Topology Optimization of Welding Spots for Stainless Steel Subway Vehicles

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Abstract—Taking the head car body of the stainless steel subway as an example, the static strength of the vehicle body and the shear strength of the welding spot is checked according to different thicknesses and weld nugget diameters under dangerous conditions. For the unqualified position of the welding spot strength, the welding spot layout schemes are improved. At the same time, the topology optimization is performed for the main welding spot layout areas in the scheme improvement. The optimization results show that the number of welding spots is reduced by 49.33% and 52.04% compared with the original scheme and the improvement scheme respectively under the premise of ensuring the structural strength. The obvious optimization effect provides a useful reference for the future design of stainless steel spot welding subway vehicles.

1. INTRODUCTION
China's subway vehicles are mainly stainless steel car and aluminum alloy car. Stainless steel spot welding cars have gradually became the mainstream of lightweight rail car at home and abroad, due to their advantages such as high corrosion resistance, light weight, relatively low maintenance costs, and relatively low operating costs[1]. Stainless steel subway vehicles are composed of a large number of complex components. However, because of the stainless steel material, the heat generated in the weld area cannot be dissipated in time during welding, which may cause welding deformation of the car body[2]. The spot welding technology can reduce welding deformation and prevent the decrease in the mechanical properties of stainless steel materials at high temperatures. At the same time, it has the advantages of high welding strength, high welding reliability[3], stable weldment quality, and is ease to automated production. As a result, there are thousands connection of resistance spot welding between car body parts.

In traditional structural design, the layout of welding spots is mainly based on some general welding that may cause the static strength distribution of welding spots exceeding the minimum allowable shear force and may produce some redundant welding spots in some areas, which needs to be further resolved. With the continuous development of computer technology and calculation methods, more and more
research results had been made in the optimization of welding spot layout of complex structures. Japanese scholar Akira Yamaguchi\[4\] et al, optimized the welding spot layout of a certain car body on the premise of improving the bending stiffness and torsional stiffness of the car body, then the whole mass had dropped by 21%. Bhatti\[5\] optimized the number of welding spots of a certain car based on the modal strain energy with the constraints of the first-order bending modal frequency and the first-order torsional modal frequency. After optimization, the layout of the welding spots were further reasonable. Varma\[6\] used welding pitch as a design variable, and combined with variety of operating conditions to perform multi-objective optimization of the welding spot layout of the commercial vehicle cab. The number of welding spots had been reduced by 9% without reducing the low-order natural frequency and overall stiffness. Domestic scholar Xie Suming\[7\] et al, based on the structural stability analysis algorithm principle, optimized the layout of the welding spots on the roof of subway stainless steel electric welding cars. Gao Jiliang\[8\] et al, carried out tensile shear tests on spot welding structures with different numbers and arrangements of welding spots, and analyzed their effects for the performance of welded joints. As well as welded the corners of car doors and windows are locally optimized. This paper takes the head car body of the stainless steel subway as an example, and performs static analysis of the car body and welding spots under multiple working conditions. Based static strength test verification on the laboratory, the topology optimization in the side wall and underframe connection is conducted with comprehensively considering for a variety of working conditions. The aim of ultimately reducing the number of welding spots and improving manufacturing efficiency, and reducing assembly costs\[9\] are realized on the basis of ensuring the structural strength and the shear strength of the welding spots.

2. Establishment and Analysis of Finite Element Model

2.1. Body structure characteristics and finite element model

A large number of welding spots are arranged among the outer skin of the side wall, the door sill, the small side beam and the stainless steel side beam. The different material grades of the various parts of the stainless steel body are correspond to different yield strengths, and each welding spot also has different minimum shear force due to different core diameters and plate thicknesses. The performance parameters of the car body material are shown in Table 1, and the minimum shear force of the main welding spots is shown in Table 2 (based on the BSEN15085 standard).

When building a finite element model of a car body, any structure that contributes to the overall stiffness and local strength of the car is considered. The car has a large number of components connected by welding spots. The main numerical simulation methods of welding spots are beam elements or rigid elements and three-dimensional solid elements. Although the simulation of three-dimensional solid elements can accurately calculate the local stress of local welding spots, for complex structures and a large number of welding spots, it is not practical to directly calculate the whole vehicle model. Therefore, the car uses BEAMS unit to simulate welding spots. In the body finite element model of the vehicle, the total number of elements was 2,753,373, the total number of nodes was 2,056,492, and the total number of welding spots was 37,485.

| Material name | density (kg/m³) | Elastic Modulus (Mpa) | Poisson's ratio | Yield Strength (Mpa) |
|----------------|-----------------|-----------------------|----------------|---------------------|
| SUS301L-DLT    | 7.93            | 183000                | 0.3            | 345                 |
| SUS301L-ST     | 7.93            | 183000                | 0.3            | 410                 |
| SUS301L-MT     | 7.93            | 183000                | 0.3            | 480                 |
| SUS301L-HT     | 7.93            | 183000                | 0.3            | 685                 |
| S500MC         | 7.93            | 206000                | 0.3            | 500                 |
| Q690D          | 7.93            | 206000                | 0.3            | 690                 |
TABLE 2. MINIMUM SHEAR FORCE OF RESISTANCE SPOT WELDED STEEL JOINTS (PARTIAL DATA)

| Plate thickness (mm) | Welding core diameter (mm) | Minimum Shear force at Each Weld (kN) |
|----------------------|-----------------------------|----------------------------------------|
|                      |                             | Tensile strength of base metal (MPa)  |
|                      |                             | $R_m \leq 360$ | $360 < R_m < 510$ | $510 < R_m < 620$ |
| 1.0                  | 5.0                         | 4.7          | 6.0            | 8.0          |
| 1.5                  | 6.0                         | 7.1          | 9.0            | 12.0         |

2.2. Static strength conditions
According to the EN12663-2010 standard, 36 working conditions were required for this subway car. But here only two of the severer working conditions were computed. One is the combination of the longitudinal compression of the center line of the coupler by 1200kN and the maximum vertical load of the vehicle. The second is the combination of the longitudinal extension of the center line of the coupler by 960kN and the maximum vertical load of the vehicle.

2.3. Finite Element Analysis
After calculation, the VonMises stress of each component of the car body did not exceed the yield strength of the corresponding material. It was found that in the two structures of 1mm side wall which had 5mm core diameter and 1.5mm side wall thickness which had 6mm core diameter, some of the joint shear forces were greater than the minimum shear force, so the static strength requirements of the joints were not met.

The results of welding spot shear force analysis were shown in Table 3, and the distribution positions of unqualified welding spots were shown in Fig. 1. It could be seen from Figure 1 that the locations of unqualified welding spots were mainly concentrated at the joints between the side walls of the second door and the fourth door and the side beams of the chassis and the lower part of the door pillars.

TABLE 3. CALCULATED RESULTS OF WELDING SPOT SHEAR FORCE

| Condition number | Substandard welding spot thickness And welding core diameter | Disqualified Number of welding spots | Maximum welding spots Shear force (N) | Allowable welding spots Shear force (N) |
|------------------|------------------------------------------------------------|-------------------------------------|---------------------------------------|----------------------------------------|
| Working condition 1 | 1mm board thickness Nugget diameter is 5mm | 32                                  | 15893.04                              | 8000                                   |
|                   | 1.5mm board thickness Nugget diameter is 6mm               | 19                                  | 16667.69                              | 12000                                  |
| Working condition 2 | 1mm board thickness Nugget diameter is 5mm | 24                                  | 13945.62                              | 8000                                   |
|                   | 1.5mm board thickness Nugget diameter is 6mm               | 34                                  | 22290.44                              | 12000                                  |

(a) 1mm board thickness Nugget diameter is 5mm

(b) 1.5mm board thickness Nugget diameter is 6mm

Figure 1 Distribution of unqualified welding spots
2.4. Scheme improvement
Combining traditional design experience and the results of finite element analysis, an improvement plan was proposed for the unqualified welding spots at the above positions. The specific plan was as follows: (1) Added a row of welding spots to the total composition of the side wall chassis. There were 8 welding spots below the side wall and 6 welding spots below the door; (2) Added a welding spot between each door post and the side wall. The welding spot at this position is increased from three to four, and the distance was changed to 31.9mm, 60mm, 70mm respectively, and added a craft hole at the corresponding position; (3) An additional row of welding spots has been added to the waist wall position of the two-bit end wall, from three rows to four rows, and the spacing has changed to 35mm, 35mm, and 40mm respectively, and the welding spots on the upper beam position were moved upward by 20mm.

After the scheme was improved, the finite element analysis of the improved model was performed again. The analysis results showed that: the VonMises stress of each component of the car body did not exceed the yield strength of the corresponding material, and the shear force of all welding spots was less than the minimum shear force specified by the standard. Therefore, the car body structure and welding spots met the static strength requirements on two conditions. However, traditional optimization methods, that is only adding welding spots at locations where the static strength of welding spots does not meet the requirements, can not to judge whether there are redundant welding spots at other locations.

2.5. Experimental comparison
Based on the calculation results of the improved scheme, the vehicle body static strength experiment was carried out. By comparing the test data, it was found that the simulation calculation results were basically consistent with the actual data as shown in Figure 2 and Figure 3 (the abscissa in the figures indicates the position of test strain gauge).

![Figure 2 Comparison of test stress and calculated stress in case 1](image1)

![Figure 3 Comparison of test stress and calculated stress in case 2](image2)

3. Topological optimization method of welding spots
The basic idea of topology optimization is actually to delete the non-transmitting force or not a main transmitting force material according to the force transmission path in the initial design domain, and finally remain the main force material distribution. That is, to find the best distribution scheme in the design space of uniformly distributed materials. In the structural topology optimization design of welding spots, the SIMP model is often used to convert a substantially integer optimization problem into a parameter optimization problem, which is defined as follows.
In the formula, $E_{ijkl}(x)$ and $E_{ijkl}^0$ are the material stiffness tensor and the initial material stiffness tensor of basic elastic element on the $x$ position. $\Omega$ is the reference design domain, $\rho(x)$ is the design variable, and $p$ is the penalty factor. In order to obtain the topology optimization design result with a distribution form of $0 \sim 1$, $p > 1$ is usually be taken.

Based on the SIMP model, the upper bound constraints on the number of welding spots in the reference design domain can be given as follows.

$$ \int_{\Omega} \rho(x) d\Omega \leq V $$

In the formula, $V$ represents the upper limit of the number of allowable welding spots in $\Omega$. After the reference design domain is parameterized based on the SIMP model shown in equation (2), the corresponding design optimization problems such as the stiffness and dynamic characteristics of the structure can be optimized, and the corresponding topological optimization design problem definitions are given[10].

4. TOPOLOGY OPTIMIZATION AND RESULT ANALYSIS OF WELDING SPOT LAYOUT

4.1. Topology optimization model

In order to retain the main force transmission, it is necessary to perform the topology optimization of the welding spot arrangement in the areas which have large number of welding spots on the improved scheme, that is in the the side wall and the underframe side beam with a welding core diameter of 6mm based on the above two schemes results. There are three elements of optimal design, namely design variables, objective functions, and constraints. Design variables are a set of parameters that change to improve performance. The objective function requires optimal design performance and is a function of the design variables. Constraints are restrictions on the design and requirements on the design variables and other performance. Considering the requirements of this optimization design, the optimization model is described as follows: (1) Optimization objective: the weighted strain energy of the design space is minimum under two dangerous working conditions; (2) Constraints: the volume of the design space after optimization cannot exceed 40% of the original volume; (3) Design variable: the element density of the design space.

4.2. Analysis of optimization results

The optimized joints between the side wall and the underframe side beams were optimized and the high-density welding spots on the second door were shown in Figure 4. Retaining the high-density elements in the optimization results, the static strength of the car body and the static strength of the welding spots were recalculated. The calculation results showed that the VonMises stress of each component of the car body was less than the yield strength of the material under both working conditions, which met the car body static strength requirements. The shear force of all welding spots was also less than the minimum shear tensile force specified in the standard, which met the requirements for the static strength of welding spots.

Figure 4 Schematic diagram of local reserved welding spots after optimization
4.3. Optimization comparison
The number of welding spots and the maximum shear force on the joint between the side walls and the underframe on different schemes were given in Table 4 and Figure 5.

It can be seen that in the optimization scheme compared with the original scheme and the improvement scheme, although the number of welding spots were not a lot, the maximum VonMises stress of the vehicle body and the maximum shear force of the welding spot had not changed significantly, which meets the requirements of the standard. It was also found that the number of welding spots had been reduced by 1464 and 1632 respectively. The optimization effect was obvious. It provided a useful reference for the future design of subway stainless steel spot welding vehicles.

| Scheme      | Working condition | VonMises stress of vehicle body (Mpa) | Number of welding spots | welding spot maximum shearing force (N) |
|-------------|-------------------|--------------------------------------|-------------------------|---------------------------------------|
| Original    | 1                 | 539.596                              | 2968                    | 18040.94                              |
|             | 2                 | 526.299                              |                         | 23956.23                              |
| Improvement | 1                 | 534.130                              | 3136                    | 10317.21                              |
|             | 2                 | 465.739                              |                         | 11863.48                              |
| Optimization| 1                 | 534.061                              | 1504                    | 9509.46                               |
|             | 2                 | 433.952                              |                         | 11364.72                              |

Figure 5 Comparison of the maximum shear force of the welding spot before and after optimization

5. CONCLUSION
Taking the head car body of the stainless steel subway as the analysis object, the improvement and topology optimization of the key parts of the welding spot were computed. The following conclusions were drawn:

(1) Based on the original scheme, the static strength simulation analysis of car body was computed and compared to experiment data. The results showed that the VonMises stress of each part of the car body was less than the material's yield strength under two dangerous working conditions, thus the reliability of the model was verified. Also the minimum shear force was computed and analyzed. It was found that shear forces of the welding spot which under some structures such as in the 1mm side wall and 1.5mm side wall were greater than the minimum shear forces specified in the standard. These welding spots did not meet the static strength requirements.

(2) Based on the static strength analysis results of the car body and previous design experience, three improvement schemes were proposed. The car body structure and welding spots met the static strength requirements. However, there were a large number of redundant welding spots in some locations which
had no effect on maintaining the strength of the structure. So it was necessary to conduct the topology optimization of welding spot distribution.

(3) After optimization, the car body structure and welding spots met the static strength requirements. Compared with the original scheme and the improved scheme, there were smaller changes in the maximum VonMises stress and the maximum shear force of the welding spot. And the number of welding spots was reduced by 49.33% and 52.04% respectively. The optimization effect was obvious, which provided useful data for the design of this stainless steel spot welding vehicles.

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