

Strength Design Method of Metallic Separator for Fuel Cell

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ABSTRACT

A strength design method was developed to form channels using ultrathin stainless steel foil in the structural design of metallic separators for a fuel cell. This method focused on the work hardening characteristic of stainless steel, and defined the deformation behavior of the metallic foil as a function of the strain value, based on the strength-related physical property values of the metallic materials. The shape range that can be formed with metallic foil was obtained using a forming limit diagram and localized strain values calculated from measurements of the material physical property values. In addition, the mechanical stress produced on the metallic separators of the fuel cell during fuel cell stack power generation was obtained from localized strain values calculated by micro Vickers hardness measurements. The metallic foil life with respect to mechanical degradation could be evaluated by plotting this stress value in the material fatigue limit diagram.

1. Introduction

One of Honda's goals is to realize use of fuel cell vehicles (FCV) on the same level as vehicles equipped with internal combustion engines. Honda's "Man Maximum Machine Minimum" philosophy calls for reduced size and weight and increased power density of the fuel cell stack mounted in FCV in order to provide a comfortable cabin befitting a sedan. A fuel cell stack contains hundreds of layered separators and membrane electrode assemblies (MEA) (Fig. 1), and reduction of the metallic separator thickness and a fine channel shape design are needed to reduce the size and weight of the fuel cell stack and realize a higher power density⁽¹⁾. This calls for ultrathin stainless steel materials.

However, thickness reduction and cracks easily occur when ultrathin stainless steel foil is stamped into a fine channel shape (Fig. 2).

It is necessary to avoid localized plastic deformation

and perform uniform work hardening in order to reduce this occurrence of thickness reduction and cracks.

Furthermore, during fuel cell stack power generation, load fluctuation occurs due to swelling and shrinking of the MEA located between the separators and pressure fluctuation occurs due to the gas and coolant. This load and pressure fluctuation produces constant stress fluctuation on the metallic separators of the fuel cell. Thus, strength design is needed to help prevent separators formed by ultrathin stainless steel foil from experiencing plastic deformation and fatigue failure due to the stress produced during power generation (Fig. 3).

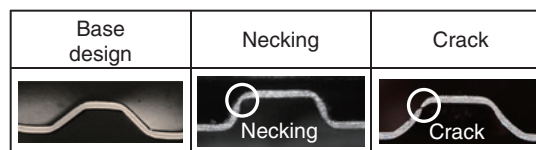


Fig. 2 Issue due to forming

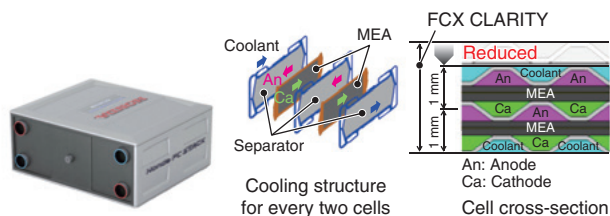


Fig. 1 FC stack and structure

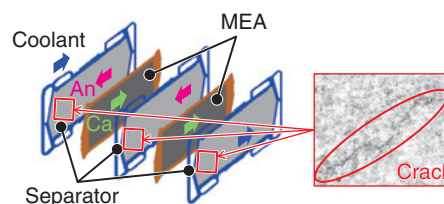


Fig. 3 Issue due to plate fatigue

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Therefore, this study focused on the work hardening characteristic, and defined the strain and stress from the physical property value of the material hardness. This enabled life evaluation by drawing the material fatigue limit curve from the stress values obtained in this manner.

2. Issues with Conventional Confirmation Method

2.1. Assessment of Forming Limit

The conventional method for achieving stainless steel foil stamping without localized thickness reduction and cracks is to create a large number of samples by stamping while varying the design parameters (flat length, corner R, angle, channel depth, and channel pitch) shown in Fig. 4. The plastic deformation limit is assessed by checking for localized thickness reduction and cracks by means such as cross-sectional observation of the created samples.

A forming limit diagram (FLD) (Fig. 5) is typically used to assess the plastic deformation limit of stamped products. The FLD shown in Fig. 5 demonstrates that localized thickness reduction does not occur when the strain is less than the forming limit curve (FLC), and that noticeable thickness reduction and cracks occur when the

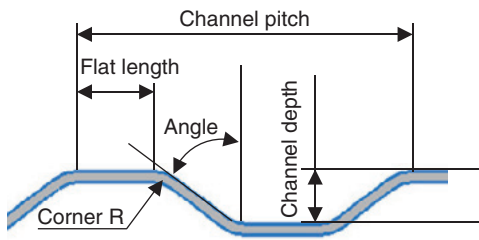


Fig. 4 Design parameters

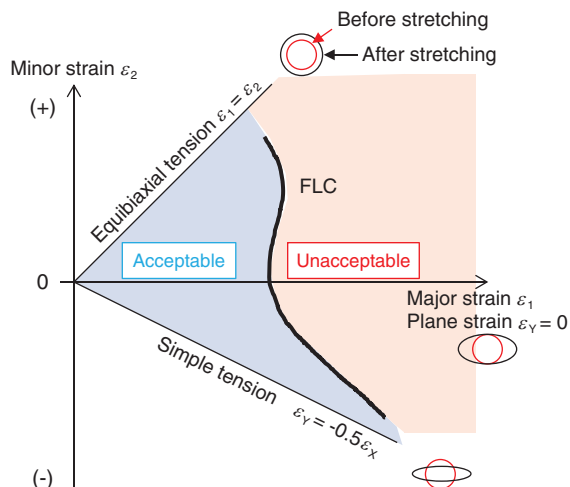


Fig. 5 FLD

strain is greater than the FLC. For this reason, FLD are widely used as a simple means of assessing the formable range of stamped products.

The scribed circle test method (Fig. 6) used when drawing the FLD stamps a steel sheet with a pre-drawn reference graphic ranging in size from $\phi 5$ mm to $\phi 20$ mm into the prescribed shape. The amount and direction of change in the pre-drawn reference graphic due to stamping are measured and plotted within a coordinate system that uses the Major strain ε_1 as the horizontal axis and the Minor strain ε_2 as the vertical axis. This enables understanding of the deformation state at the evaluation target location⁽²⁾.

The separator has a fine and complex shape, however, which makes it a challenge to microscopically draw this reference graphic in the separator location to be evaluated from the viewpoints of identifying deformation locations and measurement accuracy. Therefore, obtaining accurate separator data is an issue for performing fine and accurate design.

2.2. Assessment of Fatigue Limit

When performing strength design for a separator formed by stainless steel foil, it is necessary to accurately understand localized stress in order to help prevent the occurrence of plastic deformation and fatigue failure due to the stress produced during fuel cell stack power generation.

One method for calculating localized stress is the stress measurement method using a strain gauge. This method attaches a strain gauge in the specified location and calculates the stress from the measured strain value. However, it is a challenge to attach a strain gauge to the fine surface of the separator and confirm the actual behavior during power generation. The reasons for this are first that power generation is performed in the condition with a strain gauge wired into a fine channel, which hinders the supply of gas needed for fuel cell power generation to the channel. In addition, when a strain gauge is attached to ultrathin metallic foil, the measured localized stress produced on the separator during power generation includes the reinforcement effect of the strain gauge, which is not appropriate from the viewpoint of measurement accuracy.

Therefore, understanding the localized stress produced on the separator during fuel cell stack power generation was an issue.

Before stretching	After stretching	Definition of 'strain'
		Major strain $\varepsilon_1 = \ln(d_1/d_0)$ Minor strain $\varepsilon_2 = \ln(d_2/d_0)$

Fig. 6 Scribed circle method

3. Strength Design Method for Separator Channel

As localized strain measurement is a challenge with the conventional method, the authors focused on the work hardening characteristic of stainless steel foil, and attempted to derive the localized strain measurement from the hardness measurement as a method for more accurately and quickly assessing the localized deformation state of the separator and the fatigue failure life due to stress.

The localized strain values of the stamped separator were calculated from the hardness and the thickness reduction rate in order to assess the forming limit. The plastic deformation limit was assessed using these strain values and the FLD. Next, the localized strain values were calculated from the localized stress produced on the separator and the stainless steel foil hardness in order to assess the fatigue limit. The fatigue failure life was assessed using this value and the fatigue limit diagram. In this manner, a strength design method for the separator channel was developed by defining the stress produced on the separator and the deformation behavior as functions of the strain value.

4. Technology for Prediction of Plastic Deformation Limit Using FLD

First, stamping simulation was used to predict the strain locations and directions in order to clarify the localized strain locations and strain direction of a separator channel stamped into the prescribed shape. The formable shape range was then obtained by applying the strain values calculated from micro-hardness measurement of the obtained localized deformation locations to the FLD.

4.1. Analysis of Strain Produced on Separator during Stamp Forming

4.1.1. Confirmation of strain behavior

Since fuel cell separators have a fine channel shape, stamping simulation was used to predict the localized deformation locations and directions from the viewpoint of measurement accuracy.

Stamping simulation was performed for the shape samples shown in Table 1. The simulation conditions and analysis results for that typical shape are shown below. Analysis was performed over a range simulating part of the separator channel shape to identify localized deformation locations in the plane direction of the fine channel shape (Fig. 7).

In addition, analysis was performed with the minute mesh size setting of 1 μm to confirm locally occurring strain.

Figure 8 shows the results of predicting the locations where localized deformation occurs in the plane direction of the fine channel shape.

The greatest strain was identified to occur at the locations marked by red circles in Fig. 8. Next, Fig. 9 shows the simulation results illustrating the direction of localized strain occurrence in the A-A' plane in Fig. 8.

Table 1 Conventional method samples

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Flat length	1.00	1.00	1.00	1.00	0.00	0.00	0.53	0.34
Angle	1.00	1.07	1.10	1.11	1.07	1.10	0.80	0.89
Corner R	1.00	0.83	0.67	0.50	0.83	0.67	0.67	0.83
Channel depth	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
Channel pitch	1.00	0.96	0.92	0.88	0.48	0.44	0.76	0.76
Judge	Good	Good	Good	Good	Good	Good	Good	Good

The direction of the planar deformation produced by forming was analyzed by simulation. The results showed that at the locations where the largest localized strain occurs as marked by red circles in the A-A' plane in Fig. 9, the deformation extends in the direction of the Major strain ε_1 axis shown in Fig. 5. In a wave-shaped channel, the largest localized deformation was confirmed to occur at the corners R marked by red circles in Fig. 8, which corresponds to the Major strain ε_1 axis direction of the FLD.

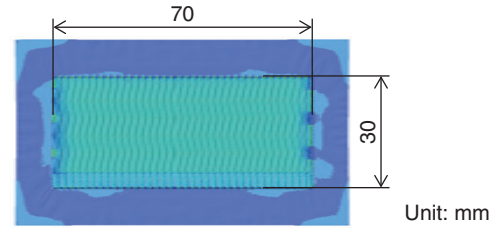


Fig. 7 Simulation method

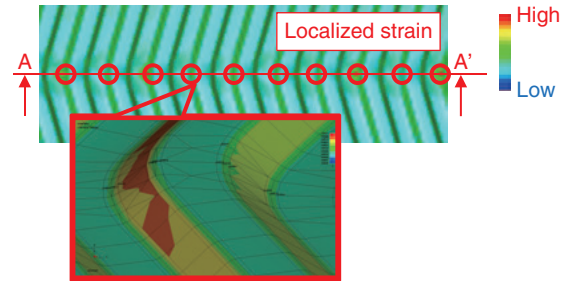


Fig. 8 Localized strain point in plane direction

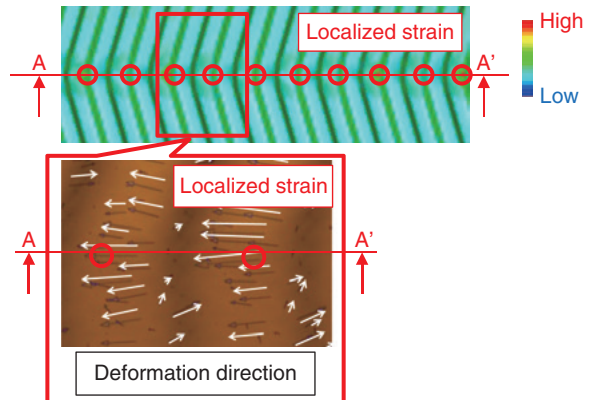


Fig. 9 Deformation direction of plane

4.1.2. Mathematical expression of stainless steel foil micro-hardness and strain

This study focused on the work-hardening characteristic of ultrathin stainless steel foil to perform strength design for the separator channel shape. The work-hardening characteristic is the characteristic whereby the hardness changes due to strain. An attempt was made to use this work-hardening characteristic to derive the localized strain measurement, which is a challenge with the conventional method, from the hardness measurement.

A micro Vickers hardness gauge that can measure microscopic locations was used to obtain the localized strain of a separator with a fine channel shape. The hardness test method conformed to the JIS Z 2244 (Vickers hardness test - Test method)⁽³⁾ specification. The shape of the diamond indenter used in the micro Vickers hardness test was a square pyramid with an angle between opposite faces of 136°. The relationship between the stainless steel foil micro-hardness and strain was obtained by creating test pieces with the prescribed strain applied by tensile tests and measuring the stainless steel foil hardness by the micro Vickers hardness test method. The test pieces for the tensile test used 13B specimens that conform to the JIS Z 2201 (Tensile test piece for metallic materials)⁽⁴⁾ specification.

Micro-hardness was expressed mathematically as a function of the strain value to create a formula for the work-hardening characteristic of stainless steel foil. Work hardening is a phenomenon that occurs when the plastic strain of the material produces the slipping motion of dislocation, and the dislocation density within the material increases together with that plastic strain. Therefore, work hardening was treated as dislocation density to formulate the relationship between work hardening and strain. This dislocation density and the true stress have a positive correlation. In addition, the true stress can be formulated as a function of strain from the tensile strength characteristic of the material, so the relationship between the dislocation density and strain was obtained. This means that work hardening can be expressed as a function of strain. The detailed results are shown below.

First, the dislocation density ρ and the true stress σ have a positive correlation as expressed by Eq. (1)⁽⁵⁾. Here, M is the Taylor factor, ϕ_D is a constant, G is the modulus of rigidity, and b is the size of the Burgers vector.

$$\sigma = M\phi_D Gb \sqrt{\rho} \quad (1)$$

As work hardening is produced by the slipping motion of dislocation, there was also thought to be a relationship between micro-hardness Hv due to work hardening and the true stress σ . In addition, the Vickers hardness and Rockwell hardness obtained with a high test load and the stress have a linear relationship for a typical steel sheet. The relationship between micro-hardness and strain was obtained from tests.

$$f(Hv) = A * \sigma + B \quad (2)$$

The true stress σ and true strain ε_P can be expressed as

a function of the nominal stress σ_0 and nominal strain ε_0 ⁽⁶⁾. Equations (3) and (4) are shown below.

$$\sigma = \sigma_0 * (1 + \varepsilon_0) \quad (3)$$

$$\varepsilon_P = \ln(1 + \varepsilon_0) \quad (4)$$

The micro-hardness can be expressed as a function of the nominal stress and nominal strain by substituting Eqs. (3) and (4) into Eq. (2).

The Vickers hardness can be formulated as a function of the strain value by using a Swift-type constitutive equation (5) that provides good approximation with respect to the true stress-true strain curve for typical stainless steel sheet described hereafter in section 4.1.4.

Here, σ is the true stress, ε_P is the true strain, and F , b , and n are constants. Work-hardening coefficient is F , work-hardening exponent is n , and strength-related physical property values of the materials were derived from the Swift-type equation.

$$\sigma = F(b + \varepsilon_P)^n \quad (5)$$

Here, the symbol f represents the function, A and B are constants, F is the work-hardening coefficient, and n is the work-hardening exponent.

$$f(Hv) = A * F[b + \ln(1 + \varepsilon_0)]^n + B \quad (6)$$

Figure 10 plots the relationship between strain and hardness for the ultrathin stainless steel materials applied to the fuel cell separator, and shows the formulated Eq. (6) results expressed as a solid line. The constants A and B were obtained from tests.

It was confirmed that hardness could be calculated as a function of the strain value as shown in Fig. 10.

These results show that conversion to the microscopic strain values produced on the separator based on the stainless steel foil hardness, which is a strength-related physical property value, makes it possible to understand the localized deformation state even in a separator with a complex and fine shape.

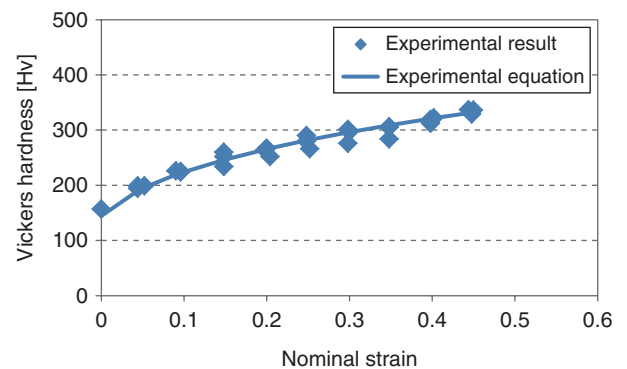


Fig. 10 Vickers hardness results under various strain conditions

4.1.3. Mathematical expression of stainless steel foil thickness reduction rate and strain

Stainless steel has a work-hardening characteristic, and the localized strain produced by plastic deformation can be defined as a function of the thickness reduction rate under constant volume conditions, so the localized strain was derived from the results of thickness measurement by cross-sectional observation. The relationship between localized strain and the thickness reduction rate for the ultrathin stainless steel foil applied to the fuel cell separator was obtained as follows.

The relationship between the strain and the thickness reduction rate was derived experimentally by creating samples with the prescribed strain applied by tensile tests and then measuring the thickness.

The amount of strain ε applied to the sample by the tensile test is expressed by Eq. (7)⁽⁶⁾. Here, L_0 is the initially evaluated length and L_1 is the evaluated length at the prescribed strain amount.

$$\varepsilon [\%] = (L_1 - L_0) / L_0 * 100 \quad (7)$$

In addition, labeling the initial thickness as T_0 and the thickness of a sample subjected to the prescribed strain as T_1 , the thickness reduction rate ΔT is expressed by Eq. (8)⁽⁶⁾.

$$\Delta T [\%] = (T_1 - T_0) / T_0 * 100 \quad (8)$$

The test pieces for the tensile test used 13B specimens that conform to the JIS Z 2201 (Tensile test piece for metallic materials)⁽⁴⁾ specification.

In addition, labeling the strain in the plane directions as ε_1 and ε_2 and the strain and true strain in the thickness direction as ε_3 , ε_3 can be expressed by Eq. (9) and Eq. (10)⁽⁶⁾.

$$\varepsilon_3 = \ln (T_1 / T_0) \quad (9)$$

Equation (10) was then derived using constant volume conditions.

$$\varepsilon_3 = -(\varepsilon_1 + \varepsilon_2) \quad (10)$$

From Eq. (8), Eq. (9), and Eq. (10), the thickness reduction rate ΔT can be expressed by Eq. (11).

$$\Delta T [\%] = \{1 - \exp [-(\varepsilon_1 + \varepsilon_2)]\} * 100 \quad (11)$$

Figure 11 plots the relationship between the strain and thickness reduction rate for ultrathin stainless steel foil, and shows the formulated Eq. (11) results expressed as a solid line.

It was confirmed that the thickness reduction rate could be calculated as a function of the strain value as shown in Fig. 11.

The above results were used to develop a method for quantifying the microscopic strain produced during stamping by confirming the thickness reduction rate, which can be measured in microscopic locations.

Based on the results in sections 4.1.2 and 4.1.3, application to FLD was investigated to obtain the formable range of ultrathin stainless steel foil.

4.1.4. Application to FLD

It was thought that measurement of strength-related physical property values such as the localized hardness and thickness reduction rate of ultrathin stainless steel foil at the localized deformation locations of the separator shown in section 4.1.1 and use of these values to calculate the localized strain values would also enable the use of FLD to design the channel shape of a separator formed by ultrathin foil. This was then verified.

The strain calculated from the localized hardness and thickness reduction rate for the conventionally manufactured samples shown in Table 1 and the Stören-Rice theory for predicting localized necking⁽⁷⁾ were used to draw FLC on the FLD shown in Fig. 5.

Equation (12) expresses the Stören-Rice theoretical formula for predicting localized necking.

$$\varepsilon_1 = [3\beta^2 + n(2 + \beta)^2] / [2(2 + \beta)(1 + \beta + \beta^2)] \quad (12)$$

Strain ratio β : $\varepsilon_2 / \varepsilon_1$

n : work-hardening exponent

Plastic deformation occurs when a material is pulled, and localized necking refers to thickness reduction in the thickness direction immediately before breaking. For thin sheet materials, the point at which localized necking occurs can be treated as the forming limit. The forming limit of ultrathin stainless steel foil was theoretically predicted by using a theoretical formula of localized necking occurrence to draw an FLC.

Here, material strength tests were performed on the stainless steel foil to obtain the work-hardening exponent and other characteristics, and a mathematical formula was created to express the relationship between the stress and strain of the stainless steel foil. The relationship between stress and strain is typically obtained by performing static tensile tests using tensile test pieces.

Thus, the stress-strain curve (S-S curve) of the stainless steel foil applied to the fuel cell separator was obtained by static tensile tests (Fig. 12).

The tensile test method conformed to the JIS Z 2241 (Method of tensile test for metallic materials)⁽⁸⁾ specification.

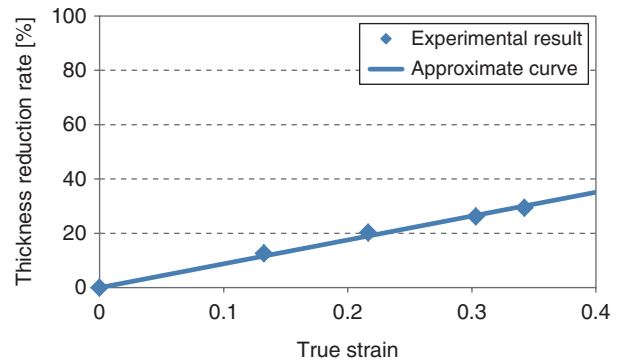


Fig. 11 Thickness reduction rate results

The test pieces for the tensile test used 13B specimens that conform to the JIS Z 2201 (Tensile test piece for metallic materials)⁽⁴⁾ specification.

Figure 12 shows the test results obtained by least square approximation using a Swift-type equation. The Swift-type constitutive equation (5) is known to provide a good approximation of the true stress-true strain curve of typical stainless steel sheet⁽⁹⁾.

In Fig. 12, T is the vertical direction, L is the flow direction, and D is the 45° direction relative to the rolling direction of the stainless steel foil.

The true stress-true strain curves for the T, L, and D directions trace almost the same line, so the material does not exhibit anisotropy. Furthermore, the test results could be approximated using a Swift-type equation, and the strength-related physical property values of the stainless steel foil needed to calculate the stress could be obtained.

The strain calculated from the localized hardness and the thickness reduction rate was plotted on the FLD (Fig. 13).

Of the obtained results, the blue plots indicate points where localized necking did not occur, and red plots indicate points where localized necking occurred.

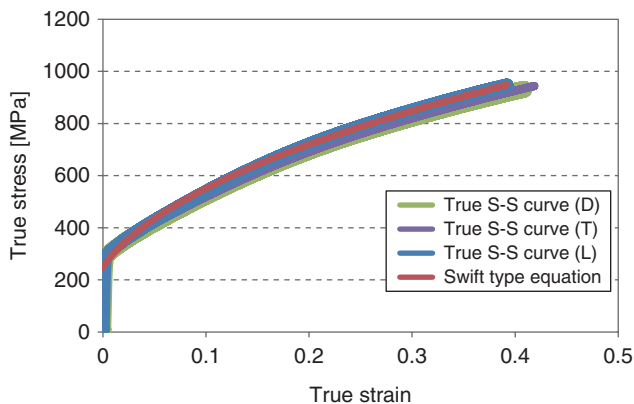


Fig. 12 True stress-true strain curve

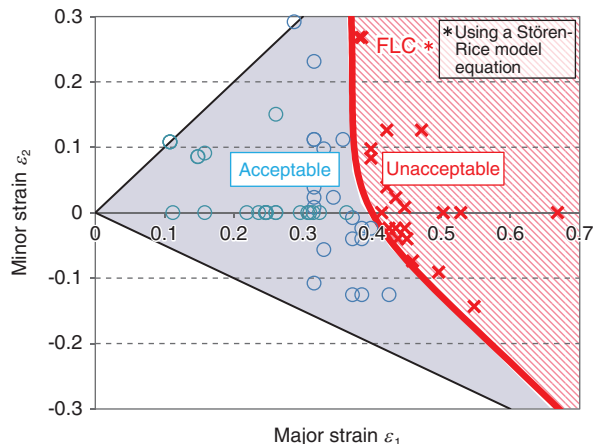


Fig. 13 FLD results

The respective plots made it possible to confirm whether localized necking occurred with the FLC on the Major strain ε_1 axis as the boundary. This clarified that FLD can also be applied to the channel shape of a separator formed by stainless steel foil by using the strain values calculated from the microscopic hardness of the material.

5. Technology for Predicting Life Using a Fatigue Limit Diagram

Next, the stress locations and degree were predicted by finite element method (FEM) analysis to obtain the stress produced on the separator during fuel cell stack power generation. Strain values calculated from micro-hardness measurements were converted into stress and compared with the prediction results to investigate the prediction accuracy. It was thought that the separator channel life relative to mechanical degradation could be evaluated by plotting the stress produced on the separator during power generation in the fatigue limit diagram.

5.1. Analysis of Stress Produced on the Generator during Power Generation

5.1.1. Mathematical expression of stainless steel foil micro-hardness and stress

Since it is a challenge to obtain localized stress values with the conventional method, localized stress values were calculated from the micro-hardness as described in chapter 2 to understand the stress produced on the separator during power generation.

First, the relationship between micro-hardness and stress was quantified. Equation (2) was formulated by first formulating the relationship between the stress and strain stainless steel foil by Eq. (5), and then converting the strain value calculated from the micro-hardness into the stress.

The strain and stress produced on a separator with fine channels formed by ultrathin stainless steel foil can be measured by measuring the micro-hardness and the thickness reduction rate.

5.1.2. Results of stress analysis using FEM

Load fluctuation occurs due to swelling and shrinking of the MEA located between the separators and pressure fluctuation occurs due to the gas and coolant during fuel cell stack power generation. This means that stress fluctuation is constantly produced on the metallic separators of the fuel cell (Fig. 14).

Various conditions exist inside a fuel cell according to the power generation state. The MEA swells when the fuel cell interior is a wet environment, and shrinks when it is cold or dry. Load fluctuation is produced on the adjacent separators when the MEA swells and shrinks due to power generation. In addition, gas and coolant flow in the separator channels, and pressure fluctuation is also produced on the separators due to fluctuations in the gas and coolant internal pressures during power generation. FEM analysis

was performed on these load- and pressure-induced stress fluctuations on the separators (Fig. 15).

The mechanical stress produced on the metallic separators of a fuel cell during fuel cell stack power generation was quantified using the fatigue limit diagram of stainless steel foil and stress values calculated from the micro-hardness, which is a strength-related physical property value of the material, in stress locations identified using FEM.

Figure 16 shows the correlation between the FEM calculation results of the stress produced at various locations within the separator plane and the stress calculated from the hardness measured at the same locations.

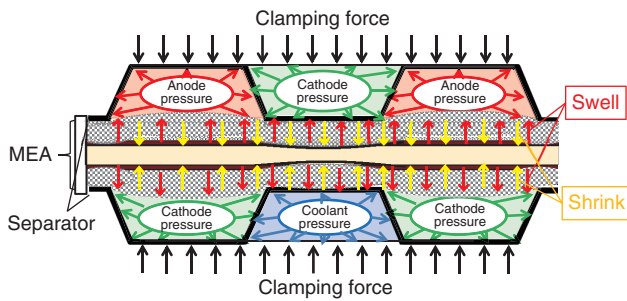


Fig. 14 Image of stress occurrence

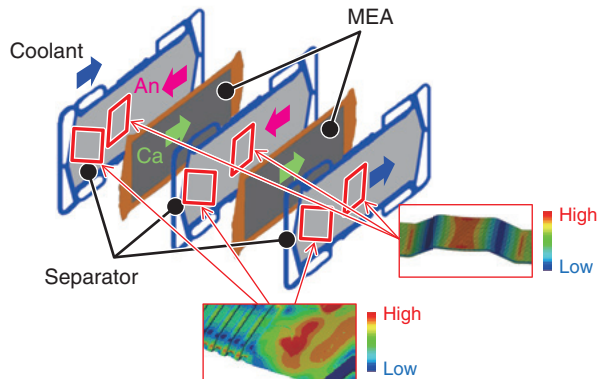


Fig. 15 Stress occurrence location by FEA

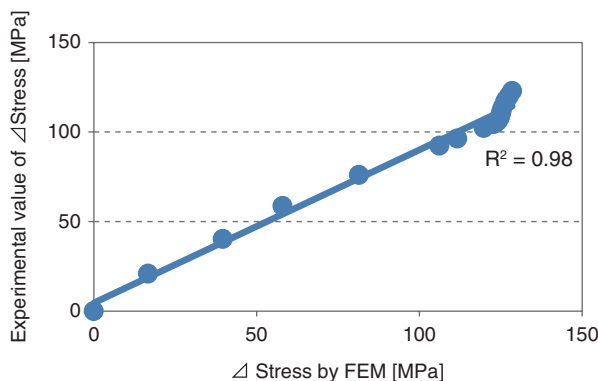


Fig. 16 Test results and correlation between FEM stress simulation and measurement results

The FEM stress calculation results and the stress results calculated from the micro-hardness were confirmed to have a high degree of correlation with a correlation coefficient of 0.98.

Based on the stress obtained by FEM and tests, application to the fatigue limit diagram was investigated to realize simple prediction of the mechanical life of a separator formed by stainless steel foil.

5.1.3. Application to fatigue limit diagram

A typical method for calculating locally produced stress is the stress measurement method using a strain gauge. However, as already described in chapter 2, it is a challenge to attach a strain gauge to the fine surface of the separator and confirm the actual behavior during power generation. It was conjectured that simple life prediction could be achieved by using the stress value calculated from the micro-hardness as the stress produced during fuel cell stack power generation, and plotting this stress value in the fatigue limit diagram.

When performing strength design, the produced stress needs to be the material strength limit or less. Therefore, the strain amplitude-number of repetitions to breaking curve (ϵ -N curve) of the ultrathin stainless steel materials applied to the fuel cell separator was obtained, and the fatigue limit diagram of the ultrathin stainless steel materials was drawn. The ϵ -N curve was used to evaluate the stainless steel foil fatigue by controlling the strain value with a pulley-bending fatigue test. The fatigue test method conformed to the JIS Z 2274 (Method of a rotary bending fatigue testing of metals)⁽¹⁰⁾ specification.

A fatigue limit diagram is a method for evaluating material fatigue strength that takes into account the influence of the average stress when fluctuating stress is received. This diagram shows the average stress on the horizontal axis and the stress amplitude on the vertical axis, and enables evaluation of the range within the yield limit and equal to or less than the fatigue limit curve as the area in which fatigue failure does not occur.

As described above, the stress values calculated from micro-hardness measurement were plotted in the fatigue limit diagram to confirm that the stress produced during fuel cell stack power generation is within the fatigue limit curve (Fig. 17).

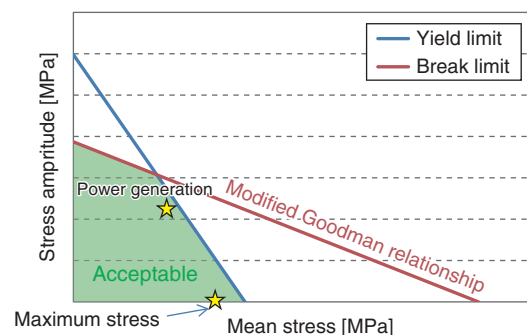


Fig. 17 Fatigue limit diagram

It was confirmed that separator channel life with respect to mechanical degradation could be evaluated by using strain values calculated from the microscopic hardness of the stainless steel foil.

6. Conclusion

This paper focused on the work-hardening characteristic of the ultrathin stainless steel foil applied to fuel cell separators. A method was developed that enables simple prediction of the available strength design range by understanding the strength-related physical property values of the materials. This method enables prediction in terms of both shape forming and life evaluation from the viewpoint of separator structure feasibility.

- (1) It was clarified both experimentally and theoretically that the stress produced on a thin metallic sheet and the deformation behavior of the sheet can be defined as a function of the strain value based on the metallic material hardness, which is a strength-related physical property value.
- (2) Measurements of localized hardness within the separator plane could be converted into stress and strain values, which confirmed that the FLD and fatigue limit diagram can be applied to the strength design of a separator channel shape formed by thin sheets.

References

- (1) Kimura, K., Kawasaki, T., Ohmura, T., Atsumi, Y., Shimizu, K.: Development of New Fuel Cell Vehicle CLARITY FUEL CELL, Honda R&D Technical Review, Vol. 28, No. 1, p. 1-8
- (2) Nakamura, K., Kuwabara, T.: Puresu shibori kakou, NIKKAN KOGYO SHIMBUN, LTD., p. 5-6, (2002), (in Japanese)
- (3) JIS Z 2244: 2009, Vickers hardness test-Test method, (in Japanese)
- (4) JIS Z 2201: 1998, Tensile test piece for metallic materials, (in Japanese)
- (5) Sawada, K., Maruyama, K., Komine, R., Nagae, Y.: Creep Life Assessment of Mod.9Cr-1Mo steel, Power Reactor and Nuclear Fuel Development Corporation, O-arai Engineering Center, PNC TN9410 97-035, p. 8, (1997), (in Japanese)
- (6) Ashby, M. F., Jones, D. R. H., Horiuchi, R.: Zairyo kougaku nyumon, UCHIDA ROKAKUHO PUBLISHING CO., LTD., p. 84-124, (2004), (in Japanese)
- (7) Stören, S., Rice, J. R.: Localized necking in thin sheets, J. Mech. Phys. Solids, 23, p. 421-441, (1975)
- (8) JIS Z 2241: 1998, Metallic materials-Tensile testing-Method of test at room temperature, (in Japanese)
- (9) Kamaya, M.: Procedures for obtaining stress-strain curve including post-necking strain (Applicability of testing method (IFD method) and estimation method (K-fit method) for stainless steels), INSS JOURNAL, Vol. 21, NT-11, p. 177, (2014)
- (10) JIS Z 2274: 1978, Method of a rotary bending fatigue testing of metals, (in Japanese)

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