MECHANICS EXAMINATION ON THE WEAR BEHAVIOUR OF SHAPE MEMORY ALLOYS

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ABSTRACT

Shape memory alloys are well recognized functional and smart materials, which have been exploited to develop intelligent structures and devices in many fields. Of particular importance is its exciting application in the field of biomechanical engineering. In addition, further potential applications of shape memory alloys are being investigated, such as shape memory alloys-based functional composites. Recent experimental research indicates that shape memory alloy nickel-titanium alloy (NiTi) is superior to stainless steel against wear and could be applied in tribological engineering. It is believed that the super wear resistance of shape memory alloys is mainly due to the recovery of the superelastic deformation. Our recent wear study indicates that wear rate is very sensitive to the maximum contact pressure. In the present study, which involves applying Hertz contact theory and the finite element method, the wear behavior of shape memory alloys is investigated through analyzing the contact pressure. In contrast to the existing explanation of the major contribution of superelasticity, our investigation indicates that the superior wear resistance of shape memory alloys is directly linked to the low Young's modulus of the alloy, the low transformation stress and large transformation strain, which result in low maximum contact pressure and therefore low wear rate. Additionally, high plastic yield strength of transformed martensite NiTi also enhances its wear resistance.

1 INTRODUCTION

Shape memory alloys (SMA) are well known for possessing shape memory effect and superelasticity behaviour due to intrinsic microstructure transition of thermoelastic martensitic transformation. Both shape memory effect and superelasticity have been exploited to design functional and smart structures in mechanical and biomedical engineering [1-3]. A number of commercial products are already available on the market. For instance, couplings and fasteners based on shape memory effect have been extensively developed and applied. A historical example is the large-scale application of SMA coupling to connect titanium hydraulic tubing in the aircraft F-14 in 1971 [4].

Many more potential applications and mechanical behaviors of SMA have been investigated. For example, an anomalous relationship between hardness and wear properties of a superelastic nickel-titanium alloy (NiTi) was reported by Qian et al. [5] through their microwear tests. Recently, several experimental wear studies of SMA indicate that SMA is superior to common wear–resistant materials against wear. For examples, Richman et al [6] discovered from their experimental tests that NiTi alloys, a typical SMA, are much more resistant to cavitation erosion than even the best stainless steels. Jin and Wang [7] discovered in their experiments that the sliding wear resistance of NiTi is better than that of nitrided 38CrMoA1A alloy steel. The high wear resistance of this alloy is believed to be mainly due to its superelasticity or pseudo-elasticity by some researchers. For instances, Jin and Wang [7] believed that one of the reasons for the high wear resistance is NiTi has high reversible strain ability. Li, in several published papers, mentioned that the high wear resistance of TiNi alloy is mainly attributed to its unique pseudo-elasticity [8, 9].

If the recovery of the large deformation due to forward and reverse transformation, i.e., superelasticity, is the major reason for the high wear resistance of austenite NiTi, then it can be expected that martensite NiTi, which could not demonstrate superelastic behaviour, would have poorer wear behaviour. However, experimental study indicates that martensite NiTi has similar erosion wear behaviour to austenite NiTi [6], which could demonstrate superelasticity. This experimental result implicates that superelasticity might not be the only reason for the higher wear resistance of NiTi. Liang et al [10] pointed out, "it therefore seems unreasonable to emphasize simply the role of pseudoelasticity in wear behavior of NiTi alloys".

From a mechanical point of view, wear of metallic materials, defined as the removal of material from surface due to cyclic mechanical contact either from sliding contact in adhesive and abrasive wear or particle impulsion in erosion wear, originates from plastic deformation; see [11-13]. Plastic deformation and accumulation of plastic deformation due to cyclic loading will initiate microcracks in the surface and eventually wear debris will form. Therefore the wear resistance of a ductile material can be evaluated by its capacity of plastic deformation under wearing conditions. Under given contact loading conditions, if plastic deformation is difficult to be generated in a material, then this material is expected to possess high wear resistance.

Generally, in a contact problem, the maximum contact pressure instead of the total contact force will directly determine the maximum stress to trigger plastic deformation. For example, the maximum shear stress is equal to 0.3 of the maximum contact pressure in a plane strain contact problem between two cylindrical bodies [14]. Therefore the maximum contact pressure can be used to evaluate the initiation of plastic deformation in materials. Based on the wear mechanism of plastic accumulation and micromechanics analysis, a computation-based wear model was established recently [13]. According to this model, the accumulation of plastic deformation, which determines the wear rate, under sliding condition is very sensitive to the maximum contact pressure. For example, Figure 1 shows the variation of the normalized wear rate, $W\varepsilon_f / l$, with the normalized maximum contact pressure, p_0 / k_c, where k_c is the shear strength of the material. The wear rate increases dramatically when the maximum pressure P_0 increases from 3.75 to 4.5 times of the shear strength. The increasing effect of maximum pressure on wear rate has also been obtained from experimental wear test, see [14]. Therefore, the maximum pressure instead of the total applied load is a key variable to initiate plastic deformation and to evaluate the wear rate.

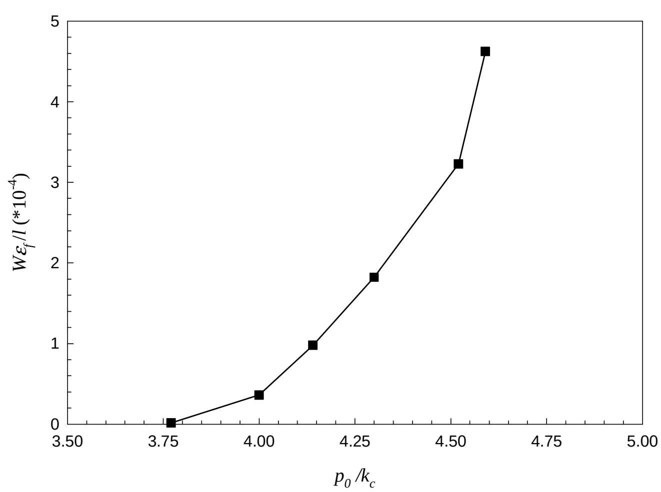

Figure 1. Influence of maximum contact pressure on sliding wear rate.

In this paper, the wear behaviour of NiTi is investigated by examining the maximum contact pressure from both Hertz contact theory of elastic contact and finite element analysis for a NiTi superelastic shape memory alloy and elastic-plastic deformation of a stainless steel. The major factors attributed to the high wear resistance of NiTi will be discussed based on the results obtained.

2 EXAMINATION BASED ON HERTZ THEORY

A simplified two-dimensional contact model is shown in Fig. 2 to simulate the mechanics action of a sliding wear process. At microscale the surfaces are contacted through asperities due to the roughness of the surfaces. The rigid cylinder in Fig.2 represents a hard asperity, which is subjected to an applied per unit thickness force F and contacts a half-infinite body. The half-infinite body represents NiTi or steel with the elastic modulus of E and the Poisson's ratio of v.

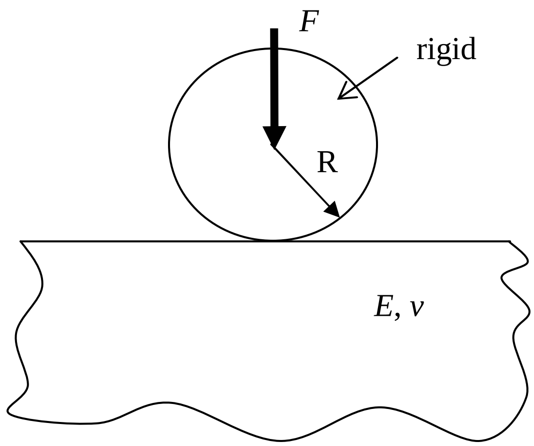

Figure 2. Illustration of a rigid asperity contacting NiTi alloy or steel

According to Hertz theory of elastic contact, the maximum pressure is

$$p_0 = \left(\frac{FE^*}{\pi R} \right)^{1/2} \tag{1}$$

where R is the radius of rigid asperity and $E^* = E/(1-\nu^2)$. The Poisson's ratios of a NiTi alloy and a steel can be reasonably assumed as the same. Therefore, the maximum contact pressure is proportional to the square root of the Young's modulus, i.e.,

$$p_0 \propto (E)^{1/2} \tag{2}$$

The Young's modulus of a steel is about 200GPa while it is much lower for NiTi alloys, which is about 60 GPa from a uniaxial test in [15]. Therefore, under same applied force and same contact geometry, the maximum pressure in NiTi about alloy is about 0.55 of the maximum pressure in typical steel from this simple Hertz elastic contact analysis. In comparison to normal steel, NiTi alloy has a lower elastic modulus, which will result in lower maximum pressure and delay the plastic deformation, therefore contributing to the increase of the wear resistance in this material.

3 EXAMINATION BASED ON FINITE ELEMENT ANALYSIS

In the previous section, we used Hertz theory to analyze the maximum contact pressure for a typical NiTi alloy and a typical steel alloy. Strictly, Hertz theory is only suitable for elastic materials. During a wear process, the material close to the failure zone should be in plastic state either for a steel or a NiTi. In the case of superelastic austenite NiTi alloys, prior to plastic deformation, the material will experience forward austenite-to-martensite transformation, which accompanies large deformation. Therefore plastic deformation in steel and the deformation due to martensitic transformation plus plastic deformation in NiTi should be considered in order to get the accurate results of the maximum contact pressure during a wear process. Here the numerical approach, the finite element method, is utilized to simulate the contact problems, elastic-plastic contact for steel and elastic-transformation-plastic contact for NiTi.

A typical NiTi superelastic alloy from [16] is considered in the current investigation. As shown in Fig. 3, in the uniaxial tensile test for superelasticity, a large deformation, over 4%, due to austenite to martensite forward transformation can be recovered during the unloading reverse transformation process, from martensite to austenite, which is indicated by the solid line. If the load is increased continuously after the full forward transformation, as indicated by the dashed line in Fig. 3, now the martensite of the NiTi alloy will have normal plastic deformation until it fails. The uniaxial tensile stress-strain curve of a typical stainless steel alloy (UNS31803) from [17] is also plotted by the dash-dotted line in Fig.3. If the load is increased continuously, the tensile steel bar will experience elastic deformation, plastic deformation and eventually breaking.

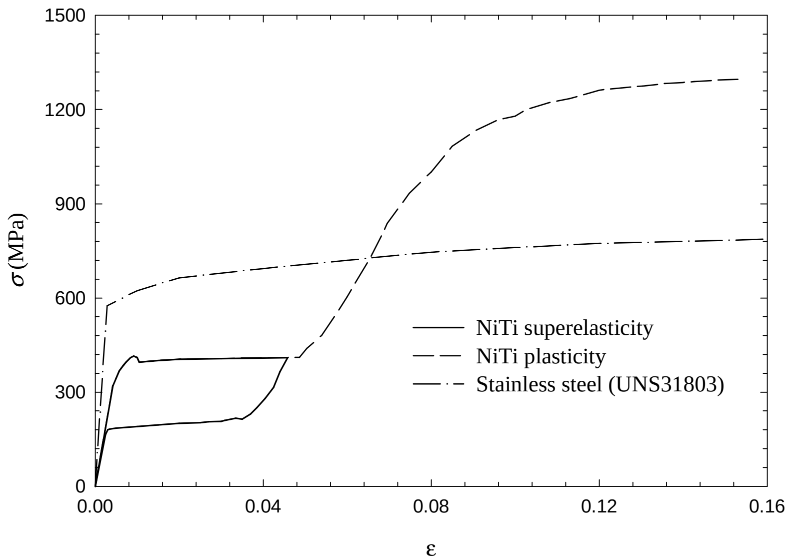

Figure 3. Superelasticity and superelastic-plastic deformation of a NiTi alloy [16] and elastic-plastic deformation of a stainless steel [17].

The basic material data for the steel and the NiTi alloy are summarized in Table 1, which are applied in the finite element simulation. The geometrical model is the same as the one shown in Fig. 1. The radius *R* of the rigid asperity is chosen as 0.4 mm. In our simulation, the plasticity of the steel is treated as normal isotropic hardening. A combined transformation plus plasticity model developed by Yan et al [18] is utilized in the present investigation. This combined model cannot only describe the superelastic phenomenon of shape memory alloy within the transformation range but also describe the plastic deformation and the constraint of plastic deformation on transformed martensite.

Table 1. Basic material data for the NiTi alloy [16] and the stainless steel [17]

Alloy	Young's modulus (GPa)	Transformation stress (MPa)	Yield strength (MPa)	Ultimate strength (MPa)
NiTi	62	407	1058	1330
Stainless steel	200	------	575	805

Figure 4 shows the numerical results of the maximum contact pressure as a function of the applied contact force for both stainless steel and NiTi alloy. It is clear to see that the maximum contact pressure, p_0, is smaller in NiTi than in the stainless steel until the applied force is over about 140 N or until the value of p_0 is over 1700 MPa. This high contact pressure corresponds to a severe sliding wear in steel. Therefore, the maximum contact pressure in the steel, in most sliding wear cases, will be much higher than that in NiTi alloy, which will contribute higher wear rate in steel based on the wear model of plastic deformation accumulation as discussed in the introduction. In the elastic contact region, as discussed in previous section, the lower Young's modulus of NiTi contribute to lower maximum contact pressure in the NiTi. In the region above the elastic contact, as shown in Table 1, the transformation stress of 407 MPa of the NiTi is lower than the yield strength of 575 MPa of the steel. Furthermore, as shown in Fig. 3, a large deformation with close to zero hardening occurs during the forward transformation. These are the two reasons for the NiTi to obtain larger contact area and lower contact pressure under the same loading condition once the load is over the elastic limit.

At the point of equal maximum contact pressure in the NiTi and in the steel, our numerical results indicate that the steel close to the contact zone experiences significant plastic deformation with the maximum equivalent plastic strain of 4.71% while it is only 0.16% in the NiTi early in yielding stage. Consequently, the steel close to the contact zone is expected to fail earlier than the NiTi under such cyclic contact conditions in a wear test, considering NiTi possessing comparable ductility. Lower plastic deformation in NiTi is due to higher yield strength of the transformed martensite in a NiTi, which is 1058 MPa against 575 MPa in the steel as shown in Table 1.

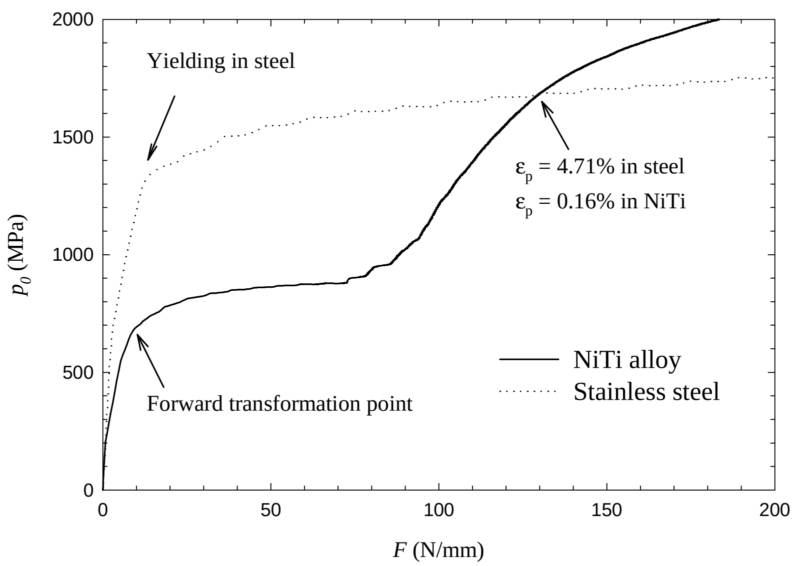

Figure 4. Variation of the maximum contact pressure with the applied contact force from FE simulations for elastic-plastic stainless steel and superelastic-plastic NiTi alloy.

4 CONCLUSION

Based on the wear model of plastic deformation accumulation, the maximum contact pressure is very sensitive to the wear rate. Higher maximum contact pressure would lead to higher wear rate. The maximum contact pressure in a typical superelastic NiTi alloy and in a typical stainless steel is examined by using Hertz elastic contact theory and the finite element method. Our results clearly indicate that lower Young's modulus results in lower contact pressure in the NiTi within the elastic contact limit. Beyond the elastic contact limit, the fact that the transformation stress in the NiTi is lower than the yield stress of the stainless steel will also result in lower contact pressure in a typical wear test. Our numerical results also indicate that higher yield stress of the transformed martensite in NiTi will increase the wearing resistance of this material further. This investigation clearly demonstrates that the high wear-resistance of NiTi is not mainly due to the recovery of the superelastic deformation.

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