Flame correction analysis of tunnel boring machine shield body roundness

Gaowei Wang[1, *], Mixue Guo[2, a], Shiyou Chen[1, b], Zhenyu Ren[1, c]

[1]CREG tunnel boring machine manufacturing co.,ltd. Henan Zhengzhou 450000

[2]Henan University of Science and Technology. Henan Luoyang 471000

* Corresponding Author Email: kzstudy@163.com, [a]255654526@qq.com, [b]912093109@qq.com, [c]531483907@qq.com

Abstract. Tunneling boring machine is a kind of special construction machinery suitable for underground excavation, mainly composed of cutter head, shield body, screw conveyor, supporting system and so on, mostly used in modern infrastructure construction. Shield body is the key accessory of tunnel boring machine which plays an important role in excavation. Its roundness affects the progress and smoothness of construction directly, so it is of great significance to analyze roundness correction technology. Due to the large self-weight of shield body and influence of irregular welding deformation, it is difficult to make roundness under control in ideal state through existing manufacturing process. The out-of-tolerance part should be corrected after welding. Flame correction is a convenient technology to correct welding deformation which apply to roundness correction of shield body. This paper mainly expound and analyze shield body compositions, difficulties of roundness control and key technical points of flame correction.

Keywords: Tunnel boring machine, shield body, roundness control, welding deformation, flame correction.

1. Introduction

The shield body plays a role of temporary support for the excavated unlined tunnel, which withstand the pressure of the surrounding stratum and prevent the tunnel from collapsing [1]. Grouting is used to fill the space between the shield body and the excavated tunnel wall. Roundness is the key dimension of shield body, and its structure tends to be larger in the front and smaller in the back. Generally, the maximum excavation diameter of the cutter head is greater than or equal to the front diameter of shield body, diameter of rear part supposed to be the smallest. Too large diameter of shield is easy to cause jam phenomenon in tunneling. But if the diameter is too small, the gap between shield body and excavated tunnel wall will be too large, which may affect the installation of subsequent segments, even may can't support the excavated tunnel and produce security risks. Therefore, it is very important to control the roundness of shield body.

There are so many difficulties in shield body manufacturing system such as lifting, transportation and machine tool, so shield body is mostly manufactured in blocks, which connected by flanges.[2] There are many welding accessories inside the front and middle shield, mainly including rib-plate, clapboard, cone plate, connecting flange, support of screw conveyor, hinge cylinder lungs, crusher support and so on. Tail shield is mainly composed of grouting block longitudinal welds, sealing ring seam welds, grease pipe welds. The shield manufacturing system has a large amount of welding, its welding consumable is about 3% ~ 7% of the shield body weight. In addition, the manufacturing cycle span is quite long. Welds will be heated and cooled in different degrees before and after welding, resulting in uneven expansion and contraction. It means welds and heat affected zone will be subjected to considerable tensile stress or compressive stress irregularly.[3] Although welding deformation control measures are taken, irregular welding deformation still occurs, resulting in the shield body roundness is out of tolerance. In order to ensure that the roundness of shield meets the requirements of manufacturing and technical specifications, it is necessary to correct the roundness of shield after welding.

2. Shield body roundness correction process

The tolerance range of shield body roundness is related to its diameter. Generally, the front radius of shield body is its theoretical diameter plus 0 ~ 10mm, and the rear end radius supposed to plus 0 ~ -10mm. For the part which out-of-tolerance, mechanical correction (screw adjustment) or flame correction can be used. Mechanical correction is mainly used for sheet steel and small deformation part. Flame correction can be applied to different deformation, large range of steel thickness, correction molding fast and stable. Roundness diameter of shield body is generally 6 meters to 16 meters, and single component is quite large. Mechanical correction method is time-consuming and the correction effect is not ideal. Flame correction is a common method used by most shield body manufacturers with simple operation and high efficiency.

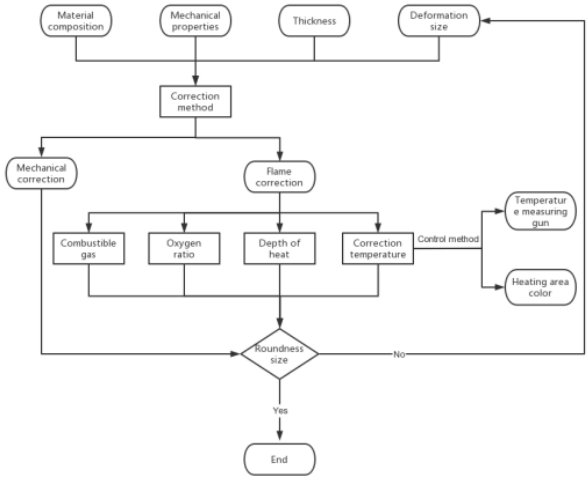


Fig. 1 Flow chart of shield roundness correction

3. Shield body material and welding process

In essence, the roundness flame correction of shield body is a process of reheating metal to make the heated area gets irreversible, compressive, plastic deformation. To ensure its mechanical properties after flame correction and to avoid adverse phase transformation during correction process, it is necessary to study the properties of base material, its welding process, and analyze the conditions of the micro-structure phase transformation before flame correction.

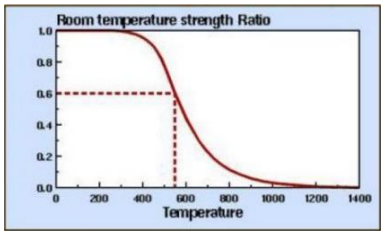


Fig. 2 Strength ratio at different temperature

The shield body is mainly made of Q355B hot-rolled steel plate. According to the diameter and strength requirements, base material thickness range is from 40mm to 80mm. Single (or double) V-shaped groove butt weld and T-shaped weld are mostly used, groove angle is generally about 35°.

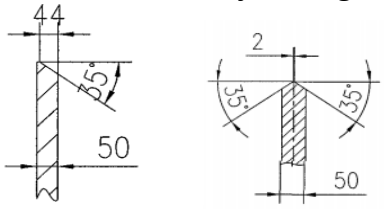


Fig. 3 Samples of grooves

Welding sequence: Backing welding should be proceed first for all horizontal and vertical weld. In addition, symmetrical welding and multi-layer multi-pass welding is also required.

Welding process parameters: preheat 100 ~ 150℃ before welding, control inter-pass temperature does not exceed 220℃. Welding consumable is ER50-6, diameter is φ1.2mm. Welding method: carbon dioxide gas shielded welding. Polarity: DCEP. Welding current is 180 to 320A, welding voltage is 22 to 32V, gas flow is 15 to 25L/min for horizontal and horizontal welding. Welding current is 120 to 220A, welding voltage is 16 to 26V, gas flow is 15 to 25L/min for vertical welding.

Anti-deformation measures: because the proportion of weld weight to shield body's total weight is about 5%, which means there's quite a bit of welding going on there. All welds supposed to be subjected to different degrees of heating and cooling before and after welding, resulting in uneven expansion and contraction. This makes irregular out-of-tolerance of roundness after welding. Riveting radius allowance should be considered due to welding shrinkage. When roundness of shield body is inspected, each block should connect with process supports. The number of technological supports between two adjacent shield blocks should not less than 3, and the interval between two supports is approximately 1 meter, meanwhile the interval between two supports should be equal.

Mechanical properties and chemical compositions of base material are as follows:

Table 1 Mechanical properties of base material Q355B

No.	Material	Mechanical properties			Charpy V impact absorbed energy	
		Yield strength/Mpa	Tensile strength/Mpa	Elongation after fracture(%)	Test temperature	Minimum impact energy Akv/J
1	Q355B	≥355	470~630	≥20	20℃	≥34

Table 2 Chemical compositions of base material Q355B

Chemical composition	C	Si	Mn	P	S	Nb	V
Content%	≤0.24	≤0.55	0.9-1.6	≤0.035	≤0.035	0.005-0.05	0.01-0.12
Chemical composition	Ti	Cr	Ni	Cu	N	Mo	Als
Content%	0.006-0.05	≤0.30	≤0.3	≤0.4	≤0.012	≤0.10	≥0.015

According to the above analysis, carbon content of base material is less than 0.24%, and the yield strength is greater than or equal to 355Mpa. This low carbon steel belongs to the category of low alloy high strength structural steel, which with good weldability, plasticity, toughness, high strength and low cold brittle transition temperature. Therefore, to ensure the mechanical properties after flame correction still meet requirements, the technological requirements of flame correction can be formulated by referring to phase transformation conditions of Fe-C binary alloy phase diagram.

4. Flame correction process

4.1. Flame correction theory

Flame correction is a method which use a flame as a heating source to heat parts of metal. High-temperature part has a tendency of expansion and elongation after heating. After cooling, metal fibers in the heated area will shorten, that means irreversible compressive plastic deformation will be gained.[4] By heating different areas of the inner and outer walls of shield body, the deformation caused by metal shrinkage is often used to offset the deformation caused by welding, so as to correct the roundness of shield body. The heating temperature must be controlled below the phase transition temperature to ensure that shield body roundness can be corrected without affecting the material properties. If heating temperature is too low, the correction efficiency will be reduced which should be considered comprehensively.

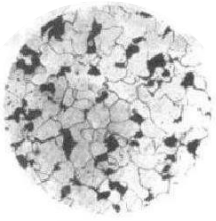
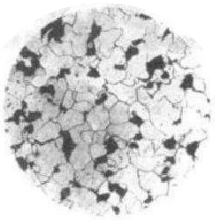
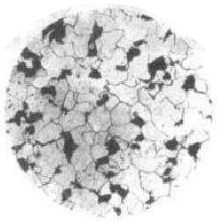
Heating temperature can be selected according to the alloying element composition, thickness, deformation size of corrected part. There are generally three heating methods: low temperature heating, medium temperature heating and high temperature heating.[5]

Low temperature heating refers to the metal temperature of heated area is approximately 500 ~ 600℃, which usually used for the correction of low carbon steel sheet. After heating, water cooling can be used to promote recrystallization, refine grain, and improve the strength and hardness slightly. Medium temperature heating refers to the heating area of metal temperature up to 600 ~ 700℃, it's also suitable for correction of low carbon steel sheet. Medium temperature heating should be accurately controlled to make sure its temperature not exceeds transition temperature of 723℃. In order to prevent the formation of organizational phase transformation, water cooling can also be used to improve grain structure. High temperature heating refers to the metal temperature of the heated area can reach 723 ~ 850℃, which between A1 and A3 line temperature. The original ferrite and pearlite will be transformed into austenite and ferrite at this temperature range. It will still remain the original metallographic structure after cooling and recrystallization, which has no effect on the properties of base material. It is suitable for flame correction of big thickness low carbon steel. Cooling method supposed to be air cooling.

4.2. Selection of flame correction heating temperature

Flame correction is essentially a process of heating metal to a certain temperature and then cooling it. Shield body is mainly made of low alloy high strength structural steel Q355B. Low carbon steel would be austenitized completely when the heating temperature of base material reaches 850℃. Grain structure is still ferrite and pearlite, which means its mechanical properties are also same after cooling. If the heating temperature is too high above A3 line (912℃), the weistenite structure will be obtained after cooling. It will significantly reduce the mechanical properties of base material, especially the plasticity and toughness. It would also significantly increase the toughness and brittle-transition temperature of base material. Therefore, flame correction temperature should not exceed 850℃ and air cooling should be used.

Table 3 Metallographic micro-structure after cooling to room temperature from different heating temperatures

Heat temperature	Metallographic micro-structure under room temperature	
	Before heating	After heating
850℃	 Ferrite + Pearlite	 Ferrite + Pearlite
912℃	 Ferrite + Pearlite	 Weistenite

4.3. Heating temperature control of flame correction

Heating temperature can be approximately estimated by observing the color of heated area surface, or measured with a temperature measuring pen or temperature measuring gun.

Table 4 Steel surface color and corresponding temperature [6]

Color	Temperature/℃	Color	Temperature/℃	Color	Temperature/℃
Hazel	500	Light cherry red	800	Yellow	1000
Auburn	600	Reddish orange	850	Pale yellow	1100
Dark red	650	Orange	900	White light yellow	1200
Dark cherry red	700	Pale orange	950	Bright white	1300
fuchsia	750				

Heating of flame correction needs to be stopped immediately once the steel color turns to be red, which means that the heating temperature is not more than 850℃. After base material cooled to room temperature, the roundness data within the heated area shall be measured. If the radius meets requirement, it shall be deemed that flame correction is up to standard.

4.4. Gas combustion ratio

Gas combustion ratio refers to the volume ratio of oxygen to combustible gas. According to the combustible gas combustion, the heating flame is divided into neutral flame, oxide flame and carbonization flame. The flame type used to correct deformation is mainly selected on the basis of deformation size, heating depth, heating rate and so on. Normally the shield body steel is quite thick, so it should be heated slowly in principle to make the temperature rise evenly. This way can also avoid excessive temperature difference between interior and steel surface.

4.5. Flame correction method

Flame correction methods for shield body roundness generally include dot heating, linear heating and triangular heating:

Dot heating method is mainly used to correct the roundness of excessive local deformation. Hot spots can be set in and around the deformation center, dot distribution can also follow the shape of quincunx to correct local deformation. The correction effect of dot heating is on the basis of dot size, location distribution. According to the roundness deformation of shield body, the appropriate heating area and heating position are selected. If the first heating cannot completely achieve the correction effect, a slightly higher temperature can be used for the second correction. Heating position of two flame corrections should be staggered more than 150mm.

Linear heating method is a continuous heating method. The heat source moves along a straight line on the shield body, and the heating trace is a strip of uniform width (about 50 ~ 70mm in width). The linear heating method has small shrinkage in the direction of heat source movement, but with obvious correction effect in the tangent direction. When the upper and lower roundness deformation of the shield body is consistent, the longitudinal linear heating along the length direction is mainly adopted, which can make the upper and lower parts of the shield body get same correction effect. Large oblique heating method is suitable for cases when upper and lower roundness deformation is not same.

Triangle heating method is suitable for correcting roundness deformation of shield body port position. This method has a large heating area and large shrinkage after cooling. It can be operated by two workers at the same time to heat up the triangle area evenly so as not to cause additional warping deformation.

5. Application of flame correction

5.1. Application examples of three heating methods

Table 5 Application examples of three heating methods

 Example 1 Linear Heating (longitudinal)	 Example 2 linear Heating (Large oblique)
 Example 3: Triangle heating method	 Example 4: Triangle heating method

5.2. Roundness comparison before and after flame correction

According to the actual welding deformation, a variety of correction methods are applied flexibly to correct shield body roundness. Roundness of tail shield with diameter 6.4m and height 3.9m is taken as an example. Base material thickness at location R4 is 10mm smaller than the front part (R1 ~ R3). Measurement position of each layer is shown in Figure 3.

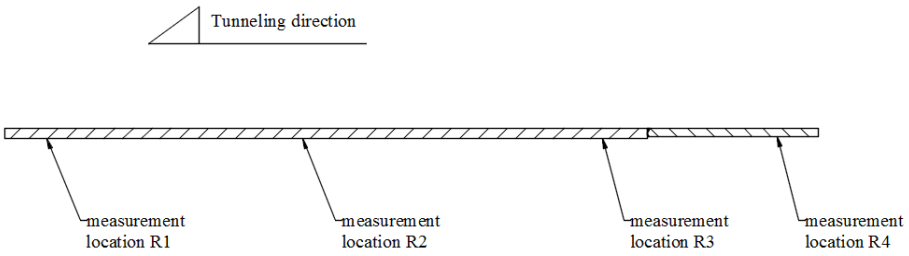


Fig. 4 Schematic diagram of measurement position

The radius of shield body before and after flame correction were measured by total station and draw radius discrete graph according to total station measurement data:

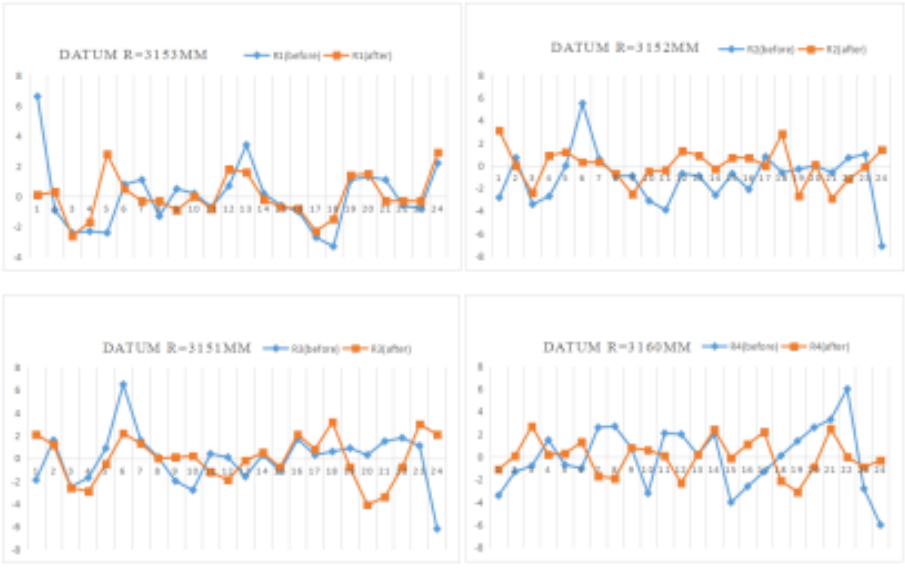


Fig. 5 Radius dispersion diagram (unit: mm)

According to standard deviation calculation formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}}$$

Calculate standard deviation of each layer and the result is shown as below:

Table 6 Comparison of radius standard deviations before and after flame correction

status standard deviation σ item	R1	R2	R3	R4
Before correction	2.11	2.3	2.29	2.73
After correction	1.4	1.52	1.96	1.54

It can be seen from Figure 5 and Table 6 that, after correction its radius R1=3153 (-2.6, +2.9), R2=3152 (-2.9, +2.8), R3=3151 (-3.4, +3.2), R4=3160 (-3.1, +2.7). Basically, in line with R1 > R2 > R3. After correction, the radius standard deviation in each layer is reduced, which means its radius dispersion degree is improved. The radius of shield body tends to be larger at the front and smaller at the trail shield, which means the result meets design requirements.

6. Conclusion

The key point of flame correction is to control the heating temperature below the phase transition temperature, and perform roundness correction of shield body without affecting the material properties. The factors influence correction include but not limited to heating temperature, heating depth, heating rate, heating area size and shape of heating surface, etc. The larger the heating area, the greater the correction effect. Therefore, the heating factors should be selected according to the roundness deformation of shield body. Heat area needs to be staggered if multiple heating is performed. When the upper and lower roundness of shield body is consistent, longitudinal dot or linear heating can be used. Large oblique heating can be selected when the upper and lower roundness is not consistent.

This paper expounded and analyzed the key technical points of flame correction of shield body roundness, which has great significance for shield body roundness correction.

References

[1] Hu Rui, Research on shield tunneling similarity and test technology based on power bond graph [D] Zhejiang University 2013-12-31.

[2] Bai Xiaobo, Wu Shengquan, Miao Zhongjie, Research on processing Technology of Large-diameter muddy water shield [D] 2019-03-15.

[3] Mehran Ghafouri, Antti Ahola, Joseph Ahn, Timo Bjork Welding-induced stresses and distortion in high-strength steel T-joints: Numerical and experimental study [D] Journal of Constructional Steel Research; 2021-12-17.

[4] Zhou Hanping, 2011 National Steel Structure Academic Conference Proceedings [C], China Conference, 2011-10-18.

[5] Liu Bing, Liang Yande, Yang Jing, XU Li Selection of Flame Correction Process Parameters [J] Heat treatment of metals 2008-06-25.

[6] Feng Xiaotao Shallow memory flame correction method [J] Enterprise Technology Development 2002-11-13.