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著者（英）	T. Muraoka, T. Tsubouchi, K. Takahashi, T. Kuboki, S. Kajikawa
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Forming method and characteristics of coiled spring in small coil diameter and with high rectangular ratio in winding wire cross-section

T. Muraoka[a*], T. Tsubouchi[a], K. Takahashi[a], T. Kuboki[a], S. Kajikawa[a]
[a]Department of Mechanical Engineering and Intelligent Systems, The University of Electro-Communications, 1-5-1, Chofugaoka, Chofu, Tokyo, 182-8585, Japan

* Corresponding author. Tel.: +81-042-443-5410.
E-mail address: muraoka@mt.mce.uec.ac.jp

ABSTRACT
This paper presents a new forming method of a coiled spring which is used as a forceps manipulator of a surgical robot. Joint parts of forceps manipulator are required to be "easy to bend and strong to twist". This demand is fulfilled by using coiled springs with high rectangular ratio in winding wire cross-section. However, the coiled springs are conventionally expensive as they are fabricated by machining. This study proposed a new and inexpensive forming method for fabrication of the coiled spring with high rectangular ratio in the wire cross-section. In this method, the coiled spring with circular shape in the winding wire cross-section is compressed in the coil axial direction by upsetting, and then the rectangle ratio of the wire becomes high. The coiled spring with high rectangular ratio of 3 was obtained by the proposed method. In addition, a numerical analysis and experiment were conducted for evaluation of the formed coiled springs in terms of tensile, torsional and bending characteristics. The formed coiled springs were "easy to bend and strong to twist" from results. Moreover, the elastic limit of the formed coiled springs improved due to work hardening by upsetting.

Keywords: Coiled spring; Upset forging; Forceps manipulator; Surgical robot

1. Introduction

In recent years, robots, which replace the work of human labor, have been expected in various scenes. For example, robots have been developed for manufacture of ship and car [1,2] for disaster relief [3-5]. Thus, robots have become requisite machine to work in hazardous places which people cannot approach. Robots are recently applied to the medical field as surgical robots [6,7]. In particular, surgical robots, which are equipped forceps manipulators, can reduce burden on the patient as they realize laparoscopic surgeries without opening the abdominal cavity. However, downsizing of the manipulator joints is a recent challenge. The joints tend to be inevitably large as a number of motors are used for active and free movement inside the body. If joint parts are large, the burden on the patient is extensive as broad incisions are necessary in the surgeries.

For downsizing of the joint, a new forceps manipulator has been developed. Tadano et al. developed of a surgical robot using pneumatic drive instead of motor drive [8]. Haraguchi et al. micrified the joint of forceps manipulator by using a coiled spring [9]. A schematic of the forceps manipulator is shown in Fig. 1. The coiled spring, which works as a compact joint, is connected to an actuator via wires. This coiled spring is “easy to bend” to bend flexibly inside body and “strong to twist” to transmit torque fully. The coiled spring with high rectangular ratio which is *b*/*t* in Fig. 1, in winding wire cross-section can achieve this character. However, fabrication of coiled spring with high rectangular ratio in the wire cross-section is difficult in normal coiling processes which wind a wire with high rectangle ratio into a coil. In particular, it is impossible when the diameter of the coiled spring is small as used in the manipulator joint. Thereby, the coiled springs are now manufactured by machining and process cost is high.

Therefore, inexpensive manufacture process of the coiled spring using as joint parts of forceps manipulator is desired. This paper proposes a new method which can inexpensively fabricate the coiled spring in small coil diameter and with high rectangular ratio in winding wire cross-section. The formed coiled spring was evaluated by a numerical analysis and experiment, and was compared with coiled spring manufactured in a conventional manner using machining.

2. Forming of coiled spring with high rectangular ratio

Coiled springs are conventionally formed by a coiling process which winds up a wire into a coil shape as shown in Fig. 2. The coiling process can easily wind a circular wire and fabricate a coiled spring with a circular shape in the winding wire as shown in Fig. 3(a), and this type of coiled spring is called “circular coiled spring” in the remainder part of this paper. On the other hand, the process cannot wind a rectangle wire with high rectangle ratio into a coiled spring in a small coil diameter, which is shown in Fig. 3(b) due to high flexural rigidity, and this type of coiled spring is called “rectangular coiled spring”

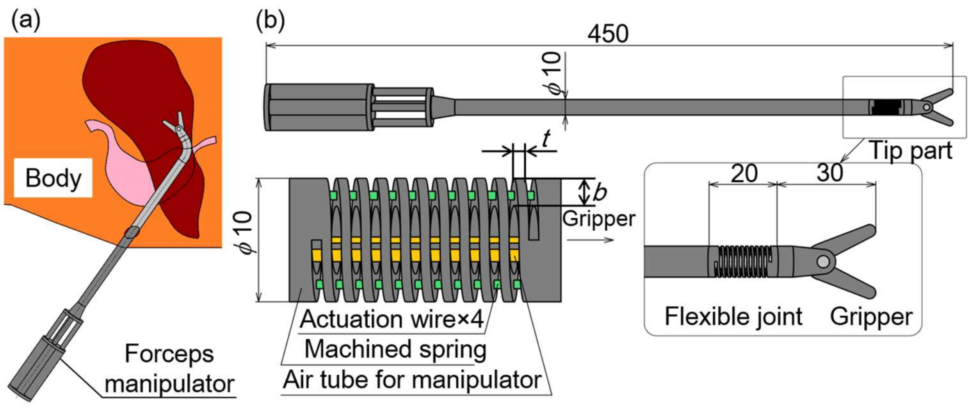

Fig. 1 Schematic of forceps manipulator with the coiled spring: (a) Example of the forceps manipulator in operation; (b) The forceps manipulator and the joint part of the coiled spring in manipulator

Edgewise winding process is a forming method of "rectangular coiled spring" such as choke coil [10]. Edgewise winding process can fabricate coiled springs with rectangular ratio b/t = 2.5 by utilizing a number of rollers. However, the process can be applied for only high ductile material such as copper which is resistant to cracking under tensile stress. Edgewise winding process would be almost inapplicable when coil diameter D_{R2}/b is smaller than 4.5 times of wire breadth b as in Fig. 3. Furthermore, the outside thickness would inevitably be thinned by the edgewise process. Thus, the coiled springs for forceps manipulator are conventionally manufactured by machining. However, the shape of "rectangular coiled spring" is three-dimensionally complicated, and then the manufacturing cost is very high and contributory to the high cost of the surgical robot itself.

This paper proposes "upset forging process" compresses a "circular coiled spring", which is formed by a conventional coiling process in advance, in its axial direction into a "rectangular coiled spring". A schematic of the proposed method is shown in Fig. 4. This method can drive down process cost significantly because the process do not require complex tool paths and complete the deformation within quite a short time.

The present research did not utilize heat treatments, such as "bluing", for improvement of mechanical properties after deformation. "Bluing" is often applied for drawn wires or coiled springs for enhancing the durability during a number of repeated cycles of loading and unloading. However, in the case of joints of forceps manipulator, the joints are assumed to be used once for one patient from the aspect of hygiene, and then the durability is not required. Therefore, heat treatments were not applied in this research.

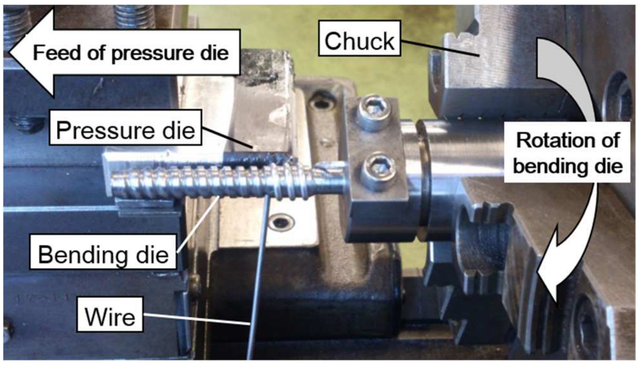

Fig. 2 The forming method of coiled spring from a wire with circular cross-section using a lathe

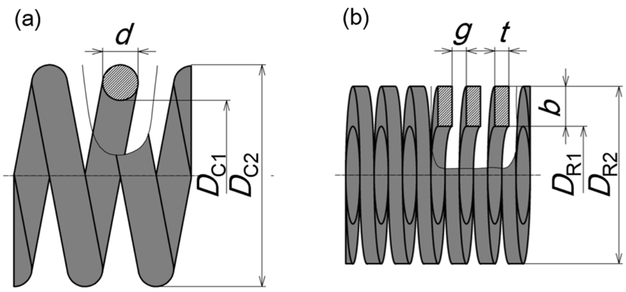

Fig. 3 Schematic of the coiled spring: (a) With circular cross-section (circular coiled spring); (b) With rectangular cross-section (rectangular coiled spring

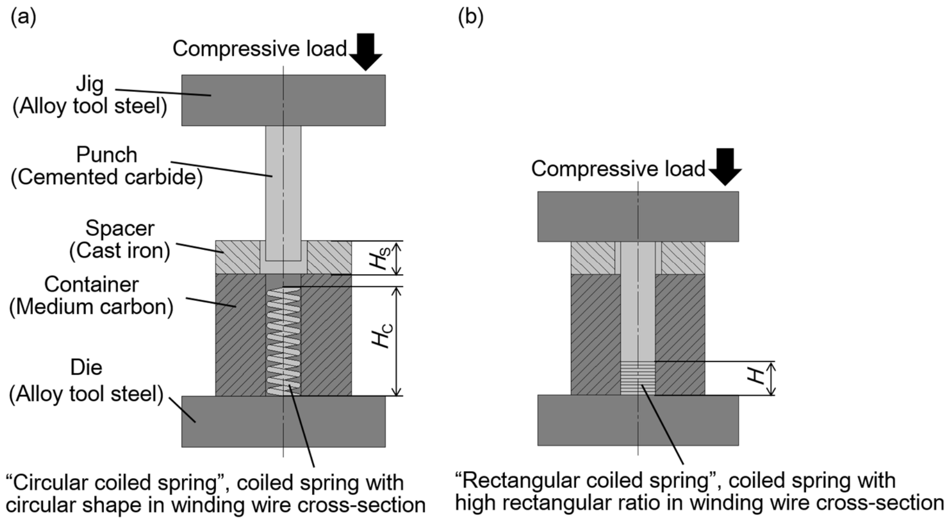

Fig. 4 New forming method for the coiled spring with high rectangular ratio in cross-section: (a) Initial set-up; (b) After upset forging process

3. Upset forging process

3.1. *Experiment*

Experiment was conducted to investigate deformational characteristics of the coiled spring in upset forging process. The experiment setup is shown in Fig. 4(a). The tools include a die and jig of SKD11 (Japan Industrial Standard, JIS), a container of medium carbon steel S45C (JIS), a punch of cemented carbide and a spacer of a casted iron. Height of the coiled spring after upset forging H was adjusted by selecting a spacer with appropriate height H_s as shown in Fig. 4(b). A wire of austenite stainless steel SUS304 (JIS) with wire diameter d = 2mm was used as raw material for coiling process in Fig. 2. SUS304 is usable as parts of forceps manipulator due to chemical stabilization in surgeries. Young's modulus E was 193GPa, Poisson's ratio ν was 0.3 and true stress-true strain diagrams of SUS304 wire rod are shown in Fig. 5. "Upset forging" was conducted by hydraulic universal test machine (Shimazu UH-1000kNA) and the compressive load and stroke were measured.

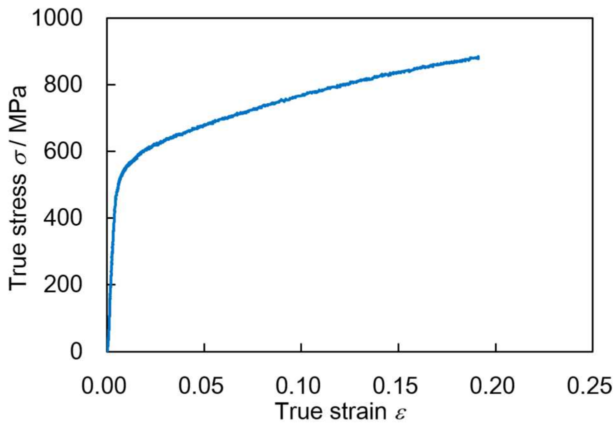

Fig. 5 True stress-true strain diagrams of SUS304 wire rod

3.2. *Experimental result*

Compressive load-stroke diagram is shown in Fig. 6. Stroke of punch S_1 for each hoop is expressed by

$$S_1 = (H_C - H)/n\,. \tag{1}$$

Here H_c is height of the coiled spring before upsetting and n is winding number of hoop in the coiled spring. While compressive load P did not increase for small stroke S_1 up to [A], P increased drastically for larger stroke. This is attributed to disappearance gap of adjacent hoops g as shown in Fig. 3(b) and wire itself started to deform. Since fracture started to appear on the surface of upset wire when $S_1 > 3$mm, the maximum stroke was set at $S_1 = 3$mm of [B]. While the gap g between adjacent hoops is zero as at [B] in Fig. 6, the gap must be a certain amount to work as a coiled spring as in Fig. 3(b). Therefore, the compressed coiled spring was plastically expanded in the axial direction so that the gap g should be equal to wire thickness t when the outer force is removed. In the case of $S_1 = 3$mm, the dimension of the coiled springs fabricated by upset forging process is shown in Table 1 and an example of formed coiled springs are shown in Fig. 7. Rectangular ratio b/t of the formed coil springs was 3 on average and the ratio of the coiled spring outside diameter to the wire breadth D_{R2}/b was 4.21. Upset forging successfully achieved the high value of b/t and D_{R2}/b, which are not attained by conventional processes.

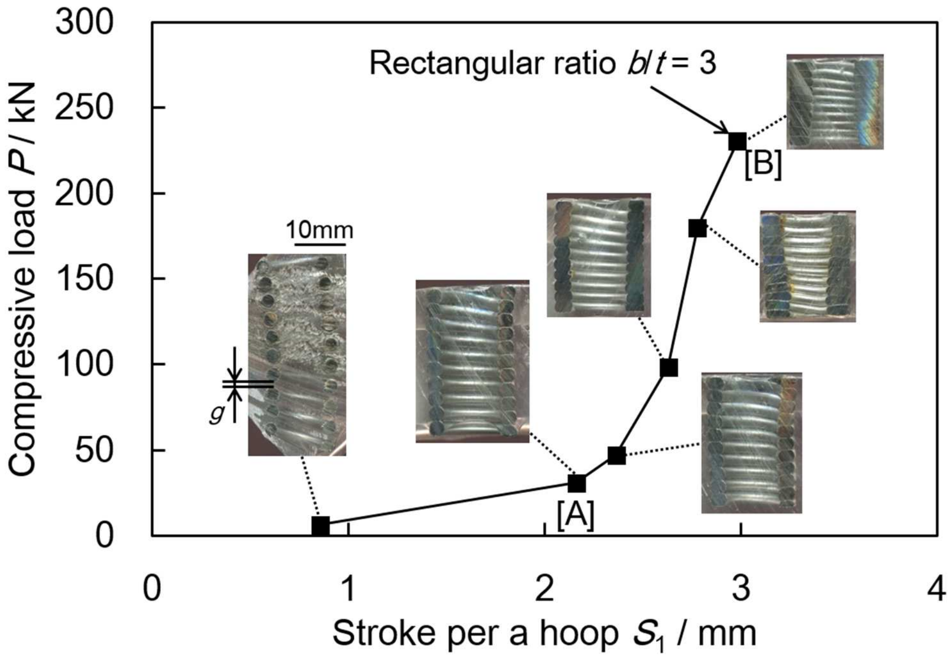

Fig. 6 Compressive load-stroke diagram

Table 1 The shape size before and after the process

	Before processing		After processing					
	D_{C1} / mm	D_{C2} / mm	D_{R1} / mm	D_{R2} / mm	b / mm	t / mm	Rectangular ratio b/t	D_{R2}/b
No. 1	8.40	12.40	7.08	13.60	3.26	1.07	3.05	4.17
No. 2	8.50	12.50	7.14	13.52	3.19	1.10	2.90	4.24
No. 3	8.60	12.57	7.19	13.57	3.19	0.97	3.29	4.25
No. 4	8.52	12.50	7.04	13.50	3.23	1.00	3.23	4.18
No. 5	8.43	12.50	7.15	13.67	3.26	1.05	3.10	4.19
No. 6	8.57	12.50	7.24	13.53	3.15	1.05	3.00	4.30
No. 7	8.50	12.53	7.25	13.68	3.22	1.05	3.06	4.25
No. 8	8.58	12.53	6.97	13.23	3.13	1.10	2.85	4.23
No. 9	8.50	12.50	6.75	13.23	3.24	1.10	2.95	4.08
Average	8.51	12.50	7.09	13.50	3.21	1.05	3.05	4.21

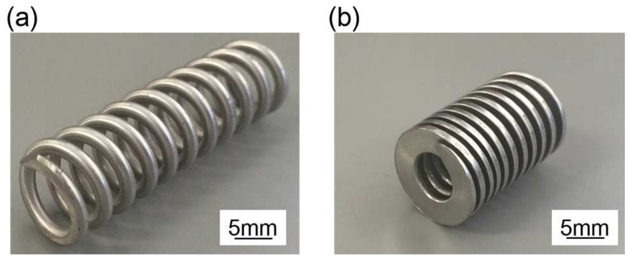

Fig. 7 The coiled spring with high rectangular ratio in winding wire cross-section fabricated by the proposed method: (a) Before upset forging process; (b) After upset forging process

3.3. *Evaluation of work hardening*

In upset forging process, the coiled spring is subjected to severe plastic deformation. Effect of work hardening must be considered in order to evaluate performance of the coiled spring. Thereby work hardening of the formed coiled spring was investigated by the finite element method (FEM).

Plastic strain is accumulated to some extent in coiling process and considerably in upset forging process. In coiling process, the maximum equivalent strain, which is accumulated at the inner and outer surfaces of the hoop in the coiling process, would approximately be expressed by

$$\varepsilon_{pc} = \frac{d/2}{r}, \quad (2)$$

where, r is bending radius at wire center and is equal to $(D_{C1}+D_{C2})/2$. Thus, ε_{pc} is 0.3 approximately.

Next, in upset forging process, equivalent plastic strain was evaluated by a FEM model. Elasto-plastic analysis was carried out using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. The FEM model of upset forging process is shown in Fig. 8. Analysis was conducted on winding wire cross-section by assuming the cross-sectional deformation would occur symmetrically around the coil axis, though the actual shape of the coiled spring is spiral. Coulomb friction rule was adopted and the friction coefficient was assumed 0.1 between tools and the wire. Tools were assumed as rigid body. The work hardening property was approximated by Swift's law and expressed as

$$\sigma = 1300(0.33 + \varepsilon_{\mathrm{p}})^{0.45}, \tag{3}$$

where, σ is stress and ε_{p} is plastic strain.

The distribution of equivalent plastic strain $\varepsilon_{\mathrm{pu}}$ after compression is shown in Fig. 9. FEM result shows that the equivalent plastic strain of 1.0 would be accumulated around the center portion, while equation (2) evaluated accumulation of 0.3 at the inner and outer surfaces. Therefore, it would be roughly estimated that the total equivalent strain $\varepsilon_{\mathrm{p}}'$ of 1.0 would be accumulated inside the wire during coiling and upset forging though it might slightly be overestimation. The next section will evaluate the performance as a product of the formed coiled spring during tensile, torsional and bending deformation by the FEM and experiment. In the FEM, the mechanical properties of coiled spring after coiling and upset forging was determined by the conversion as shown in Fig. 10. As the equivalent strain $\varepsilon_{\mathrm{p}}'$ is accumulated during coiling and upset forging, the material should accordingly be work hardened. Therefore, the offset diagram (b) was adopted for the coiled spring.

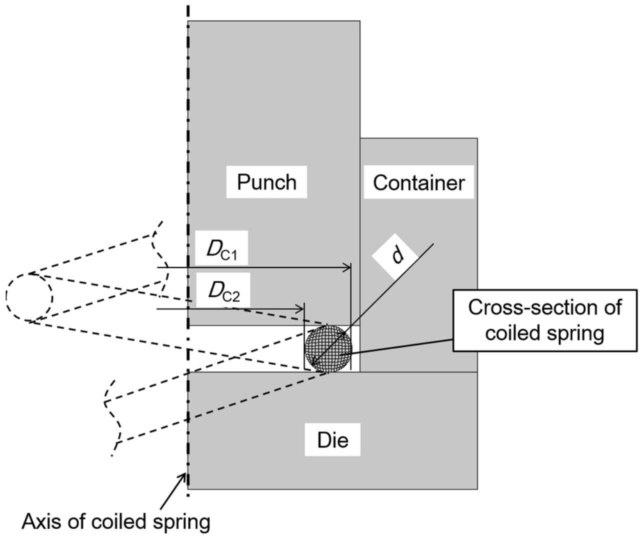

Fig. 8 The FEM simulation model of upset forging process

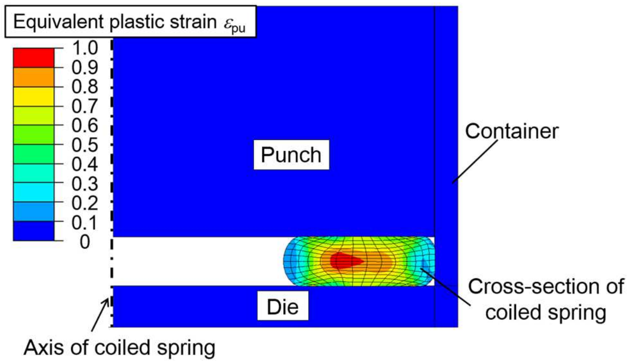

Fig. 9 Work hardening estimation in cross-section in terms of equivalent plastic strain by the FEM (Stroke S_1 = 3mm)

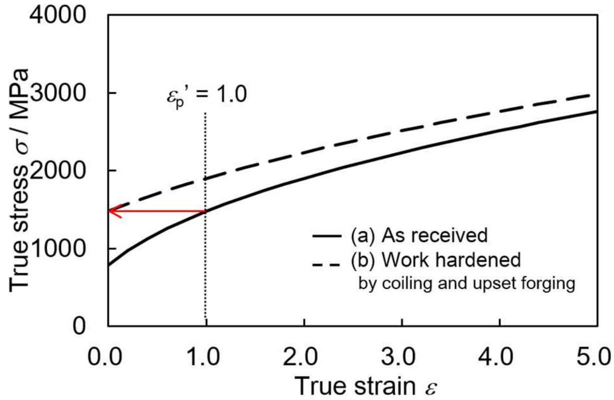

Fig. 10 Conversion of work hardening curve

4. Characterization of the coiled spring

4.1. Characteristic test

The formed coiled spring is required to be easy to bend and strong to twist assuming it is used as a joint of a manipulator. Thus, the property of formed coiled spring was evaluated by the FEM and experiment, and compared with coiled springs which are fabricated in conventional methods. Three types of coiled springs were compared and the detailed conditions are shown in Table 2. Case 1 evaluated a “circular coiled spring”, which is easily found in the market. Case 2 was conducted for a “rectangular coiled spring” without work hardening, assuming a spring which was fabricated by machining. Case 3 was for a “rectangular coiled spring” with work hardening, assuming a coiled spring which was fabricated by the proposed method, i.e. upset forging after coiling. Winding number of coiled spring is 3 in the FEM, and 9 in the experiment.

Tensile, torsional and bending tests of coiled springs were conducted. Schematics of the tests are shown in Fig. 11, Fig. 12 and Fig. 13. In the FEM, while constraint was given to the bottom end of the coil, displacement was given to the upper end. In the experiment, while hoops at the bottom end were embedded into the lower jig, displacement was given to the top end. In the experimental tensile test, the load was measured by a load cell. In the experimental torsional test, the torque was measured by cross-type strain, which was attached on the upper jig surface. In the experimental bending test, the bending moment was given by a weight via string which was attached to the top end of the spring, and the radius of bent spring was measured using photo images.

Table 2 Type of the coiled spring evaluated by the FEM and experiment

	Cross-section	Material state	Examination method	Fabrication method
Case 1	Circle	As received	FEM, Experiment	Ordinary coiled spring available on market
Case 2	Rectangle	As received	FEM	Coiled spring fabricated by machining
Case 3	Rectangle	Work hardened	FEM, Experiment	Coiled spring formed by the proposed method

(Winding number : 3 in FEM and 9 in experiment)

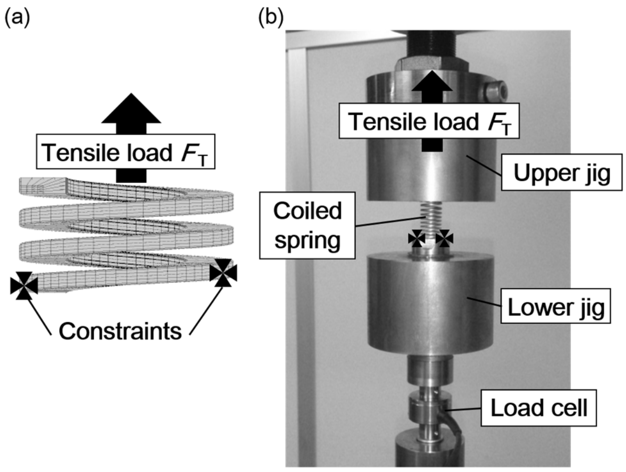

Fig. 11 Tensile test of the coiled spring

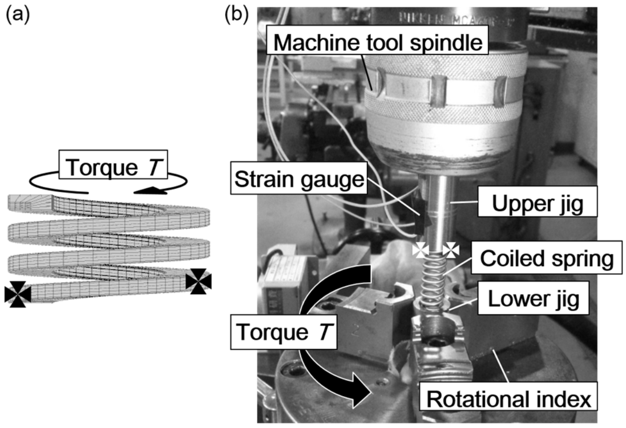

Fig. 12 Torsional test of the coiled spring

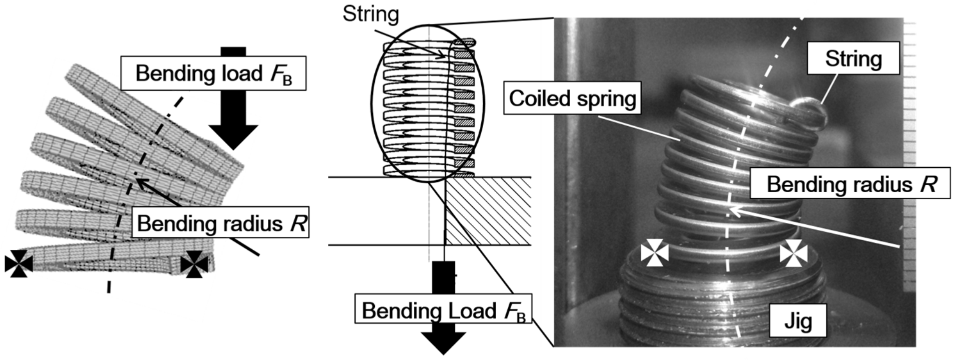

Fig. 13 Bending test of the coiled spring

4.2. *Tensile characteristics*

Theoretical value was compared with the FEM and experiment in tensile test. The spring constants of "circular coiled spring" k_C and "rectangular coiled spring" k_R are expressed by

$$k_C = \frac{Gd^4}{n(D_{C1}+D_{C2})^3} \quad \text{(for "circular coiled spring")}, \qquad (4)$$

and

$$k_R = \frac{8Gb^2t^2}{n\gamma(D_{R1}+D_{R2})^3} \quad \text{(for "rectangular coiled spring")}, \qquad (5)$$

where, G is shear modulus of rigidity and γ is constant by the cross-sectional shape [11]. The spring constant is slope of load-displacement diagram of the coiled spring. The steeper the slope, the higher the spring constants k_C and k_R are, and the higher the rigidity of the coiled spring on tensile/compressive load is.

The results in the FEM, experiment are shown in Fig. 14 by comparing with theoretical value from formulas (4) and (5). Displacement was divided by winding number n in order to evaluate displacement for each hoop.

Fig. 14(a) shows result of Case 1 and Case 3, comparing the effect of winding wire cross-sectional shape. There were differences between the FEM and experimental results. This would be attributed to slip between the wire and jig. The spring constant of Case 1 was 121.3N/mm, and that of Case 3 was 89.1N/mm in the FEM result. The spring constant of "rectangular coiled spring" was lower than that of "circular coiled spring" in both the FEM and experiment.

Fig. 14(b) shows result of Case 2 and Case 3, comparing the effect of work hardening. Elastic range of Case 3 was larger than that of Case 2 in the FEM result. This was attributed to the improvement of elastic limit of the coiled spring which was work hardened by upset forging process. Improvement of elastic limit means that the coiled spring is tolerable under strong load and can use as machine parts safely.

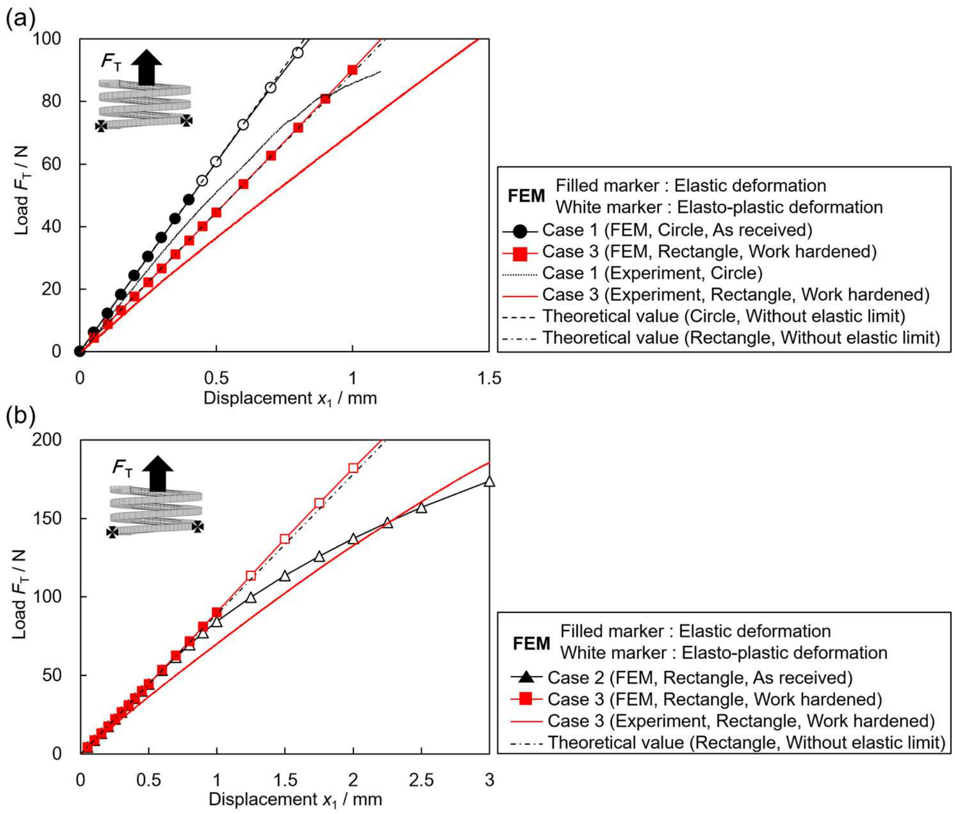

Fig. 14 Load-displacement diagrams: (a) Effect of shapes; (b) Effect of work hardening

4.3. *Torsional characteristic*

Theoretical value was compared with the FEM and experiment in torsional test. The torsional spring constants of "circular coiled spring" k_{TC} and "rectangular coiled spring" k_{TR} are expressed by

$$k_{TC} = \frac{Ed^4}{32n(D_{C1} + D_{C2})} \quad \text{(for "circular coiled spring")}, \tag{6}$$

and

$$k_{TR} = \frac{Ebt^3}{6\pi n(D_{R1} + D_{R2})} \quad \text{(for "rectangular coiled spring") [11].} \tag{7}$$

The torsional spring constant is the slope of torque-angular displacement diagram of the coiled spring. The steeper the slope, the higher torsional spring constants k_{TC} and k_{TR} are and the higher the rigidity of coiled spring on torsional load is.

The results in the FEM, experiment are shown in Fig. 15 by comparing with theoretical value from formulas (6) and (7). Angular displacement was divided by winding number n in order to evaluate angular displacement for each hoop.

Fig. 15(a) shows the result of Case 1 and Case 3, comparing the effect of winding wire cross-sectional shape. There were differences between the FEM, experimental results and theoretical value. This would be attributed to the condition of constraint. While both sides of the coiled spring were constrained in the radial direction of the spring in the FEM and experiment, the coiled spring is assumed to be able to move in the radial direction of the spring in theoretical value.

The torsional spring constant of Case 1 was 0.20N・m/°, and that of Case 3 was 0.29N・m/° in the FEM result. The torsional spring constant of "rectangular coiled spring" was higher than that of "circular coiled spring". Thus, the rigidity of the coiled spring on torsional load was successfully improved by changing the circular shape of the winding wire into rectangle.

Fig. 15(b) shows the result of Case 2 and Case 3, comparing the effect of work hardening. Elastic range of Case 3 was larger than that of Case 2 in the FEM. Elastic limit of the coiled spring on torsional load was improved by the upset forging process as well as tensile characteristic. The formed coiled spring can be also used for the strong torsional load safely. Therefore, the proposed method, upset forging after coiling, successfully improve rigidity and elastic limit on torsional deformation, which is an important characteristic required for the joint of the forceps manipulator.

4.4. *Bending characteristic*

The FEM and experimental results in bending test are shown in Fig. 16. Fig. 16(a) shows the result of Case 1 and Case 3, comparing the effect of winding wire cross-sectional shape. Bending load of "rectangular coiled spring" is lower than that of "circular coiled spring". This means that the formed coiled spring is easy to bend.

Fig. 16(b) shows the result of Case 2 and Case 3, comparing the effect of work hardening. Elastic range of Case 3 was larger than that of Case 2 in the FEM. Elastic limit of the coiled spring on bending load was also improved by upset forging process as well as other characteristics. The coiled spring of Case 3 does not plastic deform even if bent to smaller radius *R* down to 17mm. Therefore, the proposed method, upset forging after coiling, successfully improve bendability and elastic limit on bending deformation, which is another important characteristic required for the joint of the forceps manipulator.

When the coiled spring, which is fabricated by the present method, is applied as joints of forceps manipulator, it would alleviate the burden on patients and improve the operability of the manipulator. As the coiled spring can be bent down to a small radius, the space for operation inside human abdomen should be reduced. As the coiled spring can be bent without plastic deformation, the linearity on the manipulator behavior should be drastically improved and hysteresis phenomena could be eliminated.

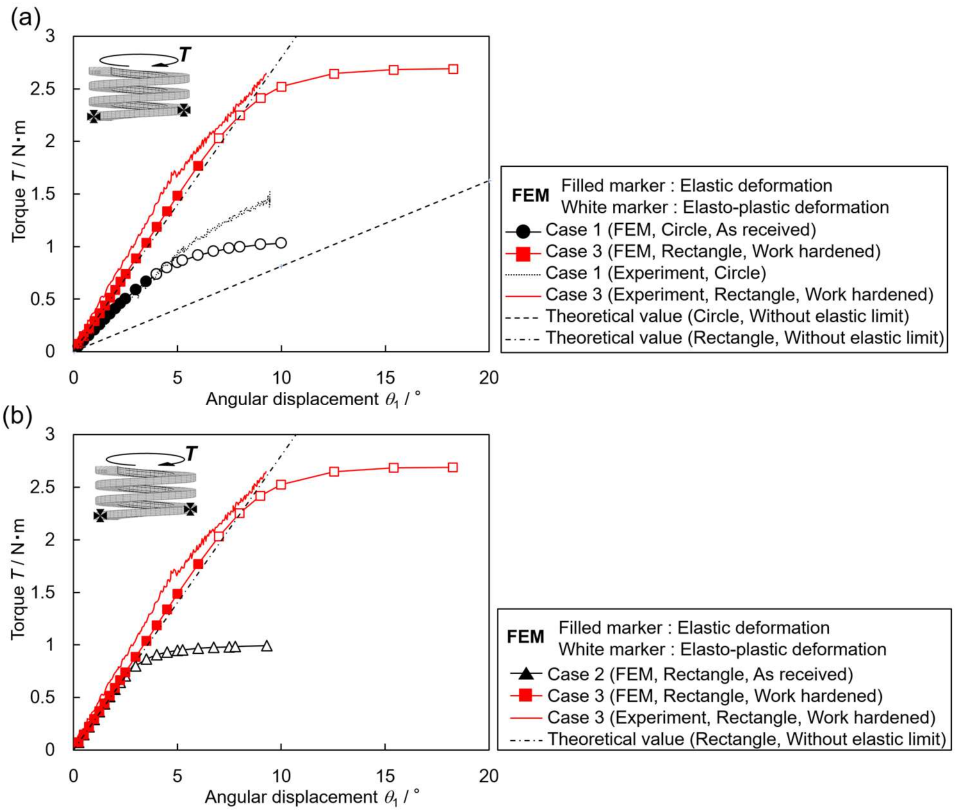

Fig. 15 Torque-angular displacement diagrams: (a) Effect of cross-sectional shapes; (b) Effect of work hardening

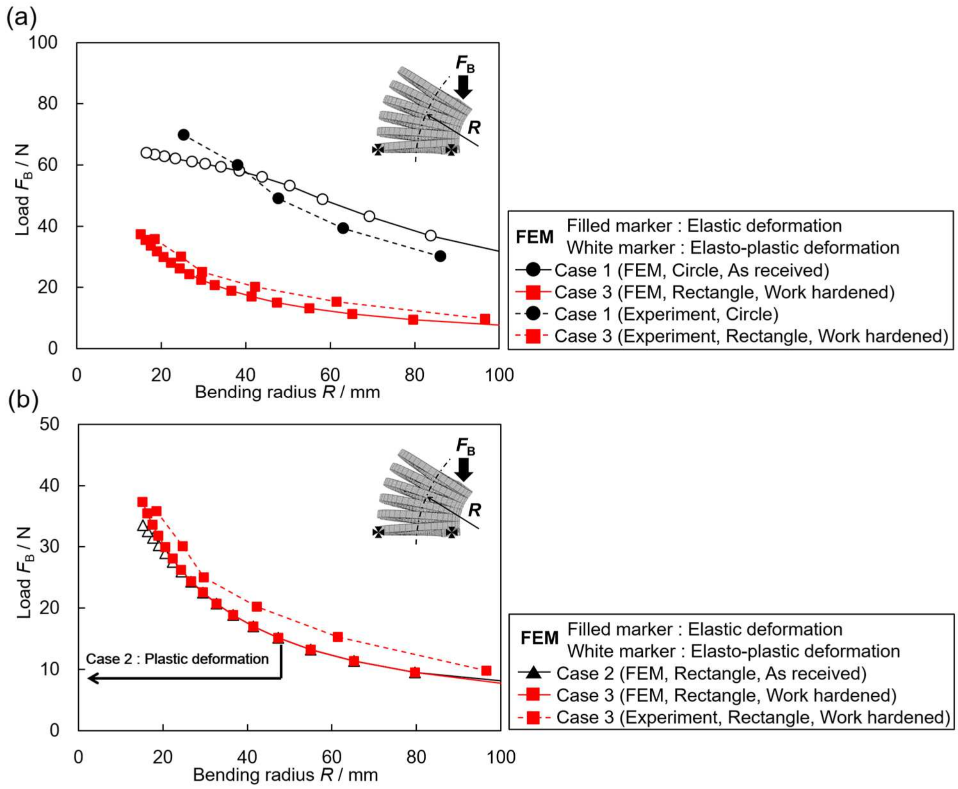

Fig. 16 Load-bending radius diagrams: (a) Effect of cross-sectional shapes; (b) Effect of work hardening

5. Conclusion

This paper proposed a new forming method for fabrication of coiled springs with high rectangular ratio in the winding wire cross-section, which are assumed to apply as joint parts of surgical forceps manipulators. The coiled spring was formed by the proposal method and compared with coiled springs fabricated conventional methods by the FEM and experiment. Obtained results are summarized as follows.

- The proposed method, upset forging after coiling, can successfully fabricate coiled springs, of which the rectangular ratio is 3 in the winding wire cross section, and the spring diameter is just 4.2 times of the wire breadth. In upset forging process, the coiled spring with circular shape in winding wire cross-section, is compressed in the coil axial direction. This shape of coiled spring was difficult to obtain in conventional technologies of plasticity and was manufactured by only machining. The proposed method would drastically drive down process cost.
- In the formed "rectangular coiled spring", bendability and torsional rigidity improved than general "circular coiled spring". The formed coiled spring was "easy to bend and rigid to twist".
- Elastic limit of the formed coiled spring on tensile, torsional and bending characteristics in each case was improved by the effect of work hardening. This means that the formed coiled spring is superior on durability and linearity, and can

be used safely as a joint part of forceps manipulator

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References

[1] Ibe Y (2009) Robot to Manufacture Car. Journal of the Robotics Society of Japan 27(1): 10–11.

[2] Tasoda T (2015) Introduction of Welding Processes and Skills Transfer for Fabrication of Large Marine Diesel Engines. Marine Engineering 50(5): 27-32.

[3] Kamegawa T et al. (2007) Development of a Remote-controlled Double Headed Snake-like Rescue Robot KOHGA. Journal of the Robotics Society of Japan 25(7): 1074–1081.

[4] Robine R et al. (2003) Rescue Robots at the WTC. Journal of the Japan Society of Mechanical Engineers 106: 794-802.

[5] Ito K et al. (2009) Development of Snake-Like Rescue Robot Designed for Ease of Use –Successfully Combine Mobility with Operability-. Journal of the Robotics Society of Japan 27(4): 51-58.

[6] Toyoda K et al. (2011) Development of Master-Slave Surgical Robot System with Heartbeat Synchronization Mechanism (Evaluation of Position Synchronization Performance and Synchronization Suture Operability). Journal of the Japan Society of Mechanical Engineers 778(77): 195-207.

[7] Ishii C et al. (2010) Double-Screw-Drive Mechanism Incorporated Multi-DOF Robotic Forceps Manipulator for Minimally Invasive Surgery. Journal of the Japan Society of Mechanical Engineers 771(76): 296-304.

[8] Tadano K et al. (2009) Development of pneumatically driven forceps manipulator with force display. Journal of the Robotics Society of Japan 27(5): 538–545.

[9] Haraguchi D et al. Development of pneumatically-driven forceps manipulator using flexible joint. Dynamics and Design Conference 2011(12): 47–51.

[10] Nakada T (1978) Observation about rolling of ribbon-shaped aluminum materials. Journal of the Japan Society for Precision Engineering 9(44): 100-106.

[11] Japan Society of Spring Engineers (2008) Maruzen Company Limited, Japan, 182-183.