Evolution of Stress and Strain in 2219 Aluminum Alloy Ring During Roll-Bending Process

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Abstract

The large quenched residual stress of large-scale aluminum alloy ring component induces severe deformation in the subsequent machining process. The conventional methods for reduction of residual stress (such as stepwise cold pressing and bulging) have little effect in the residual stress reduction for large-scale ring component and will induce inhomogeneous stress distribution. In this paper, roll bending process is adopted to reduce the quenched residual stress of 2219 aluminum alloy super-large ring. The numerical model of roll bending process was established, and the evolution and distribution of stress and strain after roll bending were studied. The influence of roll winding number on the uniformity of stress and strain was analyzed. The results show that the arch-shaped quenched residual stress of the ring changes to N-shaped distribution from inside to outside after roll bending process. The value of the residual stress reduces from $\pm 180\text{MPa}$ in quenched state to the value within $\pm 50\text{MPa}$ in roll bended state. With the increase of roll winding number, the stress uniformity is improved, but the stress reduction amplitude is basically the same. By analyzing the elastic-plastic strain distribution characteristics and strain springback law of the ring after roll bending, the formation mechanism of N-shaped residual stress distribution after roll bending is revealed.

1 Introduction

2219 aluminum alloy is widely used in rocket fuel tank, supersonic aircraft skin and other fields due to its excellent comprehensive performance[1-4]. In order to improve the comprehensive properties of aluminum alloy materials, aluminum alloy materials are usually solution strengthened[5-8]. However, in the process of quenching, due to the rapid cooling rate of the outer layer and the slow cooling rate of the inner layer, residual stress is inevitably introduced in the material, accompanied by deformation. The material warping and subsequent machining deformation caused by quenching residual stress is an urgent problem to be solved in the aerospace field. It is of great significance to control the quenching residual stress of aluminum alloy effectively.

According to the principle of residual stress relief, the current residual stress relief process can be divided into two categories, thermal stress reduction method and mechanical stress reduction method[9]. Wu studied the effect of thermal stress relief treatment on reducing residual stress and homogenization of rolling process[10]. M.G developed a new residual stress assessment method based on single Debye ring analysis. This method is especially suitable for stress analysis of coatings and samples with complex geometry[11]. LV, Nan studied a long-term natural aging treatment method, explored and verified the effect of natural aging and artificial aging on homogenizing and reducing in ferrule [12]. Ma used indentation strain gauge method to study the residual stress of 2219 aluminum alloy super large rolled ring[13]. GP Dolan uses quenching factor analysis to slowly cool the alloy from the solution heat treatment temperature to the intermediate temperature above the critical temperature region of the C curve. In the quenching process, the numerical value of residual stress generated is reduced[14]. Yang used finite element method and finite element simulation method to study the reduction of residual stress in the cold stretching process[15].

Due to the large size and special application field of large-size ring parts, the research on controlling the residual stress of large-size ring parts is less. In recent years, radial bulging method[16] and roll bending method[17] used in controlling the residual stress of large-size ring parts are reported. However, it is difficult to provide scientific guidance for the internal stress reduction process of the ring from the mechanism due to the lack of research on the evolution of the internal stress of the ring by these stress reduction processes.

In this work, the roll bending process of large size 2219 aluminum alloy ring was analyzed by using finite element method, and the evolution of stress and strain was obtained. Then the effect of the number of rolling turns on the uniformity of stress and strain in the ring was studied. It is of great significance to understand the evolution of stress-strain field in the bending process of large-scale ring for effectively formulating the stress reduction process.

2 Numerical Models

2.1 Overview of roll bending

The specific steps of roll bending experiment are as follows:

First, install the quenched ring in the proper position of the symmetrical three-axis roll bending machine, so that the feed roller and the drive roller are just in contact with the inner and outer surfaces of the ring, and ensure that the axial direction of the ring is parallel to the axial direction of the three rollers. Adjust the position of the ring and the feed roller, and place the quenched ring as shown in the figure, ensure the stability of the installation.

Then, the feed roll is moved downward along the radial direction to make it have a certain amount of reduction, and the hydraulic press is driven to make the feed roll move downward by 20 mm vertically. Mark the bottom of the ring with a marking pen along the radial direction.

Finally, the driving motor is used to set two driving rollers to rotate at the same angular speed (0.3rad/s), so that the ring is driven by the friction of the driving roller, and then the feed roller is driven to rotate passively, and the ring is driven by the friction.

After the rotation of the ring is finished, the load of the feed roller moving upward along the radial direction is applied, so that the feed roller gradually leaves the ring, and the feed roller gradually rises to leave the ring.

The principle of reducing residual stress by roll bending is that the feeding roll presses down the ring under the action of external load, and the ring part in the middle of the three rollers will be affected by bending moment. During the roll bending process, the ring will rotate with the rotation of the driving roll, and the ring will appear continuously in the middle of the three rollers, thus continuously affected by

bending moment. When the bending moment reaches a certain value, the ring will have plastic deformation, which will release and reduce the quenching residual stress.

2.2 Material parameters

The physical properties of 2219 aluminum alloy are shown in Table 1, the chemical composition of 2219 aluminum alloy is shown in Table 2.

Table 1
Physical properties of 2219 aluminum alloy

Parameter	Young's Modulus (E)	Density (ρ)	Poisson Ratio (ν)	Yield Strength (σ_s)	Coefficient of Thermal Expansion (α)
Units	GPa	kg/m ³	-	MPa	10 ⁻⁶ /°C
2219 Al-alloy	73	2840	0.3	350	22.3

Table 2
Chemical composition of 2219 aluminum alloy

Cu	Mn	Ti	Zr	V	Mg	Zn	Fe	Si	Al
5.8–6.8	0.2–0.4	0.02–0.1	0.1–0.25	0.05–0.15	≤ 0.02	≤ 0.1	≤ 0.3	≤ 0.2	The rest

2.3 Finite element model

Ring roll bending is an unsteady three-dimensional deformation process with geometric nonlinearity, physical nonlinearity and unstable boundary conditions, the roll bending model of the ring is established, as shown in the Fig. 2(a). The outer two driving rollers rotate counterclockwise to provide rotating power for the clockwise rotation of the ring. The feeding roller completes the continuous rolling extrusion of the ring through radial downward and rotary motion to produce plastic deformation. The simulation parameters are shown in Table 3. The research method in this paper is also suitable for roll bending simulation of other large diameter rings.

Table 3
Finite element simulation parameters

Simulation parameters	Specification/Values
Coefficient of friction	0.3rad/s
Mesh size	7.05*20*20.5mm
Aluminum alloy ring size	5000(4700)/410mm
Feed roller size	460/800mm
Drive roller size	770/800mm

The initial state of the roll bending is shown in Fig. 2(b). A fixed virtual ring surface with the same diameter of the aluminum alloy ring is defined to analyze the roll bending process of the ring. The virtual ring surface is divided into eight equal parts along the circumferential direction, and the equinoxes are marked as A1 to A8 successively. Along the clockwise direction, A1 to A8 corresponding to 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° respectively. A1 to A8 are used as the reference points for the analysis of the roll bending of the large ring, and the positions of A1 to A8 remain the same. A section S1 on the ring is selected to track and analyze the stress and strain evolution during the roll bending process. The initial position of section S1 locates at A1 (0°), while the position of the working roll is fixed at A3 (90°). During the roll bending process, the large ring rotates clockwise, and the section S1 passes through point A1 to A8 in turn and go on, that is the angle positions of section S1 are corresponding to 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° respectively and go on. When section S1 locates at the position of 90°, it is just in the bending roll working area.

3 Experiments

Surface residual stress of the large ring was measured using X-Ray Diffractometer (XRD, STRESSTECH OY, Jyväskylä, Finland), and the measurement result was compared with FEM result. The measurement area was shown in Fig. 3. The measurement was carried out in steps of 10 mm interval in the radial and axial direction. The diffractometer parameters used in the measurement was shown in Table 4.

Table 4
XRD measurement parameters

X-ray Diffraction Parameters	Specification/Values
Tube type	Cr
Supplied current during the experiment	6.7mA
Supplied voltage during the experiment	30kV
Exposure time for the calibration	8s
Exposure time for the measurement	10s
Collimator diameter	3mm
Collimator distance	10.390mm
Tilt angle	50mm
Number of tilts	-45°to 45°
Rotation angle	5/5
Number of rotations	2
Stress resolution	± 10MPa

4 Results And Discussion

4.1 Evolution of internal stress

4.1.1 Residual stress after quenching

The simulation results of quenching residual stress on the analysis section S1 are shown in Fig. 4. It can be seen from Fig. 4 that, the radial stress of the ring is about 100 MPa on the upper and lower surfaces, and the circumferential stress, axial stress and Mises's stress of the ring are symmetrically distributed along the geometric center of the analysis section. The circumferential stress and axial stress of the ring are composed of the tensile stress in the core region and the compressive stress on the surface. The peak compressive stress and tensile stress are 140 MPa and 130 MPa respectively. The axial stress has relatively small values at the upper and lower edges, and the axial core tensile stress is less than the circumferential core tensile stress. Mises stress distribution ranges from 40 to 140 MPa.

The radial and circumferential stresses of the simulated results and the measurement results were compared as shown in Fig. 5. It can be seen from the figure that the measurement results are in good agreement with the simulated results, which verifies the feasibility and reliability of the numerical model.

4.1.2 The evolution of inner stress during the roll bending process

As showed in Fig. 3, the radial path L1 is taken on the section S1 of the ring to analyze the change rule of stress at each node on the path during the process of 1-turn roll bending.

As can be observed in Fig. 7 and Fig. 8, as the roll bending progresses, the distribution of circumferential stress along the path L1 gradually evolves from a parabola to an N-shape, and the change rule of axial stress is consistent with that of circumferential stress. When the cross section S1 is at 0 and the feed roll is pressed down 20mm, the distribution trend of the anisotropic stress remains unchanged, but the numerical value decreases slightly. When the cross section S1 reaches the position of 45°, although the cross section is not in the roll bending zone, the stress has begun to decrease, the maximum tensile stress and the maximum compressive stress have decreased by about 10%, and the stress distribution is still parabolic. When the section S1 reaches the position of 90° (roll bending zone), the stress distribution presents the compressive stress on the inner surface of the ring and the tensile stress on the outer surface, due to the large pressure generated by the feed roller. Section S1 arrived at 135° position, at this time as a result of roll bending process in section S1 surrounding area is introduced into the plastic deformation, stress reduction amplitude is larger, the stress distribution by parabola into N shape, but because of the close section distance driven roller, work stress has not released, is still in a state of large, large ring inside for a larger compressive stress, the lateral tensile stress; When the section S1 is located at 225°, the section has left the roll bending zone and is not affected by excess working stress. Meanwhile the stress value decreases but the overall trend does not change, and the stress distribution is basically stable. When the section S1 is located at 315°, it is far away from the drive roller, the stress value and law tend to be stable and the stress size is basically the same. Meanwhile the stress is quite small and the reduction effect is good, presenting an obvious N-shaped distribution.

4.2 Evolution of internal strain

When the roll bending occurs, the ring produces elastic-plastic strain. Although the tensile stress and compressive stress exceed the yield stress, in fact, when the tensile stress inside the ring transits to the external compressive stress, a large plastic deformation occurs outside the ring, corresponding to its plastic strain. After the feed roll is lifted, the plastic strain is retained, but the neutral layer does not produce plastic deformation or small plastic deformation, and there is no plastic strain or small plastic strain. It is almost all elastic deformation. Corresponding to the elastic strain, the ring reaches the stable region. When the bending load is unloaded, the neutral layer material will inevitably rebound, and the stress is unchanged. Therefore, it is necessary to study the elastic-plastic strain law.

Fig.8 is the contour map of equivalent strain after S1 section. Path L1 is taken at the S1 section of the ring, and the results are shown in Fig.9.

Figure 8 showed the plastic strain nephogram of section S1 after roll bending. The results demonstrate that the maximum plastic strain value is at the outer contour of the ring, and the strain value is 0.0324.

The minimum strain is at the core of the ring and near the inner part of the ring, and the smallest plastic strain is 0.00098. This is because insufficient pressure of the feed roller in the roll bending process does not affect the core of the ring enough to make it produce sufficient plastic deformation.

In order to discover the distribution rule, the equivalent plastic strain and the anisotropic plastic strain were studied by taking the radial path 1. Figure 9 show the equivalent plastic strain distribution along the selected path in the longitudinal section of the ring after roll bending. The results show that the plastic deformation generated by radial path 1 present an asymmetric "U" shape along the radial direction, that is, the middle and low end are higher, and the difference is obvious. This is explained by the large radial strain difference between the inner and outer rings, so the region cannot reach the center, and plastic deformation occurs only near the inner and outer surfaces of the rings.

In the roll bending process, the ring not only produces plastic strain, because the reduction of the feed roller does not reach enough to lead to the change of its shape, therefore, there is also the corresponding elastic strain. In order to study the elastic strain law of the ring, the elastic deformation cloud image in the roll bending process is taken as follow :

Figure 10 shows the elastic strain nephogram of S1 section. The results show that the maximum elastic strain was located in the neutral layer of the ring, the elastic strain is 0.001, the minimum elastic strain is located in the inner surface of the ring, and the minimum elastic strain is 0.00073. In order to study the rule of path 1, Fig. 11 shows the elastic strain distribution along the selected path on the longitudinal section of the ring after roll bending. The results show that the elastic deformation of the middle part is large, and the elastic deformation of the inner and outer contour is smaller than that of the middle part, but the overall difference is not large.

4.3 Influence of roll bending cycle on the uniformity of residual stress and strain

4.3.1 Effect of roll bending cycle on stress

It can be seen from the evolution of the stress and strain in the ring that the stress and strain in the roll bending process are uniform. In order to examine the influence of roll bending on the uniformity of stress distribution of ring parts, four rings with the same quenching process were subjected to continuous roll bending for 1 to 4 times respectively. Eight points was uniformly distributed on the end faces of ring parts as shown in Fig. 2, and the surface stress distribution at each point of the four rings after roll bending was compared. According to the characteristics of residual stress distribution of 2219 aluminum alloy rings, the circumferential stress and axial stress of 2219 aluminum alloy rings at different points were compared and analyzed by drawing a radar chart[18]. The closer the position of eight points to the uniform octagon, the more homogeneous the residual stress of the ring is, and the more consistent the anisotropic structure is.

It can be seen from Fig. 12 that, the residual stress at each analysis point of the ring after different number of roll bending turns is far less than the original quenching residual stress. After the first roll bending, the change of residual stress of the ring is the largest, but the distribution of residual stress is uneven. With the increase of the number of roll bends, the residual stress changes little, but the residual stress tends to be uniform.

In the figure, the distribution of stress in all directions appears a "sharp Angle" phenomenon, that is, residual stress at 1 ~ 2 test points is significantly higher or lower than other test points. After the second roll bending, the stress reduction value decreases, the axial stress is on the brink of the normal octagon, but the circumferential stress still has the phenomenon of "sharp Angle". After 3 rolls bending, the residual stress in each direction tends to be a uniform octagon. There is no changes in stress after 4 rolls bending.

In order to quantify the influence of the number of turns in the roll bending process on the stress inhomogeneity, stress standard deviation S is used to evaluate and describe the distribution uniformity of residual stress on the above points. The formula for standard deviation is as following:

$$S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (4-1)$$

Where S is the standard deviation of each point,
 n is the study point, x_i is the stress value of the
study point, and $\bar{x}$ is the mean stress value. The
result is shown in Fig.13 and Fig.14:

It can be seen from the standard deviation analysis shown in Fig. 13 and Fig. 14 that, there are great differences in the distribution uniformity of ring residual stress after different number of roll bending. After one roll bending, although the stress reduction is very large, the distribution of stress at each part of the ring is also quite different, so the standard deviation of stress at each part is much larger than that in the quenched state, with the standard deviation of stress distribution of 17.35MPa, the inhomogeneity increased by 71.6%. After 2 turns of roll bending, the standard deviation of circumferential stress decreases and reaches 12.2MPa. Meanwhile the sharp Angle phenomenon is partially improved, but the fluctuation is still large, and the unevenness increases by 59.5%. After 3 turns of roll bending, the circumferential stress homogeneity decreases and reaches 2.21MPa, and the homogeneity is enhanced by 55.1%, showing good uniformity. After 4 rolls, due to the local deformation of the roll bending process, excessive number of turns will not result in the decrease of stress uniformity.

As can be observed in Fig. 14, the distribution uniformity of residual stress in the third roll bending circle has the most significant difference, reaching 1.27MPa, indicating good stress uniformity. The standard deviation of axial stress has decreased by 75.7%. Therefore, it can be assumed that the uniformity of the roll bending to the third turn is better.

4.3.2 Effect of roll bending cycle on strain

According to the strain distribution law, the maximum deformation occurred at the outer contour of the ring, while the minimum plastic deformation occurred at the core of the ring. In order to analyze the influence of different number of roll bending turns on the strain uniformity, the ratio E of the minimum strain at the core of the large ring section (aforementioned S1) and the maximum strain at the surface was used to represent the strain uniformity

$$e = \frac{\varepsilon_{min}}{\varepsilon_{max}} \quad (4-2)$$

The strain nonuniformity coefficient e was used to evaluate the distribution uniformity of plastic deformation in the ring. After adopting different roll bending processes, E ratio is shown in Table 5. In the process of roll bending with different roll bending turns, E gradually decreases. The e value of the first circle is very large, reaching 2.9%, and the strain is not uniform, but the stress reduction effect is very good. In the second lap, E gradually decreases to 1.7%, the uniformity increases, but the stress reduction effect decreases. From the third turn, E reaches 1.3%, and the strain coefficient tends to be stable after that, so it can be considered that the uniformity is good at the third cycles.

Table 5. Strain nonuniformity coefficient under different cycles

Strain values(%)	cycle			
	1	2	3	4
ε_{min}	0.261	0.122	0.051	0.0442
ε_{max}	8.81	7.12	3.74	3.18
e	2.9	1.7	1.3	1.3

4.4 Discussion

4.4.1 Evolution of N-shape stress

The ring roll bending process is similar to the three-roll bending process for beam parts as described by Abvabi [19]. In this section, a simplified three-point roll bending model of the ring is established as shown in Fig. 17, and the evolution of stress distribution from parabola to N-shape is analyzed. The roll bending part is divided into four areas: entry area, contact area, departure area and stable area. When the ring material passes through the four areas, the stress distribution along path L1 is shown in Fig. 15 and Fig. 16.

In the process of roll bending, when the ring material is located at the entry point, the inner side and the outer side of the ring are subjected to working tensile stress and working compressive stress respectively under the support of the driving roll.

When the ring material reaches the contact area, the ring will bulge from the inner side to the outer side under the pressure of the feeding roller, and the inner and outer sides of the ring are subjected to working compressive stress and the working tensile stress respectively, which is opposite to the direction of the working stress produced by the driving roller at the feeding point.

When the ring material reaches the departure area, the direction of the working stress generated by the driving roller in the ring is similar to that at the entry point.

When the ring material reaches the stable area, the tensile elastic stress caused by the tensile working load of the inner ring material, and the compressive elastic stress caused by the compressive working load are released, so that the approximate Z-type stress distribution of the previous step (at the departure area) evolves into N-type stress distribution, which is consistent with the research results of Peng[20].

After adding quenching stress, the roll bending results are shown in Fig. 16. At the entry point, due to the existence of quenching residual stress, the overall stress is greater than that in the non-stress state. However, after entering the contact point, due to the pressure of the feed roller, the ring stress changes uniformly, presenting the stress distribution of internal pressure and external tension. At this point, the stress of the ring without prestressed roll bending and the ring with quenching stress roll bending presents the same trend under the same feed roller, and the difference of stress values is small. When entering the departure point, due to the quality of the ring itself and the pressure of the feed roller, the internal stress of the ring presents the stress distribution of internal tension and external pressure. Meanwhile the stress value of the two states is basically the same. Until the ring reaches the stable area after the end of the roll bending and the elastic deformation is released, the stress distribution law of the two states presents the same, and the difference of stress value is small.

4.4.2 Effect of springback on bending

During the roll bending process of the ring, the outer material is subjected to tensile stress, and the inner material is subjected to compressive stress. The surface with zero stress of the stress neutral layer in the thickness direction of the ring is divided into tensile deformation zone and compressive deformation zone. Under the action of pure bending moment, the values of tensile, compressive stress and strain at the upper and lower parts of the neutral layer are equal, and the elastic part under the two stress states should be restored, which will produce an opposite torque and cause springback. Since the springback of each part of the profile is different, the springback of the middle part with large curvature is small, and the springback of the two ends with small curvature is large, the maximum distance between the two ends of the profile before and after unloading is defined as the springback, as shown in the Fig. 18.

When elastic-plastic bending occurs in the roll bending process of the material, the elastic strain affects the inner wall 1, the middle part 2 and the outer part 3 of the ring material, respectively. The plastic deformation of the parts 1 and 3 is retained after unloading at the end of the bending deformation, while the elastic deformation of the parts 2 is completely disappeared. At the same time, the elastic deformation components in the deformation area and the outer area produce the elastic stress opposite

to the direction of the plastic deformation stress. After the ring is removed from the roll bending zone, the corresponding deformation (springback) is generated under the action of elastic bending moment to reach a new equilibrium state. Corresponding to the departure point, the inner compressive stress and the outer tensile stress of each part of the ring bending.

It can be seen from the figure that the main springback areas are located at positions 1, 2 and 3, and the position of elastic stress generated by the springback amount of 1 and 3 is basically consistent with the position of the reverse stress. Since 2 was located in the middle part, the plastic deformation is small and the elastic deformation is large, so the stress distribution in the two parts is approximately linear, forming an N-shaped distribution. The law of strain reflects the change of stress.

5 Conclusions

The residual stress of 2219 aluminum alloy ring after quenching was reduced by roll bending process. The evolution of stress and strain during roll bending and the distribution of residual stress after roll bending were studied. The results are summarized as follows:

1. When the ring is rotated from 0° to 360° (the roll position is 90°), the arch-shaped quenched residual stress of the ring changes to N-shaped distribution from inside to outside after roll bending process. The value of the residual stress reduces from $\pm 180\text{MPa}$ in quenched state to the value within $\pm 50\text{MPa}$ in roll bended state.
2. Based on elastoplastic strain analysis during roll bending, the inner mechanism of n-type stress distribution during roll bending was revealed. Elastoplastic deformation exists in the roll bending process. Due to the small feed of the feed roll, the elastic strain is arched, the inner elastic deformation of the ring is large, and the contour is small. The springback generated along the thickness of 25% makes the part produce an opposite elastic stress. The plastic strain shows an opposite trend, presenting an inverted arch shape. The internal plastic deformation is small, the external plastic strain is large, and the internal residual stress still presents oblique distribution. The comprehensive action makes the residual stress of the ring after roll bending show an N-shaped regular distribution.
3. With the increase of roll winding number, the stress uniformity is improved, but the stress reduction amplitude is basically the same. After 1 cycle of the roll, the stress reduction amplitude is large, but the stress uniformity increases. After 2 cycles of the roll, the stress uniformity is improved, but the stress reduction amplitude is close to the first turn. After 3 cycles of the roll, the standard deviation of the principal stress and the strain inhomogeneity coefficient are 1.27 and 1.3%, respectively, indicating that the stress uniformity has reached stability.

Declarations

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Figures

Figure 1

Roll bending experiment

Figure 2

diagram of radial section-1

(a) measurement process

(b) Distribution of measuring points

Figure 3

Stress measurement

(a) Radial stress

(b) Circumferential stress

(c) Axial stress

(d) Mises stress

Figure 4

Maps of residual stress distribution after quenching.

Figure 5

Comparison diagram of finite element results and simulation results

Figure 6

Distribution of Circumferential residual stress along path 1 during roll bending

Figure 7

Distribution of axial residual stress along path 1 during roll bending

Figure 8

Plastic strain diagram

Figure 9

Plastic strain distribution along path 1 during roll bending

Figure 10

Elastic strain diagram

Figure 11

Elastic strain distribution along path 1

(a) Distribution of Circumferential residual stress.

(b) Distribution of axial residual stress.

Figure 12

Radar diagram of residual stress

Figure 13

Comparison of standard deviation of circumferential stress

Figure 14

Comparison of standard deviation of axial stress

Figure 15

Stress free roll bending path diagram

Figure 16

Prestressed roll bending diagram exists

Figure 17

Simplified diagram of roll bending process

Figure 18

Strain comparison diagram of ring before and after roll bending