Hot Water Jet Erosion Characteristics of Ti–Ni Shape Memory Alloys

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The Co-free materials with high erosion resistance are anticipated for parts of equipment in nuclear power plants. The erosion resistance of Ti–Ni shape memory alloys (SMAs) against the impact of hot water jet onto the specimen surface was investigated experimentally and by finite element method (FEM). The results are compared with that of an existing Co-based alloy (Stellite). Both of the erosion damaged cross-sectional area and the maximum damaged depth increased linearly with the elongated exposure time. The damaged areas of SMAs were extremely small compared to those of Stellite. However, no significant difference in the maximum damaged depth was found between the two materials. From the FEM results, larger values of the maximum shear stress and the mean stress were found to distribute in the specimens in testing. It is estimated that the essential erosion damage mechanism of Ti–Ni SMAs is cavitation. In Stellite a combination of the shear stress and the cavitation controls erosion. The erosion resistance of the Ti–Ni SMAs is superior to that of Stellite. It is suggested that the Ti–Ni SMAs will be one of the promising alternative materials for Stellite.

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Keywords: erosion, titanium-nickel shape memory alloy, high temperature water jet, cobalt-based alloy, cavitation, shear stress, erosion test, finite element method

1. Introduction

Some components in power plants are exposed to the pressurized high-temperature fluid flow. Especially, the drain valve in power plants is subjected to the severe erosion-corrosion damage due to the impact of the high temperature and high-speed water jets. Therefore, the parts such as valve sheets and the overlay on turbine blades have been made of high erosion resistant Co-based alloys (Stellite). However, the usage of these alloys is severely restricted in nuclear power plants, because the Co dissolved into the high temperature water is radio-activated in reactor core and thereafter it deposits on the surfaces of cooling system pipes and also components. In these situations, the Co-free alternative materials is anticipated for nuclear power plants.

Metallic materials are generally subjected to the plastic deformation due to slip mechanism, while the fractures of shape memory alloys (SMAs) are caused only by the plastic deformation followed with the twinning deformation. Authors have reported that the damage of Stellite under hot water jet is caused by shear stress and cavitation. Furthermore, generally, Ti–Ni alloys have the high corrosion resistance for the extensive corrosive environments. From these viewpoints, the Ti–Ni alloys will be promising for the application to nuclear power plants parts.

In this study, the erosion resistance of the Ti–Ni SMAs under hot water jets is investigated experimentally and by finite element method (FEM), comparing with that of Stellite. Effects of the metallographical characteristics and the mechanical factors on the erosion damages are discussed in detail.

2. Materials and Experimental Procedure

Ti–Ni SMAs used in this work were fabricated by a powder metallurgy method. The average powder sizes of Ti and Ni were 24 μm and 6 μm, respectively. The main impurities in powder Ti were 0.029Fe and 0.17O² in mass%, and those in powder Ni were 0.069O² and 0.017C, in mass%.

Table 1 Ti–Ni shape memory alloys used.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Sintering Temperature (K)</th>
<th>Duration time (ks)</th>
<th>Solution-treated density (Mg/m³)</th>
<th>Theoretical density (Mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti–50 at%Ni–1</td>
<td>1103</td>
<td>1.2</td>
<td>6.013</td>
<td>6.45</td>
</tr>
<tr>
<td>Ti–50 at%Ni–2</td>
<td>1123</td>
<td>0.6</td>
<td>6.112</td>
<td>6.49</td>
</tr>
<tr>
<td>Ti–51 at%Ni–1</td>
<td>1103</td>
<td>0.6</td>
<td>6.280</td>
<td>6.45</td>
</tr>
<tr>
<td>Ti–51 at%Ni–2</td>
<td>1123</td>
<td>0.6</td>
<td>6.367</td>
<td>6.49</td>
</tr>
</tbody>
</table>

Table 2 Transformation temperatures.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Aᵣ</th>
<th>Aₛ</th>
<th>Mₛ</th>
<th>Mᵣ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti–50 at%Ni–1</td>
<td>377</td>
<td>309</td>
<td>346</td>
<td>284</td>
</tr>
<tr>
<td>Ti–50 at%Ni–2</td>
<td>378</td>
<td>318</td>
<td>346</td>
<td>301</td>
</tr>
<tr>
<td>Ti–51 at%Ni–1</td>
<td>333</td>
<td>294</td>
<td>321</td>
<td>239</td>
</tr>
<tr>
<td>Ti–51 at%Ni–2</td>
<td>320</td>
<td>297</td>
<td>318</td>
<td>243</td>
</tr>
</tbody>
</table>

Table 1 shows the sintering conditions and densities of the 4 kinds of SMA specimens used in the experiments. Figure 1 shows the microstructures of these SMAs observed with scanning electron microscope (SEM) after chemical etching by the 50 vol.%HF + 50 vol.%HNO₃ aqueous solution. From these magnified surface aspects, many etching pits (black parts) are observed.

Table 2 shows the transformation temperatures measured with a differential scanning calorimeter (DSC) for these SMAs. The starting and finishing temperatures of martensitic transformation are noted by Mᵣ and Mₛ, respectively, and also Aᵣ and Aₛ are those of the reverse transformation. It is clear that the increase of only 1 at%Ni in the alloy decreased...
these transformation temperatures. Especially, this trend becomes remarkable for the $A_f$ and $M_f$. On the other hand, almost no change due to the difference in the sintering condition was observed in these behaviors, at least in our material-producing process. In this study, Stellite 6B (approximately 65Co–30Cr–4W–1C in mass%) was used as the reference material. The average Vickers hardness values of Ti–50 at%Ni–1, Ti–50 at%Ni–2, Ti–51 at%Ni–1 and Ti–51 at%Ni–2 measured at 298 K are 254, 372, 416 and 324, respectively. And that of the Stellite is 534.

![Image](image_url)

**Fig. 1** Microstructures of shape memory alloys before tests.

![Image](image_url)

(a) Ti-50 at%Ni-1; (b) Ti-50 at%Ni-2
(c) Ti-51 at%Ni-1; (d) Ti-51 at%Ni-2

**Fig. 2** Erosion test method.

(a). Schematic flow diagram; (b). Actual aspect of hot water jet.
Erosion test was conducted by the method shown in Fig. 2. A specimen with 16 mm in diameter and 3 mm in thickness was exposed to compressed hot water jet. Here, the temperature \( T_{in} \) and pressure \( P_{in} \) of the compressed water were 423 K and 14.7 MPa, respectively. The compressed water was gushing from the nozzle with a diameter of 0.3 mm to atmosphere. Then, the high-speed water jet impacted on the specimen located at a distance of 10 mm from the nozzle, which was made of Type 304 stainless steel with 1 mm thickness.

![Erosion Damaged Surface](image)

**Fig. 3** Determination of the maximum damaged cross-sectional area and depth.

![Damage Cross-Sectional Area](image)

**Fig. 4** The maximum erosion damaged cross-sectional area.

![Damage Surface Images](image)

**Fig. 5** Appearance of damaged surfaces eroded for 7.2 ks.
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The flow rate of water jet from the nozzle was $8 \times 10^{-6} \text{ m}^3/\text{s}$. After erosion tests, the appearances of erosion damaged surfaces were observed with SEM. Furthermore, the erosion damages were measured quantitatively with a surface roughness device. Figure 3 shows the determination of the maximum damaged cross-sectional area and the maximum damaged depth of the erosion-tested specimen.

To clarify the erosion fracture behaviors, distributions of stress components in the specimens were calculated with FEM, using MSC/Nastran for windows. The mechanical properties of a Ti–50 at% Ni SMA at austenitic phase, measured by Nakao et al. 4) were used in the analysis.

3. Results and Discussion

3.1 Results of erosion tests and FEM analysis

Figure 4 shows the relationship between the maximum erosion damaged cross-sectional area and the exposure time. It is found that the damaged area increases linearly with the elongated exposure time for all materials. Especially, comparing with that of the SMAs, the damaged area of Stellite is extremely large. The damaged area of the Ti–51 at% Ni–1 specimen is a little small, in comparison with other SMAs. However, almost no remarkable difference in the damaged areas was observed among these four kinds of Ti–Ni SMAs. Figure 5 shows the appearances of damaged surfaces exposed to the hot water jet for the same time of 7.2 ks. From this figure, it is clear that Stellite was subjected to the wide-ranged erosion damage. As an example, the magnified appearance of the damaged surface for the Ti–50 at% Ni–2 specimen is shown in Fig. 6. From this figure, some grain boundary facets and cracks are also observed in the eroded area. Results of the maximum damaged depth are shown in Fig. 7. The maximum damaged depth of Ti–51 at% Ni–1 exhibited the smallest for the elongated exposure time, comparing with those of Stellite and other Ti–Ni alloys which showed almost the same values.

It has been considered that the impact pressure on the specimen will be about 10 times of the $P_{in}$ due to the pulsating of the water jet. 6) Distributions of stress components in the round plate with 3 mm in thickness and also in diameter were analyzed with FEM, as a pressure of 150 MPa statically loaded on the center surface with a diameter of 0.3 mm. A quarter of the round plate was axi-symmetrically modeled with solid elements. Figure 8 and Fig. 9 are the results of FEM analysis showing the distributions of the maximum shear stress and the mean stress in the FEM model, respectively. From these figures, larger values of them are found to distribute in the model near the loading area.

3.2 Discussion

It is considered that the specimen temperature will become almost equivalent to that of the water jet. From the results of transformation temperatures measured by DSC, the specimen temperatures of Ti–50 at% Ni and Ti–51 at% Ni in erosion tests will be $A_f + 40 \text{ K}$ and $A_f + 90–100 \text{ K}$, respectively. On the other hand, large stress and strain can be caused partially in specimens by the high-speed hot water jet. As the stress and strain increase, the stress-introduced martensitic transformation will occur in these specimens with the parent phase of austenitic phase (B2 structure). So, the Ti–50 at% Ni alloys transform to martensite phase more easily than Ti–51 at% Ni SMAs. There is a general fact that the strength of the martensite phase is weak and that of the parent phase with B2 struc-
ture is strong. Therefore, the reason that the maximum damaged depth as well as the maximum damaged area at cross section of Ti–51 at%Ni–1 among the Ti–Ni alloys showed the smallest values should be explained by these facts.

The difference in the morphology and also the damage mechanism of the erosion due to the hot water jet impact become clear from Fig. 10. Here, the ratio of the damaged area to the damaged depth is very small for all Ti–Ni alloys, while it is extremely large for Stellite. Authors have reported that the damages of Stellite due to hot water jet impact may be caused by the simultaneous interaction effects of the shear stress induced by the high-speed hot water flow and the cavitations on the specimen surface. Therefore, the results obtained in the present tests can be discussed with the following erosion damage mechanism.

At first, it is considered that the essential reason of the erosion damage due to hot water jet should be cavitation reacted on the specimen surface, resulting in the enlarging of the damaged depth. It has been known that the growth of cavities or cracks in materials is promoted strongly by the mean stress component. From Fig. 9 of the FEM results, the larger mean stress distributed near the erosion areas. Because of the existence of the initial porosity in the present SMAs, cracks should be formed and propagated by the hydrostatic pressure (the mean stress) due to the hot water impact on specimen surfaces, leading to the erosion regions breaking away. As shown in Fig. 7, the result that Ti–Ni alloys exhibited almost the same damaged depth with Stellite should be due to the existence of the porosity in these SMA specimens (refer to Fig. 1). Concerning the improvement of erosion dam-
As plotted in Fig. 11, the damage rates in area for Ti–Ni SMAs and Stellite decrease with the increasing hardness. This behavior shows the very good correspondence with the results obtained by the cavitation test. However, the damage rate in area for Stellite with very high hardness is extremely large, as compared to that of the Ti–Ni SMAs. As mentioned above, the damaged area rate of Ti–Ni SMAs is mainly controlled by shear stress. On the other hand, Stellite is simultaneously subjected to the damage due to the shear stress and also cavitation, resulting in the increase in both of the damaged depth and the damaged area.

4. Conclusions

For Ti–Ni shape memory alloys fabricated by a powder metallurgy method, erosion resistance against the hot-water jet impact was investigated experimentally and by FEM analysis, in comparison with a Co-based alloy (Stellite). The essential results obtained are summarized as follows:

(1) The erosion damaged cross-sectional area and also the maximum damaged depth increased linearly with the elongated exposure time for all materials used in the work. The damaged areas of SMAs, exposed to the high temperature water jet, showed extremely small values than those of Stellite. However, almost no differences in the maximum damaged depth were found between the SMAs and Stellite.

(2) From the FEM results, larger values of the maximum shear stress and the mean stress were found to distribute in the specimens in testing. This behavior showed the good correspondence with the erosion test results.

(3) The essential damage mechanism of Ti–Ni SMAs is the cavitation, and that of Stellite is a combination of the cavitation and the shear stress induced by the high-speed hot water flow on the specimen surface.

(4) Considering that the cavitation is the main erosion damage mechanism for Ti–Ni SMAs, it is suggested that the reduction of the porosity in materials will be the most important subject.

The erosion resistance of Ti–Ni SMAs is extremely superior to that of Stellite. Therefore, it is suggested that the Ti–Ni SMAs will be one of the promising alternative materials for the existing Co-based alloys.

REFERENCES