Research on the influence of end effect on forming result of saddle curved part in flexible rolling process

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Abstract—Flexible rolling is suitable to manufacture small batch of 3D curvature parts with various shapes. In this paper, the influence of end effect on saddle curved part was studied firstly. The finite element model was designed based on the flexible rolling forming apparatus. The areas characteristics of forming saddle curved part were analysed, and the influence of end effect on the saddle curved part with different forming size was studied. The results demonstrate that: the forming saddle curved part consists of three forming areas by characteristics, and the forming mechanism of each forming area is analyzed deeply; under the end effect action, with the sheet length increases, the plastic strain and minimum forming thickness of forming curved part are stable; when the sheet length is 200mm, 300mm, 400mm and 500mm, the percent of the stable forming area of forming curved part is 52%, 72%, 79% and 83% respectively, and the percent of stable forming area increases by 20%, 27%, 31% respectively, therefore the utilization rate is obviously improved. With the increasing sheet width, the plastic strain is increasing and the minimum forming thickness is decreased; when the sheet width is 85mm, 90mm, 95 mm and 100mm, the percent of stable forming area of forming curved part is 67%, 61%, 59%, 58% respectively, and the percent of stable forming area decreases by 6%, 8%, 9% respectively, therefore the utilization rate is decreasing.

1. INTRODUCTION

The continuous flexible rolling processes are commonly used for sheet metal forming. The small batch and diversification demands of 3D curved parts increase in the years, traditional forming processes can’t rapidly meet the market demands. In recent years, a continuous contact rolling process was proposed. Sheet metal is bent by the contours of three flexible working rollers [1]. After that, flexible rolling process was developed, which combines rolling process and multi-points principle. Bending deformation of sheet metal is caused by the non-uniform roll gap. As there are only two flexible working rollers, the forming system is easier to control [2,3]. The forming mechanisms of 3D curved parts were studied deeply by Cai [4,5]; the improved technology in flexible rolling process were developed by Li et al [6-9]. At present, the research on flexible rolling process is still in the developing
stage, and there are still many problems to be solved. The influence of end effect on the forming result of saddle curved part is studied firstly. Based on forming apparatus, the finite element model is built, the forming area of saddle curved part is analysed; the influence of end effect on the saddle curved part with different forming size is studied.

2. MATERIAL AND METHODS

In Figure 1, the forming experimental apparatus is presented and the schematic of forming equipment is presented in Figure 2. Two flexible rollers are employed as forming tool; the each flexible roller contour is configured into a smooth and continuous arc. RU and RL are defined as upper and lower flexible roller contour radius in turn, when RU < RL, the thickness of forming curved part increases from the inside to outside, the shape of formed curved part is convex; when RU > RL, the thickness of forming curved part decreases from the inside to outside, the shape of formed curved part is saddle. The forming process is presented in Figure 3. The process consists of three steps: firstly, the roll gap is adjusted into the target distribution; secondly, lower flexible roller is motionless, and when upper flexible roller moves to the specified position, the sheet metal is caught; finally, the sheet metal is continuously fed and formed by the rotating flexible rollers, until the whole process is over. In this paper, 1050 aluminum alloy is used as forming material, as shown in Table 1.

![Figure 1. Continuous flexible rolling experimental apparatus.](image1)

![Figure 2. The forming apparatus schematic.](image2)

![Figure 3. The rolling process of curved surface.](image3)
TABLE 1. 1050 ALUMINUM MATERIAL PROPERTIES

| Material                  | Density (kg m\(^{-3}\)) | Young’s Modulus (MPa) |
|---------------------------|--------------------------|-----------------------|
| 1050 aluminum alloy       | 2720                     | 76000                 |
| Poisson’s ratio           | Yield stress (MPa)       | Tangent Modulus (MPa) |
| 0.34                      | 145                      | 25                    |

As the uneven roll gap, the sheet metal is thinned unevenly in the transversal, so transversal bending deformation of sheet metal is related to flexible rollers contours. As the length elongation is caused by changed thinning at different transversal point of sheet metal, the elongation with different length interactions with each other, so additional compressive and tensile stress generate, both stresses cause the longitude deformation (Figure 4); based on the forming principle of flexible rolling process, with the longitude elongation difference increases between both sides and center of sheet metal, the longitude bending gets larger, while with the longitude elongation difference decreases, the longitude bending gets less. The 3D curved part is obtained in this process.

![Figure 4. The bending principle of flexible rolling.](image)

3. RESULT

Based on continuous flexible rolling forming apparatus features, the flexible roller must have enough rigid to thin the sheet metal, and can be adjusted into a curve. In the forming process, the flexible rollers should rotate around their geometry middle axis. The rigid short rollers with discrete distribution can be feasible. As presented in Figure 5, each flexible roller set consists of many short rollers, and they can be arranged in a curve, as the discrete distribution, short rolls can rotate around their geometry axis at the same time. All the short rolls are used Rigid-body, sheet metal is used a flexible-body. The contact friction is set between the sheet metal and each forming roller.

![Figure 5. Finite element model.](image)

The finite element models are designed based on experimental experiment. The forming curved parts by experiments are presented in Figure 6. In numerical simulation, the forming curved parts are presented in Figure 7. By comparing Figure 6 and Figure 7, the forming curved parts features are similar, the finite element model feasibility is verified [9].

![Figure 6 and Figure 7.](image)
Figure 6. The formed curved parts by experiment.

Figure 7. The formed curved parts by numerical simulation.

Figure 8 presents the plastic strain distribution in the forming saddle curved parts. Along the transversal direction, the plastic strain distribution continuously change as roll gap uneven distribution; along the longitude direction, the plastic strain is continuously changing gradually near the end areas, when it is far away from the end area, the plastic strain trend keeps stable. By plastic deformation, the forming saddle curved part consists of three areas in the longitude direction; these areas are named the front transition forming area (FTA), which is in the front of the forming curved part; the back forming transition area (BTA), which is in the back of the forming curved part; the stable forming area (SFA), which is between the FTA and BTA. The stable forming area is used as effective area.

Figure 9 presents the plastic strain nephograms with different longitude length. Along the transverse direction, the plastic strain doesn’t present an obvious changing trend. Figure 10 presents the plastic strain curves. The maximum plastic strain of formed curved parts with different longitude length are 0.33, the minimum plastic strain are 0.02. As results present that: the plastic deformation of forming saddle curved part keeps stable with the sheet length increases.
Figure 9. The plastic strain distributions of saddle curved parts with different sheet length (a) 200mm (b) 300mm (c) 400mm (d) 500mm.

Figure 10. The plastic strain distribution curves with different longitude length.

Figure 11 presents the thickness distribution curves. The thickness is gradual increasing from outside to middle along the transverse direction; while the thickness is gradual increasing in the FTA and gradually turns to be stable in the SFA. With the processing position go deeply, the thickness decreases gradually from the stable state when it is in the BTA. The minimum forming thickness of forming curved part with different longitude length is 1.68mm. It can be seen that the thickness doesn’t change obviously with different longitude length.
Figure 11. The thickness curves with different longitude length.

Figure 12 shows the percent of forming areas in saddle curved parts with different longitude length. When the sheet length is 200mm, 300mm, 400mm and 500mm, the percent of the stable forming area is 52%, 72%, 79% and 83% respectively. As results present that: with the increasing sheet length, the percent of the SFA increases by 20%, 27% and 31% respectively.

Figure 12. The percent of forming area in the saddle curved part with different sheet length.

For the purpose to study the end effect on the saddle curved part with different transversal width, the corresponding finite element models are designed. The forming metal is 1050 aluminum alloy, the
length of sheet metal is 200mm, the thickness is 1.8 mm, and the transversal width is 85mm, 90mm, 95mm, 100mm respectively. The processing parameters are same in the comparing experiments.

Figure 13 presents the plastic strain nephograms with different transversal width. The plastic strain presents an obvious changing trend in the transverse direction. Figure 14 presents the plastic strain curves. When the width of sheet metal is 85mm, the maximum plastic strain is about 0.15; when the width of sheet metal is 100mm, the maximum plastic strain is 0.33. As results present that: the plastic deformation of saddle curved part increases significantly with the increase of sheet width.

Figure 13. The plastic strain distributions of saddle curved parts with different sheet width in flexible rolling process (a) 85mm (b) 90mm (c) 95mm (d) 100mm.

Figure 14. The plastic strain curves with different transversal width.
Figure 15 presents the thickness distribution curves. When the sheet width is 85mm, the minimum forming thickness is about 1.699mm; when the width is 100mm, the minimum forming thickness is about 1.675mm. As results present that: the minimum forming thickness decreases obviously with sheet width increases.

![Thickness Distribution Curves](image1)

Figure 15. The thickness curves with different transversal width.

Figure 16 shows the percent of forming areas in saddle curved parts with different transversal width. When the sheet width is 85mm, 90mm, 95mm and 100mm, the percent of the stable forming area is 67%, 61%, 59%, 58% respectively. As results present that: with the sheet width increases, the percent of SFA decreases by 6%, 8% and 9% respectively.

![Percent of Forming Area](image2)

Figure 16. The percent of forming area in the saddle curved part with different sheet width.
4. DISCUSSION
Under the action of end effect, as near the front end area, changing longitude elongation causes additional stress, but it is not enough to bend production into ideal curvature, therefore the front transition forming area (FTA) is formed. With the process location is gradually far away the front end, plastic deformation is continuously changing, and it gradually changes to keep stable; when the forming area is closed to the back end of production, in the meantime, the flow resistance of forming material is gradually decreasing, it accelerates the material flow to the back end, so it causes the less additional stress, then the additional stress also can’t bend the forming material to the target curvature, and the back transition forming area (BTA) is formed. While far away the both ends, the flow resistance keep balance before and after, the additional stress is enough, the plastic deformation in this area keeps stable, so the stable forming area (SFA) is formed.

With the increasing sheet longitude length, the longitude elongation distribution along the transversal width of sheet metal is unchanged, so the longitude bending deformation is unchanged, the plastic deformation is stable; similarly, the minimum forming thickness is also unchanged; with the longitude length increases, the length of insufficient bending part is unchanged, but the sufficient bending deformation length obviously increases, so the percent of SFA increases.

With the increasing sheet transversal width, the longitude elongation difference between the center and two sides along the transversal width of sheet metal obviously increases, so it makes the longitude bending larger, the plastic deformation also gets larger; as the roll gap distribution characteristics of forming saddle curved part, from center to two sides, the roll gap distance is decreasing, so the forming thickness is decreasing with increasing sheet width; with the transversal width increases, the longitude both end areas are more difficult to bend sufficiently, so the length of FTA and BTA obviously increase, and the percent of SFA decreases.

5. CONCLUSIONS
In this work, the forming area of saddle curved part was analysed; the influence of end effect on the forming result of saddle curved part with different forming size was studied.

1. The results demonstrate that: by longitude plastic deformation, the forming saddle curved part consists of three areas, the front transition forming area and the back transition forming area, which are located in the longitude front and back end in order, and the stable forming area, which is located between FTA and BTA. The plastic deformation and thickness change obviously in the FTA and BTA, while they are stable in the SFA.

2. The comparing results indicate that: with the increase of sheet length, the plastic deformation of saddle curved part keeps stable, and thickness doesn’t change obviously. When the sheet length is 200mm, 300mm, 400mm and 500mm, the percent of stable forming area of forming curved part is 52%, 72%, 79%, 83% respectively, and the percent of the stable forming area increases by 20%, 27%, 31% respectively.

3. As can be seen from results that: with the increase of sheet width, the plastic deformation of saddle curved part increases significantly, and the forming thickness decreases obviously. When the sheet width is 85mm, 90mm, 95mm and 100mm, the percent of the stable forming area of sheet metal is 67%, 61%, 59%, 58% respectively, and the percent of stable forming area decreases by 6%, 8%, 9% respectively.

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