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A rotary reduction of fine wires/tubes of a wide range of diameters using a pair of concave rolls

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ABSTRACT

This paper presents an innovative rotary reduction method of elongated fine solid wires and hollow tubes, the diameters of which could be reduced to 0.02 times of diameter of rolls as the tool. A pair of concave rolls is positioned at a skew angle to the material axis, and the rolls compress the material. The material travels between the rolls in a spiral movement with tension applied on its ends. The method is applicable for a very wide range of diameters using the same tools. Diversified shapes would be fabricated as the method reduces the diameter at arbitrary axial positions.

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1. Introduction

Elongated wires and tubes have diversely been used in many industrial fields. In particular, fine solid wires and hollow tubes have been leading advanced technologies. Fine gold and copper wires are used for connecting electric devices, including Integrated Circuits and Large Scale Integrated Circuits [1]. Fine metal tubes are used in medical instruments, including stents [2] and pain-free syringe needles. Fine wires and tubes could be used as raw materials for parts in micro machines. Finer materials could realize high functionality in electrical, medical and other fields.

Some high functional wires and tubes are schematically shown in Fig. 1. Fig. 1(a) shows thin wires, which are used as raw material in sintering. The ratio of material surface to volume is important when they are used for sintering. The higher the ratio, the faster the reaction velocity becomes due to acceleration of diffusion, and then finer wires have advantages. Compared to fine powders, fine wires would easily be positioned for controlling the local volume fractions of materials, and also give anisotropic mechanical or electric properties to the sintered material. Diameter change of fine tubes would be another high function, which is shown in Fig. 1(b) and (c). These types of micro tubes would be used as suppliers for micro fluids or parts in micro devices. Therefore, technologies for fabrication of finer wires and tubes for high function have been desired.

Drawing with a holed die is a conventional method for fabrication of fine wires and tubes, and it is excellent in stability and productivity in manufacturing. However, fabrication of the holed die has been getting difficult with the decrease of target diameters of wires and tubes.

Some new technologies have recently been proposed. ‘‘Bundle drawing’’ draws a cluster of dozens of fine wires into finer wires [3]. However, it is difficult to split the bundle into individual wires. A die-less tube drawing was proposed, and it utilizes super-plasticity at high temperature [4]. The method has now been applied for micro-tubes [5]. But this method needs to heat the material locally, deteriorating the mechanical properties.

Conventional processes for large scale wires and tubes might be converted for fine ones. Although tandem-stand rolling might be applied, twist must inevitably occur between the stands, resulting in defects when the material becomes thin.

This paper presents an innovative rotary reduction method of elongated fine wires and tubes. As the diameters of the materials could be reduced down to 0.02 times of the diameter of rolls as the tool, the fabrication of the rolls would be much easier than holed dies in drawing. The method is applicable for a very wide range of diameters using the same tools. The proposed method forms the wires and tubes without heat generation so as to maintain the material strength. Diversified shapes, as in Fig. 1(b) and (c), would be fabricated as the method reduces the diameter at arbitrary axial positions. This paper explains the composition of the method and forming mechanism. The results of a series of finite element analyses are shown, followed by experimental verification.

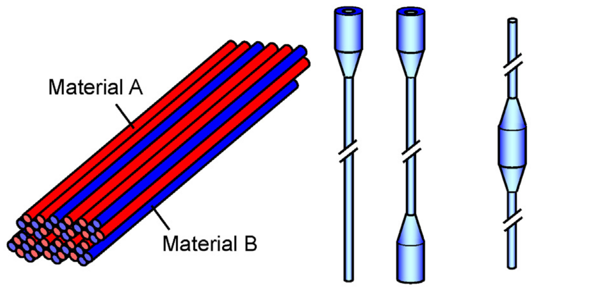

Fig. 1. Examples of high functional wires and tubes.

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2. Rotary reduction of fine wires and tubes

2.1. Composition of rotary reduction using a pair of concave rolls

The basic composition of the rotary reduction method of elongated wires and tubes using a pair of concave rolls (concave-roll drawing, CR drawing) is shown in Fig. 2. The basic composition is similar to that of a two-roll straightener for bars. A pair of concave rolls is positioned at skew angles ϕ_u and ϕ_d to the material axis. The concave shape would restrict the material movements in the horizontal direction, i.e. in the x-axis in Fig. 2. The skew angles ϕ_u and ϕ_d were set at 30° as in an ordinary straightening method. The rolls vertically compress the material and the target vertical compress δ_C is defined by

$$\delta_C = D_0 - G \quad (1)$$

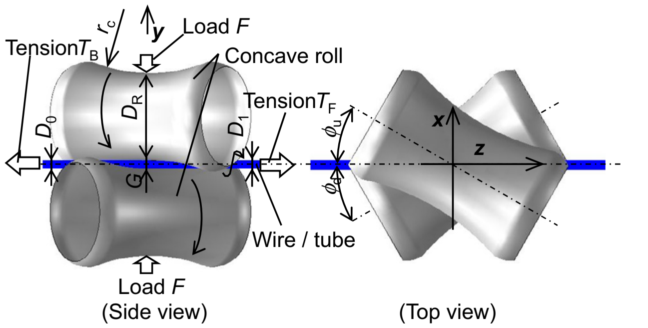

Fig. 2. Basic composition of rotary reduction method using a pair of concave rolls.

where D_0 is the material diameter and G is the gap between two rolls.

The material travels between the rolls in a spiral movement with forward and backward tensions T_F and T_B applied on its ends. The main working parameters in the method are the roll profiles, vertical compress δ_C, axial tensions T_F and T_B and the roll skew angles ϕ_u and ϕ_d. CR drawing would be applicable for a very wide range of diameters as the material with various diameters can be deformed by just arranging the gap G.

2.2. Diameter-reduction mechanism

The diameter-reduction mechanism is slightly complicated. Although the movement of the material seems to be restricted between the two concave rolls at first glance as shown in the "Rear view" in Fig. 3, spaces exist to displace the material from the ideal line along the z axis. The cross sections of the material and rolls are shown from the inlet side [A] to the centre [C] in the figure. The cross sections of the concave roll are convex at the cross section, and the wire could displace far from the z axis if the front and back tensions are too small. The tension acts as recovering force F_R on the material and the material should stay at a certain displacement

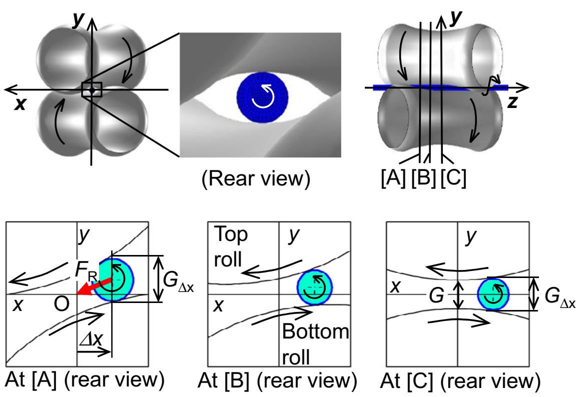

Fig. 3. Schematic illustration for mechanism of diameter reduction.

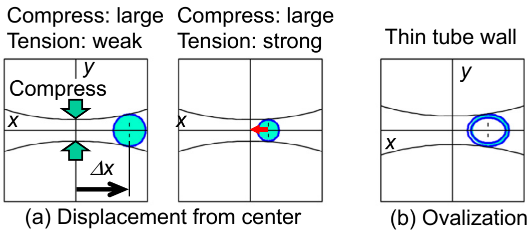

Fig. 4. Undesirable phenomena for diameter reduction.

Δx. The gap $G_{\Delta x}$ at the displacement Δx gradually decreases from [A] to [C], leading to reduction of the material diameter. The cross-sectional circularity of the material would be retained as the material keeps rotating during the deformation.

Fig. 4 schematically shows some undesirable phenomena for diameter reduction in CR drawing. When vertical compress δ_C is too large, displacement becomes large, leading to less reduction in diameter. Appropriate axial tension would reduce the displacement, resulting in recovery of diameter reduction. When the tube wall is too thin, the tube cross section becomes oval, leading to less reduction. However, when the tube is properly rotated, this ovalization would be suppressed.

Vertical compress δ_C and axial tensions T_F and T_B have positive and negative effects in CR drawing. Compress reduces the gap for enlarging reduction. However, too large compress leads to large displacement. Tension reduces the displacement and increases reduction. However, too large tension leads to the material fracture. Therefore, the combination values of compress and tension should be adjusted for the maximum reduction in diameter.

3. Examination by the finite element analysis

3.1. Working condition

A series of FE analyses was carried out for feasibility study of the proposed method. The composition of the model is similar to Fig. 2; two concave rolls are rotated and the material travels in a spiral movement with tension on both its ends.

Elastic-plastic analysis was carried out using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. A von Mises' yield criterion was adopted, and the normality principle was applied to the flow rule. Constraints were dealt with by the penalty function method. An explicit scheme was adopted. 8-node hexahedral elements with 8 integration points were adopted. The number of elements was 8 in radial direction for the wire and 4 in thickness direction in the tube. The element number was 32 in the hoop direction. The element size was 0.5 mm in the axial direction. Table 1 shows the working condition.

Calibre radius r_c was determined as 25 mm by geometric examination as shown in Fig. 5(a) and (b), which shows geometric interference between the rolls and a virtual wire with initial diameter D_0 of 1.0 mm, setting vertical compress δ_C as 5% of the material diameter D_0. When r_c is less than 16 mm as in Fig. 5(a), the

Table 1
Working condition.

Roll	Minimum diameter D_R/mm	10
	Calibre radius r_c/mm	25
	Rotation in FEM ω_R/rad s^{-1}	3.26
	Rotation in experiment N_R/rpm	50
Wire/tube	Material for wire and tube in FEM and wire in experiment	Aluminium A1100
	Material for tube in experiment	Aluminium A5052
	Wire diameter D_0/mm	0.2–1.0
	Tube diameter D_0/mm in FEM	1.0
	Tube diameter in experiment	1.5, 2.0
	Tube thickness t_0/mm	0.125–0.375
Operation	Skew angle ϕ_u, ϕ_d/°	30
	Vertical compress in FEM δ_C/D_0	0.05–0.4
	Load in experiment F/N	0–50
	Axial tension T_F, T_B/MPa	0–98
	Feed in FEM	Idle
	Feed in experiment f/mm	13.1

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