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Incremental rolling forming process to fabricate surface micro-grooves

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Abstract. The fabrication of functional micro-structures at sheet surface has a wide range of applications in noise reduction, friction reduction, heat and mass transfer, etc. By integrating the conventional rolling forming and the incremental sheet forming process, a flexible and widely applicable incremental rolling forming process was proposed in the present work to fabricate surface micro-grooves. First, a rolling tool which has hemispherical ring convex on the roller and the convex height is much higher than the height of forming groove was designed and manufactured. Then, a series of incremental rolling tests on titanium alloy (TA1) were carried out by using self-designed rolling tools, with varying roller size, rolling depth and feed rate. The results show that continuous micro-grooves with good dimensional consistency were prepared on the surface of the plate. Furthermore, by investigating rolling force and groove size after rolling, it was found that the rolling depth have significant effects on the micro-groove formation and only localized material flow is occurred at the grooved region. Compared with the traditional rolling process, the incremental rolling process has the advantages of low rolling force and adjustable groove spacing, which is conducive to the subsequent processing of the sheet.
Keywords. Incremental sheet forming, Incremental rolling forming, surface micro-grooves

1. Introduction

There is a growing demand for equipment with large-area functional surface microstructures in many areas such as aerospace and marine equipment, pipeline transport and surface antifouling. A typical surface functional microstructure is the so-called plate surface microgroove, which has special functions such as drag and noise reduction, superhydrophobicity and wear resistance.

One way of achieving cost effective production of large-area functional surface microstructures is the roll forming process. The roll forming process consists of two main types, a roll-to-roll (R2R) forming process and a roll-to-plate (R2P) forming process [1].

As a new process of microstructure forming, roll forming technology has the advantages of low production cost and high efficiency, and can realize the preparation of large area of microstructure surface. At present, scholars at home and abroad have made more researches on roll forming technology. Hirt and Thome [2] proposed a new process for the preparation of microstructures on wire-wound rolls, which successfully produced large-area riblet structures on the surfaces of Al99.5. Cao et al. [3] developed a surface microstructure R2R rolling forming device to form an array of microgrooves on the surface of AA3003 sheets. Zhou et al. [4] used a self-developed desktop surface texturing system to fabricate 5μm, 10μm and 20μm microgrooves on the surface of AA5052 sheets. Lu et al. [5] successfully prepared aluminium-based and copper-based microgrooves using the R2R forming process. Gao et al. [6] developed their own R2P micro/meso-imprinting system and carried out imprinting tests on pure copper parts with different grains. The results showed that the width and grain size had significant effects

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on the formation of micro-grooves. Klocke et al. [7] had successfully fabricated defined riblet structures on Ti-6Al-4V material using a newly developed incremental rolling forming process.
In order to fabricate a continuous array of microgrooves on the surface of TA1, a microgroove rolling forming device combining incremental rolling forming process and R2P forming process was built based on an existing CNC milling machine. The effects of hemispherical ring convex diameter, rolling depth and feed rate on rolling force and microgroove sizes as well as the feasibility of the process were investigated.

2. Experimental setup and design

2.1. Experimental setup

TA1 sheets with a thickness of 1 mm and a size of 160 mm×160 mm were used in the incremental rolling forming process. The composition of the TA1 sheet is given in Table 1. The sheet was fixed on a flat fixture during the rolling forming process.

Table 1. Composition of the TA1 sheet.

Fe	C	O	N	H
0.014%	0.008%	0.033%	0.004%	0.0013%

The forming experiments were carried out on a DAXING-VMC650 vertical machining centre. A rolling forming tool consisting of a column, a bracket and a roller was manufactured (Figure 1 (a)). Figure 1 (b) shows the dimensions of the roller, where *d* represents the diameter of the hemispherical ring convex. Only three hemispherical rings are designed and manufactured in the existing roll forming tool, but more can be designed if needed. The principle of the incremental rolling forming process for the preparation of micro-grooves is shown in Figure 2. As shown in Figure 3, the rolling forming tool is mounted on the spindle of Daxing machine tool, and the fixture and force dynamometer are mounted on the working platform.

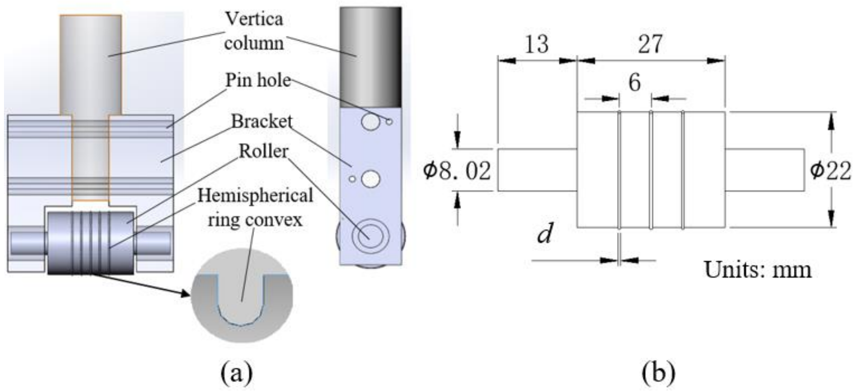

Figure 1. Rolling forming tool (a) Composition (b) Roller dimension.

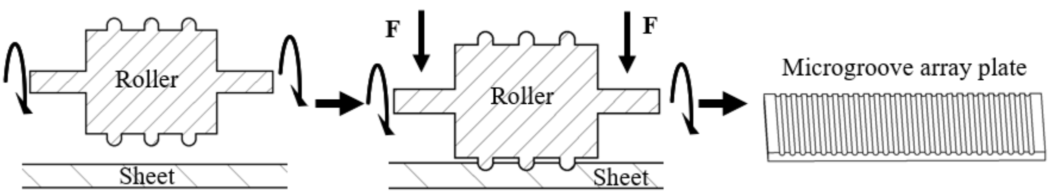

Figure 2. Process schematic.

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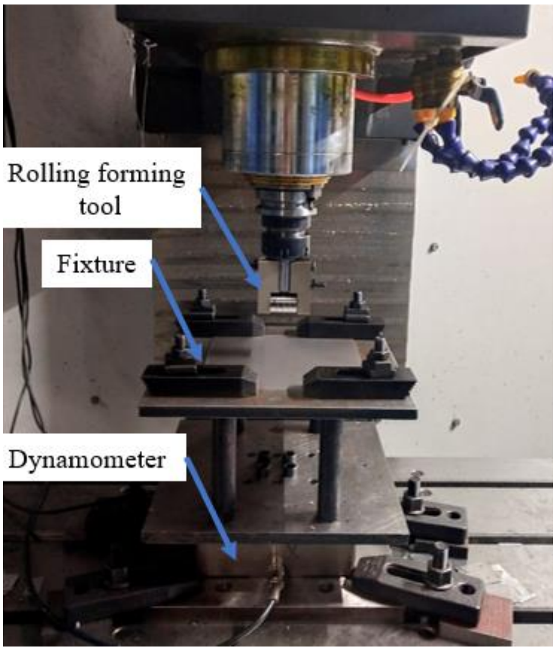

Figure 3. Experimental setup of rolling forming process.

2.2. Experimental design
In order to investigate the effects of hemispherical ring convex diameter, rolling depth and feed rate on rolling force and microgroove sizes in the incremental rolling forming process, nine sets of single-factor experiment were designed. The experiment setup shown in Table 2. d, r_d and f were used to represent the hemispherical ring convex diameter, rolling depth and feed rate, respectively. In the experiment, the centre distance between two adjacent microgrooves is 1mm.

Table 2. Incremental rolling forming experimental parameters.

No.	d (mm)	r_d (mm)	f (mm/min)
G1	0.3	0.15	600
G2	0.4	0.15	600
G3	0.5	0.15	600
G4	0.4	0.1	600
G5	0.4	0.15	600
G6	0.4	0.2	600
G7	0.4	0.15	200
G8	0.4	0.15	600
G9	0.4	0.15	1000

3. Experiment results and discussion

3.1. Effect on groove size
Microgroove sizes (including forming depth and forming width) on the sheet surface were measured using a Wyko NT9300 white light interferometer to evaluate the effect of hemispherical ring convex diameter, rolling depth and feed rate on microgroove sizes. Figure 4 shows a microgroove sheet prepared by the incremental rolling forming process and a typical microgroove profile. The spike on the left side

of the microgroove is due to a deviation in the turning of the hemispherical ring convex on the rolling forming tool, which also indicates that only local material flow occurs in the groove area.

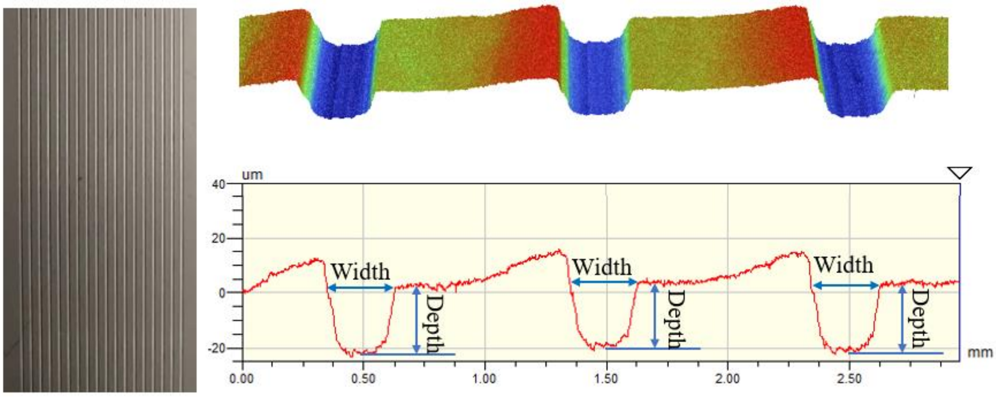

Figure 4. Microgroove plate and scanning image, G7: d=0.4mm, r_d=0.15mm, f=200mm/min.

The results of the effects of hemispherical ring convex diameter, rolling depth and feed rate on the microgroove forming depth are shown in Figure 5. From Figure 5 (a), it can be observed that the microgroove forming depth decreases with the increase of hemispherical ring convex diameter, but not to a great extent. It can be observed from Figure 5 (b) that the microgroove forming depth increases continuously with the increase of rolling depth, but the relative increment of forming depth decreases with the increase of rolling depth. When the rolling depth increases from 0.10mm to 0.15mm, the forming depth increases from 7.4μm to 19.3μm, with a relative increment of 161%. When the rolling depth increases from 0.15mm to 0.20mm, the forming depth increases from 19.3μm to 27.8μm, with a relative increment of only 44%. As can be observed from Figure 5 (c), the microgroove forming depth first increases and then decreases as the feed rate increases. In addition, the forming depth of the microgroove does not reach the rolling depth due to the backflow and springback of the material as well as the machining and assembly errors that exist at the internal and external joints of the roll forming tool during the incremental rolling process being compressed.

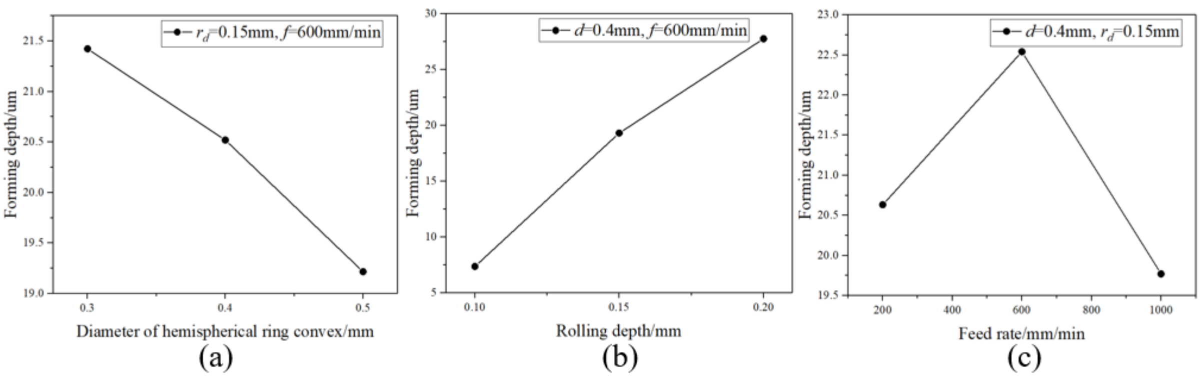

Figure 5. Effect on forming depth (a) Hemispherical ring convex diameter (b) Rolling depth (c) Feed rate.

The results of the effects of hemispherical ring convex diameter, rolling depth and feed rate on the microgroove forming width are shown in Figure 6. As can be observed in Figure 6 (a), the microgroove forming width increases with the increase of the diameter of the hemispherical ring convex. This is because the larger the diameter of the hemispherical ring convex, the wider the rectangle formed by the contact between the convex and the upper surface of the sheet, when the microgroove forming depth remains the same. As can be observed in Figure 6 (b), the width of the microgroove increases as the rolling depth increases. This is because the larger the rolling depth, the wider the rectangle formed by the upper surface of the sheet in contact with the convex, when the diameter of the hemispherical ring convex is kept constant. It can be observed from Figure 6 (c) that the microgroove forming width increases and then decreases as the feed rate increases, which is consistent with the variation pattern of microgroove depth shown in Figure 5 (c).

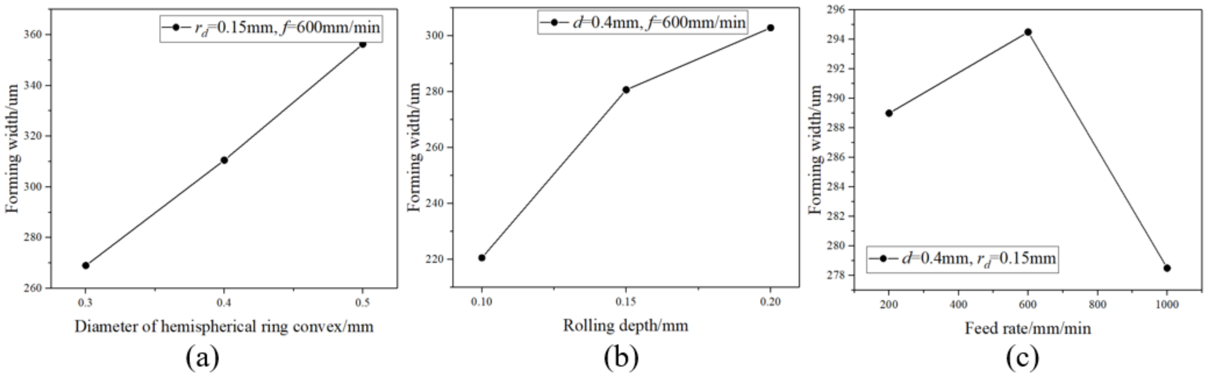

Figure 6. Effect on forming width (a) Hemispherical ring convex diameter (b) Rolling depth (c) Feed rate.

Based on these results, a larger hemispherical ring convex diameter causes greater material springback for the same rolling depth. Increasing the rolling depth significantly increases the forming depth of the microgroove, but this effect decreases with increasing rolling depth.

3.2. Effect on rolling force

Figure **7** shows the effect of different experimental parameters on the rolling force in the incremental rolling forming process. As can be seen in Figure 7 (a), the rolling force increases with the increase of the diameter of the hemispherical ring convex. When the rolling depth is the same, the contact area between the forming tool and the sheet increases with the increase in the diameter of the hemispherical ring convex, which in turn leads to more material deformation during incremental rolling forming, and ultimately to an increase in the rolling force. As can be seen in Figure 7 (b), as the rolling depth increases, so does the rolling force. From Figure 7 (c), it can be seen that the maximum rolling force increases as the feed rate increases, but the increase is not significant. At the same time, the average rolling force of G8 is greater than that of G7 and G9 in the relatively stable stage of rolling. The higher the rolling force, the larger the microgroove forming depth, when the sheet material, rolling depth and hemispherical ring convex diameter are the same, which can be reflected in Figure 5 (c).

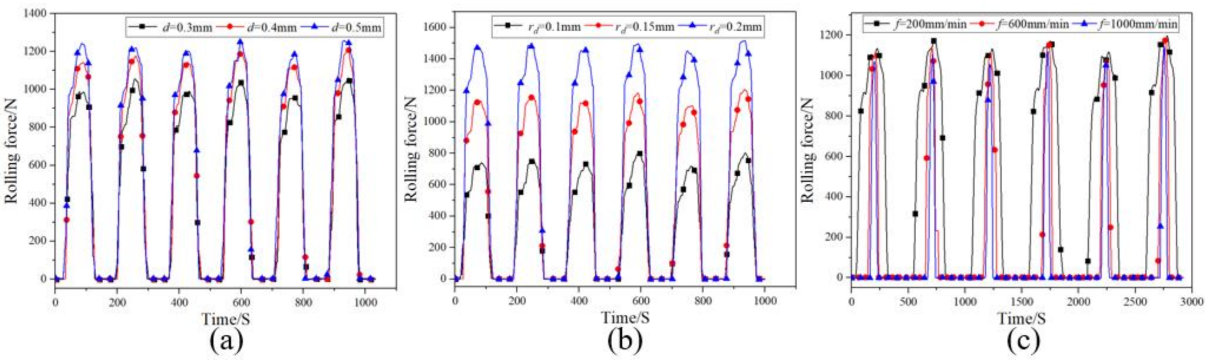

Figure 7. Effect on rolling force (a) Hemispherical ring convex diameter (b) Rolling depth (c) Feed rate.

4. Conclusions

In this paper, the effects of the hemispherical ring convex diameter, rolling depth and feed rate on rolling force and groove sizes in the incremental rolling forming process are experimentally investigated. The main conclusions are as follows:

(1) Only local material flow is occurred in the groove area during the surface rolling process.
(2) The rolling depth has a more significant effect on groove size, while rolling force increases with increasing hemispherical ring convex diameter and rolling depth.
(3) The feasibility of the incremental rolling forming process in the batch manufacture of metal parts with large-area functional surface microgrooves is verified.

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