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Operating effect of filler on filling roll bending of integral panel

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Abstract: A filling roll bending process of a 2A12 aluminum alloy integral panel with polypropylene as filler was studied. The operating effect of filler was revealed, based on analytical, numerical, and experimental methods. The results show that the position difference of the neutral layer between the ribs and the web of the integral panel leads to the error of generatrix straightness, and the filler can reduce this difference. A certain range of the width gap (1−3 mm) between filler and rib can avoid the instability of the rib and the curl of the filler. The height gap between filler and rib determines the compression degree of filler. The best pressure transmission effect can be achieved as the filler is still higher than the rib (1 mm) after compression. The elastic modulus of filler slightly affects the forming accuracy of the integral panel within a certain range (450−1300 MPa). Still, the filler transfers insufficient pressure under lower elastic modulus (50 MPa) and limits the deformation of the integral panel under higher elastic modulus (20 GPa). Experimentally measured generatrix straightness verified the operating effect of filler.
Key words: integral panel; roll bending; filler; neutral layer; generatrix straightness

1 Introduction

As an essential large-scale structure component, the integral panel is widely used in the aerospace industry due to its advantages of light weight, high stiffness, and excessive structural efficiency [1−4]. However, the updating shape characteristics of integral panels (large size, high rib, thin web, etc.) and their high precision put forward high requirements for the bending forming of the integral panel [5]. The bending forming methods of the integral panel mainly include shot peening forming, incremental bending forming, creep aging forming, electromagnetic forming, and rolling bending [6]. The application of shot peening technology is limited owing to its process complexity, additional prestress treatment, and rough surface after forming [7]. Incremental bending requires large hydraulic equipment and a long production cycle and easily leads to uneven bending radian and crease of the overall [8,9]. Creep aging forming needs a long holding time and large mould, which is unsuitable for mass production [10]. Electromagnetic forming has also been studied for integral panel bending forming but is unsuitable for the production of large-sized panels due to the equipment size limit [11,12]. Rolling bending is one of the earliest forming processes, and it is also one of the most widely

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utilized forming methods in integral panels. It has many advantages, such as simple equipment, and is suitable for mass production [13,14]. Generally, roll bending is suitable for integral panels with single curvature and thin skin. However, due to the height difference between rib and skin of the integral panel, the deviation of generatrix straightness is serious, which affects the subsequent welding operation. Therefore, additional calibration work is required to ensure the process requirements of the generatrix straightness.

To avoid this forming defect, ZHANG et al [15] took the lead in applying filling roll bending technology to integral panels and carried out experimental research, proving that the integral panels could be formed using rubber or plastic as filler on roll bending. LIU et al [16] and XIAO et al [17] established the finite element model of the integral panel filling roll bending and analyzed the filler's influence on equivalent stress, shear stress, and equivalent strain. The research proved that, on the one hand, the filler protected the rib and avoided its instability; on the other hand, the roller load is transferred to the skin to coordinate deformation with the ribs. YIN et al [18] compared the rubber and polyethylene (PE) plates. The results showed that the PE plastic plate as filler was significantly better than the rubber, and the generatrix straightness was lower. LAI et al [19] established a method to calculate the position of the neutral layer in elastic-plastic bending of integral panel structure by elastic-plastic analysis and considering the plastic strengthening effect of materials. Still, it was only limited to the rolling process of the panel without filler.

Numerous studies on filling roll bending of integral panels have been done based on experimental, analytical, or finite element (FE) methods. These studies verified that the introduction of filler could effectively improve the deformation uniformity of integral panels and the forming accuracy. However, the above studies paid less attention to the forming quality of the panel, especially the generatrix straightness. The operating mechanism of the filler during the rolling process and the influence of filler characteristics on the bending of integral panels have not been clarified so far.

According to Ref. [15], there are usually three fillers: low melting point metal, rubber, and plastic. Metal fillers will undergo plastic deformation and cannot be reused, so metals are rarely selected as fillers. The preparation cost and processing difficulty of rubber and plastics are relatively low. Generally, the elastic modulus of plastics is greater than that of rubber, which is conducive to the transmission of pressure. Polypropylene is a kind of plastic with high strength, which is suitable as filler. This study developed a filling roll bending process with polypropylene (PP) as filler. A 3D elastic-plastic FE model of the filling roll bending was set up based on the ABAQUS/Explicit. The effect of filler on neutral layer migration and the mechanism of filler ameliorating generatrix straightness were analyzed. The influence of filler elastic modulus and gaps between filler and rib was studied. Finally, the operating effect of filler was verified by experiments.

2 Methodology

2.1 Principle

Filling roll bending is an integral panel bending process that uses flexible filler in the grid as the pressure transfer medium based on the traditional roll bending process. The filler is compressed to provide pressure to the panel, eliminating the forming defects of the bent integral panel, especially the generatrix straightness. The forming principle is shown in Fig. 1. Before bending the integral panel, the grids of the panel are filled with fillers. Then under the pressure of the top roller and the bottom rollers support, the fillers are bent together with the grids, and the fillers provide pressure support for the web of the integral panel. After the top roller has a certain amount of pressure,

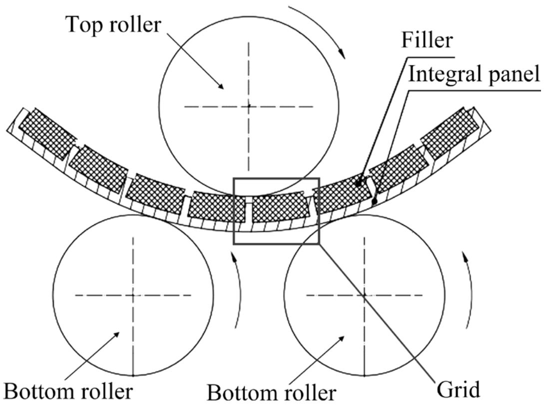

Fig. 1 Schematic of filling roll bending principle

the bottom rollers are used as the driving rollers to rotate and make the integral panel continuously plastic deformation. Finally, the integral panel reaches the ideal curvature.

2.2 Experiment

The three-roller bending machine is shown in Fig. 2(a). By controlling the lifting of the top roller and the rotation speed of the bottom rollers, this machine meets different rolling forming requirements. The top roller diameter is 420 mm, the diameter of the bottom rollers is 330 mm, and the distance between the two bottom roll centers is 480 mm. The rotation speed of bottom rollers is 50 mm/s.

The integral panel with a length of 1800 mm, a width of 1200 mm, web thickness (t) of 4 mm, rib width (a) of 6 mm, grid width (including rib) of 200 mm (b), and rib height (c) of 12 mm, was studied in this work as shown in Fig. 2(b).

The polypropylene filler used in the experiment is shown in Fig. 2(c), filled in the grid cavity during the forming and recycled at the end of the process.

2.3 FE model

The finite element (FE) model of the filling roll bending process of the integral panel was established in ABAQUS/Explicit. The dynamic explicit algorithm can simulate large deformation processes and complex contact conditions without convergence problems, so it is very suitable to simulate the filling roll bending process.

The model includes top roller, bottom rollers, integral panel, and filler, where the top roller and bottom rollers were set as rigid. The integral panel was set as an elastoplastic deformable-body. The integral panel and filler were modeled using C3D8R, an eight-node linear brick, reduced integration, and hourglass control element.

All the friction behavior in the FE model was described by the classic Coulomb friction model $\tau=\mu P$, where τ is the friction shear force, μ is the coefficient of friction, and P is the pressure on the contact surface. Surface-to-surface contact algorithms were employed at the interface between the roller and the panel, between the panel and the filler, and between the roller and the filler. In addition, to keep the filler in the mesh during the rolling process, it is necessary to add a gravity field to the finite element model to ensure that the filler does not break away from the grid due to inertia. The model's proper mass scaling was set to balance calculation accuracy and computational efficiency. The limit of mass scaling is to ensure that kinetic energy does not exceed 5% of the internal energy.

The material of the filler is polypropylene (PP), and its mechanical properties were obtained through a compression test, as shown in Fig. 3. Since there is a gap between polypropylene and rigid sleeve in the initial stage, and the triaxial compression stress−strain curve of polypropylene is divided into two stages. The first stage is the filling stage, the stress state is uniaxial compressive stress, and the elastic modulus (E) of polypropylene in the first stage is 450 MPa. In the second stage, the stress state becomes three-dimensional compressive stress, and the elastic modulus of polypropylene in the second stage is 1300 MPa.

The elastic modulus of the filler is regarded as 450 MPa under unidirectional compression. When the deformation reaches a certain degree, the filler and the grid are in complete contact with the rib, and the elastic modulus of filler is 1300 MPa.

The material of the integral panel is 2A12-T4 aluminum alloy, and the properties of which listed in Table 1 were calculated with the uniaxial tensile test data.

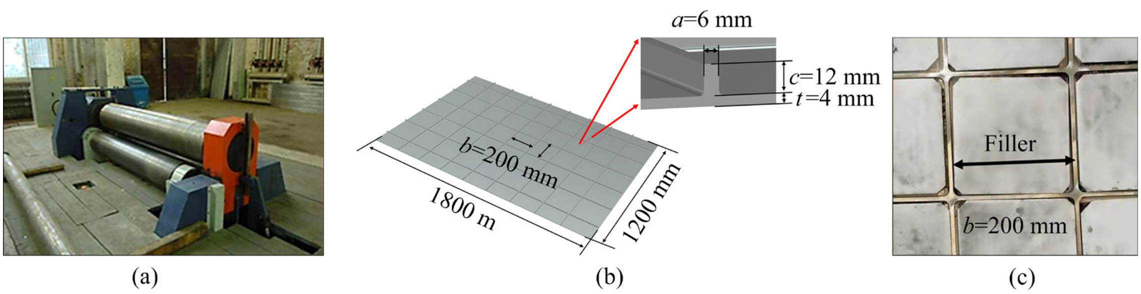

Fig. 2 Experimental equipments: (a) Three-roller bending machine; (b) Integral panel; (c) Fillers

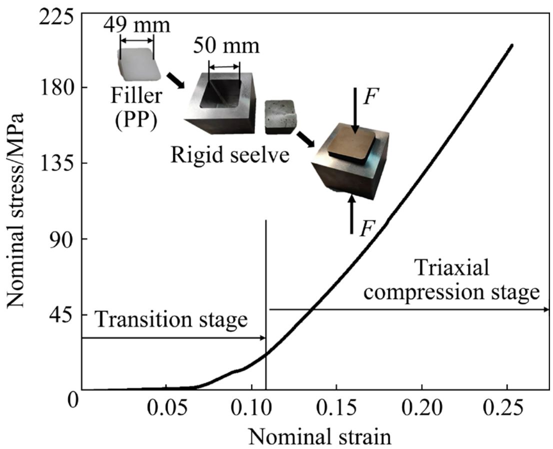

Fig. 3 Compression stress−strain curve of filler

Table 1 Properties of aluminum alloy 2A12-T4

Elastic modulus, E/GPa	Poisson ratio, ν	Initial yield stress, σ_s/MPa	Hardening coefficient, D
72.4	0.3	325	1600

3 Results and discussion

3.1 Effect of filler on neutral layer

As shown in Fig. 4(a), the X-direction is along the roll bending direction, and the Y-direction is perpendicular to the roll bending direction. Generatrix straightness refers to the maximum gap in the Y-direction on the skin side of the integral panel. When the integral panel is bent, the generatrix straightness mainly comes from the gap between the X-direction rib and the web center. The web center is not fully deformed but concaved. After the panel is formed, the generatrix straightness is measured with a generatrix rule. The degree of concave deformation of the web affects the generatrix straightness. As shown in Fig. 4(b), the deformation at the rib of the panel is large, and the bending radius is small. However, the deformation at the web center is small, and the bending radius is large. The difference in the deformation degree between the two places leads to the deviation of generatrix straightness. The generatrix straightness deviation mainly exists below the X-direction ribs and the web center during bending deformation. e_1 and e_2 are the distance between the neutral layer and the web, and ρ_1 and ρ_2 are the curvature radii of these two places, respectively.

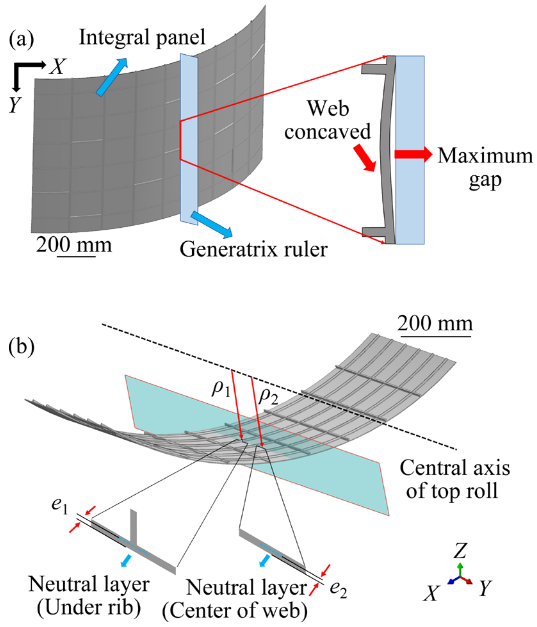

Fig. 4 Bending deformation of integral panel: (a) Concaved web; (b) Neutral layer

The bending radius of the integral panel is closely related to the position of the neutral layer. Based on the moment balance of the panel section, the position of the neutral layer below the X-direction rib and the web center is calculated. The following calculation of the neutral layer comes from Ref. [19]. Some assumptions are proposed as the premise of mechanical analysis to simplify the calculation.

(1) The integral panel material and filler material are isotropic.

(2) The integral panel material 2A12-T4 adopts the linear strengthening material model, and the stress and strain have the following relationship:

$$\sigma=\begin{cases}E\varepsilon,\ 0<\varepsilon<\varepsilon_s\\ \sigma_s+D(\varepsilon-\varepsilon_s),\ \varepsilon\geq\varepsilon_s\end{cases} \tag{1}$$

where σ_s is the yield stress, ε_s is the yield strain, and D is the hardening coefficient.

(3) Roll bending is a plane strain issue.

As shown in Fig. 4(b), e_1 is the neutral layer position at the rib, and ρ_1 is the curvature radius of the rib. The tensile stress below the neutral layer is f_1, and its resultant force F_1 (Y-direction) is

$$F_1=\int_0^{e_1}E\frac{y}{\rho_1}b\mathrm{d}y \tag{2}$$

The compressive stress received above the neutral layer is f_2, including the stress $f_{2\mathrm{p}}$ (resultant force F_{2p}) in the plastic deformation zone and the stress f_{2e} in the elastic deformation zone (resultant force F_{2e}).

$$F_{2e}=\int_0^{t-e_1}E\frac{y}{\rho_1}b\mathrm{d}y+\int_{t-e_1}^{t_s}E\frac{y}{\rho_1}a\mathrm{d}y \tag{3}$$

$$F_{2p}=\int_{t_s}^{c+t-e_1}a\left(\sigma_s+\frac{Dy}{\rho}-\frac{D\sigma_s}{E}\right)\mathrm{d}y \tag{4}$$

where t_s is the thickness of the elastic deformation layer.

$$t_s=\frac{\rho_1\sigma_s}{E} \tag{5}$$

The resultant force of the section is 0, so Eq. (6) can be obtained:

$$F_1=F_{2e}+F_{2p} \tag{6}$$

Substituting Eqs. (3)−(5) into Eq. (6), yields

$$\frac{a(E-D)t_s^2+aD(c+t-e_1)^2}{2\rho_1}-a\sigma_s\left(1-\frac{D}{E}\right)(c+t-e_1-t_s)-\frac{Ebe_1^2+E(a-b)(e_1-t)^2}{2\rho_1}=0 \tag{7}$$

Substituting the material parameters (Table 1) and dimension parameters (Table 2) into Eq. (7), the relationship between the neutral layer position e_1 and the radius of curvature ρ_1 at the rib is shown in Fig. 5. It can be found that with the decrease of bending radius, the distance between the neutral layer and the skin (e_1) first decreases and then increases. With the increase of deformation, the plastic deformation zone at the top of the rib gradually increases. The neutral layer gradually deviates from the geometric neutral layer to the skin. With the continuous increase of deformation, the bending radius gradually decreases. In this work, only the neutral layer offset during plastic deformation of the integral panel is studied, which can be regarded as e_1 and ρ_1 negative correlation.

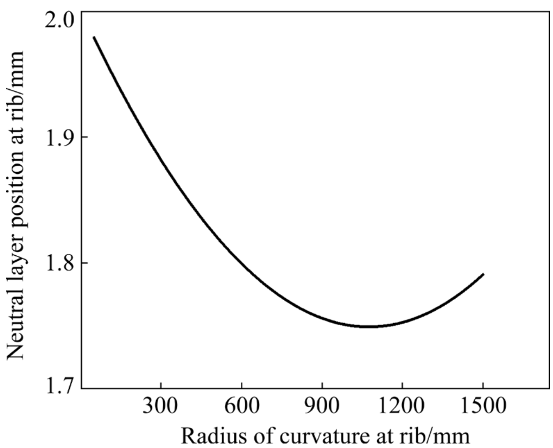

Fig. 5 Relationship between neutral layer position and radius of curvature at rib

As shown in Fig. 6(a), when no plastic deformation occurs, the neutral layer is located at the center of the structural shape. When the deformation increases, the force P from the top roller gradually increases, and the plastic deformation occurs first at the upper of the rib. The normal stress is no longer linearly distributed along the thickness direction but is closely related to the plastic strengthening of the material. Because the plastic strengthening modulus of the material is generally smaller than the elastic modulus, the two sides of the neutral layer are not symmetrical and the tensile stress and compressive stress are no longer zero, and the position of the neutral layer will shift to the skin to achieve stress balance. For high stiffened panels, plastic deformation of skin side below the neutral layer is small and can be ignored.

As shown in Fig. 6(b), the lower layer of the web is tensioned under stress f_1, and the thickness is reduced; the upper layer is compressed due to f_2, and the thickness increases, so the neutral layer shifts upward (Z-direction) during bending. e_2 is negatively correlated with ρ_2 with the increase of deformation, the bending radius decreases, and the neutral layer shifts upward slightly.

For roll bending with filler, the section stress distribution of the rib is shown in Fig. 6(c). The pressure P initially concentrated on the top of the rib is evenly distributed on the web through the filler. Therefore, f_{2e} and f_{2p} decrease because of the reduction of P. To ensure the balance of tensile and compressive stress as shown in Fig. 6, the integral regions of f_{2e} and f_{2p} increase, the plastic deformation zone becomes smaller, and the neutral layer shifts down. As a result, the deformation at the ribs decreases, and the bending radius increases. In addition, TAN et al [20] concluded electromagnetic forming of integral panels that the forming quality of panels with the load at web and rib is better than load only at rib, which is similar to the above effect of filler.

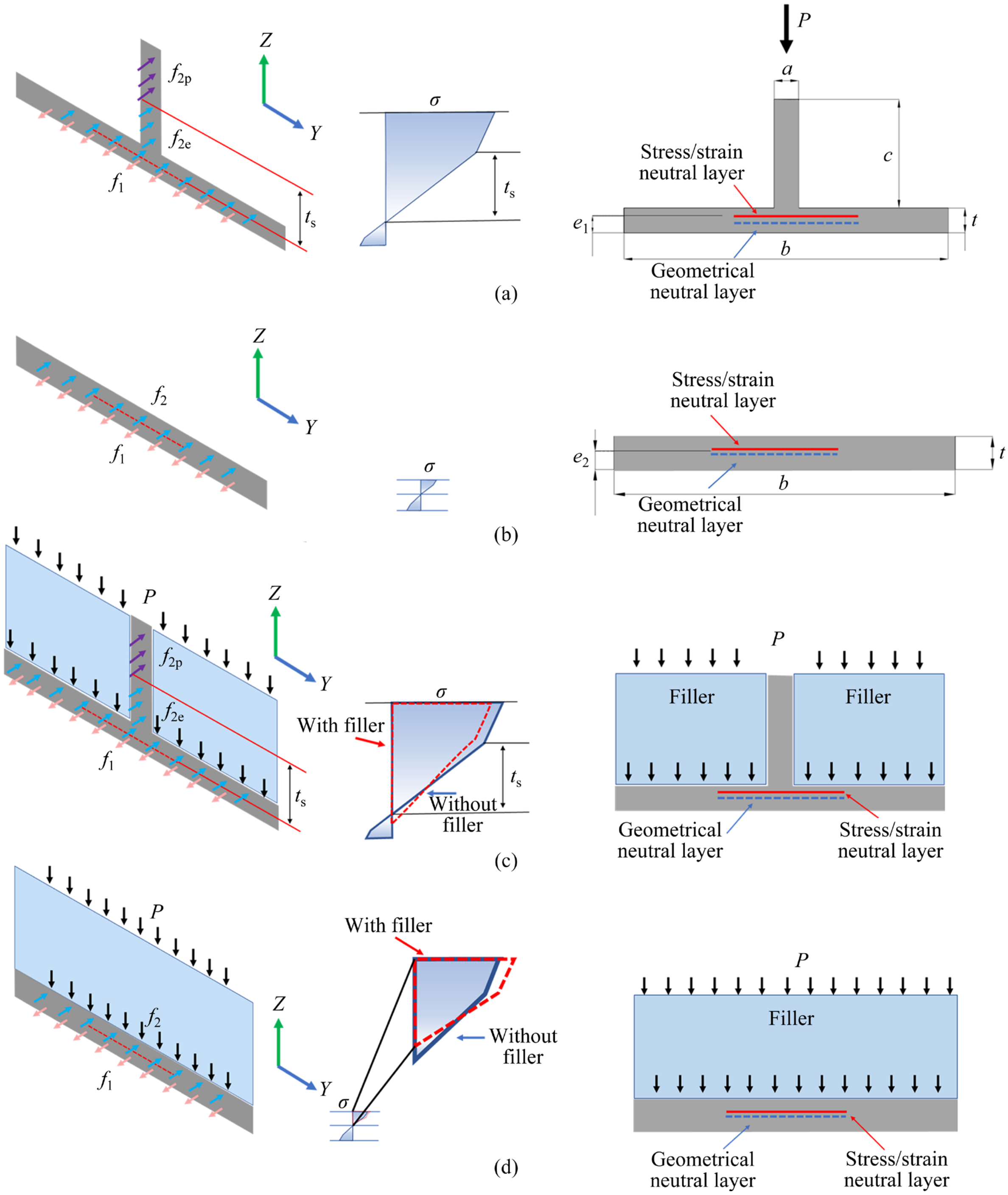

Fig. 6 Deformation of rib and web: (a) Rib without filler; (b) Web without filler; (c) Rib with filler; (d) Web with filler

For roll bending with filler, the section stress distribution of the web is shown in Fig. 6(d). The filler imposes pressure P on the web, the force f_2 above the neutral layer becomes larger. To maintain the stress balance of the section, the integral area of f_2 must be smaller, so the neutral layer shifts upward.

The results of finite element analysis can also support the above analysis. The position of the neutral layer is shown in Fig. 7(a). There is a certain degree of concave deformation in the web of the integral panel when rolling without filler. The neutral layer below the rib e_1 is higher, and the neutral layer at the web center e_2 is lower. The two neutral layers have a noticeable position difference, reaching 0.9 mm. For roll bending with filler, the neutral layer below the rib shifts downward, the neutral layer at the web shifts upward, and the position difference is reduced to 0.2 mm. Therefore, the generatrix straightness of the integral panel is reduced from 0.7 to 0.3 mm.

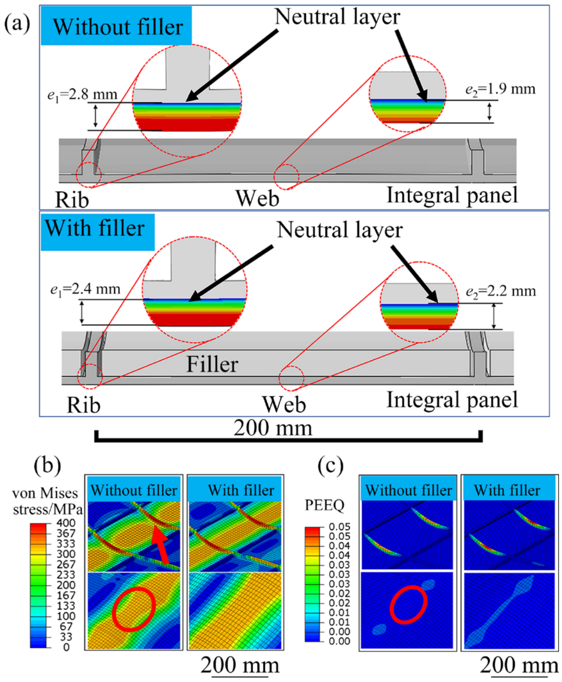

Fig. 7 FE results: (a) Neutral layer; (b) von Mises stress nephogram; (c) Equivalent plastic strain (PEEQ) nephogram

The von Mises stress nephograms of the panel with and without filler are shown in Fig. 7(b). During bending without filler, the stress is mainly concentrated on the direction perpendicular to roll bending ribs, and the stress at the web center is small. In addition, along the direction of the roll, the stress distribution is uneven. A fault with small stress appears at the ribs, and the stress at the web center on the back of the integral panel is small, and the stress on both sides is large. During bending with filler, the stress on both sides below the rib increases, the stress at the center of the back of the panel skin increases, and the stress along the direction of the roll tends to be uniform. This indicates that the filler can concentrate on the pressure at the rib and evenly transfer it to the web center to make the integral plate deform evenly.

The equivalent plastic strains of the panel with and without filler are shown in Fig. 7(c). Compared with the roll bending without filler, the filler transmits pressure to the web center, and the PEEQ of the web center and the rib increases. Because the filler is higher than the rib, and the overall thickness of the integral panel increases, the bending radius of the integral panel decreases, resulting in the deformation increases, which increases the stress and PEEQ of the rib.

3.2 Effect of filler parameters on bending

3.2.1 Gap between filler and rib

The effects of width gap and height gap between the filler and the rib on the rolling deformation of the integral panel were studied. Under different conditions, the integral panel's neutral layer was counted, combined with the panel deformation, and the influence of filler parameters on panel forming was evaluated. As shown in Fig. 8, h is the height gap between the filler and the rib, and d is the width gap between the filler and the rib.

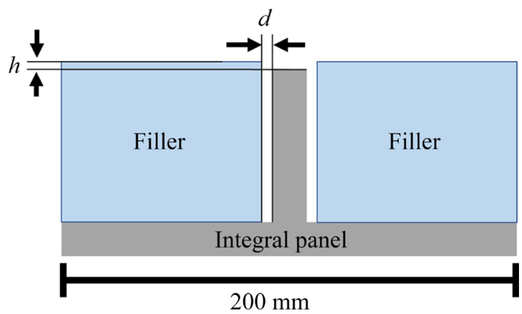

Fig. 8 Schematic of filler size

The width gap d between the filler and the rib for each simulation is shown in Table 2. The height gap h=1 mm. The modulus of elasticity of filler is the same as that in Section 2.3.

Table 2 Width gap d between filler and rib

Simulation No.	1	2	3	4	5	6
d/mm	0	0.5	1	2	3	10

The position of the neutral layer of the integral panel with the filler under different width gaps is shown in Fig. 9(a). With the width gap d increasing from 0 to 3 mm, the neutral layer at the rib and the web center shift downward; this shows that the deformation at both places is decreased. Figure 9(b) counts the neutral layer difference and the generatrix straightness of the integral panel. It can be found that with the width gap d increases from 0 to 1 mm, the position difference of the neutral layer and the generatrix straightness decreases slightly.

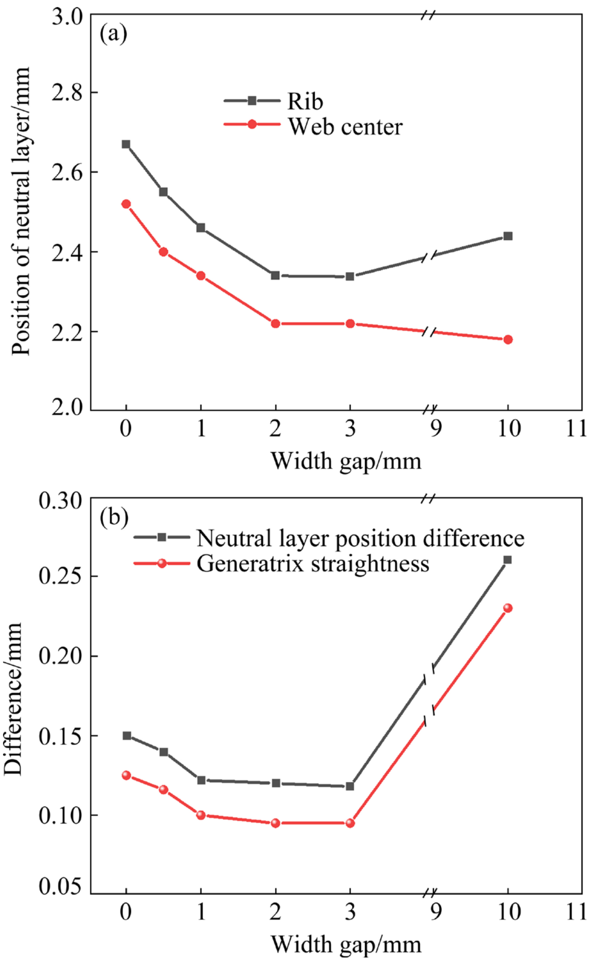

Fig. 9 FE results under different width gaps: (a) Position of neutral layer (mm); (b) Neutral layer position difference and generatrix straightness

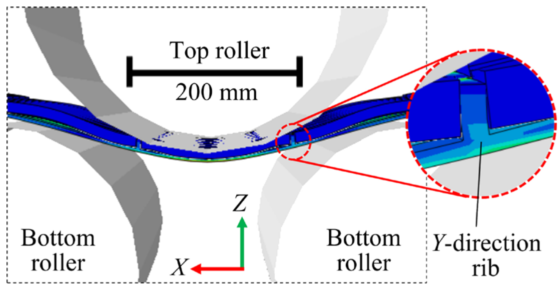

Fig. 10 Deformation of integral panel and filler

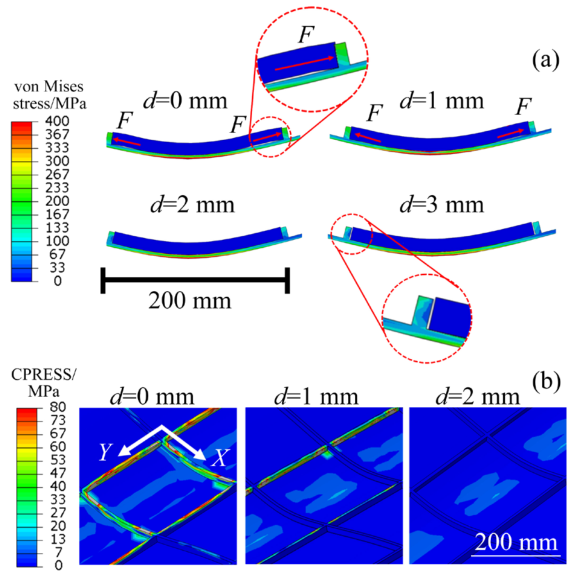

Fig. 11 Deformation of grid: (a) *XZ* section of bent panel under different width gaps; (b) Contact pressure (CPRESS) under different width gaps

When *d* increases from 1 to 3 mm, the neutral layer position difference is almost unchanged, which indicates that the deformation at the rib and the web hardly changes. The generatrix straightness also conforms to this trend. However, if *d*=10 mm, the pressure transmission effect of the filler becomes much weaker, and the position difference of neutral layer and generatrix straightness becomes larger.

The deformation of the integral panel and the filler is shown in Fig. 10. It can be found that the integral panel is bent on the *XZ* section, and the width gap between filler and *Y*-direction rib decreases with the increase of deformation. XIAO et al [17] reported that the filler plays a role in protecting the rib [17]. The filler plays this protective role for the *X*-direction rib, while for the *Y*-direction rib, the situation is complicated.

The integral panel *XZ* section is shown in Fig. 11(a). It can be found that the width gap between the filler and the rib decreases with the increase of deformation degree. When the width gap is small, such as *d*=0 or *d*=1 mm, during bending, the grid's deformation will be limited by the filler. With the increase of deformation, the filler will curl, and the *Y*-direction rib will be subjected to a lateral pressure, which could affect the verticality of the rib as rollers back and forth. When the width gap between the filler and the rib is large, such as *d*=2 mm or *d*=3 mm, the gap always exists in the bending deformation process. The filler will not restrict the deformation of the *Y*-direction rib. The deformation of the filler in the grid explains the change trend of generatrix straightness in Fig. 11(b), and too narrow width gap (0−1 mm) will lead to the curl of fillers and the instability of ribs.

The contact pressure (CPRESS) between the integral panel and the filler is shown in Fig. 11(b). It can be found that when the width gap *d* is small, the contact domain of the *X*- and *Y*-direction rib is significant, such as d=0, which is detrimental to the forming and leads to the buckling of the rib. With the increase of the gap d, such as d=1 mm, the contact area between the filler and the X-direction rib disappears, and the filler can only squeeze the Y-direction rib. When the width gap d is large, such as d=2 mm, the contact domain is mainly concentrated at the web center, and the rib does not contact the filler. The filler effectively transfers the pressure from the top roller without lateral pressure to the rib.

In the roll bending process, the height of the filler will decrease due to compression, and the height gap h between the filler and the rib determines the maximum compression space of the filler for each simulation, as listed in Table 3. The width gap d is 2 mm. The modulus of elasticity of filler is the same as that in Section 2.3.

Table 3 Height gap h between filler and rib

Simulation No.	1	2	3	4	5	6	7	8
h/mm	−3	−2	−1	−0.5	0	0.3	0.5	1

The position of the neutral layer of the integral panel with the filler under different height gaps is shown in Fig. 12(a). With the increasing height gap, the neutral layer at the rib gradually shifts downward. In contrast, the neutral layer at the web center gradually shifts upward, indicating that the deformation below the rib decreases while the deformation at the web center increases. This trend eventually tends to be stable, indicating that the pressure transfer effect of the filler reaches the upper limit. Figure 12(b) counts the neutral layer difference and the generatrix straightness of the integral panel. When the filler is lower than the rib, the position difference of the neutral layer is significant. With the decrease of the height gap, the neutral layer difference also decreases. When the filler is higher than the rib, the position of the neutral layer at the web center and below the rib increases slightly. Meanwhile, the position difference and the generatrix straightness are almost unchanged.

The integral panel XZ section is shown in Fig. 13(a). If the filler is lower than the rib, there is a certain distance between the filler and the top roller, and the top roller cannot be directly pressed to the filler. The bending deformation of the panel grid drives the deformation of both sides of the filler. If the filler is higher than the rib, there is no gap between the filler and the top roller, and the filler can effectively transfer the pressure to the web center.

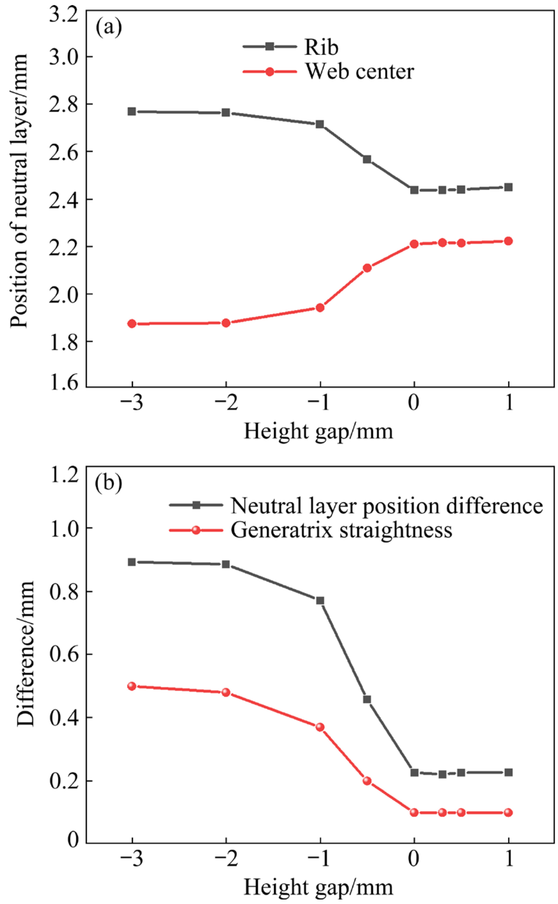

Fig. 12 FE results under different height gaps: (a) Position of neutral layer; (b) Neutral layer position difference and generatrix straightness

The contact pressure (CPRESS) between the integral panel and the filler is shown in Fig. 13(b). If the filler is lower than the rib, the X-direction rib bears the pressure from the top roller. If the filler is higher than the rib, the contact pressure applied by the top roller to the X-direction rib decreases, and the bending deformation of grid drives the filler's deformation. Constrained by the grid cavity, the filler exerts a certain pressure around the grid and the web center. If the filler height is increased on this basis, the filler will be fully deformed, which has little effect on the deformation of the integral panel. Therefore, it can be considered that when the filler is higher than the ribs, the ideal pressure transfer effect can be achieved.

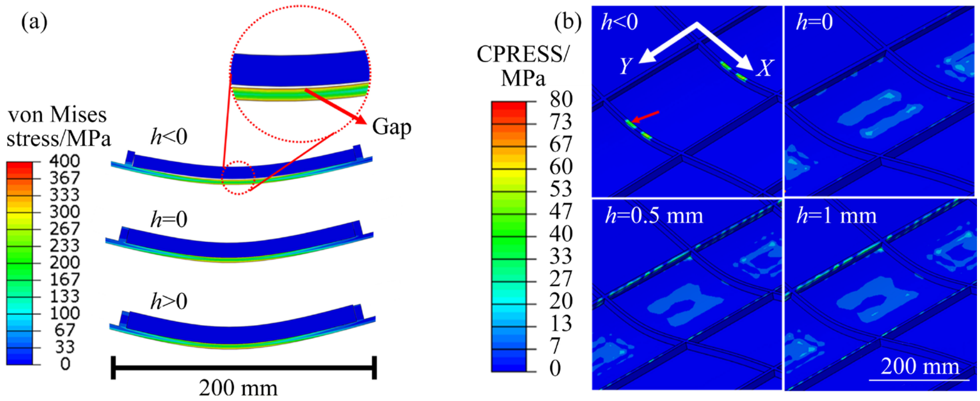

Fig. 13 Deformation of grid: (a) *XZ* section of bent panel under different height gaps; (b) Contact pressure (CPRESS) under different height gaps

3.2.2 Elastic modulus of filler

The effects of elastic modulus of the filler on the rolling deformation of the integral panel were studied. In the roll bending process, the filler's elastic modulus directly affects the filler's deformation. The elastic modulus of the filler determines whether it is easy to deform. Filler in filling roll bending includes solid rubbers, plastics, and metal [13]. Their elastic modulus varies widely.

To ensure the coordinated deformation between the filler and the web, the bending stiffness of the filler needs to be similar to that of the web. The calculation formula of bending stiffness is the elastic modulus E multiplied by the moment of inertia I of the bending section. It is known that the elastic modulus of the integral panel is E_1, the moment of inertia is I_1, the elastic modulus of the filler is E_2, and the moment of inertia is I_2. Therefore, the elastic modulus E_2 of the filler will meet the following formula:

$$E_2 = \frac{E_1 I_1}{I_2} \tag{8}$$

The filler and the integral panel are approximated as flat plates, and the calculation formula of moment of inertia is

$$I = \frac{bh^3}{12} \tag{9}$$

In the above formula, b is the plate width. The values of integral panel grid and filler are 194 and 190 mm, respectively; h is the plate thickness, and the values of integral panel grid and filler are 4 and 13 mm, respectively. The elastic modulus E_1 of integral panel material 2A12-T4 aluminum alloy is 72400 MPa. According to Formula (8), the elastic modulus E_2 of filler is 2153 MPa. That is, when the elastic modulus of the filler is 2153 MPa, the bending stiffness of the filler is similar to that of the web of the integral panel. However, a single mesh is not deformed in isolation but affected by the overall deformation of the integral panel, which is easier to bend. Therefore, the bending stiffness of the web I_1 should be lower than that calculated above, so the elastic modulus of the filler E_2 should be lower than 2153 MPa.

Based on this situation, the elastic modulus of the filler for each simulation is shown in Table 4. Other filler parameters are as follows: d=2 mm, h=1 mm.

Table 4 Elastic modulus of filler

Simulation No.	1	2	3	4
E/MPa	50	450	800	1000
Simulation No.	5	6	7	8
E/MPa	1300	2000	2500	20000

The position of the neutral layer of the integral panel with the filler under different elastic moduli is shown in Fig. 14(a). With the increase of the elastic modulus of the filler, the neutral layer at the ribs and the web center both shift upward, indicating that the deformation of the integral panel increases gradually. Figure 14(b) counts the neutral layer position difference and the generatrix straightness of the integral panel. The neutral layer position difference between the rib and the web center decreases with the increase of the elastic modulus of the filler, and the generatrix straightness after the integral panel forming also conforms to this trend, indicating that the increase of the elastic modulus improves the pressure transmission capacity of the filler. However, when the elastic modulus increases from 450 to 2500 MPa, the changes in the neutral layer difference and the generatrix straightness are small.

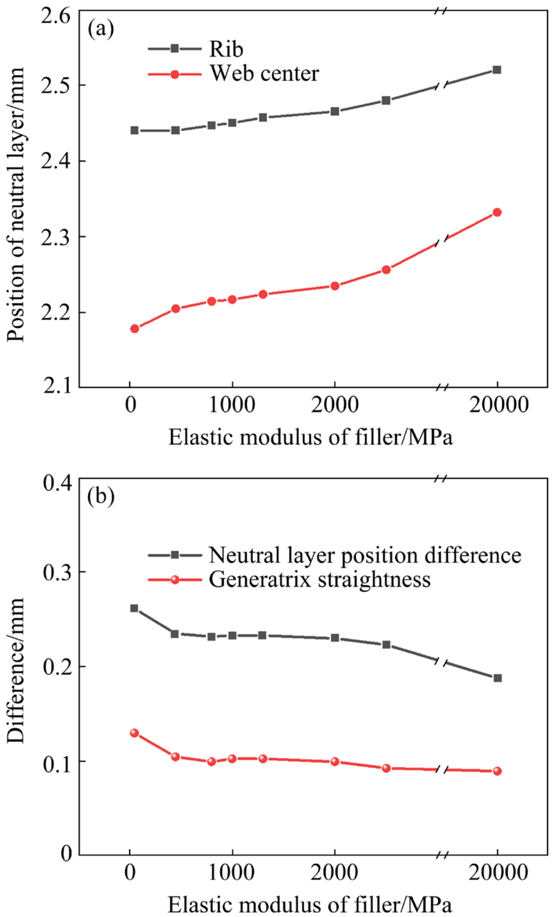

Fig. 14 FE results under different filler elastic moduli: (a) Position of neutral layer; (b) Neutral layer position difference and generatrix straightness

The integral panel *XZ* section is shown in Fig. 15(a). It can be found that if the elastic modulus of the filler is 50 MPa, the grid is completely filled with the filler after compression. However, the position difference of the neutral layer and the straightness are large, indicating that pressure transmission is limited when the elastic modulus of the filler is low. As the elastic modulus of the filler increases from 450 to 2500 MPa, the stress of the filler increases, and there is almost no difference in the deformation degree between the filler and the web. According to Fig. 14(b), the neutral layers at the rib and web shift upward slightly, indicating that when the elastic modulus of the filler changes in this area, it has little impact on the forming quality of the integral panel. However, it is supposed that the elastic modulus of the filler is 20000 MPa. In this case, there is a large gap between the filler and the web, and the filler squeezes the *Y*-direction rib, indicating that the bent grid cannot drive the deformation of the filler. In this case, the overall deformation of the integral panel is significant, but it is not easy to achieve the ideal curvature.

The contact pressure (CPRESS) between the integral panel and the filler is shown in Fig. 15(b). When the elastic modulus is 50 MPa, there is only a little pressure at the web center, and the filler does not effectively transfer the load. When the elastic modulus increases to 450 MPa, the stress distribution at the web center is improved. When the elastic modulus is 1300 MPa, the filler begins to squeeze the *Y*-direction ribs. With the increase of the elastic modulus of the filler, after reaching 2500 MPa, the pressure of the filler on *Y*-direction rib increases, while the pressure at the web center decreases, and the pressure at the rib is greater than that at the web, which is not conducive to transfer pressure to the web center. When it increases to 20000 MPa, the contact pressure between the filler and the web almost disappears. Combined with the grid deformation, when the elastic modulus of the filler is too high, there will be a gap between the filler and the web because it is not easy to bend and deform. At the same time, too high pressure will be generated on the rib of the integral panel, which is not conducive to the bending deformation of the integral panel.

Therefore, it can be found that when the elastic modulus of the filler is 50 MPa, the pressure cannot be effectively transmitted. When the elastic modulus is 20000 MPa, the grid of the integral panel is difficult to deform. When the elastic modulus is within a certain range (450−1300 MPa), it can effectively transfer pressure to the web center, and the elastic modulus of polypropylene filler is just in this range, which is a better filler choice.

3.3 Experimental verification

In the roll bending experimental verification of the integral panel with the same grid size, the generatrix straightness is measured by sampling on the side of the skin, and the results are shown in Fig. 16. The integral panel’s generatrix straightness

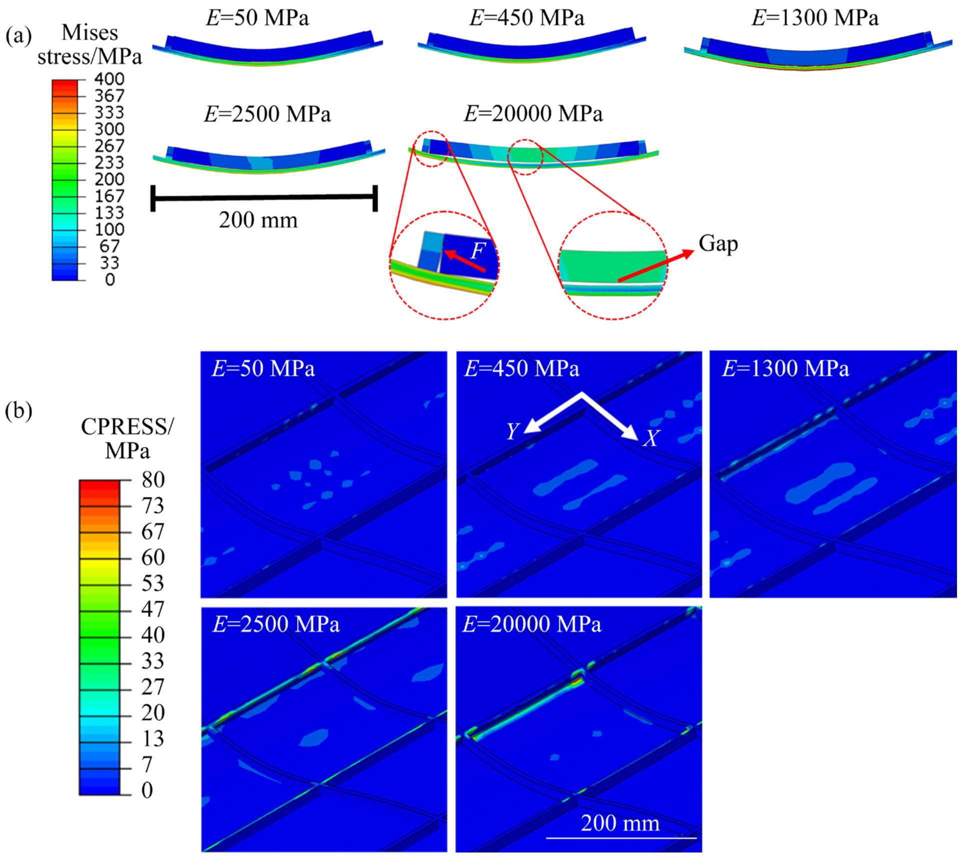

Fig. 15 Deformation of grid: (a) *XZ* section of bent panel under different filler elastic moduli; (b) Contact pressure (CPRESS) under different filler elastic moduli

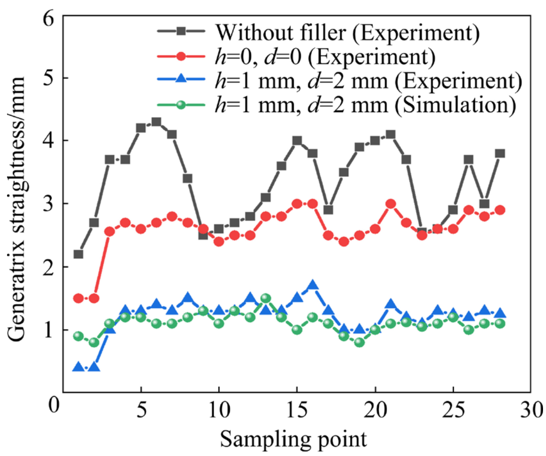

Fig. 16 Generatrix straightness of integral panel in experiment

is 3−4 mm when roll bending without filler. The initial filler is the same as the grid cavity size (*h*=0, *d*=0). In the initial stage of roll bending, the elastic modulus of the filler is 450 MPa. When the filler is in complete contact with the ribs, the elastic modulus of the filler is 1300 MPa. After roll bending, the generatrix straightness is reduced to 2−3 mm. By adjusting the height and width gaps (*h*=1 mm, *d*=2 mm), the generatrix straightness of the integral panel is further reduced to 1−1.5 mm, which meets the process requirements. This result is also close to the result obtained by the finite element method.

4 Conclusions

(1) The filler reduces the position difference of the neutral layer between the rib and the web by reducing the deformation at the rib and improving the deformation at the web, which results in the generatrix straightness amelioration of the integral panel.

(2) The width gap between the filler and the rib determines the deformation space of the filler. Keeping a certain range of width gap (1−3 mm) can protect the rib without affecting the forming accuracy of the integral panel.

(3) The height gap between the filler and the rib determines that the compression degree of the filler can be compressed. The filler height should be kept slightly higher than the height of the rib to

ensure that the pressure can still be transmitted well after compression.

(4) The elastic modulus of the filler determines the bending stiffness. The elastic modulus of filler has a little difference in the forming accuracy of the integral panel within a certain range (450−1300 MPa). When the elastic modulus of the filler is 50 MPa, the pressure cannot be transmitted effectively. When the elastic modulus of the filler is 20000 MPa, the bending stiffness of the filler is higher than that of the web, which will limit the deformation of the integral panel.

(5) Experiments verified the accuracy of the finite element model and the operating mechanism of filler on the filling roll bending. Optimizing the filler parameters can greatly improve the forming accuracy of the filling roll bending process.

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一种整体壁板填料辅助滚弯成形过程中填料作用机理

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摘　要：研究一种 2A12 铝合金整体壁板的聚丙烯填料辅助滚弯成形工艺，结合力学分析、数值模拟和实验验证，揭示填料的作用机理。结果表明，整体壁板筋条与蒙皮处的中性层位置差导致其成形后母线直线度不达标，填料可以降低这种中性层位置差。当填料与筋条有一定宽度间隙(1~3 mm)时，可以避免填料卷曲和筋条失稳。而填料和筋条的高度间隙决定填料可被压缩程度，当填料在压缩后仍高于筋条(1 mm)时，可以达到最佳的压力传递效果。填料的弹性模量在一定范围内时(450~1300 MPa)，对整体壁板的成形精度影响不大。但填料弹性模量较低时(50 MPa)，填料传递的压力不足；填料弹性模量较高时(20 GPa)，整体壁板弯曲变形受限。实验后壁板母线直线度的测量结果验证了填料的作用机理。

关键词：整体壁板；滚弯成形；填料；中性层；母线直线度

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