Simulation and experimental analysis of draw-thread products under different lubrication conditions

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Abstract. The drawing material SCM435 was attempted in this study. The experiments were carried out under three different lubricating conditions: wiredrawing powder, oil and grease to analyze its optimum stretch working conditions. In the research process, the experiment and simulation analysis of the fixed shear friction ring were used to obtain the friction coefficient under three different lubricating conditions. Then the forming software DEFORM-3D was utilized to simulate the wire drawing process under different friction coefficients to obtain the load and stress distribution required for wire drawing. The research results show that the wire drawing powder has the smallest friction coefficient and the lowest surface hardness in the experiment of the drawing material. The effective stress was generated on the wire drawing die is also the smallest of the three different lubrication conditions. Moreover, during the forming simulation of wire drawing material SCM435 on wire drawing powder or wire drawing oil, the stress of the wire drawing die will not exceed the yield strength of SKD61.

1. Introduction
The leap of screw industry in past years reveals the systematic classification of nuts, and screws are renamed fasteners. Tiny screws are negligible but significant. An unremarkable fastener could create infinite economic value. Such unremarkable fasteners are called “rice of industry” as they are universally applied to various products, including 3C products, machinery equipment, foundation of wind turbine generator set, and bridge construction.

1.1. Literature review
With Taguchi method, Chan et al. [1] preceded the experiment with orthogonal array to discuss the optimal quality of carbon steel wire rod under the process with different parameters in 2009. Meanwhile, the finite element software, DEFORM-3D, was used for the simulation analysis to discuss the homogeneity of wire drawing deformation with uneven strain factors, and the optimal combination acquired from Taguchi analysis was utilized for the verification.
In 2010, Liu [2] utilized DEFORM 3D for the stress simulation analysis in the cold forging process of cold heading to shorten the actual tryout time and rapidly grasp forming conditions and process parameters. The research Matched with Taguchi’s experimental planning method for the simulation analysis of major parameters, the effect of various factors on stress on the die and a set of parameter combination for the optimal design were acquired.
Olaru et al. [3], in 2010, used Hertz contact stress and considered the contact geometry, viscosity of lubricant grease, normal force, and rotation speed of ball to calculate rolling friction and coefficient of friction, effectively establish the theoretical model of nut and screw friction torque, and explain that ball would appear sliding force between screw and nut for dynamic balance. Preload, axial load, lubrication effect, and running speed were related to thermal displacement.
Huang et al. [4] simulated multi-pass forging of cultivator parts with DEFORM-3D in 2011. In the research, metal flow was observed to remove metal stack. In the simulation process, the interface friction was assumed a constant shear friction to calculate relevant forging information, including effective stress, effective strain, velocity field, and forging load.

In 2013, Chiang [5] expanded wire drawing system to extended system to enhance production capacity, maintain high-quality wire production, control die wear to reduce production costs, and make wire radius completely uniform and with luster. Meanwhile, the extended system simulation program for wire drawing system was constructed with equation of system dynamics, genetic algorithm was utilized for seeking the optimization factor in each batch in the wire drawing process simulation test, and optimization time was shortened to estimate the service life of die and the elimination timing.

Hsia et al. [6] discussed the forming load, geometric shape, effective stress, effective strain, and velocity field distribution in multi-pass forming and preceded experiment for the verification in 2019. By comparing the simulation size and experiment size of fasteners, the practicability of finite element simulation to fastener forming analysis was verified.

Taking cold forging hexagon and hexagon flange screws as the target in 2019, Hsia et al. [7] attempted to understand the relative stress and strain change of workpiece in the cold forging process through simulation to know whether the forging force of die designed among various passes was uniform. The result could be used for evaluating the service life of die and selecting proper machine with the forging force generated in the production of screws with the specifications in the 3-punch 3-die cold forging forming and using SCM435 alloy steel as the base material for the design guide to develop forming die.

In this study, the drawing material SCM435 was attempted and carried out under three different lubricating conditions: wiredrawing powder, oil and grease to analyze its optimum stretch working conditions. And the experiment and simulation analysis of the fixed shear friction ring were used to obtain the friction coefficient under three different lubricating conditions.

2. Basic theory

2.1. Wire drawing preproduction and wire drawing manufacturing process

The approximate manufacturing process of fasteners is shown in Figure 1. Starting from wire and going through a series of complicated manufacturing processes, each process has the relevant test method, according to different specifications, product types, and customer requirements, to ensure the approval standard of each product. Each process is different but is connected. The final product is completed through manufacturing technology and processes, from which none is omitted.

![Figure 1. Manufacturing process of fastener products.](image)

2.2. Introduction of finite element software DEFORM

2.2.1. Overview. Finite element method was originated from the research on elasticity and structure analysis in civil engineering and aeronautical engineering. The development could be traced back to
the work of Alexander Hrennikoff (1941) and Richard Courant (1942), whose methods showed great differences, but presented common essential characteristic of transforming a continuous region into a group of discrete subregions, generally called elements, with grid discretization. Hrennikoff’s discrete work was used in lattice-like grid discrete region, while Courant broke down the region into finite triangular subregions to solve second-order elliptic partial differential equations with the source of cylinder torque. Courant contributed to promoting the development of finite element, drafted the research result of early partial differential equation, and was the first person proposing the idea of finite element method. The development of finite element method started in mid to late 1950s for fuselage frame and structure analysis. In 1960s, John Argyris from Universität Stuttgart and Ray W. Clough from University of California, Berkeley, applied it in civil engineering to accumulate experiences and first used the term, Finite Element. For the first time in China, Feng Kang proposed finite element method in 1965 and published the paper to lay the mathematical theory foundation.

2.2.2. DEFORM-3D friction conditions. Constant shear friction factor \( m \) and Coulomb friction coefficient \( \mu \) are provided in DEFORM. They are briefly introduced as below.

(1) Coulomb friction model. When interface appeared relative sliding, the frictional force on the tangential direction is proportional to the positive pressure of contact surface. The friction model is applicable to contact surface, between objects, with smaller contact pressure, as formula (1).

\[
\vec{f}_t \leq -\mu \cdot f_s \cdot t
\]

where \( \vec{f}_t \) is frictional force, \( f_s \) is contact surface positive pressure, \( \mu \) is Coulomb friction factor, and \( t \) reveals \( t = \left( \frac{V_i}{|V|} \right) \), the unit vector of relative sliding speed \( V_i \).

According to Tresca yield criterion, the maximum \( \mu \) is 0.5; with von Mises yield criterion, the maximum \( \mu \) is 0.577. In metal forming process, the contact force between material and die is comparatively large that the friction model is not suitable. In real metal forming process, factors in friction factor contain temperature, viscosity of lubricant, and geometric shape of object; however, a constant is used as the friction factor of contact surface between objects, in order to simplify the calculation in the simulation analysis.

(2) Constant shear friction model. When interface appears relative sliding, the frictional force on the tangential direction is the fixed component of material’s shear yield strength. The friction model is suitable for larger contact pressure of contact surface between two objects. Basically, the friction model is mostly applied to plastic working. The constant shear friction model is also used for the simulation analysis in this study, as formula (2).

\[
\vec{f}_t \leq -m \cdot k \cdot t = -m \cdot \frac{\bar{\sigma}}{\sqrt{3}} \cdot t
\]

where \( \vec{f}_t \) is frictional force, \( k \) is shear yield stress of material, \( \bar{\sigma} \) is yield stress of material, \( m \) is constant shear friction, and \( t \) reveals \( t = \left( \frac{V_i}{|V|} \right) \), the unit vector of relative sliding speed \( V_i \).

3. Research method and experiment structure

3.1. Research method

In this study, SCM435 is experimented to discuss the research process, Figure 2. The main component and mechanical properties of the material are first acquired. In order to smoothly precede the simulation analysis and enhance the accuracy of result, cylindrical compression test is first used for acquiring the plastic flow curve and the relative data of SCM435. Ring compression test is further preceded to acquire coefficients of friction under different lubrication conditions, e.g. wire drawing powder, wire drawing cream, and wire drawing oil. In the ring compression test process, the size data of compression height and change of inner diameter are measured, and DEFORM-3D is used for
acquiring the coefficients of friction of above finished products for wire drawing forming analysis. The results could be the reference for wire drawing process.

3.2. Mechanical properties of materials
In the DEFORM analysis process, accurate plastic flow stress-strain curve is an important indicator to evaluate metal forming. Since the strain of forging is broad and the pretreatment process of materials are different due to distinct product-required attributes, the actual plastic flow stress-strain curve of the material should be acquired through compression test. Compression test is used in this study for calculating the real stress-strain relation curve of material which is imported into DEFORM for analyses to enhance the accuracy of simulation result.

The relationship between plastic flow stress, strain, and strain rate of metal mechanical properties and temperature could be denoted with constitutive equation.

$$\bar{\sigma} = f\left(\bar{\varepsilon}, \dot{\varepsilon}, T\right)$$  \hspace{1cm} (3)

where $\bar{\sigma}$ is plastic flow stress, $\bar{\varepsilon}$ is strain, $\dot{\varepsilon}$ is strain rate, and $T$ is temperature.

Generally, when the temperature of metal working is higher than recrystallization temperature, the effect of strain on plastic flow stress is not large that the effect of strain rate becomes more important. When the working temperature is lower than recrystallization temperature, strain appears more important effect (i.e. work hardening), and the effect of strain rate on plastic flow stress could be ignored.

3.3. Lubricant oil for experiment
Three different oils are used for ring compression test in this study, including wire drawing powder, wire drawing oil, and wire drawing cream. The common characteristics and drawbacks are explained
as following:
Common characteristics of 3 lubricants. In the wire drawing process, wire drawing powder, wire drawing oil, and wire drawing cream are used for increasing the lubrication effect between wire and wire drawing die to reduce the coefficient of friction, save the consumption of wire drawing energy, and prolong the service life of wire drawing die. In this case, a lubricating film is formed on the wire surface in the wire drawing process to protect the wire coating. Lubricant should present the characteristics of high voltage and high temperature tolerance so that lubricating film, under high voltage and temperature rise, could keep the continuity and lubricity, without being destroyed and caking during wire drawing, i.e. presenting physical and chemical stability and good extensibility and lubricity. It could firmly attach on the steel wire surface and deform with steel wire. At this moment, lubricating film reveals layer structure, with strong molecular association force in each layer, but weak molecular association force between layers.

3.4. Determination of constant shear friction factor

3.4.1. Establishment of constant shear friction factor calibration curve. Importing different material properties into DEFORM-3D for ring compression test simulation, various friction conditions are changed in the process to acquire distinct simulation results. With the inner diameter reduction ratio and height reduction ratio of compressed ring measured in the experiment, the approximate constant shear friction factor calibration curve could be acquired. When measuring inner diameter, the quadrature of two perpendicular bisectors are calculated the center of circle, and two points passing the center of circle is the inner radius.

3.4.2. Ring compression test. A manufacturer is entrusted to producing standard test specimen for ring compression test, with the ring specifications of outside diameter : inner diameter : height = 5.33:2.67:1.63 The actual size shows outside diameter $\phi$16mm, inner diameter $\phi$8mm, and height 4.9mm. The experiment is planned under 32°C room temperature for the compression test with/without lubrication conditions. The experiment conditions are listed in Table 1.

| Ring compression test material | SCM435          |
|-------------------------------|-----------------|
| Compression tester            | 50ton hydraulic universal testing machine |
| Experiment temperature        | 32°C            |
| Lubricant                     | Lubricant oil, Lubricant cream, Lubricant powder |
| Ring blank specification      | Outside diameter: inner diameter: height = |
|                               | 5.33: 2.67: 1.63 |
|                               | Real size=16mm: 8mm: 4.9mm |

3.4.3. Application of constant shear friction factor. Before the ring compression test, the ring surface is cleaned with alcohol; and, the upper/lower surface of the ring material is coated wire drawing oil, wire drawing powder, and wire drawing cream for wire drawing, and placed in the center of die in a universal testing machine. The upper die is then adjusted to contact the ring, and the machine settings are zeroed to start the ring compression test. The compression step is set 49, 97, 147, 195, 244, and 293 time steps, and the correspondent height reduction ratio appears 10%, 20%, 30%, 40%, 50%, and 60%. The temperature in the simulation is set 32°C, the height reduction ratio and inner diameter reduction ratio under different constant shear friction coefficients of friction could be acquired with DEFORM-3D. The simulation setting parameters are listed in Table 2.
Table 2. Ring compression simulation setting parameter.

| Type of grid element | Tetrahedron |
|----------------------|-------------|
| Workpiece material   | SCM435      |
| Plastic flow stress  | $\alpha=766.6\epsilon^{0.163}$ |
| Material/die properties | Plasticity/rigid body |
| Temperature          | 32°C        |
| Compression speed     | 1mm/sec     |
| Mesh number           | 30,000      |
| Each pressing distance | 0.01mm/step |
| Coefficient of friction | 0.12, 0.20, 0.30, 0.40, 0.70 |

3.5 DEFORM simulation parameter planning

The settings of preprocessor in DEFORM in the forming environment contain that 1. conditions are listed and thermal conduction model is not taken into account to set the wire drawing temperature 32°C; 2. wire drawing die, except wire drawing material, is assumed rigid body in the forming process and is transformed into elastomer when the stress analysis of die is considered; 3. SCM435 is selected as the wire drawing material for the simulation; 4. wire drawing die speed is set 50m/s, and each step is set 0.1mm; and 5. preprocessing setting conditions are imported into DEFORM for wire drawing simulation, referring to Table 2.

4. Result and discussions

4.1 Constant shear friction junk ring test with different lubrication conditions

Lubricant oil friction test of ring test specimen is first preceded ring compression test, aiming at different wire drawing materials SCM435 and under various height reduction ratio, and DEFORM is used for ring compression simulation. Different friction factors $f=0.12, 0.20, 0.30, 0.40, 0.70$ are used in the analysis process, and the ring material and size for the simulation are same as those of entity ring compression test. After completing the analysis, the experimental data of wire drawing powder, wire drawing oil, and wire drawing cream from the compression test and the simulation results with DEFORM are organized and calculated in Excel to acquire a constant shear friction suggested value. For ring compression, the original actual size shows outside diameter $\phi16$mm, inner diameter $\phi8$mm, and height 4.9mm. Table 3 reveals height reduction ratio and inner diameter reduction ratio acquired from ring compression test of SCM435 under distinct lubrication conditions. Table 4 reveals the friction factors $f=0.12, 0.20,$ and $0.30$ of SCM435 in the ring compression test simulation process. The friction factors 0.4 and 0.7 are omitted in this table. Figure 3 displays the SCM435 ring after the experiment with wire drawing powder, wire drawing oil, and wire drawing cream as well as height reduction ratio and inner diameter reduction ratio acquired from the simulation of DEFORM-3D. From Figure 3, with wire drawing powder, $f=0.20$ is close when height reduction ratio appears 10%-20% and $f=0.30$ is closer when height reduction ratio reaches 30%-50%. Apparently, coefficient of friction is about 0.30 when height reduction ratio is larger with wire drawing powder. With wire drawing oil, $f=0.40$ trend line is approached when height reduction ratio is 10%-30%, and $f=0.70$ trend line is approached when height reduction ratio achieves 40%-50%. Accordingly, when wire drawing oil is used for SCM435, the coefficient of friction is about 0.70 with larger height reduction ratio. With wire drawing cream, $f=0.30$ trend line is overlapped when height reduction ratio appears 10%-30%, and $f=0.30$ rises up to $f=0.40$ trend line when height reduction ratio reaches 40%-50%. As a result, when wire drawing oil is used for SCM435, coefficient of friction is 0.70 with larger height reduction ratio.
Table 3. Size of SCM435 entity after friction ring compression.

| Oil                        | Inner diameter (mm) | Height (mm) | Inner diameter reduction ratio (%) | Height reduction ratio (%) |
|----------------------------|---------------------|-------------|-----------------------------------|---------------------------|
| Wire drawing powder        | 8.1                 | 4.2         | -1.25                             | 14.29                     |
|                            | 7.8                 | 3.45        | 2.50                              | 29.59                     |
|                            | 7.3                 | 2.72        | 8.75                              | 44.49                     |
|                            | 6.9                 | 2.5         | 13.75                             | 48.98                     |
| Wire drawing oil           | 8                   | 4.9         | 0.00                              | 0.00                      |
|                            | 7.8                 | 4.2         | 4.08                              | 14.29                     |
|                            | 7.4                 | 3.5         | 12.24                             | 28.57                     |
|                            | 6.6                 | 2.9         | 28.57                             | 40.82                     |
| Wire drawing cream         | 7.9                 | 4.15        | 1.25                              | 15.31                     |
|                            | 7.7                 | 3.5         | 3.75                              | 28.57                     |
|                            | 7                   | 2.9         | 12.50                             | 40.82                     |
|                            | 5.7                 | 2.4         | 28.75                             | 51.02                     |

Table 4. Size and reduction ratio of SCM435 simulation after friction ring compression.

| Coefficient of friction | Inner diameter(mm) | Height (mm) | Inner diameter reduction ratio (%) | Height reduction ratio (%) |
|-------------------------|---------------------|-------------|-----------------------------------|---------------------------|
| 0.12                    | 8.18                | 4.41        | -2.25                             | 10.00                     |
| 8.37                    | 8.18                | 4.41        | -4.62                             | 20.00                     |
| 8.53                    | 8.18                | 4.41        | -6.62                             | 30.00                     |
| 8.56                    | 8.18                | 4.41        | -7.00                             | 40.00                     |
| 8.48                    | 8.18                | 4.41        | -6.00                             | 50.00                     |
| 8.23                    | 8.18                | 4.41        | -2.88                             | 60.00                     |
| 0.20                    | 8.02                | 4.41        | -0.25                             | 10.00                     |
| 8.01                    | 8.02                | 4.41        | -0.12                             | 20.00                     |
| 7.98                    | 8.02                | 4.41        | 0.25                              | 30.00                     |
| 7.85                    | 8.02                | 4.41        | 1.88                              | 40.00                     |
| 7.7                     | 8.02                | 4.41        | 3.75                              | 50.00                     |
| 6.93                    | 8.02                | 4.41        | 13.38                             | 60.00                     |
| 0.30                    | 8.02                | 4.41        | -0.25                             | 10.00                     |
| 7.87                    | 8.02                | 4.41        | 1.63                              | 20.00                     |
| 7.61                    | 8.02                | 4.41        | 4.88                              | 30.00                     |
| 7.24                    | 8.02                | 4.41        | 9.50                              | 40.00                     |
| 6.61                    | 8.02                | 4.41        | 17.38                             | 50.00                     |
| 5.49                    | 8.02                | 4.41        | 31.38                             | 60.00                     |

From above results, the lubrication effect is the best when using wire drawing powder for SCM435, followed by wire drawing cream, and wire drawing oil, and the coefficient of friction is sequenced wire drawing powder<wire drawing cream<wire drawing oil.
4.2 Mechanical analysis of wire drawing process and wire drawing die

From the ring compression simulation analysis results, coefficients of friction appear 0.30, 0.70, and 0.40 when wire drawing powder, wire drawing oil, and wire drawing cream are respectively used for SCM435. Substituting above coefficients of friction into DEFORM-3D, the wire drawing simulation of SCM435 is shown in Figure 4. The simulated reduction of area reveals 15.47%.

The simulation analysis result of SCM435 using wire drawing powder is shown in Figure 5. Figure 5(a) displays the distribution of effective strain, mainly from the wire drawing material front to the exit, and the maximum appears 0.732mm/mm. Figure 5(b) shows the distribution of effective stress, mainly in the entrance to the exit of die, and the maximum reveals 1220MPa. Figure 5(c) displays the distribution of velocity field, mainly on the direction towards the exit, and the maximum is 54.2mm/sec. Figure 5(d) shows the distribution of load, with the maximum 81.6kN.

The simulation analysis result of SCM435 using wire drawing oil is shown in Figure 5. Figure 6(a) displays that effective strain mainly distributes from the material front to the wire drawing exit, with the maximum 0.916mm/mm. Figure 6(b) displays that effective stress mainly distributes from the die entrance to the exit, with the maximum 1230MPa. Figure 6(c) shows that velocity field mainly distributes on the direction toward the exit, with the maximum 54.3mm/sec. In Figure 6(d), the maximum load appears 117kN.

The simulation analysis result of SCM435 using wire drawing cream is shown in Figure 7. Figure 7(a) displays that effective strain mainly distributes from the material front to the wire drawing exit, with the maximum 0.869mm/mm. Figure 7(b) shows that effective stress mainly distributes from the die entrance to the exit, with the maximum 1210MPa. Figure 7(c) displays that velocity field mainly distributes on the direction towards the exit, with the maximum 55.4mm/sec. Figure 7(d) shows the maximal load 89.3kN.
Figure 5. Analysis result of SCM435 using wire drawing powder.
Above analysis results reveal that wire drawing powder presents the best effect when using different lubricants for the wire drawing material SCM435, the required load is lower, and the effective strain is comparatively low. The load is 30.25% different from the worst wire drawing oil. With lower load, the machine bears lighter load that wire drawing powder presents better lubrication effect on the wire drawing material SCM435, followed by wire drawing cream and wire drawing oil.

Die stress analysis after wire drawing simulation: From Section 4.1, wire drawing powder is the best lubricant with the best lubrication effect on the wire drawing material, and wire drawing oil is the worst. Using such two oils for die stress analyses could understand the effect of oil on the service life.
of die due to frictional force change. The used die is SKD61 and a die requires constraint is required to prevent the die from being bounced off due to large strength. Figure 11 shows the distribution of principal stress on the wire drawing die using wire drawing powder for SCM435; the major principal stress appears in 30.4MPa (equal-stress line D)-160MPa (equal-stress line E). Figure 12 displays the distribution of effective stress, with the maximum 1, 440MPa. Figure 13 shows the distribution of principal stress on the wire drawing die using wire drawing powder for SCM435; the major principal stress reveals 84.9MPa (equal-stress line D)-218MPa (equal-stress line E). Figure 14 displays the distribution of effective stress, with the maximum 1460MPa.

5. Conclusion
The wire drawing material SCM435 under 3 lubrication conditions of wire drawing powder, wire drawing oil, and wire drawing cream are used for the simulation and experimental analyses to discuss the optimal wire drawing conditions in this study. The following conclusions are summarized.

(1) The compression test of constant shear friction junk ring, under the use of wire drawing powder, appears the smallest coefficient of friction; when wire drawing oil is used, the coefficient of friction is the largest.

(2) Using wire drawing powder as the lubricant for the wire drawing material SCM435 requires lower load. In comparison with wire drawing oil, which appears the worst effect, the load reveals 30.25% difference. Consequently, the use of wire drawing powder could reduce the load on the machine.

(3) When using wire drawing powder for the die simulation analysis, the stress on various wire drawing materials is smaller, while the stress is larger when using wire drawing oil for the die simulation analysis. SCM435 would exceed the yield strength of SKD61 that it is suggested to use
die material with the yield strength higher than 1,500MPa for wire drawing. In sum, wire drawing powder presents the smallest coefficient of friction on steel SCM435, the surface hardness after wire drawing appears the lowest, and the load for the wire drawing die is the lowest. Apparently, wire drawing oil is suitable for SCM435 steel as the lubricant oil.

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