Fatigue Strength Simulation of Natural Porous Structure

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Rice hull which is one of the agricultural wastes in Japan has been demanded to reuse as the industrial materials. Rice hull silica carbon (RHSC) material, made from rice hull is produced by mixing rice hull powder with a phenol resin, and then carbonizing and the mixture in the nitrogen gas atmosphere at high temperatures. The RHSC is a porous carbon material utilizing natural porous structure originated from the rice hull. Therefore, reduction in environmental pollution is expected by the RHSC which is inexpensive and unique. In addition, a core competence of low friction coefficient, lubrication free, and high water resistance was reported for the RHSC in previous research. However, the RHSC has low reliability of strength originated potentially from the porous structure. Since the reliability of the RHSC is evaluated by a fatigue test which is required several weeks, calculating the fatigue strength by simulation analysis is useful. In this study, fatigue strength simulation analysis in natural porous structure was figured out and the size effect which influences the strength of the material was investigated.

Keywords : Rice Hull, Fatigue strength, Strength simulation, Hardness, Pore distribution

1 INTRODUCTION

Japan, which is the poor country in natural resources, is required to use renewable energy. The rice is a staple food and the amount of its production is about 9 million tons per year in Japan [1]. Rice hull is a non-edible part and has produced 1.9 million tons per year [2]. Among them, about 1.2 million tons have been utilized as fertilizer and soil conditioner. However, about 700 thousand tons are disposed of as agricultural waste. The rice hull silica carbon material (RHSC) is developed in order to utilize the rice hull to protect the global environment and promote recycling. The various basic physical properties have already been evaluated for the RHSC by this research group [3].

The RHSC is a porous carbon material utilizing natural porous structure originated from the rice hull. The RHSC is manufactured by impregnating a phenol resin with rice hull, and carbonizing it in a nitrogen gas atmosphere [4, 5]. The raw rice hull contains about 20 mass% of inorganic constituent and 80 mass% of the organic constituent. Among them, about 95 mass% of the inorganic constituent is silica. Therefore, the RHSC is material with high water resistant [6] and seawater resistant [7, 8]. Moreover, the RHSC, which has excellent low friction and abrasion resistant under un lubricated conditions [6], is expected to be used as sliding materials such as the linear slide rail in future.

Generally, structures and machine elements are subjected to cyclic loads. Since fatigue failure caused by cyclic load often brings disaster, evaluation of fatigue strength is important. However, obtaining the strength experimentally is required several weeks. Therefore, simulation method of fatigue strength is useful for machine designer.

Murakami has derived [9] a fatigue strength evaluation formula for metallic materials which is based on material hardness and defect size. The fatigue strength simulation method for steel gears adopting Murakami’s formula was proposed by one of the authors [10]. The dispersion of fatigue strength is also estimated by the simulation method. There is a similarity between the RHSC and metallic materials in the viewpoint of defect including materials. In this study, fatigue strength simulation analysis in natural porous structure was figured out and the size effect which influences the strength of the material was investigated.
\[ \sigma_w = \frac{1.43(H_v + 120)}{(\sqrt{\text{area}})^{1/6}} \left(1 - \frac{R}{2}\right)^{a} \]  
(1)

\[ R = \frac{\sigma_{\text{max}}}{\sigma_{\text{min}}} \]  
(2)

\[ a = 0.226 + 10^{-4}H_v \]  
(3)

where, \( \sigma_w \) is the fatigue strength [MPa], \( H_v \) is Vickers hardness [HV], \( \text{area} \) is the projected area of defects or inclusions [\( \mu \text{m}^2 \)].

This fatigue strength simulation in the RHSC is based on Murakami’s formula.

### 2.2 Simulation procedure [10]

Figure 1 shows the flowchart of fatigue strength calculation. This simulation is executed by a plane model, and a solid is expressed by using multiple of these. Firstly, the imaginary material plane is created on the simulation, and pores are arranged. The position of pores are random, diameter and density of pores are decided based on microscopic observation result. In this simulation, random numbers were generated using Mersenne Twister [11] method to enhance the reproduction cycle. Next, Figure 2 shows the relationship between test piece shape and imaginary material plane. The heavy line in the figure is the test piece shape. In this study, the test piece shape and the stress are unchanged in the depth direction. Therefore, the strength of three-dimensional shapes is simulated by superposing imaginary material planes. To express the test piece width, imaginary materials are multiplied \( n \) times. Where, \( n \) = \( w/d \), \( w \) = width of the test piece and \( d \) = average pore distance.

Bending stress by initial load at each pore position is calculated by theoretically, bending fatigue strength also calculated at the same place by using Eq.(1). In this state, stress at any pore is lower than strength as shown in Figure 3(a), so the load is increased step by step. Figure 3(a) and (b) are images of stress distribution in the test piece and strength at a pore when bending stress was loaded. Where, pores are distributed in the tensile side, because strength evaluation is done in tensile stress field. Background color indicates stress and circle color is the strength which calculated by Murakami’s formula. Figure 3 shows the relationship between strength and stress at one of the imaginary material plane. When stress at one pore reaches strength (Figure 3(b)), the test piece is assumed to be broken. The strength of the test piece is expressed by stress at the pore divided by the maximum stress of the test piece.

### 2.3 Loading conditions

The consistency of the simulation analysis results is verified by comparison with the bending strength at static fracture in the RHSC. The 4 points bending strength in the RHSC has already been evaluated by this research group.

Figure 4 shows the overview of the jig in the 4 point bending test. The 4 point bending test is based on JIS R1664 “Testing method for bending strength of porous fine ceramics”. Moreover, the distance between inside loading points was 30 mm, and the distance between outside loading points was 60 mm, in the jig.

Figure 5 shows the test piece for bending strength. The dimension of the test piece is 70(w)×8(d)×5(t) mm and 70(w)×8(d)×10(t) mm in order to evaluate the influence of the size effect.

The bending strength at the time of static fracture in the 4 points bending test is calculated from the formula which was shown as follows.
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\[
\sigma = \frac{3P_{cr}(L - l)}{2wt}
\]

where, \(\sigma\) is the bending strength which is obtained from 4 points bending test [MPa], \(P_{cr}\) is the load which broke test piece [N], \(L\) is the distance between outside loading points [mm], \(l\) is the distance between inside loading points [mm], \(w\) is the test piece width [mm], \(t\) is the test piece thickness [mm].

In all experiments and simulations, the stress ratio \(R\) equal 0. In the actual test and simulation, the number of test pieces is 20 and 100, respectively based on JIS R1664 “Testing method for bending strength of porous fine ceramics”.

3 MODELING OF MATERIAL DEFECTS

3.1 Materials

Figure 6(a) shows the microstructure of the raw rice hull. It has a natural porous structure. The diameter of the unit cell is about 10 \(\mu\)m. The microstructure of the RHSC powder is shown in Figure 6(b). The natural porous structure retains even after the carbonizing.

Figure 7 shows the manufacturing process of the RHSC. At first, the raw rice hull was impregnated with a 25 mass\% of thermosetting phenol resin, and then carbonized in the nitrogen gas atmosphere at 900°C for 3 hours. Afterwards, the carbonized rice hull was pulverized by a mill to obtain the RHSC powder. The RHSC powder was sieved using 106 \(\mu\)m meshed filter to obtain the powder with 60 \(\mu\)m median diameter.

The RHSC powder was mixed with a 25 mass\% of phenol resin. Afterward, a rectangular plate of the RHSC is obtained by pressure forming. After drying, the plate was carbonized at 900°C for 3 hours in a nitrogen gas atmosphere again. The dimension of the plate is 150\(w\) × 75\(d\) × 5\(t\) mm and 150\(w\) × 75\(d\) × 10\(t\) mm.

3.2 Hardness of materials

Figure 8 shows the measurement area of the Vickers hardness which has been evaluated by this research group, in the RHSC. The RHSC was obtained by uniaxial pressure molding machine. According to this molding method, the tendency that the center position becomes harder than the edge position is confirmed. In addition, since the RHSC was utilized natural porous structure, the bulk density of the material is non-uniform. The 4 test pieces for hardness measurement are cut from the each area of the RHSC plate. The dimension of the test piece is 10\(w\) × 10\(d\) × 5\(t\) mm. In one test piece, the hardness at 5 places was measured, and the
average hardness of the test piece in each area was taken as the measurement result. Moreover, for the hardness measurement conditions, the test force is 98 N, and the duration of the test force is 15 sec. Vickers hardness in the areas A, B, C was 44.4 HV, 51.4 HV, and 55.5 HV, respectively. In order to simplify the simulation, Vickers hardness 50.4 HV, which is the average value of the three areas, is used for Murakami's formula.

3.3 Measurement of probability distribution of pore in RHSC

At first, the test piece is cut from the RHSC plate with $150(w) \times 75(d) \times 5(t)$ mm. Figure 9 shows the cutting area of the test piece. The RHSC formed body is a pressed compact. Therefore, the bulk density is higher near the center of the material, and becomes lower as it becomes closer to the end portion. In order to obtain various pore distributions, a total of 6 test pieces were cut from the left end and the center of the material. Also, the dimensions of the test piece was $5(w) \times 5(d) \times 5(t)$ mm.

Figure 10 shows the microscope observation area of the test piece. Scanning electron microscope (ABT-32, TOPCON) was used for observation of the pore distribution. Before observation, buffing was applied to the observation surface to improve the smoothness. Also, ultrasonic cleaning was applied to wash the observation surface. In each test piece, electron microscopic photographs of the near of the surface, the center, and the near of the back surface of the material were taken.

Figure 11 shows the pore model and its arrangement method. A pore model of 10 μm unit expressed as "diameter of 30 to 110 μm, 120 μm or more" was prepared. In the photographed electron microscopic photograph, a pore model which has a size approximate to that was placed at a place which is presumed to be pore. After these operations are performed on observable pores, the pore distribution was obtained from the diameter and the number of the pore models which has placed on the photograph.

There is the dispersion on distribution of pore size and pore number. So, in this paper, evaluation of strength is done according to bulk density. It is expressed by total pore area per unit area.

Figure 12 shows the pore distribution per unit area of 1 mm² in the area with the maximum and minimum bulk density. These pore distributions were applied to the simulation, and fatigue strength was figured out.

4 SIMULATION RESULTS

The fatigue strength simulation for the RHSC test piece was carried out. In the actual test and simulation, test piece with $150(w) \times 75(d) \times 5(t)$ mm and $150(w) \times 75(d) \times 10(t)$ mm was used. Also, the number of test pieces is 20 in the actual test, and 100 in the simulation.

Figure 13 shows the average fatigue strength of each test piece, which was obtained by simulation analysis applying each pore distribution. The fatigue strength of the test piece with the minimum bulk density was 4.72% lower on average than the
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Figure 13 Average fatigue strength of each test piece which was obtained by simulation analysis applying each pore distribution.

Figure 14(a) shows the average bending strength which was obtained the actual test, and the average fatigue strength which was obtained from the simulation analysis applying the pore distribution of maximum bulk density is shown in Figure 14(b). In the actual test, the average bending strength of the test piece with a thickness of 5 mm was higher than the test piece with a thickness of 10 mm. In addition, the standard deviation of the test piece which has the thickness of 5 mm was larger than the test piece which has the thickness of 10 mm. On the other hand, the same tendency was obtained for the fatigue strength obtained from the simulation analysis. Therefore, size effect was confirmed from the Murakami’s formula in the porous structure. Focusing on a test piece which has a thickness of 5 mm, the average bending strength was obtained 23.63 MPa in the actual test. On the other hand, the average fatigue strength was obtained 107.56 MPa in the simulation analysis.

Figure 15 shows the relationship between the thickness of the test piece and probability of the presence of the pore in the high-stress area. When material size is small, the area with high-stress decreases. Therefore, in the high-stress area, the probability of the presence of the pore is low, so the strength is high. Murakami’s formula is derived from metal materials. Therefore, when applied to the RHSC, the fatigue strength is not the optimum value. However, the formula can be optimized for the RHSC, since the tendency of the size effect is confirmed in the simulation, by finding the optimum coefficient in the Murakami’s formula.

5 CONCLUSION

The fatigue strength simulation analysis which adapts Murakami’s formula to the pores was figured out in the RHSC which has natural porous structure inside the material, and the size effect which influences the strength of the material was investigated. The summary of the obtained results was shown as follows.

1. The tendency of the size effect was confirmed in the simulation analysis results.
2. In order to obtain quantitative simulation analysis results, investigation on several kinds of ceramics materials is required.

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