Exploration on the Materials Quality Control of Railway Vehicle Weld Structure Based on Service Safety Demand

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Abstract. With the continuous increasing of service-rail-vehicle in China, some defects such as cracks appeared at different stages of service when they had not reached the design life, while current theories and methods cannot explain the appearance of defects, which brought risks and hidden dangers to the operation of the vehicles. It was found that the reasons were mainly caused by one or several factors such as material performances, design, manufacturing process and operating environment. Since more and more sensors being installed on the vehicles to supervise the health of structure, it is more improtant to focus on the performances of materials. Through comparing different material standards including international, national, railway industry and enterprise standards, as well as the technical delivery conditions of other industries, it was recommended that the fracture mechanical parameters such as fracture toughness and fatigue crack growth should be proposed into the materials quality control regulations of original equipment manufacturers (OEMs). Furthermore, based on the testing data of materials from OEMs, several suggestions were proposed on the basic performance of materials such as raising the requirements contained impact, metallography and corrosion resistance properties in order to provide guarantee for the service safety of vehicles.

1. Introduction

At the end of 2020, the number of railway passenger vehicles in China is 76,000, of which there are 3918 standard groups including 31340 electrical multiple units (EMUs). For urban rail transit, there are 49,424 rail transit vehicles[1]. However, with the continuous increase in the number of rail vehicles, some trains have cracks and other defects at all stages of service when they have not reached the design life, which brings risks and hidden dangers to the normal operation of the vehicles.

Through the analysis of the cracks, it was found that the possible reasons include material properties, design, process and operating environment. Although the design processes of trains were checked, the performance problems of the materials still bring a lot of uncertainty to the later service of the vehicles. Current standard and service assessment theory and methods cannot explain the
appearance of defects. Therefore, it is necessary to propose the fracture mechanical method into the quality control regulations. There is no doubt that how to control the quality of materials in order to meet the safety needs of trains is a process which requires long-term exploration and continuous modification and improvement.

1.1. Cracks appearance in different stage of service cases
In July 2013, during a regular inspection of the vehicle by the Singapore Metro Operating Company, it was found that there were microcracks on the surface of the vehicle body bolster (Figure 1). A total of 26 trains were involved. 95% of the cracks were shorter than 30 cm. There were only two tracks which are between 40 to 50 cm. Laboratory tests have shown that these microcracks were caused by the localized impurity of the aluminum alloy car body material during the manufacturing process.

![Figure 1. Crack on Singapore metro bolster.](image1)

In 2016, a bolster on a metro line cracked when it reached the late stage of service. After the failure analysis, it was caused by hydrogen embrittlement of the high-strength aluminum alloy welding seam. As shown in Figure 2.

![Figure 2. Crack on a metroline bolster.](image2)
1.2. Sever service environment and higher quality control requirement
Due to the vast territory of China, temperature varies greatly from northern city (Harbin, -43.2°C) to south (Haikou, 43.4°C). Moreover, the enormous humidity and salinity diversity covers from coast to inland, as shown in Figure. Nevertheless, it is necessary to consider the relationship between materials quality control and the vehicles service environment, which brings more severe requirements to the quality of materials.

![Figure 3. Diverse service environment for railway vehicles bring challenges to train service.](image)

2. Comparison and analysis on current technical delivery conditions
With the analysis and comparison of international, national, industry and original equipment manufacturers (OEMs) standards, a great deal of investigation was launched on the widely-recognized technical delivery conditions in other industrial fields.

2.1. Investigation on standards in Railway industry
According to the comparison, on the one hand, the common inspection items in current technical delivery conditions were chemistry composition, tensile strength and impact strength. On the other hand, most standards covered the bending tests and CEV requirements while a few standards mentioned the metallography analysis, as shown in Table 1.

During the further research, it was found that besides of the different test item, there was several inconsistencies in the enterprise standards including diverse standard parameters of the same item and acceptance process.
Table 1. Testing items in different steel standards.

| Testing item  | EN 10025-5[2] | JIS G 3114[3] | GB/T 1591[4] | TB/T 1979[5] | Factory A | Factory B |
|---------------|--------------|--------------|--------------|-------------|-----------|-----------|
| Composition   | ○            | ○            | ○            | ○           | ○         | ○         |
| CEV           | ○            | ○            | ○            | ○           |           |           |
| Tensile       | ○            | ○            | ○            | ○           | ○         | ○         |
| Bending       | ○            | ○            | ○            | ○           |           |           |
| Impact        | ○            | ○            | ○            | ○           | ○         | ○         |
| Z direction   | ○            | ○            | ○            | ○           |           |           |
| Grain size    | ○            | ○            | ○            | ○           |           |           |
| Inclusions    | ○            | ○            | ○            | ○           |           |           |
| Band structure| ○            | ○            | ○            | ○           |           |           |
| Corrosion resistance | ○            | ○            | ○            | ○           |           |           |

2.2. Investigations on other industry standard

2.2.1. EN 10225 weldable structural steels for fixed offshore structures - technical delivery conditions[6]. Research was also done on the standards in other industries including ocean engineering. The standard EN 10225 shows a proper example of the entry specification. The content included were shown in Table 2. In the annex E of the context, the terms related to fracture toughness were added, which require to test the crack tip open displacement on some welding seam area. The detailed description was shown in Table 3[6].

Table 2. Testing item in offshore standard.

| Testing item/Standard ID | EN 10225 |
|--------------------------|----------|
| Composition              | ○        |
| CEV                      | ○        |
| Tensile                  | ○        |
| Bending                  | ○        |
| Impact                   | ○        |
| Z direction              | ○        |
| Grain size               | ○        |
| Inclusions               | ○        |
| Band structure           | ○        |
| Corrosion resistance     | ○        |
| Fracture toughness       | ○        |
Table 3. Descriptions of fracture toughness in EN10225.

| Annex E |
|---------|

2.2.2. BS 7910:2013 guide to methods for assessing the acceptability of flaws in metallic structures[7]. BS 7910, the UK procedure for the assessment of flaws in metallic structures, was first published almost 30 years ago in the form of a fracture/fatigue assessment procedure, PD6493. The standard has been broadly applied in nuclear, offshore and petrochemical industry. However, now in the railway industry in China, the service assessment method still depends on the traditional fatigue design regulations. BS 7910 provided the basis for analyzing fabrication flaws and the need for life-evaluation in a rational fashion (Table 4)[7].

Table 4. Descriptions of crack growth rate in BS 7910[7].

| 8.4.5 |

3. Key properties discussion
On the basis of the investigations, some key properties have obvious influence on the quality of steels, especially fracture toughness and crack growth rate, etc. These properties were emphasized in following context.

3.1. Impact property
Basic properties experiments were conducted on the S355J2W steel plates provided by OEMs. On the impact property, a phenomenon appeared that the results of tests far exceeded the minimum requirements in normal standards while the ductile-to-brittle transition temperature was approaching -20°C (as shown in Figure 5), which means the materials tend to break or experience dramatic decrease of ductility if the vehicle service in cryogenic area. Therefore, it is suggested that the impact energy ought to be raised.
3.2. Fracture toughness
Fracture toughness is the resistance value displayed by the material when the starting point is a crack or crack-like defect in the sample or component, which no longer breaks rapidly with the increase of load.\cite{8} According to ISO 12135,\cite{9} the crack tip open displacement (CTOD) experiments were conducted on some welded joint seams based on the experience from ocean engineering. Based on the result analysis, the fracture toughness decrease from -20°C to -60°C (Table 5). As CTOD suggests the development of cracks in the microstructure of materials, it is strongly suggested to add the fracture toughness requirements to the materials quality controlling.

Table 5. CTOD tests on the welding seams at different temperatures.

| temperature | CTOD/mm |
|-------------|---------|
| -20°C       | 0.893   |
|             | 0.239   |
|             | 0.751   |
| -40°C       | 0.302   |
|             | 0.406   |
|             | 0.176   |
| -60°C       | 0.250   |
|             | 0.062   |

3.3. Crack growth rate
Crack growth rate is the property which reveals the materials sensitivity to cracks. Crack growth rate tests were done on the S355J2W steel plates according to ASTM E647\cite{10}. The results were
demonstrated in Figure and Table. The data were fit by Paris law (equation 1) and the parameter ‘A’ and ‘m’ were analyzed and compared with the recommendation in standard BS 7910[7]. It can be illustrated from Figure that the curve obtained by test is lower than the recommend curve in BS 7910 while the curves were close to each other, as shown in Figure 6[7]. Consequently, the parameters for crack growth rate in BS 7910 were intended to be adopted in materials quality control[7].

\[
da/dN = A(ΔK)^m
\]  

(1)

3.4. Metallography
Metallographic inspections were researched on the samples from 355 steel plates. Strong band structure was found during observation and martensite segregation arose even, as shown in Figure 7. Martensite shows greatly higher hardness than ferrite, causing dramatic property change in the microstructure, bringing hidden danger to the service safety of vehicles.

3.5. Corrosion resistance
Atmospheric salt spray corrosion resistance tests were done on a great number of S355J2W samples on the purpose of investigating the corrosion performance of the materials. Domestic and imported materials demonstrated an obvious difference (Figure 8). Level evaluation of corrosion resistance was conducted according to GB/T 6461, the results were shown in Table 6[11].
Figure 8. Six-hour-corrosion morphology of overseas and localized steels.

Table 6. Corrosion resistance level evaluation of overseas and localized steels

| Materials            | Corrosion resistance level |
|----------------------|---------------------------|
| S355J2W(Overseas)    | 6                         |
| S355J2W(Localized)   | 0                         |

4. Conclusions

Some defects such as cracks appeared at different stages of service when the rail-vehicle had not reached the design life, while current theories and methods cannot explain the appearance of them. Since more and more sensors were used to supervise the safety of structure, it is necessary to focus on the performance of materials.

- Due to the severe service environment of the vehicles, the requirements on impact, metallography and corrosion resistance property should be raised.
- It is recommended that the requirements of fracture toughness and crack growth rate need to be considered in the current materials entry specification, in order to ensure the service safety of the vehicles.
- Further research should focus on the fracture toughness parameters of both parent materials and weld joints to guarantee the safety during the service of vehicles.
- From the perspective of integrated consideration on the whole-life cycle, the thought of service safety of vehicles should be involved in the design, manufacture and operation sections.

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