Nano Structured Surface Modification of Tool Steel and its Beneficial Effects in Mechanical Properties

In Ho Cho*
Graduate School, SunMoon University, Asan, South Korea
Gil Ho Song
Technical Research Laboratories, Pohang Iron & Steel Co., Ltd. Kwangyang, Korea
Chang Sik Kim, Azuma Nobuhide, A. Combs, Jin Park
DM R&D Institute, DesignMecha Co., Ltd. Asan, South Korea
Chang Min Suh
Department of Mechanical Engineering, Kyungpook University, Taegu, Korea
Jeong Hyun Park, Young Shik Pyoun
Department of Mechanical and Control Engineering, SunMoon Univ., Asan, South Korea

The industrial beneficial effects of nano-structured surface modification of tool steel (SKD 61) have been studying. Ultrasonic cold forging technology (UCFT) is one of severe plastic deformations for the improvement of mechanical properties by making nano-structure on surface. The basic mechanism of UCFT and experimental device for treatment of trimmer knives (SKD 61) are presented. Test results of UCFT treated knives in cold steel milling line and analysis why the improved service life is achieved are explained.

Key Words : Nano-Surface Modification, Ultrasonic Vibration, Property, Tool Steel

1. Introduction

In steel industry, the harder and tougher edge of trimmer knives have been required in order to reduce processing time and cost and to improve the quality of products. New special alloy with heat treatment technology and surface treatment technology have been developed for this purpose (Pye, 1997). But for the development of new special alloyed knives, high cost and earth rare component such as V, W, Mo and high cost heat treatment are required (Toith, 1971). In surface treatment on the knives, the base and coating materials are incoherent and physical boundary between base material and coating material gives weakness to surface layer (Mirtich, 1981).

As shown by Hall-Petch equation, nano crystal structured materials is one ideal solution to achieve toughness and hardness simultaneously in the edge of knives. Equal-Channel Angular Pressing (ECAP) improved the yield strength of steel 18-10 more than 5.6 times by making nano crystal. High Pressure Torsion (HPT), Accumulative Roll Bonding (ARB) and Repetitive Corrugation and Straightening (RCS) are also one of severe plastic deformation (SPD) technologies making nano crystal in bulk materials (Kaloshkin, S. D., 2002 ; Alexandrov et al., 2002 ; Segal, 1995). But ECAP can not be applied to trimmer knives yet due to their size and cost limitation and other technologies are not suitable process for making knives also. The more difficulties of these technologies are post process after nano structurizing process such as heat treatment, sintering and machining.

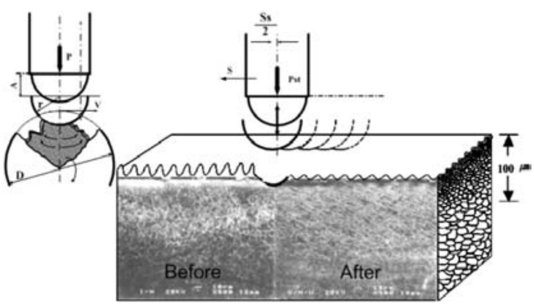
* Corresponding Author,
E-mail : cie8905@sunmoon.ac.kr
TEL : +82-41-530-2859; **FAX** : +82-41-530-2307
Graduate School, SunMoon University, Asan, South Korea. (Manuscript **Received** January 25, 2005; **Revised** May 13, 2005)

Ultrasonic Cold Forging Technology (UCFT) (Pyoun et al., 2001 ; Han et al., 2002 ; Pyoun, 2003), which is one of SPD technologies also, can improve toughness and hardness of knife edge simultaneously by nano structurizing of surface layers. The nano structurizing of surface layers by UCFT requires low energy and no post process and has no size limitation. In this paper, the basic mechanism of UCFT and how to apply it to trimmer knives are presented with test results and analysis why such improved service life is achieved.

2. The Basic Mechanism of Micro Cold Forging Technology using Ultrasonic Wave

Fig. 1 shows the basic mechanism of ultrasonic cold forging technology (UCFT).

Ultrasonic Cold Forging Technology (UCFT) uses ultrasonic vibration energy. In Fig. 1, Pt is total force loaded to the surface and psin2πft is the dynamic force by ultrasonic energy. The ball with Pt strikes several 10 thousands times per second on the rotated surface. These strikes, which is called micro cold forging, bring severe plastic deformation to surface layers and thus induce nano crystal structure. Beside nano structurizing of surface layers, UCFT improves surface roughness, hardness, compressive residual stress, etc.



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

P_{st} : static load   A : amplitude

V : speed (m/min)   S : feed (mm/rev)

D : Specimen diameter   r : ball radius

Fig. 1 Basic mechanism of ultrasonic cold forging technology (UCFT)

3. Experiment

3.1 The selection of trimming knives

SKD61, which is common material for trimmer knives in cold steel milling lines, is selected to compare the effect of UCFT treatment. The diameter of trimmer knife is 250 mm and hardness is HRc 47 after vacuum heat treatment. Surface is ground as roughness Ra=0.3.

3.2 Experimental device

Ultrasonic device consists of piezo-transducer (vibrator), booster (amplifier and transmitter of vibration), and horn. In the end of horn, there is a ball which transmits mechanical vibration to the material. The material of booster, horn and ball gripper is titanium alloy which is good wave propagation property and fatigue durability. The material of ball is tungsten carbide (WC) which is good wear resistance and hardness. The amplitude of ultrasonic wave is 20～100 μm at the end of ball tip. Fig. 2 is overview of ultrasonic devices.

A CNC Lathe is used. Trimmer Knife is fixed in the chuck of spindle. UCFT unit is built on turret slide. Fig. 3 shows the schematic configu-

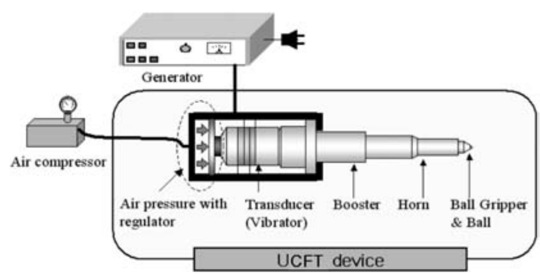


Fig. 2 Overview of Ultrasonic Device

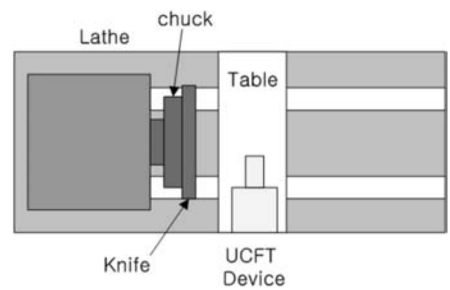


Fig. 3 Schematic configuration of experimental devices

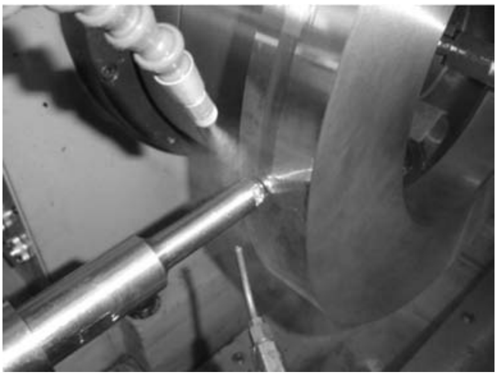


Fig. 4 Scene of UCFT process

ration of experimental devices setup and Fig. 4 shows a scene of UCFT process.

3.3 Process variables of UCFT treatment

Proper static load, amplitude and number of strikes in unit area are major process variables to achieve nano crystal structure and additional effects such as improved roughness and hardness, compressive residual stress, etc. About 7.5 Kgf static load with 20～100 μm amplitude and 3,000-6,000 strikes per unit area are selected for this experiment.

4. Analysis of Beneficial Effect

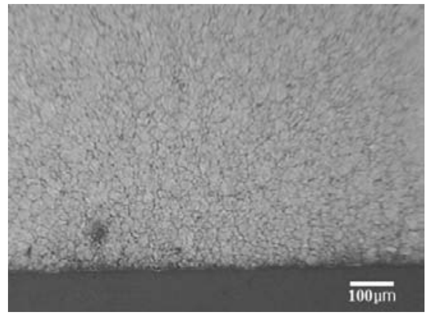
4.1 Topology of nano structured layer

4.1.1 Grain size observation through optical microscope

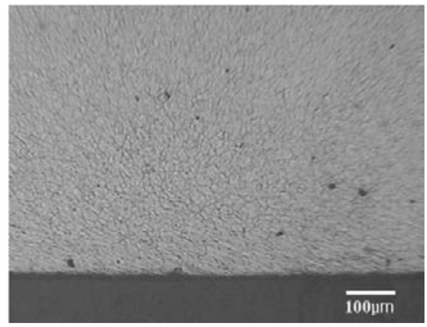
Fig. 5 shows topology of cutting surface to normal direction of knife surface before and after UCFT treatment. Before UCFT treatment, the grains in micro size are uniformly distributed on the surface, but after UCFT treatment, grain size becomes very fine. According to Hall-Petch equation (Hall, 1953), grain size becomes smaller, yield strength and hardness become higher.

4.1.2 Observation through TEM

In order to analyze the grain size and crystal structure, TEM is used. Specimen for TEM is made through several process (cutting, micro grinding, dimple grinding, ion milling) to get



Before UCFT



After UCFT

Fig. 5 Topology of before and after UCFT (x160)

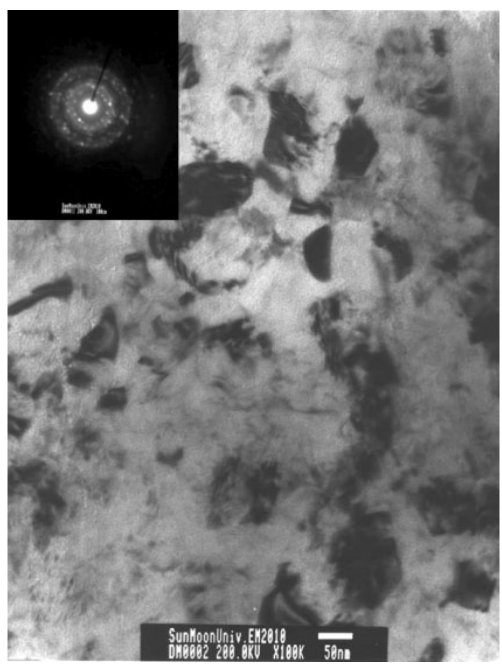


Fig. 6 UCFT treated surface layers observed by TEM

better surface condition for observation. Fig. 6

shows surface observation with TEM after UCFT treatment. JEOL EM2010 is used for observation of TEM.

Generally, before UCFT treatment carbide is formed as micro lath. But after UCFT treatment, carbide is distributed with average grain size 50 nm and the grain boundary is not clear in the base phase. The picture of diffraction pattern in the left top shows also the mixed phase of nano and amorphous crystalline. This factor can explain that the main reason of increasing the yield strength and hardness due to surface nano-structurization.

4.2 Surface hardness

Fig. 7 shows hardness value of trimmer knives before and after UCFT treatment. Micro Vickers hardness tester is used and the applied load is 100 g. Hardness values are measured every 30 μm from surface to 280 μm depth.

Before UCFT treatment, hardness value of surface is HRc 48, but after UCFT treatment, surface hardness becomes HRc 62. The depth beneath surface of the increased hardness is about 180 μm.

4.3 Compressive residual stress

Compressive residual stress is the most important factor in fatigue durability. Compressive residual stress are measured by the RIKAGU residual analyzer and X-ray Goniometer including stress analysis program.

X-ray target of residual stress measurement is Cr which is appropriate with SKD 61. Measured crystal face is 211, 2θ is 156deg, and ψ is 0, 5, 10, 15, 20, 25, 30, 35 and 40. Coefficient of stress is 98 ksi/deg. Fig. 8 shows residual stress value before and after UCFT treatment.

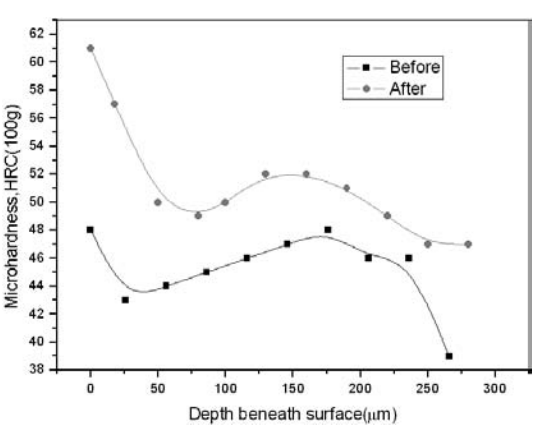


Fig. 7 Surface hardness before and after UCFT

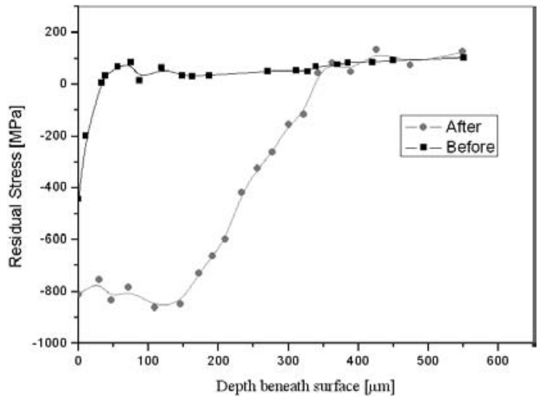


Fig. 8 Residual stress value before and after UCFT

Before UCFT treatment, residual stress value was −443 Mpa at top surface but after UCFT treatment, this value becomes −811 Mpa and keeps same value till 150 μm depth. The affected depth is about 350 μm.

4.4 Surface roughness

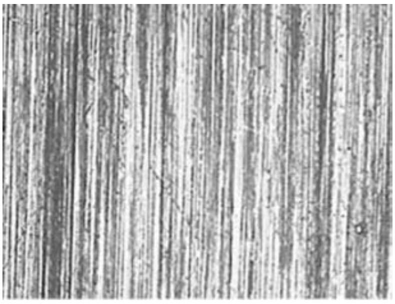
The surface roughness before UCFT treatment was Ra=0.3 μm, but it becomes Ra=0.08 μm after UCFT treatment. Mitutoyo SJ-300 is used as roughness tester.

4.5 Analysis of surface topology

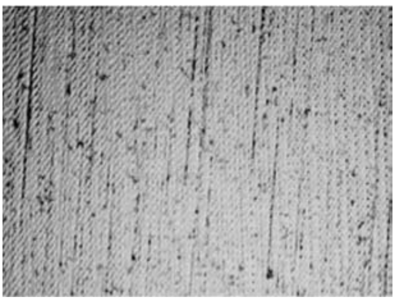
Fig. 9 shows surface before and after UCFT treatment. Before UCFT treatment, many sharp grinding scratches are shown, but after UCFT treatment, these scratches, which cause stress concentration, are removed and become dimple figures.

4.6 Fatigue test

Fatigue tests were performed with an MTS tensile tester. All high cycle fatigue tests were performed under constant stress amplitude load at ambient temperature. The maximum load amplitude used was 1700 MPa, which is approximately 70% of the ultimate tensile strength. The cyclic frequency and load ratio, R, were 20 HZ and 0.1,



Before UCFT



After UCFT

Fig. 9 Surface topology of before and after UCFT

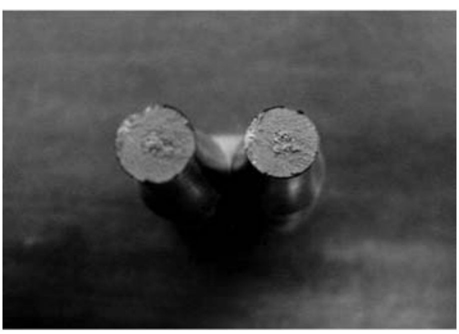


Fig. 10 Fracture surface

respectively.

Following fatigue testing, each specimen was examined optically to identify fatigue origins and fracture modes. Fractographs were taken with a camera attached to a Nikon stereoscope. Fig. 10 shows the fracture surface of a test specimen after the fatigue test.

Fig. 11 shows the fatigue limit curve of tested SKD61 steel. Fatigue strength at a fatigue life of 10^6 cycles is 620 MPa before UCFT and 1125 MPa after UCFT. The fatigue strength has been almost doubled by the UCFT treatment, which induces a deep compressive residual stress layer

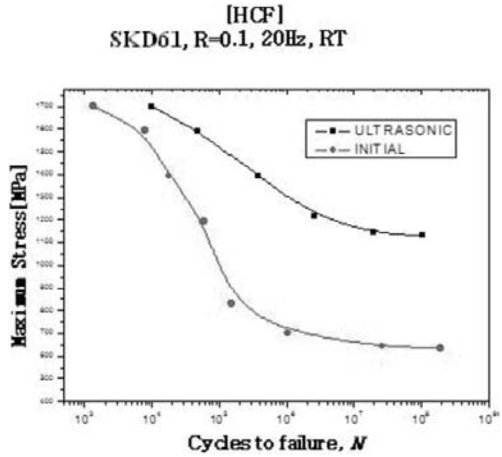


Fig. 11 The fatigue limit curve of tested SKD61 steel

on the surface. Compressive residual stress in the surface layer is believed to contribute to the improvement of fatigue durability.

4.7 Result of test cutting

In field trials conducted at the 2nd cold rolling mill line of POSCO in Pohang, Korea, edge cracking of UCFT treated trimmer knives began to appear after shearing 80 km of strip steel on the average as compared to 50 km of shearing with conventional trimmer knives. After removing the edge cracks of the knives by regrinding, the tests were repeated several times and showed similar results.

Field trials were also conducted in a TPL line at Dongbu Steel in Asan, Korea for more than a year. The field trial results demonstrated that the service life of UCFT treated trimmer knives has increased by 170% at the TPL line of Dongbu Steel.

Table 1 summarizes the field trial test results of UCFT trimmer knives in each line.

Table 1 Field trial test results of UCFT trimmer knives

Line Name	Company	Before UCFT	After UCFT	Remark
2nd Cold Mill	POSCO	50 km	80 km	1.6 times improvement
TPL	Dongbu Steel	3000 tons	8000 tons	2.7 times improvement

5. Discussion and Future Study

The 1.6～2.7 times increased service life after UCFT treatment of trimmer knives can be explained by following effects or reasons.

(1) Nano crystal structure surface layer is created by UCFT

(2) The yield strength and hardness of surface layers are increased by nano crystal structurization.

(3) Fatigue durability of edge crack is improved due to the increased yield and ultimate strength and compressive residual stress.

Fatigue wear can be improved due to increased hardness, compressive residual stress and improved roughness, and friction force can be also reduced due to improved roughness and dimple topology of surface after UCFT treatment. Fatique wear improvement and friction force reduction by UCFT treatment can be another reasons of increasing service life of trimmer knife.

In order to analyze what factors of UCFT treatment bring such effect, many experiments such as wear test, fatigue test under torsion moment, friction coefficient and etc are needed. Some tests are being carried out and the others are planned in near future.

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