Key technology and equipment for local heating roll-forming of high strength square tube

Xue-Feng Peng¹, Jing-Tao Han² and Zong-Miao Dai¹
¹Ninth department, 713th Research Institute of China Shipbuilding Industry Corporation, Zhengzhou 450015, China
²School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

Abstract. The application of advanced high strength steel and the development innovation manufacturing technology is an effective way to realize the automobile lightweight and improve the safety performance design of high strength steel products. In this paper, a local heating “square to square” roll-forming process was proposed to solve the difficult problems of the introducing high strength steel into the traditional roll-forming equipment. Two kinds of inductors structure were compared and analyzed. Based on the “round to square” process, the size design of the rollers in forming process was deduced by the mutual relationship of the angle. And the relationship between the frame layout was given. The calculation of example and the key technical equipment were completed. Based on this new technology, the performance test of high strength tubes was carried out. It was found that the mechanical properties of the corner and the dimensional accuracy of the section are significantly improved. The research shows that this key technology and equipment of hot roll-forming can effectively overcome the problems of high strength steel.

1. Introduction
With the development of automobile lightweight, high-strength steel square tubes have been widely used in vehicles. The traditional forming process of square tube mainly has two kinds. One is directly formed by bending the steel plate, after welding, referred to as the “directly to square” process. The other one is first bending the steel plate into a round tube, after welding, then finishing into a square tube, known as the “round to square” process [1]. For the traditional square tube, the two processes have their own characteristics and can be selected according to customer needs. However, for the high-strength steel square tube, because of its high strength and low elongation, the advantage of “directly to square” process in terms of elongation is obvious, but the upper corner defects caused by empty bending and the phenomenon of thinning of bending angle in forming process are inevitable. This paper combines the advantages of “round to square” process and “directly to square” process as well as induction heating technology, and puts forward a local heating “square to square” roll-forming process”. Its technological principle is that the steel plate is bent into a preformed tube with a larger fillet radius by using “directly to square” process at first. Only a slight strain occurs at the corner of the square tube. The fillet of the square tube is local heated linearly before finishing, and the forming performance is improved when the fillet reaches a certain temperature. When the heated preformed tube is into finishing pass, the high quality square tube with excellent mechanical properties and small radius or sharp fillet can be obtained by controlling the technological parameters. In this paper, the key
technology and equipment analysis will be carried out from two aspects of inductor structure design and pass design of “square to square” process.

2. Design of local heating inductor

The structure design of inductor is closely related to the local heating roll-forming process, which determines whether the hot roll-forming technology can be successful. In the process of induction heating, there will be sharp-angle effect. When there is a special sharp angle area in the heated parts, the magnetic induction line is easily gathered at this sharp area, which makes the induction current density larger. The traditional inductor design generally avoids the sharp-angle effect to cause over-burning. This paper makes full use of the sharp-angle effect of induced current to realize local heating at the fillet of high-strength square tube. According to the characteristics of square tube section, the layout principle of the inductor designed is shown in figure 1 (a).

In the design, the “driving” effect of the magnetizer is also utilized. The U-type magnetizer is mounted on the induction coil of inductor, so that more magnetic induction lines can pass through the square tube from the open side of magnetizer, as shown in figure 1 (b), which is called the “driving” effect of the magnetizer. Essentially, the magnetizer changes the direction of the magnetic induction lines, thereby increasing the amount of magnetic flux that through the inner of square tube.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of inductor structure.

The inductor is made of copper tube by drawing and welding. The copper tube is heated and filled with sand to avoid shrinkage of rectangular section in the forming process. The structure design of inductor is shown in figure 2, which are named as single coil inductor and compound coil inductor, respectively. The single coil inductor is a circular shape, and the silicon lamination is embedded in the heating zone to change the direction of the magnetic induction line to obtain a higher temperature in the corner area. This coil has a higher flux utilization rate, but the heating time is shorter at the same forming speed. The composite coil inductor is also attached with silicon lamination in the heating zone, which can realize a long-term linear heating process, but the magnetic flux efficiency is relatively low.

![Figure 2](image2.png)

**Figure 2.** Design of two inductor structures.

Figure 3 shows the temperature distribution of the outer surface of square tube obtained by the two inductor structures in ANSYS simulation analysis software [3]. Figure 4 is a physical diagram of the surface temperature distribution of square tube heated by local induction during the experiment.
Setting target temperature at the corner of square tube is 600 °C. It is found from figure 3 that the maximum temperature is at the corner of square tube, which illustrates that the magnetizer plays the role of “driving” function. Both inductors can achieve the local heating effect of square tube. However, it is found that the heat affected zone of single coil inductor is larger and the temperature is higher than the value of composite coil inductor from figure 3 (a). And the heat affected zone temperatures at the center of the preformed tube plane are 86 °C and 195 °C for both inductors, respectively. For the composite coil inductor, it is clear that there is no blackening in the square tube plane as shown in figure 4 (b). Considering that the high temperature in heat affected zone caused by single coil inductor will affect the microstructure and mechanical properties of the undeformed zone, so the composite coil inductor is selected.

![Figure 3. Simulated temperature distribution of two inductor structures.](image1)

![Figure 4. Heating effect diagram of two inductor structures.](image2)

3. Design of “square to square” process

The design theory of “square to square” process is based on the pass design of the “round to square” process. Researchers have accumulated a lot of experience about the pass design of “round to square” process. Sun Jia [4] introduced a design method of square tube with deformation angle and deflection coefficient as basic design parameters. This method can accurately reflect the deformation process. Cao Guo-fu [5] proposed the coefficient design method of “round to square” based on the specific coefficient relationship between the sizes of round tube and square tube, and deduced the coefficient $\mu$ and $\lambda$ of pass design. Liu Rong-pei [6] gave a method of pass design angle mutual method, i.e. the sum of the radians corresponding to the long side, the short side and the fillet of square tube is constant during the roll-forming process. This design method is simple, the process parameters are easy to control and the forming accuracy is high.

3.1. Pass design method of “square to square” process

In this paper, the mutual relationship of angle is used to deduce the design of rollers for every pass in design of “square to square” process. The variation of section dimension of square tube during forming process is shown in figure 5. The design principle is that the linear topological relationship each line section is maintained during the change of preformed tube to square tube. That is to say, it is one-to-one correspondence and unchanged between the long side $L_{\mu}$, the short side $L_{\nu}$ and arc length $A B_i$ of the corners of square tub with the distribution lines of preformed tube. The preformed tube has the behavior of reducing diameter and extending after each pass of deformation. Where $\mu_i$ is the elongation coefficient of the $i$ pass, then:

$$
L_{\mu_i} = L_{\mu} + \mu_i A B_i, \quad L_{\nu_i} = L_{\nu} + \mu_i C D_i, \quad A_i D_i = \mu_i B_i C_i
$$

(1)
When the angle $\alpha$, $\theta$ and $\beta$ corresponding to the deformed arc $AB$, $BC$ and $CD$ are determined, there is a unique value corresponding to $\alpha$, $\theta$ and $\beta$. It can be proved that the sum of the angle corresponding to the long side half, the short side half and the transition arc of the square tube during deformation is a constant 90°.

### 3.2. Frame layout for finishing pass

The finishing frame uses four passes, of which only the latter three pass participate in the deformation, and the first one only plays the guiding role. The principle of average distribution of the amount of deformation is adopted. In the method of pass design angle mutual, the amount of deformation is expressed by the change of the angle corresponding to the long side, short side and transition corner of the last square tube.

### 3.3. Design and calculation of pass

Taking the high-strength square tube with cross-section size of 40×40×2 mm and an outer radius of $r=4$ mm as an example, the total elongation coefficient is $\mu=1.04$ and the number of finishing passes $n$ is three. And the radius of the preformed tube is assumed to be $r=10$ mm. According to the expansion width of the sheet, the outer diameter of the preformed tube is determined to be $D_0=42.88$ mm, and the circumference of the preformed tube is:

$$L_0 = 4(D_0 - 2r_0) + 2\pi r_0 = 154.35 \text{ mm} \quad (2)$$

The literature [3] shows that the corner wall of square tube has obvious thickening behavior in the “square to square” process, so there is a certain amount of reduction in the forming process. Then the actual circumference and outer diameter of preformed tube are respectively:

$$L = \mu L_0 = 160.52 \text{ mm}, \quad D = 44.42 \text{ mm}$$

Therefore, the total diameter reduction in the forming process is as follows:

$$\Delta D = (D - D_0)/2 = 2.21 \text{ mm} \quad (3)$$

During the deformation process, the outer circumference of each pass and the arc of each section are basically unchanged, so as to ensure the forming precision. Although the reduction exists in each forming pass, because of its small size, assuming that the reducing is evenly distributed in every forming pass, the outer circumference of the pass is:

$$L_i = 4(D - 2\left(r - \frac{i}{n}\Delta D\right)) + 2\pi\left(r - \frac{i}{n}\Delta D\right) \quad (4)$$

The length of four plane edges of square tube and the arc length corresponding to transition arc are respectively:

$$L_{ui} = (D - 2\left(r - \frac{i}{n}\Delta D\right)) \text{ and } B_iC_i = \frac{\pi}{2}\left(r - \frac{\Delta D}{n}\right) \quad (5)$$

The angle of the transition arc before deformation is:

$$\theta_i = \frac{\pi R_i}{2R_i} \quad (6)$$

- **Figure 5.** Deformation of square tube in “square to square” process.
According to the angle mutual relationship and the same angle corresponding to the long side and the short side during roll-forming process, the angle corresponding to the length of the tube plane before the deformation is:

\[
\alpha_i = \beta_i = \left(90^\circ - \frac{\pi R_i}{2R_e}\right) / 2
\]

(7)

The calculation results of the roller each pass the “square to square” process are shown in Table 1.

| Pass | Circumference L / mm | Side length L_{Ai} / mm | Arc length / mm | Angle/° | Radius / mm |
|------|----------------------|--------------------------|----------------|---------|-------------|
| 0    | 160.52               | 12.21                    | 15.71          | 27°     | 36°         | 10.00       |
| 1    | 158.38               | 13.68                    | 12.24          | 21.9°   | 46.2°       | 7.79        |
| 2    | 156.27               | 15.16                    | 8.76           | 12.7°   | 64.6°       | 5.57        |
| 3    | 154.19               | 16.00                    | 6.28           | 0°      | 90°         | 4.00        |

In the pass design of “square to square” process, the angle corresponding to the straight line section changes from 27° to 0°, and the angle corresponding to the transitional arc section changes from 36° to 90°. Therefore, the values of rollers each pass can be obtained only by setting the varied angle \(\alpha_i\) and \(\beta_i\) during the rolling process. Figure 6 is schematic diagram of pass frame of “square to square” process.

![Figure 6. Schematic diagram of pass frame.](image)

4. Equipment of hot roll-forming for high-strength square tube

According to the design of inductor and the analysis of pass of “square to square” process, the equipment of local heating roll-forming process for square tube has been completed. As shown in figure 7, it mainly includes the finishing frame, induction heating equipment, temperature recorder and infrared thermometer. QSTE700TM high strength steel is selected as raw material to prepare preformed tube. The self-designed composite coil inductor is used to realize local heating of four corner parts of square tube, as shown in figure 8. And the target temperature is guaranteed to be constant through the automatic feedback system. The hot roll forming temperature is 650°C. When entering the finishing stage, the square tube is subjected to extrusion force in four directions of the rollers. Due to the influence of temperature, the square tube with excellent mechanical properties and small rounded radius is obtained [7]. Figure 9 gives the mechanical properties of the corner of the hot-formed square tube. It can be seen in figure that the cold work hardening effect of high strength square tubes formed at room temperature has been significantly slowed down. The corner elongation of square tube increased from 6.2% at room temperature to 14.8% after hot roll-forming. Figure 10 shows that the plane section size accuracy of high-strength square tube after hot roll-forming is higher...
than that at room temperature, which illustrated that there was a significant springback in the corner of the square tube.

5. Conclusion
In order to solve the problems of equipment and process caused by traditional roll-forming technology for high strength square tube, a local heating “square to square” forming process for high strength square tube is proposed in this paper. By comparing the two inductor structures, it is found that the heating area of composite coil inductor is more concentrated and the temperature of heat-affected zone is smaller than that single coil inductor. The frame layout of finishing pass and design as well as calculation of rollers of “square to square” process for square tube are given. And the key technical equipment of hot roll-forming process is developed. The mechanical properties and section sizes of high strength square tube manufactured by this new technology are tested. It is found that the mechanical properties of the corner and the dimensional accuracy of the section are significantly improved. The corner elongation of square tube increased from 6.2% at room temperature to 14.8% after hot roll-forming and the dimension accuracy of square tube section was reduced from 6.62 mm to 0.74 mm, which effectively overcomes the production problems of the high-strength square tube.

6. References
[1] Rossi B, Degée H and Boman R 2013 F. E. Ana. Des. 72 13
[2] Xu H 2003 Weld. Pip. Tub. 03 45
[3] Peng X F, Chen Q and Wang Y 2016 Chin. J. Chem. Eng. 07 973
[4] Sun J 1992 Weld. Pip. Tub. 05 40
[5] Cao G F 2014 Weld. Pip. Tub. 07 49
[6] Liu P R and Zhang H L 2000 Weld. Pip. Tub. 02 32
[7] Peng X F, Han J T and Yan P J 2016 Chin. J. Chem. Eng. 06 820