CIRP Annals - Manufacturing Technology 66 (2017) 277–280

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Upset of bent wire/tube for fabrication of in-plane bent sheet metals with extremely large breadth and small bending radius

Takashi Kuboki (2)*, Tsuyoshi Muraoka, Tsubasa Tsubouchi, Shohei Kajikawa

The University of Electro-Communications, 1-5-1 Chofu Gaoka, Chofu-shi, Tokyo, Japan

ARTICLE INFO

Keywords:
Metal forming
Cold forming
In-plane bending

ABSTRACT

This paper presents a new method for fabrication of a ring/coil of in-plane bent sheet metal using a wire/tube as a raw material. The method conducts upset of a wire/tube bent by a coiling process. The coiling process bends a circular wire/tube into a ring/coil, and the upset process compresses it into a ring/coil with extremely flattened cross-section and small bending radius, which was difficult to obtain by conventional processes. The breadth-to-thickness ratio reached 6.0 and the outer radius-to-breadth ratio decreased to 1.7. When the method is applied for coils, the fabricated coils would be used as joints in a surgical manipulator.

1. Introduction

The development of in-plane bending processes of sheet metals has been receiving attention from many researchers and engineers. One of the reasons is the usefulness of the bent metals, and another reason is that it is difficult and challenging to fabricate in-plane bent metals. The bent rings with a single layer of hoop are used as sealing parts and sliding members in machines. The rings would also be used as parts in micro-machines and so on. Coils with multilayers of hoops are used as shock absorbers and joints in automobiles and other machines.

It is challenging to manufacture rings and coils which are bent in an in-plane manner as the metals have high flexural strength in the plane. A coiling process, which winds a sheet metal around bending dies, is practically realized to manufacture copper coils for motors and dynamos. However, it is applied only to ductile metals. Yamada et al. developed another bending process, which utilizes wedge rolling and bends a sheet metal by thinning the extrados side [1]. Jin et al. also developed an incremental bending process using a tilted punch for giving thickness distribution to the metals for in-plane bending [2]. Kuboki et al. furthermore expanded the function by enabling the punch with a trapezoid beating face to be tiltable so that the process could be applied to thin foils [3]. However, all those previous processes inevitably give thickness distribution, and the extrados side of the bent metals becomes thinner than the intrados side. Li et al. developed equal-thickness in-plane ring roll-bending using twin conical rolls [4]. However, stability might still be open to question as friction plays an important role for the bending phenomenon, and the applicability would be limited in terms of breadth-to-thickness ratio and radius-to-breadth ratio.

* Corresponding author.
E-mail address: kuboki@mce.uec.ac.jp (T. Kuboki).

http://dx.doi.org/10.1016/j.cirp.2017.04.120

This paper presents a new method for fabrication of a ring and a coil of in-plane bent sheet metal using a wire/tube as the raw material. The method conducts upset of a wire/tube bent by a coiling process. The coiling process bends a circular wire into a ring or a coil, and the upset process compresses it into a ring or coil with an extremely flattened cross-section and small bending radius with keeping the thickness homogeneity, which was difficult to obtain by conventional processes. Experimental and numerical verification is made for both the ring and the coil, using experimental set-ups and the finite element method.

2. Combination of coiling and upset

2.1. Coiling and upset processes

The new method for bending sheet metals in an in-plane manner is shown in Figs. 1 and 2. The process is composed of coiling and upset processes. The coiling process flexibly bends a wire/tube into a ring or coil using a coiling tool and a guide. A pair of feed rolls push the wire through the guide against the wall of the coiling tool. The force from the wall raises the moment on the wire

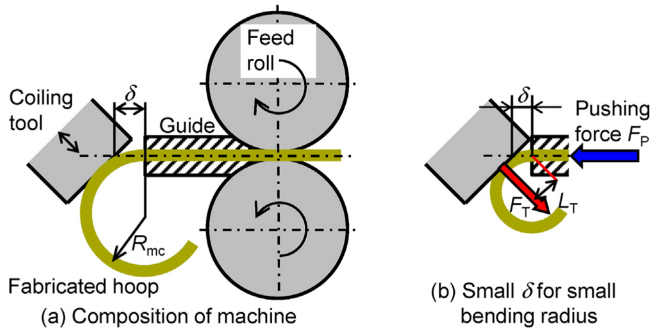

Fig. 1. Coiling as 1st process in process combination.

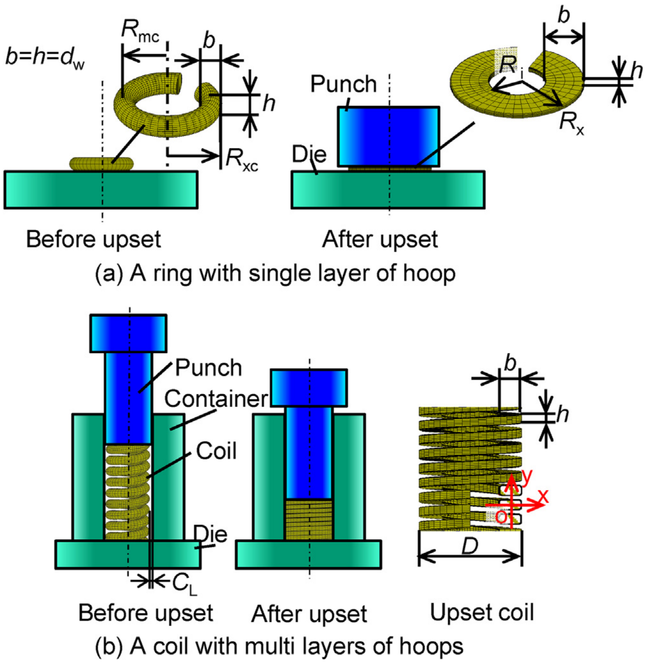

Fig. 2. Upset as 2nd process in process combination.

at the guide exit, and then the wire is bent. The coiling radius R_{mc} is easily and flexibly controlled by setting the coiling-tool position δ, which is the distance between the coiling tool and the guide exit. The situation for small δ is depicted in Fig. 1(b).

The upset process decreases the height h and increases the breadth b and then realizes in-plane bending with very high breadth-to-height ratio b/h, and very low radius-to-breadth ratio R_x/b as shown in Fig. 2. The upset process is applied for both a ring with a single layer of hoop and a coil with multilayers of hoops. A container should be used in the case of a coil upset for prevention of misalignment of the hoops. Both wire and tube would be used as the raw material, and the shape difference between them affects the deformed ring and coil. The detailed results will be discussed in the later part of this paper.

Conventional coiling processes cannot bend a wire in a stable manner when the bending radius R_x is smaller than a certain limit. When the wire is required to be bent at a small radius, the coiling-tool position δ should be small as shown in Fig. 1(b), and the distance L_T becomes small, resulting in drastic increase of force F_T and F_P as a sufficient moment should be generated. The forces F_T and F_P might exceed the machine capacity, depending on the motor and the rigidity of tools. Moreover, the small R_x would cause a geometric interference between the coiling tool and the guide. Therefore, a wire/tube cannot be bent under a certain limit.

Conventional coiling processes can also bend a wire with a rectangle cross-section. However, the bendable limit of the coiling radius increases with the increase of breadth-to-height ratio b/h, due to increase of the bending moment, difficulty of gripping the material by the feed rolls, occurrence of twist, wrinkle at the bending intrados or fracture at the extrados and so on.

The excellence of the proposed method is conceptually explained in Fig. 3. The bendable limit for the 1st process of coiling is expressed in terms of radius-to-breadth ratio R_x/b and breadth-to-height ratio b/h. The wire can be bent at the bendable area above the bendable limit curve. The bendable limit curve is qualitatively expressed because the limit changes depending on the machine capacity and the rigidity, and the properties of the wire. The limit of bendable radius ratio R_x/b increases with the increase of b/h as explained in the previous paragraph. The wire with a circular cross-section can be bent by coiling on the bendable limit line as denoted by [a], or above the line as denoted by [b].

The 2nd process of coiling easily overcomes the forming limit as [a] to [A] and [b] to [B]. The upset coils [A] and [B] should have the characteristics of small radius ratio R_x/b and large breadth-to-height ratio b/h at the same time outside the bendable area in coiling. The proposed method is also applicable to wires with a rectangle cross-section. The 1st process of coiling bends the wire to the shape on the bendable limit as [c]. The 2nd process of upset deforms the wire from [c] to [C] outside the bendable area. Although the coiling causes thickening at the bending intrados and thinning at the extrados, the upset equalizes the thicknesses.

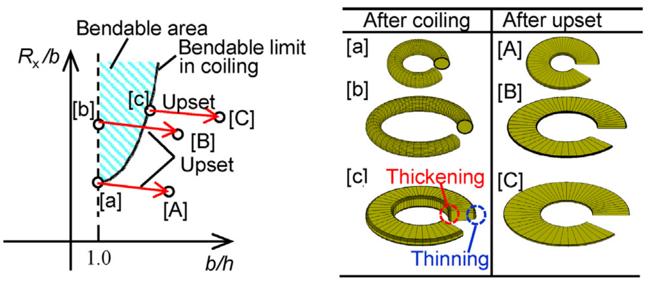

Fig. 3. Expansion of forming limit by upset after coiling.

2.2. Available shapes

Available shapes fabricated by the proposed method and possible products are shown in Fig. 4. In addition to C-shape rings, S-shape metal would be fabricated by improving the positioning mechanism of the coiling tool for bending the wire in two ways. Swirl shapes are also available by increasing the coiling-tool position δ in Fig. 1 during the coiling process. Coils with flattened hoop-cross-section would be applicable as the joints in a surgical manipulator which was developed by Kawashima et al. and is expected to be used for laparoscopic surgery [5].

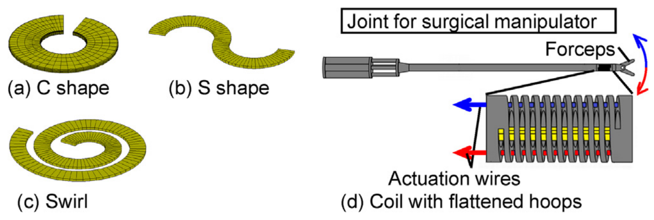

Fig. 4. Available shapes.

3. Numerical and experimental verifications

3.1. Coiling and upset conditions

Experimental verification for the proposed method was conducted by a prototype coiling machine and a hydraulic universal test machine using upsetting tools. Elastic-plastic analysis by the finite element method (FEM) was also carried out for the upset process, using the commercial code ELFEN. A von Mises' yield criterion was adopted, and the normality principle was

Table 1
Working condition.

Wire/tube	Material	Aluminium A1050
	Flow stress Approximated from a curve obtained by tension test up to strain = 0.05 when uniform elongation appeared	$\sigma = 110\ (\varepsilon_p + 0.00077)^{0.05}$ σ: true stress, ε_p: plastic strain
	Diameter d_w/mm	2.0
	Thickness t/mm	0.5 (tube)
Coiling	Outer coiling radius R_{xc}/mm	5–22 (ring) 5 (coil)
	Number of hoops	1 (ring), 10 (coil)
Upset	Upset ratio $S_r = (d_w - h)/d_w$	0–0.8
Operation	Lubrication (experiment)	Without lubricant
	Friction coefficient μ (FEM)	0.1
Others	Size of elements in FEM (mm)	0.25–0.5 (wire radial) Around 0.4 (wire hoop) 0.44–1.23 (wire axial)