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Mechanical Characteristics of Nano-Structured Tool Steel by Ultrasonic Cold Forging Technology

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Ultrasonic cold forging technology (UCFT) utilizing ultrasonic vibration energy is a method to induce severe plastic deformation to a material surface, therefore the structure of the material surface becomes a nano-crystal structure from the surface to a certain depth. It improves the mechanical properties; hardness, compressive residual stress, wear and fatigue characteristics. Applying UCFT to a rolling process in the steel industry is introduced in this study. First, the UCFT specimens of a tool steel (SKD-61/equivalent H13) are prepared and tested to verify the effects of the UCFT in a variety of mechanical properties, the UCFT is applied to the trimming knives in a cold rolling process. It has been determined that UCFT improves the mechanical properties effectively and becomes a practical method to improve productivity and reliability by about two times compared with the conventionally treated tooling in the trimming process in a cold rolling line.

1. Introduction

For several decades, the automotive industry has been one of the most important markets for steel companies. The global demand of automotive steels is currently estimated at around 90 million tons, which is approximately 13% of the total global market share. Recently, the use of high strength steels (HSS) for automotive applications has been dramatically increased not only to enhance the safety and durability of vehicles, but also to lighten the vehicle's weight for improving fuel efficiency. To fulfill the increased demands, steel companies have focused on development of high strength steels. However, the increase of production of high strength steels has created new challenges in the steel-making process. One example of such a challenge is in the side-trimming process, which cuts from 7 to 10mm from both edges of a cold-rolled strip in order to produce the desired width required by customers and to eliminate cracks on the edges of hot-rolled strips. In the side trimming operation in the production of HSS and mild steel, knife breakage and burring frequently occur. This results in poor edge quality of strip as well as the reduction of productivity and reliability in production line. Thus, a variety of studies on new design of special alloy elements [1], advanced heat treatment technology [2,3], various methods of producing severe plastic deformation [4~10] on the surface of the trimming tools, and improving quality of the strip cutting face [11] have been conducted to prevent knife breakage and to decrease burr magnitude. When the trimming knives simultaneously have higher hardness, toughness and lower friction, these problems will be clearly mitigated. UCFT is a nano- structured surface modification technology which can improve hardness, toughness and friction characteristic. In this study, the variation of mechanical properties of nano-structured surface of the UCFT tool steel (SKD-61/equivalent H13) is examined and the same UCFT process is applied to produce trimming knives. In order to show their effectiveness and reliability, UCFT trimming knives are tested at the trimming process in a cold rolling line of POSCO. The principles, device and effects of UCFT are also described briefly.

2. Ultrasonic Cold Forging Technology (UCFT)

2.1 Principles and Application of UCFT

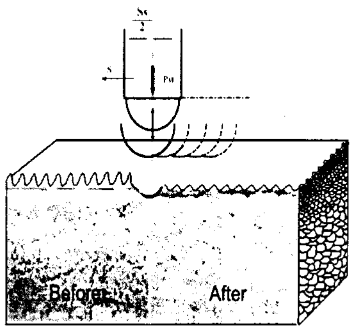

Fig. 1 Process of the UCFT

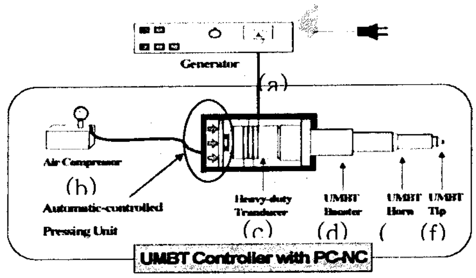

Fig.2 Configuration of the UCFT device

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.

$$P_t = P_{st} + P \sin 2\pi f t \quad (1)$$

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 force was 100 N.

2.2.1 Observation of Nano-Structured Surface by Optical Microscope and TEM

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

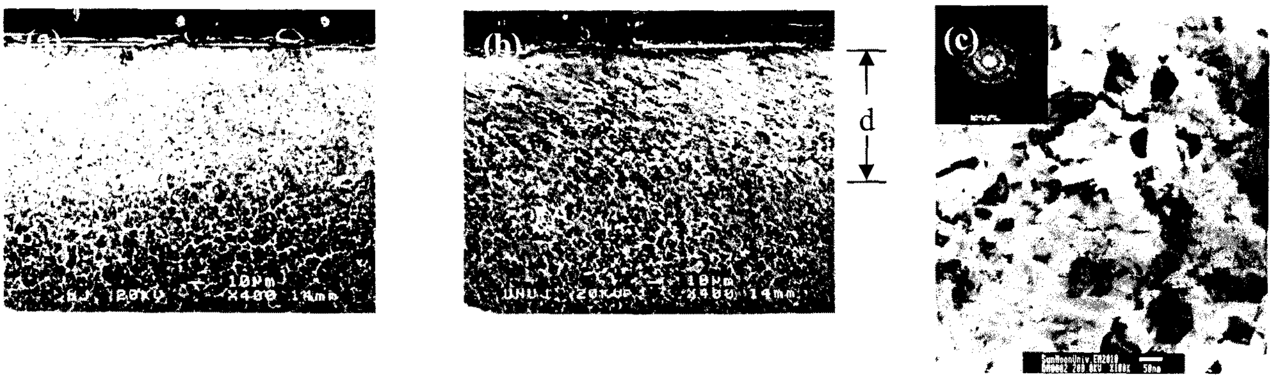

Fig.3 Microstructure of SKD 61; (a) before and (b) after the UCFT
(c) UCFT treated surface layers observed by TEM

2.2.2 Variation of Surface Hardness and Compressive Residual Stress

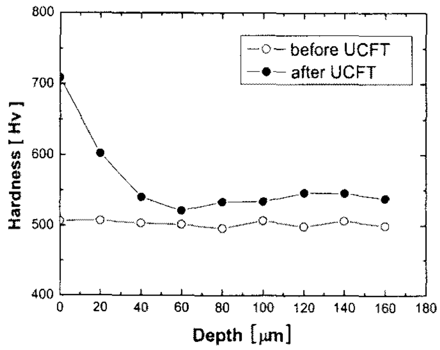

Fig.4 Variation of micro Vickers hardness for before and after by the UCFT

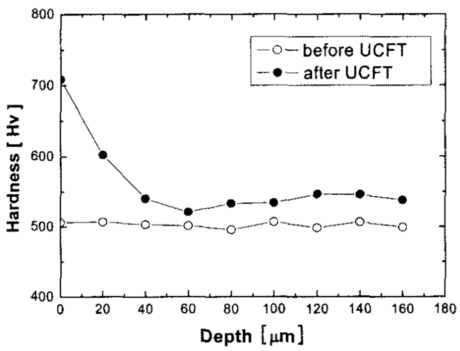

Fig. 5 Variation of compressive residual stress and depth by the UCFT

Comparison between the hardness of the material both before and after UCFT shows 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 before UCFT the compressive residual stress 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 Si_3O_4. 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.

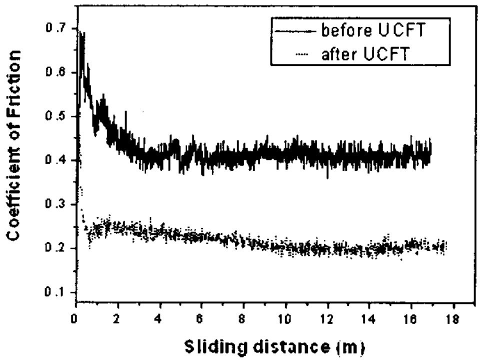

Fig.6 Variation of friction coefficient as a function of sliding distance for the UCFT

Table 1 Comparison of wear amount & Friction coefficient

UCFT	Wear amount [mg]	Friction coefficient
Before	1.179	0.42
After	0.039	0.21~0.24

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 of revolution at 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 was 899MPa, which represented a 25% increase.

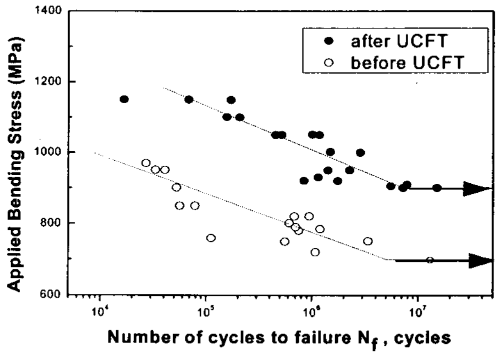

Fig. 7 S-N curves of the smooth specimen for before and after the UCFT

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 20μm. 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.

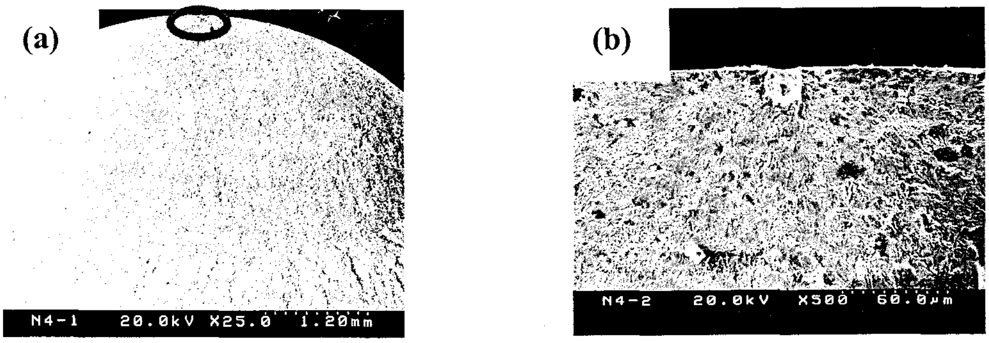

Fig. 8 SEM micrographs of fracture surface of surface-originating fracture before the UCFT; (a) lower magnification view and (b) enlargement of crack initiation site

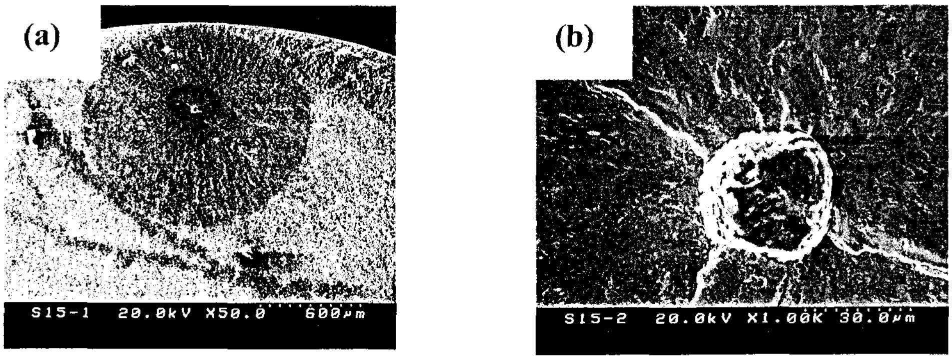

Fig. 9 SEM micrographs of interior-originating fracture after the UCFT; (a) lower magnification view of fish-eye crack and (b) enlargement of fish-eye

3. Field Test

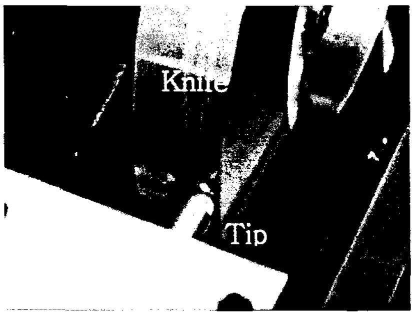

Fig.10 Front view of the UCFT process for trimming knife

Table 2 Summary of field test results (* TRIP (Transformation-induced Plasticity))

Kind	Steel grade	Strip size (mm)	Amount of test	Results
UCFT knife	80 TRIP	1.8t x 1049	230 Ton (16 Coils)	No knife breakage until 16 coils were trimmed, twice production of conventional knives
Conventional knife	80 TRIP	1.6t x 1303	207 Ton (13 Coils)	Knife cracks and breakage by the 3rd coil slit and knife replacement at the 8th coil

In order to show the effectiveness and reliability of UCFT, same process to test coupon was applied to produce trimming knives and similar mechanical properties was obtained. Fig. 10 shows the UCFT treatment process on the face of circumference of the knife. A field test was conducted to verify the effect of the UCFT trimming knives in recoiling line (RCL) of POSCO in Kwangyang. Trimmed strip material was TRIP80 which was one of high strength steels (HSS) whose tensile strength was 780MPa. As shown at the Table 2, the UCFT trimming knives prolonged their service life by about two times. UCFT trimming knives became standard operating tool of this line and are giving better effect than that of test. The increased hardness, nano-crystal surface structure and the reduced friction coefficient are major effects to prolong wear of knife edge. The compressive residual stress and nano-crystal surface structure are major effects to increase fatigue strength and shock resistance. What characteristics influence which effects should be evaluated in future study.

4. Conclusions

1) The grain size of SKD61 surface treated by ultrasonic cold-forging technique became very fine to nano-scale crystal and the nano-scale structure is observed till certain depth from surface.
2) The surface hardness of SKD61 was increased up to 37% and the compressive residual stress becomes -811MPa to a 150μm depth after the UCFT.
3) Fatigue limit of 10^7 cycles of SKD61 is increased by 25% after UCFT smooth specimen. Interior-originating fracture, fish-eye crack, occurs after UCFT because of nano-structured modification by surface plastic deformation and compressive residual stress in case of the smooth specimen.
4) UCFT improves the mechanical properties effectively and is becoming a practical method to improve the service time of the trimming knives. Productivity and reliability of cold rolling process have improved more than 2 times by the application of UCFT to trimming knives.

References

[1] Hwang, S. Y. : "Improvement of Mechanical Properties of Knife for Tandem Cold Rolling", RIST report (2000)
[2] D. Pye, 1997, "Nitriding Techniques and Methods", Steel Heat Treatment Handbooks, G. E Totten and M. A. Howes, Ed., Marcel Dekker, pp. 721-764
[3] L. E. Toith, 1971, Transition Metal Carbides and Nitrides, Academic Press, New York
[4] R. Z. Valiev, Investigation and Applications of Severe Plastic Deformation, Ed., T. C. Lowe and R. Z. Valiev
[5] V. Alexandrov, A. A. Dubravina and Kim, H. S, 2002, Defect and Diffusion Forum
[6] V. M. Segal, 1999, "Equal Channel Angular Extrusion from Macro-mechanics to Structure Formation, Meter, Sci. Eng. Vol.271, pp.322-333
[7] Pyoun, Y. S, Han, C. H and Azuma, N, 2001, "Development of an Automated Super Surface Finishing System for the 3D Sculptured Surface of Model and Dies using Ultrasonic Micro Burnishing Technology", Processing of the 32nd ISR
[8] Han, C. H ,Pyoun, Y. S and Kim, C. S, 2002, "Ultrasonic Micro Burnishing in view of Echo-materials Processing", ATM, Vol.4, pp. 25-28
[9] Yunhua Xu, Liang Fang, Qihong Cen, Jinhua Zhu, "Nano structure and transformation mechanism of white layer for AISI 1045 steel during impact wear, wear 258, 2005, pp. 537-544
[10] V.S. Zhernakov, V.V. Latysh, V.V. Stolyarov, A.I. Zharikov, R.Z. Valiev, "Ther Developing of nano structured SPD Ti for structural use, Scripta mater. 44, 2001, pp. 1771-1774
[11] Teruo Horisawa, 1997, "New Trimming Method for Burr-Less Trimming", SEAISI, Vol.1, No.1~11, pp.1/1~1/8
[12] Hall E.O: Proceedings of Physical Society of London, B64, 1951, 747: Petch N.J, Journal of Iron and Steel Institute, 174, 1953, 25.