Prepared for:

Mr. Hiroshi Murao
Kawasaki Heavy Industries

Prepared by:

Digitally signed by Brett Pond
Date: 2016.10.05 21:38:35 -04'00'

Brett Pond, PhD, PE
Principal Metallurgist

Scope of Investigation

TUV Rheinland Group (TUV) was requested by Mr. Hiroshi Murao of Kawasaki Heavy Industries (KHI) to assist in the investigation of C151A trains with lateral cracks in the bolsters. TUV performed the following assessments:

A. Perform a review and assessment of KHI assumptions and opinions.

B. Perform a review and assessment of KHI calculations of residual life of bolster.

C. Perform an independent assessment of the operational safety of C151A trains with lateral cracks in the bolsters.

A. Review and Assessment of KHI Assumptions and Opinions

Documentation provided by KHI was carefully reviewed, and all noted assumptions both explicit and implied were recorded and their validity assessed. In some instances, the distinction between assumption and opinion was blurred, and those cases were considered to be assumptions. There were two primary opinions offered by KHI, and the TUV assessment of these opinions are summarized below:

Opinion 1 – *The primary root cause of cracking was inherent defects in certain lots of bolsters.*

There has been an abundance of evidence provided to support this opinion, and little evidence to indicate otherwise. TUV is in general agreement with this opinion based on the root cause evidence provided to date.

Opinion 2 - *The trains with cracked bolsters are currently safe to operate, and will be so until a permanent solution is in place.*

The closely monitored crack growth rates provide solid evidence for this opinion. TUV is in general agreement with the opinion that the trains are currently safe to operate.

B. Review and Assessment of KHI Calculations of Residual Life of Bolster

In summary, the method used by KHI to calculate the residual life of cracked bolsters was to calculate an incremental daily crack growth rate between previous visual inspections of crack length for each bolster. That daily crack growth rate was then used to predict the number of days before the current cracks reached the assigned threshold of 85% of the full length of three of the four vertical webs.

To enable these calculations, KHI implemented a crack monitoring procedure, which TUV considered to be appropriate and sufficient.

The predicted residual life of each bolster was calculated after each inspection, both including and excluding newly observed cracks. The residual life prediction excluding newly formed cracks serves as a good indicator of the growth of the cracks that were previously present. However, the predictions that include the newly observed cracks serve as a better indicator of total accumulated damages and consequently residual life.

Interpretation of Data

The crack measurement data was interpreted and considered in multiple ways by KHI. As mentioned above, separate calculations of crack growth rates were performed for measurements including and excluding newly observed cracks at each inspection interval.

An attempt was made to correlate train mileage with cumulative crack length or total number of cracks. It was concluded that there was no correlation between the mileage and the length or quantity of cracks. There was a linear correlation between number of cracks and crack length, however. The linear relationship between number of cracks and cumulative crack length indicate that the multiple cracks initiated independently, and provide indirect evidence for internal defects as a root cause of failure.

Assessment of KHI Calculations

Considering the calculations performed by KHI, TUV considers that the methods were sound and the calculations were performed correctly. Due to the variability in the individual bolster crack growth rates and the variation in growth rates between inspection intervals for a given bolster, it is recommended that the following precautions be taken:

1. The residual life calculations by KHI be used conservatively (the worst case calculation) to estimate the safe operating life an individual bolster.

2. The residual life of a given bolster be determined independent from other bolsters. Special consideration should be given to bolsters that can be linked to the extrusion lots with a higher number of cracks.

3. A factor of safety should be applied to the residual life calculations to account for the variations between intervals. It should not be assumed that the highest growth rate for an individual bolster has already been observed.

C. TUV Assessment of Operational Safety of Trains with Cracks

In order to provide an independent assessment of the operational safety of these trains, documentation was provided regarding the observation, root cause determination, monitoring, and analysis of the bolster cracks. The methodology used to perform the assessment can be summarized as follows:

Develop an understanding of the severity or extent of cracking in the bolsters

To develop a thorough understanding of the severity and extent of cracking in the bolsters, documents which contained information on observations, visual inspection, ultrasonic testing, and videoscope imaging were studied. Relevant details regarding the statistical distribution of cracks were obtained, and the following key facts were reported or observed:

- Some bolsters have significantly more cracks than others, and these bolsters appear to be linked to specific heats of extrusions.

- Cracking generally occurred near the inner three of the four vertical webs in the bolster extrusions. The web with no cracks was the closest on each bolster to the end of the railcar. Collaboration with FEA results indicated that the stresses in the bolster near the vertical web with no observed cracks are significantly lower than locations near the other three vertical webs.

- There was a lateral symmetry in the distribution of cracks on each bolster. There was, however, a significant bias toward cracking toward the No. 1 end of the railcar as opposed to the No. 2 end. This indicates that the stresses during operation, which likely vary from one end of the railcar to the other based on direction of travel, play a significant role in the crack growth.

- There was a linear relationship between the number of cracks on a given bolster and the cumulative length of cracks. This indicates that most of the cracks on a given bolster are of comparable length and signify crack initiation at multiple locations along the length of the bolster rather than a single crack initiation site.

- There was a strong correlation between crack location and high stress locations as predicted by FEA results.

Examine the root cause of cracking

Initial evidence has been provided that the primary root cause of cracking is inherent defects in certain bolsters manufactured using a fusion process. Additional evidence has been provided which indicates that inclusion content has been introduced during the manufacturing process and has caused initiation of the cracks. It is anticipated that a confirmation of the assumed root cause of failure will provide us with confidence that a permanent solution can be obtained.

Assess the effect that the cracks have on the performance and safety of the bolsters

KHI calculated the remaining performance life of the bolsters under the assumption that the observed cracks would continue to grow at their current exponential growth rate until the defined threshold of 85% of the maximum possible cumulative crack length. These calculations included a 20% safety factor based on the recommendation of TUV to account for the inconsistency in crack growth rate between inspection intervals. KHI estimated that the worst case bolster 2544-1 will reach the 85% threshold by April 15, 2017 based on the daily crack growth rate between the 34th and 35th inspections.

TUV tested the validity of the KHI remaining life estimates be examining historic inspection data from eight bolsters with the highest historic crack growth rates. This data was used to determine the probability distribution of average daily crack growth rates for each individual crack and estimate the remaining life of those bolsters within a 98% confidence interval. The results of these calculations indicated that the remaining life estimates provided by KHI were reasonable.

Review the operational requirements of the trains

Instrumented test results provided by KHI provide a general idea of the accelerations and stresses that the bolsters experience during operation. Accelerations during normal operation were typical limited to 1 m/s^2, and these longitudinal accelerations occur twice for each stop. Based on the data provided by KHI, it was estimated that each train averages approximately 746 load cycles per day.

After removal of several of the worst case bolsters over the course of 35 inspection periods, the expected residual life calculations provided by KHI were a minimum of 482 days based on the latest observed crack growth rates.

Assess the current state of operational safety of the trains with cracked bolsters

The crack growth data produced by KHI over the course of 35 inspections has provided enough information to confidently determine risks and estimate the remaining life of each bolster.

Based on the documentation provided to date and the above considerations, TUV is of the current opinion that there are no immediate risks of fracture to the bolster, and the remaining life estimates provided by KHI should be considered reasonable.

The gradual decline of cumulative crack length of all 26 trains over time indicated that the inspection and bolster replacement schedule has been successful in managing the overall risks associated with the cracked bolsters.