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# Temperature-dependent characteristics of weibull statistical analysis for vickers hardness of corroded $Al_2O_3$ ceramics

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**In this paper, $Al_2O_3$ ceramics with sintering additives, $Y_2O_3$ and SiC were prepared. SiC were added at 10, 15 and 20 wt.%, Respectively. $Y_2O_3$ was constant at 3 wt.%. The specimens were carried out the heat treatment for 0.5 hr, 1 hr, and 10 hrs at three different temperatures (1473 K, 1573 K and 1673 K). In acidic solution, the hardness of the corroded AS10 specimen was similar to regardless of the temperature at 0.5 hr and 1 hr. The probability distribution of 10 hrs was decreased than as-received specimen as temperature increase. The corroded AS15 specimen for 0.5 hr was similar except to the highest 1673K. The 1673 K-1hr and 10hrs specimens showed the lowest probability distribution, but others were similar. The probability distribution of the corroded AS20 specimens for 0.5 hr and 1hr were similar regardless of temperature. The probability distribution of 10h decreased as temperature increase. In alkaline solution, the hardness of the corroded AS10 specimen at 0.5 hr was similar to regardless of the temperature. The probability distribution of 1 hr and 10hrs had large dispersion as temperature increase. The corroded AS15 and AS20 specimen for 1 hr and 10hrs was smaller than the corroded as-received specimen. The compositions of $Al_2O_3$ ceramic 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.**

**Key words: $Al_2O_3$ ceramics, SiC weight ratio, Heat treatment time and temperature, Corrosion, Vickers hardness, Weibull statistical analysis.**

## Introduction

Ceramics are candidate materials for industrial applications because of their excellent mechanical, tribological and thermal properties. These applications include bearings, turbo charger rotors, diesel engine components and cutting tools. However, because ceramics are brittle materials, fracture toughness is lower than that of metallic materials, resulting in lower reliability in mechanical properties. To overcome this problem, there are three ways: (a) inspect carefully and repair the unacceptable flaws, (b) toughen the ceramics by fiber reinforcing, (c) heal the flaws and recover strength. For method (a) and (b), many studies have been made around the world. Recently, the studies have been made of method (c). Some engineering ceramics have the ability to heal a crack [1-32].

From the above points of view, many study of the following items were carried out: ① a method to evaluate a crack-healing ability of a material [5-7, 12, 17, 21, 31, 32], ② effect of chemical compositions on the crack-healing ability of ceramics [9, 11, 16, 18, 20, 23-25], ③ effect of healing condition on the mechanical behaviors of crack-healed zone [6, 7, 9, 12, 13, 28], ④ maximum crack size which can be healed completely [7, 9, 15, 26], ⑤ high temperature strength of crack healed member [6, 7, 9, 12, 13, 19, 22, 27, 33], ⑥ crack-healed member at high temperature [10, 12, 15, 28-30], ⑦ crack-healing behavior under static or cyclic loading and crack-healing potential [12, 14]. ⑧ rolling fatigue and crack growth by shot peening [37-39], ⑨ corrosion and wear behavior [33, 34].

As described above, the heat treatment (crack healing) of the sintered ceramic increases the mechanical properties and secures the stability of the structure. However, the mechanical properties of ceramics are not a determined value, but have variability. The authors therefore statistically analyzed the mechanical properties of SiC and $ZrO_2$ ceramics by immersing them in acidic and alkaline solutions. [35, 36, 40-42]

In this paper, the $Al_2O_3$ ceramic with sintering additives, $Y_2O_3$ and SiC, was prepared. The as-received specimen and heat treated specimen were corroded in acidic and alkaline solutions and Vickers hardness was measured. The measured hardness was analyzed by Weibull statistic in order to evaluate the hardness reliability characteristics according to temperature at a constant heat treatment time.

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

| | $Al_2O_3$ | SiC | $Y_2O_3$ |
|---|---|---|---|
| AS10 | 87 | 10 | 3 |
| AS15 | 82 | 15 | 3 |
| AS20 | 77 | 20 | 3 |

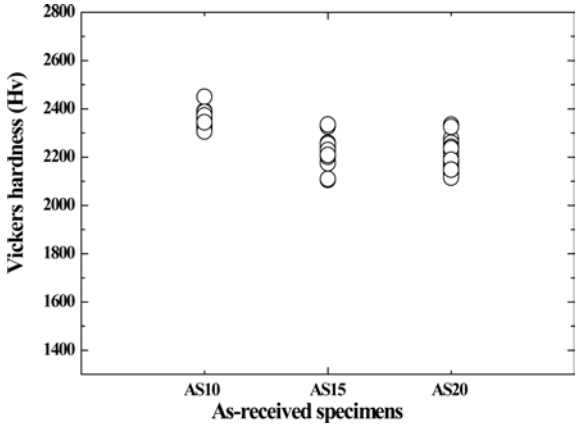


**Fig. 1.** Vickers hardness from as-received specimens.

## Materials and Experimental Method

The powders used were $Al_2O_3$ (AKP-30, $\alpha$-$Al_2O_3$) having an average particle diameter of 0.3 mm, SiC (Betarundum UF) having an average particle diameter of 0.27 mm and $Y_2O_3$ (Nippon Yttrium) having an average particle diameter of 0.27 mm. Table 1 shows the batch composition of specimens. After mixing powders, Alumina balls and alcohol was added to this mixture. After mixing for 24 hrs, the mixture was dried on a hot-plate. The sintering was carried out for one hour under 35 MPa in $N_2$ gas of 1873 K.

The mirror-polished specimens were carried out the heat treatment for 0.5 hr, 1 hr, and 10 hrs at 1473 K, 1573 K, and 1673 K. 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 5mol/L were used to test the corrosion resistance of the ceramic. Hardness was measured using a Vickers hardness tester (HV-114, Mitutoyo). The specimens 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.

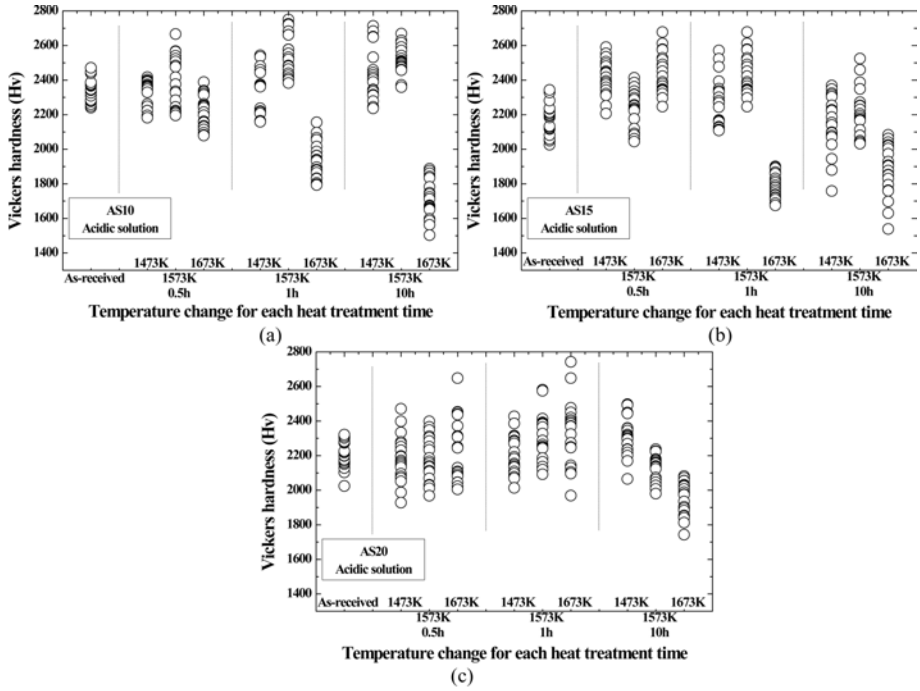


**Fig. 2.** Vickers hardness from corroded specimens of different heat treatment temperatures under same hrs in acidic solution. (a) AS10, (b) AS15, (c) AS20.

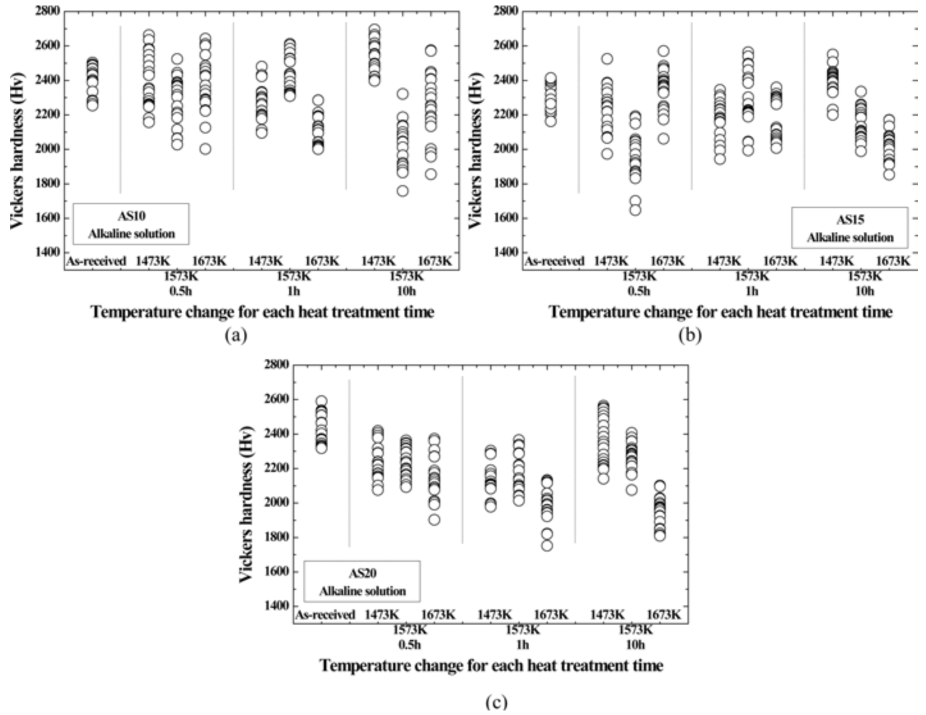


**Fig. 3.** Vickers hardness from corroded specimens of different heat treatment temperature under same hrs in alkaline solution. (a) AS10, (b) AS15, (c) AS20.

## Results and Discussion

Fig. 1 shows the Vickers hardness from the as-received specimens of AS10, AS15, and AS20. Figs. 2 and 3 show the Vickers hardness of the corroded as-received specimens and the corroded heat treated specimens of AS10, AS15, and AS20, respectively. Figs. 2 and 3 were corroded in acidic and alkaline solutions using the as-received specimens and the heat treated specimens, respectively. The corroded as-received specimens and the corroded heat treatment specimens are difference, but it can be seen that shows the dispersion. Like this, 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.

$$P(x) = 1-\exp[-(x/\beta)^{\alpha}]$$

Here, $\alpha$ is the shape parameter indicating the variability of the probability parameter. If it is larger, the statistical dispersion becomes smaller, which increases the reliability. $\beta$ is a scale parameter indicating the characteristic lifetime at a 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. Table 2 shows the shape parameter and the scale parameters of the Weibull distribution function estimated from the Vickers hardness of the as-received specimen. Tables 3 and 4 show the shape parameter and the scale parameters of the Weibull distribution function estimated from the Vickers hardness of the corroded as-received specimen in acidic and alkaline solution, respectively. 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 AS10 as-received specimen was higher than that of the AS15 and AS20 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 AS10 as-received

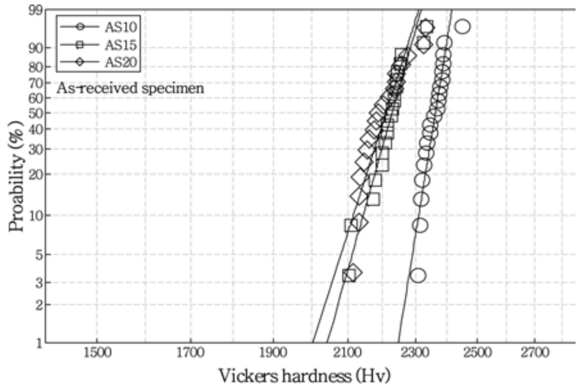


**Fig. 4.** Weibull plot of Vickers hardness from as-received specimens.

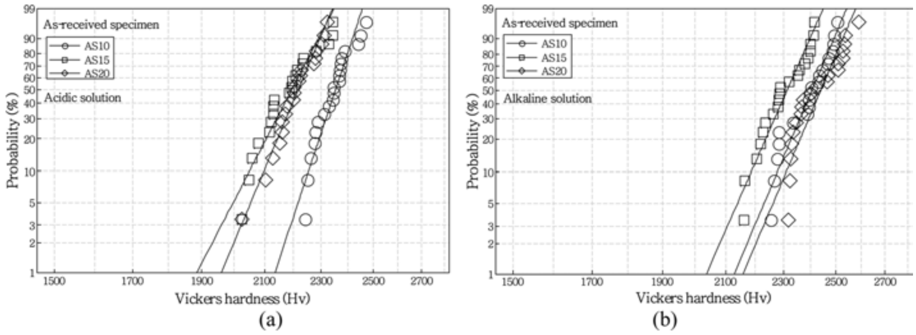


**Fig. 5.** Weibull plot of Vickers hardness from corroded as-received specimens with different amount of silicon carbide. (a) Acidic solution, (b) Alkaline solution.

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

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| AS10 | 84.3114 | 2373.38 | 35.40/2358/0.015 |
| AS15 | 48.5423 | 2246.79 | 55.98/2222/0.025 |
| AS20 | 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 |
|---|---|---|---|
| AS10 | 43.7987 | 2371.07 | 65.66/2343/0.028 |
| AS15 | 27.9635 | 2220.89 | 95.60/2180/0.044 |
| AS20 | 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 |
|---|---|---|---|
| AS15 | 34.5699 | 2431.13 | 83.74/2395/0.035 |
| AS20 | 33.3053 | 2338.58 | 83.24/2302/0.036 |
| AS10 | 34.5704 | 2465.19 | 90.06/2428/0.037 |

specimen in acidic solution was higher than that of the corroded AS15 and AS20 as-received specimens. The corroded AS15 and AS20 as-received specimens showed similar hardness distributions. The Vickers hardness of the corroded AS10 and AS20 as-received specimens in alkaline solution showed similar hardness distributions. They showed higher hardness distribution than the corroded AS15 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 AS20, followed by AS15 and AS10. Especially, the dispersion of the AS15 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 parameter 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 parameters representing the characteristic life of 63.2% were a little similar. From this, it can be inferred that the alumina ceramics used in this study were corroded by acidic and alkaline solution.

Figs 6-8 show the Weibull probability of Vickers hardness from corroded AS10, AS15, and AS20 specimens in different heat treatment temperature under same hours in acidic solution, respectively. Since hardness is expressed as a straight line, it can be seen as applicable to the Weibull probability distribution. In each figure, the same heat treatment time was performed at (a) 1473 K, (b) 1573 K, and (c) 1673 K. 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 AS10 specimen at 0.5, 1 and 10 hrs in acidic solution. In Fig. 6(a), the hardness distribution of the corroded specimen at 0.5 hr was similar to the probability distribution of the corroded as-received specimens, but the corroded 1673 K-0.5 hr specimen showed larger dispersion than the corroded as-received specimen. The corroded 1473 K-0.5 hr specimen was similar to probability distribution of the corroded as-received specimen. In Fig. 6(b), the hardness distribution of the corroded 1473 K-1hr specimen showed lower probability distribution than the corroded 1573 K and 1673 K specimens, and was greatly dispersed. The corroded 1573 K and 1673 K specimen showed the higher probability distribution than the corroded as-received specimen. In Fig. 6(c), the hardness of the corroded as-received specimen showed the highest probability distribution. The corroded specimens with heat treatment for 10 hrs showed a low probability distribution and large dispersion according to increasing of the temperature.

Fig. 7 shows the Vickers hardness of the corroded AS15 specimen at 0.5, 1 and 10 hrs in acidic solution.

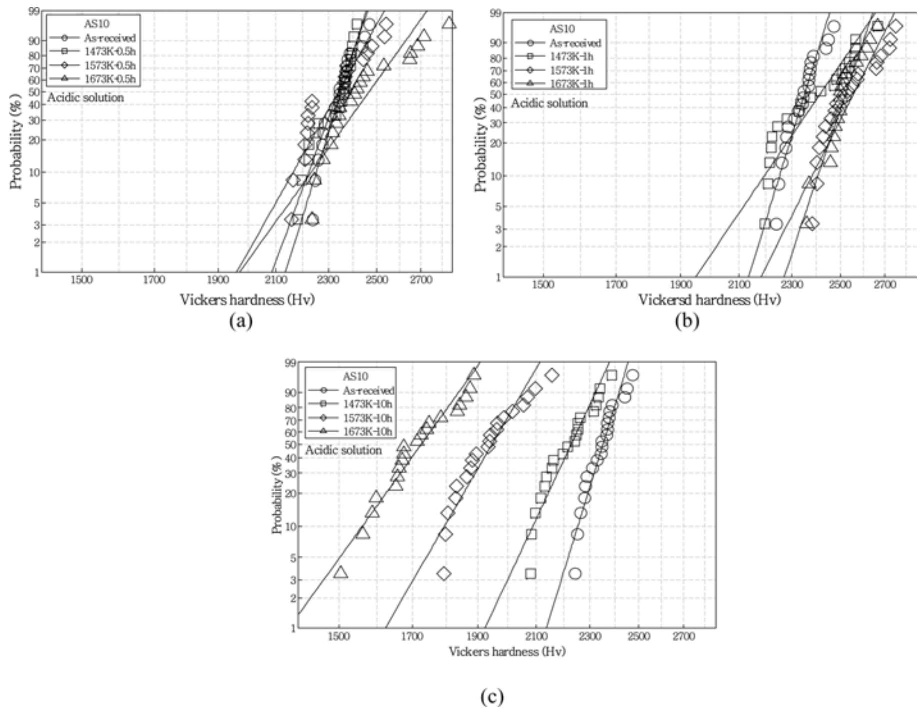


**Fig. 6.** Weibull plot of Vickers hardness from corroded AS10 specimens of different heat treatment temperature under same hours in acidic solution. (a) 0.5 h, (b) 1 h, (c) 10 h.

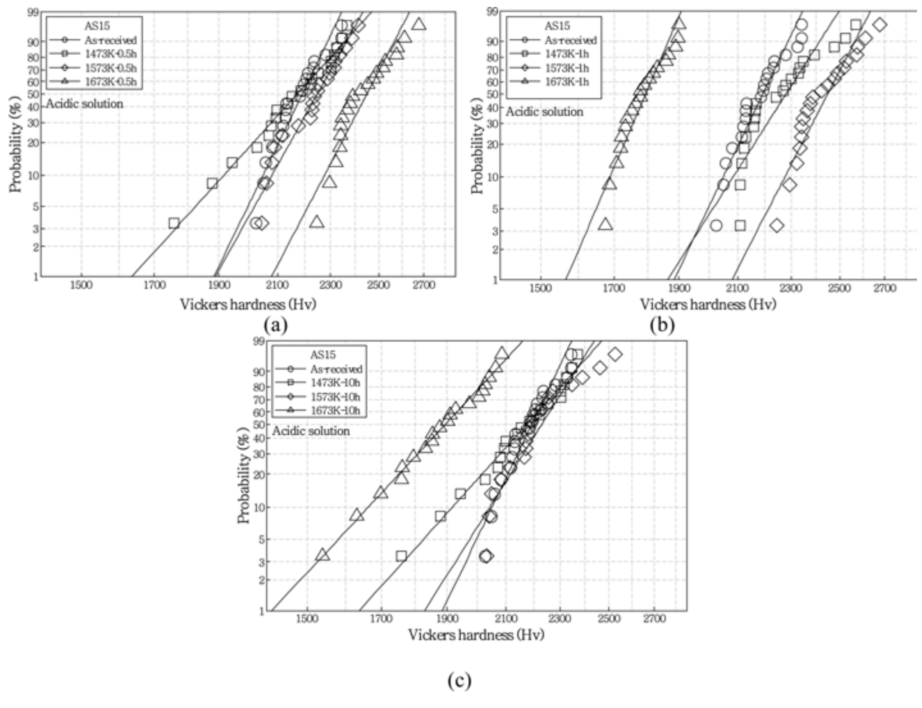


**Fig. 7.** Weibull plot of Vickers hardness from corroded AS15 specimen of different heat treatment temperature under same hours in acidic solution. (a) 0.5 hr, (b) 1 hr, (c) 10 hr.

In Fig. 7(a), the hardness distribution of the corroded 1673 K-0.5 hr specimen showed the highest probability distribution. The corroded 1573 K-0.5 hr specimen showed a slightly higher probability distribution than the corroded as-received specimen, but the dispersion was slightly larger. The corroded 1473 K-0.5 hr specimen showed the lowest probability distribution, and showed the greatest dispersion. In Fig. 7(b), the hardness of the corroded 1573 K-1 hr specimen showed the highest probability distribution. The hardness of the corroded 1673 K-1 hr specimen showed the lowest probability distribution. The hardness of the corroded as-received and 1473K-1h specimens were similar to the probability distribution. The corroded 1473 K-1 hr specimen

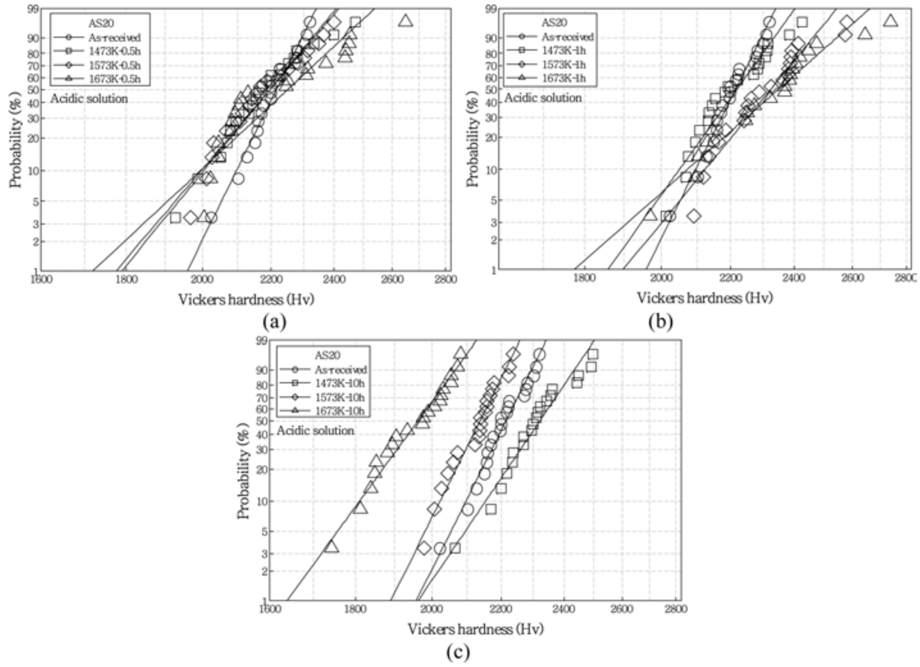


**Fig. 8.** Weibull plot of Vickers hardness from corroded AS20 specimen of different heat treatment temperature under same hours in acidic solution. (a) 0.5 hr, (b) 1 hr, (c) 10 hr.

showed a slightly higher probability distribution than the corroded as-received specimen, but the dispersion was slightly larger. In Fig. 7(c), the hardness of the corroded 1673 K-10 hr specimen showed the lowest probability distribution, but the others specimens was similar to probability distribution. The corroded 1473 K-10 hr specimen showed a slightly lower probability distribution than the corroded as-received and 1573 K-10 hr specimen, In particular, the corroded 1473 K and 1673 K-10 hr specimens were greatly dispersed.

Fig. 8 shows the Vickers hardness of the corroded AS20 specimen at 0.5, 1 and 10 hr in acidic solution. In Fig. 8(a), the hardness of the corroded 1473 K-0.5 hr specimen was similar to the probability distribution of the corroded 1573 K-0.5 hr specimen. The dispersion of the corroded 1673 K-0.5 hr specimen was the largest, but showed the greatest dispersion. The corroded as-received specimen showed a lower dispersion than all of the other specimens. In Fig. 8(b), the hardness of the corroded as-received specimen was similar to the probability distribution of the corroded 1473 K-1 hr specimen at a probability of about 50%, but the dispersion was small. On the other hand, the hardness of the corroded 1573 K-1 hr specimen was similar to the probability distribution of the corroded 1673 K-1 hr specimen at a probability of about 35%, but the dispersion was small. The corroded 1573K and 1673K-1hr specimens showed the highest probability distribution, but the dispersion was larger than the corroded as-received and 1473 K-1 hr specimens. In Fig. 8(c), the hardness of the corroded 1473 K-10 hr specimen showed a higher probability distribution than the corroded as-received specimen. The hardness of 1573 K and 1673 K-10 hr specimens showed a lower probability distribution than

**Table 5.** The estimated Weibull parameters from corrosion of acidic solution for 0.5 hr using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 43.7987 | 2371.07 | 65.66/2343/0.028 |
| 1473K-0.5h | 36.9509 | 2362.35 | 76.28/2329/0.033 |
| 1573K-0.5h | 23.9807 | 2376.82 | 123.5/2327/0.053 |
| 1673K-0.5h | 18.8927 | 2516.32 | 171.2/2450/0.070 |

**Table 6.** The estimated Weibull parameters from corrosion of acidic solution for 1 hr using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 43.7987 | 2371.07 | 65.66/2343/0.028 |
| 1473K-1h | 19.7727 | 2459.18 | 151.7/2397/0.063 |
| 1573K-1h | 26.6154 | 2592.17 | 121.1/2542/0.048 |
| 1673K-1h | 40.0154 | 2545.63 | 76.86/2512/0.031 |

**Table 7.** The estimated Weibull parameters from corrosion of acidic solution for 10 hrs using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 43.7987 | 2371.07 | 65.66/2343/0.028 |
| 1473K-10h | 28.8234 | 2255.96 | 94.30/2216/0.043 |
| 1573K-10h | 23.2297 | 1977.21 | 104.4/1934/0.054 |
| 1673K-10h | 18.7619 | 1758.93 | 109.4/1712/0.064 |

**Table 8.** The estimated Weibull parameters from corrosion of acidic solution for 0.5 hr using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 27.9635 | 2220.89 | 95.60/2180/0.044 |
| 1473K-0.5h | 28.1008 | 2453.75 | 101.4/2409/0.042 |
| 1573K-0.5h | 24.1816 | 2283.75 | 109.8/2236/0.049 |
| 1673K-0.5h | 25.8996 | 2483.59 | 117.7/2435/0.048 |

**Table 9.** The estimated Weibull parameters from corrosion of acidic solution for 1 hr using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 27.9635 | 2220.89 | 95.60/2180/0.044 |
| 1473K-1h | 20.9481 | 2320.94 | 143.5/2266/0.063 |
| 1573K-1h | 25.3674 | 2433.55 | 117.7/2385/0.048 |
| 1673K-1h | 31.0871 | 1815.96 | 70.47/1786/0.039 |

**Table 10.** The estimated Weibull parameters from corrosion of acidic solution for 10 hrs using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 27.9635 | 2220.89 | 95.60/2180/0.044 |
| 1473K-10h | 14.9153 | 2228.16 | 164.8/2155/0.077 |
| 1573K-10h | 21.3588 | 2268.26 | 133.5/2215/0.06 |
| 1673K-10h | 14.4240 | 1942.81 | 148.8/1877/0.079 |

**Table 11.** The estimated Weibull parameters from corrosion of acidic solution for 0.5hr using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.3714 | 2239.04 | 75.74/2205/0.034 |
| 1473K-0.5h | 19.9194 | 2236.71 | 132.5/2180/0.060 |
| 1573K-0.5h | 20.7113 | 2234.70 | 127.3/2180/0.058 |
| 1673K-0.5h | 15.7375 | 2302.82 | 186.2/2232/0.084 |

**Table 12.** The estimated Weibull parameters from corrosion of acidic solution for 1hr using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.3714 | 2239.04 | 5.74/2205/0.034 |
| 1473K-1h | 23.8562 | 2254.01 | 113.2/2206/0.051 |
| 1573K-1h | 20.8907 | 2366.28 | 136.3/2309/0.059 |
| 1573K-1h | 15.1069 | 2407.60 | 186.6/2329/0.080 |

that of the corroded as-received specimen. The corroded 1673 K-10 hr specimen showed the lowest probability distribution and the dispersion was similar to the 1473 K-10 hr specimen. Meanwhile, the dispersion of the corroded as-received and 1573 K-10 hr specimens were similar.

**Table 13.** The estimated Weibull parameters from corrosion of acidic solution for 10 hrs using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.3714 | 2239.04 | 75.74/2205/0.034 |
| 1473K-10h | 25.3023 | 2354.97 | 109.2/2307/0.047 |
| 1573K-10h | 34.5035 | 2160.12 | 72.87/2128/0.034 |
| 1673K-10h | 23.4613 | 1993.53 | 97.54/1950/0.050 |

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 specimen (AS10, AS15, and AS20) at same time in acidic solution. The tables also show the average, standard deviation (STD), and coefficient of variation (COV) according to mathematical statistics.

Figs. 9-11 show the Vickers hardness of the corroded AS10, AS15, and AS20 specimens at same time 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) 1473 K, (b) 1573 K, and (c) 1673 K of 0.5, 1 and 10 hrs, respectively. 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 AS10 specimen in alkaline solution. In Fig. 9(a), the hardness distribution of the corroded 1473 K-0.5 hr specimen was similar to the probability distribution of the corroded 1673 K-0.5 hr specimens, but the dispersion was a little small. The corroded 1573 K-0.5 hr specimen showed a lower probability distribution than the corroded a1473 K and 1673 K specimens, and the dispersion was small. The corroded as-received specimen showed higher probability distribution than all corroded specimens. In Fig. 9(b), the hardness of the corroded 1573 K-1 h specimen was the highest probability distribution, and was 1473 K-1 h and 1673 K-1 hr. But the dispersion was similar to all specimens. The corroded 1573 K-1 hr specimen was similar to the corroded as-received specimen, but the dispersion was slightly larger. However, the probability distributions of corroded specimens were similar. In Fig. 9(c), the hardness of the corroded 1473 K-10 h specimen was the highest probability distribution. The as-received specimen was lower than the corroded 1473 K-10 hr specimen. But the dispersion was similar. The corroded 1573 K-10 hr specimen showed the lowest probability distribution and the dispersion was a large. The corroded 1673 K-

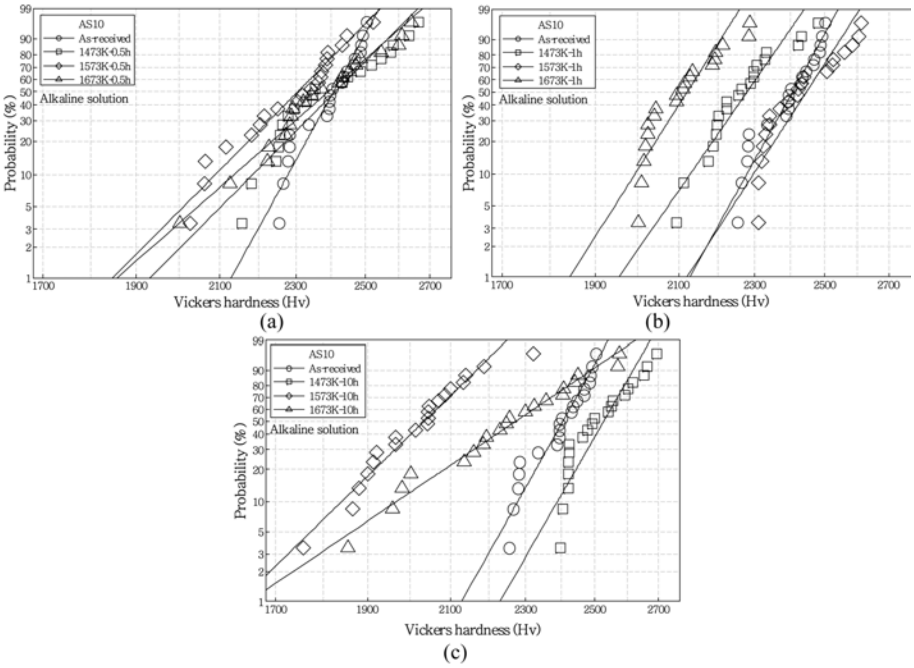


**Fig. 9.** Weibull plot of Vickers hardness from corroded AS10 specimen of different heat treatment temperature under same hour in alkaline solution. (a) 0.5 hr, (b) 1 hr, (c) 10 hr.

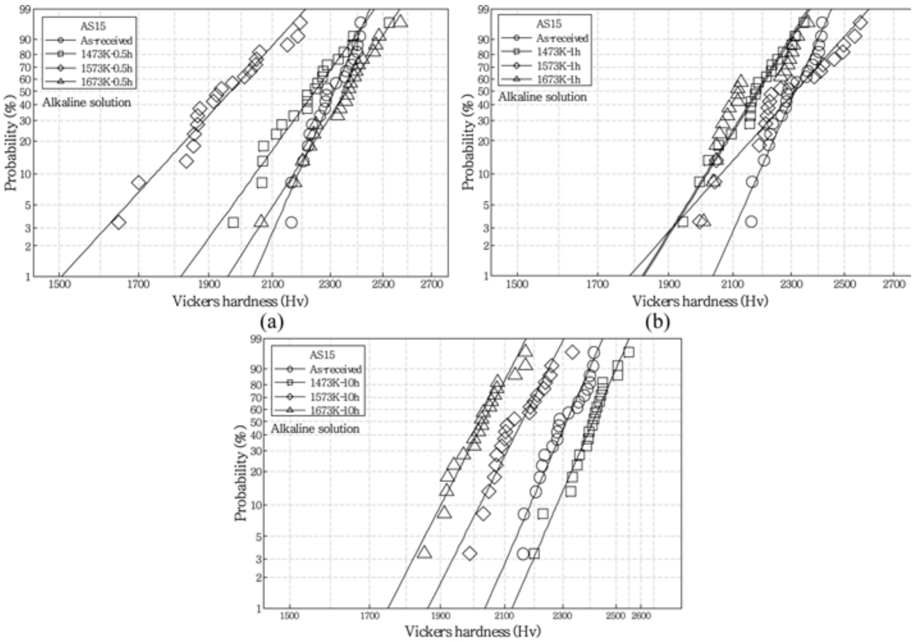


**Fig. 10.** Weibull plot of Vickers hardness from corroded AS15 specimen of different heat treatment temperature under same hours in alkaline solution. (a) 0.5 hr, (b) 1 hr, (c) 10 hr.

10 hr specimen showed a lower probability distribution than the corroded as-received specimen and the corroded 1473 K-10 hr specimen, and the dispersion was the largest.

Fig. 10 shows the Vickers hardness of the corroded AS15 specimen in alkaline solution. In Fig. 10(a), the probability distribution of the corroded 1673 K-0.5 hrs specimen was similar to that of the corroded as-received specimen, and the dispersion was large. The corroded 1573 K-0.5 hr specimen showed the lowest probability distribution. However, the corroded 1473 K-0.5 hr specimen showed a higher probability distribution than that of the corroded 1573 K-0.5 hr specimen, and the dispersion of the corroded 1473 K-0.5 hr specimen was similar to the corroded 1573 K-0.5 hr specimen. In Fig. 10(b), the hardness of the corroded 1473 K and 1673 K-1 hr specimen showed the lowest probability distribution and the dispersion was similar. The corroded

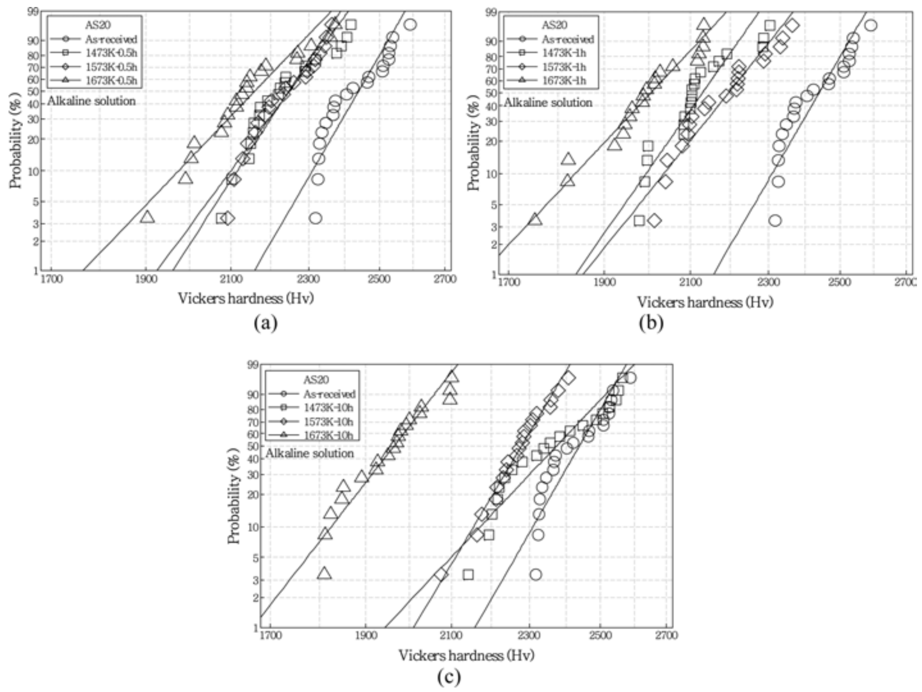

**Fig. 11.** Weibull plot of Vickers hardness from corroded AS20 specimen of different heat treatment temperature under same hours in alkaline solution. (a) 0.5 hr, (b) 1 hr, (c) 10 hr.

1573 K-1 hr specimen was similar to the corroded as-received specimen at a probability of about 50%, but the dispersion was a little large. In Fig. 10(c), the hardness of the corroded 1473 K-10 hr specimen showed the highest probability distribution. The second was as-received specimen, third was the corroded 1573 K-10 hr specimen. The corroded 1673 K-10 hr specimen showed the lowest probability distribution. The dispersions of all specimens were similar.

Fig. 11 shows the Vickers hardness of the corroded AS20 specimen in alkaline solution. The hardness distribution of all corroded heat-treated specimens (1473 K, 1573 K, and 1673 K) showed a lower probability distribution than that of the corroded as-received specimens. In Fig. 11(a), the order of probability distributions are the corroded as-received specimen > the corroded 1473 K and 1573 K-0.5 hr specimen > the corroded 1673 K-0.5 hr specimen. The dispersion was the largest for the corroded 1673 K-0.5 hr specimen, while the corroded 1473 and 1573 K 0.5 hr 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 1573 K-1 hr specimen > the corroded 1473 K-1 hr specimen > the corroded 1673 K-1hr specimen. The hardness dispersion was similar. The dispersions of the corroded as-received specimen, the corroded 1573 K and 1673 K-1 hr specimen were similar, but that of the corroded 1473 K-1 hr specimen was slightly smaller. In Fig. 11(c), the probability distributions were in the order of the corroded as-received specimen > the corroded 1473 K-10 hr specimen > the

**Table 14.** The estimated Weibull parameters from corrosion of alkaline solution for 0.5 hr using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5699 | 2431.13 | 83.74/2395/0.035 |
| 1473K-0.5h | 19.1278 | 2456.62 | 155.6/2392/0.065 |
| 1573K-0.5h | 19.1257 | 2348.97 | 140.9/2287/0.062 |
| 1673K-0.5h | 16.7545 | 2442.75 | 165.9/2370/0.070 |

**Table 15.** The estimated Weibull parameters from corrosion of alkaline solution for 1 hr using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5699 | 2431.13 | 83.74/2395/0.035 |
| 1473K-1h | 27.7531 | 2308.62 | 101.2/2266/0.045 |
| 1573K-1h | 29.7280 | 2476.17 | 105.8/2433/0.044 |
| 1673K-1h | 30.1974 | 2146.99 | 90.68/2110/0.043 |

**Table 16.** The estimated Weibull parameters from corrosion of alkaline solution for 10hr using AS10 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5699 | 2431.13 | 83.74/2395/0.035 |
| 1473K-10h | 33.7587 | 2554.75 | 95.96/2516/0.038 |
| 1573K-10h | 18.9356 | 2074.42 | 128.6/2020/0.064 |
| 1673K-10h | 13.1125 | 2337.57 | 199.8/2251/0.089 |

**Table 17.** The estimated Weibull parameters from corrosion of alkaline solution for 0.5hr using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 33.3053 | 2338.58 | 83.24/2302/0.036 |
| 1473K-0.5h | 20.0626 | 2285.13 | 133.6/2228/0.060 |
| 1573K-0.5h | 15.8974 | 2009.70 | 145.4/1947/0.075 |
| 1673K-0.5h | 22.5497 | 2397.71 | 121.3/2344/0.052 |

**Table 18.** The estimated Weibull parameters from corrosion of alkaline solution for 1hr using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 33.3053 | 2338.58 | 83.24/2302/0.036 |
| 1473K-1h | 23.6439 | 2219.72 | 107.2/2172/0.049 |
| 1573K-1h | 16.3855 | 2365.83 | 168.8/2294/0.074 |
| 1673K-1h | 23.7650 | 2212.69 | 118.9/2166/0.055 |

**Table 19.** The estimated Weibull parameters from corrosion of alkaline solution for 10 h using AS15 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 33.3053 | 2338.58 | 83.24/2302/0.036 |
| 1473K-10h | 33.3912 | 2437.93 | 84.72/2400/0.035 |
| 1573K-10h | 28.7583 | 2184.92 | 91.77/2146/0.043 |
| 1673K-10h | 28.2601 | 2058.10 | 85.60/2021/0.042 |

**Table 20.** The estimated Weibull parameters from corrosion of alkaline solution for 0.5 h using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5704 | 2465.19 | 90.06/2428/0.037 |
| 1473K-0.5h | 27.2045 | 2279.22 | 103.3/2236/0.046 |
| 1573K-0.5h | 31.0080 | 2272.41 | 86.93/2235/0.039 |
| 1673K-0.5h | 20.9914 | 2196.44 | 124.2/2144/0.058 |

**Table 21.** The estimated Weibull parameters from corrosion of alkaline solution for 1h using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5704 | 2465.19 | 90.06/2428/0.037 |
| 1473K-1h | 28.7591 | 2156.62 | 94.31/2118/0.045 |
| 1573K-1h | 25.1055 | 2227.44 | 106.0/2182/0.049 |
| 1673K-1h | 21.4952 | 2039.68 | 108.9/1992/0.055 |

corroded 1573 K-10 hr specimen > the corroded 1673 K-10 hr specimen. The hardness of the corroded 1673 K-10 hr specimen showed the lowest probability distribution. The dispersion of corroded 1473 K-10 hr specimen was the largest. The dispersion of others was similar.

**Table 22.** The estimated Weibull parameters from corrosion of alkaline solution for 10h using AS20 specimen with different heat treatment temperature.

| | Shape parameter | Scale parameter | Std/Mean/COV |
|---|---|---|---|
| As-received | 34.5704 | 2465.19 | 90.06/2428/0.037 |
| 1473K-10h | 20.9868 | 2417.55 | 138.6/2360/0.059 |
| 1573K-10h | 33.4894 | 2304.88 | 79.45/2269/0.035 |
| 1673K-10h | 25.5316 | 1992.49 | 92.69/1953/0.048 |

Tables 14-22 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 specimen (AS10, AS15, and AS20) at same time in alkaline 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 of Table 2 and Tables 5-13 from acidic solution. Open symbols and solid symbols indicate the shape and scale parameters, respectively. The square symbol (□, ■), circle symbol (○, ●), and triangle symbol (△, ▲) were obtained from the AS10 specimen, AS15 specimen, and AS20 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 AS10 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 AS15 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 AS20 specimens were about −20% smaller than those of the as-received specimen, and the scale parameters were about 0.4%.

In the heat treated AS10 specimen, the shape parameters of 0.5 h were smaller than those of the corroded as-received specimen by about −16% (1473 K), −45%(1573 K), and −57%(1673 K). The shape parameters of 1h were smaller than those of the corroded as-received specimen by about −34% (1473 K), −39% (1573 K), and −27% (1673 K). The shape parameters of 10h were smaller than those of the corroded as-received specimen by about −54% (1473 K), −47% (1573 K), and −57% (1673 K). The scale parameters of 0.5 hr were similar to or higher than those of the corroded as-received specimen by about 0.4% (1473 K), 0.2% (1573 K), and 6% (1673 K). The scale parameters of 1h were similar to or higher than those of the corroded as-received specimen by about 3.7% (1473 K), 9.3% (1573 K), and 6.8% (1673 K). Also, the scale parameters of 10h were smaller than those of the corroded as-received specimen by about -5% (1473 K),

−16.6% (1573 K), and –25.6% (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 1573 K.

In the heat treated AS15 specimen, the shape parameters of 0.5h were similar to or smaller than those of the corroded as-received specimen by about 0.5% (1473 K), −14% (1573 K), and −7% (1673 K). The shape parameters of 1h were smaller to or higher than those of the corroded as-received specimen by about –25% (1473 K), –9% (1573K), and 11% (1673 K). The shape parameters of 10h were smaller than those of the corroded as-received specimen by about –47% (1473 K), –24% (1573 K), and –48% (1673 K). The shape parameters of 0.5hr were higher than those of the corroded as-received specimen by about 10.5% (1473 K), 2.8% (1573 K), and –11.8% (1673K). The shape parameters of 1h were higher than those of the corroded as-received specimen by about 4.5% (1473 K), 9.6% (1573 K), and –18.2% (1673 K). Also, the shape parameters of 10hr were about 0.4% (1473 K), –2.2% (1573 K), and –12.5% (1673 K). 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 hr, and the largest were observed at 1573 K. All of the shape parameters of the corroded AS15 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 1473 K and 1573 K. The scale parameter of 1673 K-0.5 hr was large, but those of 1673 K-1 hr and 10 hr were small.

In the heat treated AS20 specimen, the shape parameters of 0.5 hr were smaller than those of the corroded as-received specimen by about –42% (1473 K), –40% (1573 K), −54% (1673 K). The shape parameters of 1h were smaller than those of the corroded as-received specimen by about −31% (1473 K), −39% (1573 K), and −56% (1673 K). The shape parameters of 10 hr were similar to or smaller than those of the corroded as-received specimen by about –26% (1473 K), 0.4% (1573 K), and –32% (1673 K). The scale parameters of 0.5 were similar to those of the corroded as-received specimen by about –0.1% (1473 K), 0.2% (1573 K), and 2.8% (1673 K). The scale parameters of 1 h were about 0.7% (1473 K), 5.6% (1573 K), and 7.5% (1673K). Also, the scale parameters of 10h were about 5% (1473K), –3.5% (1573K), and –11% (10 hr). The shape parameter of the corroded AS20 heat treatment specimen was similar to that of the corroded as-

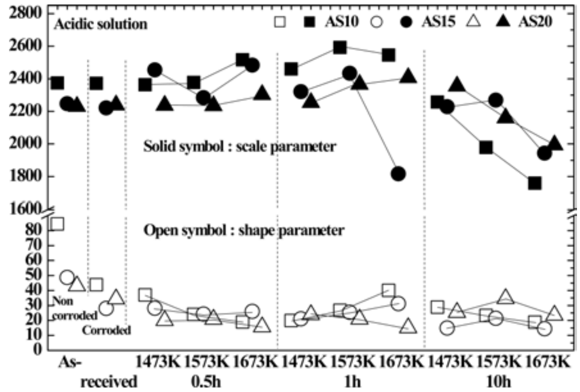


**Fig. 12.** Shape parameter and scale parameter from Weibull probability of corroded specimens in acidic solution.

received specimen at 1573 K-10 hr, but the shape parameters of the other specimens were smaller than those of the corroded as-received specimen. Also, the dispersion was large. However, the scale parameters were similar for each heat treatment temperature of 0.5 hr, but increased for 1 h. Meanwhile, the scale parameters increased after 10 hr at 1473 K, but were smaller than those of the corroded as-received specimen at 1573 K and 1673 K.

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 1573 K-1 hr, 1673 K-0.5 hr, and 1hr were larger than those of the corroded as-received specimen. Considering the probability distribution and dispersion of hardness, the corrosion resistance of the corroded 1573 K-1 hr heat treatment specimen was superior.

Fig. 13 shows the shape parameters and the scale parameters of Table 2 and Tables 14-22 from alkaline solution. 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 AS10 specimen, AS15 specimen, and AS20 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 AS10 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 AS15 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 AS20 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 AS10 specimen, the shape parameters at 0.5hr were smaller than those of the corroded as-received specimen by about –44.7% (1473 K), –44.6% (1573 K), and –51.5% (1673 K). The shape parameters at 1 h were about –19.7% (1473 K), –14% (1573 K) and –12.6% (1673 K). The shape parameters at 10 hr were about –2.3% (1473 K), –45.2% (1573 K), and –62% (1673 K). The scale parameters at 0.5 h were about 1.0% (1473 K), 3.4% (1573 K), and 0.5% (1673 K). The scale parameters at 1 h were about –5.1% (1473 K), 1.8% (1573 K), and –11.7% (1673 K). All of the shape parameters of the corroded AS10 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 AS10 heat-treatment specimen were similar for 1473 K-10 hr, 1573 K-1 hr, and 1673 K-0.5 hr, and those of the other specimens were small.

In the heat treated AS15 specimen, the shape parameters at 0.5 hr were smaller than those of the corroded as-received specimen by about –40% (1473 K), –52.3% (1573 K), and –32.3% (1673 K). The shape parameters at 1 h were small at about –29% (1473 K), –51% (1573 K), and –28.6% (1673 K). The shape parameters at 10 hr were about 0.3% (1473 K), –13.7% (1573 K), and –15% (10 hr). The scale parameters at 0.5h were about –2.3% (1473 K), –14% (1573 K), and 2.5% (1673 K). The scale parameters at 1h were about –5% (1473 K), 1.2% (1573K), and –5.4% (1673 K). Also, the scale parameters at 10hr were about 4.2% (1473K), –6.6% (1573K), and –12% (10hr). All of the shape parameters of the corroded AS15 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 1473 K-10 hr, 1573 K-1 hr, and 1673 K-0.5 hr, but the shape parameters of the other specimens were smaller.

In the heat treated AS20 specimen, the shape parameters at 0.5 hr were smaller than those of the corroded as-received specimen by about -21.3% (1473 K), –10.3% (1573 K), and –39.3% (1673 K). The shape parameters at 1 h were about –16.8% (1473 K), –27.7% (1573 K), and –37.8% (1673 K). The shape parameters at 10 hr were about –39.3% (1473 K), –3.1% (1573 K), and –26.1% (1673 K). The scale parameters at 0.5 hr were smaller or higher than those of the corroded as-received specimen by about –7.5% (1473 K), -7.8% (1573 K), and –10.9% (1673 K). The scale parameters at 1hr were about 12.5% (1473 K), –9.6% (1573 K), and –17.3% (1673 K). Also, the scale parameters at 10hr were about –2% (1473 K), –6.5% (1573 K), and –19.2% (1673 K). The shape parameters of the corroded AlSi20Y3 heat treatment specimen were smaller than

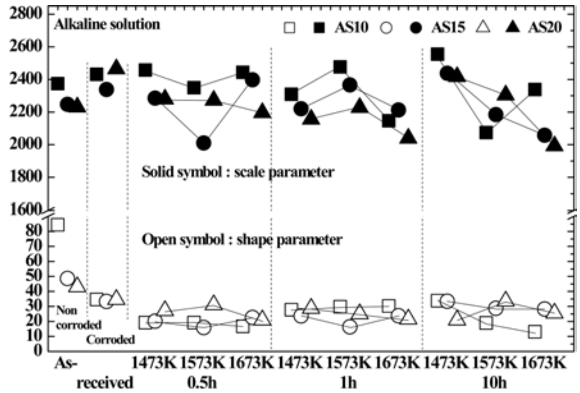


**Fig. 13.** Shape parameter and scale parameter from Weibull probability of corroded specimens in alkaline solution.

**Table 23.** The mean Vickers hardness for corroded specimens in acidic solution (K).

| | AS10 | AS15 | AS20 |
|---|---|---|---|
| | 1473/1573/ 1673 | 1473/1573/ 1673 | 1473/1573/ 1673 |
| As-received | 2358 | 2222 | 2204 |
| As-received (corroded) | 2343 | 2180 | 2205 |
| 0.5h | 2329/2327/ 2450 | 2409/2236/ 2435 | 2180/2180/ 2232 |
| 1h | 2397/2542/ 2512 | 2266/2435/ 1786 | 2206/2309/ 2329 |
| 10h | 2216/1934/ 1712 | 2155/2215/ 1877 | 2307/2128/ 1950 |

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 AS20 as-received specimen were larger than those of the corroded as-received specimen by about 10%. The corroded heat treated specimens of 1473 K -0.5 hr, 1473 K-10 hr, and 1573K-1hr were larger than those of the corroded as-received specimens. Considering the probability distribution and dispersion of hardness, the 1473K-10 hr and 1573 K-1 hr specimens were the most corrosion resistant.

## Summary

The Al2O3 composite ceramic dependent on weight % of SiC was sintered. The specimens were carried out the heat treatment for 0.5 hr, 1 hr, and 10 hr at three kinds of temperatures (1473 K, 1573 K and 1673 K). The Weibull statistical analysis was performed to Vickers hardness from temperature change at constant time.

In acidic solution, the hardness of the corroded AS10 specimen was similar to regardless of the temperature at 0.5 hr and 1 hr. The probability distribution of 10 hr was decreased than as-received specimen as temperature increase. The corroded AS15 specimen for 0.5hr was similar except to the highest 1673 K. The 1673K-1hr and 10 hr specimens showed the lowest probability distribution, but others were similar. The probability distribution of the corroded AS20 specimens for 0.5 hr and 1 hr were similar regardless of temperature. The probability distribution of 10 hr decreased as temperature increase.

In alkaline solution, the hardness of the corroded AS10 specimen at 0.5 hr was similar to regardless of the temperature. The probability distribution of 1h and 10 hr had large dispersion as temperature increase. The corroded AS15 and AS20 specimen for 1hr and 10 hr was smaller than the corroded as-received specimen.

The compositions of $Al_2O_3$ ceramic 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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## References

1. J.J. Lange, and T.K. Gupta, J. Am. Ceram. Soc. 53 (1970) 54-55.
2. J.J. Lange, and K.C. Radford, J. Am. Ceram. Soc. 53 (1970) 420-421.
3. J.J. Petrovic, and L.A. Jacobson, J. Am. Ceram. Soc. 59 (1976) 34-37.
4. T.K. Gupta, J. Am Ceram. Soc. 59 (1976) 259-262.
5. S.R. Choi, and V. Tikara, Scripta Metall. Mater. 26 (1992) 1263-1268.
6. K. Ando, T. Ikeda, S. Sato, F. Yao, and Y. Kobayashi, Fatigue Fract. Eng.Mater. Struct. 21 (1998) 119-122.
7. K. Ando, K. Furusawa, K. Takahashi, and S. Sato, J. of the European Ceramic Society 25 (2005) 549-558.
8. Y.Z. Zhang, L. Edwards, and W.J. Plumbridge, J. Am. Ceram. Soc. 81 (1998) 1861-1868.
9. K. Ando, K. Tsuji, T. Hirasawa, Y. Kobayashi, M.C. Chu, and S. Sato, J. Soc. Mater. Sci. Jpn. 48 (1999) 484-494.
10. K. Ando, K. Tsuji, M. Ariga, and S. Sato, J. Soc. Mater. Sci. Jpn. 48 (1999) 1173-1178.
11. K. Ando, M.C. Chu, Y. Kobayashi, F. Yao, and S. Sato, Jpn. Soc. Mech. Eng. 65 (1999) 1132-1139.
12. K. Ando, K. Takahashi, S. Nakayama, and S. Saito, J. Am. Ceram. Soc. 85 (2002) 2268-2272.
13. Y. Korous, M.C. Chu, M. Nakatani, and K. Ando, J. Am. Ceram. Soc. 83 (2000) 2788-2792.
14. K. Ando, K. Tuji, K. Furusawa, T. Hanagata, M. C. Chu, and S. Sato, J. Soc. Mater. Sci. Jpn. 50 (2001) 921-925.
15. K. Takahashi, B.S. Kim, M.C. Chu, S. Sato, and K. Ando, J. of the European Ceramic Society 23 (2003) 1971-1978.
16. M.K. Kim, H.S. Kim, S.B. Kang, S.H. Ahn, and K.W. Nam, Solid State Phenomena 124-126 (2007) 719-722.
17. H.S. Kim, M.K. Kim, J.W. Kim, S.H. Ahn, and K.W. Nam, Trans. of the KSME A31 (2007) 425-431.
18. K.W. Nam, M.K. Kim, S.W. Park, S.H. Ahn, and J.S. Kim, Materials Science and Engineering A471 (2007) 102-105.
19. K.W. Nam, H.S. Kim, C.S. Son, S.K. Kim, and S.H. Ahn, Trans. of the KSME A 31 (2007) 1108-1114.
20. H.S. Kim, M.K. Kim, S.B. Kang, S.H. Ahn, and K.W. Nam, Materials Science and Engineering A483 (2008) 672-675.
21. K.W. Nam, S.W. Park, J.Y. Do, and S.H. Ahn, Trans. of the KSME A32 (2008) 957-962.
22. K.W. Nam, J.S. Kim, and H.B. Lee, Trans. of the KSME A 33 (2009) 652-657.
23. K.W. Nam, S.H. Park, and J.S. Kim, Journal of Ceramic Processing Research 10 (2009) 497-501.
24. K.W. Nam, S.H. Park, S.W. Park, and S.J. Moon, Trans. of the KSME A 33 (2009) 957-962.
25. K.W. Nam, and J. S. Kim, Journal of Ceramic Processing Research 11 (2010) 20-24.
26. K.W. Nam, and J. S. Kim, Materials Science and Engineering A 527 (2010) 3236-3239.
27. K.W. Nam, J. S. Kim, and S. W. Park, Materials Science and Engineering A 527 (2010) 5400-5404.
28. K.W. Nam, and E. S. Kim, Trans. of the KSME A 35 (2011) 779-784.
29. K.W. Nam, J.W. Kim, T. Hinoki, A. Kohyama, J. Murai, and T. Murakami, Journal of Nuclear Materials 417 (2011) 353-355.
30. K.W. Nam, C.K. Moon, and I.S. Seo, Journal of Ceramic Processing Research 12 (2011) 646-649.
31. K.W.Nam, and S.W. Park, Journal of Ceramic Processing Research 13 (2012) 11-14.
32. K.W. Nam, and E.S. Kim, Materials Science and Engineering A 547 (2012) 125-127.
33. S.H. Ahn, and K.W. Nam, Transactions of the KSME A 38 (2014) 1117-1123.
34. S.H. Ahn, J.R. Hwang, and K.W. Nam, Journal of Ceramic Processing Research 15 (2014) 451-456.
35. K.W. Nam, S.J. Kim, and D.S. Kim, Trans. Korean Soc. Mech. Eng. A 39 (2015) 901-907.
36. S.J. Kim, D.S. Kim, and K.W. Nam, Trans. Korean Soc. Mech. Eng. A 39 (2015) 955-962.
37. S.H. Ahn, and K.W. Nam, Journal of Ceramic Processing Research 17 (2016) 365-368.
38. K.W. Nam, Journal of Ceramic Processing Research 17 (2016) 543-549.
39. K. Takahashi, K. Iwanaka, and H. Koike, Materials Science and Technology 33 (2017) 623-628.
40. S.H. Ahn, S.C. Jeong, and K.W. Nam, Journal of Ceramic Processing Research 17 (2016) 994-998.
41. S.H. Ahn, D.S. Kim, and K.W. Nam, Trans. Korean Soc. Mech. Eng. A 40 (2016) 987-995.
42. S.C. Jeong, S.H. Ahn, and K.W. Nam, Journal of Ceramic Processing Research 17 (2016) 1088-1094.