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# Cavitation erosion resistance and ratio of elastic deformation energy to total deformation energy for $Ti_3Al$ and TiNiNb alloys①

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**Abstract:** The cavitation erosion of Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel has been investigated in tap water by using rotating disc equipment. It is shown that Ti-24Al-15Nb-1Mo alloy has the highest cavitation erosion resistance among the three tested materials and Ti-46Ni-9Nb alloy is more resistant to cavitation erosion than 0Cr13Ni5Mo stainless steel. To simulate the effect of collapse of vapor cavities or bubbles, the Rockwell hardness tester was used to exert a load on the small area of the tested materials, and the elastic deformation energy and total deformation energy in indentation were determined. The experiment results show that there is a good correlation between cavitaton erosion resistance and the ratio of elastic deformation energy to total deformation energy in indentation for the three tested materials. The higher the ratio, the better the cavitation erosion resistance.

**Key words:** energy; cavitation erosion; indentation; $Ti_3Al$; TiNiNb
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## 1 INTRODUCTION

Cavitation erosion is caused by the growth and collapse of vapor cavities or bubbles due to local pressure fluctuation in a liquid[1]. It is a serious problem in high-speed components of hydraulic machines. Although a great amount of work on the cavitation phenomena has been published, the cavitation erosion mechanism of materials is still not understood completely. It is generally believed[2, 3] that mechanical attack is a dominant mechanism for cavitation erosion. Many investigations[4-6] attempted to correlate the mechanical properties such as yield or ultimate stress, hardness, impact toughness, ductility, with cavitation resistance of materials. Unfortunately all such attempts have been unsuccessful. There is no general correlation between cavitation erosion resistance and conventional mechanical properties. It is suggested that cavitation erosion should be considered as a unique type of material damage in its own right[1].

In recent years, Ti-Ni shape memory alloys have been found to exhibit excellent wear resistance[7, 8] and cavitation erosion resistance[9, 10], which are mainly ascribed to their pseudoelasticity. In view of the localized loading condition experienced by a metal exposed to cavitation, Cheng et al[11] established an empirical relationship between the cavitation erosion resistance $R_e$ and indentation-derived properties, i.e. the quantity $w/\delta_u$, where $w$ is the work of indentation and $\delta_u$ is the unrecoverable plastic deformation. Liu et al[12] also used a indentation technique to evaluate the pseudoelasticity of Ti-Ni alloy. They showed that the higher the recoverable deformation energy and the ratio of the recoverable deformation energy to the total deformation energy in indentation test, the higher the pseudoelasticity and wear-resistance of Ti-Ni alloy. Therefore indentation test is a good method of evaluating elasticity and cavitation resistance of materials. However, up to now no work on the indentation behaviour of metals with ordinary elasticity has been published. Their good cavitation erosion resistance is usually ascribed to high work-hardening ability or strain-induced phase transformation. The effect of elastic deformation energy is not considered. In the present study, $Ti_3Al$-based alloy with ordinary elasticity was chosen as the test material, and its cavitation erosion resistance and elasticity were investigated.

The TiNiNb alloy is developed from a TiNi shape memory alloy. It is distinct from other shape memory alloys for its wide phase transformation temperature hysteresis. Because there is no relative report on its cavitation erosion behavior, this work also

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studies the cavitation erosion behavior and indentation behavior of TiNiNb alloy.

## 2 EXPERIMENTAL

The tested alloys Ti-46Ni-9Nb and $Ti_3Al$-based Ti-24Al-15Nb-1Mo were obtained from Beijing Institute of Aeronautical Materials, China. Ti-46Ni-9Nb alloy was received in the cast and heat treated condition. Its microstructure consists of equiaxed TiNi grains, net eutectic( β-Nb+ NiTi) and β-Nb particles, as shown in Fig. 1( a). Ti-24Al-15Nb-1Mo alloy was tested in the hot rolled and heat treated condition. Its microstructure consists of $\alpha_2$-$Ti_3Al$ and β transformed structure, as shown in Fig. 1 ( b). 0Cr13Ni5Mo martensitic stainless steel, which is commonly used for hydroturbines in China, was chosen for comparison.

The cavitation erosion experiment was carried out in the tap water by using rotating disc equipment. The rotating speed is 2 960 r/min. The linear velocity of specimens is 45 m/s. An electronic balance, with a weighing accuracy of ±0.1 mg in the range from 0 to 210 g was used to determine the mass loss of the specimens due to cavitation erosion. The specimens were removed at intervals, washed in alcohol, and dried prior to weighing. The microstructures of eroded surfaces were studied by X-ray diffraction (XRD).

Because it is simple, nondestructive and localized in loading[11], indentation test was chosen to simulate the impact of microjet to the surfaces of Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel. An HRD-150 elastic Rockwell hardness tester with a diamond cone indenter was used. The applied load was 588 N, 980 N, and 1 470 N respectively and the loading time was 10 s. During indentation, the loading and unloading process was recorded automatically, resulting in a load-displacement curve. The total deformation energy $E$, elastic deformation energy $E_e$ and the ratio of elastic deformation energy to total deformation energy $\eta$ were determined. Every energy value was measured, with an accuracy of ±0.1 mJ, for 5 times.

## 3 RESULTS AND DISCUSSIN

### 3.1 Cavitation erosion resistance

Fig. 2 shows the cumulative volume loss versus time of exposure to cavitation erosion for Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel. After a short incubation period, 0Cr13Ni5Mo stainless steel loses volume rapidly. Ti-24Al-15Nb-1Mo alloy exhibits a longer incubation period and loses volume slowly. Although Ti-46Ni-9Nb alloy has higher volume loss in the early stages of cavitation erosion , its volume loss rate is nearly constant. The experiment result indicates that among the three tested materials, Ti-24Al-15Nb-1Mo alloy exhibits the best cavitation erosion resistance, and Ti-46Ni-9Nb allov is more resistant to cavitation erosion than 0Cr13Ni5Mo stainless steel.

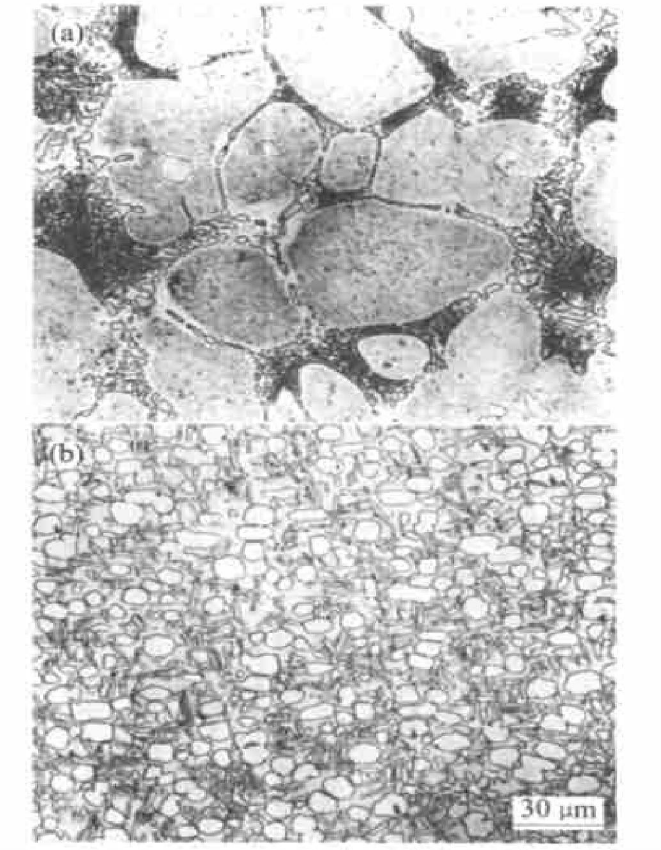


**Fig. 1** Microstructures of Ti-46Ni-9Nb alloy( a) and Ti-24Al-15Nb-1Mo alloy( b)

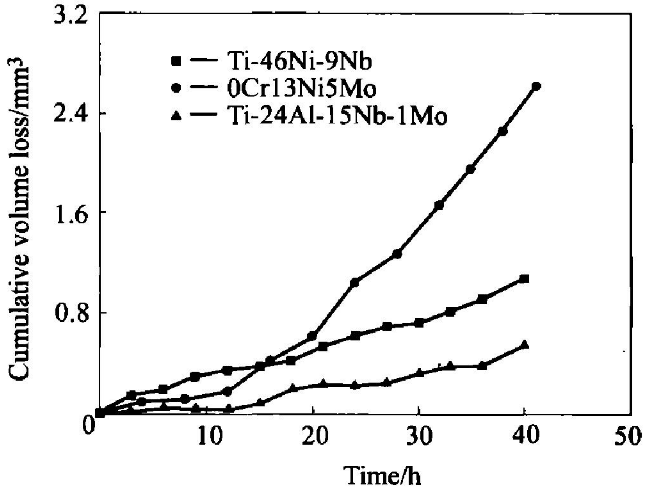


**Fig. 2** Cumulative volume loss as function of time for Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel

The X-ray diffraction traces obtained from Ti-46Ni-9Nb alloy before cavitation erosion and after 40 h of exposure to cavitation erosion are shown in Fig. 3. It is shown that the composed phases after cavitation are NiTi and β-Nb, the same as those before cavitation, indicating that Ti-46Ni-9Nb alloy does not

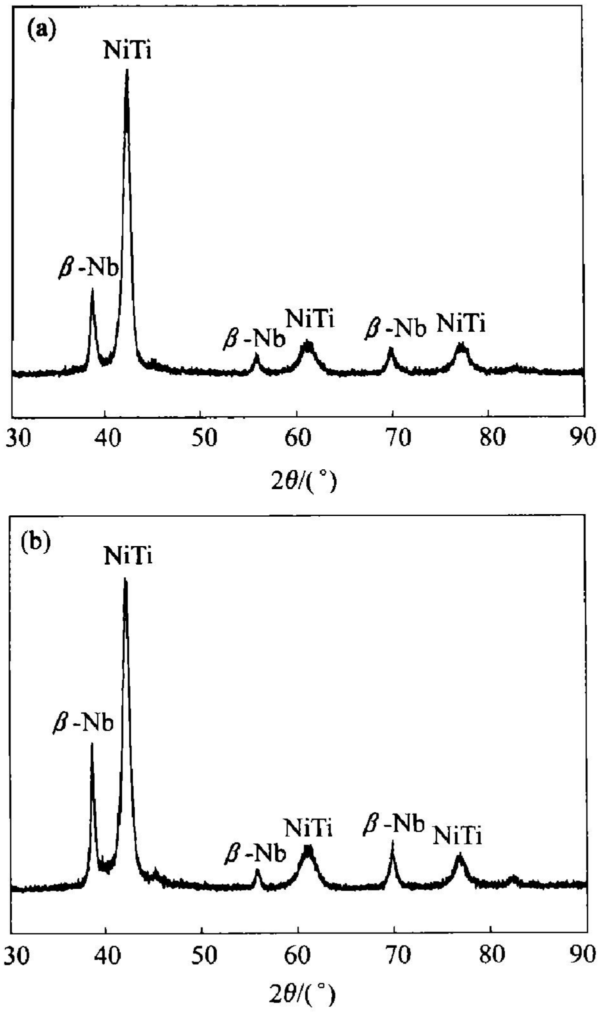


**Fig. 3** X-ray diffraction spectra of surfaces for Ti-46Ni-9Nb alloy before(a) and after(b) cavitation erosion

undergo strain-induced martensitic transformation during cavitation erosion. Its better cavitation erosion resistance is not ascribed to phase transformation

## 3.2 Indentation behavior

Cavitation erosion is caused by microjet. The impact energy of microjet mainly transforms into elastic deformation, plastic deformation and fracture energy of materials etc. The higher the ability of absorbing and dissipating impact energy without damage, the better the cavitation erosion resistance for the materials. It is necessary to study the cavitation erosion resistance of materials in view of energy and localized load. Because the indentation process is somewhat similar to the impact of microjet on the surface of solid during cavitation erosion, the indentation test was employed for the characterization of localized mechanical behavior of Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel.

Fig. 4 shows the load-displacement curve for Ti-46Ni-9Nb alloy, Ti-24Al-15Nb-1Mo alloy and 0Cr13Ni5Mo stainless steel under a load of 1 470 N in indentation. The area between the loading curve and the X-axis represents the total deformation energy $E$. The area between unloading curve and X-axis represents the elastic deformation energy $E_e$. Similarly, $E$ and $E_e$ values under a load of 588 N and 980 N respectively can be obtained. The results are listed in Table 1. The ratio of elastic deformation energy to total deformation energy is also shown.

As shown in Table 1, Ti-46Ni-9Nb and Ti-24Al-15Nb-1Mo alloys are more elastic than 0Cr13Ni5Mo stainless steel. Under a load of 588 N, the elastic deformation energy of 0Cr13Ni5Mo stainless steel is 0.006 1 J, while the $E_e$ values of Ti-46Ni-9Nb and Ti-24Al-15Nb-1Mo alloys are 0.010 7 J and 0.008 4 J. The $E_e$ values of three tested materials increase greatly with an increase in the applied load. The higher elastic deformation energy of Ti-46Ni-9Nb and Ti-24Al-15Nb-1Mo

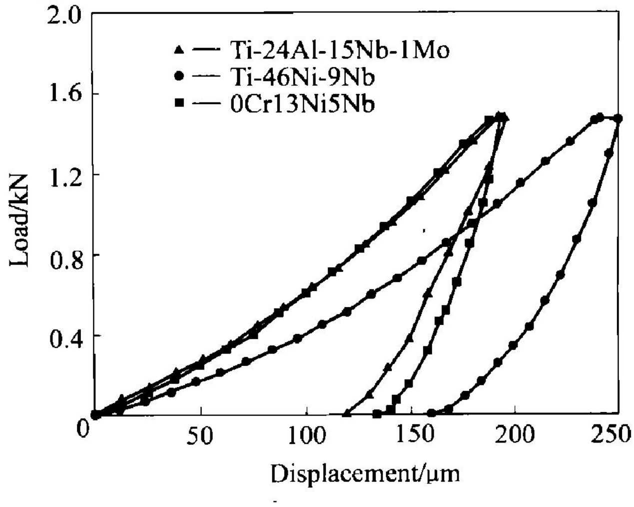


**Fig. 4** Load-displacement curves in indentation

**Table1** Total energy $E$, elastic deformation energy $E_e$ and elastic deformation energy to total deformation energy η in indentation for three kinds of materials

| Material | 588 N | | | 980 N | | | 1 470 N | | |
|---|---|---|---|---|---|---|---|---|---|
| | $E$/J | $E_e$/J | η/% | $E$/J | $E_e$/J | η/% | $E$/J | $E_e$/J | η/% |
| Ti-24Al-15Nb-1Mo | 0.023 7 | 0.008 4 | 35.4 | 0.059 7 | 0.021 2 | 35.5 | 0.125 3 | 0.045 9 | 36.6 |
| Ti-46Ni-9Nb | 0.034 8 | 0.010 7 | 30.7 | 0.079 5 | 0.026 0 | 32.7 | 0.159 3 | 0.046 6 | 29.3 |
| 0Cr13Ni5Mo | 0.025 6 | 0.006 1 | 23.8 | 0.058 5 | 0.014 1 | 24.1 | 0.122 7 | 0.031 0 | 25.3 |

alloys means that they can absorb more impact energy. However, Ti-46Ni-9Nb alloy, having the highest elastic deformation energy, does not exhibit the best cavitation erosion resistance, as shown in Fig. 1. Ti-46Ni-9Nb alloy not only has high elastic deformation energy, but also high plastic deformation energy. Unrecoverable plastic deformation due to dislocations or deformed twins leads to damage in the surface of materials. Thus to evaluate the capability of resisting cavitation erosion of materials, both elastic deformation energy and plastic deformation energy should be considered. The ratio $\eta$ of the elastic deformation energy to the total deformation energy involves both of them.

Under a load of 588 N, the $\eta$ values of Ti-24Al-15Nb-1Mo alloy, Ti-46Ni-9Nb alloy and 0Cr13Ni5Mo stainless steel are 35.4%, 30.7% and 23.8%, respectively. Unlike $E_e$ value, the ratio $\eta$ of the three tested materials changes a little with an increase in the applied load, so that the $\eta$ value can be determined under only one load. It is worth noting that the Ti-24Al-15Nb-1Mo alloy with the highest ratio $\eta$ exhibits the best cavitation erosion resistance, and the 0Cr13Ni5Mo stainless steel with the lowest ratio has the least cavitation erosion resistance. There is a good correlation between the ratio $\eta$ and cavitation erosion resistance: the higher the ratio, the better the cavitation erosion resistance. This is because those materials with the higher ratio can absorb more recoverable deformation energy with less damage. Therefore the ratio of the elastic deformation energy to the total deformation energy in indentation can be used to evaluate the cavitation erosion resistance of the three tested materials.

## 4 CONCLUSIONS

1) The Ti-24Al-15Nb-1Mo alloy has the highest cavitation erosion resistance among the three tested materials. Ti-46Ni-9Nb alloy is more resistant to cavitation erosion than 0Cr13Ni5Mo stainless steel.

2) There is a good correlation between cavitation erosion resistance and the ratio of elastic deformation energy to total deformation energy in indentation for the three tested materials. The higher the ratio, the better the cavitation erosion resistance.

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