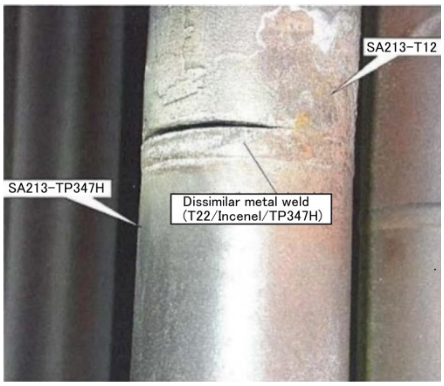
Development of Maintenance Guidelines for Dissimilar Metal Welds of Low-Alloy Steel Boiler Tube



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To determine the cause of the failure of the fusion line of boiler heat transfer tube dissimilar metal welds (DMW), which is a common problem worldwide because the failure mechanism has not been elucidated, Mitsubishi Heavy Industries Group (MHI Group) carried out research on the extraction of factors that influence failure and the proposal of a failure mechanism using metallurgical investigation and creep analysis by FEM (Finite Element Method). In addition, based on the proposed failure mechanism, we developed maintenance techniques against the failure of the fusion line of heat transfer tube low alloy steel DMW[(1)].

1. Introduction

Heat transfer tube of boilers, which are one of the main pieces of equipment of thermal power generation facilities, are often exposed to severe environments under high temperatures and high pressures. This results in failures of the fusion line at DMW of heat transfer tube, which is the generation and propagation of cracks along the fusion line between the base metal and the weld (**Figure 1**) [(2)]. Since such failures found in the past in our group occurred only in DMW that had undergone repair welding, we have taken measures such as not allowing repair welding when manufacturing joints. Since 2015, however, it has been confirmed that this failure occurs after long-term use even in areas other than repair welds. In addition, according to a report [(3)] by EPRI (Electric Power Research Institute), etc., similar failures have occurred not only in the boilers manufactured by our group, but also in those manufactured by other companies, so this is a common problem worldwide.

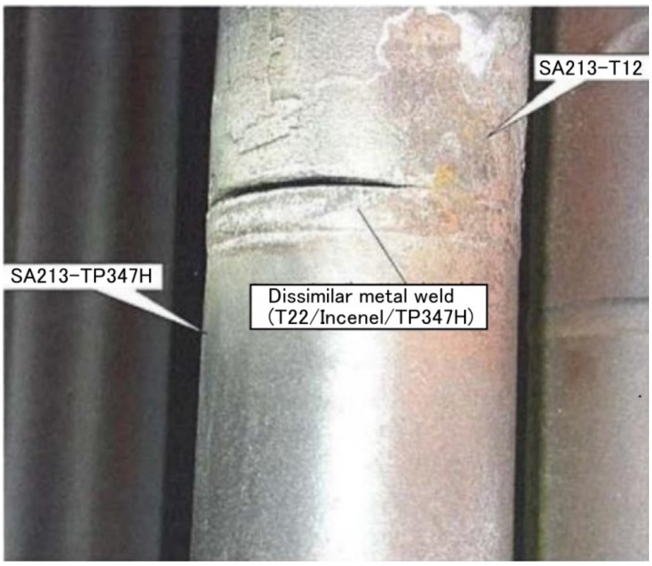

Figure 1 Example of failure on fusion line of dissimilar metal weld

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In this way, the problem of the failure of the fusion line of boiler heat transfer tube DMW has become apparent, but the failure conditions and failure mechanism have not been elucidated, so there is an urgent need to establish maintenance techniques such as risk assessment and inspection.

2. Failure morphology

Figure 2 shows the cross-sectional observation results of the failure of the fusion line that occurred on a boiler heat transfer tube low alloy steel DMW. This failure is the generation and propagation of a crack along the fusion line caused by voids (vacancies) generated in the fusion line on the low alloy steel side. Strictly speaking, voids and cracks often occur at a location on the low alloy steel side, about several micrometers from the fusion line. Another characteristic of this failure is that a row of precipitates and a decarburized layer (**Figure 3**) are formed near the fusion line due to the atomic diffusion between the weld metal and the base metal.

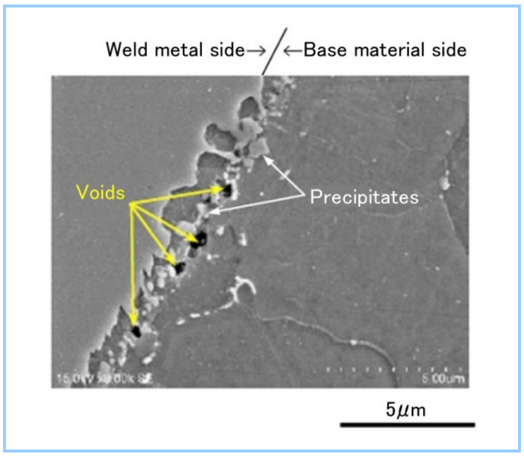

Figure 2 Example of cross-sectional observation of failure on fusion line using scanning electron microscope

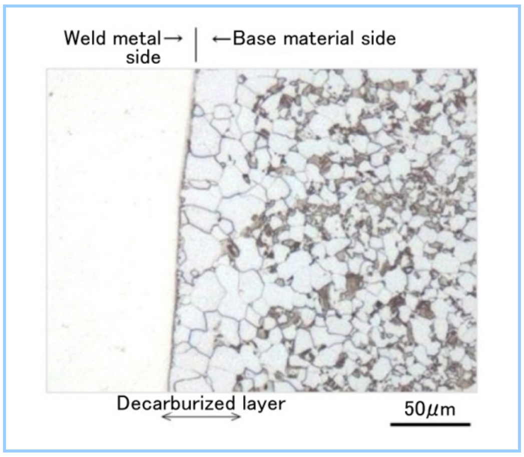

Figure 3 Observation example of decarburized layer formed near fusion line

3. Failure example

Figure 4 shows a typical example of the failure of a fusion line. Failures found in the past in our group occurred only on the DMW of a superheater tube and no failures occurred on the DMW of a reheater tube. This failure was considered to be rare because there were few cases that led to a leak accident. However, recently a crack was detected by UT (Ultrasonic Test) as shown in Figure 4, so this failure should be subject to maintenance.

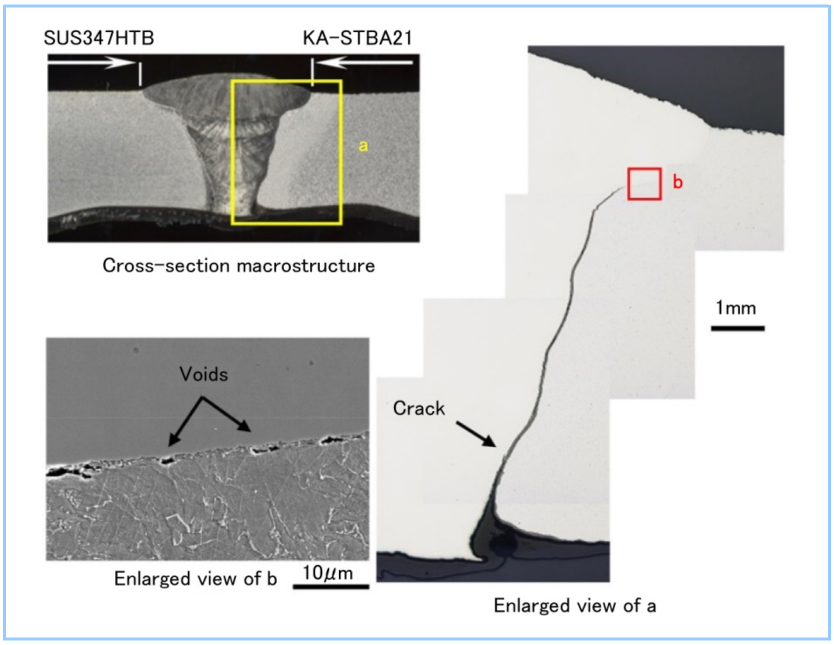

Figure 4 Examples of crack detected by UT inspection

4. Factors that affect failure

In order to investigate the mechanism of this failure, we first identified the factors that affect this failure. Specifically, we compared and arranged the design conditions and operating conditions of the failure material and non-failure material and conducted metallurgical investigations such as cross-section survey and chemical analysis. During the metallurgical investigation, it was found that there is a difference in the structural composition of the HAZ (Heat Affected Zone) between the superheater tube and the reheater tube (**Figure 5** and **Figure 6**). As described above, since no failure has occurred on the DMW of reheater tubes, it was hypothesized that this difference in structural composition is one of the factors that affect the failure.

In order to verify this hypothesis, we performed elastic － creep analysis by FEM under the same conditions except for the structural composition. As a result of the FEM analysis, it was clarified that the difference in structural composition causes a difference in the axial stress required for the generation and propagation of cracks, so it was found that a difference in structural composition can be one of the factors that affect failure (**Figure 7**). In addition, as a result of FEM analysis of several models we created, it was clarified that the higher the base acting stress (axial stress due to internal pressure), the higher the axial stress acting on the fusion line, so it was found that the magnitude of this acting stress can also be one of the factors that affect failure (**Figure 8**).

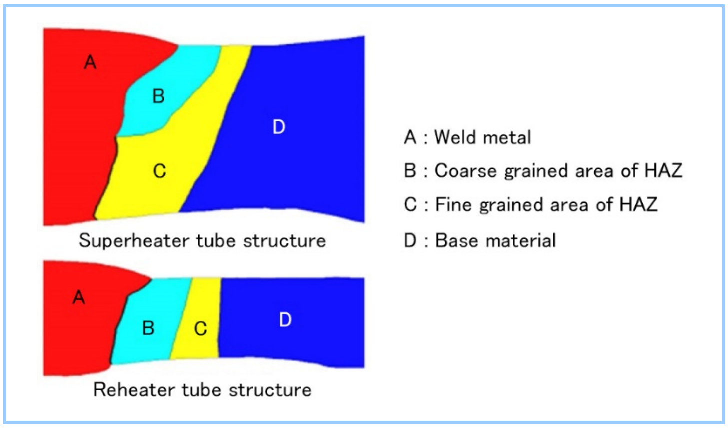

Figure 5 Difference in the structural composition between superheater tube and reheater tube

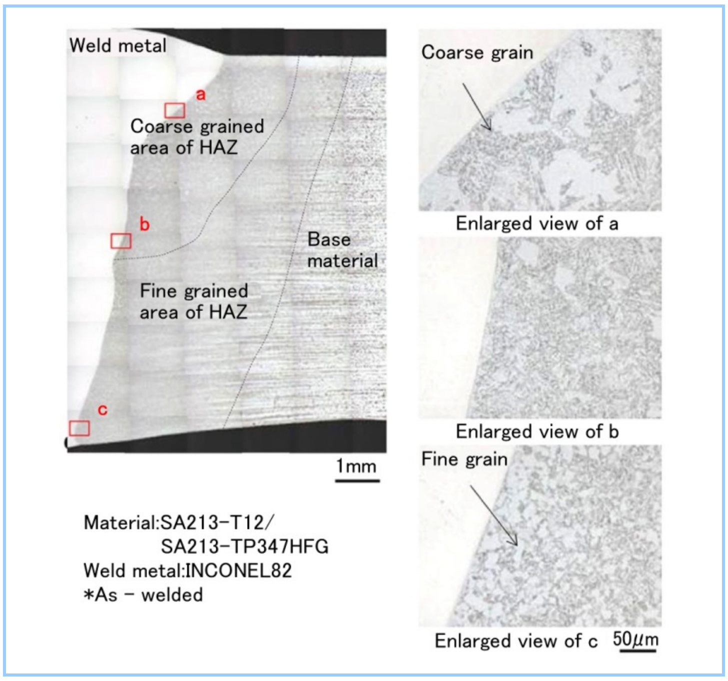

Figure 6 Typical example of superheater tube structural composition

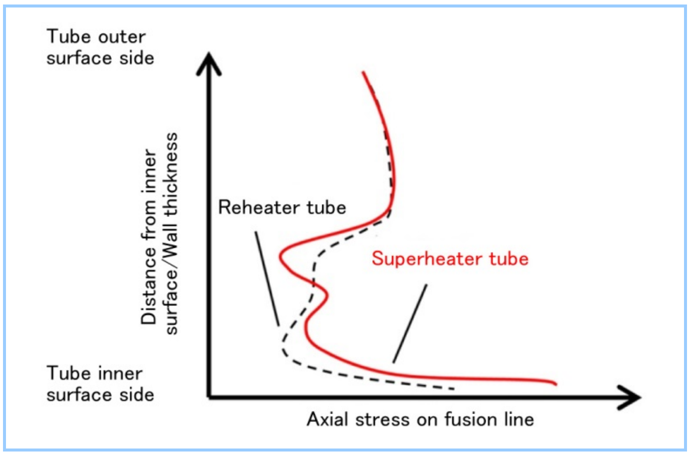

Figure 7　FEM analysis result image

Case	Case1	Case2	Case3	Case4
Analysis model	Superheater tube	Superheater tube	Reheater tube	Reheater tube
Design temperature [°C]	484	505	509	528
Axial stress due to internal pressure [MPa]	28.4	12.1	18.6	12.7
Analysis time [x10⁴ hours]	20	20	20	20

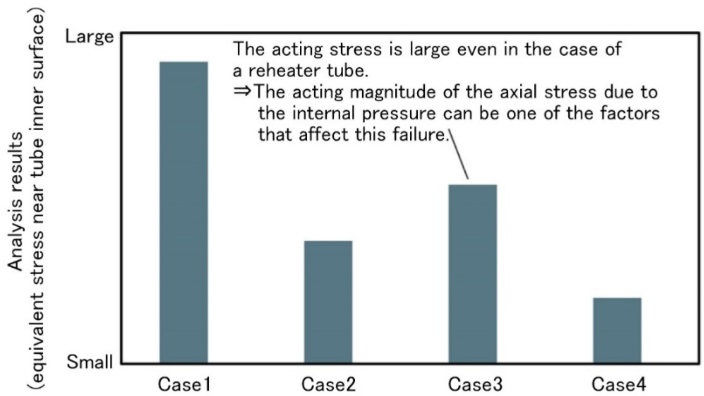

Figure 8　Comparison of FEM analysis results using multiple models

5. Failure mechanism

Based on the aforementioned factors that affect failure, we investigated the failure mechanism of the fusion line of boiler heat transfer tube low alloy steel DMW. The failure mechanism estimated at this time is shown below.

(1) The structural composition of a heat transfer tube DMW differs between superheater tubes and the reheater tubes (Figure 5 and Figure 6). In the case of superheater tubes, the fined grain area of HAZ is located from the inner surface side of the tube near the fusion line to the center of the tube thickness. In a low alloy steel dissimilar joint, since the creep deformation resistance of the fine grained area of HAZ is higher than the creep deformation resistance of the coarse grained area of HAZ*, stress redistribution due to creep during operation occurs and high axial stress is generated on the inner surface side of the tube or near the center of the tube thickness (Figure 7). This axial stress includes not only the axial stress due to the internal pressure, but also the tensile bending stress caused by the difference in thermal expansion between the stainless steel, weld metal and low alloy steel.

(2) In the case of superheater tubes, generally the difference between the nominal wall thickness and tsr (minimum required thickness) is smaller than that for reheater tubes and the axial stress caused by the internal pressure, which is one of the factors that affect failure as mentioned above, is relatively high in many cases.

(3) In the case of superheater tubes, in addition to the high stress on the fusion line on the inner surface side and near the center of the tube thickness, the presence of a decarburized layer

with less creep deformation resistance than the surrounding structure makes it easier to accumulate creep strain. This decarburized layer is formed by atomic diffusion between the weld metal and the parent phase due to heat input during welding and is observed in both superheater tubes and reheater tubes.

(4) Furthermore, due to the difference in Cr concentration between the parent phase and the weld metal, precipitates such as $M_{23}C_6$ and M_6C are formed in the decarburized layer mainly in a row shape (**Figure 9**).

(5) Due to the accumulation of creep strain during operation, atomic vacancies are likely to accumulate at the fusion line between the precipitate in the decarburized layer and the parent phase and creep voids are preferentially generated (Figure 9).

(6) As the formation of voids progresses, they are connected to each other, leading to the generation and propagation of microscopic cracks and eventual fractures .

Note that even with the same tube specifications and working conditions, the degree of this failure may differ and the reason and mechanism have not been clarified at this time, so further research is needed.

* As a result of a creep characteristic survey using minute test pieces collected from both the coarse grained area of HAZ and the fine grained area of HAZ of a 1Cr steel DMW for confirmation of the creep deformation resistance of the structure of a 1Cr steel DMW, it was confirmed that the creep deformation resistance was lower in the coarse grained area of HAZ.

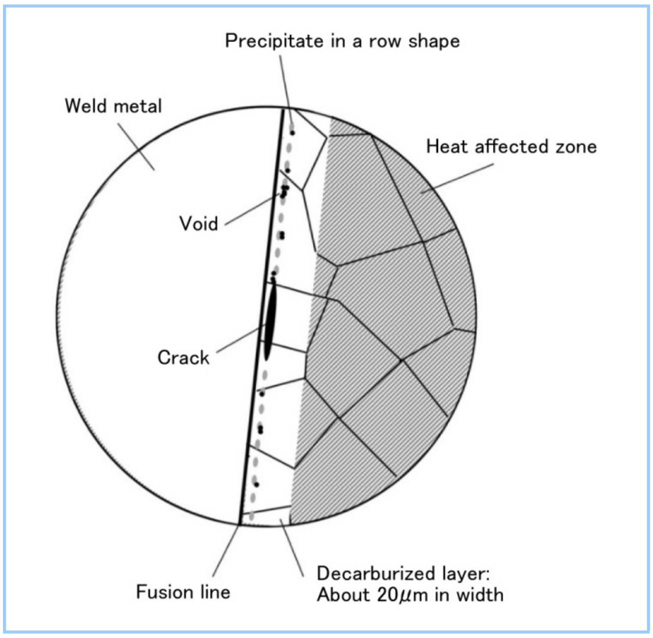

Figure 9 Schematic view of failure

6. Maintenance techniques

Based on the factors that affect failure and the failure mechanism mentioned above, we examined maintenance techniques against the failure of the fusion line of boiler heat transfer tube low alloy steel DMW and formulated effective maintenance guidelines to prevent failure. **Figure 10** shows the outline of the maintenance guidelines.

The statistical risk assessment method, which has been developed this time, included in these maintenance guidelines is described below. This assessment method builds a learning model through machine learning of the factors that affect failure and some of the working conditions described in Chapter 4, as well as actual failure cases. By analyzing data including tube specifications and working conditions with this learning model, the risk of failure occurrence for each tube specification and each working condition can be assessed in a relative manner. By incorporating the factors that affect failure into the variables of the learning data, this method enables highly accurate risk assessment and can prioritize the targets to be inspected from a huge number of DMW. Furthermore, by regularly learning additional inspection results, the accuracy of the risk assessment can be improved (**Figure 11**).

Since this failure often occurs from the inside of the wall thickness or the inner surface side of the tube, UT inspection was adopted. UT inspection uses our proprietary thin UT probe and the unique flaw detection sensitivity and detection standard value are set based on a simulation and actual equipment inspection results, which results in the minimum detectable failure size of 1 mm.

In this way, by utilizing maintenance techniques that combine statistical risk assessment, UT inspection, etc., the prevention of failures on boiler heat transfer tube low alloy steel DMW and reduced maintenance costs can be expected.

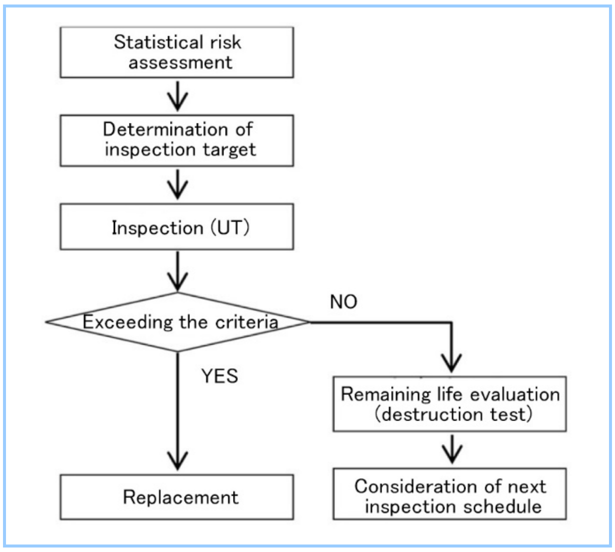

Figure 10 Conceptual diagram of maintenance flow against failure on weld interface of low alloy steel dissimilar welds

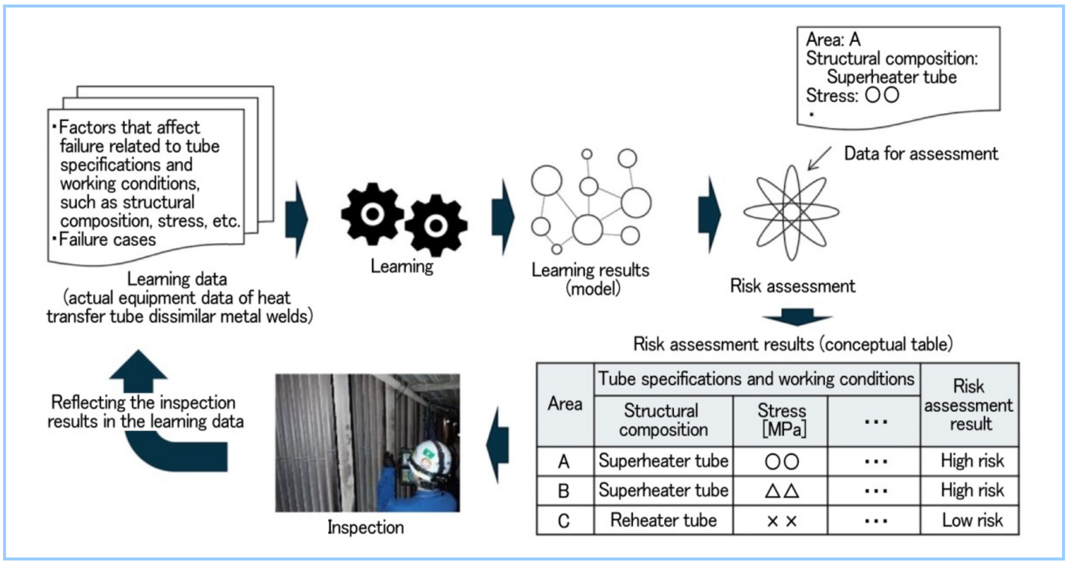

Figure 11 Conceptual diagram of risk assessment with statistical analysis

7. Conclusion

Failure of the fusion line of boiler heat transfer tube DMW is a common problem worldwide because the failure mechanism has not been elucidated. In order to solve this problem, MHI Group extracted some factors that affect the failure by metallurgical investigation and creep analysis through FEM of the failure material and non-failure material and proposed a probable failure mechanism. We also established maintenance techniques based on the failure mechanism.

We will continue research on this failure—which is still partially unclear—and contribute to the prevention of failures and the improvement of the reliability of boilers by using the established maintenance techniques.

References

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