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Weibull statistical analysis on Vickers hardness of immersed Al_2O_3 ceramics in acidic and alkaline solution

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This study measured the Vickers hardness of Al_2O_3 ceramics, and Weibull statistical analysis was used to evaluate the reliability of the measured data. The specimens were heat-treated for 0.5 hr, 1 hr and 10 hrs at temperatures of 1473 K, 1573 K, and 1673 K. The as-received specimen and the heat treated specimen were corroded for 400 hours in acidic and alkaline solutions. The specimens were as-received specimen, corroded as-received specimen, heat treatment specimen and corroded heat treatment specimen. The specimens were measured Vickers hardness. The two-parameter Weibull probability distribution can be applied to the Vickers hardness. In the Weibull statistical analysis of the corroded Al_2O_3 composite ceramics, the shape parameters and scale parameters can be used to determine the dispersion and to predict the strength/ hardness.

Key words: Al_2O_3 ceramics, Corrosion, Acidic solution, Alkaline solution, Vickers hardness, Weibull statistical analysis.

Introduction

Ceramics is becoming a key material in the machinery field due to its excellent abrasion resistance, heat resistance, and high strength. Ceramics are important for advanced industrial and next-generation industrial technologies such as marine development, nuclear power, energy, telecommunications, aerospace, biomedical, and medical industries. Ceramics are used in marine industries for applications such as artificial reefs, gas turbine blades, ceramics vibrators of sonar, seawater filters, and marine civil engineering and construction. However, Al_2O_3 shows typical brittle material properties and has the disadvantage of very low toughness compared to metals. Therefore, Al_2O_3 is not only difficult to process, but also has the disadvantage of high defect occurrence rate in processing [1]. To overcome this weakness, a method of healing to a ceramic has been proposed [2-6]. If such a method is used, it will be possible to overcome the brittleness which is the weakest feature of structural ceramics, and to heal cracks generated during use. Furthermore, if it is possible to recover ceramics to a sufficient strength at a cured temperature, an improvement in reliability before and/or after use can be expected [7]. Further, ceramics with surface defects that act as the origin of fractures can easily and inexpensively be made defect-free, and fatigue cracks occurring during use can be mended on site depending on their use in the environment [8-10]. Therefore, in this study, the sintering aid Y_2O_3 is proposed to improve the crack healing effect. The crack healing temperature, additional amount of ceramic powder, and mechanical properties were studied [11, 12]. Ceramic is also known as a highly corrosion-resistant material, and studies have been conducted on the characteristics of ceramic with immersion in acidic and alkaline solutions [13-16].

In this study, the Vickers hardness of Al_2O_3 ceramics was measured, and Weibull statistical analysis was used to evaluate the reliability of the measured Vickers hardness. The as-received specimen and the heat treated specimen were heat-treated for 0.5, 1, and 10hrs at temperatures of 1473 K, 1573 K, and 1673 K, and were corroded in acidic and alkaline solutions.

Materials and Experimental Method

A powder composed of 0.3 μm Al_2O_3 (Sumitomo Chemical, AKP-30), 0.27 μm SiC (Ibiden, Betarundum UF), and 0.27 μm Y_2O_3 (Nippon Yttrium) was used for the experiments. In order to evaluate the heat treatment characteristics according to the amount of SiC, different amounts of SiC were added. Table 1 shows the batch composition of specimens. Alcohol and SiC ball was added to this mixture, and the mixture was blended completely for 24 hrs. The mixture was placed in a desiccator to extract the solvent, and to form a dry powder mixture. The mixtures were subsequently hot-

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Table 1. Batch composition of specimens (wt.%).

	Al_2O_3	SiC	Y_2O_3
AlSi10Y3	87	10	3
AlSi15Y3	82	15	3
AlSi20Y3	77	20	3

pressed in N_2 gas for one hour under 35 MPa at 1873 K. The mirror-polished specimens were carried out the heat treatment at 1473 K, 1573 K, and 1673 K for 0.5 hr, 1 hr, and 10 hrs. The corrosion test of the as-received specimen and the heat treated specimen were conducted for 400 hrs using the acidic and alkaline solution for fine ceramics under the KS standard, KSL1607. Solutions of H_2SO_4 3 mol/L and NaOH 5 mol/L were used to test the corrosion resistance of the ceramic.

Hardness was measured using a Vickers hardness tester (HV-114, Mitutoyo). The as-received specimen and the heat treated specimen were measured for 10 seconds from the indentation loads of 9.8 N. Weibull statistical analysis was used with hardness data of 20 measured on each specimen.

Results and Discussion

Fig. 1 shows the Vickers hardness of the as-received specimens (AlSi10Y3, AlSi15Y3, and AlSi20Y3). Figs. 2 and 3 show the Vickers hardness of the corroded as-received specimens and the corroded heat treated specimens, respectively (AlSi10Y3, AlSi15Y3, and AlSi20Y3). The Vickers hardness differs according to the type of specimen, but a variation can be clearly observed. For the hardness evaluation of the ceramics, as a brittle material, a probabilistic evaluation considering the variation distribution is important in order to increase the accuracy of the assessment. In addition, it can be seen that Vickers hardness is not a determined value, and changes statistically. Accordingly, considering the ease of analysis and the weakest link assumptions, the Weibull statistical analysis needs to be applied as a two-parameter Weibull distribution as shown below [10].

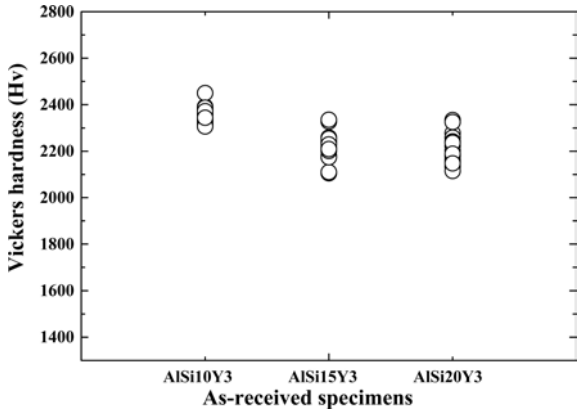

Fig. 1. Vickers hardness values from as-received specimens.

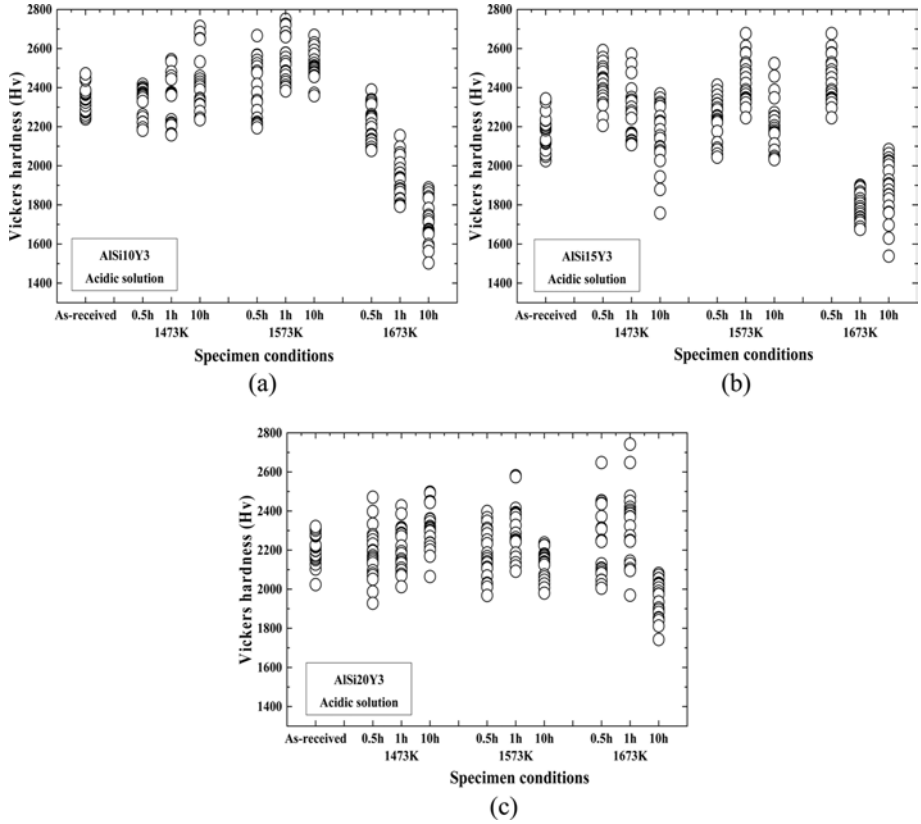

Fig. 2. Vickers hardness values from corroded specimens for 400 hours in acidic solution. (a) AlSi10Y3, (b) AlSi15Y3, (c) AlSi20Y3.

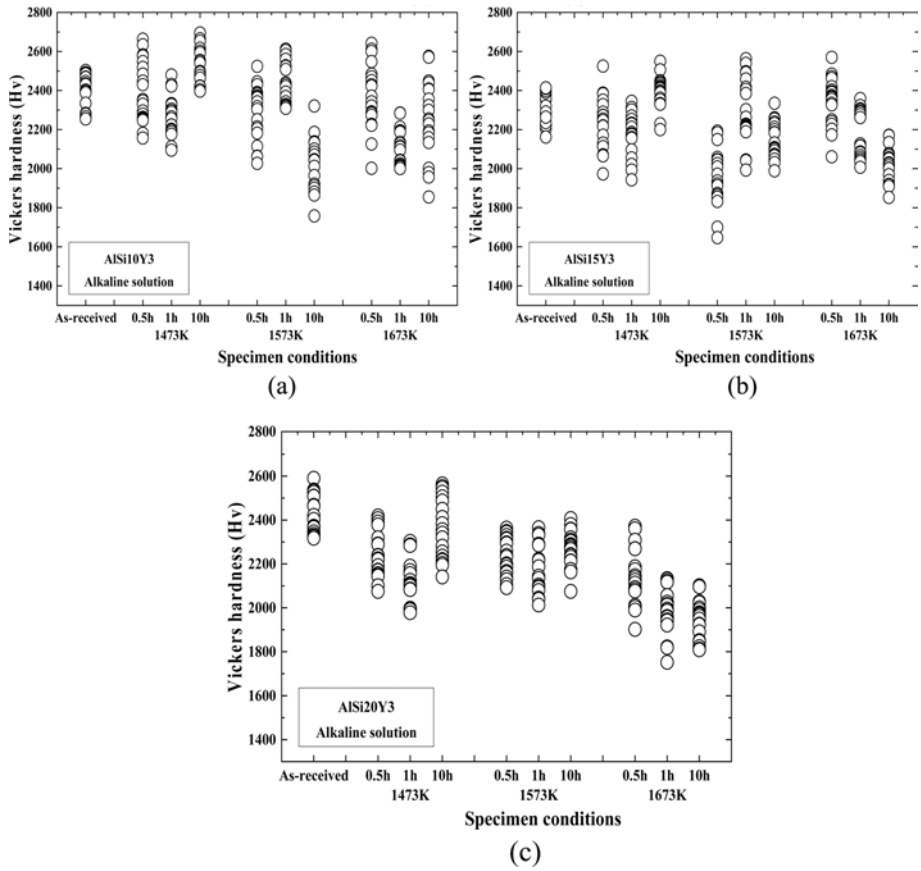

Fig. 3. Vickers hardness values from corroded specimens for 400 hours in alkaline solution. (a) AlSi10Y3, (b) AlSi15Y3, (c) AlSi20Y3.

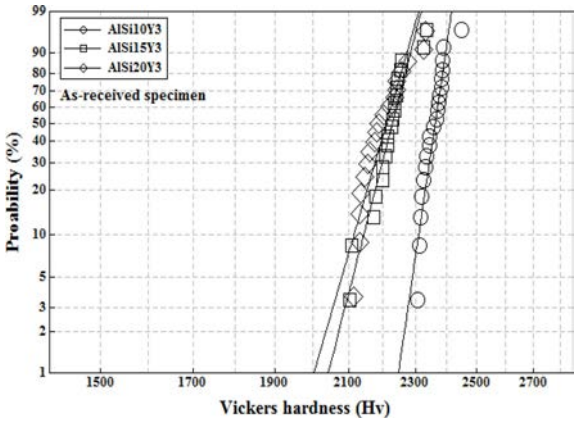

Fig. 4. Weibull plot of Vickers hardness from as-received specimens

$$F(x) = 1 - exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \quad (1)$$

Here, α is the shape parameter, which refers to the variability of the probability parameter, and β is the scale parameter indicating the characteristic lifetime, which is the failure probability of 63.2%.

Figs. 4 and 5 show the Vickers hardness of the as-received specimen and the corroded as-received specimen according to the Weibull probability, respectively.

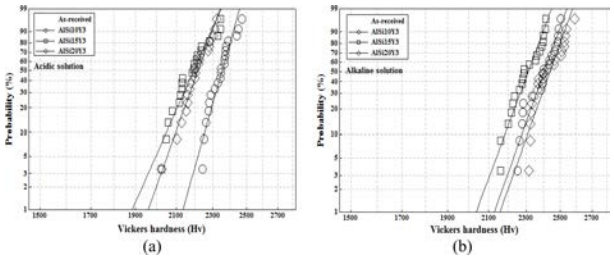

Fig. 5. Weibull plot of Vickers hardness from corroded as-received specimens. (a) Acidic solution, (b) Alkaline solution.

Tables 2-4 show the shape parameter and the scale parameters of the Weibull distribution function estimated from the Vickers hardness of the as-received specimen and the corroded as-received specimens. The table also shows the average, standard deviation (STD), and coefficient of variation (COV) according to mathematical statistics.

In Fig. 4, the Vickers hardness of the AlSi10Y3 as-received specimen was higher than that of the AlSi15Y3 and AlSi20Y3 as-received specimens. The hardness showed a tendency of a decreasing probability distribution value as the content of SiC increased.

In Fig. 5, the Vickers hardness of the corroded AlSi10Y3 as-received specimen in acidic solution was higher than that of the corroded AlSi15Y3 and AlSi20Y3 as-received specimens. The corroded AlSi15Y3 and

Table 2. The estimated Weibull parameters for as-received specimens.

	Shape parameter	Scale parameter	Std/Mean/COV
AlSi10Y3	84.3114	2373.38	35.40/2358/0.015
AlSi15Y3	48.5423	2246.79	55.98/2222/0.025
AlSi20Y3	43.0397	2230.82	64.81/2204/0.029

Table 3. The estimated Weibull parameters for corroded as-received specimens from acidic solution.

	Shape parameter	Scale parameter	Std/Mean/COV
AlSi10Y3	43.7987	2371.07	65.66/2343/0.028
AlSi15Y3	27.9635	2220.89	95.60/2180/0.044
AlSi20Y3	34.3714	2239.04	75.74/2205/0.034

Table 4. The estimated Weibull parameters for corroded as-received specimens from alkaline solution.

	Shape parameter	Scale parameter	Std/Mean/COV
AlSi10Y3	34.5699	2431.13	83.74/2395/0.035
AlSi15Y3	33.3053	2338.58	83.24/2302/0.036
AlSi20Y3	34.5704	2465.19	90.06/2428/0.037

AlSi20Y3 as-received specimens showed similar hardness distributions. The Vickers hardness of the corroded AlSi10Y3 and AlSi20Y3 as-received specimens in alkaline solution showed similar hardness distributions. They showed higher hardness distribution than the corroded AlSi15Y3 as-received specimen. The corroded as-received specimen in alkaline solution showed higher hardness distribution than that corroded in acidic solution. In addition, the hardness distribution of the corroded as-received specimens in the alkaline solution showed similar dispersion; the hardness distributions of corroded as-received specimens in acidic solution showed the largest dispersion in AlSi20Y3, followed by AlSi15Y3 and AlSi10Y3. Especially, the dispersion of the AlSi15Y3 specimen showed almost the same dispersion as that of the corroded as-received specimen in acidic solution. In the as-received specimens shown in Fig. 4 and the corroded as-received specimens shown in Fig. 5, the shape factor and standard deviation of the as-received specimen were larger than those of the corroded as-received specimen, and the variance was smaller. However, the scale coefficients representing the characteristic life of 63.2% were similar. From this, it can be inferred that the alumina ceramics used in this study were corroded by acidic and alkaline solution.

Figs. 6, 7, and 8 show the Vickers hardness of the corroded AlSi10Y3, AlSi15Y3, and AlSi20Y3 specimens in acidic solution, respectively, according to the Weibull probability. Since hardness is expressed as a straight line, it can be seen as applicable to the Weibull probability

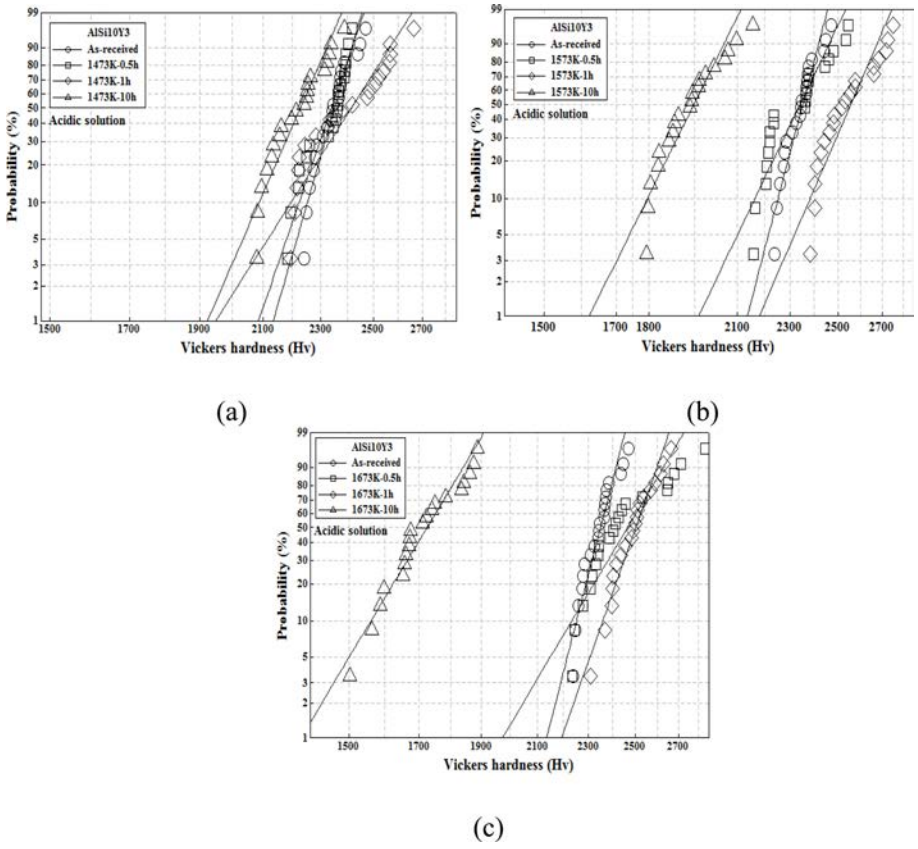

Fig. 6. Weibull plot of Vickers hardness for corroded AlSi10Y3 specimen from acidic solution. (a) 1473K, (b) 1573K, (c) 1673K.

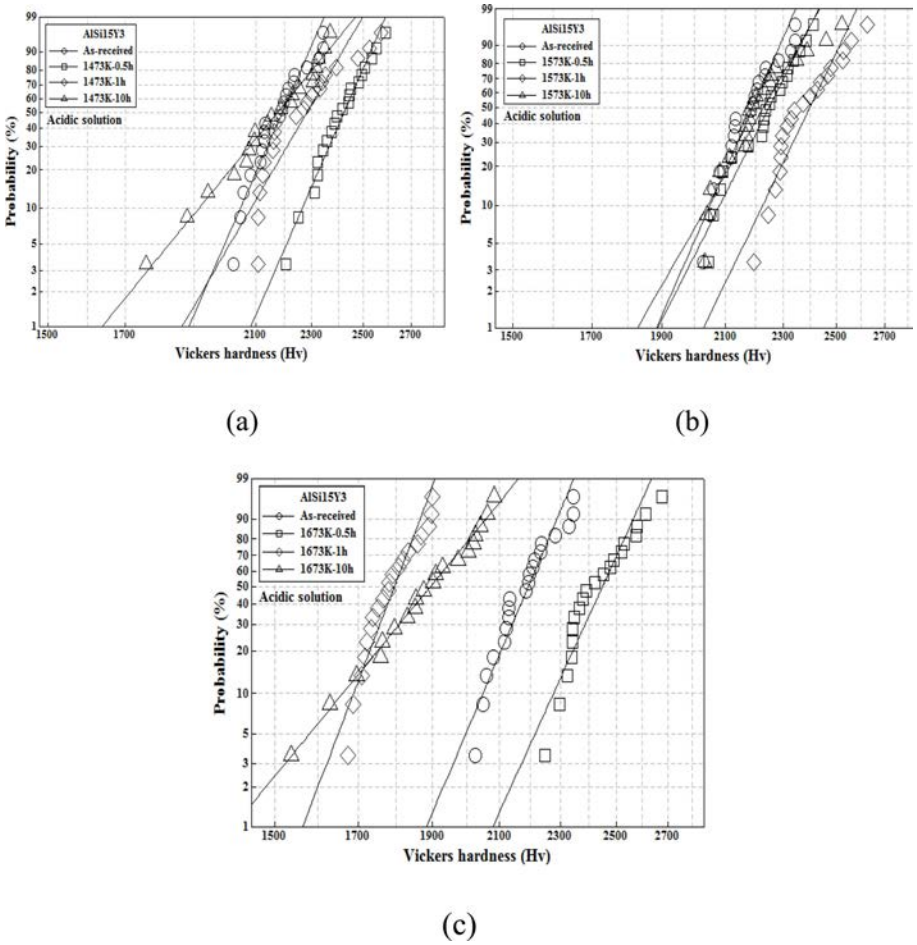

Fig. 7. Weibull plot of Vickers hardness for corroded AlSi15Y3 specimen from acidic solution. (a) 1473K, (b) 1573K, (c) 1673K.

distribution. In each figure, the heat treatment was performed at (a) 1473K, (b) 1573K, and (c) 1673K. The corroded as-received specimens are shown together for comparison with the corroded heat-treated specimens.

Fig. 6 shows the Vickers hardness of the corroded AlSi10Y3 specimen in acidic solution. In fig. 6(a), the hardness distribution of the corroded 1473K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens, but the corroded 1473K-1h specimen showed larger dispersion than the corroded as-received specimen. The corroded 1473K-10h specimen showed lower probability distribution than all corroded specimens. In Fig. 6(b), the hardness distribution of the corroded 1573K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 60%, but was greatly dispersed. The corroded 1573K-1h specimen showed the highest probability distribution. However, the corroded 1573K-10h specimen showed the lowest probability distribution and showed a lower probability distribution than the corroded 1473K-10h specimen. In Fig. 6(c), the hardness distribution of the corroded 1673K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 10%, but was greatly dispersed. The corroded 1673K-1h specimen showed a high probability distribution, while the corroded 1673K-10h specimen showed the lowest probability distribution and large dispersion.

Fig. 7 shows the Vickers hardness of the corroded AlSi15Y3 specimen in acidic solution. In Fig. 7(a), the hardness distribution of the corroded 1473K-0.5h specimen showed the highest probability distribution. The corroded 1473K-1h specimen showed a slightly higher probability distribution than the corroded as-received specimen, but the dispersion was slightly larger. The corroded 1473K-10h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 60%, but showed the greatest dispersion. In Fig. 7(b), the hardness distributions of the corroded 1573K-0.5h and 1573K-10h specimens were similar to the probability distribution of the corroded as-received specimen, while the corroded 1573K-1h specimen showed the highest probability distribution. The corroded 1573K-1h specimen showed a probability distribution similar to the corroded 1473K-0.5h specimen, but the dispersions were similar. In Fig. 7(c), the hardness distribution of the corroded 1673K-0.5h specimen showed the highest probability distribution, but the corroded 1673K-1h and

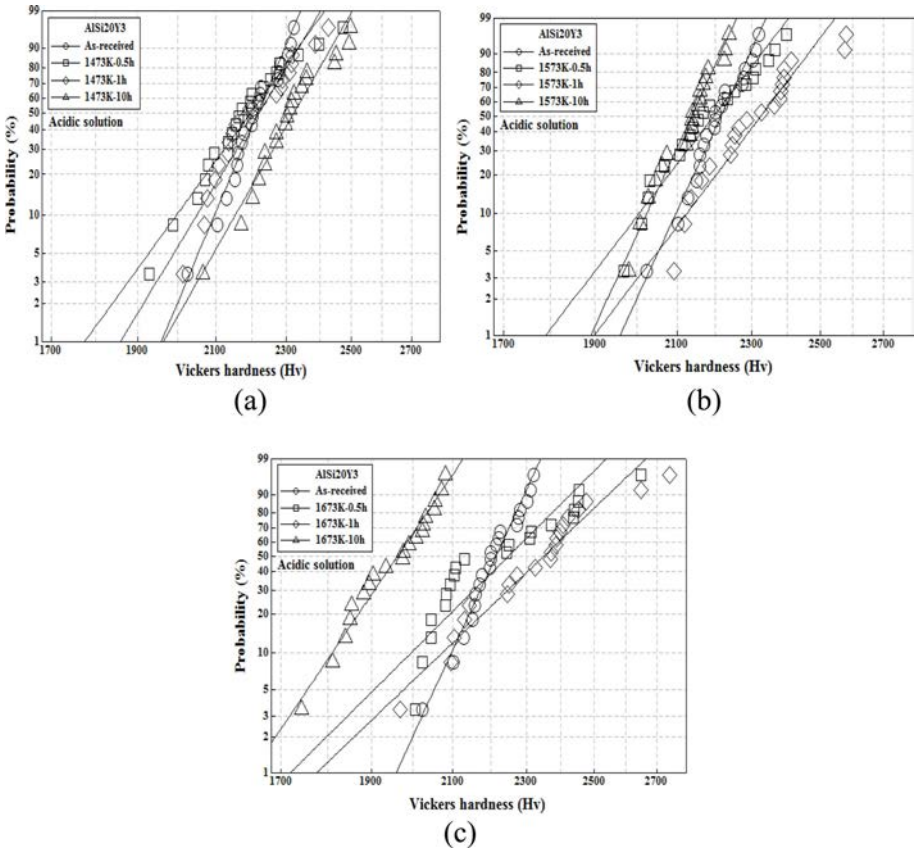

Fig. 8. Weibull plot of Vickers hardness for corroded AlSi20Y3 specimen from acidic solution. (a) 1473K, (b) 1573K, (c) 1673K.

1673K-10h specimens showed a lower probability distribution than the corroded as-received specimen, In particular, the corroded 1673K-10h specimen showed the largest dispersion.

Fig. 8 shows the Vickers hardness of the corroded AlSi20Y3 specimen in acidic solution. In Fig. 8(a), the hardness distribution of the corroded 1473K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 60-70%. The dispersion of the corroded 1473K-0.5h specimen was the largest, and the corroded 1473K-1h specimen is more dispersed than the corroded as-received specimen. The corroded 1473K-10h specimen showed a higher probability distribution than all of the corroded specimens, but the dispersion was larger than the corroded as-received specimen. In Fig. 8(b), the hardness distribution of the corroded 1573K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 70%, but the dispersion was large. The corroded 1573K-1h specimen showed the highest probability distribution, but the dispersion was larger than the corroded as-received specimen. The corroded 1573K-10h specimen showed the lowest probability distribution, and the dispersion was similar to that of the corroded as-received specimen. In Fig. 8(c), the hardness distribution of the corroded 1673K-0.5h specimen showed a probability distribution similar to that of the corroded as-received specimen at a probability of 40%, but the dispersion was large. The corroded 1673K-1h specimen was similar to the corroded as-received specimen at a probability of 15%, but the dispersion is larger than that of the corroded 1673K-0.5h specimen. The corroded 1673K-10h specimen showed the lowest dispersion and the dispersion was relatively large.

Fig. 9, 10, and 11 show the Vickers hardness of the corroded AlSi10Y3, AlSi15Y3, and AlSi20Y3 specimens in alkaline solution according to the Weibull probability, respectively. Since hardness is expressed as a straight line, it can be seen as applicable to the Weibull probability distribution. In each figure, the heat treatment was performed at (a) 1473K, (b) 1573K, and (c) 1673K. The corroded as-received specimens are shown together for comparison with the corroded heat-treated specimens.

Fig. 9 shows the Vickers hardness of the corroded AlSi10Y3 specimen in alkaline solution. In Fig. 9(a), the hardness distribution of the corroded 1473K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 50%, but the dispersion was large. The corroded 1473K-1h specimen showed a lower probability distribution than the corroded as-received specimen, but the dispersion was similar. The corroded 1473K-10h specimen

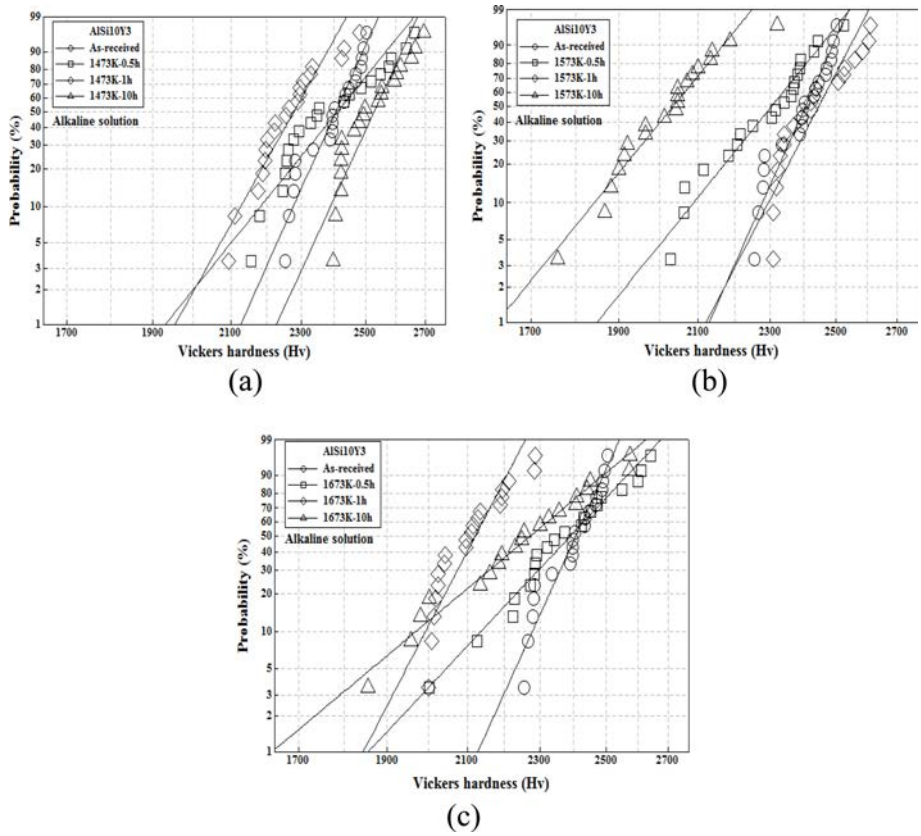

Fig. 9. Weibull plot of Vickers hardness for corroded AlSi10Y3 specimen from alkaline solution. (a) 1473K, (b) 1573K, (c) 1673K.

showed higher probability distribution than all corroded specimens. In Fig. 9(b), the hardness distribution of the corroded 1573K-0.5h specimen was lower than the probability distribution of the corroded as-received specimens, and the dispersion was larger. The corroded 1573K-1h specimen was similar to the corroded as-received specimen, but the dispersion was slightly larger. However, the corroded 1573K-10h specimen showed the lowest probability distribution and the dispersion was similar to that of the corroded 1573K-0.5h specimen. In Fig. 9(c), the hardness distribution of the corroded 1673K-0.5h specimen was similar to the probability distribution of the corroded as-received specimens at a probability of 60%, but the dispersion was large. The corroded 1673K-1h specimen showed the lowest probability distribution and showed similar dispersion to that of the corroded as-received specimen. The corroded 1673K-10h specimen showed a lower probability distribution than the corroded as-received specimen and the corroded 1673K-0.5h specimen, but the dispersion was the largest.

Fig. 10 shows the Vickers hardness of the corroded AlSi15Y3 specimen in alkaline solution. In Fig. 10(a), the hardness distribution of the corroded 1473K-0.5h specimen showed a lower probability distribution than that of the corroded as-received specimen, and the dispersion was large. The corroded 1473K-1h specimen showed the lowest probability distribution and the dispersion was large. However, the corroded 1473K-10h specimen showed a higher probability distribution than all of the corroded as-received specimens, and the dispersion was similar to the corroded as-received specimen. In Fig. 10(b), the hardness distribution of the corroded 1573K-0.5h specimen showed the lowest probability distribution and the dispersion was large. The corroded 1573K-1h specimen was similar to the corroded as-received specimen at a probability of about 50%, but the dispersion was large. The corroded 1573K-10h specimen showed a lower probability distribution than the corroded as-received specimen, but the dispersion was similar. In Fig. 10(c), the hardness distribution of the corroded 1673K-0.5h specimen was similar to that of the corroded as-received specimen at a probability of 20%, but the dispersion was slightly larger. The corroded 1673K-1h specimen showed a lower probability distribution than the corroded as-received specimen, but the dispersion was slightly smaller. The corroded 1673K-10h specimen showed the lowest probability distribution, and the dispersion was similar to that of the corroded as-received specimen.

Fig. 11 shows the Vickers hardness of the corroded AlSi20Y3 specimen in alkaline solution. The hardness distribution of all corroded heat-treated specimens (1473K, 1573K, and 1673K) showed a lower probability distribution than that of the corroded as-received specimens. In Fig. 11(a), the order of probability

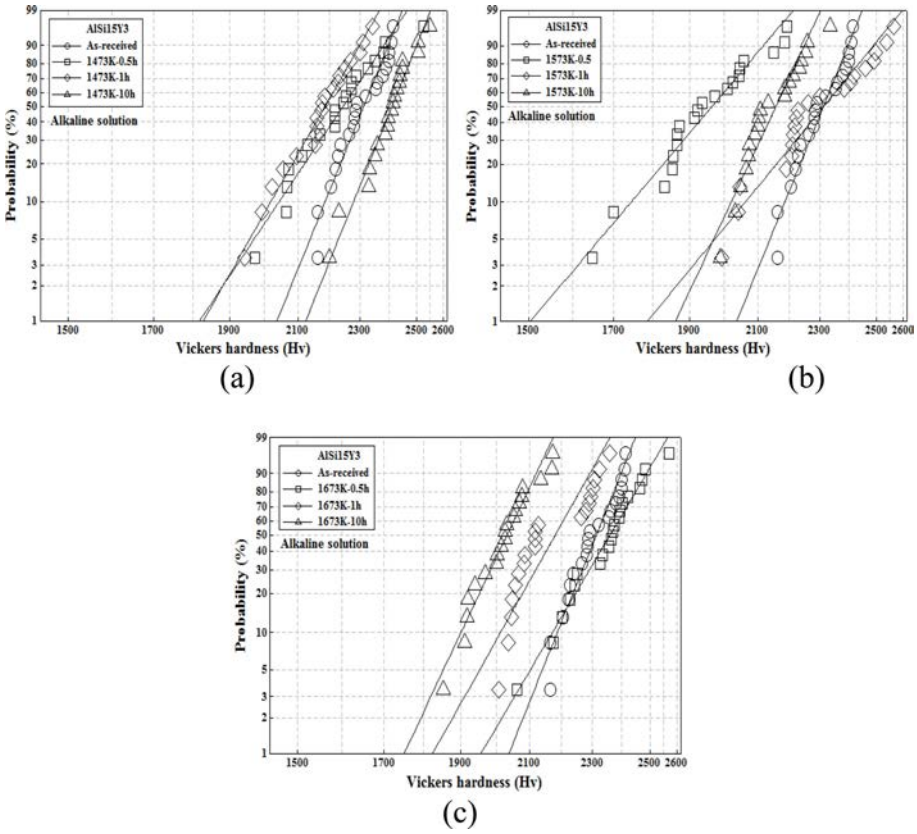

Fig. 10. Weibull plot of Vickers hardness for corroded AlSi15Y3 specimen from alkaline solution. (a) 1473K, (b) 1573K, (c) 1673K.

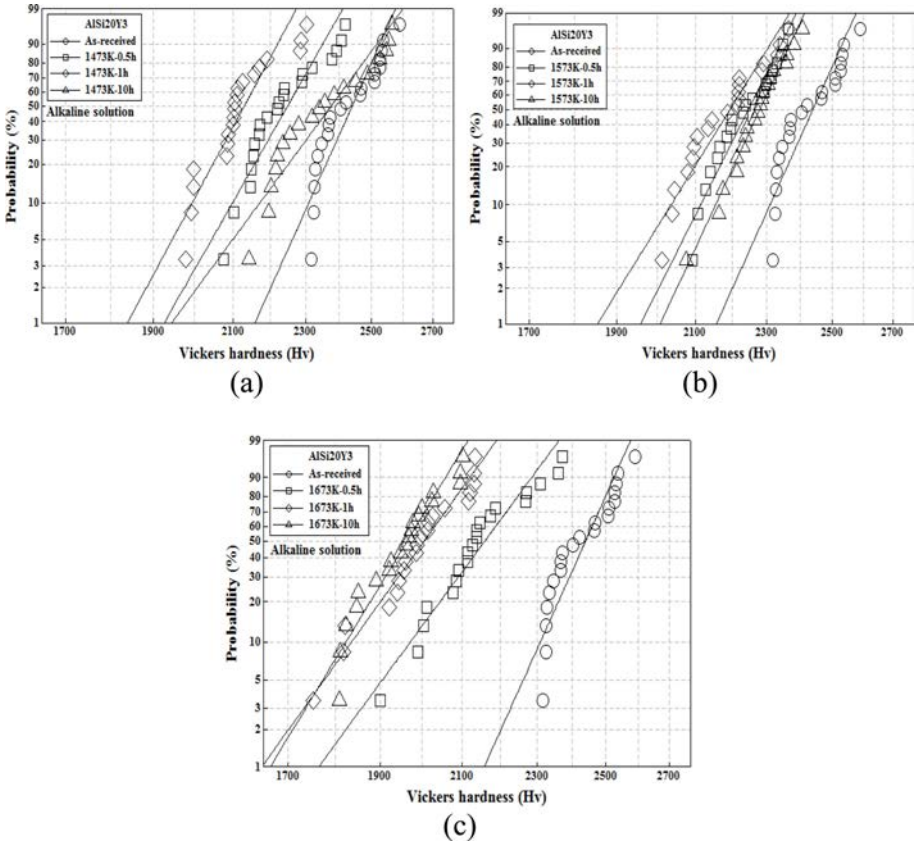

Fig. 11. Weibull plot of Vickers hardness for corroded AlSi20Y3 specimen from alkaline solution. (a) 1473K, (b) 1573K, (c) 1673K.

distributions are the corroded as-received specimen > the corroded 1473K-10h specimen > the corroded 1473K-0.5h specimen > the corroded 1473K-1h specimen. The dispersion was the largest for the corroded 1473K-10h specimen, while the corroded 1473K-0.5h specimen and the corroded 1473K-1h specimen showed similar dispersion to that of the corroded as-received specimen. In Fig. 11(b), the order of the probability distributions was the corroded as-received specimen > the corroded 1573K-10h specimen > the corroded 1573K-0.5h specimen > the corroded 1573K-1h specimen; the hardness distribution was concentrated in a similar range. The dispersions of the corroded as-received specimen and the corroded 1573K-10h specimen were similar, but those of the corroded 1573K-0.5h specimen and the corroded 1573K-1h specimen were slightly smaller. In Fig. 11(c), the probability distributions were in the order of the corroded as-received specimen > the corroded 1673K-0.5h specimen > the corroded 1673K-1h specimen > the corroded 1673K-10h specimen, but the probability distributions of the corroded 1673K-1h and the corroded 1673K-10h specimen were concentrated in a similar range. The hardness distribution of the heat treatment temperature of 1673K showed a lower probability distribution than that of 1473K and 1573K.

Table 5. The estimated Weibull parameters for corroded AlSi10Y3 specimen from acidic solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	43.7987	2371.07	65.66/2343/0.028
0.5 h	36.9509	2362.35	76.28/2329/0.033
1 h	28.8234	2459.18	151.7/2397/0.063
10 h	19.7727	2255.96	94.30/2216/0.043

Table 6. The estimated Weibull parameters for corroded AlSi10Y3 specimen from acidic solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	43.7987	2371.07	65.66/2343/0.028
0.5 h	23.9807	2376.82	123.5/2327/0.053
1 h	26.6154	2592.17	121.1/2542/0.048
10 h	23.2297	1977.21	104.4/1934/0.054

Table 7. The estimated Weibull parameters for corroded AlSi10Y3 specimen from acidic solution (heat treatment at 1673K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	43.7987	2371.07	65.66/2343/0.028
0.5 h	18.8927	2516.32	171.2/2450/0.07
1 h	31.9037	2533.14	93.73/2492/0.038
10 h	18.7619	1758.93	109.4/1712/0.064

Dispersion was similar or slightly smaller than that of the corroded as-received specimen.

Tables 5-13 show the shape parameter and the scale parameters of the Weibull distribution function estimated from the Vickers hardness of the corroded as-received specimen and the corroded heat-treatment

Table 8. The estimated Weibull parameters for corroded AlSi15Y3 specimen from acidic solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	27.9635	2220.89	95.60/2180/0.044
0.5 h	28.1008	2453.75	101.4/2409/0.042
1 h	20.9481	2320.94	143.5/2266/0.063
10 h	14.9153	2228.16	164.8/2155/0.077

Table 9. The estimated Weibull parameters for corroded AlSi15Y3 specimen from acidic solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	27.9635	2220.89	95.60/2180/0.044
0.5 h	24.1816	2283.75	109.8/2236/0.049
1 h	25.3674	2433.55	117.7/2385/0.049
10 h	21.3588	2268.26	133.5/2215/0.06

Table 10. The estimated Weibull parameters for corroded AlSi15Y3 specimen from acidic solution (heat treatment at 1673K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	27.9635	2220.89	95.60/2180/0.044
0.5 h	25.8996	2483.59	117.7/2435/0.048
1 h	31.0871	1815.96	70.47/1786/0.039
10 h	14.4240	1942.81	148.8/1877/0.079

Table 11. The estimated Weibull parameters for corroded AlSi20Y3 specimen from acidic solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.3714	2239.04	75.74/2205/0.034
0.5 h	19.9194	2236.71	132.5/2180/0.06
1 h	23.8562	2254.01	113.2/2206/0.051
10 h	25.3023	2354.97	109.2/2307/0.047

Table 12. The estimated Weibull parameters for AlSi20Y3 specimen from acidic solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.3714	2239.04	75.74/2205/0.034
0.5 h	20.7113	2234.70	127.3/2180/0.058
1 h	20.8907	2366.28	136.3/2309/0.059
10 h	34.5035	2160.12	72.87/2128/0.034

specimen (AlSi10Y3, AlSi15Y3, and AlSi20Y3) in acidic solution. The tables also show the average, standard deviation (STD), and coefficient of variation (COV) according to mathematical statistics.

Fig. 12 shows the shape parameters and the scale parameters from Table 2 and Tables 5-13. Open symbols and solid symbols indicate the shape and scale parameters, respectively. The square symbol (□ , ■), circle symbol (○ , ●), and triangle symbol (△ , ▲) were obtained from the AlSi10Y3 specimen, AlSi15Y3 specimen, and AlSi20Y3 specimen, respectively. The shape and scale parameters of the corroded as-received specimens were compared with those of the as-received specimen as follows. The shape parameters of the corroded as-received AlSi10Y3 specimens were approximately –48% smaller than those of the as-received specimen, but the scale parameters were similar in the acidic solution. The shape parameters of the corroded as-received AlSi15Y3 specimen were about –42% smaller than those of the as-received specimen, but the scale parameters were about –1.15%. The shape parameters of the corroded as-received AlSi20Y3 specimens were about –20% smaller than those of the as-received specimen, and the scale parameters were about 0.4%.

In the heat treated AlSi10Y3 specimen, the shape parameters of 1473K were smaller than those of the as-received specimen by about –16% (0.5 h), –34% (1 h), and –54% (10 h). The shape parameters of 1573K were smaller than those of the as-received specimen by about –45% (0.5 h), –39% (1 h), and –47% (10 h). The shape parameters of 1673K were smaller than those of the as-received specimen by about –57% (0.5 h), –27% (1 h), and –57% (10 h). The scale parameters of 1473K were similar to or smaller than those of the as-received specimen by about 0.4% (0.5 h), 3.7% (1 h), and –5% (10 h). The scale parameters of 1573K were similar to or higher or smaller than those of the as-received specimen by about 0.2% (0.5 h), 9.3% (1 h), and –16.6% (10 h). Also, the scale parameters of 1673K were higher or smaller than those of the as-received specimen by about 6% (0.5 h), 6.8% (1 h) and –25.6%

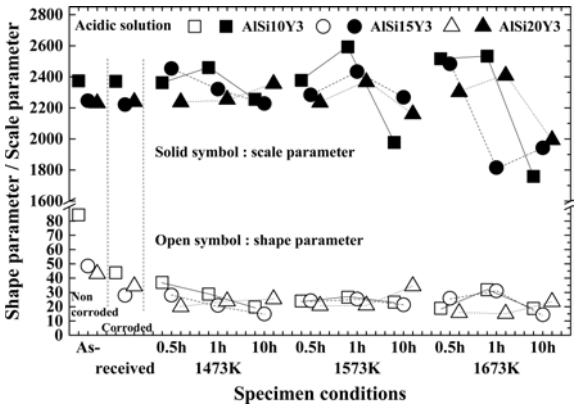

Fig. 12. Shape parameter and scale parameter from Weibull probability of corroded specimens in acidic solution.

(10 h). All of the shape parameters of the corroded AlSi10Y3 heat-treatment specimen were smaller than those of the corroded as-received specimen, but the dispersion was larger. However, the scale parameters were mostly observed after the heat treatment of 1 hour of each specimen, and were the largest at 1573K.

In the heat treated AlSi15Y3 specimen, the shape parameters of 1473K were similar to or smaller than those of the as-received specimen by about 0.5% (0.5h), –25% (1h), and –47% (10h). The shape parameters of 1573K were smaller than those of the as-received specimen by about –14% (0.5 h), –9% (1 h), and –24% (10 h). The shape parameters of 1673K were about –7% (0.5 h), 11% (1h) and –48% (10 h). The scale parameters of 1473K were high at about 10.5% (0.5 h), 4.5% (1 h), and 0.4% (10 h). The shape parameters of 1573K were higher than those of the as-received specimen by about 2.8% (0.5 h), 9.6% (1 h), and 2.2% (10 h). Also, the shape parameters of 1673K were about 11.8% (0.5h), –18.2% (1h), and –12.5% (10 h). All of the shape parameters of the corroded AlSi15Y3 heat-treatment specimen were smaller than the corroded as-received specimen, but the dispersion was larger. However, the scale parameters were large after the heat treatment of 1 hour, and the largest were observed at 1573K. All of the shape parameters of the corroded AlSi15Y3 heat-treatment specimen were larger than or equal to the corroded as-received specimen at the heat-treatment temperature of some. Most of shape parameters were small and showed a large dispersion. However, the scale parameters were observed as large at all heat treatment times of 1473K and 1573K. The scale parameter of 1673K-0.5h was large, but those of 1673K-1h and 10h were small.

In the heat treated AlSi20Y3 specimen, the shape parameters of 1473K were smaller than those of the as-received specimen by about –42% (0.5 h), -31% (1 h), and –26% (10 h). The shape parameters of 1573K were smaller than or similar to those of the as-received specimen by about –40% (0.5 h), –39% (1 h), and +0.4% (10 h). The shape parameters of 1673K were smaller than those of the as-received specimen by about –54% (0.5 h), –56% (1 h), and –32% (10 h). The scale parameters of 1473K were similar to those of the as-received specimen by about –0.1% (0.5 h), 0.7% (1 h), and 5% (10 h). The scale parameters of 1573K were about 0.2% (0.5 h), 5.6% (1 h), and –3.5% (10 h). Also, the scale parameters of 1673K were about 2.8% (0.5h), 7.5% (1 h), and –11% (10 h). The shape parameter of the corroded AlSi20Y3 heat treatment specimen was similar to that of the corroded as-received specimen at 1573K-10h, but the shape parameters of the other specimens were smaller than those of the a-received specimen. Also, the dispersion was large. However, the scale parameters were similar for each heat treatment temperature of 0. 5h, but increased for 1 h. Meanwhile, the scale parameters increased after 10 h at 1473K, but

were smaller than those of the as-received specimen at 1573K and 1673K.

From the above results, all of the shape parameters of the corroded as-received specimens in acidic solution were smaller than those of the as-received specimen, and those of all the corroded heat treatment specimens were smaller than those of the corroded as-received specimen. The scale parameters of the as-received specimen and the corroded as-received specimen were similar, but the scale parameters of the heat treated corrosion specimen at 1573K-1h, 1673K-0.5h, and 1 h were larger than those of the corroded as-received specimen. Considering the probability distribution and dispersion of hardness, the corrosion resistance of the corroded 1573K-1h heat treatment specimen was superior.

Tables 14-22 show the shape parameter and the scale parameters of the Weibull distribution function estimated

Table 13. The estimated Weibull parameters for AlSi20Y3 specimen from acidic solution (heat treatment at 1673K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.3714	2239.04	75.74/2205/0.034
0.5 h	15.7375	2302.82	186.2/2232/0.084
1 h	15.1069	2407.60	186.6/2329/0.08
10 h	23.4613	1993.53	97.54/1950/0.05

Table 14. The estimated Weibull parameters for AlSi10Y3 specimen from alkaline solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5699	2431.13	83.74/2395/0.035
0.5 h	19.1278	2456.62	155.6/2392/0.065
1 h	27.7531	2308.62	101.2/2266/0.045
10 h	33.7587	2554.75	95.96/2516/0.038

Table 15. The estimated Weibull parameters for AlSi10Y3 specimen from alkaline solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5699	2431.13	83.74/2395/0.035
0.5 h	19.1257	2348.97	140.9/2287/0.062
1 h	29.7280	2476.17	105.8/2433/0.044
10 h	18.9356	2074.42	128.6/2020/0.064

Table 16. The estimated Weibull parameters for AlSi10Y3 specimen from alkaline solution (heat treatment at 1673K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5699	2431.13	83.74/2395/0.035
0.5 h	16.7545	2442.75	165.9/2370/0.07
1 h	30.1974	2146.99	90.68/2110/0.043
10 h	13.1125	2337.57	199.8/2251/0.089

Table 17. The estimated Weibull parameters for AlSi15Y3 specimen from alkaline solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	33.3053	2338.58	83.24/2302/0.036
0.5 h	20.0626	2285.13	133.6/2228/0.060
1 h	23.6439	2219.72	107.2/2172/0.049
10 h	33.3912	2437.93	84.72/2400/0.035

Table 18. The estimated Weibull parameters for AlSi15Y3 specimen from alkaline solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	33.3053	2338.58	83.24/2302/0.036
0.5 h	15.8974	2009.70	145.4/1947/0.075
1 h	16.3855	2365.83	168.8/2294/0.074
10 h	28.7583	2184.92	91.77/2146/0.043

Table 19. The estimated Weibull parameters for AlSi15Y3 specimen from alkaline solution (heat treatment at 1673K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	33.3053	2338.58	83.24/2302/0.036
0.5 h	22.5497	2397.71	121.3/2344/0.052
1 h	23.7650	2212.69	118.9/2166/0.055
10 h	28.2601	2058.10	85.60/2021/0.042

Table 20. The estimated Weibull parameters for AlSi20Y3 specimen from alkaline solution (heat treatment at 1473K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5704	2465.19	90.06/2428/0.037
0.5 h	27.2045	2279.22	103.3/2236/0.046
1 h	28.7591	2156.62	94.31/2118/0.045
10 h	20.9868	2417.55	138.6/2360/0.059

Table 21. The estimated Weibull parameters for AlSi20Y3 specimen from alkaline solution (heat treatment at 1573K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5704	2465.19	90.06/2428/0.037
0.5 h	31.0080	2273.41	86.93/2235/0.039
1 h	25.1055	2227.44	106.0/2182/0.049
10 h	33.4894	2304.88	79.45/2269/0.035

Table 22. The estimated Weibull parameters for AlSi20Y3 specimen from alkaline solution (heat treatment at 1673 K).

	Shape parameter	Scale parameter	Std/Mean/COV
As-received	34.5704	2465.19	90.06/2428/0.037
0.5 h	20.9914	2196.44	124.2/2144/0.058
1 h	21.4952	2039.68	108.9/1992/0.055
10 h	25.5316	1992.49	92.69/1953/0.048

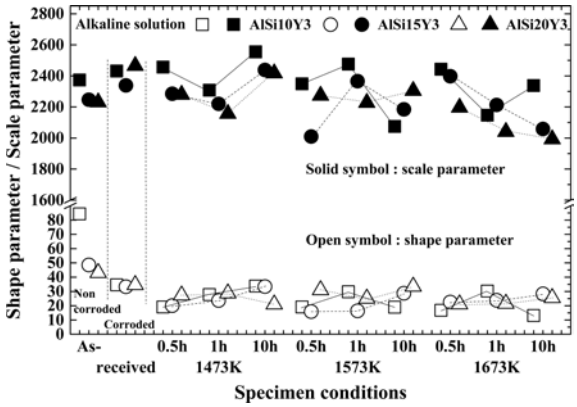

Fig. 13. Shape parameter and scale parameter from Weibull probability of corroded specimens in alkaline solution.

from the Vickers hardness of the corroded as-received specimen and the corroded heat-treatment specimens (AlSi10Y3, AlSi15Y3, and AlSi20Y3) in alkaline solution. The tables also show the average, standard deviation (STD), and coefficient of variation (COV) according to mathematical statistics.

Fig. 13 shows the shape parameters and the scale parameters from Table 2 and Tables 14-22. Open symbols and solid symbols refer to the shape and scale parameters, respectively. The square symbol (□ , ■), circle symbol (○ , ●), and triangle symbol (△ , ▲) were obtained from the AlSi10Y3 specimen, AlSi15Y3 specimen, and AlSi20Y3 specimen, respectively. The shape and scale parameters of the corroded as-received specimens were compared with those of the as-received specimen as follows. The shape parameters of the corroded AlSi10Y3 specimen were approximately –59% smaller than those of the as-received specimen, and the scale parameters were similar in the alkaline solution. The shape parameters of the corroded AlSi15Y3 specimen were about –42% smaller than those of the as-received specimen, and the scale parameters were about 4%. The shape parameters at the corroded AlSi20Y3 specimens were about –20% smaller than those of the as-received specimen, and the scale parameters were about 10% higher than those of the as-received specimen.

In the heat treated AlSi10Y3 specimen, the shape parameters at 1473K were about –44.7% (0.5 h), –19.7%, (1 h) and –2.3% (10 h). The shape parameters at 1573K were about –44.6% (0.5 h), -14% (1 h) and –45.2% (10 h). The shape parameters at 1673K were about –51.5% (0.5 h), –12.6% (1 h), and –62% (10 h). The scale parameters at 1473K were about 1.0% (0.5 h), –5.1% (1 h), and 5% (10 h). The scale parameters at 1573K were about 3.4% (0.5 h), 1.8% (1 h), and –14.7% (10 h). Also, the scale parameters at 1673K were about 0.5% (0.5h), –11.7% (1h), and –3.9% (10h). All of the shape parameters of the corroded AlSi10Y3 heat-treatment specimen were smaller than those of the corroded as-received specimen, and the dispersion was also large. The scale parameters of the corroded AlSi10Y3 heat-treatment specimen were similar for 1473K-10h, 1573K-1h, and 1673K-0.5h, and those of the other specimens were small.

In the heat treated AlSi15Y3 specimen, the shape parameters at 1473K were similar to or smaller than those of the as-received specimen by about –40% (0.5 h), –29% (1 h), and 0.3% (10 h). The shape parameters at 1573K were small at about –52.3% (0.5 h), –51% (1 h), and –13.7% (10 h). The shape parameters at 1673K were smaller than those of the as-received specimen by about –32.3% (0.5 h), –28.6% (1 h), and –15% (10 h). The scale parameters at 1473K were about –2.3% (0.5 h), –5% (1 h), and 4.2% (10 h). The scale parameters at 1573K were about –14% (0.5 h), 1.2% (1 h), and –6.6% (10 h). Also, the scale parameters at 1673K were about 2.5% (0.5 h), –5.4% (1 h), and –12% (10 h). All of the shape parameters of the corroded AlSi15Y3 heat-treatment specimen were smaller than those of the corroded as-received specimen, but the dispersions were larger. However, the scale parameters were larger than those of the corroded as-received specimen at 1473K-10h, 1573K-1h, and 1673K-0.5h, but the shape parameters of the other specimens were smaller.

In the heat treated AlSi20Y3 specimen, the shape parameters at 1473K were smaller than those of the as-received specimen by about –21.3% (0.5 h), –16.8% (1h), and –39.3% (10 h). The shape parameters at 1573K were smaller than those of the as-received specimen by about –10.3% (0.5 h), –27.7% (1 h), and –3.1% (10 h). The shape parameters at 1673K were smaller than those of the as-received specimen by about –39.3% (0.5 h), –37.8% (1 h), and –26.1% (10 h). The scale parameters at 1473K were smaller or higher than those of the as-received specimen by about –7.5% (0.5 h), 12.5% (1 h), and –2% (10 h). The scale parameters at 1573K were smaller than those of the as-received specimen by about –7.8% (0.5 h), –9.6% (1 h), and –6.5% (10 h). Also, the scale parameters at 1673K were smaller than those of the as-received specimen by about –10.9% (0.5 h), –17.3% (1 h), and –19.2% (10 h). The shape parameters of the corroded AlSi20Y3 heat treatment specimen were smaller than those of the corroded as-received specimen, and the dispersion was large. Also, all of the scale parameters were small.

The above results show that all of the shape parameters of the corroded as-received specimen in alkaline solution were smaller than those of the as-received specimen, and those of all the corroded heat treatment specimens were similar to or smaller than those of the corroded as-received specimen. The scale parameters of the as-received specimen and the corroded as-received specimen were similar, but the scale parameters of the corroded AlSi20Y3 as-received specimen were larger than those of the corroded as-received specimen by about 10%. The corroded heat

treated specimens of 1473K-0.5h, 1473K-10h, and 1573K-1h were larger than those of the corroded as-received specimens. Considering the probability distribution and dispersion of hardness, the 1473K-10h and 1573K-1h specimens were the most corrosion resistant.

Tables 23 and 24 show the average Vickers hardness of the as-received specimen, the corroded as-received specimen, and the corroded heat treatment specimen of AlSi10Y3, AlSi15Y3, and AlSi20Y3. Fig. 14 shows Table 2, Table 23, and Table 24. Figs. 14(a) and 14(b) were obtained from an acidic solution and an alkaline solution, respectively. The solid line of the figure shows the standard deviation.

In Fig. 14(a), the average hardness of the as-received AlSi10Y3 specimen was similar to that of the corroded as-received specimen. The corroded heat treatment specimen was compared with the as-received specimen. The average hardness of the as-received AlSi10Y3 specimen was similar to that of the corroded as-received specimen. The average hardness at 1473K was −1.2% (0.5 h), 1.6% (1 h), and −6.0% (10 h). The average hardness at 1573K was smaller or larger than of the as-received specimen by about −1.3% (0.5 h), 7.8% (1 h) and −18.0% (10 h). The average hardness at 1673K was smaller or larger than those of the as-received specimen by about 3.9% (0.5 h), 6.5% (1 h), and −27.4% (10 h). The average hardness of the as-received AlSi15Y3 specimen was about 1.9% greater than that of the corroded as-received specimen. The average hardness at 1473K was smaller or larger than those of the as-received specimen by about 8.4% (0.5 h), 2.0% (1 h), and −3.0% (10 h). The average hardness at 1573K was similar or larger than those of the as-received specimen by about 0.6% (0.5 h), 9.6% (1 h), and −0.3% (10 h). The average hardness at 1673K was smaller than those of the as-received specimen by about −9.6% (0.5 h), −19.6% (1 h), and −15.5% (10 h). The average hardness of the as-received AlSi20Y3 specimen was similar to that of the corroded as-received specimen. The average hardness at 1473K was smaller or larger than those of the as-received specimen by about −1.08% (0.5 h), 0.1% (1 h), and 4.7% (10 h). The average hardness at 1573K was smaller or larger than those of the as-received specimen by about -1.08% (0.5 h), 4.8% (1 h), and −3.4% (10 h). The average hardness at 1673K was smaller or larger than those of the as-received specimen by about 1.3% (0.5 h), 5.7% (1 h), and −11.5% (10 h). The average hardnesses of the as-received AlSi10Y3, AlSi15Y3, and AlSi20Y3 specimens in acidic solution were similar to that of the corroded as-received specimen. However, the average hardness of the corroded heat treatment specimen was smaller than that of the as-received specimen, but that of 1573K-1h was the largest. Also, the average hardnesses of the corroded heat treatment specimen at 10 h for each temperature was less than that at 0.5 h and 1 h.

Table 23. The mean Vickers hardness for corroded specimens in acidic solution.

	AlSi10Y3	AlSi15Y3	AlSi20Y3
	1473K/1573K/ 1673K	1473K/1573K/ 1673K	1473K/1573K/ 1673K
As-received	2358	2222	2204
As-received (Corroded)	2343	2180	2205
0.5 h	2329/2327/2450	2409/2236/2435	2180/2180/2232
1 h	2397/2542/2512	2266/2435/1786	2206/2309/2329
10 h	2216/1934/1712	2155/2215/1877	2307/2128/1950

Table 24. The mean Vickers hardness for corroded specimens in alkaline solution.

	AlSi10Y3	AlSi15Y3	AlSi20Y3
	1473K/1573K/ 1673K	1473K/1573K/ 1673K	1473K/1573K/ 1673K
As-received	2358	2222	2204
As-received (Corroded)	2395	2302	2428
0.5 h	2392/2287/2370	2228/1947/2344	2236/2235/2144
1 h	2266/2433/2110	2172/2294/2166	2118/2182/1992
10 h	2516/2020/2251	2400/2146/2021	2360/2269/1953

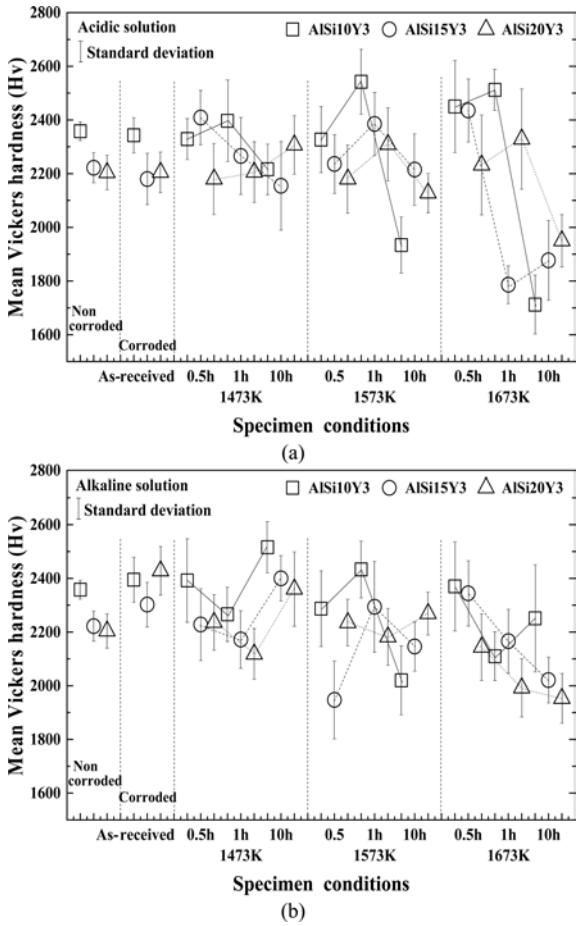

Fig. 14. Mean Vickers hardness according to corroded specimen conditions. (a) Acidic solution, (b) Alkaline solution.

In Figs. 4 and 14(b), the average hardness of the as-received AlSi10Y3 specimen was about –1.5% smaller than that of the corroded as-received specimen. The corroded heat treatment specimen was compared with the as-received specimen. The average hardness at 1473K was smaller or larger than those of the as-received specimen by about 1.4% (0.5 h), –3.9% (1 h), and 6.7% (10 h). The average hardness at 1573K was –3.0% (0.5 h), 3.2% (1 h), and –14.3% (10 h). The average hardness at 1673K was smaller or similar than those of the as-received specimen by about 0.5% (0.5 h), -10.5% (1 h), and –4.5% (10 h). The average hardness of the as-received AlSi15Y3 specimen was about –3.5% smaller than that of the corroded as-received specimen. The average hardness at 1473K was larger than those of the as-received specimen by about 0.3% (0.5 h), 2.3% (1 h), and 8.0% (10 h). The average hardness at 1573K was smaller or larger than those of the as-received specimen by about –12.4% (0.5 h), 3.2% (1 h), and –3.4% (10 h). The average hardness at 1673K was smaller or larger than those of the as-received specimen by about 5.5% (0.5 h), -2.5% (1 h), and –9.0% (10 h). The average hardness of the as-received AlSi20Y3 specimen was –9.2% smaller than that of the corroded as-received specimen. The average hardness at 1473K was smaller or larger than those of the as-received specimen by about 1.5% (0.5 h), –3.9% (1 h), and 7.1% (10 h). The average hardness at 1573K was smaller or larger than those of the as-received specimen by about 1.4% (0.5 h), –1.0% (1 h), and 2.9% (10 h). The average hardness at 1673K was smaller than those of the as-received specimen by about –2.7% (0.5 h), –9.6% (1 h), and –11.4% (10 h). The average hardness of the as-received AlSi10Y3, AlSi15Y3, and AlSi20Y3 specimens in alkaline solution was slightly smaller than that of the corroded as-received specimen. The average hardness of the corroded heat treatment specimens (0.5 h and 1 h of 1473K and 1573K, 0.5h of 1673K) was almost similar to that of the as-received specimen, but those at 1573K-10h, 1673K-1h, and 1673K-10h were small.

Results

In this study, SiC (10 wt.%, 15 wt.%, and 20 wt.%) and sintering aid Y_2O_3 (3 wt.%) were added to Al_2O_3. Al_2O_3 composite ceramics were heat-treated for 0.5, 1, and 10 hrs at 1473K, 1573K, and 1673K. These specimens were corroded for 400 hrs by acidic and alkaline solutions. Vickers hardness testing was performed with Weibull statistical analysis in order to evaluate the reliability of the measurement data.

(1) The hardness distribution of the as-received specimen showed a tendency for the probability distribution to decrease as the content of SiC increased.

(2) In acidic solution, the hardness distribution of the corroded as-received AlSi10Y3 specimen showed a higher probability distribution than that of the corroded as-received AlSi15Y3 and as-received AlSi20Y3 specimens, and the corroded as-received AlSi15Y3 and as-received AlSi20Y3 specimens showed similar hardness distribution. In alkaline solution, the corroded as-received AlSi10Y3 and as-received AlSi20Y3 specimens showed a similar hardness distribution and a higher probability distribution than those of the corroded as-received AlSi15Y3 specimen.

(3) In acidic solution, the shape parameter of all of the corroded as-received specimens was smaller than that of the as-received specimen, and the shape parameter of all of the corroded heat treatment specimens was smaller than that of the corroded as-received specimen. In alkaline solution, the shape parameter of all of the corroded as-received specimens was smaller than that of the as-received specimen, and the shape parameter of the corroded heat treatment specimen was similar to or smaller than that of the corroded as-received specimen.

(4) The shape parameter and standard deviation of the as-received specimen were larger than those of the corroded as-received specimen, and the dispersion was smaller. However, the scale parameters representing the characteristic life of 63.2% were similar.

(5) The shape parameter of the corroded heat treatment specimen was lower than that of the as-received specimen and the corroded as-received specimen regardless of the solution, and the dispersion was larger. The scale parameter of the corroded as-received specimen was similar to that of the as-received specimen. Considering the probability distribution and dispersion of hardness, the corrosion resistance of the corroded 1573K-1h heat treatment specimen is superior regardless of the solution.

(6) The compositions of alumina ceramics used in this study were found to be corroded by acidic and alkaline solutions. The shape parameters and scale parameters of the Weibull statistical analysis can be used to predict the life of the alumina ceramics.

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