Effect of Diameter Expansion Ratio on Recovery Properties of TiNiFe Alloy Pipe Coupling

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Abstract. The reverse transformation temperature, recovery strain and pull-out force of TiNiFe alloy pipe couplings under different diameter expansion ratios (7%, 9%, 11%, 13%, 15%) were studied. The results show that the martensite reorientation occurs and the elastic strain energy released decreases with the increase of the expansion ratio, which leads to the increase of martensite reverse transformation temperature as’ and A’r. The recovery strain increases and the recovery rate decreases with the increase of expansion ratio. The expansion ratio of pipe couplings has a great influence on the pull-out force, which is related to the fit clearance and the diameter of the connected rod. When the fit clearance is the same, the larger the expansion ratio is, the greater the pull-out force is, and when the diameter of the connected rod is the same, the pull-out force decreases with the increase of the expansion ratio.

1. Introduction

TiNiFe alloy is a kind of TiNi-based shape memory alloy. The martensitic transformation temperature of TiNiFe can be as low as -190°C [1], and it has high fracture stress (>900 MPa) [2]. Pipe couplings made of TiNiFe are widely used in the aerospace devices. The pipe coupling will not cause stress-induced martensitic transformation due to low working temperature, resulting in softening or loosening [3], and it can also guarantee that the pipe coupling will still maintain high connection strength at higher internal pressures, so it is the earliest practical memory alloy pipe coupling [4]. The effect of pre-strain on the recovery properties of TiNiFe and TiNiNb alloys have been investigated [5, 6], but there are few studies on the recovery behavior of TiNiFe alloy pipe couplings. The recovery temperature, recovery strain and pull-out force of TiNiFe alloy pipe coupling all affect its practical application, so this paper mainly investigated the effects of diameter expansion ratio on the recovery properties of TiNiFe alloy pipe coupling, including reverse martensite transformation temperature, recovery strain and pull-off force.
2. Experimental

The material used in this paper is a cold rolled Ti50Ni47Fe3 (at %) alloy tube with cold rolling deformation of 20%. It was processed into a pipe coupling with inner diameter of 11.45 mm, outer diameter of 16.00 mm and length of 8 mm. Finally, the pipe couplings were annealed at 500°C for 1 hour and cooled in air. The recovery properties of TiNiFe alloy pipe couplings were measured under 5 different diameter expansion ratios, which are 7%, 9%, 11%, 13% and 15%, respectively.

The reverse transformation temperature of the TiNiFe shape memory alloy used in this experiment are extremely low, and the conventional DSC has been difficult to accurately measure, so we used the following method for measurement. The inner diameter, outer diameter and length of pipe couplings were measured at room temperature. Pipe couplings were immersed in an ultra-low temperature petroleum ether solid-liquid mixture after pipe couplings were expanded in liquid nitrogen at -196°C. The bore dial indicator was used to record the change of the inner diameter of pipe couplings, and record changes of temperature with thermocouple. When the petroleum ether solution was heated, the pipe couplings shrank due to the reverse martensite transformation, and the change of inner diameter-temperature curve of the tubes was obtained (As shown in Figure 1). We can get the reverse transformation starting temperature $a_s'$, reverse transformation finishing temperature $a_f'$ and the strain of pipe couplings from this curve. The pull-out force test was carried out on a universal tensile test machine with a strain rate of 4 mm/min, displacement of 8 mm. The connected rod was made of stainless steel with a length of 120 mm.

![Figure 1. Change of inner diameter-temperature curves under 5 different expansion ratios](image)

3. Experimental Results and Discussion

3.1. Effect of Diameter Expansion Ratios on Reverse Transformation Temperature of TiNiFe Alloy Pipe Couplings

Figure 1 shows the change of inner diameter-temperature curves of pipe couplings under 5 different diameter expansion ratios. The reverse transformation temperature $a_s'$ and $a_f'$ under 5 different pre-strains can be obtained by drawing tangents, and the curves of the reverse transformation temperature-expansion ratios is shown in Figure 2.

As shown in Figure 2, as the diameter expansion ratio increases, the reverse transformation temperature $a_s'$ rises from -135.5°C to -120.7°C, and $a_f'$ rises from -132.4°C to -115.3°C. T.Y. Hsu [7]
pointed out that the elastic strain energy of martensitic can be used as the driving force of reverse martensitic transformation, and the magnitude of energy affects the recovery starting temperature. In this experiment, the larger the diameter expansion ratio, the more the reorientation martensite, the lower the energy of martensite interface, after pipe couplings were expanded. As a result, the driving effect is weakened, it is necessary to inverse transform to austenite at higher temperature. When the diameter expansion ratio continues to increase, the energy is substantially completely released, and the defects and plastic deformation in the alloy increase sharply, which also hinders the interface migration. \( A_s' \) still rises, but becomes more gradual.

The reduction in elastic strain energy, the increase in defects and plastic deformation, both of which also affect the magnitude of the reverse transformation temperature range \( \Delta T \) (\( A_f' - A_s' \)). As shown in Figure 2, when the diameter expansion ratio is small, \( \Delta T \) shows an upward trend, indicating that the defect has a great effect on \( \Delta T \). The influence of elastic storage energy is greater when the change of \( \Delta T \) is gentle.

![Figure 2](image_url)

**Figure 2.** The effect of different expansion ratios on the reverse transformation temperature

3.2. Effect of Diameter Expansion Ratios on Recovery Strain of TiNiFe Alloy Pipe Couplings

Figure 3 shows the effect of different expansion ratios on the plastic strain and recovery strain of the TiNiFe alloy pipe couplings after expansion. As the expansion ratio increases, the plastic strain and recovery strain increase gradually. However, the recovery strain is always smaller than the plastic strain, which is because of the increase of the elastic strain after expansion. The larger the diameter expansion ratio, the more the reorientation martensite can become austenite in the reverse martensitic transformation, so the recovery strain increases.
Figure 3. The effect of different expansion ratios on the recovery strain and elastic strain

Figure 4 shows the effect of different expansion ratios on the residual strain and recovery rate of the TiNiFe alloy pipe couplings. The recovery rate shows a decreasing trend, which is due to the additional plastic deformation of the martensite during expansion, and the additional plastic strain will not recover, so residual strain is greatly increased. Its defects are also increasing, which will hinder the martensitic interface migration, resulting in a decrease in recovery rate. The recovery rate has been drastically reduced to about 88% when the expansion ratio is 15%.

Figure 4. The effect of different expansion ratios on the residual strain and recovery rate

3.3. Effect of Diameter Expansion Ratios on Recovery Strain of TiNiFe Alloy Pipe Couplings

Figure 5 shows the effect of different expansion ratios on the pull-out force of the TiNiFe alloy pipe couplings in the case where the fit clearances between pipe couplings and connected rods are the same. It can be seen that the pull-out force increases with the increase of the expansion ratio. It is pointed out that the recovery stress is generated by the transformation of the transformation strain of the shape memory alloy into elastic strain [8]. When the fit clearance is the same, the recovery strain increases as
the expansion ratio increases, and the transformation strain also increases after reverse martensitic transformation, lead to the increases of pull-out force. However, the larger the expansion ratio, the more irrecoverable strains such as residual strain and defects, which causes the pull-out force to rise slowly.

Figure 5. The effect of different expansion ratios on the pull-out force at the same fit clearance

Figure 6 shows the effect of different expansion ratios on the pull-out force of the TiNiFe pipe couplings with the same diameter of the connected rods, that is, the fit clearance between pipe coupling and the connected rod is different. It can be seen from Figure 6 that the pull-out force of the tubes decreases as the expansion ratio increases. The fit clearance increases with the increase of the expansion ratio. When the pipe coupling is in contact with the connected rod, the stress of the pipe coupling with a large expansion ratio has been consumed by the fit clearance, resulting in a decrease in the pull-out force, and the larger the expansion ratio, the more the pull-out force decreases.

Figure 6. The effect of different expansion ratios on the pull-out force at the different fit clearance
4. Conclusion
The effect of diameter expansion ratio on recovery property of TiNiFe shape memory alloy pipe couplings were investigated. The important conclusions are as follows:

(1) with the increase of expansion ratio, the reverse martensite transformation temperature as' and \( A_f' \) of pipe fittings increase with the decrease of martensite elastic strain energy. Due to the influence of elastic strain energy and deformation defects, the inverse transformation temperature range \( \Delta T \) of pipe couplings tends to increase at first and then remain unchanged.

(2) With the increase of diameter expansion rate, the recovery rate of pipe fittings decreases, due to a sharp increase in residual strain. At 15% diameter expansion ratio, the maximum recoverable strain is about 9%.

(3) The diameter expansion ratio of pipe couplings has a great influence on the pull-out force, which is related to the fit clearance and the diameter of connected rod. When the fit clearance is the same, the larger the expansion ratio is, the greater the pull-out force is. When the diameter of the connecting rod is the same, the pull-out force decreases with the increase of the expansion ratio.

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