New Materials, Machinery and Vehicle Engineering
J. Xu and J.P. Davim (Eds.)

doi:10.3233/ATDE230152

Radial Envelope Forming Law of Thin Wall Cylinder with Vertical Reinforcements

Yanlei Min[a,b] and Wuhao Zhuang[a,b,1] and Zushen Deng[a,b]
[a] *Hubei Key Laboratory of Advanced Technology of Automotive Components, Wuhan University of Technology, Wuhan, 430070, China*
[b] *School of Automotive Engineering, Wuhan University of Technology, Wuhan, 430070, China*

Abstract. In this paper, the law of radial envelope forming (REF) of thin wall cylinder with vertical reinforcements is studied by finite element numerical simulation. First, a finite element model for REF of thin wall cylinder with vertical reinforcements is established by using Deform-3D software. Then, the evolution and distribution of strain and metal flow velocity during REF of thin wall cylinder with vertical reinforcements are analyzed, and the growth law of vertical reinforcement during this REF is analyzed in detail. The results show that radial compression strain, circumferential tensile strain and axial tensile strain occur in the web. Radial tensile strain, circumferential compressive strain and axial tensile strain occur in the vertical reinforcements. The metal flows mainly in radial direction and circumferential direction during REF of thin wall cylinder with vertical reinforcements. The vertical reinforcements show nonlinear growth, and the middle part of the vertical reinforcement is higher than both ends of the vertical reinforcement.

Keyword. Thin wall cylinder with vertical reinforcements, Radial envelope forming, Forming law, Finite element simulation

1. Introduction

Thin wall cylinder with vertical reinforcements is a cylindrical part with evenly distributed vertical reinforcement on the inner layer, as shown in Fig. 1. Thin wall cylinder with vertical reinforcements is widely used in the manufacture of rocket fuel storage tanks, rocket compartments, aircraft fuselages, space station cabins and other key main bearing parts of aerospace equipment. Its mechanical properties determine the operation performance and service life of aerospace equipment.[1-4] The thin wall cylinder with vertical reinforcements is mainly manufactured by milled, bent and welded composite process, which has the disadvantages of long process, low manufacturing efficiency and low material utilization rate. Moreover, milling cuts off the continuous metal streamline, cannot refine the grain structure, and weakens the mechanical properties of thin wall cylinder with vertical reinforcements.[5-8] Therefore, it is urgent to develop high performance manufacturing technology of thin wall cylinder with vertical reinforcements. REF is an advanced plastic forming manufacturing process with local loading and continuous deformation, which can realize the whole near-net plastic forming of thin wall cylinder with vertical reinforcements. REF not only has small

[1] Wuhao Zhuang; Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan, 430070, China. E-mail address: zhuangwuhao@whut.edu.cn.

forming force and high forming efficiency, but also can refine grain structure and obtain continuous metal streamline, which is conducive to improving mechanical properties of components, and has broad development space in the manufacturing field of thin wall cylinder with vertical reinforcements.[9-11] In this paper, REF of thin wall cylinder with vertical reinforcements was studied, the finite element model of REF of thin wall cylinder with vertical reinforcements was established, the strain and metal flow velocity law of REF of thin wall cylinder with vertical reinforcements was revealed, and the growth law of REF of thin wall cylinder with vertical reinforcements was analyzed.

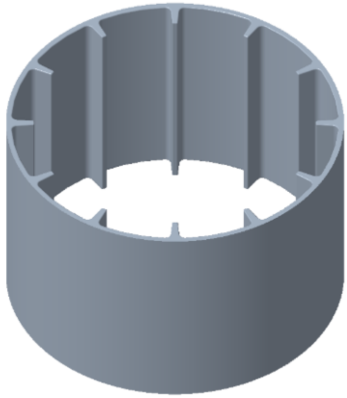

Figure 1. Thin wall cylinder with vertical reinforcements

2. Principle of radial envelope forming of thin wall cylinder with vertical reinforcements

The device of REF of thin wall cylinder with vertical reinforcements is composed of billet, envelope mold and restraining cylinder mold, in which billet is thick-wall cylinder, envelope mold is cylinder with vertical reinforcement cavity, and constraint cylinder mold is cylinder with top and bottom cover plates. As shown in Fig. 2, The restraining cylinder mold rotates itself at ω_1 speed and drives the billet to rotate, and the enveloping mold rotates itself at ω_2 speed and extrudes the billet with a feed motion along the radial direction of the billet at speed v. Under the joint action of envelope mold and restraint cylinder mold, the wall thickness of billet is gradually thinned, and the metal on the wall is forced to flow into the vertical reinforcement cavity of the envelope mold, and the vertical reinforcement structure is gradually formed. In order to ensure the uniform thickness of the wall of thin wall cylinder with vertical reinforcements, the REF of thin wall cylinder with vertical reinforcements enters the finishing stage when the radial feed of the envelope mold reaches the wall thickness of the target thin wall cylinder with vertical reinforcements. At which time the envelope mold is no longer radially fed, but only actively rotates itself at ω_2 speed, and the restraining cylinder mold still actively rotates itself at ω_1 speed. In order to realize the accurate forming REF of vertical reinforcement, the rotational speed ratio between restraint cylinder mold and envelope mold should be equal to the number of vertical reinforcements of envelope mold and the number of vertical reinforcements of thin wall cylinder with vertical reinforcements. Under the multi-pass envelope of the envelope mold, the thickness of the wall of thin wall cylinder gradually tends to be uniform, and finally thin wall cylinder with vertical reinforcements is accurately formed.

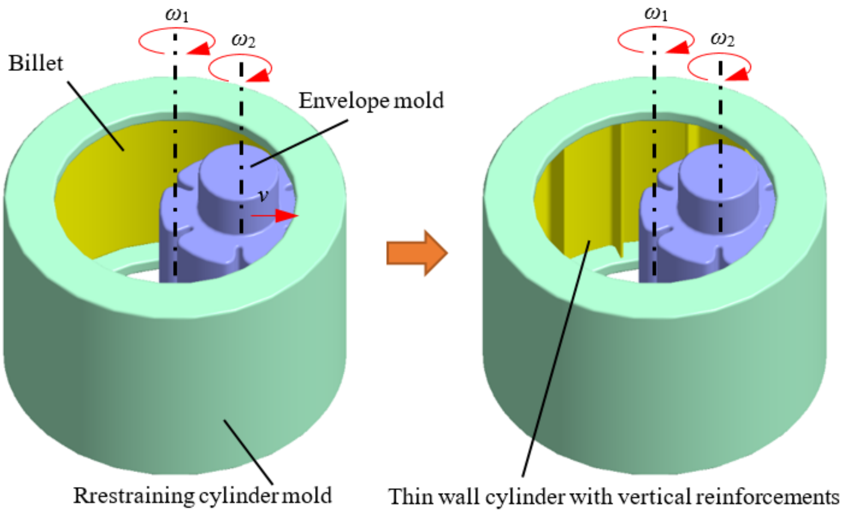

Figure 2. Principle diagram of REF of thin wall cylinder with vertical reinforcements

3. Finite element simulation of thin wall cylinder with vertical reinforcements

This paper is based on Deform-3D finite element numerical simulation software to verify the REF of thin wall cylinder with vertical reinforcements. The main parameters of the finite element model of REF of thin wall cylinder with vertical reinforcements are shown in Table. 1, the billet material is 2219 aluminum alloy and the mold material is AISI-H-13. The initial temperatures of the billet and the mold are set to 450°C and 350°C, and the thermal conductivity is set to 11kW/(m2·K). The shear friction condition is used to calculate the friction relationship between the envelope mold and the billet and the restrained cylinder mold and the billet, and the friction coefficient is 0.3. The simulation is carried out by dividing the billet into tetrahedral cell meshes, and in order to improve the simulation accuracy, the thinning area of web and vertical reinforcements are refined locally. The ratio of the mesh size of the refined area to the unrefined area is set to 0.3, and the minimum mesh cell size is 0.5mm. The finite element model of REF of thin wall cylinder with vertical reinforcements is shown in Fig. 3.

Table 1. Finite element model parameters of thin wall cylinder with vertical reinforcements

Parameter	Value
Thickness of billet (mm)	8
Outside diameter of billet (mm)	300
Height of billet (mm)	192
Feed rate of envelope mold	0.5
Rotate speed of envelope mold (rad/s)	4π
Rotate speed of restraining cylinder mold(rad/s)	2π

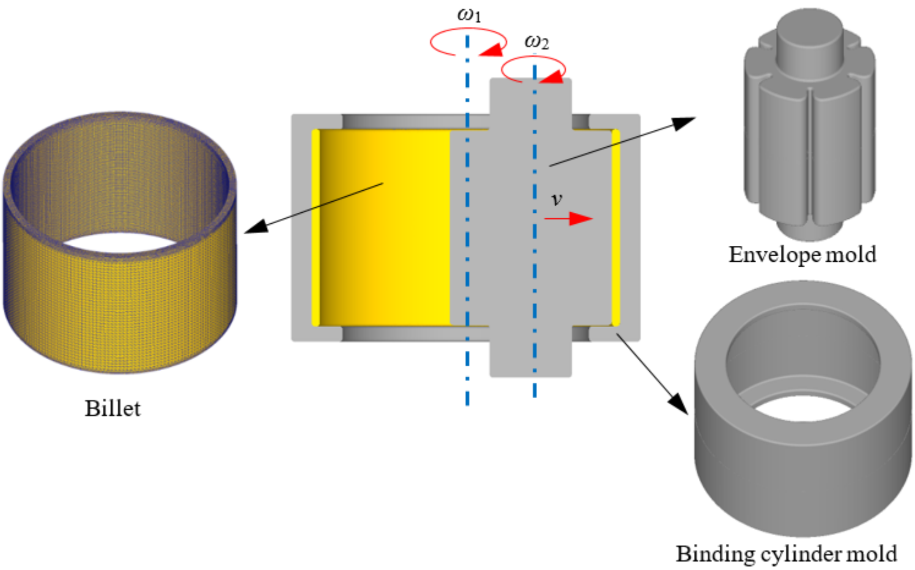

Figure 3. Finite element model of REF of thin wall cylinder with vertical reinforcements

Fig. 4 shows the results of REF of thin wall cylinder with vertical reinforcements. The wall thickness of the billet is thinned under the radial extrusion of the envelope mold, and the web metal flows into the vertical reinforcement cavity of the envelope mold under the action of the envelope mold, and the vertical reinforcement is formed gradually. The final vertical reinforcement height can reach 20 mm and the reinforcement thickness is 5 mm.

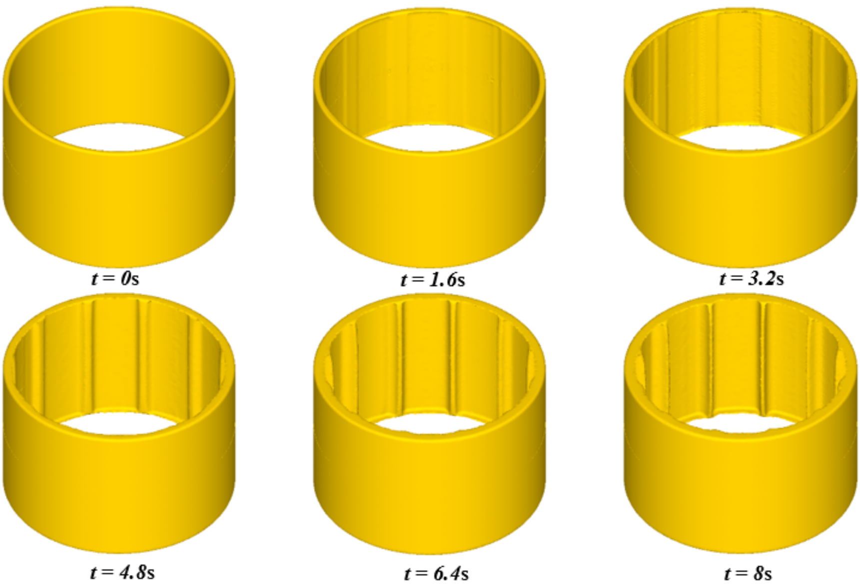

Figure 4. Evolution of REF of thin wall cylinder with vertical reinforcements

4. Forming law of thin wall cylinder with vertical reinforcements

4.1 Strain evolution and distribution law

Fig. 5 shows the evolution and distribution of the equivalent strain of REF of thin wall cylinder with vertical reinforcements, from which it can be seen that with the increase of envelope passes, plastic deformation occurs in each region of thin wall cylinder with vertical reinforcements and the equivalent strain gradually increases. The thin wall cylinder with vertical reinforcements is not uniformly distributed, and the equivalent strain is greater in the web than in the vertical reinforcements, because the metal in the web is enveloped by multiple passes of the envelop mold. The equivalent strain is the most intense at the transition corners between the vertical reinforcement and the web. This is because when vertical reinforcement cavity of the envelope mold meshes with the vertical reinforcement the transition corners between the vertical reinforcement and the web is locally loaded by the envelope mold. The flow direction of the metal at the corner of the root changes rapidly from circumferential to radial, and drastic plastic deformation occurs at the rounded corner. Due to the circumferential rolling of the envelope mold, more metal flows from the corner below the vertical reinforcement into the cavity, so the equivalent strain on the corner below the reinforcement is greater than that above the reinforcement. The equivalent strain gradually increases from the top to the bottom of vertical reinforcement, because the metal at the bottom of vertical reinforcement has undergone more rolling and more severe deformation.

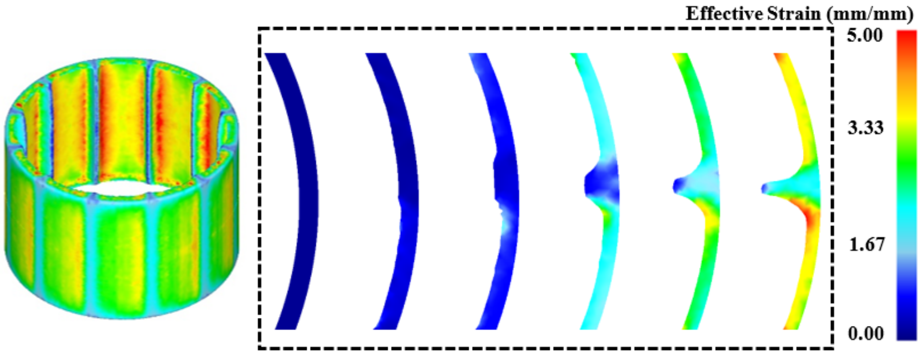

Figure 5. Equivalent strain evolution of REF of thin wall cylinder with vertical reinforcements

In order to further reveal the strain distribution characteristics at different locations in REF of thin wall cylinder with vertical reinforcements, radial, circumferential and axial strain values were measured on the inner layer, middle layer and outer layer of thin wall cylinder with vertical reinforcements, and the three-way strain curve of thin wall cylinder with vertical reinforcements was obtained, as shown in Fig. 6.It can be seen from the figure that radial compression strain occurs in the web and radial tensile strain occurs in the vertical reinforcements, because the web is thinned by the radial loading of the envelope mold and the metal fills the vertical reinforcements cavity of the envelope mold in the radial direction. Since the envelope mold acts on the inner layer of the web, the force of the envelope mold on the web gradually spreads from the inner layer of the web to the outer layer of the web, so the radial strain value of the web gradually decreases from the inner layer to the outer layer. The radial strain in the vertical reinforcement gradually increases from the inner layer to the outer layer, because the metal of the inner layer of the vertical reinforcement is inside the envelope model, which is almost not in contact with the envelope mold and suffers less radial extrusion deformation from the envelope mold. The circumferential tensile strain in the web and the circumferential compressive strain in the vertical reinforcement are due to the circumferential flow of the metal inside the web under the radial envelope of the envelope mold, while the metal filling vertical reinforcement is circumferentially constrained by the vertical reinforcement cavity. The metal of the inner layer of the cylinder flows axially toward the ends of the cylinder under the radial extrusion of envelope mold, but the ends of the cylinder are axially restrained by the top and bottom cover plates, and a small axial tensile strain is generated in the web and vertical reinforcement.

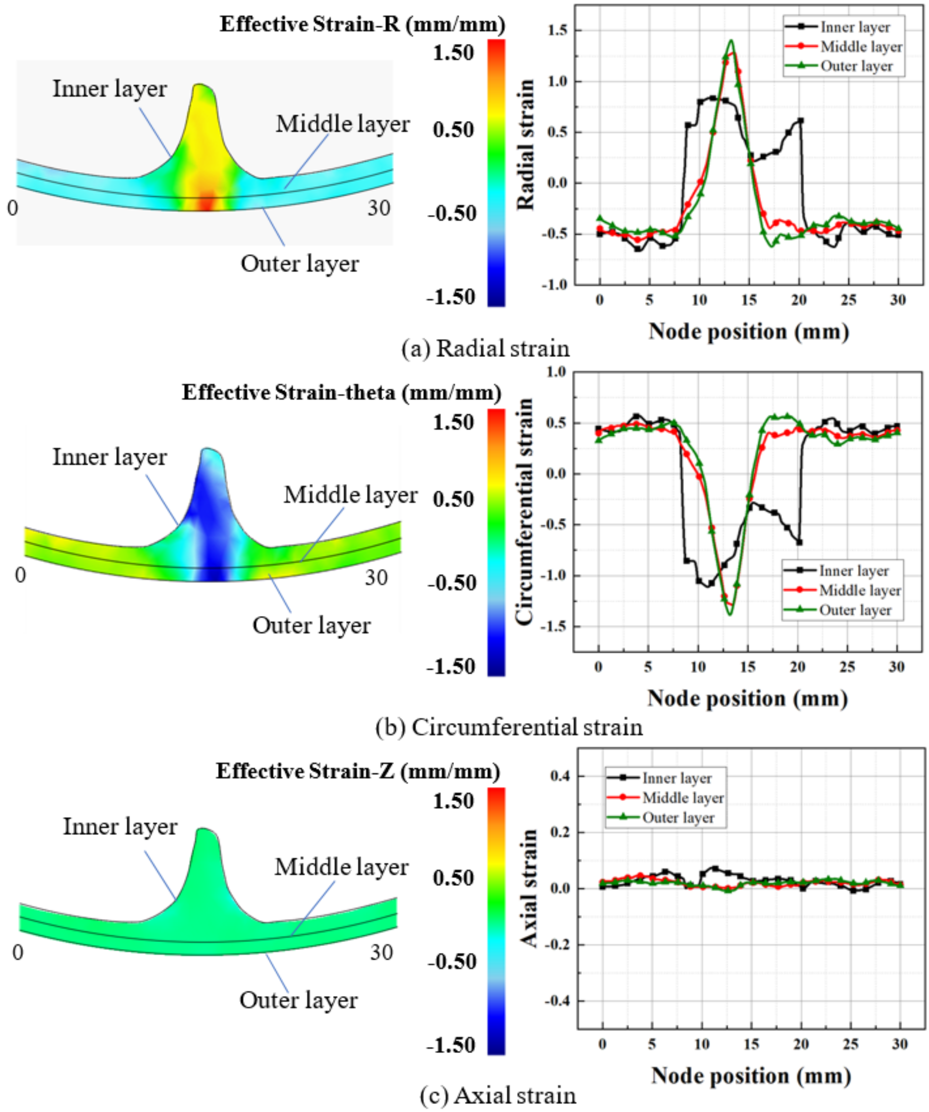

Figure 6. Radial, circumferential and axial strain diagrams of REF of thin wall cylinder with vertical reinforcements

4.2 Metal velocity law

As shown in Fig. 7, the metal flow velocity of thin wall cylinder with vertical reinforcements when the envelope mold moves to the web of thin wall cylinder with vertical reinforcements, it can be seen from the figure that complex multi-directional flow occurs in the contact area between the envelope mold and thin wall cylinder with vertical reinforcements, in which the metal in the contact area mainly flows in the radial direction under the radial compression of envelope mold, the metal on both sides of the contact area mainly flows in the circumferential direction, and the metal at both ends of the contact area flows in the axial direction relatively weakly.

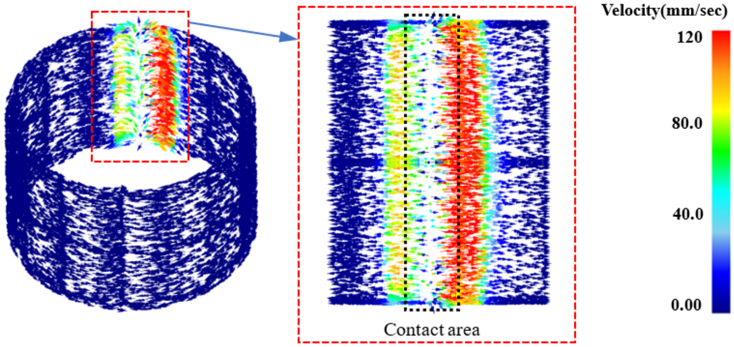

Figure 7. Metal flow rate diagram of REF of thin wall cylinder with vertical reinforcements

In order to investigate the metal flow rate law of vertical reinforcements during REF of thin wall cylinder with vertical reinforcements, this paper intercepts the axial and radial sections of thin wall cylinder with vertical reinforcements to analyze the circumferential and radial metal flow rate law of the vertical reinforcements during REF, as shown in Figure 8. In the circumferential direction, the contact area between the envelope mold and thin wall cylinder with vertical reinforcements has obvious diversion surfaces, and the diversion surfaces move with the circumferential movement of the envelope mold, in which the circumferential flow direction of the metal in the pre-contact area is the same as the engagement direction of the envelope mold, and the metal in the post-contact area flows in the opposite direction. When the envelope mold is engaged in and engaged on vertical reinforcements, the metal flow near vertical reinforcement cavity side is more intense because the flow resistance near vertical reinforcements cavity side is smaller. When the envelope mold is engaged out of vertical reinforcement cavity, the envelope mold squeezes the web and the metal flow in the post-contact area is more intense. In the radial direction, it can be seen from Fig. 8 that radial diversion surfaces are generated on both sides of the contact area, Metals in the contact area flow outward in the radial direction, while metal on both sides of the contact area flow inward in the radial direction， and the metal flow in the contact area is more intense, which finally makes the web in the contact area significantly thinned. When the envelope mold engages with vertical reinforcements, the envelope mold contacts the rounded corners on both sides of vertical reinforcements, the accumulated metal is released in vertical reinforcements cavity, and the metal flows radially inward and gradually fills vertical reinforcements cavity.

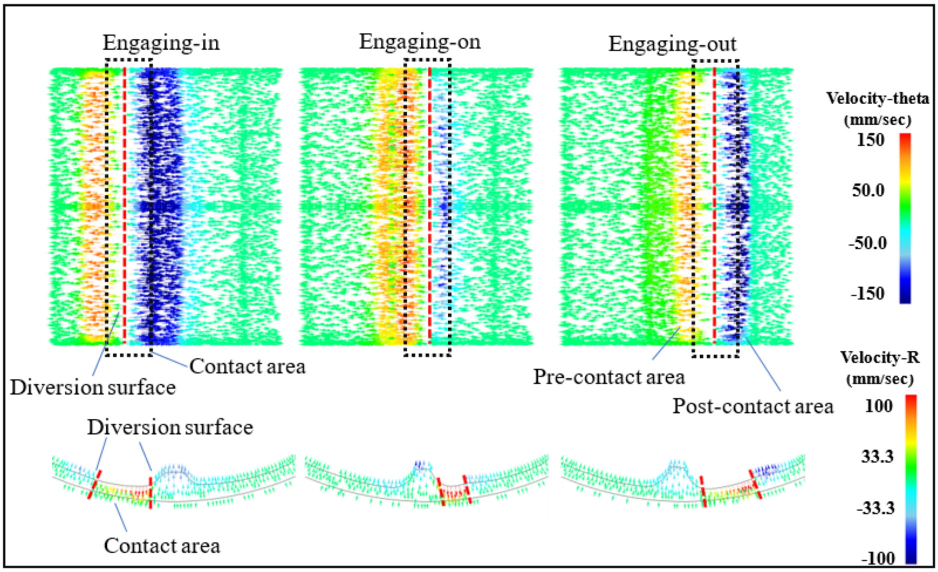

Figure 8. Circumferential and radial metal flow velocity distribution of REF of thin wall cylinder with vertical reinforcements

4.3 Growth law of vertical reinforcements

Fig. 9 shows the profile evolution of vertical reinforcement of thin wall cylinder with vertical reinforcements under different passes during REF. It can be seen from the figure that the height of the vertical reinforcement of thin wall cylinder with vertical reinforcements keeps increasing with the continuous feeding of the envelope mold, but the growth rate of vertical reinforcement height is different at different positions of vertical reinforcement. And the vertical reinforcements profile of thin wall cylinder with vertical reinforcements finally shows a distribution trend of high in the middle and low at the ends.

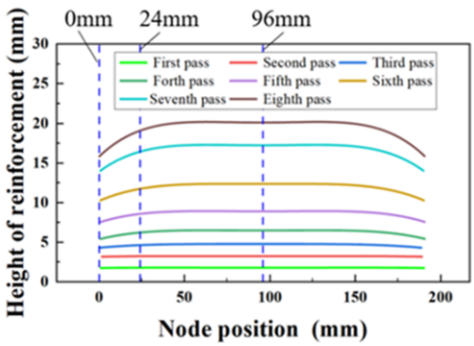

Figure 9. Vertical reinforcement profile evolution of REF of thin wall cylinder with vertical reinforcements

In order to investigate the growth law of the height of the vertical reinforcement during REF, the height of the vertical reinforcement was measured at three positions of 0mm node (end of vertical reinforcement), 24mm node and 96mm node (middle of vertical reinforcement), and the height of the vertical reinforcement growth curve was obtained at different positions of vertical reinforcement, as shown in Fig. 10. It can be seen from the figure that 1-2 passes are the initial stage of forming, the envelope mold gradually engages the billet, the growth rate remains unchanged, and the height of the vertical reinforcement shows linear growth. 3-6 passes enter the stable forming stage, the contact area between the envelope mold and billet gradually increases under the continuous radial feeding of the envelope mold, and the growth rate of vertical reinforcement increases significantly. 7-8 passes enter the finishing stage, the envelope mold stops radial feeding, and the contact area between the envelope mold and the billet decreases, and the growth rate of vertical reinforcement slows down. In the stable forming stage, the growth rate of vertical reinforcement at 96mm node position exceeds that of 0mm and 24mm node position, the vertical reinforcement profile is high in the middle and low at both ends. And as the envelope pass increases the closer to the middle of vertical reinforcement, the higher the growth rate of vertical reinforcement, the greater the gap between the 0mm node position and the 96mm position, this is because the closer the metal is to the end of thin wall cylinder with vertical reinforcements, the easier it is to flow axially into the fly gap at the end of thin wall cylinder with vertical reinforcements.

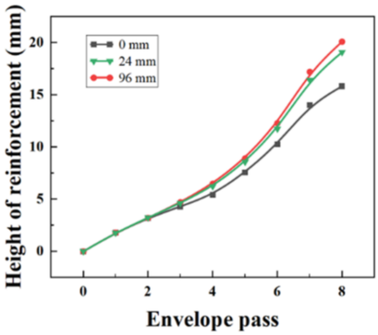

Figure 10. Growth curves of vertical reinforcement height at different positions

5. Conclusions

(1) The equivalent strain in the web is larger than that in vertical reinforcement of thin wall cylinder with vertical reinforcements, and the equivalent strain is greatest at the transition corners between the vertical reinforcement and the web. The radial compressive strain, circumferential tensile strain and axial tensile strain are generated in the web, the radial tensile strain, circumferential compressive strain and axial tensile strain are generated in vertical reinforcements.

(2) The metal mainly flows along the radial and circumferential direction during REF of thin wall cylinder with vertical reinforcements, and divergence phenomenon of metal flow occurs on both circumferential and radial direction.

(3) During REF of thin wall cylinder with vertical reinforcements, the growth rates of vertical reinforcements are different at different forming stages due to the different contact areas between the envelope mold and the billet. The different growth rates of the vertical reinforcement at different positions of the vertical reinforcement leads to uneven height of the vertical reinforcement, i.e. the middle part of the vertical reinforcement is higher than both ends of the vertical reinforcement.

References

[1] Ronald Heinz Norbert W, Christian H, Niemann S, Kuo T, Bo W, Hao P. Robust knockdown factors for the design of cylindrical shells under axial compression: Analysis and modeling of stiffened and unstiffened cylinders. Thin-Walled Structures. 2018 Jun;127: 629-645.

[2] Yan Z, Kuo T, Shengli X, Bo W. Two-scale buckling topology optimization for grid-stiffened cylindrical shells. Thin-Walled Structures. 2020 Jun;151: 106725.

[3] Xiang Z, Xiaoguang F, Hongwei L, Shuhui L. Flow forming process of thin-walled tubular parts with cross inner ribs. Procedia Manufacturing. 2018 Jan;15: 1239-1246.

[4] Wei L, Mei Z, Pengfei G, Rui L, Yudong L, Fei M. Improvement of rib-grid structure of thin-walled tube with helical grid-stiffened ribs based on the multi-mode filling behaviors in flow forming. Journal of Materials Processing Technology. 2021 Apr;296: 117167.

[5] Wei L, Mei Z, Pengfei G, Fei M, Rui L, Hongrui Z , Yunda D. Rib filling behavior in flow forming of thin-walled tube with helical grid-stiffened ribs. The International Journal of Advanced Manufacturing Technology. 2022 Jan;119(5):2877-2894.

[6] Jin Z, Ming C, Cheng H, Huaqiang Z. Influence of feed ratio on spinning-extrusion compound forming rule and mechanical properties of 2195 Al-Li alloy shell with ribs. Journal of Central South University. 2022 Feb;53(2): 443-450.

[7] Zhongqi Y, Fengqi W, Donghua D, Dongdong G, Shuhui L, Zhongqin L. A review of flow spinning technology of stiffened thin-walled cylinders. Journal of plasticity engineering. 2021 Aug;28(8): 1-10.

[8] Xiang Z, Xiaoguang F, Hongwei L, Mei Z, Pengfei G, Qi C. Recent Developments in Spinning of Complex Thin-walled Parts with Inner Ribs. Journal of netshape forming engineering. 2019 Sep;11(5): 21-31.

[9] Xinghui H, Lin H, Lu P, Wei F. An innovative radial envelope forming method for manufacturing thin-walled cylindrical ring with inner web ribs. Journal of Materials Processing Technology. 2020 Dec;286: 116836.

[10] Duanyang T, Xinghui H, Lin H, Xuan H. An innovative constraining ring rolling process for manufacturing conical rings with thin sterna and high ribs. Chinese Journal of Aeronautics. 2022 Aug;35(8): 324-339.

[11] Duanyang T, Xinghui H, Lin H, Xiaokai W, Fei C. Constraining ring rolling of thin-walled conical rings with transverse ribs. International Journal of Mechanical Sciences. 2022 Jul 15;226: 107394.