The role of martensite reorientation in the fretting behaviour of nickel titanium shape memory alloy

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Abstract: In this study, fretting tests of a GCr15 steel ball against a nickel titanium (NiTi) shape memory alloy plate (NiTi/GCr15) are performed on a horizontal servo-hydraulic fretting machine. It is found that the martensite reorientation plays an important role in the fretting behaviour of NiTi. Similar to that in a cyclic torsion test, the shear-induced martensite reorientation deformation of NiTi is reversible in tangential fretting, where the material undergoes a cyclic shear process. With an increase in the number of fretting cycles, the additional tangential displacement due to the martensite reorientation deformation in NiTi reaches its peak value at about 50–100 cycles after the initial increase, and finally decreases to a constant value after 1000 cycles. As a result, the martensite reorientation in fretting increases the elastic-accommodation ability of NiTi/GCr15 pairs, and further expands the partial slip regime of NiTi/GCr15 pairs. In addition, similar to the martensite phase transition in NiTi, the martensite reorientation in NiTi exhibits a strong shielding effect to decrease the contact stress of NiTi/GCr15 pairs and improve the wear resistance of NiTi.

Keywords: fretting, nickel titanium shape memory alloy, shear-induced martensite reorientation

1 INTRODUCTION

Nickel titanium shape memory alloys (NiTi SMAs) have attracted extensive interest in scientific research during the past decades [1, 2] for their unique superelasticity (SE) and shape memory effect (SME). The term superelasticity refers to the property by which an austenite–martensitic phase transition can be induced by applying stress and is recoverable after the removal of the stress. The shape memory effect is demonstrated by a plasticity-like strain due to a stress-induced austenite to martensite transformation that can be recovered by a reverse transformation to the austenite phase upon heating. Besides being widely used in medical surgery, NiTi SMAs have been recognized as promising and high-performance materials in the field of microelectromechanical systems (MEMS), such as, micropump, microvalve, microswitch, micromotor, etc. [3, 4]. In these applications, the NiTi alloy may be damaged due to fretting wear under vibration or cyclic loading conditions [5]. It is believed that the stress-induced martensite phase transition may play an important role in the deformation and fretting behaviours of NiTi in the SE region [6–9]. Nevertheless, most of the previous tribological studies focused on the macro-abrasive or erosion-wear resistance of NiTi, the fretting behaviour of NiTi alloy in the SME region has not been well addressed so far [10–14].

In previous studies, the unique temperature-dependent phase transition properties of superelastic NiTi was found to play a key role in its fretting behaviour, where the stress-induced phase transition not only improved the elastic accommodation ability of fretting pairs through a large recoverable phase transition deformation, but also increased its wear resistance by the transformation shielding effect [7, 8].
However, the effects of martensite reorientation on the fretting behaviour of NiTi in the SME region are not entirely clear. In this paper, the fretting tests of a NiTi plate in the SME region against a GCr15 steel ball (NiTi/GCr15) were performed at room temperature. The role of martensite reorientation in the fretting behaviour of NiTi is the focus of this study.

2 MATERIALS AND TESTING METHODS

Commercial 0.5 mm thick NiTi polycrystalline cold-rolling sheets were purchased from Shape Memory Applications, Inc. (San Jose, CA, USA). The nominal alloy compositions are Ni 50.7 and Ti-49.3 per cent. The size of the grains is about 50–100 nm as observed by transmission electron microscope \[15\]. With a differential scanning calorimeter (DSC 92, SETARAM, France), the characteristic transformation temperatures \(T_R^s, T_R^f\) (rhombohedral phase start and finish temperatures on cooling); \(T_M^s, T_M^f\) (martensite start and finish temperatures on cooling); \(T_A^s\) and \(T_A^f\) (austenite start and finish temperatures on heating) – were measured at heating and cooling rates of 1 °C/min and listed in Table 1. The results indicate that the material can exhibit the shape memory effect under stress at room temperature (\(\sim 20\) °C).

To characterize the mechanical properties of NiTi, tensile tests on sheet samples were performed by a universal testing machine (MTS SINTECH 10/D, USA) at various temperatures. Before measurements, the polished NiTi sheet was heated to 100 °C for 10 min, cooled down in liquid nitrogen for 1 h and finally heated to 20 °C so that it was in the martensite phase at room temperature. As shown in Fig. 1(a), the tensile stress versus strain curves of NiTi exhibits various behaviours at different temperatures. At 20 °C, since the NiTi is in the martensite phase, it will experience two stages of deformation during the loading process: martensite elastic deformation and martensite reorientation. During the unloading process for temperatures below 46 °C, the NiTi will remain in the martensite phase, and the residual deformation can be totally recovered by heating it above \(T_A^f\) (59 °C). Shear tests show similar curves except with lower martensite reorientation stress \[16\]. In a cyclic torsion test, the martensite reorientation deformation is found to be reversible since no plastic deformation happens in this process \[16\]. Similarly, the shear-induced martensite reorientation deformation of NiTi may also be reversible in tangential fretting, where the material will undergo a cyclic shear process. In addition, superelastic behaviour is observed in the tensile tests of NiTi at temperatures above 59 °C. Figure 1(b) shows a complete stress versus strain curve of NiTi at room temperature, which involves martensite elastic deformation, martensite reorientation, and martensite plastic yield. Similar to the superelastic NiTi alloy, the martensite yield stress of NiTi in the SME region is about 1600 MPa \[6\].

To prepare the samples for fretting tests, NiTi plates were cut into 10 × 20 mm² pieces with a wire-cutting machine and glued onto 10 × 20 × 10 mm³ cast iron blocks. Silicon carbide and aluminum oxide sand papers of various grades were used to polish the plate surfaces until a root mean square roughness of about 40 nm was reached.

The fretting tests were carried out on a horizontal servo-hydraulic fretting machine (Plint and Partners...
The schematic of the horizontal servo-hydraulic fretting test machine. The lower sample is a NiTi plate glued onto a cast iron block. During fretting tests, the upper GCr15 steel ball (diameter 40 mm) moved horizontally with displacement amplitude $D$ under a normal load $F_n$.

Three fretting regimes, namely the partial slip regime, mixed regime and gross slip regime, can be identified from Figs 3 and 4. For the value of $D \leq 5 \mu$m at $F_n = 100$ N and $D \leq 15 \mu$m at $F_n = 200$ N, all the $F_t$-$d$ curves of NiTi/GCr15 are quasi-closed except in the first few dozens of parallelogram-like loops (Figs 3(II-c) and (III-c)–(III-d)), which show the typical characteristics of the partial slip regime. Their corresponding tangential forces $F_t$ tend to be stable after the increase in the initial cycles (Figs 4(b) and (c)).

The mixed regime is located in $D = 5 \mu$m at 50 N, $D = 10 \mu$m at 100 N, as well as $D = 20 \mu$m at 200 N, where the shape of the $F_t$-$d$ curves becomes elliptical after the initial 1000 quasi-closed loops (Figs 3(I-d), (II-c), and 3(III-b)) [19]. With the increase in $N$, the corresponding values of $F_t$ show a slow decrease after the initial increase as shown in Fig. 4.

Finally, the gross slip regime of NiTi/GCr15 is found for $D \geq 30 \mu$m at 50 N, $D \geq 15 \mu$m at 100 N, as well as $D \geq 30 \mu$m at 200 N, where the shape of the $F_t$-$d$ curves changes gradually either from an ellipse to parallelogram or from an initially thick parallelogram to a thinner stable one. At the same time, the values of $F_t$ exhibit a sharp decrease after the initial increase, and finally reach a relatively stable situation after about 1000 cycles (Fig. 4).

Therefore, both Figs 3 and 4 indicate that the fretting behaviour of NiTi depends strongly on the displacement amplitude $D$ and normal load $F_n$. With the increase in $F_n$, the partial slip regime of NiTi/GCr15 expands and the mixed regime and gross slip regime move into a relatively large displacement amplitude.

Figure 5 shows the curves of $F_t/F_n$ as a function of $D$ at 5000 cycles. With the increase in $D$, the value of $F_t/F_n$ tends to be a constant after an initial quick increase. In the slip regime for $D \geq 30 \mu$m, the values of $F_t/F_n$ (or friction coefficient) are almost the same at various normal loads, which are very close to the friction coefficient of superelastic NiTi/GCr15 pairs under the same condition [7, 8].

3 EXPERIMENTAL RESULTS

3.1 The frictional logs of NiTi/GCr15 pairs

Figure 3 shows the friction log plots of a NiTi/GCr15 pairs under various values of $D$ and $F_n$. The $F_t$-$N$ curves, tangential force $F_t$ versus the number of fretting cycle $N$, are shown in Fig. 4. It is found that all the $F_t$-$N$ curves show an increase in $F_t$ during the first 50–200 cycles, and then $F_t$ reaches a maximum due to the adhesive contact between the pure NiTi alloy and GCr15 steel [17]. Finally, $F_t$ either stays constant or decreases depending on the presence of debris [18].

3.2 Morphology of NiTi/GCr15 wear scars

To understand the fretting mechanism of NiTi alloy, the full views of the wear scars on the NiTi plate were examined by an optical microscope and are shown in Fig. 6. The wear scars for various values of $D$ and $F_n$ exhibit different morphological features corresponding to three fretting regimes, which are separated by two black lines.

1. In the partial slip regime, namely for $D \leq 5 \mu$m at 100 N and $D \leq 15 \mu$m at 200 N, the wear scars can be clearly divided into two parts: the adhesive zone in the center and the micro-slip zone around the edge.
2. In the mixed regime, namely for $D = 5 \mu m$ at 50 N, $D = 10 \mu m$ at 100 N and $D = 20 \mu m$ at 200 N, no adhesive zone is observed in the wear scars and the area of the wear scars remains the same as that in the partial slip regime.

3. Finally, in the gross slip regime, namely for $D \geq 10 \mu m$ at 50 N, $D \geq 15 \mu m$ at 100 N and $D \geq 30 \mu m$ at 200 N, the area of the wear scars become larger than those obtained in the partial slip regime and mixed regime. Plenty of wear debris suggest that serious wear happened in the gross slip regime. Clearly, the features of the wear scars on NiTi are very consistent with the friction logs of the NiTi/GCr15 pairs.

With a laser confocal scanning microscope, the wear scar area $A$ on NiTi was measured and results are plotted in Fig. 7. The area $A$ increases with $D$ at the same value of $F_n$ or increases with $F_n$ at the same value of $D$.

3.3 Unique $F_t−d$ curve of NiTi/GCr15 pairs

Due to the stress-induced martensite reorientation of NiTi, the tangential force $F_t$ versus displacement $d$ (or $F_t−d$) curve of NiTi/GCr15 pairs is found to exhibit a unique shape. Figure 8 shows a typical $F_t−d$ curve of NiTi/GCr15 pairs (solid line) under the fretting conditions: $D = 30 \mu m$, $F_n = 100$ N, and $N = 50$. A typical $F_t−d$ curve of GCr15/GCr15 pairs (dashed line) under the same conditions is plotted together as a comparison. Different from the normal parallelopipedic shape $F_t−d$ curve in the slip regime, the part of the $F_t−d$ curve of NiTi/GCr15 pairs before gross slip can be
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Fig. 4 The tangential force $F_t$ versus the number of fretting cycles $N(F_t-N)$ curves of NiTi/GCr15 pairs under various fretting displacement amplitudes $D$ and normal loads $F_n$: (a) 50 N, (b) 100 N, and (c) 200 N.

Fig. 5 The stable value of $F_t/F_n$ of NiTi/GCr15 pairs after 5000 fretting cycles plotted as a function of $D$.

Clearly divided into two linear segments, AB and BC in Fig. 8 with different slopes. The tangential stiffness of NiTi/GCr15 therefore shows a variation as $F_t$ begins to change its direction. Here, since the line AB is mainly related to the elastic deformation of NiTi/GCr15 pairs, its slope is defined as the elastic tangential stiffness $K_e$. Nevertheless, since the line BC is related not only to the elastic deformation of contact pairs but also the shear-induced martensite reorientation deformation of NiTi plate, its slope is defined as the martensite reorientation tangential stiffness $K_m$. Thus, the displacement $\delta_m$ in fact reveals the additional tangential displacement due to the shear-induced martensite reorientation in NiTi under fretting.

The unique $F_t-d$ curve can be found in all the fretting cycles of NiTi/GCr15 pairs. Figure 9 shows the evolution of $F_t-d$ curves with an increase in $N$ for $D=30 \mu m$ and $F_n=100$ N. Even the $F_t-d$ curves show a large variation in shape with an increase in $N$, they are found to exhibit a similar unusual behaviour, namely with two different tangential stiffness $K_e$ and $K_m$ in the part of $F_t-d$ curve before gross slip.

4 DISCUSSION

4.1 Analysis on the contact of SME NiTi/GCr15 pairs

To provide a quantitative understanding of the role of martensite reorientation in the fretting process of NiTi/GCr15, a simple contact mechanics analysis was performed by applying the Hertzian contact theory. As shown in Fig. 10, the radius $R$ of the GCr15 steel ball is 0.02 m, the elastic modulus of GCr15 and NiTi were measured by a nanoindenter as 270 and 55 GPa,
The optical morphology of the wear scars on the NiTi plate under various fretting displacement amplitudes \( D \) and normal loads \( F_n \) with \( N = 5000 \).

Fig. 7 Area of wear scars on NiTi plate at various values of \( D \) and \( F_n \) with \( N = 5000 \) respectively. Assuming linear elasticity (no martensite reorientation occurs before NiTi yields), the maximum contact pressure \( \sigma_c \) in the contact area can be obtained by [20]

\[
\sigma_c = \frac{6F_nE^2}{\pi^3R^2}
\]  

Here, the effective elastic modulus \( E \) is calculated as 50 GPa. When the normal load \( F_n \) increases from 50 to 200 N, \( \sigma_c \) increases from 393 to 623 MPa as shown in Table 2. Since the friction coefficient of NiTi/GCr15 pairs in the gross slip regime is in the order of 0.6–0.7 (Fig. 5), the corresponding maximum shear stress \( \tau_c = 0.625\sigma_c \) will occur on the contact surface and increase from 246 to 389 MPa according to the analysis of Hamilton [21]. Due to the asymmetry of martensite deformation during tension and torsion, the martensite reorientation stress under shear is about 0.5 times that under tension (\( \sim 200 \) MPa) [20]. Based on the Tresca yield criterion, since all the values of \( \tau_c \) are higher than 100 MPa, the martensite reorientation deformation will happen in the NiTi sample under the given normal loads.

To verify the martensite reorientation deformation during indentation, three indents have been made on SME NiTi by a GCr15 steel ball under the normal load \( F_n \) of 50, 100, and 200 N. Figure 10 shows the profiles of the indents on SME NiTi. As shown in Fig. 10(a), with the increase in \( F_n \) from 50 to 200 N, the maximum indentation depth increases from 0.8 to 5 \( \mu \)m. However, after heating to 80 °C for 10 min, all the indents are recovered as shown in Fig. 10(b). These results clearly indicate that the residual deformation of the
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Fig. 9 The evolution of $F_t - d$ curves with the increase in $N$; $D = 30 \, \mu m$ and $F_n = 100 \, N$. All the curves exhibit two different tangential stiffnesses $K_e$ and $K_m$ in the part of $F_t - d$ curve before gross slip.

Fig. 10 The profiles of the indents on SME NiTi under various $F_n$: (a) before heating; (b) after heating to $80 \, ^\circ\text{C}$ for $10 \, \text{min}$

Table 2 Hertz contact press $\sigma_c$ and the maximum shear stress $\tau_c$ of NiTi/GCr15 pairs under given loads

<table>
<thead>
<tr>
<th>Normal load, $F_n$ (N)</th>
<th>50</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hertz contact press, $\sigma_c$ (MPa)</td>
<td>393</td>
<td>495</td>
<td>623</td>
</tr>
<tr>
<td>Maximum shear stress, $\tau_c$ (MPa)</td>
<td>246</td>
<td>309</td>
<td>389</td>
</tr>
</tbody>
</table>

Indents on SME NiTi is the martensite reorientation deformation, which can be totally recovered by heating above $A_f (59 \, ^\circ\text{C})$. The presence of this reorientation might show a shielding effect which decreases the contact stress in NiTi. For GCr15 steel ball contacts on the NiTi sheet, the representative strain $\varepsilon_r$ in NiTi can be estimated as [20]

$$\varepsilon_r = \frac{0.2a}{R}$$

where $a$ is the contact radius of NiTi/GCr15. By taking the contact radius $a$ as the radius of the wear scars on NiTi in Fig. 7, the representative strain $\varepsilon_r$ can then be evaluated as 0.36–0.86 per cent corresponding to various $F_n$. Since the representative strains $\varepsilon_r$ are far below the martensite reorientation strain ($\sim$4 per cent), the deformation region below the contact area of NiTi consists of only two parts under the given normal loads: the martensite elastic deformation zone and martensite reorientation zone as shown in Fig. 11. The maximum real contact stress $\sigma_r$ in NiTi should then be limited to the martensite reorientation stress under compression ($\sim$300 MPa) [16]. As the real contact stress $\sigma_r$ is lower than the Hertz contact stress $\sigma_c$ under similar conditions, it may be concluded that the martensite reorientation of NiTi can also exhibit a shielding effect to reduce the local stress in the contact area [7, 8]. This shielding effect can further improve the wear resistance of NiTi in fretting.

4.2 The shear-induced martensite reorientation of NiTi in fretting

From the above contact analysis, it is known that the loads in fretting tests are not large enough to induce the plastic yield of the NiTi plate and GCr15 ball. For the sphere–plane elastic contact in the fretting tests,
the tangential stiffness \( K \) can be determined by the following function [20]

\[
K = 8a \left( \frac{2 - v_1}{G_1} + \frac{2 - v_2}{G_2} \right)^{-1}
\]

(3)

where \( G_i \) and \( v_i \), for \( i = 1 \) and 2, are the shear modulus and Poisson ratio of the contact pairs, respectively. According to equation (3), \( K \) may be kept constant if the contact area did not change in fretting cycles. However, the experimental results in Fig. 9 indicate that the tangential stiffness of NiTi/GCr15 could periodically vary by as much as 60 per cent in fretting cycles. Since it is not possible for the contact area to have such cyclic variations in the fretting process, it is interpreted as the results of tangential stiffness change due to the shear-induced martensite reorientation of NiTi in fretting.

As shown in Fig. 11, the NiTi plate in fact not only suffered the normal force \( F_n \) but also the tangential force \( F_t \) in a real fretting test. For the given \( F_n \) between 50–200 N, the above analysis indicated that martensite reorientation deformation will happen in the NiTi sample and the maximum contact stress \( \sigma_t \) is limited to 300 MPa. In the gross slip regime, since the stable friction coefficient \( f \) is about 0.65 as shown in Fig. 5, the maximum shear stress \( \tau_c \) induced by \( F_t \) can then be estimated by [22]

\[
\tau_c = f\sigma_t = 195 \text{ MPa}
\]

(4)

Thus, since the maximum shear stress \( \tau_c \) is higher than the martensite reorientation stress under shear (100 MPa), the martensite bands in NiTi will reorient along the shear direction during the fretting cycles. As a result, an additional tangential displacement \( \delta_m \) due to the shear-induced martensite reorientation appears in the \( F_t - d \) curve of NiTi/GCr15 pairs, as well as the part of the \( F_t - d \) curve before gross slip exhibits two different values of tangential stiffness: \( K_1 \) and \( K_m \).

As known, the shear-induced plasticity could also contribute to the non-linear shape in the \( F_t - d \) curve before gross slip [23, 24]. Especially for the material under the condition of plastic shakedown, the part of the \( F_t - d \) curve before gross slip may assume a non-linear shape until it has been through a very large number of fretting cycles. However, the shear-induced plasticity is very different from the shear-induced martensite reorientation. Since the shear-induced plastic deformation is non-reversible and accommodated by dislocations, the non-linear part of the \( F_t - d \) curve before gross slip may quickly become linear due to the strain-hardening of the material under the condition of elastic shakedown. Even under the condition of plastic shakedown, since the amplitude of strain in the shakedown process is normally below 1 per cent, the part of the \( F_t - d \) curve before gross slip will exhibit a very small non-linear deformation [25]. On the other hand, during a cyclic torsion test of NiTi in the SME region, the amplitude of the martensite reorientation strain can be as high as 9 per cent [16]. Since no plastic deformation happens in the process, the shear-induced martensite reorientation deformation is found to be reversible during a cyclic torsion test. Similarly, as tangential fretting is a typical cyclic shear process, the shear-induced martensite reorientation deformation in SME NiTi should also be reversible under fretting. Consequently, NiTi may exhibit a very large reversible martensite reorientation deformation under shear after a much higher number of fretting cycles. This is demonstrated by the experimental results in Fig. 9, which shows an obvious martensite reorientation deformation in the \( F_t - d \) curve of NiTi/GCr15 even after 5000 fretting cycles.
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Since the tangential stiffness $K_e$ and $K_m$ are two important kinetic constants in fretting, it is interesting to study their dependence on the displacement amplitude $D$ and the normal load $F_n$. As the $F_t-d$ curve became stable at $N = 5000$ cycles, it is possible to fit the curves AB and BC to obtain the values of $K_e$ and $K_m$ for each stable $F_t-d$ curve corresponding to various values of $D$ and $F_n$. As shown in Fig. 12, both $K_e$ and $K_m$ increase with an increase in the normal load $F_n$, which may be explained by the increase in the contact area with the increase in $F_n$ according to equation (3). On the other hand, due to the additional martensite reorientation deformation, the value of $K_m$ is about half the value of $K_e$ at each $F_n$ in the slip regime.

The difference between $K_e$ and $K_m$ is in fact due to the additional tangential displacement $\delta_m$ in fretting. For $D = 50 \mu \text{m}$ and at various normal forces $F_n$, the curves of $\delta_m$ versus the number of fretting cycles $N$ (or $\delta_m-N$) are plotted in Fig. 13(a) (solid lines). It is found that the shape of the $\delta_m-N$ curve is very similar to that of its $F_t-N$ curve under the same conditions (dashed line), namely that $\delta_m$ reaches its peak values at 50–100 cycles after an initial increase and then decreases to a constant at 5000 cycles. This might be explained by the fact that a higher $F_t$ for the same contact area would induce a larger area of shear-induced martensite reorientation in NiTi and thus a longer $\delta_m$. Since $\delta_m$ can be as much as 12 $\mu \text{m}$ after 5000 cycles for $F_n = 200 \text{ N}$, it may be concluded that the NiTi can exhibit excellent damping property under complex loading condition. Figure 13(b) shows the $\delta_m$ versus $D$ (or $\delta_m-D$) curves for $N = 5000$ and at various normal forces $F_n$. With the increase in $D$, $\delta_m$ first increases quickly during the partial slip regime and mixed regime, then tends to be a constant in the gross slip regime, which is consistent with the variation of $K_m$ in Fig. 12.

### 4.3 The Effect of Martensite Reorientation on the Fretting Behaviour of NiTi

Based on the above discussion, it is understood that martensite reorientation exhibits significant effect on the fretting behaviour of NiTi. First, the martensite reorientation in NiTi plays a very important role in the fretting kinetics of NiTi/GCr15 pairs. Since the martensite reorientation in NiTi provides an additional reversible martensite deformation under shear, the tangential stiffness of NiTi/GCr15 pairs exhibits a large variation during a fretting cycle. In addition, the existence of $\delta_m$ further increases the elastic accommodation ability of NiTi/GCr15 pairs and decreases the slip displacement. As a result, the martensite reorientation in fretting might expand the partial slip regime of NiTi/GCr15 pairs and move the mixed regime and gross slip regime into a higher displacement amplitude.
Second, the martensite reorientation in NiTi could also improve the wear resistance of NiTi considerably. Accompanying the increase in the elastic accommodation ability of NiTi/GCr15 pairs, the area of wear scars on NiTi decreases. Similar to the martensite phase transition in superelastic NiTi, the martensite reorientation in SME NiTi exhibits a strong shielding effect which decreases the contact stress of NiTi/GCr15 pairs and improve the wear resistance of NiTi.

Therefore, the martensite reorientation in NiTi not only greatly increases the elastic accommodation ability of NiTi/GCr15 pairs through the large reversible reorientation deformation, but also highly improves the wear resistance of NiTi through its shielding effect.

5 CONCLUSIONS

Fretting tests were performed on NiTi in the SME region at various displacement amplitudes and normal loads. The main conclusions can be summarized as follows.

1. In the slip regime of NiTi/GCr15 pairs, the part of $F_t - d$ curve before gross slip can be clearly divided into two linear segments with different slopes. The tangential stiffness of NiTi/GCr15 therefore shows a variation as $F_t$ begins to change its direction. This is attributed to the shear-induced reorientation deformation of martensite bands in NiTi.

2. The martensite reorientation in NiTi increases the elastic accommodation ability of NiTi/GCr15 pairs in fretting. With the increase in the number of fretting cycles, the additional tangential displacement $\delta_m$ due to the martensite reorientation deformation in NiTi shows a similar variation to the tangential force $F_t$. The NiTi is also found to exhibit excellent damping property in fretting.

3. Accompanying the increase in the elastic accommodation ability of NiTi/GCr15 pairs, the area of wear scars on NiTi decreases. Due to its shielding effect, the martensite reorientation in NiTi reduces the contact stress of NiTi/GCr15 pairs and further improves the wear resistance of NiTi.

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