

Life Design and Evaluation Method of Type 3 High-Pressure Hydrogen Tank for Fuel Cell Electric Vehicle

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ABSTRACT

Failure in Type 3 high-pressure hydrogen tanks occurs as a result of the growth of cracks in the boss of the liner or the cylinder until the liner is penetrated. The boss of the liner is prone to exposure to corrosive environments, for example by being splashed with water during driving. For this reason, it is essential to evaluate the life of a tank until a leak occurs with consideration of the corrosive environments in an actual vehicle. A life design method based on the mechanism of failure of the boss, in which evaluations are conducted with consideration of stress corrosion cracking and sustained load cracking, was therefore developed. The correlation between the results produced by the method and the results of tests using a Type 3 high-pressure hydrogen tank was examined, demonstrating the validity of the method. This paper also discusses a method of evaluation of Type 3 high-pressure hydrogen tanks that considers their fatigue characteristics in the type of corrosive environments occurring in actual vehicles.

1. Introduction

Development projects and studies are proceeding, centering on the automotive industry, towards the introduction of fuel cell electric vehicles to the market. Hydrogen storage systems are an important element technology of fuel cell electric vehicles. Today, the main focus is on storage systems using 70 MPa hydrogen tanks that make it possible to drive further on a single hydrogen refill, and which make the storage system more compact due to their increased storage density. The main components of high-pressure hydrogen tanks for automotive use are a liner, which functions as a hydrogen gas barrier layer, and a carbon fiber-reinforced plastic (CFRP) layer, which reinforces the outer surface of the liner. When the liner is metal (mainly aluminum alloy), the tank is classified as a Type 3 high-pressure hydrogen tank (Type 3 tank) and when the liner is plastic, the tank is classified as a Type 4 high-pressure hydrogen tank (Type 4 tank) (Fig. 1). Both types of tank are large and high-priced for automotive components, and the reduction of size and cost therefore represent issues.

Weight, price, filling rate, safety and other tank characteristics differ between Type 3 and Type 4 tanks, and tank design methods are also different. This makes it necessary to develop evaluation methods suited to a tank's

type and failure mechanism. Failure in Type 3 tanks occurs as a result of the growth of cracks in the aluminum alloy liner, which eventually penetrate the liner. Type 3 tanks are designed with consideration of crack growth due to fatigue in order to achieve weight reductions (i.e., designed in the finite life range). In addition, due to the way that high-pressure hydrogen tanks are installed in vehicles, there is a strong possibility that a corrosive environment will be created, for example due to exposure of the boss of the tank to water during vehicle operation. Based on the above, it is necessary to evaluate the durability performance of a Type 3 tank with consideration of the corrosive environment in an actual vehicle.

Turning to issues in evaluation methods for the

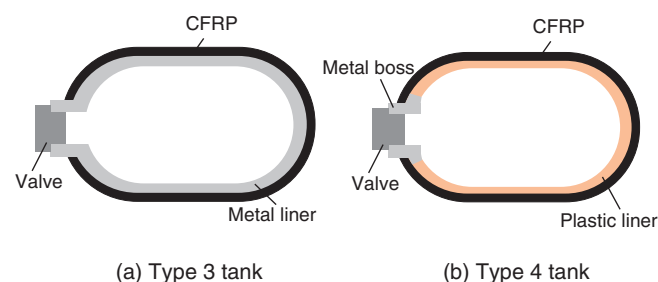


Fig. 1 Structural schematics of Type 3 and Type 4 tanks

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corrosion resistance of high-pressure hydrogen tanks as defined by regulations and standards, in the second half of the 1990s, several incidents of failure of scuba cylinders (Type 1) manufactured from A6351-T6 aluminum alloy occurred^{(1), (2)}. In Japan, the cause of these failures was interpreted as Stress Corrosion Cracking (SCC), while overseas the cause was considered to be Sustained Load Cracking (SLC). In an attempt to prevent these incidents, a high-pressure container regulation was formulated that prohibits the use of excess silicon 6XXX series aluminum alloys, which have a yield strength above 250 MPa⁽³⁾. In addition, Annex B of ISO 7866 stipulates SLC tests to help ensure that even when a high-pressure tank remains under load in the use environment for an extended period, failure will not occur due to the crack growth. However, based on reports that in the case of 7XXX series aluminum alloys SLC characteristics are dependent on the test environment (the water content in the test environment)^{(4), (5)}, SLC tests, which are evaluations conducted in the air without specifying humidity, cannot be considered an appropriate evaluation method for high-pressure tanks for automotive use. While the intercrystalline corrosion tests and SCC tests specified in Annex A of ISO 7866 are tests for the evaluation of the occurrence of corrosion and crack growth in aluminum tanks in saltwater environments, they involve passing or failing the material. Because of this, the evaluative tests specified by ISO 7866 are not able to judge the severity of the corrosion environment or the life design of the product. A method of evaluation of stress corrosion cracking in aluminum alloys that considers the corrosion environment and life design is necessary.

A life design method able to adequately evaluate the boss of a Type 3 tank, which could be assumed to be exposed to the exterior environment and damaged by SCC and SLC, was therefore developed. In addition to the development project, this paper will also discuss the results of tests conducted to verify the effectiveness of the method. As part of the process of examination towards reducing the weight and the cost of Type 3 tanks in the future, the paper will also present an analysis of the potential for the high-strength aluminum alloy A6066, which is also the subject of a NEDO project⁽⁶⁾, for use in the liners of Type 3 tanks.

2. Regulations and Standards Related to High-pressure Hydrogen Tanks and Design Concept

2.1. Related Regulations and Standards and Methods of Evaluation

This section will deal with technological standards related to high-pressure hydrogen tanks. Looking at domestic regulations first, the technical standard for containers of compressed hydrogen employed as vehicle fuel devices (KHK S0128)⁽⁷⁾, dealing with devices with a maximum filling pressure of 70 MPa, was issued in 2013. This regulation restricts the metals able to be used in the

tanks to aluminum alloy A6061-T6 and stainless steel SUS316L, the fatigue strength of both of which has been evaluated in high-pressure hydrogen gas⁽⁸⁾. Turning to the situation overseas, Global Technical Regulations (GTR) for fuel cell electric vehicles are presently under examination⁽⁹⁾. The formulation of the GTR has been divided into two phases. In Phase 1, issues including basic evaluation methods for the tanks were deliberated and compiled. Time was required to achieve a consensus between the participating countries regarding the details of materials evaluations, and deliberation of these points is continuing in Phase 2. The details of the GTR are important, given that it can be assumed that if a consensus is achieved, domestic standards will come into line. It is possible that the GTR evaluation standards might relax restrictions on materials and structure for conforming tanks (allowing the use of materials other than the A6061-T6 and SUS316L specified by domestic regulations).

As indicated above, no consensus concerning evaluation methods of the hydrogen compatibility of metals was reached in Phase 1 of the GTR, and discussions are continuing in Phase 2. In addition, accurate evaluation of corrosion fatigue strength and stress corrosion cracking in saltwater environments will also be important in attempting to ensure the soundness of metal materials used in automotive components.

At present, judgment of the compatibility of aluminum alloys for use in high-pressure tanks in terms of corrosion is based on Annexes A and B of ISO 7866⁽¹⁰⁾ and similar regulations. Annex A specifies intercrystalline corrosion tests that determine environmental sensitivity based on the depth of intercrystalline corrosion, and SCC tests, which evaluate stress corrosion cracking via saltwater wetting and drying cycles. These can be considered to be tests for the evaluation of the occurrence of corrosion and crack growth in aluminum alloys when exposed to saltwater environments. Annex B specifies the SLC tests discussed in the previous chapter. However, the evaluation methods specified by ISO 7866 assume aluminum alloy high-pressure tanks that are not reinforced with CFRP (Type 1 tanks). In Type 3 tanks, the outer surface of the aluminum alloy liner is covered by CFRP, and the status of occurrence of corrosion and the areas that are exposed to a corrosion environment differ from Type 1 tanks. Because of this, in addition to the evaluation methods of hydrogen compatibility described above, the evaluation of the aluminum alloys used in Type 3 tanks necessitates evaluation methods of corrosion resistance that adopt a fracture mechanics perspective suited to composite containers.

2.2. Concept of Safety Design

The concept of “leak before burst” (LBB) is part of the thinking regarding safety design for high-pressure equipment and high-pressure tanks^{(11), (12)}. This concept seeks to prevent the bursting of high-pressure equipment

and tanks, which might result in terrible accidents, by promoting leaking of the internal gas prior to bursting when unforeseen events occur. In concrete terms, judgments are first made for each part of the tank regarding whether it will be able to fulfill LBB criteria. For parts that do fulfill the criteria, life design based on an S-N curve expressing the relationship between loaded stress and life is employed. For the parts that do not, life calculations are performed based on crack growth analyses, and design attempts to ensure a life that is sufficiently longer than the parts that fulfill the LBB criteria.

In Type 3 tanks, the aluminum liner normally fails due to fatigue cracks developing and penetrating the liner. Despite this, because the liner is covered by CFRP, the liner leaks rather than bursts. Given this, Type 3 tanks basically fulfill the LBB criteria. Finite life design based on the relationship between the stress occurring in the liner and its life (an S-N curve) is therefore used for these tanks. However, the boss is not completely covered by the CFRP, and does not fulfill the LBB criteria. For example, the existence of a defect at thread root in the boss of a size that has not been considered in the design process may be hypothesized. In this case, if a crack grows from the defect and penetrates the boss, the failure mode of the boss will be bursting. Structurally, therefore, the boss does not fulfill the LBB criteria. In order to help prevent bursting of the boss, the existence of an initial defect of a certain size in the boss is assumed from a design perspective, and the life of crack growth in the boss is designed to be sufficiently longer than the life before leaking of the parts that fulfill the LBB criteria. By this means, the tank as a whole needs to meet the LBB criteria.

3. Life Design and Test Method for the Boss

3.1. Life Design Method

The bosses of hydrogen tanks can be exposed to corrosive environments, for example by becoming wet during vehicle operation. It has been reported with regard to SLC in aluminum alloys that the higher the humidity of the environment to which the alloy is exposed, the lower its resistance to crack growth^{(4), (5)}. Because of this, it is necessary for the life design of the boss to consider SLC in a corresponding corrosion environment. Figure 2 shows the

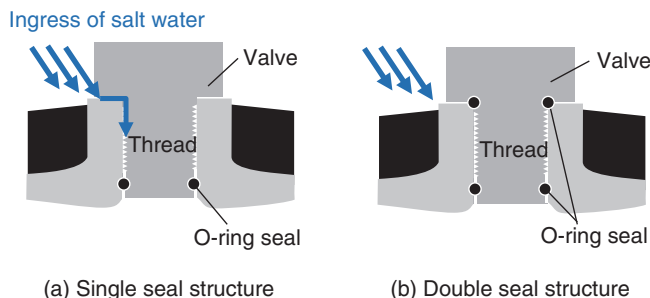


Fig. 2 Schematics of seal structure

structure of a boss seal. Because of the seal structure, the threads are exposed to a different environment. The research discussed in this paper focused on life design of the structure shown in Fig. 2(b), which seals the external surfaces of the threads to help prevent infiltration of saltwater and other corrosive agents. The structure shown in Fig. 2(b) helps to prevent water containing corrosive ions from reaching the thread section of the liner boss from the exterior, making the environment to which the threads are exposed the air. The threshold stress intensity factor at which SLC occurred (the SCC threshold stress intensity factor, K_{ISCC}) was therefore measured in humid air, a more severe environment for SLC, and this measurement was reflected in the life design. The high-pressure container industry treats the phenomenon of crack growth in aluminum alloys under long-term loads as SLC, but this is generally interpreted as SCC. This paper makes no distinction between the detailed mechanisms of SLC and SCC, and treats crack growth under static loads in a corrosive environment as SLC, which it evaluates using K_{ISCC} . Taking SLC into consideration, the life design method for the tank boss is as follows (Fig. 3):

- (1) A limit dimension for a defect that could be detected in a non-destructive inspection in the manufacturing process is projected, and the initial defect dimension for the design is set on this basis. This dimension is treated as the initial crack length.
- (2) The threshold stress intensity factor for SCC in humid air, K_{ISCC} , is measured.
- (3) The fatigue crack growth rate in humid air is measured.
- (4) The life of fatigue crack growth is analyzed.
- (5) The design is adjusted to help ensure that the stress intensity factor of cracks in the boss does not reach K_{ISCC} during the designed life of the tank.

3.2. Initial Crack Length

When setting the initial crack length for design purposes, employing a larger figure than the minimum figure able to be detected in a non-destructive inspection of thread root in the tank boss makes for a safer design. For the analysis of fatigue crack growth conducted in this research, a circumferential defect of 2 mm in depth was assumed. This could be seen with the naked eye, and was assumed to be a

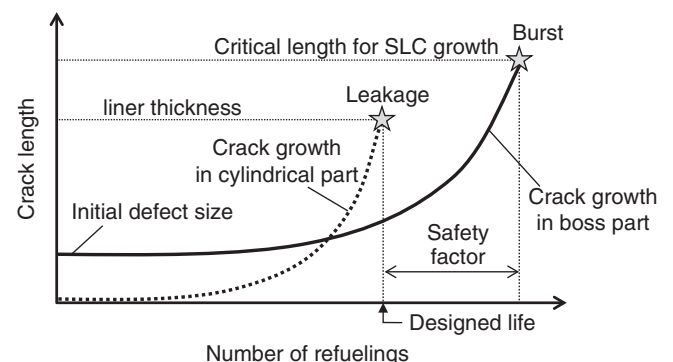


Fig. 3 Schematic of fatigue crack growth life design

defect of a size that could not occur in the actual machining process.

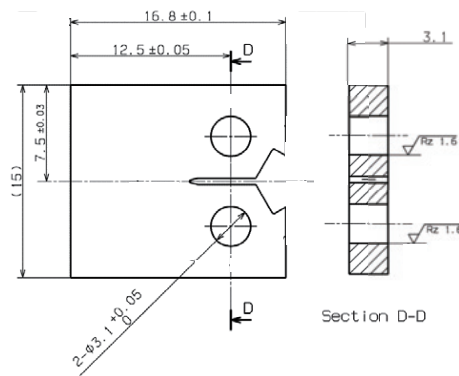
For a crack initiation from a defect, several numbers of cyclic stress load of a certain level are necessary. Normally, when dealing with metal fatigue, the number of cycles to crack initiation is approximately 10% of fatigue life, and the number of cycles for the crack growth to failure represents the greater part of the fatigue life of the product. Given this, for the design life calculations conducted in this research, the number of cycles until the crack initiated from the defect was ignored, and the initial defect was regarded as the crack.

3.3. Measurement Method of Crack Growth Data

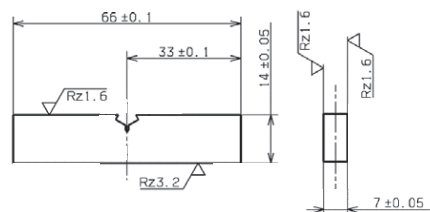
Crack growth tests were conducted in order to measure crack growth rate of material in the tank boss. These tests used a CT specimen taken from the boss of an A6066 aluminum alloy liner. Figure 4(a) shows the shape of the CT specimen. This shape conforms to ASTM E647⁽¹³⁾. The test was conducted in humid air, with a relative humidity of more than 90% at room temperature (25°C). The initial stress intensity factor range for the test was set at $\Delta K = 6 \text{ MPa}\sqrt{\text{m}}$, and the decreasing method and the increasing method were applied. The methods used for procedures such as measurement of crack length and calculation of the stress intensity factor were based on ASTM E647. The stress ratio, R , was 0.1, and the test frequency was 5 Hz to 20 Hz.

3.4. Method of K_{ISCC} Measurement

In order to determine K_{ISCC} , three-point-bend test specimens of the shape shown in Fig. 4(b) (conforming



(a) CT specimen for crack growth test



(b) 3-point bend specimen for measuring K_{ISCC}

Fig. 4 Size and shape of specimens

to ASTM E399⁽¹⁴⁾) were taken from close to the boss of an A6066 aluminum alloy liner and an A6066-T6 plate for liner use. In addition, in order to provide a reference to help determine the difference between the fracture surface of the fatigue pre-crack and the fracture surface of the SLC, test specimens were also created from A6351-T6, which has a similar excess silicon composition to A6066 and is considered to be prone to SLC.

Based on ISO 7359-6⁽¹⁵⁾, K_{ISCC} was determined by observing whether there had been any crack growth in the pre-cracked specimens following exposure to the environment. The load was applied so as to impart a specific displacement. The conditions for exposure to the environment were a temperature of 25°C, a relative humidity of more than 90%, and a period of exposure of 90 days. In order to study the behavior of crack growth under sustained loads, tests were also conducted in which the exposure period was reduced to 10 days and 30 days. Following exposure, the load on the test specimen was measured. Fatigue tests were then conducted in order to propagate cracks for observation of the fracture surface. In the period necessary for the cracks to newly grow by at least 1 mm, care was taken to attempt to prevent the maximum stress intensity factor from exceeding 0.6X the stress intensity factor when the load was initially applied prior to exposure. The crack growth during exposure was examined by observing the fracture surfaces with a scanning electron microscope (SEM). Crack lengths were measured in the direction of thickness of the test specimen, at 25%, 50% and 75% of the thickness of the specimen. The average of these three figures was regarded as the crack length. Based on the loads measured following exposure to the environment and the crack lengths measured by SEM observation, the stress intensity factor when the test specimen was under load was recalculated. Using the results of these measurements of crack length, the maximum value of the stress intensity factor among load conditions in which crack growth was not observed was taken as K_{ISCC} , the threshold stress intensity factor for SLC.

3.5. Relationship between Crack Length and Stress Intensity Factor

The calculation of the stress intensity factor for thread root cracks in the tank boss section was performed using the method specified by KHK S0220 Annex IX⁽¹¹⁾. This method was employed because it makes it simple to calculate the stress intensity factor from the results of stress analysis of the threads of the boss.

The method used for stress analysis of the threads of the boss is described below. This stress analysis used an axisymmetric FEM model (Fig. 5). Normally, the contact surfaces of each thread would be moved relative to each other by the application of the load, but for the sake of simplicity in the present analysis, the contact surfaces were fixed. The load pressure was set at 87.5 MPa, the maximum pressure of a 70 MPa hydrogen tank.

The following method was employed to calculate the stress intensity factor. First, the cubic equation Eq. (1) was used to approximate, σ , the stress distribution on the thread root. Equations (2) to (7) were then run with this figure as a coefficient. These calculations employed the stress distribution in the threads, where the maximum stress occurs in the thread section. For the approximation, the stress distribution was divided into four sections.

$$\sigma = A_0 + A_1x + A_2x^2 + A_3x^3 \quad (1)$$

$$K_I = F\sqrt{\pi a} + \sum_{i=1}^3 \Delta K_{I,i} \quad (2)$$

$$F = A_0F_1 + \frac{2aA_1F_2}{\pi} + \frac{a^2A_2F_3}{2} + \frac{4a^3A_3F_4}{3\pi} \quad (3)$$

$$F_1 = 1.1259 + 0.2344\left(\frac{a}{t}\right) + 2.2018\left(\frac{a}{t}\right)^2 - 0.2083\left(\frac{a}{t}\right)^3 \quad (4)$$

$$F_2 = 1.0732 + 0.2677\left(\frac{a}{t}\right) + 0.6661\left(\frac{a}{t}\right)^2 + 0.6354\left(\frac{a}{t}\right)^3 \quad (5)$$

$$F_3 = 1.0528 + 0.1065\left(\frac{a}{t}\right) + 0.4429\left(\frac{a}{t}\right)^2 + 0.6042\left(\frac{a}{t}\right)^3 \quad (6)$$

$$F_4 = 1.0387 - 0.0939\left(\frac{a}{t}\right) + 0.6018\left(\frac{a}{t}\right)^2 + 0.3750\left(\frac{a}{t}\right)^3 \quad (7)$$

Here, x is distance from the thread root in the radial direction. A_0 , A_1 , A_2 , and A_3 are constants. $\Delta K_{I,i}$ is the difference between the stress intensity factor at the boundaries of a section and the stress intensity factors of the previous section and the following section. a is the crack length from the thread root, and t is the thickness of the boss of the liner.

3.6. Test Method for Design Verification

Tests were conducted using a Type 3 tank with an A6066 aluminum alloy liner in order to verify the validity of the life design of the tank boss. The 2 mm initial defect used in the analysis of crack growth was introduced to the

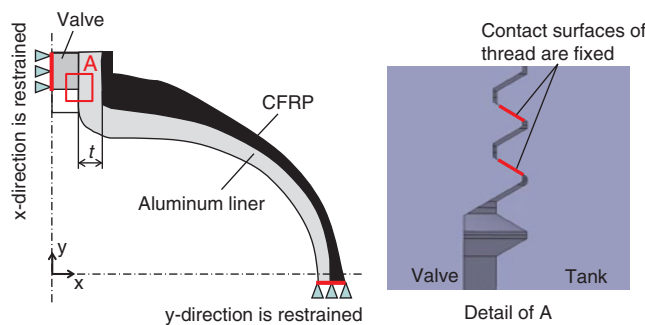


Fig. 5 Simulation model for stress analysis for calculating stress intensity factor

test tank at the position of maximum stress at thread root in the boss, with a circumferential notch being produced by electrical discharge machining (Fig. 6). Using this tank, 87.5 MPa hydraulic pressure cycle tests were conducted until a leak occurred. Following this, cracks from the bottom of the notch were observed, and the correlation with the life design was determined.

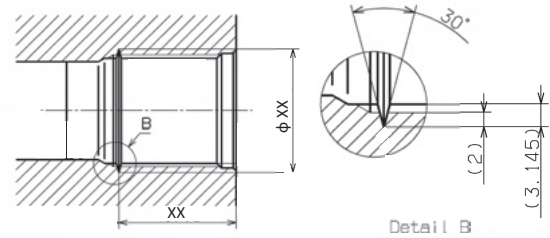


Fig. 6 Configuration of artificial notch machined into thread

4. Results of Crack Growth Analysis and Test Results

4.1. Fatigue Crack Growth in Humid Air

Figure 7 shows the results of a crack growth test in humid air conducted using a test specimen cut from the boss of an A6066 aluminum alloy liner. The approximation curve for the crack growth rate, da/dN , used in crack growth analysis, was set based on these results using the following equations. Here, N is the number of cycles.

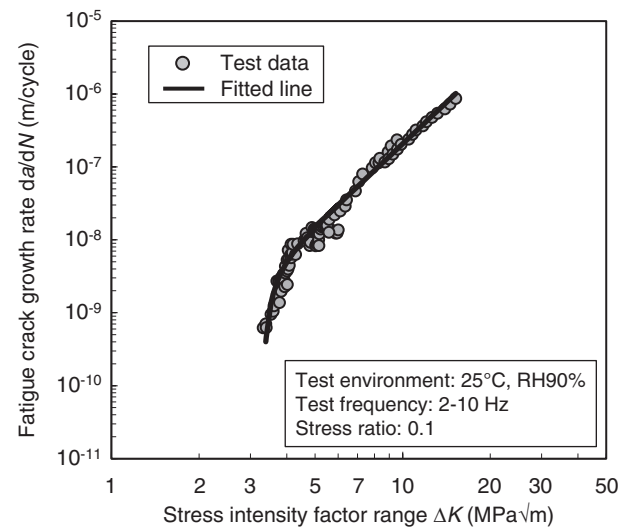


Fig. 7 Fatigue crack growth rate of specimen cut from A6066 aluminum alloy Type 3 tank liner boss

$$\frac{da}{dN} = f(\Delta K) \quad (8)$$

(i) When $3.4 \leq \Delta K \leq 5.0$

$$f(\Delta K) = 1.088 \times 10^{-9} \Delta K^2 - 6.724 \times 10^{-10} \Delta K - 1.020 \times 10^{-8} \quad (9)$$

(ii) When $5.0 < \Delta K$

$$f(\Delta K) = 3.433 \times 10^{-11} \Delta K^{3.781} \quad (10)$$

4.2. K_{ISCC} Test

In the fracture surfaces where cracks had clearly progressed in specimens of A6351, intergranular facets forming dimples were observed (Fig. 8). The fracture surfaces were observed with this characteristic as a reference and the crack lengths were measured.

Figure 9 shows the results of the K_{ISCC} test. Figure 9(a) shows the relationship between crack length and exposure time when the stress intensity factor under the initial load, K_{IAPP} , is the value specified in the ISO 7866 SLC test. For A6351, crack length increases with time under load. By contrast, in the case of A6066, there was almost no growth in the cracks. Figure 9(b) shows the amount of crack growth following 90 days of exposure for differing K_{IAPP} . This figure indicates that for each material, there is a stress intensity factor at which SLC does not occur. In addition, while A6066 is an excess silicon alloy like A6351, it clearly

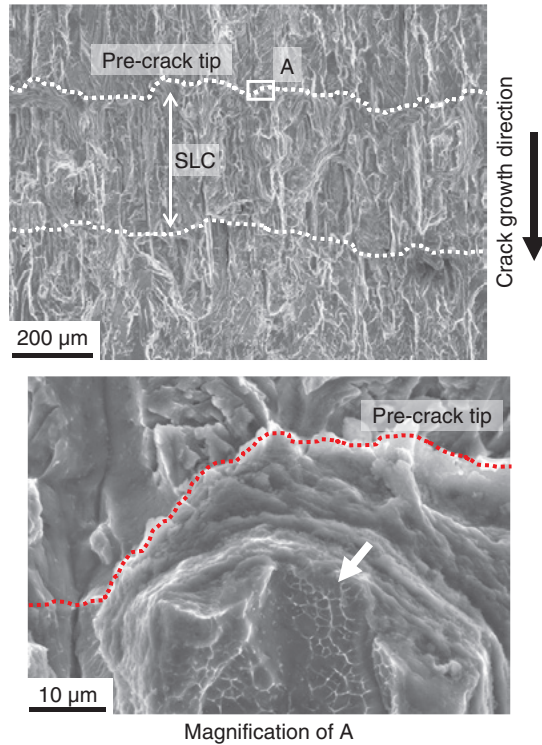


Fig. 8 SEM observation of A6351-T6 fracture surface caused by SLC ($K_{IAPP} = 17.2 \text{ MPa}\sqrt{\text{m}}$)

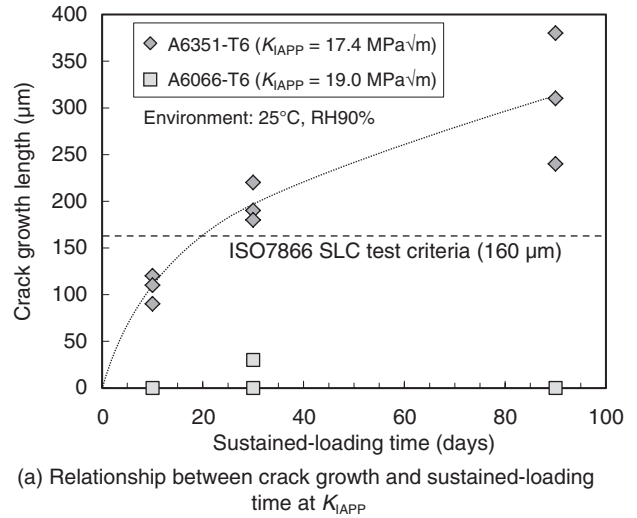
surpasses A6351 in terms of resistance to SLC.

Based on Figure 9(b), the highest stress intensity factor among the stress intensity factors for which SLC does not occur, $18.7 \text{ MPa}\sqrt{\text{m}}$, was taken as K_{ISCC} for A6066.

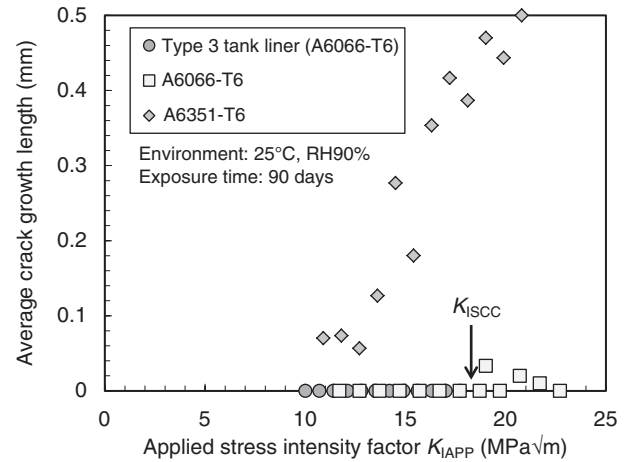
4.3. Calculation of Stress Intensity Factor Range and Crack Growth Life

Figure 10 shows the relationship between the stress intensity factors determined from the results of the stress analysis of the thread section of the liner boss and crack length.

Based on this relationship, crack growth life was calculated by integrating Eq. (8) using the crack length, as shown in Eq. (11). The stress intensity factor range ΔK was found using Eq. (12). This calculation assumed that each time the hydrogen tank was used, it went from the maximum pressure (gauge pressure) of 87.5 MPa to the minimum pressure of 0 MPa .



(a) Relationship between crack growth and sustained-loading time at K_{IAPP}



(b) Relationship between average crack growth length by SLC and applied stress intensity factor

Fig. 9 Results of K_{ISCC} test

$$N = \int_{a_0}^{a_{cr}} \frac{1}{f(\Delta K)} da \quad (11)$$

$$\Delta K = K_{p=8.75 \text{ MPa}} - K_{p=0 \text{ MPa}} \quad (12)$$

Here, a_0 is the initial crack length (the initial defect size assumed for calculations) and a_{cr} is the crack length that represents K_{ISCC} . Figure 11 shows the results of a crack growth analysis. The crack growth life from an initial crack of 2 mm to a crack length ($a_{cr} = 9.7$ mm) at which $K = K_{ISCC}$ (18.7 MPa $\sqrt{\text{m}}$) is 44,500 cycles. This figure is sufficiently long in relation to the maximum of 15,000 cycles in the life of a high-pressure hydrogen tank specified by the regulations⁽¹⁶⁾. The results discussed above indicate that SLC will not occur in the designed Type 3 tank before it reaches the end of its life as specified in regulations.

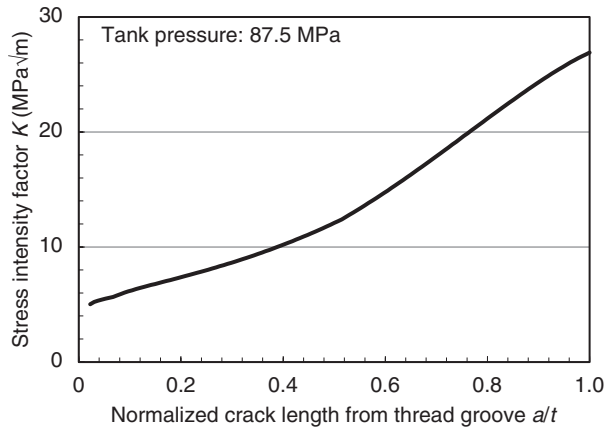


Fig. 10 Relationship between stress intensity factor and crack length from thread root

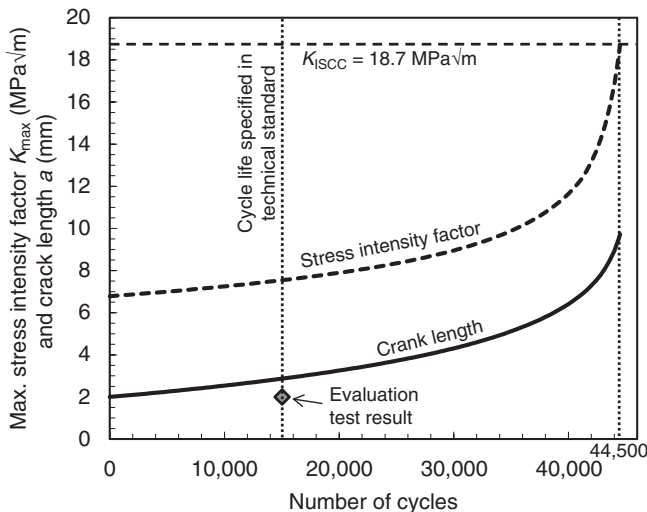


Fig. 11 Result of fatigue crack growth analysis

5. Discussion and Considerations

5.1. Considerations Concerning Results of Crack Growth Analysis

In order to assess the validity of the life design of the tank boss, hydraulic pressure cycle tests were conducted using an A6066 aluminum alloy Type 3 tank on which a notch had been machined in the thread section of the boss. The results showed that a leak occurred in the cylinder section of the tank at a greater number of cycles than 15,000, the maximum number specified in regulations. According to the crack growth analysis, it was predicted that at 15,000 cycles, the 2 mm notch representing the initial crack length would have grown to a maximum of 2.9 mm.

In order to compare these analysis results and the test results, following the completion of the test, a cross-section of the boss cut out from the liner was observed microscopically. Figure 12 shows a photograph of the cross-section. Investigation of the cross-section showed that a crack of approximately 60 μm in length extended from the tip of the notch, and that the length of this crack, including the notch, was 2.06 mm. It was therefore judged that the prediction based on the crack growth analysis was on the safe side. The following two points can be considered as factors in this.

- (1) In this crack growth analysis, because calculations were performed based on the assumption that the machined notch was the crack, the number of cycles to crack initiation from the notch was not considered.
- (2) The calculated value of the stress intensity factor in relation to the crack length was on the safe side.

Because the crack that was initiated in this test was very small at around 60 μm , it was considered that (1) was the main factor. At the same time, understanding the extent to which predictions fall on the safe side is important in discussing the life guarantee, and the following test was performed in order to study factor (2).

First, the depth of the machined notch was increased to greater than 2 mm without changing the shape of the tip or the width. This was to help ensure that cracks would grow from the defect. Next, the tank in which the notch had

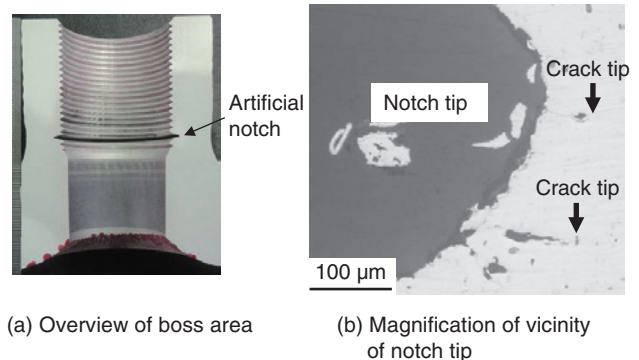


Fig. 12 Cross-sectional view of boss after cycle test

been machined was subjected to the cycle test described above in order to promote the crack growth from the defect. Following this, the tank boss was cut out, and the fracture surfaces were observed in order to assess the crack growth rate from fatigue striations.

As Fig. 13 shows, a crack has grown from the notch. In addition, this fracture surface shows fatigue striations. The intervals between these striations are known to correspond to the amount of crack growth for a single application of the load. The crack growth rate as obtained from the interval between striations and the crack growth rate as determined by the analysis were compared. Figure 14 shows the relationship between crack length and the crack growth rate. This figure indicates that the crack growth rate obtained

from the striations ranges from approximately 1/3 to 1/2 the rate determined by the analysis. Figures 7 and 10 also indicate that the stress intensity factors in relation to crack length determined by the analysis were 20 to 30% larger, indicating that the calculations were firmly on the safe side. This demonstrates the validity of the life calculation method discussed in this paper, including the simple method used for the calculation of stress intensity factors.

5.2. Evaluation Method with Consideration of Vehicle Use of Tank

The failure in the tank boss occurs as a result of cracks growing from the thread and penetrating the liner. Annexes A and B of ISO 7866, as discussed above, specify intercrystalline corrosion tests and SCC tests using smooth test specimens to evaluate crack initiation and SLC tests to evaluate crack growth. However, none of these can be considered appropriate evaluation methods, because they are not based on the failure mechanism of tanks. An evaluation method that does consider the failure mechanism will therefore be proposed here.

Due to the location where high-pressure hydrogen tanks are installed in vehicles, there is a high possibility. Given this, this section will touch on the reports of crack growth characteristics in various types of aluminum alloys in corrosive environments previously conducted by the authors^{(17), (18)}. Figure 15(a) shows results for A6061-T6, and indicates that the fatigue crack growth rate for this alloy increases even in the presence of only a slight concentration of saltwater (around 0.1%). Figure 15(b) shows the stress intensity factor when the crack growth rate in various test environments reaches 10^{-8} m/cycle. This figure indicates that resistance to crack growth increases in proportion to the stress intensity factor. Like A6061-T6, all of the aluminum alloys tested became prone to the growth of cracks in a low-concentration saltwater environment of around 0.1%. 6XXX series aluminum alloys display approximately the same resistance to fatigue crack growth in saltwater environments of 0.1% and 3.5%. When the shaft seal configuration shown in Fig. 2(a) was used, it was possible for saltwater and other corrosive agents to infiltrate the screw section of the tank boss from the exterior. Because the saltwater infiltrating the screw section would accelerate crack growth, as indicated above, it would be desirable to measure crack growth rate and K_{ISCC} with consideration of the saltwater environment during actual vehicle operation. In addition, sealing the outer surfaces of the screws, for example by using the seal configuration shown in Fig. 2(b), helps to prevent infiltration of saltwater. However, given that the use temperature range for the tanks is -40°C to 85°C , it can be predicted that condensation will occur in the airtight space maintained by the seals. The measurement of crack growth rate and K_{ISCC} for humid environments, as in the analysis discussed in this paper, can therefore be considered the appropriate method.

At the same time, the evaluation of tank performance

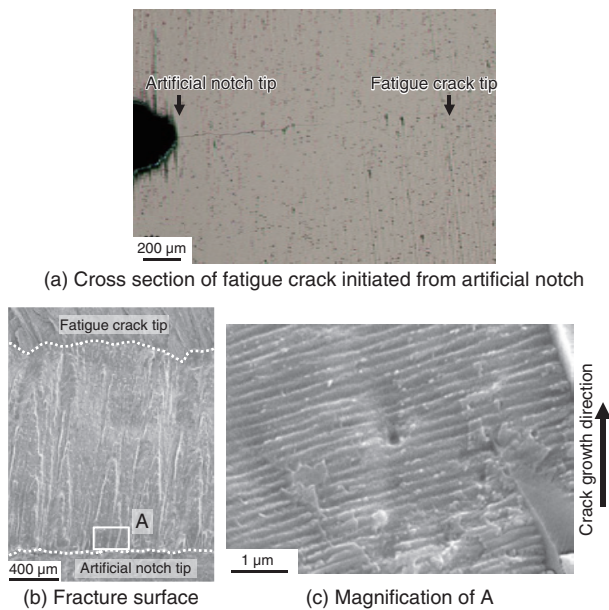


Fig. 13 SEM observation of striations

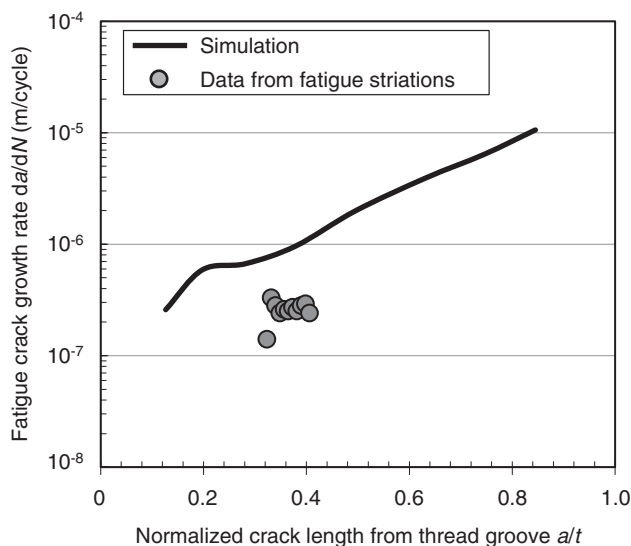
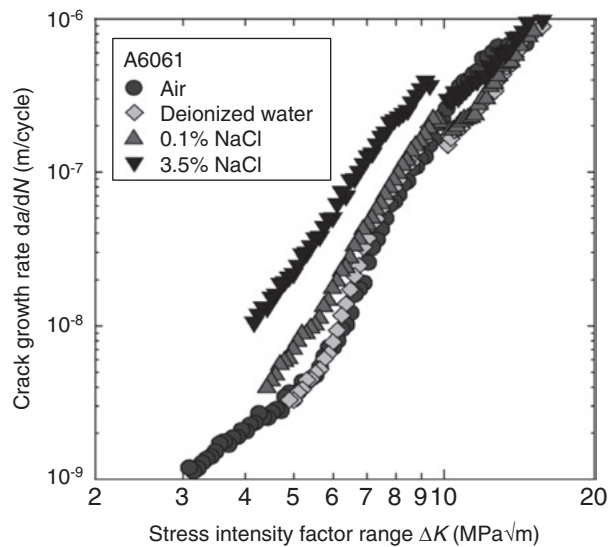


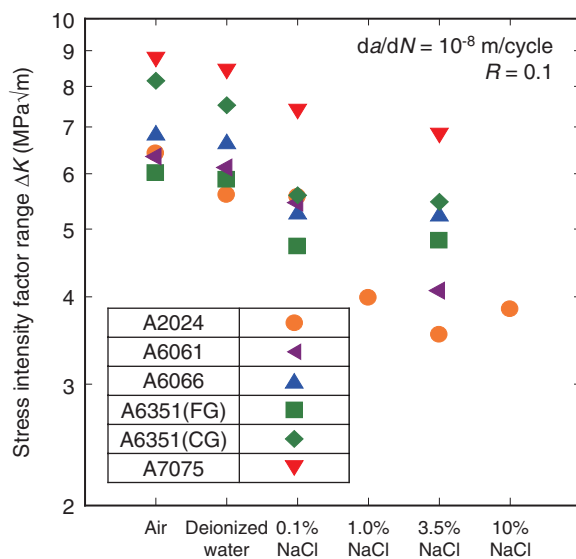
Fig. 14 Comparison between simulation and data obtained by fracture surface observation

in the GTR focuses on methods involving the tank itself rather than the evaluation of materials data for design use. A method of evaluation that takes this into consideration is as follows.

- (1) A limit dimension for a defect that could be detected in a non-destructive inspection in the manufacturing process is projected, and the initial defect dimension for the design is set on this basis.
- (2) A circumferential notch of the dimensions (depth) mentioned above is machined in the position at which maximum stress occurs at thread root in the tank boss.
- (3) The tank is subjected to hydraulic pressure cycle tests while the tank boss is sprayed with saltwater until the



(a) Fatigue crack growth rate of A6061-T6 under corrosive environments



(b) Fatigue crack growth resistance under various environments of various aluminum alloys

Fig. 15 Corrosion fatigue crack growth characteristics

designed life of tank has been exceeded.

- (4) In order to evaluate SLC, the tank is exposed to internal pressure for long periods (for example, 1,000 hours) as a load.

Figure 16 shows a schematic of the method described above. If tank failure does not occur at the boss, the life of the boss is sufficiently longer than the design life of the tank. Based on the following three points, it can be considered essential to use the saltwater spray discussed above in order to demonstrate that the tank will not be damaged even under the most severe conditions that it could be expected to face during its service life.

- (1) Saltwater accelerates the crack growth rate in aluminum alloys.
- (2) The internal and external surfaces of seamless aluminum alloy gas cylinders are inspected at specified intervals. Tanks found to have cracks during these inspections cannot be used⁽¹⁹⁾.
- (3) The hydrogen tanks used in fuel cell electric vehicles are inspected at regular intervals, but the interior surfaces are exempt from inspection⁽²⁰⁾. Because of this, cracks on the inner surfaces of the tanks cannot be detected.

The configuration of the boss for Type 4 tanks is the same as that used in Type 3 tanks, and it will therefore also be necessary to conduct evaluations of the type described in this paper for Type 4 tanks.

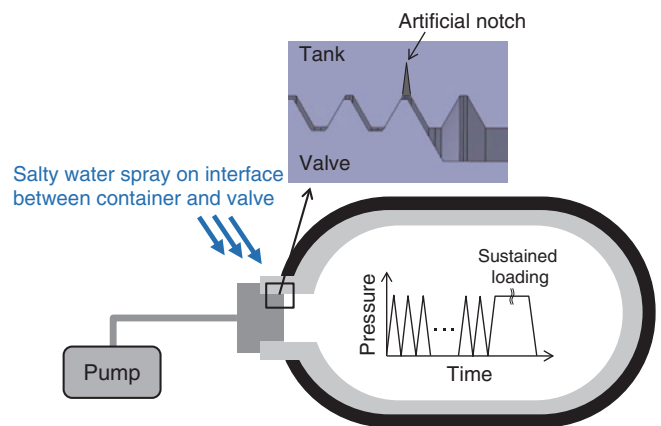


Fig. 16 Schematic of performance-based test for evaluating integrity of boss part against corrosive environments expected in vehicles

6. Conclusion

Suitable design and evaluation methods were developed for Type 3 high-pressure hydrogen tanks based on the failure mechanism of the tank boss, and tests were conducted in order to verify the effectiveness of the methods. The main outcomes of this process were as follows.

- (1) A life design method for the tank boss that considered SLC in humid environments was developed. The

validity of the life determined using this method was verified.

- (2) The environments that hydrogen tanks are exposed to in fuel cell electric vehicles and the fatigue characteristics of aluminum alloys in corrosive environments were taken into consideration, and an evaluation method of tank performance able to be reflected in regulations was proposed.

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