Simulation and experimental research on ultrasonic drawing of copper shaped wires

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Abstract. Ultrasonic vibrations contribute to drawing force reduction and surface finish improvement in the production of round wires. However, their effects on the drawing of irregular-shaped wires are rarely reported, as the process involves not only the shrinkage but also the reshaping of the cross-sections, which increases the difficulty in both numerical and experimental research. This work aims to investigate the influences of ultrasonic amplitude, drawing velocity, and area reduction ratio on the drawing force during the manufacturing of copper wires with rectangular, pentagon, and hexagon cross sections. The surface microtopography of the wire products was inspected using the Leica digital microscope and Hitachi scanning electron microscope (SEM). A remarkable drawing force reduction by up to 47% was observed when ultrasonic vibrations were added, especially for larger ultrasonic amplitude and lower drawing velocity occasions. The surface finish, however, was actually worse compared with under conventional drawing conditions, especially when ultrasonic amplitude exceeded 7 μm. This paper provides a potentially valuable method to enhance the efficiency of industrial production of irregular-shaped wires.

1. Introduction
According to the cross section shapes, metallic wires can be divided into round wires, flat wires, and shaped wires. S and Z shaped wires are normally applied to construct the bridge cable due to their superior sealing performance [1,2]. Fine square shaped wires can be used to fabricate high efficient small motors as the stator core slots can be wrapped with higher coil density compared with using round wires [3]. Square twisted nails made of shaped steel wires are commonly used to make wooden pallets, as they provide greater resistance of joined elements to loosening under external loads than round nails [4]. Trapezoidal wires are employed to make aluminum conductor steel supported/trapezoidal wire (ACSS/TW) for the purpose of decreasing the overall diameter, improving the outer surface smoothness, and achieving greater cross-sectional utilization [5,6]. In the manufacturing of shaped wires, two methods are normally adopted: rolling the circular wires to required cross-section by pressure rollers, or drawing the round wires through a series of dies with specific profiles [7]. Compared with the first method, cold drawing process provides good surface finish and excellent dimension accuracy, especially for long thin products. However, multi-pass drawing and essential softening and heating treatment between passes are required during the process. In addition, the dies for intermediate passes generally have complex geometries which have to be designed specifically [8]. Therefore, the manufacturing difficulty and cost of the shaped wire products will increase remarkably with the increment of drawing passes [9].
Ultrasonic wire drawing is the technology of superimposing ultrasonic vibrations on dies during the wire drawing process. The influences of various forms of ultrasonic vibrations, along axial, torsional, or radial directions on the drawing process have been discussed numerically and experimentally in previous studies [10–12]. Benefits being sought include reduced drawing force, improved surface, greater area reduction per pass, prolonged tool life, increased drawing speed, etc. [13]. Several hypotheses have been proposed to reveal the mechanism of ultrasonic assisted metal forming process, among which the most prevailing are acoustic softening assumption and stress superposition theorem. The first hypothesis attributes the stress reduction phenomenon to the interaction between ultrasonic waves and dislocations. Acoustic energy absorbed by the dislocations facilitates the release and movement of other dislocations [14]. The second theory, however, claims the plastic behavior of material has not been changed, and the yield stress is the sum of a static stress and the oscillating stress caused by ultrasonic vibration [15]. Moreover, the sliding friction coefficient within the wire-die contacting region will be changed with the influence of the acoustic field, especially when ultrasonic amplitude gets larger [16].

In this research, round copper wires are drawn into square, pentagonal, and hexagonal wires in a single pass. The extremely high impact force produced by the periodical collision between the output tip of the vibrator and the die is expected to exert great influence on the drawing force and surface finish of the wire products. The present report will investigate the peculiar effects of this dynamical metal forming process to explore a low-cost high-efficiency and eco-friendly approach for the cold drawing of shaped wires.

2. Numerical simulation
The drawing process of shaped wires can be described as the nonlinear contact problem between the copper wire and the internal surfaces of the vibrating die. A finite element (FE) model was established in the commercial software ABAQUS®, the section view of which is shown in Figure 1. The materials of the wire and the die core are T2 pure copper and cemented carbide, with the density, elastic modulus, and Passion ratio of 8900 kg/m³, 110 GPa, 0.32 and 9500 kg/m³, 1220 GPa, 0.001, respectively. The wire was modeled as the deformable body and meshed with the 8-node three-dimensional continuum (C3D8R) element, while the die was defined to be rigid analytical surfaces using three-dimensional quadrilateral (R3D4) element, considering its much larger stiffness. Transient analysis was performed to determine the time variation of the drawing force at different drawing speeds and under various ultrasonic amplitudes. In this particular problem, the raw wire, with an initial diameter of 1.2 mm, was pulled through the die along the -Y direction, as shown in figure 1. The processed wire has a regular hexagonal cross-section with an inside diameter of 0.91 mm. Multilinear Isotropic Hardening (MISO) model was chosen to reflect the response of the typical commercial purity copper. The internal surface of the die could be divided into two regions: the reduction area with a semi-cone angle of 20°, and the bearing area with the length of 0.82 mm. Coulomb friction was assumed for the mechanical behavior at the wire-die interface, with a friction coefficient of 0.1. Heat generation, temperature and strain rate dependence of the metal flow stress were not taken into account in the simulation.
established and deformation of the wire begins. In the second step, ultrasonic vibrations were applied to the die along the wire drawing direction. These vibrations were subsequently removed before the third step. To save computational sources, the wire was meshed with different element density. The region drawn with the assistance of ultrasonic vibration was meshed with fine grids, while other regions were only coarsely meshed.

The variation of drawing force at the wire drawing velocity of 300 mm/s is illustrated in Figure 2. In the first and third calculation steps, when ultrasonic was not applied, the drawing force increased gradually from 0 N to 150 N and stabilized at this value. In the second step, when longitudinal ultrasonic vibration of 30 μm, 21 kHz was applied, the drawing force changed dramatically between 0 N and 170 N, as shown in Figure 2(a). From Figure 2(b), it can be seen that the fluctuation cycle of the drawing force equals the period of applied ultrasound, which means ultrasonic vibration should be responsible for the regular changes of the drawing force. In addition, the average drawing force saw a remarkable drop from 145.5 N to 50.5 N, achieving a reduction ratio of 65.3%.

![Figure 2](image)

3. Experiments, results and discussion
Figure 3 illustrates the experimental setup for ultrasonic drawing of shaped wires. Raw copper wires with circular cross section were pulled through the die and collected by the reel drum which was subsequently connected to the electromotor. The torque sensor was respectively connected to the motor and the drum at its two sides to measure the drawing torque, the signal of which was acquired by NI9215 and then transferred to the computer. The drawing force was calculated and recorded using a LabVIEW® program, with values indicated on the digital display in real time. The oscillating frequency and amplitude of the die were regulated by the ultrasonic generator and the drawing velocity was adjusted using the frequency modulator.

![Figure 3](image)
Similar to the simulation procedure, the experiment process can also be divided into three stages and ultrasonic vibrations were only introduced at the second stage. Figure 4 illustrates the variation of drawing force when raw copper wire with an initial diameter of 1.2 mm was processed into regular hexagonal wire with an inside diameter of 1.05 mm at the drawing speed of 168 mm/s. An abrupt drop from 156 N to 92 N could be observed when ultrasound with an amplitude of 10.73 μm was imposed onto the die, realizing a 41% reduction in drawing force. When ultrasonic vibration was removed, the drawing force immediately restored to its original value.

Figure 4. Influence of ultrasound on drawing force.

Above phenomenon was observed in all conducted wire drawing experiments, however, the reduction ratio of the drawing force varied. Overall, the influence of ultrasound became stronger with the increment of ultrasonic amplitude but got weakened as the drawing velocity increased, which coincides with previous studies. Table 1 summarizes the recorded drawing forces when round wire, 1.0 mm in diameter, was drawn into hexagonal wire, 0.875 mm in inside diameter, at the drawing speed of 168 mm/s and with ultrasonic amplitudes changed from 6.1 μm to 12.43 μm. It can be seen that the drawing force reduction rate grows steadily from 23.43% to 44.9% with the increment of ultrasonic amplitude. In Table 2, however, the ultrasonic amplitude was set as a constant value of 10.73 μm, while the drawing velocity rises from 100 mm/s to 354 mm/s. We can find that the effectiveness of ultrasonic vibration was weakened with the force reduction ratio decreased from 47.56% to 32.03%.

Table 1. Variation of drawing force with ultrasonic amplitude.

| Amplitude (μm) | Without ultrasound (N) | With ultrasound (N) | Reduction ratio (%) |
|---------------|------------------------|---------------------|---------------------|
| 6.1           | 114.57                 | 87.73               | 23.43               |
| 7.07          | 121.68                 | 90.99               | 25.23               |
| 8.88          | 123.66                 | 81.32               | 34.24               |
| 10.73         | 125.33                 | 76.27               | 39.14               |
| 12.43         | 122.98                 | 67.76               | 44.90               |

Table 2. Variation of drawing force with wire drawing velocity.

| Velocity (mm/s) | Without ultrasound (N) | With ultrasound (N) | Reduction ratio (%) |
|----------------|------------------------|---------------------|---------------------|
| 100           | 78.36                  | 41.09               | 47.56               |
| 168           | 77.40                  | 46.02               | 40.54               |
| 231           | 78.71                  | 48.97               | 37.78               |
| 298           | 80.27                  | 53.54               | 33.29               |
| 354           | 75.60                  | 52.06               | 32.03               |
The cross-section shape and size of drawn wires also exert influence on the drawing force reduction phenomenon, as indicated by Table 3. Among the three type of wire products with the same inradius, the influence of ultrasound is most remarkable for hexagonal wires, then for pentagon wire, and least for square wires, which means the effectiveness of ultrasound will be improved as the cross-section geometry gets closer to the circular wire. As for the influence of the input wire diameter, there is still much uncertainty, which might be induced by the random measurement error of the wire drawing system.

| Cross-section shape | Diameter (mm) | Without ultrasound (N) | With ultrasound (N) | Reduction ratio (%) |
|---------------------|--------------|------------------------|---------------------|---------------------|
| Hexagon             | 1.2          | 156.10                 | 91.86               | 41.26               |
| Hexagon             | 1.0          | 125.33                 | 76.27               | 39.14               |
| Hexagon             | 0.8          | 74.27                  | 42.39               | 42.93               |
| Pentagon            | 1.2          | 170.72                 | 108.62              | 36.38               |
| Pentagon            | 1.0          | 109.87                 | 69.85               | 36.42               |
| Pentagon            | 0.8          | 73.85                  | 44.46               | 39.80               |
| Square              | 1.2          | 157.35                 | 79.53               | 49.46               |
| Square              | 1.0          | 112.85                 | 57.44               | 49.10               |
| Square              | 0.8          | 70.20                  | 36.82               | 47.54               |

The surface finish of drawn hexagonal wire with and without ultrasonic vibration were inspected using Leica DVM5000 and Hitachi S4300 microscope with magnification factors of 200 and 450, respectively. Figure 5a and 5b represents the surface microtopography of wire samples drawn without ultrasound and with an ultrasonic amplitude of 10.73 μm, respectively. When ultrasound was not applied, mainly some scratches appear along the wire drawing direction. However, when vibrations were added, many indentations could be found on the surface of drawn wire, and their distribution seems less directionally dependent. Figure 5c and 5d show the further examining results of the two samples under the scanning electron microscope (SEM). It can be found that some metal was peeled off from the surface layer of the wire products when ultrasound was introduced. These defects should be caused by the periodical impact between the wire and the inner surface of the die within the contacting area, however, they could be eliminated in the follow-up normal cold drawing passes.

![Figure 5](image-url)
4. Conclusions
This work investigated the influence of ultrasonic vibration on the cold drawing process of shaped wires with square, pentagonal, and hexagonal cross-sections through numerical simulation and experiments. It was found that ultrasonic vibration contributes to decreasing the wire drawing force. This effect will be strengthened with the increasing of the ultrasonic amplitude and gets weakened with the increment of drawing velocity. With appropriate ultrasound amplitude and drawing speed, a reduction in drawing force of nearly 50% was achieved at room temperature without lubricants, which greatly helps to save the costs and enhance the efficiency of shaped wire production. The surface finish was actually worse when ultrasound was introduced. However, these defects could be repaired by the subsequent drawing passes.

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