Ultra-fine high-carbon steel wire drawing with ultrasonic vibration

Hengqiang Cao, Xiaobiao Shan*, Shen Liu, Yongjun Shi, Tao Xie
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China;

*Correspondence: shanxiaobiao@hit.edu.cn; Tel.: +86-451-8641-7891

Abstract. Ultra-fine high-carbon steel wires are widely used in the field of diamond wire saws. The traditional method for drawing ultra-fine high-carbon steel brings many drawbacks. This paper designed an ultrasonic transducer whose frequency is 28 kHz to overcome the above drawing problem of ultra-fine steel wire with a diameter 65 μm. Influences of the ultrasonic vibration on the drawing force and the diameter of wire cycle were investigated by experimental methods. The experimental results showed that the drawing force was reduced by up to 16.6% and the diameter of wire cycle was enlarged by up to 9.7%. Besides, the continuous drawing time of the ultra-fine wire was effectively prolonged. This study can contribute to enhancing the productivity of the ultra-fine wire processing in practical production.

Keywords: ultra-fine wire, ultrasonic vibration, transducer, drawing force, wire cycle

1. Introduction
The ultra-fine high-carbon steel wire, which is widely used in many productions, has many advantages compared with other wires, including the winding capacity, the ability of strong corrosion resistance and high tensile strength. In the process of silicon chip cutting, the ultra-fine high-carbon steel wire is the bus bar of diamond wire saws. However, this steel wire is a kind of difficult-to-machine material. Especially, as the diameter is ultra-fine. The difficulty of wire drawing with traditional methods is greatly increased. At present, there are many shortcomings in the conventional wire drawing method for ultra-fine steel wires, such as low efficiency, severe die loss, worse surface quality, small finished wire circle, and high rate of broken wires. The above problems are urgent problems to be solved in the field of wire drawing.

The research about ultrasonic vibration drawing started from Blaha and Langencker’s study on Single crystal zinc [1]. Then Siegert and Möck [2] discussed the relationship between the drawing force and oscillating dies. Several Japanese scientists like Hayashi, Masahiro [3] made simulation of ultrasonic vibration with FE method which broadened the research field. Hung [4] and Daud [5] studied the drawing performance of aluminum alloy materials respectively and summarize the function of temperature in ultrasonic drawing. Mousavi, Akbari et al [6] studied the effects of extrusion in drawing process. Yang and Liu [7,8] designed a longitudinal-torsional ultrasonic vibrator to study the effects of different vibration modes. Wu et al [9] believed that the anti-friction effect of ultrasonic vibration mainly depends on the separation time of the die and the wire.
From previous researches mentioned above, we can find that the studies about the ultrasonic vibration assisted drawing has achieved many meaningful research results. However, those previous researches mainly focused on materials that are easy-to-draw with a larger diameter compared with ultra-fine high-carbon wire and rarely involved difficult-to-draw materials. Besides, the parameters considered in previous studies have focused on the drawing force and the surface quality of the wire, while there are still many parameters that need further study.

Therefore, this work aims to design and manufacture an effective ultrasonic transducer to draw the ultra-fine high-carbon. FEA simulation were conducted to explore the dynamic characteristics of the ultrasonic transducer vibrator in Section 2. Experiments of the wire drawing were performed in Section 3. The experimental phenomenon that the steel wire bends into a circle after drawing process, the value of drawing force, the diameter of the wire circle, and the continuous drawing time with and without ultrasonic vibration were recorded and discussed in detail.

2. Structure design and FE Simulation

2.1. Structure design of an ultrasonic transducer
Figure 1 shows a schematic diagram of explosion structure and components of a longitudinal ultrasonic transducer. This transducer is mainly composed of eight parts, including a forcing screw, a die, a front horn, a rear horn, four PZT rings, four copper poles, a rear cover, and a bolt. The transducer was assembled by threaded connection and the design frequency was 28 kHz. The first and the third PZT are polarized along the $Z$ axial direction, while the second and the fourth along the $-Z$ axial direction. All parts are axially drilled before assembling in order to string. The planes on the two horns are used for fixing during assembling. The horns were made of 2A12 aluminum alloy, and the screws were made of steel.

Figure 1. Schematic diagram of explosion structure for the ultrasonic transducer

2.2. Modal analysis of the ultrasonic transducer
The modal analysis was conducted in an FE software to find the vibration form and vibration frequency of the ultrasonic transducer. Figure 2 shows the first longitudinal mode shape of the ultrasonic transducer. It can be seen that the deformation where fixed on the fixture is small. The vibration form of the transducer is a first longitudinal mode along the $Z$-axis with a frequency of 28.260 kHz, which is basically consistent with the design frequency. The rear end of the transducer is of greater mass than the front end, which helps the vibration to propagate forward. The front end section of the front horn shrinks sharply for concentrating energy.
2.3. Harmonic analysis of the ultrasonic transducer

Based on the modal simulation, the harmonic response simulation analysis of the transducer is further carried out with a constant damping ratio of 0.01. The plane to be simulated is the front end face of the die. The frequency response was assigned to the range of 27 kHz to 29.4 kHz under the voltage of 200 V. Figure 3 shows the results of the simulation. Figure 3 shows that the maximum displacement of 20 μm was generated at the longitudinal vibration frequency point of 28.26 kHz. This result is consistent with the modal analysis result.

According to the vibration amplitude of the transducer 20 μm, the vibration angular frequency ω is obtained as follows

$$\omega = 2\pi f = 2\pi \times 28260 = 1.776 \times 10^5 \text{ rad/s}$$

(1)

By substituting Eq. (3) into Eq. (2), the speed function of die can be obtained

$$V = A\omega\cos(\omega t) = 3.551\cos(1.776 \times 10^5 t)$$

(2)

The wire speed in the wire drawing experiments was 2.78 m/s, which was lower than the vibration velocity of the die. So the separation phenomenon would appear theoretically.

3. Experiments, results and discussion

An ultrasonic transducer was manufactured to verify the improvement of the drawing performance. Its structural parameters and material properties are consistent with the simulation. The core of the die is made of diamond and its diameter is 65 μm. Figure 4 shows the experimental system and a prototype of the ultrasonic transducer assembled.
In the drawing experiments, three key parameters including the drawing force, the wire circle diameter and the continuous drawing time were recorded, compared and analyzed. The speed was controlled around 2.78 m/s in the drawing force experiments. The output signal of the tension sensor is collected. Figure 5 shows the relationship between the drawing force and time.

From Figure 5, it can be seen that the drawing force has slight fluctuations, but after applying ultrasonic vibration, the drawing force value drops significantly. Since the drawing force changes rapidly, we use the average force to characterize the force value. It is calculated that the drawing force is reduced from 12.881 N to 10.749 N, which is reduced by about 16.6%. The reduction in drawing force can effectively improve the quality of the wire and reduce the rate of wire breakage, extending the continuous drawing time.

Through observation and research, it is found that the wire drawn by the die will bend into a circle under natural conditions, and the larger the diameter of the circle, the better the property of the finished wire. Especially for the ultra-fine high-carbon steel wire, the size of the circle diameter is closely related to the property of the wire. The large diameter of the wire circle indicates that the wire is evenly drawn, and the residual stress is also small. Figure 6 shows a comparison of the diameters of the wire circles before and after the application of ultrasonic vibration. From Figure 6, it can be seen that the circle diameter increased from 145.06 mm to 158.92 mm, which is approximately increased by 9.7%.
The experiment on drawing time was first carried out by conventional wire drawing without ultrasound. The wire was broken after several consecutive times of no more than fifteen hours, but the continuous drawing time can be up to 26 hours after applying ultrasonic vibration. We think the main reason is that the anti-friction effect of ultrasonic vibration is beneficial to protecting the wire and reducing the average value of the drawing force, thereby prolonging the drawing time.

4. Conclusions
In this work, a high-frequency ultrasonic vibration transducer was designed for the difficult-to-draw material of ultra-fine high-carbon steel wire. Modal analysis and harmonic response analysis were carried out to verify its vibration mode and amplitude. The drawing experiments with ultrasonic vibration were performed. The experimental results show that the ultrasonic vibration can effectively reduce the drawing force of the ultra-fine high-carbon steel wire by approximately 16.6%. Furthermore, ultrasonic vibration can distinctly increase the diameter of the wire cycle and effectively extend the continuous drawing time.

Acknowledgments
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References
[1] B. Langenecker. Effects of Ultrasound on Deformation Characteristics of Metals[J]. IEEE Transactions on Sonics & Ultrasonics. 1966,13(1):1-8
[2] K. Siegert, A. Möck. Wire Drawing with Ultrasonically Oscillating Dies[J]. Journal of Materials Processing Tech. 1996,60(1)
[3] M. Hayashi, M. Jin, S. Thipprakmas, M. Murakawa, J.-C. Hung, Y.-C. Tsai, C.-H. Hung. Simulation of Ultrasonic-Vibration Drawing Using the Finite Element Method (Fem)[J]. Journal of Materials Processing Technology. 2003,140(1-3):30-35
[4] J. C. Hung, C. Hung. The Influence of Ultrasonic-Vibration on Hot Upsetting of Aluminum Alloy[J]. Ultrasonics. 2005,43(8):692-698
[5] Y. Daud, M. Lucas, Z. Huang. Modelling the Effects of Superimposed Ultrasonic Vibrations on Tension and Compression Tests of Aluminium[J]. Journal of Materials Processing Technology. 2007,186(1-3):179-190
[6] S. A. A. A. Mousavi, H. Feizi, R. Madoliat. Investigations on the Effects of Ultrasonic Vibrations in the Extrusion Process[J]. Journal of Materials Processing Technology. 2007,187-188:657-661
[7] C. Yang, X. Shan, T. Xie. A New Piezoelectric Ceramic Longitudinal–Torsional Composite Ultrasonic Vibrator for Wire Drawing[J]. Ceramics International. 2015,41:S625-S630
[8] S. Liu, X. Shan, W. Cao, Y. Yang, T. Xie. A Longitudinal-Torsional Composite Ultrasonic Vibrator with Thread Grooves[J]. Ceramics International. 2017
[9] C. Wu, S. Chen, C. Xiao, K. Cheng, H. Ding. Study of Longitudinal-Torsional Ultrasonic Vibration Assisted Side Milling Process[J]. Part C:Journal of Mechanical Engineering Science. 2018