Shape Rolling Process Combined with In-line Induction Heat Treatment for Rectangular Wire Die Springs*

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Abstract
In recent years, environmental issues and high labor costs have been receiving increasing attention. One example is the manufacturing process of conventional oil tempered shaped wire which is high cost, time-consuming and polluting. The aim of this study is therefore to attempt to solve the problems of producing this particular form of wire. In this study we investigate the shape rolling process combined with the in-line induction heat treatment process for tempered trapezoidal wire. The round wire was heated to austenitic temperature using in-line induction heating equipment, and the wire was formed into a trapezoidal shape using a tandem cantilever type rolling mill, then quenched in water and tempered. The entire sequence was carried out in a single procedure with an automated line, the above-mentioned shape rolling process was verified by means of the finite element method, and finally the tempered trapezoidal wire was coiled to a helical form, i.e., rectangular wire die springs, which then underwent fatigue testing. The results revealed that the mechanical properties and the fatigue testing results of the die springs all satisfied industrial standards. The advantages of the manufacturing process of this study are that is highly efficient, low cost, and more environmentally friendly than the conventional process.

Key words: Shape Rolling, In-Line Induction Heat Treatment, Trapezoidal Wire, Die Springs, Fatigue Testing

1. Introduction
Die springs are widely used for plastic molds and metal press molds. Oil tempered die spring wire is used for die springs designated in JIS B5012 and ISO 10243, as presented in Table 1. Oil tempered wire with a circular section is used for round wire die springs, while wire with a trapezoidal or rectangular section is used for rectangular wire die springs (hereinafter referred to as die springs). In recent years, the space of molds has become more compact. A rectangular section wire can provide a more compressed length than a circular section of spring. Hence, the cross section of die springs has gradually changed from circular to rectangular due to the large amount of energy that must be stored within a limited space. The trapezoidal section wire is designed so that after the wire is coiled, the thickness of the inside coil can be equivalent to that of the outside coil in the small spring index (1).

The raw material commonly used for die springs is chrome-silicon spring steel, such as SAE 9254 and SUP12, which is difficult to form into a trapezoidal shape with the successive drawing process due to the fact that the strain hardening rate of spring steel is very high at room temperature. Fig. 1 is the flowchart of the shaped wire drawing and heat treatment processes of trapezoidal wire for the die springs. The process of annealing or
spheroidizing needs to be carried out before the wire drawing processes, and acid pickling, phosphate coating, and wire drawing are required three or four times until the circular section is formed into a trapezoidal section. Finally the wire is transformed into a tempered martensite structure by means of the oil quenching and lead tempering process. Hence, the tempered trapezoidal wire for the die springs is both difficult and expensive to produce.

Table 1 Type and color of various die springs

| Type            | Color  | JIS B5012 | ISO 10243 |
|-----------------|--------|-----------|-----------|
| Lightest load   | Yellow | —         |           |
| Light load      | Blue   | Green     |           |
| Medium load     | Red    | Blue      |           |
| Heavy load      | Green  | Red       |           |
| Ultra heavy load| Brown  | Yellow    |           |

Fig. 1 Flowchart of the shaped wire drawing and heat treatment process

Electromagnetic induction heating is often used in heating processes such as welding, metal melting and heat treatment. The main advantages of induction heating, in comparison with the conventional oil quenching and lead tempering processes, are its high thermal efficiency, fast heating process and ease of control of the operating parameters. Because the induction heating times are short, the scales of the surface of the wire are significantly reduced and do not cause oxidation or decarburization on the surface of the steel wire (2).

Kawasaki et al. (3, 4) compared the induction heat treatment process with the conventional oil quenching and lead tempering process, with their results showing that various characteristics of induction heat treatment are superior to those of the conventional process.

Shape rolling, which is also called caliber rolling, is one of the most complex deformation processes. A round wire or bar is rolled in several passes into complex sections such as rails, H shapes, and V shapes. The purpose of the roll pass design is to ensure the long production of the correct profile within permissible dimensional limits with a good surface that is free of defects, to ensure the maximum quantity of output at the minimum cost, and to reduce the roller wear and tear. However, the design of these intermediate shapes of the conventional method is based on experience and trial and error, as estimating the shape of the groove roller for each pass is the most difficult aspect of the science of shape rolling.

Researchers have developed many methods for the simulation of the shape rolling process. Mori and Osakada (5) developed a rigid plastic 3D finite element method to simulate steady state deformation in shape rolling with grooved rolls. Park and Oh (6) developed a rigid plastic 3D finite element method program for the simulation of shape rolling processes, which is capable of handling arbitrary cross-sections. Kim et al. (7) developed a new simplified 3D numerical method to simulate the shape rolling process,
which combines the rigid-plastic 2D finite element method for the generalized plane strain condition. Glowacki (8) presented the simulation of rail rolling by means of the generalized plane strain method that was applied to the modeling of the 3D problem using a 2D finite element formulation, in which the memory capacity and computational time can be significantly reduced. Iankov (9) presented the 2D generalized plane strain finite element model that is incorporated with the commercial software MSC MARC to solve the complicated shape rolling problem. The generalized plane strain approach saves computing time and computer memory, which is very useful when several subsequent passes are simulated.

In this study, the round wire was heated to austenitic temperature by in-line induction heating in a few seconds, and the wire was formed into trapezoidal wire using a tandem cantilever type rolling mill, then quenched in water and tempered. Finally, the round wire was transformed into trapezoidal wire with a tempered martensite structure. The feasibility of the roll pass design was verified by means of finite element simulation, and the tempered trapezoidal wire was examined using the tensile test. In addition, the tempered trapezoidal wire is coiled to the rectangular wire die spring using a mandrel winding machine, which followed by fatigue testing to verify the fatigue life.

2. Theory and Finite Element Formulation

The shape rolling process is an important metal forming process that is divided into hot rolling and cold rolling, where hot rolling refers to the temperature of the wire exceeding half melting temperature. The primary objective of the shape rolling process is to reduce the cross section of wire and to obtain the required section profile. A series of rolling mills in tandem is often used to achieve high production rates in the long product manufacturing process. The basic assumption was adopted in order to simplify the shape rolling process as follows. The material of the roller is assumed to be rigid, and the material of the wire is assumed to be isotropic and incompressible.

The theory of plasticity is based on elasticity; thus, when combined with the yield theory and stress-strain relation, the governing equation for the solution of the mechanics of plasticity is summarized as Eqs. (1) to (4) (10):

\[
\text{Equilibrium equations} \quad \sigma_{i,j} = 0 \quad (1)
\]

\[
\text{Yield criterion} \quad f(\sigma_{y}) = C \quad (2)
\]

\[
\text{Constitutive equations} \quad \dot{\varepsilon}_{y} = \dot{\lambda} \sigma_{y}' \quad (3)
\]

\[
\text{Compatibility condition} \quad \dot{\varepsilon}_{y} = \frac{1}{2} (u_{i,j} + u_{j,i}) \quad (4)
\]

However, it is difficult to obtain an exact solution that satisfies all of the governing equations; hence, various approximate methods and numerical analysis methods have been proposed, such as upper bound, slip line field, slab and the finite element methods. The basis for the finite element formulation is the variational principle, a general functional form that can be represented as Eq. (5). In order to satisfy the condition of incompressibility on admissible velocity fields, Eq. (5) can introduce a Lagrange multiplier as Eq. (6), where \( \bar{\sigma} \) is the effective stress, \( \dot{\varepsilon} \) is the effective strain rate, \( \sigma_{y}' \) is the stress deviator tensor, \( \dot{\varepsilon}_{y} \) is the strain rate, \( F_{i} \) is the surface traction, \( u_{i} \) is the velocity vector, \( \lambda \) is the Lagrange multiplier and \( \dot{\varepsilon}_{V} \) is the volumetric strain-rate.

\[
\Pi = \int_{\Omega} \bar{\sigma} \dot{\varepsilon} dV - \int_{S_{y}} F_{i} u_{i} dS \quad (5)
\]
\[ \Pi_i = \int_{V} \sigma \hat{\epsilon} dV + \int_{V} \lambda \hat{\epsilon}_v dV - \int_{S_{y}} F u_i dS \]  

(6)

where,

\[ \sigma = \sqrt{\frac{3}{2} \sigma_y' \sigma_y'} \]

\[ \hat{\epsilon} = \sqrt{\frac{2}{3} \epsilon_y \hat{\epsilon}_y} \]

\[ \epsilon_v = \hat{\epsilon}_x + \hat{\epsilon}_y + \hat{\epsilon}_z \]

To invoke the stationarity condition \( \delta \Pi_i = 0 \) in Eq. (6) obtains Eq. (7) which can be expressed in terms of the nodal value and discretization with the finite element method.

\[ \delta \Pi_i = \int_{V} \sigma \delta \hat{\epsilon} dV + \int_{V} \lambda \delta \hat{\epsilon}_v dV + \int_{V} \delta \epsilon_v dV - \int_{S_{y}} F_i \delta u_i dS \]  

(7)

Considering the heat transfer of the wire with the rollers, the energy balance equation can be expressed as Eq. (8).

\[ k T_{i,j} + \dot{q} - c \rho \dot{T} = 0 \]  

(8)

where \( k \) is the conductivity, \( T \) is the temperature, \( \dot{q} \) is the heat generated due to plastic work, \( \rho \) is the density, \( c \) is the specific heat, and \( \dot{T} \) is the temperature rate. The heat generation in the deformation body is due to plastic deformation that is expressed as Eq. (9), where \( \eta \) is the heat generation efficiency.

\[ \dot{q} = \eta \sigma_y \epsilon_i \]  

(9)

The energy balance equation Eq. (8) can be written in the form of Eq. (10) for the arbitrary variation in temperature \( \delta T \).

\[ \int_{V} k T_{i,j} \delta T dV + \int_{V} \eta \sigma_y \epsilon_j \delta T dV - \int_{V} c \rho \dot{T} \delta T dV = 0 \]  

(10)

By using the Gauss theorem, Eq. (10) becomes Eq. (11), where \( q_n \) is the heat generated at the boundary \( S_n \), and \( n \) denotes the unit normal to boundary surface.

\[ \int_{V} k T_{i,j} \delta T dV + \int_{V} c \rho \dot{T} \delta T dV - \int_{V} \eta \sigma_y \epsilon_j \delta T dV - \int_{S} q_n \delta T dS = 0 \]  

(11)

where,

\[ q_n = k T_n \]

Friction is a very complex physical phenomenon, such that surface roughness, pressure, temperature, and relative speed could all change the friction coefficient. In this study the friction stress on the contact surface of the rollers and the wire should be considered. Kobayashi et al. \(^{11}\) suggested that friction stress can be expressed as Eq. (12), where \( F_s \) is the frictional stress, \( m \) is the friction coefficient, \( u_s \) is the sliding velocity of the wire to the roller, \( A \) is a small positive number compared to \( u_s \), and \( t \) is the tangential vector of the slide velocity \( u_t \).

\[ F_s = -m \frac{\sigma}{\sqrt{3}} \left[ \frac{2}{\pi} \tan^{-1} \left( \frac{u_t}{A} \right) \right] t \]  

(12)
3. Manufacturing process conditions and Material properties

In conventional heat treatment, the steel wire is heated to austenitic temperature and then quickly cooled to obtain a martensitic structure. In the modified ausforming method, the steel is plastic deformed before phase transformation and then quickly cooled to obtain a martensitic structure. The ductility and toughness of the modified ausforming method are superior to those of the conventional oil quenching process (12).

A schematic outline of the manufacturing process of this study is presented in Fig. 2. The concept of this process is similar to the modified ausforming method. Fig. 3 is the production facility that is based on the abovementioned concept. The production facility consists of induction heating equipment, tandem cantilever type rolling mills, water spray cooling systems, and auxiliary equipment, where the drive motor of the rolling mills is a servo-motor that can perform the tension control between stands to prevent wire distortion. The round wire was heated by the induction heating equipment from room temperature to 1050°C in a few seconds, and the wire was continuously formed into various shapes using a three pass tandem cantilever type rolling mill, and then the shaped wire was quenched in pure water and tempered at various temperatures from 500°C to 560°C. Finally, the steel wire was transformed into the shaped wire with a tempered martensite structure. The heating rate of the wire is 125°C/s, the maximum cooling rate is 180°C/s, and the initial rolling speed is 0.25m/s.

![Fig. 2 Schematic outline of the manufacturing process](image_url)

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![Fig. 3 Production facility of the shape rolling process with in-line induction heat treatment](image_url)
The detail of the trapezoidal wire with 7 mm height and 8.5 mm width is presented in Fig. 4. The roll pass design is an essential part of the shape rolling process, and the primary goal of the roll pass design is to ensure that the finished products have the correct profile, and are free of surface defects. The roll pass design was verified by means of the commercial finite element program MSC MARC in this study. The grooves of the roll pass can be classified into active or dead, as well as open or closed. An open roll pass is composed of two concave grooves or of one concave and one convex groove. On the contrary, a closed roll pass is composed of one concave and one convex groove. The three pairs of high chrome alloy groove roller with 180 mm outside diameter are presented in Fig. 5(a) to (c), where the first and second passes are closed roll passes, the third pass is an open roll pass, and the outside diameter of round wire is 10 mm.

![Fig. 4 Detail of the trapezoidal wire](image)

The chemical composition of the alloy steel wire used in this study is listed in Table 2. The constitutive relation of SAE 9254 alloy steel adopted Y. Lee’s method which extended Shida’s constitutive equation to predict the constitutive relation of three types of alloy steel (SAE9254, AISI 52100 and AISI 4140) by incorporating a carbon equivalent model \(^{(13)}\). The flow stress of wire is presented in Figs. 6(a) to (c), where the material model was rigid-plastic and according to the von Mises yield criterion.

![Fig. 5 Various roll groove shapes of the trapezoidal wire](image)

| Steel grade | C (%) | Mn (%) | Si (%) | Cr (%) | Ni (%) |
|-------------|-------|--------|--------|--------|--------|
| SAE 9254    | 0.55  | 0.75   | 1.4    | 0.75   | 0.7    |
Assuming that the rollers are rigid with a smooth surface, the friction coefficient is 0.3 to 0.35 between the roller and the wire \(^{(14)}\). The initial temperature of the rollers and environmental temperature are both set to 30°C, and the initial temperature of the wire is assumed to be 1050°C. The environmental heat transfer coefficient and the contact heat transfer coefficient are assumed to be 100W/m\(^2\)°C and 20kW/m\(^2\)°C, respectively. The
thermal conductivity, specific heat and density of the austenitizing wire are assumed to be 32W/m°C, 780J/kg°C and 7850kg/m³, respectively, and the heat generation efficiency is assumed to be 0.9. In order to simplify the finite element model, all rolling processes are considered to be a 2D generalized plane strain problem, incorporating thermal mechanical coupling.

4. Results and Discussion

The effective plasticity strain distributions of the finite element analysis for the three roll passes are shown in Figs. 7(a) to (c), respectively. As shown in these figures, the effective strain increased as the pass proceeded due to the effect of deformation in the previous pass. The temperature distributions obtained by finite element analyses are shown in Figs. 8(a) to (c), respectively. Although the temperature distributions of Figs. 8(a) to (c) are non-uniform, they tend to become uniform in a few seconds due to thermal conduction. The finished trapezoidal wire was 7 mm in height and 8.5 mm in width with a tolerance of ±0.05 mm, as shown in Fig. 9, where the total area of the cross section is 49.5 mm² (equivalent diameter is 7.9 mm). A comparison between Figs. 8(c) and 9 revealed that the experimental result was consistent with the finite element analysis result.

![Effective plasticity strain distribution of the finite element analysis](image)

Fig. 7 Effective plasticity strain distribution of the finite element analysis (a) 1st pass (b) 2nd pass (c) 3rd pass
Fig. 8 Temperature distribution by the finite element analysis (a) 1st pass (b) 2nd pass (c) 3rd pass

Fig. 9 Finished trapezoidal wire product
The mechanical properties of heat treated alloy steels are strongly influenced by the grain size of the parent austenite phase before quenching. There are a number of standards that are used to evaluate the prior austenite grain size, such as ASTM E 112. The prior austenite grain size in the as hot rolled steels is about 20µm, but it can be refined by controlling the hot rolling and the heat treatment process. Figure 10 is the prior austenite grain boundaries of the tempered trapezoidal wire by using aqueous saturated picric acid plus CuCl₂ and surfactant, where the average diameter of the prior austenite grain size is less than 12µm, which is in accordance with the ASTM E112 standard. The fine grain size is due to the wire being heated to austenitic temperature by induction heating and plastic deformation due to the shape rolling process.

Fig. 10 Prior austenite grain boundaries of the tempered trapezoidal wire

Mechanical properties include yield and ultimate strength, reduction of area, hardness, and toughness, where the fatigue is correlated with the ultimate strength, and the toughness directly affects the resistance of the fracture. Toughness is commonly evaluated by an impact test, but it is difficult to sample a specimen from the wire with the Charpy impact test. In practice, toughness is often replaced by ductile evaluation such as elongation and reduction of area. Figure 11 shows the influences of tempering temperature on the hardness of the trapezoidal wire, where the hardness decreases as the tempering temperature increase. The tensile strength of the trapezoidal wire is nearly proportional to the hardness as shown in Fig. 12. Because of the tempered trapezoidal wire being coiled into a helical form in the small spring index such that the outside and inside surfaces suffered drastic plastic deformation, if the tensile strength of the tempered trapezoidal wire is too high, the wire might have cracks or seams on the surface. In general, the tempered trapezoidal wire has a maximum tensile strength of 1,690MPa with Rockwell hardness of 48.5 HRC, and the percent reduction of the area of the tempered trapezoidal wire is 46%.

Table 3 is the specification of the die spring for fatigue testing, where the type of the die spring is ultra heavy load in accordance with the JIS standard. Fig. 13(a) shows the die spring coiling procedure using a mandrel winding machine. The trapezoidal wire became a rectangular shape with a semicircular side after coiling as shown in Fig. 13(b). The die spring then performed the following procedures: stress relief, grinding, shot peening and presetting. Finally, fatigue testing was performed on the die springs to verify their failure life. Figure 14 is the die spring fatigue testing procedure using a fatigue testing machine.
Table 3 Specification of the die spring for fatigue testing

| Type               | Ultra heavy load (JIS) |
|--------------------|------------------------|
| Steel grade        | SAE 9254               |
| Tensile strength (MPa) | 1690               |
| Inner diameter (mm) | 17.5                  |
| Outer diameter (mm) | 35                    |
| Free length (mm)   | 70                    |
| Number of total coils | 7                   |
| Spring rate (N/mm) | 343                   |
| Fatigue test       |                        |
| Load (N)           | 4800                  |
| Deflection (mm)    | 14                    |
Fig. 13 Coiling procedure of the die spring (a) coiling procedure (b) after coiling

(b) After coiling

Fig. 14 Die spring fatigue testing
In the automotive industry, fatigue life prediction widely uses the Weibull plot, which exhibits a straight-line plotting of the cumulative failure probability versus life cycles. The advantage of Weibull analysis is the ability to provide accurate failure analysis and failure forecasts with small samples (15). Figure 15 is the Weibull plot of the die spring fatigue testing, the abscissa is the number of cycles to failure and the ordinate is the cumulative failure probability, where the total number of the die spring samples is eight, $\beta$ indicates the scatter of the distribution of the die spring fatigue testing, $\eta$ indicates the 63.2% failure point for the population of the die spring fatigue testing. In the die spring fatigue testing of this paper $\beta$ is 3.247, $\eta$ is 805000, and the B10 life of the die spring fatigue testing is 402500, revealing that the fatigue life of the die springs satisfies the demand of industrial standards.

Fig. 15 Weibull plot of the die spring fatigue testing

The manufacturing process of conventional oil tempered shaped wire involves annealing, acid pickling, phosphate coating, and wire drawing three or four times, until the round wire is formed into the trapezoidal shape, then the shaped wire is transformed into a tempered martensite structure by means of the oil quenching and lead tempering process. For the above reasons, the conventional process is high cost and labor-intensive. The process of this study adopted the shape rolling process with in-line induction heat treatment to produce tempered martensite trapezoidal wire, with the entire sequence carried out in a single procedure. There is no need to perform annealing, acid pickling, phosphate coating, or wire drawing. Consequently, the problems of the conventional process can be completely solved by this process.

5. Conclusions

In this study, we present the shape rolling process combined with in-line induction heat treatment for rectangular wire die springs. The roll pass design was verified by means of the rigid plastic 2D generalized plane strain finite element method, and the results revealed that the mechanical properties and the fatigue testing results of the die springs all satisfied the industrial standards. The advantages of the manufacturing process of this study are summarized as follows:

(1) The wire is heated to austenitic temperature by induction heating in a few seconds, so the heating process does not cause oxidation or decarburization on the surface of the
steel wire.

(2) It is evidenced that the mechanical properties and microstructure are up to the standards.

(3) The manufacturing process of this study is environmentally friendly, because there is no need for acid pickling, annealing, spheroidizing or phosphate coating, and the quenchant is pure water.

(4) This manufacturing process is highly efficient, low cost, and provides much higher heating rates than the furnace due to the induction heating process, and induction heating equipment could allow quicker start-up than conventional furnaces.

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