Effect of aging treatment on fatigue behavior of Nb-added ferritic stainless steel type 429 welds in 3% NaCl solution*

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The effect of aging treatment on fatigue behavior of Nb-added ferritic stainless steel type 429 welds in 3% NaCl solution was investigated. Two filler metals with different chemical compositions, Filler I and II, had been used for the MIG butt welding of type 429. After aging treatment at 700°C for 100 hours was applied to the smooth specimens of the welds, the fully reversed axial fatigue tests were performed in 3% NaCl solution. In the case of the welds with Filler I, there was almost no change in corrosion fatigue strength even after aging treatment. On the other hand, in the case of the welds with Filler II, the corrosion fatigue strength decreased after aging treatment. It was concluded that the combination of aging treatment and heat history of welding using Filler II caused the sensitization of the base metal of the welds and increased the sensitivity to the corrosive environment.

Key Words: Ferritic stainless steel, MIG weld, Fatigue, Corrosion fatigue, Aging, Sensitization

1. INTRODUCTION

Ferritic stainless steel which has good stress corrosion cracking (SCC) resistance, low coefficient of linear expansion and excellent thermal conductivity, is widely used for automobile exhaust system members1)~7). Recently, high Cr ferrite stainless steel, which has better corrosion resistance against the internal corrosion of exhaust system members, has also been used8). Furthermore, the temperature of exhaust gas tends to rise to comply with the regulation of exhaust gas and to achieve the compact high power9), and ferritic stainless steel with excellent high-temperature strength is required. Nb-added ferritic stainless steel, type 429, is recently used for automobile exhaust system members because it has good high-temperature strength and low Cr content, which makes it economical10). Welding is often used to manufacture exhaust system members used at high temperature. Therefore, ferritic stainless steel of the same type as the base metal is used as the weld metal mainly for the purpose of preventing hot crack. In most cases of fracture accidents of welded structures, a fatigue crack initiates at the weld toe and grows, leading to the final fracture11). Therefore, it is important to understand the fatigue behavior of welds. Furthermore, stainless steel used for automobile exhaust system members experiences severe environment. However, in recent years, the durability of automobile exhaust system members due to sensitization, that is, the influence of corrosion fatigue has become a problem12). In the previous study, we investigated the fatigue behavior of Nb-added ferritic stainless steel type 429, which was MIG welded with two ferritic stainless weld metals with different chemical compositions13). The authors had reported that welding with the weld metal including Al and Ti elements could prevent grain coarsening due to welding heat input. The hardness around the welded zone was almost the same in base metal (BM), heat affected zone (HAZ) and fusion zone (FZ) of both welded joints. The fatigue strength in 3% NaCl solution was lower than that in laboratory air. The intergranular crack fracture appeared on the fatigue fracture surface of each welded specimens fractured at HAZ.

However, when type 429 welds are used for automobile exhaust system members, they are exposed to high temperature for a long time. Therefore, the authors investigated the fatigue behavior of type 429 base metal, which was aged for a long time in the temperature range of 700 to 900°C14). As a result, it was clarified that the fatigue strength of the aged type 429 in 3% NaCl solution was lower than the fatigue strength in laboratory air. In this way, it is known that the fatigue strength of type 429 base metal in the corrosive environment is decreased due to aging treatment, and it is necessary to understand the effect of aging treatment on type 429 welds. However, there are no studies on the fatigue strength of aged type 429 welds in the corrosive environment.

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In this study, fully reversed axial fatigue tests were performed in 3% NaCl solution using smooth specimens in which type 429 were MIG welded with two ferritic stainless steel filler metals with different chemical compositions and aged at 700℃ for 100 hours. The effect of aging treatment on fatigue behavior of aged type 429 welds in the corrosive environment was investigated.

2. EXPERIMENTAL PROCEDURE

2.1 Test materials

The test material used is Nb-added type 429 with a plate thickness of 4.5 mm. This type 429 has been improved high temperature strength and sensitization resistance by adding 0.446% Nb. The material was held at 960℃ for 10 min, then annealed and MIG welded. Before MIG welding, the ends of plates were prepared into a 60° V shape and then welded in one pass. Ferritic stainless steel welding wires Filler I and II with different chemical compositions were used as the filler metals. Table 1 shows the chemical composition (wt.%) of the base metal and both filler metals. The addition of Nb suppresses the sensitization caused by welding in both types of filler metals. Filler II (19.23% Cr) has a larger amount of Cr than Filler I (17.69% Cr), so it exhibits excellent heat resistance and corrosion resistance. In addition, Filler II is designed to provide a fine and stable microstructure of weld metal by adding Al and Ti elements. Table 2 shows the welding parameters and the welding heat inputs. The mechanical properties of the base metal type 429 are 0.2% proof stress $\sigma_{0.2}$: 310 MPa, tensile strength $\sigma_B$: 464 MPa, elongation $\delta$: 35%, reduction of area $\varphi$: 78%.

2.2 Specimens and Test procedure

Fig. 1 shows the shape of the fatigue specimen. The specimen was a plate-shaped specimen having a parallel gauge section with 30 mm length, and was taken from the weld plate so that the welding line was perpendicular to the loading axis and was located in the center of the parallel part. And the weld reinforcement part was removed by machining. As an aging treatment, the specimens were kept in an electric furnace at 700℃ for 100 hours and then air-cooled. Prior to fatigue tests, the all specimens were mechanically polished using progressively finer grades of emery paper followed by buff-finishing. The measurement of hardness was carried out using a Vickers microhardness tester (test load 4.9 N, loading time
The fatigue tests were conducted using an electro-hydraulic fatigue testing machine with the sinusoidal waveform of load ratio, $R = -1$, frequency, $f = 10$ Hz and at room temperature. The fatigue tests in 3% NaCl solution were performed by sending the 3% NaCl solution to a corrosion tank attached to the parallel part of the specimen and circulating it using the constant rate pump. During the fatigue test, the BM, HAZ and FZ were all in 3% NaCl solution. The details of experimental procedures are in the reference\(^7\).

### 3. RESULT AND DISCUSSION

#### 3.1 Microstructures and Vickers hardness

Fig. 2 shows the microstructures of the side surfaces of the aged Filler I and II welds specimens. The coarse columnar microstructures were observed in the FZ of the Filler I welds. On the other hand, the finer equiaxed grain microstructures were observed in the FZ of the Filler II welds. It is considered that the grain growth was suppressed by the effect of the Al and Ti elements included in Filler II\(^9\). Comparing the average grain sizes before and after the aging treatment, the average grain sizes of FZ and HAZ hardly changed in both welds. On the other hand, the grains in BM were coarsened due to the aging treatment, and the average grain sizes before and after the aging treatment were about 34 and 60 $\mu$m, respectively. Fig. 3 shows the hardness distributions around the weld zone at the center of the specimen thickness. The welding center line was taken as the origin of the $x$-axis, and the hardness measurements were performed at 0.5 mm spaces in a range of 8 mm from the weld center. The dotted lines in Fig. 3 show the average hardness (205 HV) of the base metal. In both welds, the hardness of FZ and HAZ before aging treatment was about the same as that of BM. On the other hand, it can be seen that after the aging treatment, the hardness of FZ and HAZ hardly changed, but the hardness of BM decreased. It is considered that the hardness of BM decreased due to the coarsening of the average grain size.

#### 3.2 Fatigue behavior in 3% NaCl solution

Fig. 4 shows the $S$-$N$ diagram in 3% NaCl solution. The results of Filler I and II welds are shown by red triangles and blue squares, respectively. In addition, the results of the as-weld specimen and the aged specimen are shown by the open symbol and the solid symbol, respectively. Furthermore, the results of type 429, which is the base metal, are also shown for comparison. When type 429 was aged at 700°C for 100 hours, the intergranular crack fracture occurred due to sensitization, and as a result, the corrosion fatigue strength was slightly lower than that of unaged materials\(^9\). In the case of Filler I welds, however, there was almost no change in the corrosion fatigue strength even after aging treatment. On the other hand, it can be seen that the Filler II welds has lower corrosion fatigue strength than the as-weld Filler II welds after the aging treatment, and the reduction rate of the fatigue limit was the largest.

![Fig. 2](image_url) Microstructure in aged type 429 welded joint: (a) Filler I welded joint, (b) Filler II welded joint.

![Fig. 3](image_url) Vickers hardness distributions of type 429 welded joints: (a) Filler I welded joint, (b) Filler II welded joint. Dotted lines show the average of base metal.

![Fig. 4](image_url) $S$-$N$ diagram in 3% NaCl solution.
Fig. 5 shows the S-N diagram classified by the fatigue fracture regions. Most of the all as-weld Filler I welds fractured at HAZ, and showed the appearance of intergranular crack fracture. But the aged Filler I welds fractured at the BM or FZ, but the fracture appearance was intergranular crack fracture similar to that of the as-weld specimens. In the case of as-weld Filler I welds, it is considered that sensitization occurred around HAZ due to heat input during welding. It is considered that in the case of aged Filler I welds, the aging treatment caused sensitization of the entire specimen, so that the fracture region became FZ or BM, and the appearance of intergranular crack fracture exhibited (Fig. 6(a)).

In the case of the as-weld Filler II welds, all the specimens fractured at BM except one result, and there was no fracture at FZ, that is, the weld metal. Demo showed that the addition of Al and Ti elements to ferritic stainless steel improves the corrosion resistance\(^\text{17}\). In the fatigue tests in 3% NaCl solution, the reason why FZ of the Filler II welds did not fracture is considered to be that the corrosion resistance of weld metal was improved by the Al and Ti elements included in Filler II. On the other hand, all the aged Filler II welds fractured at BM, and the appearance of intergranular crack fracture was observed on the fracture surface (Fig. 6(b)). The welding parameters were different between Filler I and II. Therefore, it was considered that the combination of aging treatment and heat history in the welding caused the sensitization only in the BM of Filler II welds and increased the sensitivity to the corrosive environment.

4. CONCLUSIONS

Fully reversed axial fatigue tests were performed in 3% NaCl solution using smooth specimens which type 429 were MIG welded with two ferritic stainless steel filler metals with different chemical compositions and aged at 700°C for 100 hours.

The welds with Filler II had higher fatigue strength than those with Filler I. Although corrosion fatigue strength decreased due to aging treatment in the case of Filler II, the aging had little effect on corrosion fatigue strength in the case of Filler I. It was considered that the combination of aging treatment and heat history in the welding caused the sensitization of the base metal of the welds with Filler II and increased the sensitivity to the corrosive environment.

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