanical properties

To verify the feasibility of the UCFT, various experiments were carried out with a tool steel SKD 61, which is the material of the trimming knife used in the cold rolling mill. Specimens were treated using the UCFT. 20kHz of frequency applied to the ball tip, and the applied static forces were changed three kinds of load; 40N, 60N and 80N respectively.

2.2.1 Observation of nano-structured surface by optical microscope and TEM

The microscopic grain size is uniformly distributed on the surface before the UCFT (Fig.3a), while Fig.3 (b) presents the tendency of change in nano-crystal structure of SKD 61 to 100µm depth (d) after the UCFT. According to Hall-Petch equation [12], when grain size becomes smaller, yield strength and hardness become greater.

TEM is used for analyzing the grain size and crystal structure and in order to obtain better surface condition for observation, a TEM specimen is made through several processes; cutting, micro grinding, dimple grinding, ion milling. Fig. 3 (c) shows a surface observation using TEM after UCFT. Generally, carbide is formed as micro lath before UCFT. But after UCFT, carbide is distributed with average grain size 50nm and the grain boundary is unclear in the base phase. The diffraction pattern in the top left shows also the mixed phase of amorphous and nano crystalline. This factor shows the main reason for increased hardness and fatigue strength.
Fig. 3 Microstructure of SKD 61; (a) before and (b) after the UCFT

Fig. 3(c) UCF treated surface layers observed by TEM

2.2.2 Variation of surface hardness and compressive residual stress

Comparison between the hardness of the material both before and after UCFT is shown in Fig. 4. A micro Vickers hardness tester was utilized, and 200g of the load was applied for the test. The hardness of each specimen was measured every 20µm from the surface to a 160µm depth. The hardness of the surface after UCFT was increased by 37% compared with that of before UCFT. The hardness after UCFT was rapidly decreased to about 60µm from the surface and stabilized. Fig. 5 shows the tendency of the change in residual stress along the depth direction both before and after UCFT. Compressive residual stress is the most crucial factor in the increased fatigue resistance. The residual stress was measured every 20µm depth using an X-ray residual stress measurement tester (RIKAGU). Electrolysis-polishing was used to cut out the constant depth. As shown in Fig. 5, compressive residual stress was -443MPa at the top surface before UCFT. But the value becomes -811MPa after UCFT and remained until 150µm depth. It was also observed that the effective depth of UCFT was about 350µm. While the compressive residual stress before UCFT is very small and remained just at the top surface.
2.2.3 Variation of wear characteristics and surface roughness

Wear test was conducted by a pin-on-disk method to examine the wear characteristics before and after UCFT. Force of 5N was applied under 1 hour of sliding time. Frequency was set to 3Hz, and the counterpart material was Si₃O₄. Fig.6 shows the change in the friction coefficient as a function of the sliding distance before and after UCFT. Table 1 shows comparison between the wear amount and the friction coefficient. Before UCFT, the friction coefficient was rapidly decreased along time, whereas it was slightly changed after UCFT. It was also observed that the wear amount is about 30 times less and the friction coefficient was decreased by 50% after UCFT in laboratory test. In the field test for reliability the wear amount was confirmed to be about 3 times less than that of after UCFT.

The surface roughness before UCFT was Ra=0.3 µm, and it became Ra=0.08 µm after the UCFT. Mitutoyo SJ-300 was used as roughness tester.

<table>
<thead>
<tr>
<th>UCFT</th>
<th>Wear amount (mg)</th>
<th>Friction coefficient</th>
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<tbody>
<tr>
<td>Before</td>
<td>1.179</td>
<td>0.42</td>
</tr>
<tr>
<td>After</td>
<td>0.039</td>
<td>0.21–0.24</td>
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</tbody>
</table>
2.2.4 Variation of fatigue characteristics

Fatigue tests were conducted using Ono type rotary bending machine (H5 type, 98µm, Shimadzu Co.) at 3,400rpm in room temperature, and the specimens were prepared under the JIS Z2274 standard. The fatigue characteristics of smooth specimen before and after UCFT, are shown in Fig.7. The $10^7$ cycles fatigue limit before UCFT was 719MPa, whereas that of after UCFT under load 80N was 848MPa, which represented a 17.9% increase.

![Fig. 7 S-N curves of smooth specimen before and after static load variation 40N, 60N and 80N by the UCFT](image)

2.2.5 SEM observations of fractured surface

Fig. 8 (a) shows SEM micrograph of fracture surface of surface-originating fracture in case of SKD61 raw material; before UCFT smooth specimen. Fig. 8 (b) shows enlargement of surface-originating crack site which indicates an inclusion, its size is about 20 µm. This inclusion is analyzed by EDS and contains Fe 94.51%, Cr 4.86%, V 0.63%.

Fig. 9 (a) shows SEM micrographs of interior-originating fracture, fish-eye crack, in case of UCFT smooth specimen. Fig. 9 (b) shows high magnification of fish-eye contains Fe 94.63%, Cr 5.37%. From these SEM observations, surface-originating fracture occurred at raw material while interior-originating fracture, fish-eye crack, occurred after UCFT because of nano-structured modification by severe plastic deformation and compressive residual stress in case of smooth specimen.
Fig. 8 SEM micrographs of fracture surface of surface-originating fracture before the UCFT; (a) lower magnification view and (b) enlargement of crack initiation site

Fig. 9 SEM micrographs of interior-originating fracture after the UCFT; (a) lower magnification view of fish-eye crack and (b) enlargement of fish-eye

2.2.6 Relationship between the fisheye crack and the fatigue life

Fig. 10 shows the relationship between the fisheye area ($A$) and fatigue life. The fisheye area shows linear relationship with the fatigue life and shows the function as eq. (2).

Fig. 10 Relationship between the fisheye crack area and the fatigue life
\[ A = -9.23 \times 10^5 + 2.15 \times 10^5 N_f \]  

(2)

3. Conclusions

1) Interior-originating fracture, fish-eye crack, occurs after UCFT, while surface-originating fracture in case of SKD61 raw material before UCFT, because of nano-structured modification by surface plastic deformation and compressive residual stress in case of the smooth specimen.

2) Fatigue limit of \(10^7\) cycles of SKD61 is 719MPa before UCFT. However fatigue limits are increased by 8.3, 11.2, 17.9\% respectively when the static loads of UCFT are changed as 40N, 60N and 80N.

3) The fisheye area shows linear relationship with the fatigue life.

Acknowledgement

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References